CRANFIELD UNIVERSITY

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COASTAL MANAGEMENT AND ADAPTATION: AN INTEGRATED DATA-DRIVEN APPROACH

School of Water, Energy and Environment

PhD
18th March 2019

Supervisor: Dr Stephen H. Hallett
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This thesis is submitted in partial fulfilment of the requirements for the degree Doctor of Philosophy

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ABSTRACT

Coastal regions are some of the most exposed to environmental hazards, yet the coast is the preferred settlement site for a high percentage of the global population, and most major global cities are located on or near the coast. This research adopts a predominantly anthropocentric approach to the analysis of coastal risk and resilience. This centres on the pervasive hazards of coastal flooding and erosion. Coastal management decision-making practices are shown to be reliant on access to current and accurate information. However, constraints have been imposed on information flows between scientists, policy makers and practitioners, due to a lack of awareness and utilisation of available data sources. This research seeks to tackle this issue in evaluating how innovations in the use of data and analytics can be applied to further the application of science within decision-making processes related to coastal risk adaptation. In achieving this aim a range of research methodologies have been employed and the progression of topics covered mark a shift from themes of risk to resilience. The work focuses on a case study region of East Anglia, UK, benefiting from the input of a partner organisation, responsible for the region's coasts: Coastal Partnership East.

An initial review revealed how data can be utilised effectively within coastal decision-making practices, highlighting scope for application of advanced Big Data techniques to the analysis of coastal datasets. The process of risk evaluation has been examined in detail, and the range of possibilities afforded by open source coastal datasets were revealed. Subsequently, open source coastal terrain and bathymetric, point cloud datasets were identified for 14 sites within the case study area. These were then utilised within a practical application of a geomorphological change detection (GCD) method. This revealed how analysis of high spatial and temporal resolution point cloud data can accurately reveal and quantify physical coastal impacts. Additionally, the research reveals how data innovations can facilitate adaptation through insurance; more specifically how the use of empirical evidence in pricing of coastal flood insurance can result in both communication and distribution of risk.

The various strands of knowledge generated throughout this study reveal how an extensive range of data types, sources, and advanced forms of analysis, can together allow coastal resilience assessments to be founded on empirical evidence. This research serves to demonstrate how the application of advanced data-driven analytical processes can reduce levels of uncertainty and subjectivity inherent within current coastal environmental management practices. Adoption of methods presented within this research could further the possibilities for sustainable and resilient management of the incredibly valuable environmental resource which is the coast.

Keywords: Coastal management, resilience, evidence-based decision-making, data analytics, open source data, insurance, geomorphological change detection, GIS, Big Data

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ABM	Agent Based Model
AIS	Automatic Identification System
ANN	Artificial Neural Network
API	Application Programming Interface
BDB	Bathy DataBase
BGS	British Geological Survey
BODC	British Oceanographic Data Centre
C2C	Cloud to Cloud
CAT	Catastrophe
CCAG	Coastal Concern Action Group
CCC	Committee on Climate Change (UK)
CCMA	Coastal Change Management Area
CCO	Channel Coastal Observatory
CEDA	Centre for Environmental Data Analysis
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CPE	Coastal Partnership East (UK)
CVI	Coastal Vulnerability Index
DAC	Data Archive Centre
DEFRA	Department for Environment Food and Rural Affairs
DEM	Digital Elevation Model
DFT	Department for Transport
DoD	DEM's of Difference
DSAS	Digital Shoreline Analysis System
DSS	Decision Support System
EA	Environment Agency (UK)
EC	European Community
EMODnet	European Marine Observation Data network
EO	Earth Observation
ESA	European Space Agency
ESRI	Environmental Systems Research Institute
FAST	Foreshore Assessment using Space Technology
GCD	Geomorphological Change Detection
GIS	Geographical Information Systems
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GUI	Graphical User Interface
HDFS	Hadoop Distributed File System
HELCOM	Helsinki Commission- Baltic Marine Environment Protection Commission
HPCC	High Performance Computing Cluster
HPPC	High Performance Pre-Computing
iCOASST	integrating COASTal Sediment Systems
ICZM	Integrated Coastal Zone Management

INSPIRE	Infrastructure for Spatial Information in Europe
IoT	Internet of Things
ISO	International Organisation for Standardisation
IT	Information Technology
IUCN	International Union for Conservation of Nature
JNCC	Joint Nature Conservation Committee
LGA	Local Government Association
LIDAR	Light Detection and Ranging
LM TOM	London Market Target Operating Model
LoD	Limit of Detection
MAGIC	Multi-Agency Geographic Information for the Countryside
MAREMAP	Marine Environmental Mapping Program
MBES	Multibeam Echosounder
MCZ	Marine Conservation Zone
MEDIN	Marine Environmental Data and Information Network
MET	Meteorological
MKEN	Marine Knowledge Exchange Network
MLS	Mobile Laser Scanning
MMO	Marine Management Organisation (UK)
MODIS	Moderate Resolution Imaging Spectroradiometer
MPA	Marine Protected Area
MSP	Maritime Spatial Planning
MSW	Making Space for Water
MVI	Multi-scale Vulnerability Index
NCEI	National Centre for Environmental Informatics (NOAA, USA)
NCERM	National Coastal Erosion Risk Mapping
NERC	National Environmental Research Council
NGO	Non-governmental organisation
NLP	Natural Language Processing
NOAA	National Oceanographic and Atmospheric Association (USA)
ODN	Ordnance Datum Newlyn
OECD	Organisation for Economic Co-operation and Development
OGA	Oil and Gas Authority
OGC	Open Geospatial Consortium
ONS	Office for National Statistics
OS	Ordnance Survey
OSPAR	Oslo/Paris convention (for the Protection of the Marine Environment of the North-East Atlantic)
QA	Quality Assurance
QSR	Quick Scoping Review
RDBMS	Relational Database Management System
REST	Representational State Transfer (web services)
RISC-KIT	Resilience-increasing Strategies for Coasts–toolkit
SaaS	Software as a Service
SAR	Synthetic Aperture Radar

SCAR	Suffolk Coast Against Retreat
SFM	Structure From Motion
SIG	Special Interest Group
SMP	Shoreline Management Plan
SPRC	Source-Pathway-Receptor-Consequence
SQL	Structured Query Language
TIN	Triangulated Irregular Network
TLS	Terrestrial Laser Scanning
UKHO	United Kingdom Hydrographic Office
UNEP	United Nations Environment Programme
WFS	Web Feature Service
WMS	Web Map Service

1 Introduction

1.1 Data-driven coastal management

Coastal regions are vulnerable to environmental hazards; risk levels are further increased by their mismanagement and the execution of maladaptive practices. 'No other region is more threatened by natural perils than the coasts' (Kron, 2013, p.1378), and resources related to the sea and coastal zone are some of the most exposed. Within Europe alone it has been estimated that 'about twenty thousand kilometres of coasts, corresponding to 20%, faced serious impacts in 2004' (Centre for Climate Adaptation, 2015). Furthermore, 25% of Europe's coastline has been reported as experiencing erosion (Dodds, 2009). Since 2004 the situation has not improved, leading to the European Union proposing a directorate for maritime spatial planning and integrated coastal management in 2013 (European Commission, 2016). A report published by the UK Committee for Climate Change (2018) also highlighted how in England 520,000 homes face at least a 0.5% risk from coastal flooding and nearly 9,000 properties are at risk from coastal erosion.

Decision-making in this realm is reliant on access to the most up to date information and sound analytical outputs. However, a reliance on expert-opinion, subjective judgements and an inadequate evidence base, can further contribute to problems related to coastal environmental hazards (McLaughlin and Cooper, 2010; Smith, 2012; Viavattene et al., 2015; Westmacott, 2001). A wealth of data exists for many vulnerable coastal regions. This data underlies scientific advances in our understanding of coastal processes and evaluation of risk in these areas. Furthermore, novel information and computational techniques hold potential to improve how these data sources are utilised within planning, management, risk evaluations and resilience assessments of coastal regions (Pollard et al., 2018).

For governments to adopt the optimal coastal adaptation strategies, decision-making needs to be based on sound science and a diversified evidence base (Nicholls et al., 2015a). However, this knowledge base has been underutilised by coastal practitioners and land planners globally, many of whom are unaware of the full potential which holistic data evaluations can present (O'Mahony et al., 2015). Technological advances in acquisition, processing and analysis of datasets related to the coast, present new, largely untapped, opportunities for decision makers working in this domain. Yet there are many hurdles preventing the application of these scientific and technological developments. These can relate to a lack of awareness of what data is available, and how this can be combined and analysed to provide information outputs (which can reduce uncertainty and subjectivity, inherent within coastal management practices) (Wheeler et al., 2010). Through close contact with coastal management professionals, this project has sought to bridge the divide between science and industry, completing valuable research into how innovations in the use of data can result in the application of science within evidence-based coastal management decision-making practices.

1.2 Aim and Objectives

The aim of this study is:

'To evaluate how innovations in the use of data and analytics can be applied to further the application of science within decision-making processes related to coastal risk adaptation'.

In addressing this aim the research had the following objectives:

1. Identify and analyse challenges and knowledge gaps in relation to data-driven approaches to coastal risk evaluation.
2. Evaluate how open source data can be utilised within holistic coastal risk evaluations.
3. Evaluate the application of point cloud based geomorphological change detection to analysis of coastal change, in doing so generate insight on the nature of recent morphological impacts across the region of East Anglia.
4. Evaluate the potential for innovations in the utilisation of data within coastal flood risk evaluations for the insurance industry, allowing insurance to act as a soft adaptation mechanism, distributing and communicating risk.
5. Explore how coastal practitioners can incorporate important missing aspects of coastal resilience in their decision-making processes at a regional scale, through a data-driven approach.

The aim and objectives of this study were achieved through a case study approach focusing on the vulnerable coastal region of East Anglia, UK. This region is representative of some of the major coastal challenges faced at a global level, and further benefits from having an extant wealth of data available relating to physical processes, society, and the economy within the coastal zone. Throughout the research close collaboration has been maintained with the two key stakeholders and partners: British Geological Survey (BGS) and Coastal Partnership East (CPE). Additional input has been provided by Lloyd's insurance market, the Environment Agency (EA) and bodies such as the Anglian Coastal Monitoring Group.

This study set out to tackle the core issue of reduction of uncertainty within coastal management decision-making processes, through application of new and advanced forms of data acquisition and analyses. The main hazards studied were coastal flooding and erosion.

1.3 Thesis Structure

The research adopted a staged approach. The method involved:

1) Establishing the role of data within coastal risk management processes, and the associated challenges (Chapter 2);
2) Evaluating the available evidence base (involving a holistic evaluation of open source data), and development of a conceptual framework, for coastal risk evaluations (Chapter 3);
3) Determining the application of high-resolution point cloud data and GIS based workflows to geomorphological change analyses for coastal test sites (Chapter 4);
4) Investigating how innovations in the use of data, allowing more robust risk assessments, can enable insurance to act as an adaptation mechanism (Chapter 5); and
5) An evaluation of how data-driven resilience assessments are able to draw together data sources and analytical techniques profiled within this study, in addressing the requirements of a coastal authority (Chapter 6).

The progression of topics covered sequentially within the chapters of the thesis are presented in Figure 1. The process involved collaboration with coastal practitioners and stakeholders, in framing the research questions tackled and evaluating the relevance of outputs generated.

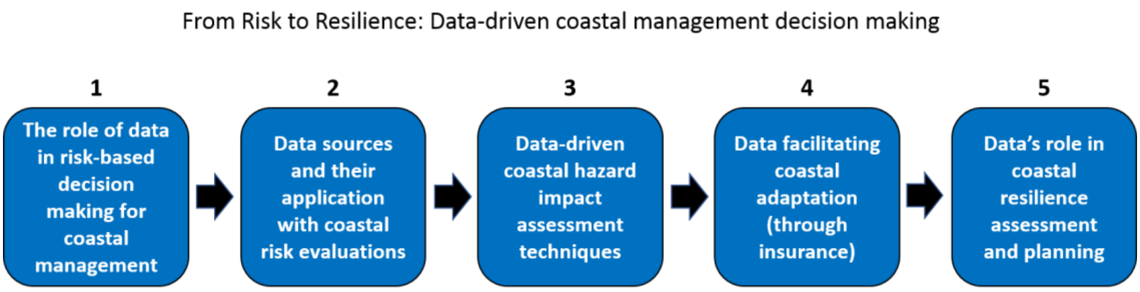


Figure 1: Thesis schematic flow diagram

The thesis is made up of 5 journal papers arranged as individual chapters. A short introduction is provided prior to each paper, giving an overview of the research contained within the chapter, and to set the paper within the context of the wider thesis.

Each journal article contained within this thesis was co-authored. Table 1 gives a breakdown of the roles and contribution of each author for the respective papers.

Table 1: Author contributions to thesis articles

Article Title	Publication Date	Author Contribution			
		A. Rumson	S. Hallett	T. Brewer	A. Payo Garcia
Coastal risk adaptation: the potential role of accessible geospatial Big (Chapter 2)	3rd June 2017	Conceived of the presented idea, undertook the research and compiled the manuscript.	Supervised this work, verified the analytical methods used, reviewed and approved of the final text.	Co-supervised this work, reviewed and approved of the final text.	N/A
Opening up the Coast (Chapter 3)	25th April 2018	Conceived of the presented idea, undertook the research and compiled the manuscript	Supervised this work, verified the analytical methods used, reviewed and approved of the final text.	N/A	N/A
The application of data innovations to geomorphological impact analyses in coastal areas: an East Anglia, UK, case study (Chapter 4)	20th July 2019	Conceived of the presented idea, undertook the research and compiled the manuscript	Supervised this work, verified the analytical methods used, reviewed and approved of the final text.	Reviewed, edited and approved of the final text.	N/A
Innovations in the use of data facilitating insurance as a resilience mechanism for coastal flood risk (Chapter 5)	14th January 2019	Conceived of the presented idea, undertook the research and compiled the manuscript	Supervised this work, verified the analytical methods used, reviewed and approved of the final text.	N/A	N/A

Data-driven coastal resilience assessment: an East Anglia, UK, case study (Chapter 6)	Under Review (on 26th July 2016)	Conceived of the presented idea, undertook the research and compiled the manuscript	Supervised this work, verified the analytical methods used, reviewed and approved of the final text.	N/A	Supervised this work, verified the analytical methods used, reviewed and approved of the final text.

1.4 Research Methods

A variety of research methods were employed during the course of this research. Chapters 2-6 are presented in the form of individual papers, given this each chapter represents a stand-alone study, in which unique methodologies were employed. The topics of the five papers differ substantially, therefore each chapter includes a preliminary literature review of the area focussed on, establishing the contextual background and critically evaluating existing studies for each respective area. Chapter 2 differs in that the whole chapter takes the form of a review, whilst chapter 6 involved an initial Quick Scoping Review (presented as an Appendix). Chapters 3, 4 and 6 all involved experimentation with available technical methods and software, specifically GIS. Chapter 4 involved quantitative analysis using a specialist hydrographic survey software package to generate change estimates for the case study region. This reflects a positivist research style (Keats, 1971) in that objective evidence (which took the form of analysis of point cloud data sets) generated empirical results (volumetric change estimates for discrete sites). However, it was not the outputs of the analysis that this study was primarily concerned with, but the suitability of the processes which allowed these results to be obtained. This still was based on a more objective approach than other chapters in we tried to establish objective criteria which could be used to determine the choice of Geomorphological Change Detection (GDC) technique, or data type selected depending on clear parameters. Whilst Chapter 5 represented an alternative mode of research, which was based around semi-structured interviews conducted with industry practitioners and academics. This took more of a naturalist research style (Keats, 1971), drawing more on phenomenological perspectives, using an exploratory approach based on subjective experiences. This aimed to draw conclusion from a combination interview feedback and reported technological progress, which required the researcher to make sense of the contrasting viewpoints obtained.

This research involved substantial engagement with coastal practitioners and stakeholders, as such time was spent working within the organisation of the industrial partner, CPE, a district level coastal management authority. Additionally, time was spent at stakeholder workshops, conferences, forums, and other engagement activities. Knowledge acquired as a result of this influenced the direction the research has taken, and the topics focussed on. This can be viewed in terms of the naturalist research paradigm in that the researcher became part of the social world investigated, and as a result this directly influenced the scope of the research and contributed to formation of the hypotheses tested. The researcher made efforts to retain neutrality, through drawing on the opposing viewpoints from a range of stakeholders. This was achieved through attending community engagement events, and coastal forums which involved a diverse range of attendees.

In addition to engagement with coastal management professionals, a three-month placement was undertaken within the insurance industry, based at Lloyd's of London. This provided first hand input on how data and analytics are being utilised within risk analysis in the private sector (for insurance), yet also in relation to some of the similar hazards and consequences focussed on by public sector coastal management professionals. In this it was difficult to detach the researchers' position and perspective from many of the results obtained, this is further discussed within the Conclusions, Section 7. The research documented with chapters 3, 4 and 6 required suitable data sources and datasets to be identified and obtained. Initially this process involved internet-based investigations, which were followed up by contact with and site visits to data custodians, to understand the nature of information they held, how this was obtained, data veracity and availability. The penultimate chapter presents research in the area of resilience, in this a more positivist research approach is sought through attempts to replace subjective judgement of individuals with analyses based on empirical evidence. Through trying to link quantifiable parameters represented within many of the datasets we have listed, we seek to establish objective measures on which decision making can be based.

1.5 Background Context

The subsequent chapters of this thesis focus on the application of various forms of data-driven analysis to the domain of coastal management. Within these chapters, the coastal management context addressed in each is introduced, yet to provide adequate background context of the domain, a more detailed introduction to coastal management is provided here. Within this, emphasis is placed on the role of data within coastal management decision-making. The principal approach to coastal management in England is governed through 'Shoreline Management Plans, SMPs'. A central tenet of the SMPs involves a shift in human responses to coastal hazards in respect to the adaptation methods implemented, this is further discussed in Section 1.7.3. Coastal management involves management of risks in coastal areas, this is central to this thesis, as such prior to the discussion on coastal management a short introduction to coastal risk is presented.

1.6 Coastal Risk

Coastal risk management is reported to involve 'the integrated management of coastal hazards using a risk-based framework' (Dodds, 2009, p.26). Risk is the product of a hazard and its consequences. In consideration of environmental hazards in coastal areas, consequences can be taken to comprise of three components: Hazard (H), Exposed values at risk (E), and Vulnerability (V) (the lack of resistance to damaging/destructive forces) (Kron, 2013). In relation to flood risk, these components may be represented in the form of a risk triangle (Dávila et al., 2014) (Figure 2).

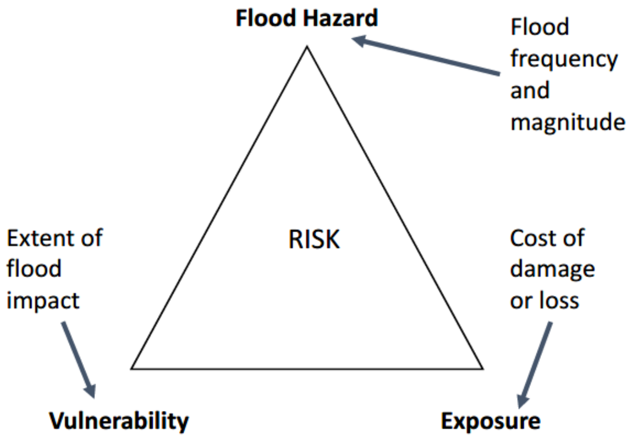


Figure 2: Risk Triangle (from Crichton and Mounsey, 1997 in Dávila et al., 2014)

The Tyndall Coastal Simulator project (Dawson et al., 2009) focused mainly on a stretch of coastline, encapsulated by SMP-6 on the North Norfolk coast. The project aimed to generate simulations for future projections based on various climate change, wave, weather, demographic, and economic scenarios. Results from the Tyndall project indicated that, for East Anglia, flood risk is an order of magnitude higher than erosion risk (Nicholls et al., 2015a). Studies focusing on other regions of the UK, for example Yarmouth on the Isle of White (Wadey et al., 2015), also recognise how sea level rise, coupled with population and economic growth, have resulted in an increased risk of flooding. According to Kron (2013, p.1380) 'development policy and land-use regulation simply do not work'; this has contributed to 8 out of 10 natural disasters that produced the most fatalities occurring on the coast, in the period 1991-2011. In analysing the consequence element of the risk equation, it is necessary to focus on vulnerability. Value accumulation on the coast, that is, the increasing prevalence of properties and infrastructure and rising property and land values, has been cited as the main driver of risk (Connelly, 2015), with continuous increases occurring in the relative value at risk in flood prone areas due to rising property values.

The wider implications of risk need to be acknowledged. Society bears the ultimate burden for rising risk levels on the coast (Roberts, 2012), due to the requirement for the state to fund emergency rescue, recovery and rehabilitation when things go wrong. This assertion supports the finding of the 'The Foresight Future Flooding report' in the UK, which identified 'development on tidal floodplains as being a significant driver of increased risk in the future' (Defra, 2005, p.105), as well as the conclusions reached by Stocker et al (2011, in Roberts, 2012) whereby poor planning on the coast can exacerbate risks relating to natural processes and climate change induced hazards.

Calculation of risk is not a straight forward process, objectivity does not always follow logically, given that 'messages on risk are susceptible to distortion or misrepresentation'

(Muro et al., 2012, p.1) and calculations can involve the use of 'subjective probability'. Defra (2009, p19-21) advocated the use of a risk neutral approach to enable 'a consistent and objective comparison of different combinations of consequence and probability'. This aims to better determine if, to reduce risk, it is best to focus on a strategy of 'reducing the probability, the impacts or both' – through engineered solutions, land management, forecasting and warnings, or improved resilience. Another approach developed, which has been applied to the coastal risk process, is the Source-Pathway-Receptor (S-P-R) conceptual model (Defra and Cranfield University, 2011) or in the form that Villatoro et al. (2014) applied in their study: Source, Pathway, Receptor, Consequence (SPRC) scheme. In relation to the coast, this model can represent:

Source = hazards

Pathway = coastal defences

Receptor = inland system/land use

Consequence = loss

Risk calculations are clouded further when one considers the lack of objectivity apparent due to the manner in which risks are often framed. Different risk frames can determine the impact of situations, these can derive from external motives, such as the necessity to command and control, or to restore the status quo rapidly. This is evident within the coastal management domain, in the militaristic emphasis placed on the notion of a battle with the sea i.e. expectations to 'Hold the line' and 'Defend' as opposed to implementing complementary adaptation measures. This ties in with the notion that traditionally the sea has often been seen as a 'cruel enemy to be fought at all times' (Rupp-Armstrong and Nicholls, 2007, p.1418). Furthermore, risk awareness is another significant factor altering outcomes. In cases where individuals have been deemed risk aware, flood risk in the coastal zone has been seen to decrease (Dubbelboer et al., 2017; Filatova et al., 2011). Ultimately though, coastal risk appears to be an inescapable truth for many who use and live on the coast. In many cases this can only be reduced by adapting to natural processes. Through this discussion of risk it becomes apparent that adaptation is a clear requirement; a real challenge for future coastal management practices is how to create sustainable adaptation methods which both maintain coastal ecosystems and provide ecosystems services offering adaptive capacity. As such an increasing emphasis is being placed on adaptation options which incorporate nature based solutions (van der Nat et al., 2016). Furthermore, with the increased imperative for action to be taken in exposed coastal locations due to climate change related hazards, more traditional engineered coastal protection measures are now commonly viewed as unsustainable, and hybrid options combining both natural and engineered features are being looked to (Hamin et al., 2018).

1.7 Coastal Management

Societies around the world have embarked on various strategies in managing their coasts. Unfortunately, these have not always been sustainable, for example, traditional responses to coastal hazards across Europe have been termed by Dodds (2009, p.25) as being 'short term, reactive and parochial'. Much progress is evident in the methods currently being trialled and implemented. England has been at the forefront of implementing many new coastal management initiatives, such as Integrated Coastal Zone Management (ICZM) with it being one of only thirteen countries in the world who had approved a marine spatial plan in 2015 (Ehler, 2015).

1.7.1 Integrated Coastal Zone Management (ICZM)

A major aim of ICZM is 'to recognise threat(s) to the coastal zone… and protect against the loss of life, property damage and social and economic disruption' (World Bank, 1993, in Roberts, 2012, p.11). The proliferation of ICZM is 'a logical consequence of the rapid environmental and socio-economic changes occurring around the world's coastlines' (Thumerer et al., 2000, p.279). ICZM is a fairly recent concept, first formally acknowledged in 1972 when the USA established the Coastal Zone Management Act (Isager, 2008). ICZM sets out to manage multiple uses of the coast in an integrated way through 'cooperation and coordination of governance agencies at different levels of authority and different economic sectors' (Ehler, 2003, p.336). This involves collaboration between partner governments, communities, the private sector, research institutions and NGOs. Risk management of flood and erosion issues is an important part of ICZM (Defra, 2005). The integration and involvement of multiple stakeholders is essential. However, this is not straightforward and multiple problems arise in addressing stakeholders' and government agencies' conflicting agendas (Isager, 2008). ICZM can involve multi-scale arrangements such as co-management, with the aim of achieving vertical and horizontal integration of government agencies in a phased project cycle (Isager, 2008). This involves a dynamic process where objectives can change in line with altered understanding (Ehler, 2003). The role of information in this process is paramount, providing the means to generate an understanding of the processes at work on the coast. ICZM is thus seen to provide an enabling mechanism, facilitating capacity building and exploiting knowledge exchange (O'Mahony et al., 2015). Nevertheless the process can lack credible commitment from stakeholders. Cooper & McKenna (2009) highlight how in many countries in Europe, coastal zone management *per se* is not a statutory responsibility and authorities may therefore choose not to fund new coastal zone management initiatives and can suspend ongoing ones.

ICZM is based on a number of broad principles and objectives. These are summarised by Defra (2005) in what are termed the 8 principles of ICZM:

1. A broad overall perspective;
2. A long-term perspective;
3. Adaptive management;
4. Local specificity;
5. Working with natural processes;
6. Involving all parties concerned;
7. Support of relevant administrative bodies;
8. Using a combination of instruments.

To ensure sustainability of ICZM plans they require credible political commitment (Godschalk, 2009). Governments therefore have a huge role in enforcing ICZM. In some areas, legalistic backing is required for measures which can be reliant on privatisation and property rights. The international community has played a major role in the furtherance of ICZM and international guidelines have been published by the World Bank, UNEP, IUCN, OECD and the World Coastal Conference (Isager, 2008). At a national scale, government has a crucial role in achieving cross-sectoral collaboration, this can be seen in its central role in facilitating ICZM projects. In the UK, the Environment Agency (2015) has concluded that to deal with the imminent threat posed by climate change and sea level rise an integrated approach is required which is in line with the core principles of ICZM.

The European Commission (EC) has done much to champion adoption of ICZM principles across its member states. In 2002, it published a recommendation on the implementation of ICZM in Europe (European Commission, 2002). Following this, in 2013, the EC launched a 'Proposal for a Directive establishing a framework for maritime spatial planning and integrated coastal zone management' (European Commission, 2013a). This required member states to establish ICZM strategies. The Directive stresses the key role of data for informing and guiding the planning phase of strategies. England publicly codified its plans for an ICZM strategy in 2008 with the publication by Defra of the report, 'A strategy for promoting an integrated approach to the management of coastal areas in England' (Defra, 2008). In relation to coastal partnerships in England[1], the Coastal Partnership Working Group (CPWG) was formed in 2009, which led to coastal partnerships being recognised as a delivery mechanism for ICZM (Fletcher et al., 2014). The Local Government Association Coastal Special Interest Group (LGA Coastal SIG) in England was formed to champion the collective interests of all maritime local authorities. Key among the themes upon which they focus is ICZM and they recognise the instrumental role local authorities have played in England in developing an ICZM approach (LGA Coastal SIG, 2012). The implementation of ICZM initiatives across the UK has produced positive outcomes (Stojanovic and Ballinger, 2009). East Anglia is particularly relevant in terms of the application of ICZM, as areas such as North Norfolk have been seen to represent 'a microcosm of current coastal zone management issues in England and Wales' (Brennan, 2007, p.589). Yet Milligan et al. (2009) argued that the UK's coastal governance arrangements (at the time of writing) were so ill-coordinated that ICZM plans would be hampered.

ICZM is not, however, confined to national and subnational levels (Rochette and Billé, 2012). The IOC/UNESCO (2011) states that partnerships should occur at all levels: industry, government and community. The issue of scale is pertinent to regional body formation. The UNEP Regional Seas program is one of the most prominent regional initiatives, with over 143 states participating (UN Environment, n.d.). The program has seen regional level cooperation emerge as a stepping-stone towards global cooperation. The Partnership in Environmental Management for the Seas of East Asia (PEMSEA) is

[1] See Section 1.7.2 for more details about Coastal Partnerships in England.

another significant project, where partner governments, authorities, resource users, stakeholders and local communities are linked together (PEMSEA, 2019). This study focuses on a region whose coast boarders the North Sea. The North Sea is bordered by many other strong economies and there are a number of collaborative agreements reached between these (European MSP Platform, 2019), such the North Sea Commission (CPMR North Sea Commission, 2019), which focuses on issues including, marine resources, and energy and climate change. OSPAR (Oslo/Paris Convention for Protection of the Marine environment in the North East Atlantic) (OSPAR, n.d.) is a wider grouping which extends beyond, but includes, the North Sea. It focuses on protection of the marine environment in the North East Atlantic and North Sea, marine spatial planning, and they also make datasets available for marine and coastal areas in the North Sea and beyond. A regional approach can bring together countries bordering an ecosystem and can result in: technology-transfers, capacity building and scientific knowledge creation and exchange. In terms of information provision, within Europe a maritime data exchange project, EMODnet (Calewaert, 2015) was recently created, this aims to standardise data exchange and collation, building an open access spatial database approach at a regional scale, thus empowering decision makers in Europe, who require access to cross-border coastal data sets.

1.7.2 Coastal Management in England

This research focuses on the coastal region of East Anglia, England. The following discussion outlines the roles and responsibilities of a selection of the main coastal management stakeholders in East Anglia and England. This leads into a discussion of the approach dominating the management of England's coasts, the Shoreline Management Plans (SMPs).

1.7.2.1 Organisations and Actors

The responsibility for coastal management in England is split across a broad range of actor organisations. These include national, regional and local level organisations, both private sector and public bodies, civil society groupings and academia. For East Anglia, a selection of the stakeholder organisations involved with the coastal management process for the region are presented in Figure 3. This list is not exhaustive but highlights the variety of organisations involved. The main responsibilities for coastal management in England fall on public sector bodies, however private sector actors play a crucial role. This thesis focuses on coastal management decision making processes, and these mostly relate to public sector actors, however, private sector firms such as HR Wallingford, Jacobs and Royal Haskoning DHV play a crucial role in relation to coastal research, analysis, information provision, and practical implementation of adaptation measures. In addition to this, data and analytics firms play a key role in provision of datasets and analytics, relevant to coastal risk and resilience evaluations; many such firms are detailed throughout this thesis, especially in Chapters 5 and 6.

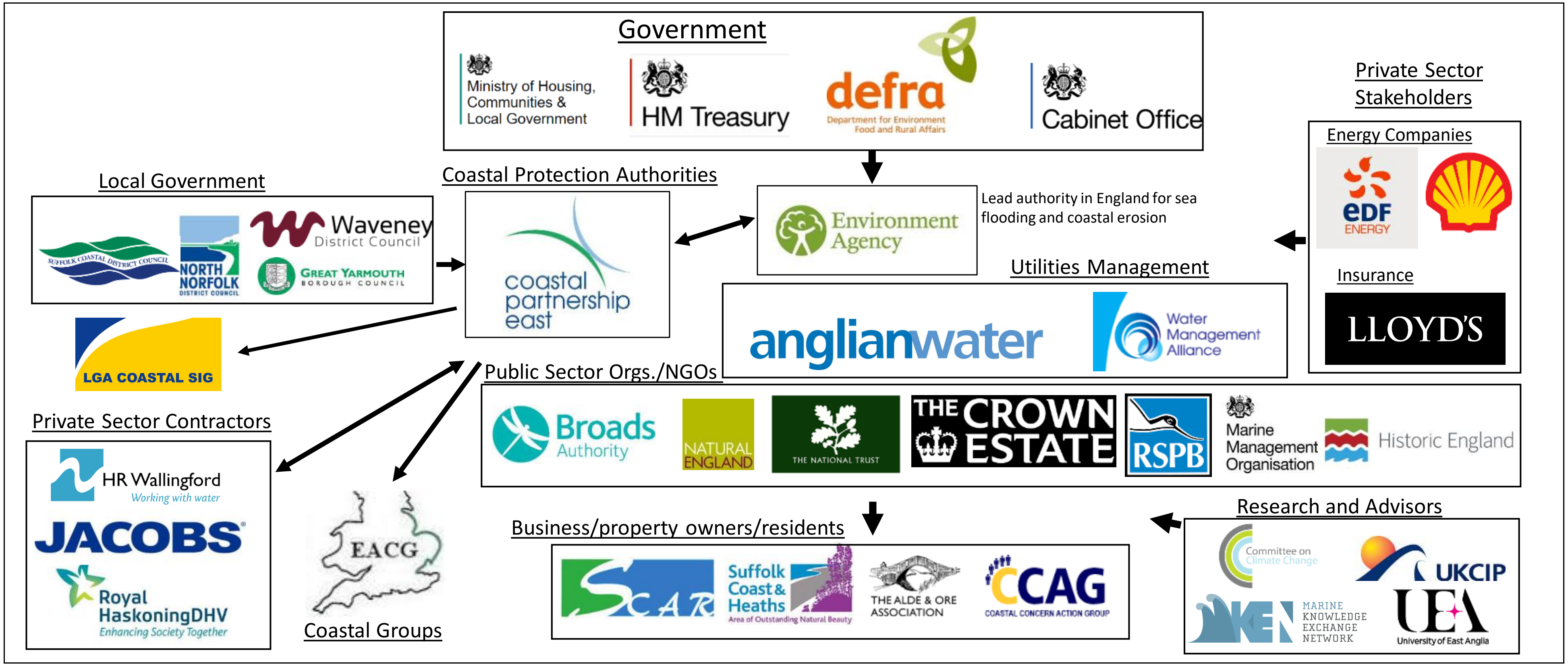


Figure 3: A selection of the organisations involved with coastal management in East Anglia, representing a loose approximation of groupings and relationships.

Coastal management roles and responsibilities in England have altered somewhat in recent times (Defra, 2015). The lead government body currently remains Defra, who retain responsibility for policy setting (Environment Agency, 2010), whilst responsibility for flood defence (the floodable coast) and coastal protection (the eroding coast), is split between the EA and maritime district councils, respectively. The split in responsibilities for flooding and erosion can provide benefits in that some overlapping powers between the EA and local authorities have been removed, yet flooding and erosion can be difficult to separate in many instances as they can occur in tandem (Defra, 2005)**.** The EA takes an oversight role and undertakes monitoring activities of the coastline (Environment Agency, 2010). This involves collection of physical data relating to the coast, and data management and analysis, which are included in asset management plans. At a county level, under the Flood and Water Management Act (FWMA) (Defra, 2010), county councils take the role of Lead Local Flood Authorities (LLFA), who coordinate localised flood risk management strategies. LLFAs work closely with the Environment Agency, ensuring local and national plans are aligned (Local Government Association, 2019).

The EA is one of many specialist Non-Departmental Public Bodies (NDPBs) involved in the coastal management process in England. Others include the Marine Management Organisation (MMO), Natural England and Historic England. The English coast is split between private and public ownership. On behalf of the British public the Crown Estate administers publicly owned coastal land. The Crown Estate is a semi-independent, incorporated public body, which is one of the UK's largest coastal land owners (Crown Estate, 2019). The Crown Estate also 'owns almost all of the seabed within 12 nautical miles' and has 'rights to all minerals' (Environment Agency, 2010). It is a significant stakeholder in relation to matters of coastal governance, and has 'extensive experience of managing activities within the marine environment and of balancing economic activity with stewardship of natural resources' (Rodwell et al., 2014, p.253)**.** The National Trust, a conservation organisation and independent charity, is another significant land owner on the coast of England as a result of its acquisition of coastal land through the Neptune Project (National Trust, 2019a). It has completed a number of surveys of the coast of England the most recent being related to the 'Shifting Shores' project (National Trust, 2015a).

Alongside the EA, district level government has a central role in the coastal management process in England. In 1949, the Coastal Protection Act identified coastal protection authorities as district or unitary councils on the coast (Environment Agency, 2010).The role of councils is broad and can involve managing information about the coast, working with others in relation to coastal management issues, maintaining coastal communities, and finance. In terms of coastal management responsibilities, local authorities have powers that are permissive, that is they have powers not duties and are not obliged to maintain the coast (Rupp-Armstrong and Nicholls, 2007). This can render landowner opposition to coastal policies as less effective in England than elsewhere in Europe such as the federal states of Lower Saxony in Germany, because 'coastal defence authorities can either just walk away or ask for contributions by landowners' (Rupp-Armstrong and Nicholls, 2007, p.1427). Local authorities take the lead on coastal erosion risk management activities. They also have powers to control third party activities on the coast (Environment Agency, 2010). Therefore they take a central role within the risk assessment process alongside the EA who have been tasked with providing risk maps of the coastline of England (Defra, 2005).

In England, coastal groups have been formed which deal specifically with coastal management issues, these comprise of coastal managers, district and county councils, port authorities, the EA and other organisations such as Natural England and English Heritage (SCOPAC, 2019). The role of the groups has evolved, in 2008 the EA worked with local authorities to increase the size of coastal groups making them more strategic. In the past there were 90 coastal groups, yet these have merged to leave 7 voluntary groups in England, all without government funding (Environment Agency, 2010). The groups are now seen as a natural forum for coastal practitioners, where sound advice on coastal issues can be sought.

Wider than the coastal groups, covering the UK, and encompassing a broader membership, are Coastal Partnerships. Coastal Partnerships formed in the early 1990s (Fletcher, 2003) as an organic reaction, occurring outside of national guidance, in response to local coastal problems. In the UK local partnerships do not work in isolation, there is close collaboration with broader governmental organisations (similar to that occurring in coastal groups) such as the EA, Defra, and other interested parties including the National Trust, Natural England and Historic England. This broad membership illustrates an integrated management process, where local governance units are nested within wider government departments such as Defra. Yet the effectiveness of partnerships has been questioned. It is argued that they have proven to be financially unsustainable in many cases (Fletcher et al., 2014) with concerns over accountability. It has also been argued that their operation can be undemocratic with stakeholders poorly representing coastal user groups (Fletcher, 2003). However, following the Marine and Coastal Access Act (2009) coastal partnerships were 'recognised as a key delivery partner in the ICZM strategy for England' (Fletcher et al., 2014).

In 2016 the coastal management landscape in East Anglia altered and the coastal management resources of Great Yarmouth Borough Council, North Norfolk District Council, Suffolk Coastal District Council and Waveney District Council were amalgamated to form a wider partnership covering the whole region, entitled 'Coastal Partnership East' (Coastal Partnership East, 2019). This movement to bring experts together to cover a wider geographic area ties in with the previous shift to reduce the number of coastal groups. The aim of this wider regional focus is to allow appropriate resources and expertise to be brought together at a regional level, allowing more sustainable outcomes to be reached for coastal communities in the long-term (Coastal Partnership East, 2019). These themes tie in with the objectives of this current study, which focuses on collation of coastal data at a regional level for East Anglia.

1.7.2.2 The recognition of natural processes within coastal management

In recent years the government's stance in relation to coastal adaptation has altered (Defra, 2006). Following a major storm surge in 1953 the dominant paradigm was to 'Hold the Line' and thus a series of hard adaptation measures were installed along the coastline of East Anglia (Mokrech et al., 2011) and the rest of the UK. In more recent times a gradual shift in approach has occurred, with increasing consideration given to the wider impacts of installation of coastal protection measures. This was highlighted in the report published in 2004 entitled *The Foresight Future Flooding report* (Goverment Office for Science, 2004). This report marked a significant step forwards in realising the value of knowledge of this domain. Following this, a subsequent report was published by the government entitled *Making space for water* (Defra, 2004). Publication of this was seen to mark a policy change (Cooper and McKenna, 2009), embracing more sustainable options. This was then furthered within the *FutureCoast* project, released under *Making Space for Water* (Defra, 2006), which embraced a whole system approach to coastal management. In these progressive shifts in coastal policy, the government has heeded successive advice from the scientific community, realising that installation of hard defences can contribute to distortion of natural sediment transport cycles (Environment Agency, 2010); the government position recognising that, in hindsight, less hard adaptation measures should have been constructed on the coast in the post-1953 period (which, in many cases, have created adverse long-term effects), and that land use planning should allow for some natural erosion. In East Anglia, it has been reported that this would result in lower management costs and creation of beaches, fronting the Norfolk Broads (Nicholls et al., 2015a).

In the past coastal group boundaries in England were not coincident with natural boundaries (Environment Agency, 2010). Yet coastal processes in the region are interlinked and do not operate in isolation, based on arbitrary political boundaries. In recognition of this, sediment cell boundaries (relating to longshore sediment transport pathways) have been accepted as the basis for appropriate coastal management (Environment Agency, 2010). A modern shoreline management approach in England, based on sediment cell mapping first began in 1993 (Motyka and Brampton, 1993). A key milestone in the development of this was the formation of Shoreline Management Plans (SMPs) (Section 1.7.2.4).

1.7.2.3 Natural Capital

Natural capital has been defined as ‘the world’s stocks of natural assets which include geology, soil, air, water and all living things’ (World Forum on Natural Captial, 2019). Furthermore natural capital is taken to be the biophysical structures constituting ‘the elements of nature that directly and indirectly produce value or benefits to people’ (Natural Capital Committee, 2013), with emphasis being placed on the stock of biotic and abiotic elements within an ecosystem, rather than the flow of services they provide (UK Natural Capital Committee, 2014). Valuation of the benefits humans derive from natural capital can be difficult due to the complexity of natural processes working to deliver them. As such they are often not included in economic analysis, and as a result left to degrade and not protected. Valuation and understanding of the role played by natural habitats can justify it being protected and enhanced. This can also lead to it being included within decision making processes. One project worth noting, which is addressing this issue is the Defra Pioneer project (UK Research and Innovation, n.d.). This recognised these requirements and aimed to test new and novel mechanisms to manage the natural environment. Four Pioneer projects are running at separate sites across the UK, with two of them being Marine Pioneer projects, which focus on coastal locations in Suffolk and North Devon. The projects seek to identify natural assets at risk and improve monitoring of these. The Pioneer projects set out to inform the delivery of the UK government's 25-year environment plan. This seeks to promote restoration and sustainable use of environment within all society's decision making (GOV.UK, 2019a). The Suffolk Pioneer focuses specifically on saltmarsh and their habitats and natural capital's role in flood resilience (GOV.UK, 2019b). The Marine Pioneer is coordinated by the MMO and is directed by a steering group representing a range of the stakeholder organisations, including some of those detailed in Figure 3. It is employing a collaborative approach to finding solutions, working with communities, businesses and the public sector (Suffolk Coast & Heaths, 2019a), in doing so community relation issues, relative to coastal management, have been addressed.

1.7.2.4 Shoreline Management Plans (SMPs)

The 22 SMPs that have been produced for England and Wales are large-scale planning documents, being particularly concerned with adaptation strategies for limited stretches of the coast. They are reported to relate to a self-contained sediment cell or group of cells, reflecting a shift to acknowledging natural processes within the practise of risk management on the coast (Defra, 2004)**.**

The original SMPs, which formed SMP1 (completed in 1998) were based on the concept of littoral sediment cells, and their boundaries, as outlined within a report by Motyka and Brampton (1993). This related to the movement of sand and shingle along the coast. The original boundaries were where the 'net along shore movement of sand and shingle changes direction' (Defra, 2006, p.4) or littoral drift divides (usually occurring where the orientation of the shoreline abruptly changes direction) (Motyka and Brampton, 1993). This was also influenced by coastal authority boundaries, in certain places. Motyka and Brampton (1993) acknowledged that the basis of their littoral sediment cells did not account for the movement of fine-grained material. However, the basis of the current SMP boundaries, has been highlighted as inadequate, due to not accounting for fine grained, cohesive sediment transport, in addition to factors such as SMPs not covering intertidal estuaries (Cooper and Pontee, 2006). This poses a problem for the region of East Anglia, as much of the east coast of England and its buffering shallow water coastal landforms are formed of fine (silt/clay) sediments (BGS, 2018). The erosion, transport, and deposition of such sediments is therefore ignored by the current SMPs.

The introduction of SMPs in England and Wales, was seen as a move towards a more strategic, holistic approach, where clear distinctions were made between passive and active retreat (retreat being acknowledged as a real option for the first time) (Rupp-Armstrong and Nicholls, 2007). Stretches of coastline were grouped into four categories: Advance the line, Hold the line, No active intervention and Managed Realignment. In East Anglia, many parts of the coast were re-categorised in terms of No Active Intervention, or Managed Realignment (Figure 4). The SMPs give an overview of the risks faced on the coastline, outlining a long-term policy framework to tackle these. However, SMPs are non-statutory documents (Environment Agency, 2010), being produced as the result of collaboration between coastal groups, maritime local authorities, the EA, coastal landowners, local stakeholders, interest groups and other related public bodies (Defra, 2005). The EA has the responsibility of reviewing and approving all SMPs, and allocates subsequent funding related to coastal risk management (Environment Agency, 2010). SMPs have a clear role in relation to spatial planning policy on the coast, being designed to ensure development does not occur where there is a risk of flooding (Defra, 2006). Yet SMPs are limited in that they only give intent of management, with no direct funding attached to the plans (Suffolk Coastal District Council, 2010).

In 2006, the government produced revised guidelines in the form of an updated second generation of SMPs (Defra, 2006), representing a shift in the dominant position to a whole system approach. The SMPs are continually evolving, working documents, where risks are seen to guide policy and support decision-making (Milligan et al., 2009). The SMPs are due to be revised every 10 years to account for updated information (Suffolk Coastal District Council, 2010). At the time of writing an SMP refresh was being undertaken by the EA, which aimed to ensure the SMPs, developed between 2006 and 2012, are fit for purpose.

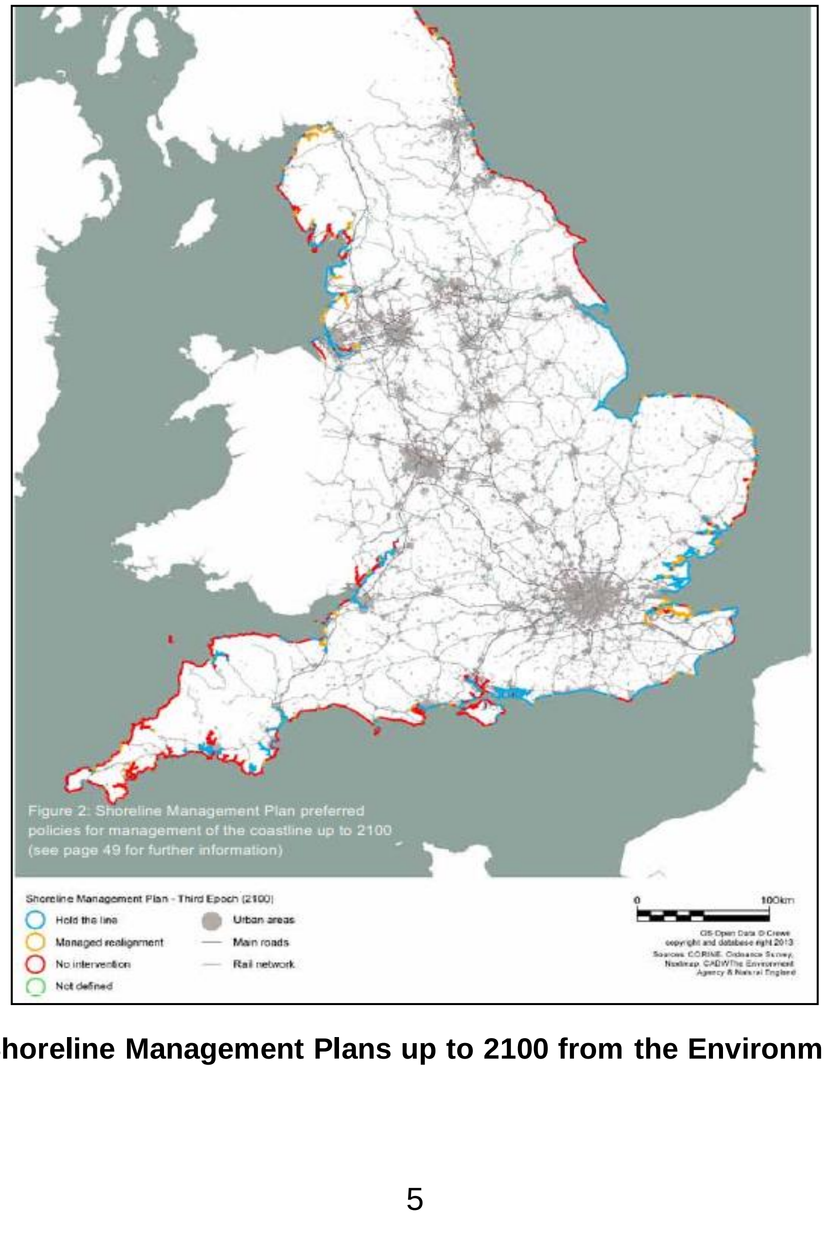


Figure 4: Shoreline Management Plans up to 2100 from the Environment Agency (2015)

Implementation of the SMPs has been fraught with problems. The original SMPs implemented in the 1990s were less contentious as they still embraced a Hold the Line stance. Yet, post-2005, a policy shift occurred, resulting in many defences not being replaced or repaired, and rapid coastal erosion ensuing (Nicholls et al., 2015a). Civil society groups formed, representing business and the public (Smith, 2013), which vociferously oppose the government's plans with regards to abandoned, unsustainable hard adaptation measures; examples of such groups operating in East Anglia are: Coastal Concern Action Group (CCAG) (Happisburgh Village Website, n.d.), Suffolk Coast Against Retreat (SCAR, n.d.) and Suffolk Coast & Heaths (2019). In certain areas, where coastal defences have been removed, such as Happisburgh, on the North Norfolk coast, where the CCAG formed, there has been widespread public backlash. Early implementation of SMP directives were not seen to make adequate provision for the local communities, which were impacted by increasing rates of erosion (Smith, 2013). The formation of coastal groups by local communities such as CCAG and SCAR, are reported to highlight 'a lack of meaningful involvement in the decision-making process' by the local population (Brennan, 2007, p.594). Up to 10m/year retreat of the coastline has been witnessed in areas where coastal defences have not been renewed or have been removed, such as Happisburgh (Dawson et al., 2009). Figure 5 illustrates the areas of coast lost in Happisburgh (as of 2014) (National Trust, 2019b). Plans have been put in place, such as the Pathfinder schemes (Environment Agency, 2010), to try to engage with the public and to address their concerns, and to put provisions in place for those directly impacted, such as resettlement options. This has generated some positive results, nevertheless, widespread acceptance of future coastal policy has not yet been reported (Smith, 2013).

Figure 5: Area of coast (in Black) lost to the sea in Happisburgh, taken from the National Trust 'Mapping Our Shores' Project 2014 (National Trust, 2019b)

The SMP process, despite its well-intentioned motives has proved inadequate in preventing homes continuing to be built in high risk coastal areas (Brennan, 2007, p.595) and has been criticized for failing to appreciate the long-term evolution of the coastline (Brennan, 2007). Furthermore, Defra (2005) is still seen to recognise the need to focus investment on 'defences' despite its embrace of a more holistic whole shoreline approach. The SMP process can be viewed as a means of communicating science to stakeholders, yet Rodwell et al. (2014) argue that the effectiveness of this process needs to be improved. The Committee on Climate Change (2018) also recently concluded that SMP actions are not rigorously analysed so may not be viable.

1.7.2.5 Stakeholder Collaboration and Data Sharing

From the discussion presented in the preceding sections, it is evident that the coastal management landscape in England is complex. Sectoral divisions have been observed between coastal protection, flood defence and land use planning (Dodds, 2009)**.** As a result, collaboration between the organisations involved can become fragmented. This is especially so in relation to the provision of information related to coastal issues. There are many different organisations involved with the collection, storage and processing of data related to the coast. Lack of adequate collaboration has resulted in duplication of efforts in this realm (Siemers, 2015; Dyer and Millard, 2002). This can be compounded by data becoming caught up in sector and organisation-specific information 'silos' (Adger et al., 2016; Leone, 2015; O'Mahony et al., 2015). Political boundaries splitting the coastline into separate management areas can also act as a barrier to utilising scientific approaches within decision-making processes (Environment Agency, 2010). In this sense the notion of scale is vitally important (Swaney et al., 2012), and management initiatives require an awareness of the wider context. Moving beyond sector-specific silos and fragmented localised plans, formulated in isolation, is a clear necessity (O'Mahony et al., 2015). For ICZM to work, cross-scale solutions are necessary (Ehler, 2003). However, problems can occur due to lack of capacity at a local level, combined with inadequate government investment and support. Nicholls et al. (2015a) highlighted how a gulf has been witnessed between national and local decision-making, and that there is a consequent need to reconcile local and national priorities through the implementation of appropriate government institutions. Power struggles can ensue between communities and local government agencies, and government decision-making can also prove overly focused on economic benefits, side-lining environmental and community concerns. Nevertheless the Environment Agency (2010) have recognised that in both England and Wales future coastal management involves a partnership approach between national, regional and local government.

Cooperation between local governance organisations, facilitated by groupings such as the LGA Coastal SIG, can enable knowledge and experiences derived locally or regionally to be adopted nationally. In this sense, the UK can be seen as making significant advances in the realm of coastal management; this being acknowledged within the EU Maritime Spatial Management Conference 2015 (European Commission, 2015). It has also been recognised that since '1999, the UK marine and coastal governance framework has radically evolved', representing 'a genuine attempt to provide an integrated governance framework' (Fletcher et al. 2014, p.267). Roberts (2012) argued that the process of planning coastal land use needs to take account of context and temporal perspectives, yet cannot be undertaken in isolation. One key advantage of collaboration between national level authorities and district and subnational organisations is improved access to sources of information. When combined in a systematic way this information has the potential to significantly enhance decision-making capabilities within localities, and to increase understanding of future vulnerability (Environment Agency, 2010). O'Mahony et al. (2015) have expressed the importance of drawing on all objective knowledge that already exists and in doing so breaking down sector-specific silos. A working environment more conducive to cross-sectoral knowledge exchange and information sharing is thus essential. Hurst et al. (2016) also highlighted how a more joined-up approach is required, and how sectors that have traditionally been managed independently need now to be integrated. However an integrated flood risk management plan does not currently exist for the coast of England (MKEN, 2015). Nevertheless the need for different organisations to work together and share information has been outlined by Defra (2005) in the *Making Space for Water* report; in this Defra also identify how there is a clear role for GIS and spatial data in this process.

For sustainable management of coastal regions, a proactive planning approach is required, drawing on a shared evidence-base, which can reveal where action is required. For this to take place, a wide ranging body of data needs to be collated and analysed (MKEN, 2016). Furthermore, it is essential that those who need access to important sources of coastal data are able to gain this, as 'ignoring information that has been carefully researched and put together is [*deemed*] craziness' (Andy Miller, Natural England, Suffolk Coastal Forum, 2016[2]). The role of the Environment Agency in collecting data related to the coastline (such as Lidar-derived elevation), at regular temporal intervals, provides a means for the dynamic changes on the coastline to be revealed. This offers a clear example of how an understanding of coastal processes can be enhanced through the provision of coastal datasets. Boehlert and Gill (2008) and Swaney et al. (2012) stressed the importance of data in providing insight into spatial and temporal scales, when evaluating effects and impacts. Villatoro et al. (2014) further indicated how combining data can reveal correlations between processes and factors, including waves and storm surges. In locations such as Blythe, England, a lack of coherent data has been deemed a 'key limiting factor for the development of coastal strategy' (Suffolk Forum, Luciana Esteves, 2016[3]). Moreover, Dyer & Millard (2002) argue that both public and private organisations should take steps to disseminate their data holdings and work, potentially improving the value derived from environmental data, using a framework for data interchange.

A key issue encountered as a result of inadequate collaboration between those collecting and holding data is duplication, not only increasing the administrative burden, but encouraging the potential for error. This can be addressed through the process of collation of datasets held by different organisations and identifying where double data

[2] Meeting on 12042016, Minutes available from: http://www.greensuffolk.org/assets/Greenest-County/Water--Coast/Suffolk-Coast-Forum/Minutes/SCF-minutes-12-04-16.pdf (Accessed 03/10/2016)
[3] Meeting on 12042016, Minutes available from: http://www.greensuffolk.org/assets/Greenest-County/Water--Coast/Suffolk-Coast-Forum/Minutes/SCF-minutes-12-04-16.pdf (Accessed 03/10/2016)

has been collected. Duplication has been recognised to occur across Europe (Siemers, 2015), generating a clear requirement for coordination of mapping activities. This is a particular problem in England where, in the past public sector organisations such as Natural England and the EA have undertaken parallel surveys of certain areas. This highlights a clear problem with regards to a lack of collaboration between public sector organisations. In dealing with problems of this nature, Dyer and Millard (2002) state that to manage data value effectively, there is a need to establish which of the partners are already using similar data. Collaboration over wider geographical areas than has been common in the past is therefore vitally important within the process of coastal risk management, enabling consideration of a 'whole system', identifying wide-scale inevitable changes (Nicholls et al., 2015a). This can be achieved via partnerships and other initiatives which enable stakeholders to share data. Given this, a clear future requirement for coastal management is to draw together the vast and varied banks of data pertaining to the coast, derived from many stakeholders, from multiple sectors. This can lead to the development of comprehensive and coherent data repositories (shared or distributed), in which access should not be limited by organisational boundaries.

1.7.3 Coastal Risk Adaptation

1.7.3.1 A shifting stance to adaptation

Coastal regions represent the interface between development pressures and natural processes. This juxtaposition has intensified in recent times due to trends of rising populations settling in coastal areas. Coastal management authorities have frequently installed engineered coastal defences, which have resulted in shoreline hardening. This has reduced levels of naturally occurring protection offered by ecosystem services (such as habitat protection and sediment stabilisation) (Gittman et al., 2016). Moreover, human responses to coastal hazards have typically been: retreat, accommodate or protect (Rupp-Armstrong and Nicholls, 2007). Historically coastal societies have resorted to some form of coastal engineering in an attempt to survive in this volatile environment, potentially 'storing up problems for another day and another generation' (Cooper and McKenna, 2009, p.537). Yet the transient nature of the coast was acknowledged by past generations; Pilkey (1995 in (Landry et al., 2003), p.107) draws attention to how historically 'residential structures on or near beaches were built with salvaged or inexpensive materials in recognition of storm and erosion risks'. This historic aspect is also important in stressing how coastal erosion is not a new phenomenon, given the multiple records of places lost to the sea in the past (Connelly, 2015). Nevertheless, recorded coastal modifications date back to the sixth century in the Netherlands, in the form of a process of dune management termed 'Polderisation' (Dodds, 2009), and there are records of reclamations made during the 12th century in Morecombe, UK, and in the 17th century, along the North Norfolk coast and areas bordering the Dutch Wadden Sea (French, 2001). Human intervention in the form of adaptations have facilitated the establishment of coastal settlements, protected behind artificially stabilised and engineered coasts (Dodds, 2009). In Europe in the 18th century a trend emerged of using the coast for leisure purposes. This resulted in a new range of semi-permanent engineered adaptations, such as esplanades, piers and seawalls being implemented (French, 2001). Much of this decaying legacy has now been passed to the current generation of coastal managers. Another widely used engineered adaptation is the creation of dykes. Dykes have been implemented widely (Misdorp, 2011), especially in the Netherlands, to reduce the impact of high water levels and to facilitate drainage.

The world is dominated by hard coastal protection measures, which can work against natural processes. Yet, soft adaptation measures are open to criticism due to the limited solutions they provide and the difficulty of fitting them in with government plans. The reasoning behind this is that soft measures can prove costly and disruptive, so cannot be implemented where governments have decided not to intervene. They are also inadequate in guaranteeing that the existing coastal configuration will be maintained, so may not be suitable where the policy is to 'hold the line'. Despite this, soft measures such as sandscaping 'buy time for adaptation' (Thomas, 2015).

Adaptation strategies can combine both hard and soft measures. As such a UNEP report (Zhu et al., 2010) grouped adaptation technologies and practices into: (a)Protection approaches - beach nourishment, artificial dunes, seawalls, dykes, barriers, land reclamation; (b) accommodation approaches – flood-proofing, wetland restoration, floating agriculture, flood hazard mapping and warning; (c) retreat approaches – managed realignment, coastal setbacks. In a comparative study focusing on the relative economic efficiency of beach erosion management alternatives, Landry et al. (2003) grouped adaptation measures into three scenarios, namely: 1. Beach nourishment with armouring; 2. Beach nourishment without armouring, and; 3. Shoreline retreat. Aside from physical adaptations, which were reported to be showing their limits, Dávila et al. (2014) outline how non-structural measures, such as land use planning and insurance schemes, are now being recognised as effective adaptation options. Land use planning policies, in some regions such as Suffolk, can encourage innovative measures such as mobile buildings being constructed on cliff tops (Nicholls et al., 2015a). This has been a common part of a management process entitled 'rollback', which has involved the relocation/replacement of properties at risk and, in 2012, saw the introduction of 'Coastal change management areas', allowing movable asset construction in specific risk areas (National Trust, 2015b). Yet many of these initiatives of rollback and realignment are yet to be properly established and have been viewed by the public with some suspicion (National Trust, 2015b). In relation to a study of the situation in the Netherlands, Filatova et al. (2011) recommend that urban planners should consider landscape reconfiguration by building on higher ground and terraces. This is seen to have dual benefits, in that it can communicate a risk message and can also protect inhabitants from flooding. In terms of who has the responsibility to implement adaptations, the burden does not always fall on governments. In relation to the situation in the UK, private landowners can fund their own adaptation measures, albeit with consent from coastal groups, and adhering to planning regulations.

Contrasting with the man-made adaptations noted, natural adaptation mechanisms have also evolved. Some of the soft adaptation methods detailed utilise these natural functions. In particular, ecosystem services bring many benefits to coastal populations. These include: 'food, aquaculture, carbon storage-sequestration, energy extraction, protection against natural hazards, tourism, recreation and pollutant filtering' (Kullenberg, 2010, p.412). Natural capital in the form of coastal habitats, such as coral reefs and seagrass is acknowledged to reduce impacts of storm surges (Partnership for Environment & Disaster Risk Reduction (PEDRR), 2015). Globally, the value of mangroves and coastal brackish wetlands, are frequently underrated in many regions, whilst in locations such as Bangladesh they are realised by some to offer an effective buffer from storm surges (Shamsul Huda, 2004). Roberts (2012, p.11-12) concludes that 'functional integrity of natural ecosystems must be protected to allow self-adaptation and to absorb recurring hazards'. In the UK, along its coastal margins, ecosystem services provided by wetlands are seen to deliver important regulatory services (Maltby, 2012). Rupp-Armstrong and Nicholls (2007) draw attention to the important, often undervalued function, coastal wetlands perform, in supporting and sustaining plants and animals, and acting as pollution sinks and flood defences. Wetlands are estimated to have reduced impacts from Hurricane Sandy, in the north-eastern states of the USA by over $625 million (Colgan et al., 2017). Furthermore, Arkema et al. (2013) estimate, for the coasts of the USA, that the value of residential property and the number of people exposed to coastal hazards could be reduced by half if existing habitats remain fully intact. The important role natural habitats play in offering coastal communities protection from storm-induced erosion and flooding is acknowledged within models such as that created as part of the InVEST[4] Coastal Vulnerability Project (Arkema et al., 2013; Natural Capital Project, 2015); the project is explained in more detail in Appendix B (7.4B.2).

A shift to an approach embracing natural processes and ecosystem services is being adopted in England (Environment Agency, 2018; Lawton et al., 2010; RSPB, 2016). Defra (2005) have outlined the need to work with natural processes and to use a wide range of risk management options, including softer adaptation measures, such as realignment, to re-establish inter-tidal habitat, saltmarshes and multi-function wetlands, thereby reducing coastal squeeze. The widespread adaptation option of 'managed realignment' is now firmly on the agenda in the UK, and other parts of Europe such as Germany (Rupp-Armstrong and Nicholls, 2007). Managed realignment has been termed 'a low cost means of recreating natural habitats' (Milligan et al., 2009, p.205). The process involves setting back actively maintained defences to a new line and has been is a suitable shoreline management option for low-lying, flood prone, soft coastal areas. It has readily recognisable benefits in that it can be used to promote creation of intertidal habitats and salt marshes and also to produce recreational benefits. It is seen to mark 'a radical departure from the recent past of protection only' (Rupp-Armstrong and Nicholls, 2007, p.1418). However, obstacles to its implementation have included a 'lack of adequate compensation to landowners and lack of public support' (Milligan et al., 2009, p.205). Relocation of coastal populations/businesses represents a serious obstacle to the success of measures such as managed realignment, and the issue of compensation to landowners is recognised as especially contentious (Nordstrom et al., 2015). Kron (2013, p.1373) argued that 'convincing people they should leave their homes is a futile exercise'. Despite this, in an attempt to address issues such as these, the Coastal Change

[4] See: http://www.naturalcapitalproject.org/invest/

Pathfinder programme was established in England in 2009. Initially this involved an £11m fund, to work with communities on ways to plan and adapt to coastal change, such as purchase of the most vulnerable houses (Defra, 2012). In a 2011 review, Defra found that for the five largest Pathfinders, public access to beaches was secured and cliff top environments were improved. This review is criticised though for taking a short term view (Nicholls et al., 2015a).

In their assessment of adaptation strategies Landry et al. (2003) found that beach nourishment with shoreline armouring was the least desirable of the options they reviewed, due to evidence indicating that armoured beaches tend to be narrower and steeper, armouring being expensive and can generate negative aesthetic consequences and environmental impacts. They found beach nourishment also to be expensive and temporary, yet could result in recreational benefits. They pointed to a trade-off between the needs of beachfront property owners and beachgoers. Beachgoers who are more numerous, generally prefer a beach devoid of seawalls and groynes, which local residents by contrast may demand to protect their properties. Landry et al. (2003) concluded that the potential benefits from maintaining wide beaches without shoreline armouring are substantial and economically prudent. This corresponds with problems reported on the UK coast, where the cost of protection can exceed the economic benefits it generates (Environment Agency, 2014; Hall, 2016). Conclusions drawn by Kron (2013, p.1374-5) expand upon this; Kron found technical flood protection, in the form of hard coastal protection measures, to be the most important factor in preventing large disasters, yet states that the 'strongest best designed systems have limited effect'.

Roberts (2012) argues that coastal risk mitigation policies can drive equity development in protected areas, yet can increase risk in other unprotected stretches of coast. This can ultimately result in greater vulnerability and loss of equity. Filatova et al. (2011) drew attention to an unintended negative consequence of hard adaptations, in that coastal engineering significantly decreased flood probability but made individuals unaware of coastal risk. Hard adaptation measures have also been found to reduce biodiversity and marine specie numbers, negatively impacting the function of ecosystems (Gittman et al., 2016). Arkema et al. (2013) outline many drawbacks of 'hardened shorelines' including: they are expensive, enhance erosion, negatively impact on fisheries and water quality, and impair recreation. Whilst Ramieri et al. (2011) acknowledge that hard protection plays a role in protecting infrastructure and settlements, it can generate negative consequences for ecological processes and ecosystem services. Adaptation measures are seldom evenly distributed along coastlines and, in many areas, have been influenced by value accumulation on the coast, with an outcome being: 'different patterns of wealth resulting in different patterns of shoreline' (Murray et al., 2016). Governments have added to the uneven distribution of mitigating measures along the coast as they have in some cases prioritised local defences due to economic and societal concerns, defending local neighbourhoods at the expense of adjacent coastlines (Adger et al., 2016).

1.7.3.2 Risk Adaptation on the coast of East Anglia

In East Anglia a mixture of hard and soft adaptation measures have been implemented, such as seawalls, groynes, revetments, gabions, reefs, rock armour and nourishment, and managed realignment (North Norfolk District Council, 2019a); and currently sandscaping is being implemented at a site in Bacton (Flikweert, 2016; North Norfolk District Council, 2019b; Vikolainen et al., 2017). In terms of managed realignment, Defra (2005) have outlined how the UK government continues to provide finance where land and property is required for this and how the government are focused on the creation of wetlands and washlands through managed realignment schemes. Other forms of adaptation, such as rollback, have involved placement of movable assets in vulnerable locations on the coast. The logic underlying this is that, new properties can be moved to different locations when threatened by erosion. An example of this kind of development is the chalet buildings which have been developed by Bourne Leisure at Corton in Suffolk (National Trust, 2015a).

Following the 1953 storm surge, many storm defences were constructed, including one project at Sea Palling, which combines both soft and hard adaptation measures and involves nine detached breakwaters, resulting in major beach nourishment (Dawson et al., 2009; Nicholls et al., 2015a).

In the recent past East Anglia has been subjected to historic high levels of erosion and flooding, and coastal squeeze has been observed in many locations (AECOM, 2012). Large changes in habitat and ecosystems are predicted for the future, with real threats of inundation of the Norfolk Broads (the UK's largest wetland), and beach volumes are facing significant reduction (Nicholls et al., 2015a). As recently as 2013 another North Sea storm surge resulted in localised impacts that were felt across Norfolk and Suffolk (Spencer et al., 2015; Environment Agency, 2016). Extensive flooding resulted in widespread damage such as 'localised breaching, overtopping and back barrier flooding' (Spencer et al., 2015, p.120), partially due to lack of predictive capacity. Many urban port areas were impacted, for example, in Lowestoft both people and industry were impacted, where a local car warehouse reportedly lost over £1.5 million in damaged stock (Woods, 2014), with over 300 cars damaged (Environment Agency, 2016). Following this storm surge, the introduction of an early warning system to monitor factors of sea level rise and wave activity has been advised for the region (Spencer et al., 2015). Spencer et al. (2015) also highlight the role played by natural barriers, in reducing the impact from the storm surges, in that tide-surge-wave signals were modified by inshore bathymetry and the range of coastal ecosystems.

The regions' coast has been transformed in the last two centuries by human interventions, such as land reclamation and construction of sea defences (Nicholls et al., 2015b). There are mixed reactions to the success of adaptation measures along the East Anglian coast. Brennan (2007, p.589) argues that management strategies have impeded the natural evolution of the north Norfolk coastline due to 'site specific and piecemeal hard engineering defences'.

1.8 Land Planning

Spatial management of coastal regions is especially challenging, due to the potentially ubiquitous risk of damage from flooding and erosion. Kron (2013, p.1373) captures the essence of the issue of land planning, for coastal management, stating in simple terms: 'the most efficient way of reducing risk is to avoid settlement in hazardous locations'. Yet this is easier said than done. The majority of coastal locations can be classified as hazardous, ultimately destined to become part of the sea. However, this has not deterred humans from settling on the coast. As a result, risk levels have increased, and high costs have been imposed on national economies. This has been interpreted as a product of injudicious land use decisions, combined with unpredictable extreme weather events (Lloyd et al., 2013).

If spatial management is viewed through the lens of the risk equation it is clear that increasing risk awareness impacts on land use patterns and thus housing prices. An indirect effect of this can be reduction of capital values at risk on the coast, thus lowering the economic impacts resulting from coastal hazards. In the contemporary world, urbanisation is increasing at a rapid rate in coastal regions, therefore efficient allocation of space and preservation of natural areas is paramount (Filatova and Veen, 2006). Filatova & Veen (2006) further argue that it is the government's responsibility to inform coastal populations of risk in these regions, but that due to their inadequacy in doing so an inefficient allocation of land has resulted and as a consequence demand for protection has increased in line with rising economic values (Filatova et al., 2011; Landry et al., 2003). This has led to the indirect result of the standards of protection against hazards such as flooding, generally becoming higher in areas with greater population densities and potential losses (Kind, 2013 in Jongman et al., 2014). This highlights an ethical question as to whether the public purse should be used to maintain private land. This problem is compounded, due to the coastline and housing often being managed by different public bodies (Cooper and McKenna, 2009); a lack of departmental collaboration can thus result in increased property values in these regions skewing cost-benefit analyses in favour of defence. Filatova et al. (2011, p.171) argue that government intervention has negatively distorted a free market and thus 'skewed it towards coastal developments' with the consequence of 'inefficient economic land use outcomes'.

Land developers are also seen to play a key part in this inefficient allocation of land, due to the pressure they place on governments to release undeveloped coastal land for development (Roberts, 2012). As a result, a supply of properties in high risk locations becomes available to buyers. Roberts (2012) deems this to be a clear indication of short term economic planning perspectives. Despite evidence indicating how this situation is prevalent in the UK, Defra (2005) state that flood risk assessment is strongly encouraged at each stage of the planning process, however, less is said about erosion risk. The National Trust (2015a) have reported on some positive aspects of the planning policy system in England and Wales. They assert that 74% of the coast in England, Wales and NI has remained undeveloped as a result of a strong town and county planning system, and that the planning system is becoming more capable of directing development to the most appropriate areas. However, Rupp-Armstrong & Nicholls (2007) highlighted that a problem exists in England due to a long, complicated planning and approval process. Yet in the drive to meet the rising housing demand in the UK, planning laws are becoming more lax, and even government funded schemes have been approved in flood risk areas (Heighton, 2015). Brennan (2007) draws attention to a conflict existing between land-use and planning policies, arguing that planning policies have allowed (and are still permitting) homes and businesses to be built in high risk coastal areas. This is despite Planning Policy Guideline 20 (PPG 20, 1992) recognising that few developments require a coastal location and that new developments generally should not be permitted in areas that require extensive coastal protection (Defra, 2005). The Environment Agency (2010) have backed this, stating that Planning Policy Guidance is key to discouraging inappropriate development in areas of flood risk. The British government can be seen to acknowledge this problem through the creation of Coastal Change Management Areas (CCMAs) from 2010 onwards (National Trust, 2015). CCMAs seek to prevent new permanent developments specifically in areas where there is a high risk of coastal erosion and flooding. Despite developments such as this though, many remain sceptical. Milligan et al. (2009) argue that coastal erosion and flood policy are incompatible with durable land use planning which controls development in higher risk areas.

1.9 Perceived gaps this research seeks to address

The methodology employed within each subsequent chapter of this thesis addresses specific issues relating to the use of data within the field of coastal management and adaptation. Each chapter takes the form of an academic paper, in which the specific issues tackled are presented fully. However, an overview is provided here of a range of data related gaps, associated with coastal management decision-making processes, which are covered within this thesis.

Current coastal decision-making processes lack robustness and are in need of shifting from a reactive to a more proactive approach. Dodds (2009) stressed how scientific information in this domain should flow from scientists to decision makers. In line with this, the Environment Agency (2010) advocate a risk-driven approach to coastal management where evidence-based long-term decision-making occurs. The National Trust (2015b) have identified the requirement for provision of more information relating to coastal risk in planning guidance. The stance taken by Defra (2009) concurs; Defra have emphasised the importance of long time frames in the understanding of coastal risk, where assessments of past probabilities are projected into the future. These various requirements all centre on the need to increase coastal data utilisation, allowing informed, evidence-based decision-making to occur. Moreover, increased understanding of the potential offered through geospatial analysis of existing datasets is required.

Section 1.7.2.5 highlighted the problem of data being retained in 'silos'. Given the large number of organisations working in this field, this is a significant challenge and can result in duplication of efforts. Communication of the work that organisations are undertaking, and provision of access to the resulting data is essential in addressing and overcoming these problems (MKEN, 2015). However, information provision is often uncoordinated (Dyer and Millard, 2002), resulting in duplication of work, both in data collection and its processing. As a result, excessive redundancy can be introduced, and datasets thereby devalued. With increasing volumes of open source data being made available, earlier barriers to creating data-sharing platforms, such as Intellectual Property Rights (IPR) and copyright issues, are reduced. Within the domain of coastal management, data sharing has been highlighted as essential by many (Visser, 2015; Dávila et al., 2014). Yet, despite many open source mapping and data sharing projects existing, progress is necessary in this area. Within Europe problems exist due to inaccessibility of data relating to surveys of ocean habitats (Visser, 2015). This is being addressed by the EMODnet project. However, this project focuses only on physical datasets. As such, a requirement exists to identify and catalogue open source data available for the coast, and to establish how this can be utilised in addressing core aspects of coastal management, and furthermore, be applied within coastal risk and resilience assessments.

Spencer et al. (2015) outline how, in relation to understanding impacts related to storm surges, a wide range of sources need to be drawn upon, including environmental data, landscape change surveys and socio-economic databases. Consideration of a wider range of factors is also imperative when evaluating the vulnerability of future risk within planning frameworks. Roberts (2012, p.274) highlights this, arguing that 'coastal developments cannot be driven by economic interests alone'. Health impacts and other softer impacts on humans represent factors that many studies such as the Tyndall project (Nicholls et al., 2015a) often omit. Moreover, a clear gap can be observed in existing risk evaluation processes, in relation to the data they include. In addressing this, both the breadth of variables included in a study, and the density of data incorporated within models, needs to be considered. Therefore, there is a requirement to identify how holistic coastal data sources can be acquired, combined and analysed.

There are many valuable datasets, held by stakeholder organisations, which have yet to be combined and analysed (Section 1.7.2.5). Much of this data is held in the public domain and is today easily accessible via open source data portals, such as that hosted by the Channel Coastal Observatory (CCO) (National Network of Regional Coastal Monitoring Programmes of England., n.d.)[5]. Yet, only a limited number of studies focus specifically on the application of innovations in the use of data within this field. Progress needs to be made in this area, especially in combining and analysing the large quantities of point cloud data routinely collected as part of coastal monitoring programs (in England this involves the EA, the CCO, and other public bodies). Furthermore, this data holds untapped potential for more accurately modelling physical coastal impacts.

In order to represent accurately the wide range of factors that need to be considered in a risk assessment, more detailed data is required. This can be achieved by increasing the density of data used and the variety of sources drawn on. In the development of risk management strategies for the coast, the advent of freely available high resolution

[5] The CCO runs a network of regional coastal monitoring programmes and, operating in partnership with the EA and local authorities, is funded by DEFRA (Environment Agency, 2010).

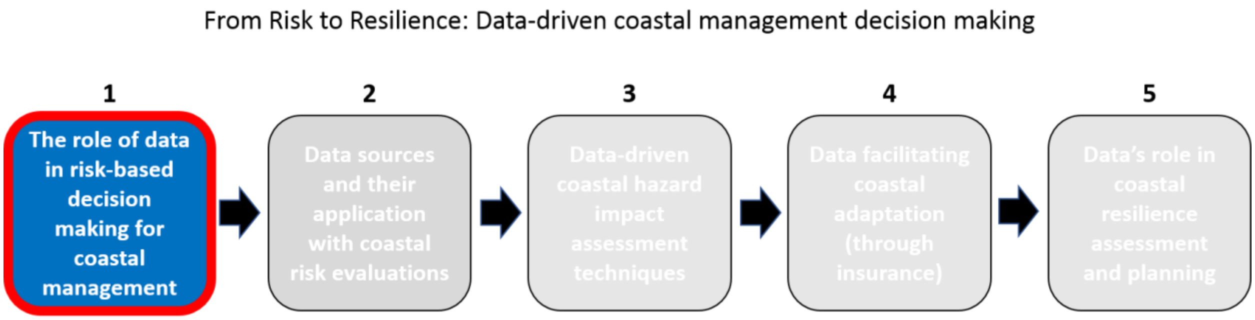
topographic data can act as a solid base, especially in relation to flood and erosion prediction (Villatoro et al., 2014). Much of this topographic data is now derived from Lidar, however Lidar datasets can prove so large that restraints are placed on storage and processing, especially when considering data for extended spatial and temporal scales. Given this, research is required into suitable geomorphological change detection (GCD) methods which can be applied to high resolution point cloud data, acquired by airborne Lidar and other sensors such as Terrestrial Laser Scanning (TLS). Application of such advanced methods and datasets can also help to address specific requirements of coastal management practitioners, who have expressed a requirement to compare current real-time changes in coastal geomorphology to predicted changes detailed within SMP documents.

Dávila et al. (2014) argue that risk awareness can be increased at a national level if knowledge and tools are pooled. Such pooling of resources can enable risk mapping, sought by those in the private sector such as insurance companies, in addition to public sector coastal management organisations. Yet access to, and appropriate analysis of, information is a constraint to achieving this. Scope exists to improve risk-mapping, which can work to limit development in high risk areas (Botzen and van den Bergh, 2008). As early as 2005, the UK government is reported to have outlined plans to broaden the evidence-base accessible to coastal managers and to widen the portfolio of risk management tools available to them (Defra, 2005; Milligan et al., 2009). Progress continues to be made in this area, by the Environment Agency through projects such as the National Coastal Erosion Risk Map, NCERM (Frampton et al., 2017), and within East Anglia, coordinated data collection efforts continue to be orchestrated through the Anglian Coastal Monitoring Group (East Anglian Coastal Group, n.d.). Demands for risk mapping made at a national level are also echoed at a supranational level; for example, agreements reached by the EU Council of Environment Ministers have stated that flood risk mapping should be undertaken across Europe (Defra, 2004). Furthermore, such measures have been implemented as part of the EU's Flood Risk Management Directive (European Commission, 2019). In line with this, Defra (2005) outlined a strategy to develop the reliability and coverage of risk information and mapping. Risk mapping can form an integral part of a decision support tool, enabling multiple scenarios to be compared and risk management strategies to be developed (Villatoro et al., 2014). Outputs from such analysis can form an essential input to land planning on the coast. Moreover, a clear requirement exists for identification and implementation of emerging innovations used in the acquisition and analysis of data. This can allow public and private sector organisations (such as insurers) to more accurately evaluate risk in coastal area. If the results are communicated to the public this can indirectly result in risk adaptation and increased levels of resilience.

One important factor this research seeks to address, is that the process of bringing together information for the coast is not a static exercise, as such dynamic systems and data sources need to be identified and utilised to ensure the resulting models and analysis accurately resemble the continually evolving reality. This is especially important when attempting to complete resilience assessments in coastal areas, as the human, environmental and societal factors, which need to be accounted for, within the metrics that form the basis of resilience assessments, are highly dynamic. Therefore, data sources and tools, allowing accurate representation of such fluid, evolving factors, need to be identified, in addition to methodologies allowing their incorporation within future decision-making processes.

Government Open Data initiatives such as Data.gov.uk are working to make data accessible to those who need it. Yet, online mapping/open data projects seldom incorporate the analytical functionality and core geovisualisation functions found in desktop mapping software (Smith, 2016). Given this, a methodology needs to be developed, allowing the large volumes of geospatial coastal data, now readily available for regions such as East Anglia, to be incorporated within spatially-based risk and resilience assessments.

2 Coastal risk adaptation: the potential role of accessible geospatial Big Data



The main theme tackled within this chapter is the role that data plays within decision-making processes on the coast. The chapter takes the form of a literature review, which initially covers the underlying themes which should be considered within a coastal risk assessment, i.e. vulnerability, hazards, impacts, and adaptation measures. These themes form a central component of this thesis. A concise discussion on coastal risk is presented here; aspects relating to vulnerability and hazards are further expanded upon in Appendix A. In assessing the role of information within coastal decision-making processes, many past studies are discussed, from which spatial planning emerges as an important topic. The work in this thesis builds on progress made in numerous past studies which have applied data-driven approaches to tackling issues relating to coastal risk. A brief critique is made of some of the more prominent studies, especially those utilising Geospatial Information Systems (GIS), Decision Support Systems (DSS) and Big Data technologies. A more extensive review of past studies is presented within Appendix B.

The discussion within this chapter reveals how a wide range of holistic data variables need to be drawn on when evaluating risk in coastal areas. Also, the provision of adequate spatial coverage at the required level of detail and granularity emerges as a key consideration, to enable evaluations to be undertaken at the required scale. Furthermore a mismatch was revealed in some instances, between the scale of data collection and the scale required for decision making. However, sourcing and collating disparate datasets related to the coast has been associated with a number of challenges. Many of these challenges have been addressed within subsequent chapters of this thesis. In line with the key themes identified within the summary in Table 2 , the subsequent chapters of this thesis explore some of the proposed solutions which have been highlighted. In doing so, this research seeks to generate insight into how emerging data sources, and advanced means of data processing and analysis, can be drawn on to enable a comprehensive evidence base to be established, aiding decision-making for coastal areas. Yet there are a number of factors that place limits on the tools developed to evaluate coastal risk; prominent among these is the need for reliable and accurate data (Siemers, 2015). This chapter broaches this issue, revealing how verification of data veracity is something which can present a potential hurdle for a project in which a large number of datasets are combined. This cannot be overlooked, as such there is a fundamental requirement for the establishment of a coherent metadata system for such projects, enabling data source, date quality, age and original format to be determined.

An introduction is provided within this chapter to a factor that can potentially set this study apart from those completed in this area previously, this being the consideration of rapidly emerging innovations in methods for data acquisition and analysis. These are considered in relation to their ability to tackle issues of scale, data density, incompatibility of data formats, and for deriving meaning from the heterogeneous data forms, and diverse ranges of variables, covering large geographical areas and time periods. Currently, there are a limited number of studies completed in relation to application of data innovations to coastal datasets, yet those that exist, and are profiled within this chapter, do suggest that there is considerable scope for such technologies to improve understanding of coastal risk adaptation (Chailan et al., 2012; Lee and Kang, 2015; Millie et al., 2013; Usery and US Geological Survey, 2015).

The problems and potential solutions identified within this chapter, form the basis of those addressed within the subsequent chapters of this thesis. These include: the ability to source and collate holistic coastal datasets; to utilise high spatial and temporal resolution, attribute rich datasets; application of advanced analytical methods within assessments; and the capacity to draw on novel data sources. Further examination of such issues can permit the development of approaches capable of revealing patterns and interactions between the diverse range of environmental, economic and societal factors present in coastal areas, and to reduce levels of subjectivity within coastal management decision-making practices.

Coastal Risk Adaptation: the potential role of Accessible Geospatial Big Data

ABSTRACT

Increasing numbers of people are living in and using coastal areas. Combined with the presence of pervasive coastal threats, such as flooding and erosion, this is having widespread impacts on coastal populations, infrastructure and ecosystems. For the right adaptive strategies to be adopted, and planning decisions to be made, rigorous evaluation of the available options is required. This evaluation hinges on the availability and use of suitable datasets. For knowledge to be derived from coastal datasets, such data needs to be combined and analysed in an effective manner. This paper reviews a wide range of literature relating to data-driven approaches to coastal risk evaluation, revealing how limitations have been imposed on many of these methods, due to restrictions in computing power and access to data. The rapidly emerging field of 'Big Data' can help overcome many of these hurdles. 'Big Data' involves powerful computer infrastructures, enabling storage, processing and real-time analysis of large volumes and varieties of data, in a fast and reliable manner. Through consideration of examples of how 'Big Data' technologies are being applied to fields related to coastal risk, it becomes apparent that geospatial Big Data solutions hold clear potential to improve the process of risk-based decision-making on the coast. 'Big Data' does not provide a stand-alone solution to the issues and gaps outlined in this paper, yet these technological methods hold the potential to optimise data-driven approaches, enabling robust risk profiles to be generated for coastal regions.

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2.1 Introduction

Decision-making in coastal regions needs to be based on sound science and accurate information. Access to appropriate ‘information’ has been outlined as comprising a vital component within the coastal management process [1]. Data and information form the basis of comprehensive mapping and analysis of coastal risk [2–5]. However, there exists a vast body of data for coastal zones, and the volume and variety of datasets requiring collation, organisation, and subsequent analysis can prove overwhelming. If progress is to be made in this area a new paradigm must be developed for data, information and knowledge management. Emergent information and computational techniques hold potential benefits in the realisation of this goal. The rapidly evolving field of ‘Big Data’ and associated analytical approaches are proposed to be well-suited to facilitate such decision-making.

This paper focuses on coastal risk adaptation, the role of information, and potential application of Big Data solutions within this domain. This is addressed through assessment of literature dated from 2000[6] to 2017, focussing especially upon the application of data-driven approaches to coastal zone management. This has permitted emergent themes to be highlighted and investigated, providing a new understanding as to the efficacy of these methods. As yet, there have been only limited studies completed in relation to coastal Big Data approaches, yet those which do exist suggest there is considerable scope for application of these technologies to enable the generation of robust environmental risk profiles for coastal regions [3,6–8].

At the outset, it must be stated that this work cannot represent a comprehensive evaluation of all materials published concerning coastal decision support approaches, within the seventeen-year time-period reviewed. This work instead sets out to characterise and reflect upon emergent developments and, in so doing, presents a discerning representation of relevant key works, providing a structure to support an appraisal of developing opinion concerning the complexities surrounding coastal risk assessment. The publications addressed are categorised within three themes, namely: coastal risk adaptation, data-driven approaches, and the application of Big Data to coastal management. Table 2 provides an overview of issues addressed within this research in relation to these three themes. It is considered that these themes provide a useful foundation for addressing the developments in this new area, with each selected publication exemplifying pertinent issues from the current debate.

2.2 Coastal Risk and Adaptation

2.2.1 Vulnerability/Hazards

Sustainable management approaches in coastal zones are challenged through the wide-ranging, dynamic hazards threatening the status quo in these regions. Hazards have been defined by authors, such as Kron [12, p.1369], as representing ‘the threat posed by natural forces that cannot be influenced….. beyond mankind’s control’. Muro et al., [13, p.4] define a hazard as ‘the

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[6] The cut-off point, of the year 2000, was selected so to incorporate some important coastal management developments made in the early years of the new millennium.

potential to cause harm (or intrinsic capacity to cause damage)'. In an anthropocentric sense hazards are seen in general as exerting a potential threat to humans and their welfare. Of the naturally occurring coastal hazards, flooding and erosion are the two most significant, and are therefore focused on primarily within this paper. Flooding of coastal systems in particular is considered 'one of the most frequent and damaging natural hazards, affecting countries across the globe' (UNISDR, 2011 cited in [11]). Nevertheless, impacts are also generated from human activity in coastal areas and the ocean. Unsustainable overuse of maritime resources represents a significant concern, and land-based pollutants (such as sewage and industrial wastewater) are major threats to coastal ecosystems [12].

Coastal hazards lead in turn to societal vulnerabilities, affecting properties, persons and infrastructure. Smit & Wandel [15, p.284] state the term vulnerability is used to describe 'the estimated net or residual impacts (being the initial impact costs, minus net adaptation savings)'. For England and Wales, Defra [17, p.104] estimated that approximately '100,000 properties, having a total value of £8 billion, in areas without protection could be eroded in the next century' with 1 million coastal properties being at risk of flooding, with an estimated value of £130 billion.

Population growth within the coastal zone has been widely cited as a catalyst factor raising levels of vulnerability [16,17]. Natural hazard losses can be related directly to the number of people living in risk prone areas, especially where a large number of people, assets and complex infrastructure are concentrated in single vulnerable locations.

2.2.2 Risk

In acknowledging coastal hazards and associated vulnerabilities, the nature and extent of coastal risk can be identified. Risk may be defined as the probability of a given hazard occurring, factored by the severity of its consequences [1,9,14,18–24], thus:

$$Risk = Probability\ x\ Consequence \quad (1)$$

Risk represents 'the main instrument and criteria leading to coastal zone management policy' [18]. The Tyndall Coastal Simulator project [25], identified for a case study site in East Anglia that flood risk is predicted to grow exponentially during the 21st century, whilst erosion risk is predicted to remain relatively constant. Jongman et al. [11] state that, in the Netherlands, exposure to flooding has increased by 300% over the last 50 years, as economic value in coastal areas has risen at a rate above that of the national average. Poor planning on the coast and unsustainable natural resource use has been cited as major factors exacerbating a wide range of environmental risks, such as those relating to natural processes, Climate Change induced hazards and pollution [16].

2.2.3 Impacts

Within the progression of the coastal risk cycle, hazards create vulnerabilities, which in turn lead to the propagation of these hazards, resulting in consequences, which can be labelled 'impacts'. The term impact 'implicitly deals with severity, intensity, or duration of the effect' [28, p.69], Impacts can become compounded in some instances because of human attempts at adaptation.

As a result 'Coastal Squeeze' can occur, as habitats and natural coastal features become caught between defences and rising sea levels and so become lost at accelerated rates [15,27].

One implication of human intervention is that many stretches of coast, lying adjacent to protected areas, have become sand-starved [28]. This concurs with the most apparent impact from physical coastal processes being the landward transition of the shoreline, becoming especially apparent when extreme events occur, such as the North Sea Storm Surges of 1953 and 2013 [29,30]. Damage arising from natural disasters has been reported to increase in recent times as a result of capital accumulation in flood-prone areas [19].

2.2.4 Adaptive measures

Adaptations have been termed: 'adjustments in a system's behaviour and characteristics that enhance its ability to cope with external stress' [15, p.282]. Conflict is almost inevitable where continued development in coastal areas requires stability, whilst natural processes involve change [31]. As a result, humans who wish to develop coastal sites are required to adapt to natural processes.

In terms of physical adaptations, conventional coastal adaptations can be split into groupings of 'hard' and 'soft' measures. Hard adaptation measures are generally semi-permanent installations on the coast. Examples of these are seawalls, revetments, groynes, and breakwater sills. Soft adaptation measures include beach feeding (recharge), dune building, and 'Managed Realignment' [28]. Soft measures are those designed to work with natural processes [22]. In the UK, Defra [14] have outlined the need to 'work with natural processes' and to use a 'wide range of risk management options', including softer adaptation measures. Furthermore, in enacting *Making Space for Water*[7] [15], Defra is reported to be using ecosystems services in some areas, instead of relying on hard measures (in tackling flood and coastal erosion risk) [32].

In economic terms people begin to rely on coastal protection structures, making their property more valuable [31]. In this sense government can be seen to provide inverse incentives to invest in hazardous areas through the provision of protection [11]. For the right adaptive strategies to be adopted, rigorous evaluation of the available options is required [33]. This evaluation hinges on the availability and use of suitable datasets.

2.2.5 Coastal Risk Assessment –the role of information

Building on notions of coastal risk, it becomes apparent that a core driving aspect of managing the coastline is the completion of reasoned risk assessments. Within risk assessments, hazards need to be identified, together with estimations of their probability, and quantification of the impacts these hazards will have on vulnerable areas. This enables adaptive management strategies to be developed. Advances in computing power can prove critical in this process as responses to events can be altered by data-driven modelling [1]. Without this a situation of

[7] Making Space for Water is a key document relating to government coastal policy in England and Wales, published in 2004 [15.

inappropriate development of coastal land can arise. Generally though, increased construction on the coast is seen to result in long-term damage to the environment and increased risk from flooding and erosion [31]. Therefore, in making decisions about future developments on the coast it is critical to evaluate the full range of risks.

In their first response to, *Making Space for Water*, Defra [14] emphasise how risk information must drive activities, highlighting the specific requirement for inclusion of better data on the consequences of coastal flooding and erosion. In relation to coastal partnerships in England, Milligan et al. [34] argue that a fresh approach should better incorporate flood and erosion risk assessments in its planning phases. Yet this is not simple, and difficulties for risk assessors are seen to involve a choice between different subjective estimates of risk, and ultimately real risk being perceived as an 'inherently unknowable entity' [16, p.4]. In addressing these problems we need to determine where the most rational analysis of the most relevant evidence has been completed [1]. In particular, factors such as 'the location of a development is crucial in determining flood risk' [19].

Kron [9] elaborates on the elements required for inclusion in risk assessments, stating that risk components included must account for: physical, economic, social, political, psychological, and cultural factors. Risk assessments may thus involve development of what Smit & Wandel [15, p.282] labelled 'Vulnerability Indices', seen as an aid to identification of adaptation strategies. The reasoning underlying this is that coastal threats need to be predicted so that communities and civil protection agencies are able to respond and so hazard reduction 'measures can be put in place to reduce the risk' [35].

The scale at which risks are measured, and the methodology underlying aggregation of data variables used to calculate risk, can prove problematic to the generation of representative risk assessments. Jongman et al. [36] concur with this, concluding that caution should be exercised 'when using aggregated land-use data for flood risk assessment', as this has resulted in over/under-estimation of flood damages. Moreover, Kron [9] highlights how integrating data for large spatial areas, in terms of average intensity, may obscure values derived from modelling of flood losses. However, the methodology of many risk assessments for the coast have incorporated some form of aggregation [37–39]. Therefore, it is evident that progress is required in this area.

One theme neglected in many coastal risk assessments relates to recognition of the role of ecosystem services. Yet ecosystem based coastal management approaches are now recognised as essential [40]. Arkema et al. [41] argue that evaluation methods focusing on the role of natural defences lag behind those focusing on hard adaptation measures. To ensure representative coastal risk evaluations take place more thorough syntheses are called for, incorporating a diverse range of statutory data, such as climate scenarios, demographic information and ecological data, alongside hazard models. Ramieri & Hartley [39] stress the importance of moving beyond an anthropogenic perspective, considering ecological needs and the socio-economic context as a hazard in itself. This more holistic approach to risk assessment fits in with the wider aims of Decision Support Systems (DSS) outlined by Westmacott [42], as seeking to improve 'our understanding of inter-relationships between the natural and socio-economic variables', thus improving decision-making.

The process of accurate risk analysis, and importantly how the results of this can be conveyed to the public, can serve to increase risk perception. If risk awareness is low, negative results can ensue, such as an increase in properties being built and purchased in areas prone to flooding [16,19]. Risk perceptions are shaped by a wide range of factors, socioeconomic, demographic and cultural; given this, it is imperative that risk assessments account for a wide range of elements, otherwise risk perception bias can ensue [19].

2.3 Big Data

The terminology of Big Data, relates not only to the handling of large volumes of data, but refers also to broader data issues such as the ability to manage concurrently a wide variety of data formats, with the incorporation of high currency and even real-time (high velocity) data [43,44]; allied to which are a new generation of analytical and data processing capabilities. Central to the concepts surrounding Big Data are the multi-node computer infrastructures employed, enabling the collective storage of large volumes of data in a distributed and scalable manner [45]. Big Data approaches can enable the large, diverse databanks associated with comprehensive environmental risk mapping exercises, to be incorporated successfully within a single modelling framework.

Of particular importance to coastal risk evaluation is how Big Data tools and associated technologies offer the potential to tackle issues of scale, data density, and incompatibility of data formats for data covering large geographical areas and time periods [46–48]. The following sections address data and information use and requirements, with a review of existing research in this area. Following this, in Section 6, an assessment is provided of the current application of Big Data to this domain.

2.4 Data driven approaches to Managing Risk in the Coastal Zone

2.4.1 Coastal Management

Coastal Management has historically been 'characterised by a fundamental lack of understanding of natural coastal processes' and a view that the 'land sea boundary is fixed' [46, p.587]. In recent times, governments worldwide have been identifying the need to prioritise scientific understanding of coastal regions, which are inherently dynamic. The role of information and accurate science is recognised as important for the governance of ocean and coastal resources [50,51]. Therefore, to achieve knowledge-based decision-making, a data-driven approach is fundamental and can provide the means to generate a clearer understanding of the processes at work on the coast [1].

When solutions are required to issues which span across scales of governance, then problems can occur due to a lack of systematic environmental data and metadata exchange between nations and the international community [51]. Key to Integrated Coastal Zone Management (ICZM) are the associated data management initiatives, which include best practice guidelines for data exchange and metadata standards, and which contribute to ICZM being able to maximise and bring into focus value derived from environmental data [40,52]. Implementation of data management through spatial planning is therefore deemed a typical aspect of ICZM which is seen to contribute to generation of an improved knowledge base [53].

2.4.2 Spatial Data and Land Planning

Spatial management is viewed a significant factor contributing to understanding and addressing the levels of risk experienced in coastal regions [20]. Flood risk in particular, is a key aspect of spatial planning [15]. In China, Li et al. [3] researched the consequences of rapid urbanisation in the coastal city of Haikou. They revealed a large, emerging disparity between developments in different areas within the same coastal zone. They concluded that this indicates a requirement for planning policy to ensure the sustainability of future coastal developments, as land utilisation is a key human activity increasing vulnerability on the coastline. Low awareness of risk can be a causal factor leading to inefficient spatial developments [22]. A core aspect of coastal management involves creation and implementation of a risk-based framework, reducing vulnerability through controlling future development [18].

Filatova & Veen [18] argue that it is the government's responsibility to inform coastal populations of risk in these regions, but due to their inadequacy in doing so, inefficient allocations of land have resulted and as a consequence demand for protection has increased in line with rising economic values [19,54]. This problem has been reduced to a cycle, illustrated in Figure 6, in which property is constructed in vulnerable locations in the coastal zone, resulting in increased demand for protection; following installation of (temporary) protection, a false sense of security is generated and the density of habitation increases further, thus causing risk to rise once again. Filatova et al. [21, p.165] argue that this a 'self-reinforcing cycle that has a negative effect on flood risk'.

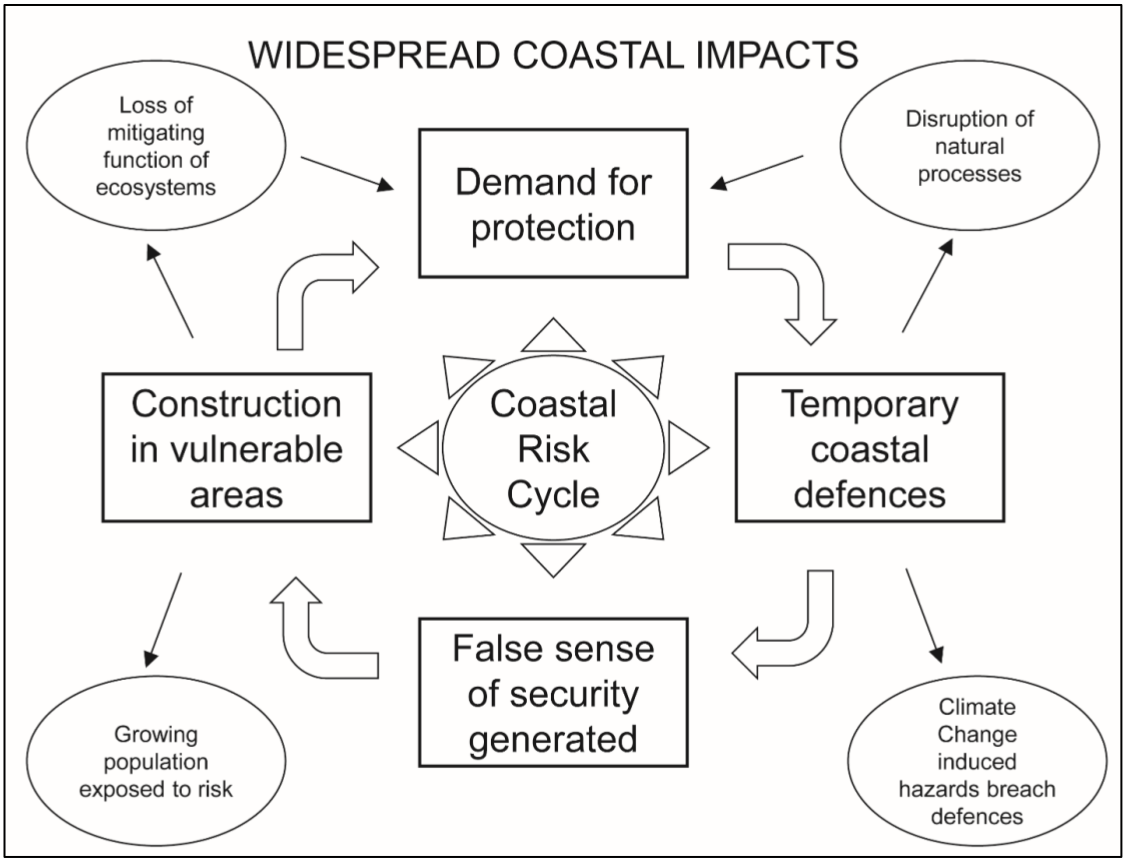

Figure 6: Coastal risk cycle

2.4.3 From Data to Knowledge

Coastal Decision Support Systems (DSS) which are used for testing management strategies and vulnerability assessments, hinge on the availability, accuracy and resolution of appropriate data. Linking 'high resolution data, numerical flood models and visualisation tools provide opportunities for society to respond to …. flooding events' [54, p.238]. In Ireland, data was identified as a core requirement within the Cork ICZM plan, being recognised as providing the foundation of a knowledge base for climate adaptation and spatial land use planning [53]. Yet when assembling such large quantities of data, many challenges are encountered. Despite there being significant bodies of data made freely available via Open Data platforms, utilisation of this data is not always straightforward for non-specialists. In their study Dyer & Millard [52] drew attention to some of these issues, which they linked to the use and exchange of coastal data. Yet much progress has been made in this field since publication of their seminal paper, and the current momentum of the Open Data movement, combined with advances in web-mapping tools are supporting an increase in access to data, presenting new analytical opportunities [56].

The issue of scale can present specific challenges [57]. It is one of the clear drivers necessitating the use of Big Data technologies. In assessing coastal vulnerability and risk a requirement has emerged to draw on the high level of detail offered by comprehensive localised datasets, yet also to combine this with the enhanced perspective gained from conducting analysis at a regional or national level [38]. To achieve this requires technical approaches to be implemented, able to contend with substantive volumes of 'high density' geospatial data (such as that generated by Lidar systems and satellite sensors), as well as large attribute rich datasets from sources comprising, for example, collections of static, legacy data. In the past, however, this has proved problematic due to restrictions in data availability, storage and processing power [46]. Nevertheless, it is now possible to draw on distributed, networked, dynamic data sources and services, which can potentially enable such an enterprise to be realised.

Generation of knowledge in this domain is reliant on data relating to the coast being continually collected and analysed. The UK's first Marine and Coastal Policy Forum in 2011 outlined that, to enable evidence-based policy making, it is necessary to secure improved data access, sharing, and its utilisation in DSS approaches [58]. There are increasing volumes of data now becoming available, spurred on by Open Data initiatives such as data.gov.uk[8], which can provide policy makers with new opportunities to make informed decisions [14, p.1245]. Yet the technology utilised to enable collection, processing and sharing of data is rapidly evolving and becoming obsolete as successive technologies emerge [52]. This necessitates consideration of new Big Data tools and techniques, such as those discussed in Section 6.

2.4.4 Big Data and the INSPIRE Directive

Within a European context, the INSPIRE Directive [59] is a key facet in the adoption of Big Data techniques in support of European Community environmental policies. In considering issues relating to environmental (coastal) data access, sharing and use within decision-making, it is valuable to look to some general aspects of INSPIRE which hold global relevance. INSPIRE is necessary. INSPIRE sets out a framework for a Spatial Data Infrastructure (SDI), designed to facilitate co-ordination and implementation of spatial information for policy purposes. It comprises of protocols developed to aid interoperability of metadata, spatial data sets and services, and network services and technologies. INSPIRE also includes agreements on data sharing, use, coordination, monitoring mechanisms, and procedures. This is achieved through five guiding principles within the Directive such that: data should be collected once and maintained at the most appropriate level; that it must be possible to combine seamlessly and share spatial data from many sources across the EU; that it must be possible for spatial data to be shared between all levels of government (e.g. recognising the merits of the 'reuse of public sector information (PSI)'); that spatial data needed for good governance should be freely available; and that it should be easy to discover and evaluate which spatial data is available, and any usage restrictions made apparent.

Through INSPIRE, data specifications are adopted across over 30 themes with societal or environmental relevance (such as sea regions, oceanographic/geographical features and hydrography). These specifications permit national data repositories and geoportals to implement a common interface to aid the interoperability of their data holdings throughout the European Community. Keay et al. [60] describe the process of moving national scale terrestrial

[8] The Data.gov.uk resource [95], is a British Government Open Data Portal, which was launched in 2010.

data repositories towards INSPIRE compliance, with related case studies of best practice ([61], p.179-183). INSPIRE has established mechanisms enabling extensive quantities of information to be interoperated, integrated and analysed, permitting interrelationships between natural and socio-economic factors to be revealed. Essentially this can work to improve the role of evidence within decision-making. The Directive allows a 'multi-view' across layers of interactions between the SDIs and their users. In relation to this current research this is especially pertinent given the wide range of themes needing to be considered within coastal risk assessments (requiring integration of marine and terrestrial datasets), and the many stakeholders involved in the coastal management process [62].

Existing Coastal Risk Adaptation studies

2.4.5 Collaborative academic coastal projects within Europe

Many large scale, collaborative studies have been undertaken in the field of coastal risk adaptation, drawing together expertise and resources from industry, the public sector and academia [27]. Within England the Tyndall Coastal Simulator[9] and iCOASST[10] are two recent projects, focussing on issues of coastal vulnerability, and modelling of the physical processes taking place in the near-shore environment. A wide range of projects addressing similar themes have been completed at a European level. Examples include PEARL[11], THESEUS[12], C-SCOPE[13] and RISC-KIT[14].

2.4.6 Studies focusing on coastal risk

Much research has focussed specifically on coastal risk. Filatova & Veen [18] completed a study focusing on land use change on the coast, concentrating on a case study in Northern Holland and using an Agent Based Model (ABM) approach. The approach was concerned with how interactions between different actors affect land use configuration. The study is important, illustrating how economic and human behaviour data may be combined with other data, such as geomorphology, to model and predict land use change. A study by Jongman et al. [11] also focused on the human aspect of coastal risk, using detailed property level data to enable enhanced decision-making on the coast, in relation to flood risk financing at a national scale. The study demonstrates the benefits of combining both scale and detail (noted in Section 4.3). The methodology employed involved combining different spatial scales, using open source data from

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[9] As part of the Tyndall Coastal Simulator project, the SCAPE tool, developed by Walkden & Hall [96], was applied to the North Norfolk coast [97,98]. The SCAPE tool focuses on drivers of coastal change such as sediment transport and coastal engineered features.

[10] The iCOASST project [99], built on work completed within the Tyndall Coastal Simulator. It went on to further understanding of coastal processes with case study sites in Suffolk and Liverpool [67].

[11] The PEARL [100] project commenced in 2013 and is still underway (2017) [101]. The project focusses on extreme hydro-meteorological events, and examines holistic risk assessments, including cascading effects.

[12] The THESEUS project [102] ran between 2009 and 2013 and focused on a number of study sites across Europe, representing a range of coastal conditions [33].

[13] C-SCOPE [103] ran as a cross-border cooperation programme in Northern Europe [94].

[14] RISC-KIT [104] is another European collaboration, running from 2013 - 2017. It represents a consortium made up of 18 partners from 10 European countries and two international organisations [64].

a national property database. The level of detail used was reported as not being common, and the study concluded that aggregated land use data fails to represent accurately changes in property density in urban areas. Property level data, when collated for large areas and combined with hazard datasets, however was shown to enable national level risk mapping.

A wider comparative study by Villatoro et al. [35], incorporated four case studies, and covered open beach study sites in England, Italy, Spain and Bulgaria, considering vulnerability to flooding and erosion. The study established an interdisciplinary methodology for estimating quantitative risk at the study sites. Geographical Information Systems (GIS) were used within some of the case studies to combine and analyse a wide variety of data [35]. Both the Italian and English case studies illustrate the benefits of methods using real data to assess the effectiveness of existing adaptation measures. The study concluded that natural and man-made coastal defences are both crucial in delimitation of the 'extent of coastal erosion' and floods. This concurs with the work reported by Heip et al. [27].

In the UK, outside academia, in 2001 the government commissioned a *Foresight review of future flooding* [23]. This set out to provide a vision for coastal defence and flood policy between 2030 and 2100. Cross-cutting analysis of economic, social and environmental impacts acted as a powerful driver, resulting in recommendations for future nature-based adaptation measures. The review clearly sets out a justification for future data-driven research and model creation. Following the Foresight Review, the National Trust undertook an independent project entitled Shifting Shores [63]. This revealed that, between 2005 and 2014, buildings were still being constructed in areas vulnerable to flooding and erosion, despite the existence of prohibitive planning laws. The study concluded that evidence-based assessments are needed to identify vulnerable locations and urged for more details of coastal risk to be provided in future planning guidance.

2.4.7 Coastal Decision Support Systems and Vulnerability Assessments

There are several projects which have reported the creation of coastal risk and vulnerability assessment tools, also often referred to as Decision Support Systems (DSS). DSS approaches were adopted in many collaborative projects, such as THESEUS and RISC-KIT [33,64]. A DSS is a computerised system incorporating a knowledge base or database [42]. The DSS approach covers a wide variety of fields, including socio-economic and ecological factors. Yet Westmacott's study identified how many past attempts have failed in this respect, as they have not produced results relevant to the economic or political context in which they operate.

DESYCO [65] (Decision Support System for Coastal climate change impact assessment) is a regional, GIS-based DSS, focusing on climate change hazards and ICZM. Of the DSS approaches evaluated by Ramieri & Hartley [39], DESYCO was identified as one of the approaches which held the most potential for coastal vulnerability assessments in European seas. The application of GIS aided the project in enabling visualisation and comparison of assessments. Yet the project was disadvantaged by the need to include heterogeneous data sources, formats and spatial scales [39]. Consequently, the inability of the DSS to handle large volumes and varieties of data was seen to constrain this project. This is an issue which Big Data tools can potentially address directly. In this sense, Big Data solutions can possibly enable the benefits of some suitable DSS methods, as in this case, to be unlocked.

In a paper by McLaughlin & Cooper [38], the authors outline the application of the Multi-scale Vulnerability Index (MVI) DSS. The project involved case studies considering three contrasting scales of application in Ireland: national, regional and local. Many issues already highlighted were drawn out from this, including data availability, comparability problems at different scales, and the need to include socio-economic data in assessments (topics also addressed by Bigagli [57]). The correct representation of scale is an issue that has traditionally limited vulnerability assessments. McLaughlin & Cooper [38] reveal how incompatible results have been generated from past assessments at different scales. This is explained in terms of the need, yet inability, to combine local level, high density datasets within larger scale assessments. Some important local level variations are reported to have been masked because of oversimplification within national level assessments. As Jongman et al. [4] McLaughlin & Cooper [38] acknowledge, simplification and aggregation have proven a problem in past studies. Yet due to limitations imposed by data availability, storage and processing power, incorporation of high density datasets has frequently not been possible in past DSS implementations [39]. This highlights the requirement to seek technical solutions, such as those offered in the field of Big Data.

One significant ongoing project that utilises the MVI methodology is the Natural Capital project, in which the InVEST tool was developed [37]. The hazard index, which the InVEST tool creates, includes a typology relating to the role ecosystems play in protecting the coast. Arkema et al. [66] applied this tool to the entire coast of the USA, revealing how important natural habitats are for the protection of coastal areas. The InVEST tool has produced useful insight, but the index it generates has failed to account for interactions between the typologies upon which it is based. The Natural Capital Project acknowledges [37], that the geometric mean of the seven variables considered in the model, can over simplify the complex, dynamic interaction between coastal processes. Unlike the Tyndall [2] and iCOASST [67] projects, the InVEST model does not consider 2D, hydrodynamic or sediment transport processes, in the nearshore region [37].

2.4.8 The role of GIS within coastal risk studies

Due to the geospatial characteristics of coastal risk, GIS are suitable tools to apply to coastal risk assessments [17]. GIS have been used extensively within vulnerability assessments and DSS. For example, in relation to the THESEUS project, Zanuttigh et al. [33] reported how GIS based tools can be adopted as an efficient technical solution, supporting decision-making within coastal risk management, and further how GIS can be used as a platform to enable the combination of social, economic and environmental data, facilitating scenario creation. Thumerer et al. [68] presented a study based in East Anglia, involving the creation of a GIS based coastal risk management DSS, which adopts a Microsoft 'Visual Basic' software front-end and modelling application. The study found GIS to be suitable to ICZM, enabling integration of large databases and evaluation of interactions between a large range of factors. Building on the theme of inappropriate coastal developments, the Chinese study by Li et al. [3] incorporated a range of data types and sources within a GIS-based vulnerability assessment tool for use within spatial planning. Overall, the study found GIS to play an important role in facilitating spatial analysis of urban ecosystems and vulnerability assessments.

There are now an expanding array of web-based opportunities for interactive mapping/online cartography, facilitated by Open Data releases and Cloud service innovations [69]. This has driven a number of UK projects, such as MAREMAP [70] (The Marine Environmental Mapping Program), MEDIN [71] (The Marine Environmental Data and Information Network) and Magic [72] (Multi-Agency Geographic Information for the Countryside), and at the European scale, EMODNET [73] (European Marine Observation Data network). Smith [56] notes how Cloud service innovations, as well as data exploration functionalities offered by powerful and accessible, interactive mapping platforms, can work to complement Big Data analysis and Open GIS. ‘Web-mapping Cloud services’ are seen to have ‘lower technical demands’. In particular, ‘on-the-fly’ rendering is reported to permit ‘navigation between thousands of possible map layer variables’; Smith [56] also deems this to work in tandem with developments in Big Data allowing a diverse range of indicators (economic, demographic and environmental) to be combined. Notwithstanding that, one caveat of the advances made in this domain that Smith highlights, is that the functionality within online mapping sites is generally basic and lacks desktop geovisualisation functions.

Web-based GIS have been used in identification of coastal hazards. Moszynski et al. [74] generated a web-based Safe City & Coastal Zone GIS (SCCZ- GIS). This successfully demonstrated how real-time feeds can be combined, to monitor security effectively in the coastal zone (for people and critical infrastructure). Aside from the direct application of GIS to coastal vulnerability, another relevant example of its application, in a web-based format, is the mapping of data relating to population and demographics, which has been completed within the DataShine Census project in England [66]. This project exemplifies the positive contribution that the increasing amount of open source, demographic data can have, in revealing underlying geospatial patterns.

2.5 The Application of Big Data to Coastal Management

For this paper, Big Data is considered as a process [43], able to facilitate evidence-based decision-making. Solutions utilising Big Data approaches can rarely be found off-the-shelf, yet Big Data software frameworks allow development of bespoke approaches to a wide range of problems [43]. Currently, there are limited examples of its application to the area of coastal management. Nevertheless, research reported in associated fields highlight its suitability to this domain.

Underlying the requirement to draw on Big Data approaches is the ever-expanding number of data sources available for coastal areas. Examples include data derived from real-time sensors and the ‘internet of things’, and potentially, community-sourced data, (such as volunteered geographic information (VGI)) [76]. Many initiatives are underway involving trial and validation of novel marine sensors. One such initiative is SmartBay Ireland [77] in which novel methods are being developed for collection and dissemination of real-time marine data, to national and international stakeholders. Yet the real-time nature of such data can present challenges to information systems. In relation to hydrological/oceanographic data, Big Data approaches combined with Cloud-Based solutions are regarded by Dow et al. [78], as opening opportunities for access to dynamic, up-to-date data repositories and visualization functionality. Projects such as that conducted by Maier et al. [7] have outlined the need to combine and analyse large quantities of 'Big Data', derived from ocean sensors, utilising both archive and real-time streaming data. Their research indicates how existing methods of dealing with these large bodies of data have proved flawed. Through the cases they highlight, it is apparent that Big Data technology could transform the way that vast quantities of physical ocean data are handled. In the United States some progress has been made in terms of combining real-time sensor feeds (from large-scale monitoring networks of rivers and estuaries) together with warehoused, archive data, to enable multi-parameter modelling to take place, of dynamic interactions in aquatic ecosystems [79]. Furthermore, in 2012 the US government announced a Big Data Initiative, with $200 million devoted [80]. As part of this, 'Big Data Regional Innovation Hubs' were established. Of these, the South Big Data Hub has recently outlined coastal hazards as a priority area for future innovation [81]. Also in the US, the National Oceanic and Atmospheric Administration (NOAA) are currently undertaking work on a Big Data project (BDP) [82], in which Cloud-Based solutions are being developed for storage and processing of ocean data [83].

Chailan et al. [6] completed a study which focused on the application of High Performance Pre-Computing (HPPC) architecture to coastal flooding, in developing an alert system based on precomputed scenarios. The system they developed incorporated a web-based user application, utilising Cloud-Based solutions to enable communication with a remote cluster, permitting them to undertake statistical analysis in relation to the precomputed scenarios. The results indicated that this methodology proved valuable. Future work, building on the achievements of the project, was outlined in relation to optimisation of storage. This is one area where specific Big Data software frameworks, such as those offered by Hadoop Distributed File System (HDFS) [84] may further the advances made using HPPCs.

Big Data approaches can be viewed both in terms of the ability to store and process large volumes of data, and the advanced analytical techniques which can be applied to this data [46]. For example, the technique of 'Complex Event Processing' (CEP) [48] enables multiple data streams (including geospatial data) to be combined, so events or patterns indicating more complex situations can be inferred. In a study completed by Millie et al. [8] the deployment of advanced analytical tools, such as Machine Learning and Artificial Neural Networks (ANNs), was shown to be suitable for deriving insight from the vast array of automated sensors used for coastal monitoring, which generate large, 'high dimensional data streams'.

In the field of environmental risk, ANNs have been shown to offer potential in the realm of modelling and predicting the future financial impact of natural calamities (or extreme events) [85]. This work applied open source software and Cloud-based solutions, indicating that these methods could prove cost effective options for governments with limited budgets, to draw on. ANNs have also been trialled in relation to geospatial environmental data by Pijanowski et al. [86], who employed this technology in a project titled: *The Land Transformation Model*. ANNs were used to derive patterns, and combined with High Performance Computers (HPCs). This project focused on national level datasets, combined using GIS. The techniques developed within the project offer promise to coastal management, specifically in the ability to generate models of land use change and urban growth. Big Data processes present the potential to enhance the application of methods developed in such projects, for example, through implementation of 'Batch' processing techniques that can reduce the requirement for some routine, time-consuming tasks to be undertaken manually, thus improving performance [84].

Geospatial data (such as that relating to coastal areas) has been deemed particularly suited to parallel processing methods made possible using Big Data techniques [48,87,88]. Lee & Kang [48] developed a 'spatial online analytical processing' system, which allows rapid processing of spatio-temporal data. This employed PostGIS as a data warehouse and Spatial Hadoop as a base platform. As part of the research carried out by Li et al. [3], relating to Haikou City in China (see Section 4.2), Big Data analyses of social media streams (Weibo) were used to identify tourism hotspots on the coast. Li et al. found links between commercial activity, tourism, urbanisation and vulnerability. Coastal vulnerability was also found to be greater in areas where higher levels of traffic activity were recorded. Location-based service data, generated by mobile phones, is similarly being used to understand the movement of people in urban areas [89]; this technique can potentially be applied to coastal regions to monitor footfall on beaches and traffic activity on coastal roads and facilities. Another area where Big Data has been applied successfully is crisis management, especially in relation to incidents such as flooding. What has been termed 'Big Crisis Data' [90], holds promise in relation to coastal emergency incident response.

Big Data infrastructures can enable efficient storage and processing of vast amounts of coastal data. The advanced analyses that Big Data approaches offer (such as Machine Learning and data mining) make possible a better understanding of the relationship between the diverse range of variables relating to the coast. The comprehensive information outputs generated from this analysis could then form inputs for web-mapping interfaces to serve remote users (potentially through internet enabled mobile devices) [78].

2.6 Gaps identified in existing solutions

Information and knowledge is an integral part of ICZM and thus ICZM is seen to require an instrument for coordinated information provision [52]. Improved knowledge management has been cited as an integral component of efforts to mitigate future coastal vulnerability [3]. As such, data management can improve data value and thereby make ICZM initiatives more effective. Yet this presents a challenge with regard to data accessibility. O'Mahony et al. [53] highlight clear problems with information flows between scientists, policy makers and practitioners, hampering decisions made at the local level; implementing an evidence-base through the appropriate tools is therefore deemed a key part of any adaptation framework. The approach can permit a methodology able to tackle the issue of scientific uncertainties in social and ecological systems, which can hamper effective long-term decision-making [49].

Numerous online GIS software suites now exist, such as ESRI ArcGIS Online (www.arcgis.com/home). These benefit from the potential of web-based services and Cloud-based solutions to increase access to large volumes of data stored remotely. However, despite the increasing number of open source mapping and data sharing projects, the data provided is often only available in a basic format, which still requires users to manipulate, analyse and generate their own visualisations from this data in order to derive insight from it [75].

In terms of risk mapping and analysis of data, a clear downfall observed in previous reported attempts relates to issues surrounding geo-spatial and/or temporal aggregation of data (variables). Many 'disaster risk management' decisions made at the national and international level are reported to be based on risk analysis using aggregated land-cover data [11], creating a substantial degree of uncertainty. To tackle this problem, risk mapping projects require the capability to bring a greater number of high density/attribute rich data types and sources together, providing more comprehensive representations of the variables they contain. Also in relation to scale, previous comprehensive analyses have been restricted to the level of cities or small regions, due to limitations imposed by data availability and high computing power requirements [11]. Contemporary Big Data tools and technology can potentially address these issues, enabling detailed risk mapping over wider geographical areas.

In formulating risk management strategies, there is a clear requirement to move beyond a focus limited to physical datasets. Many authors, such as Nicholls et al. [1] and Spencer et al. [29]**,** stress that a wider range of impacts now need to be incorporated within risk modelling approaches, such as health impacts arising from flooding, house price impacts [91], sophisticated impact analysis and socio-economic feedback. In line with this, Arkema et al. [41] have stressed how more work is required in developing holistic approaches, in which the adaptive role of natural habitats is recognised, as this can enable identification of locations where ecosystem-based and engineered approaches have been combined effectively. In determining future development plans, Milligan et al. [34] deem it necessary to enable planners to understand what social, cultural and economic gain, future adaptation options can offer an area. Nevertheless, many existing models are deemed lacking in that they fail to monitor the microeconomic forces associated with land use change such as human behaviour and interactions [18]**.**

Collating wide ranging data for coastal regions is not in itself novel, yet value can be added to this process by using Big Data technologies to enable a huge body of information to be stored in a way, so that it can be accessed in (near) real-time and analysed. The analytical capabilities in particular, can enhance our understanding of coastal risk, by allowing relationships, between a wide range of data variables to be realised. To maximise the real-world relevance of such an enterprise, researchers need to consider the dynamic nature of the rapidly evolving data landscape [1]. Big Data solutions can enable a data repository/geoportal to be created, continually updated, and for real-time data feeds to be incorporated. An example of Big Data software functionality that could enable this, can be found in *Batch and Stream processing* within the Hadoop Distributed File System (HDFS) [45,46,84] and Apache Spark [88].

In enabling large datasets to be stored, processed and analysed in locations remote from the user, Big Data infrastructures can work to empower coastal managers by providing 'Cloud' access to huge volumes of information. Nevertheless, there are many new challenges presented by the rapidly evolving Big Data era. Among these are issues of data provenance [92], and long-term scientific stewardship of environmental and geospatial data [93]. To give a clearer indication of how Big Data solutions identified within this research address the problems and opportunities discussed, Table 2 draws together key themes covered, pertaining to coastal risk management.

Table 2: Summary of key themes in risk-based decision-making in coastal regions

	Theme	Problem Context: Coastal Risk Adaptation	Opportunity: Data-driven approaches	Proposed Solution: Application of Big Data to coastal management
Environmental	The role of ecosystems and nature	Requirement to shift from 'Hard' to 'Soft' adaptation measures [19,20] Recognition of the role of natural defences and ecosystem services [40] Recommendations for future nature based adaptation measures [15,23] Natural and manmade defences both critical in controlling the extent of flooding [35] Need to identify where ecosystem and engineering approaches have been combined successfully [41]	Evaluation of the role of natural defences is inadequate [41], evaluation of data and modelling required Holistic approaches (drawing a wide range of data) required to account for the adaptive role of natural habitats [41] Need to account for interactions between factors, can enhance understanding of nature, such as the 2D hydrodynamic or sediment transport processes operating in the nearshore environment [37].	Complex interactions between factors, such as urbanisation and ecosystems, can be revealed [79]. Better understand relationships between the diverse range of data variables High density data streams from real-time hydrological sensor networks can be incorporated within analysis [7] Geomorphological change derived from analysis of high resolution environmental monitoring data
	Socio-Economic context	Population growth a catalyst factor, resulting in vulnerable assets, people, and infrastructure [16,17] Human induced hazards need accounting for, that can create coastal squeeze and a sand-starved coast [32]	Data is required detailing the consequences of flooding and erosion [14] Knowledge of vulnerability can enable communities to respond to threats [35]	Enable development of alert systems for flooding [6] Facilitate coastal emergency incident response [90] Enable multi-parameter modelling of dynamic interactions between factors [79]
	Coastal Risk	Risk =probability x consequences [1,9,14,18–24] Requirement to consider both risk to humans and the environment Flooding and Erosion are major hazards Flood risk seen to rise fastest [25]	Hazards need to be modelled and impacts predicted, to evaluate the full range of risks Need to develop vulnerability indices [15, p.282] Modelling of data enables responses to be developed to natural calamities [85]	Enable representative risk profiles to be generated Inclusion of high resolution data in wide scale national level analysis [86] Reduce uncertainty –allow coastal risk assessment parameters to be derived from the data

Societal / Institutional responses and governance	Risk Perception	Fundamental lack of understanding of natural processes [46] Need to increase stakeholder confidence in policy based on analytical outputs Coastal protection measures can produce inverse incentives to settle in high risk areas [11]	Data driven modelling underlies science [1] Scientific understanding of dynamic coastal processes needs to be clearly communicated [50,51]. Risk assessment needs to account for a wide range of elements otherwise risk perception bias can ensue [19]	Can link high resolution data, flood modelling and visualisation tools [55] Ability to tap into unconventional data sources Mining of social media streams [3] to derive public perceptions
	Coastal Management	Information flows between scientists, policy makers and planners can hamper decision-making [53] Government responsibility to inform public about coastal risk [18]	Data is the foundation of the knowledge base for ICZM [53] Extensive guidelines for data management initiatives relating to ICZM [40,52] ICZM requires an instrument for coordinated data provision [52]	Can provide access for coastal managers, to large quantities of data stored remotely Allow novel forms of data to be included in assessments such as mobile phone positioning data [89], revealing footfall on beaches, traffic flow densities, tourist and commercial activity, etc.
	Spatial Planning	Reduce vulnerability by ensuring future developments are sustainable [18] Requirement to reveal interactions between factors impacting land use [18] Details of coastal risk provided in planning guidance [63] Planners need to understand social, cultural, economic gain future adaptation options offer [34]	Data-driven risk assessment can enable evaluation of available planning options [33] Implementation of data management through spatial planning is key to ICZM [53] Vulnerability assessment tools are required in spatial planning [3] Data can enable monitoring of forces associated with land use change [18]	Enable inclusion of detailed property level data in assessments Automated processes enable patterns to be derived of land use change and urban growth [86] Allow comprehensive analysis at wider scales
Technological	Geospatial and temporal GIS and Decision Support	Evidence based assessments need to identify vulnerable locations [63] Risk management in the coastal zone is a geospatial issue [17]	GIS is used extensively in DSS and vulnerability assessments [38,63,3,65] GIS can combine many social and environmental data layers [33]	Big Data system proven application to geospatial data [48,87,88] Big Data can build on advances in web-mapping and Cloud-based solutions [56]

			Draw on web-mapping and Cloud services [69] Web-mapping interfaces can enable data to be made available to remote users [78] Open geospatial data available, via online portals: MEDIN/EMODNET (Section 7.4B.3)	Enable large bodies of open source data to be collated in data repositories Unlock the benefits of some suitable DSS tools (Section 7.4B.2)
	Information Requirements	Need to tackle scientific uncertainties in social and ecological system, which hamper decision-making [49] Need to reduce subjectivity in coastal risk assessments and planning (inherent in some past assessments [24,38,42,94]) Requirement for robust risk profiles derived from reliable data	Comprehensive analysis hinges on the availability, accuracy and resolution of appropriate data [55] Combining hazard datasets with property level data can enable national level risk mapping [11] Data required for large spatial-temporal extents Aggregation of data variables in assessments can equal uncertainty [36]	Big Data frameworks offer advances in data storage, processing power and speed [45] Enable creation of up to data repositories (including large bodies of data derived from Ocean Sensors [7]) Better understand relationships between diverse range of data variables. Enable storage, processing and analysis of high resolution datasets, combining scale and detail, moving beyond aggregation of data
	Technological Capabilities	Requirement for more comprehensive representation of processes taking place in the coastal zone [14] Need to consider a wide range of factors in any analysis, and interactions between these, including the social and economic context [44,17]	DSS can be constrained by the ability to handle large quantities, types and density of data [39]. Knowledge in this domain is reliant on data being continuously collected and analysed (temporally representative) [58]	Heterogeneous data types and sources can be combined and data-mining techniques applied to them [43,44] Advanced analysis, such as Machine Learning and ANNs, used to derive insight and realise relationships, from high-dimensional data streams [8] Inclusion of real-time streaming data with archive data (via Batch and Stream capabilities) [84]

2.7 Conclusion

Records of previous and on-going projects reveal how coastal data has been used effectively within DSS, risk studies and open source mapping projects. The numerous examples of GIS application to coastal regions, combined with the emerging opportunities afforded by the Big Data approaches outlined, indicate that this is an area where geospatial Big Data analysis can potentially transform coastal planning processes. Big Data does not provide a standalone solution to the issues and gaps outlined above. However, it does potentially provide a framework in which the large volumes and varieties of coastal datasets can be collated and analysed, particularly in the context of the current trend towards geoportal development and the growing awareness of the need for key authoritative integrated land/marine datasets - recognized as a fundamental enabler to good management of the coastal zone. Past coastal assessments have been noted to involve subjective judgements [24,38,42,94], and in some cases this has reduced stakeholder confidence in the outputs they have generated. By enabling such a wide range of data representing a complex array of factors, to be combined, Big Data can potentially allow assessment criteria to be derived from reliable geospatial and temporal data. This new generation of Big Data approaches can tackle uncertainty through enabling robust environmental risk profiles to be generated for coastal regions.

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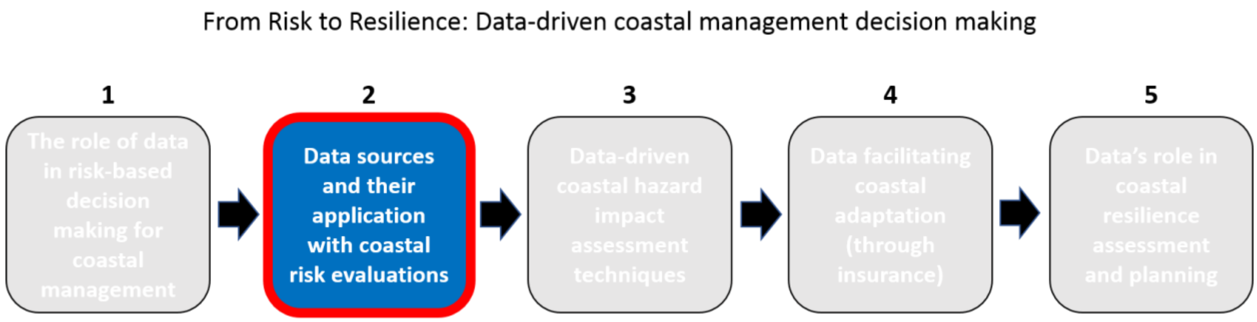
3 Opening up the Coast



Long-term investment strategies on the coast can be based on risk assessments, specifically of existing infrastructure and natural capital (Hall, 2016). In England and Wales, Defra (2009) advocate a holistic approach to risk assessment, stating how operating authorities must provide information on risk levels, which should include the various types of risk, assessed on a comparable basis i.e. economic, social and environmental, as characterised by the triple bottom line' approach (Elkington, 1997). In evaluating risk on the coast, it is necessary to ensure that an appropriate trade-off has been made between coupled hazards and economic risks, societal wellbeing and the environment. In determining risk assessment strategies specific to coastal flooding the following sectors should be considered: public (authorities), private (people, companies), and insurance (primary insurance, reinsurance, finance). Nicholls et al. (2015a) state that the level of economic risk on the coast depends on the distribution of buildings (impact factors). In coastal risk assessment strategies, a more thorough synthesis has been called for, which includes climate scenarios, demographic information and ecological data, alongside hazard models. Consideration of a diverse range of factors has been deemed a requirement to make coastal vulnerability assessments sustainable and representative (Ramieri et al., 2011).

Given this, risk assessment strategies must account for vulnerability, impacts and adaptations. This chapter presents a conceptual risk assessment framework, allowing holistic open source datasets to be brought together, that account for these factors. This framework forms the basis of subsequent chapters, which address individual framework stages, i.e. impacts and adaptation, and Chapter 6 incorporates aspects of this framework within a wider resilience assessment framework. In focusing on the case study region of East Anglia, this chapter reveals how open data sources exist which can provide data variables representing social, economic and environmental factors. The data sources identified have been utilised and referred to within subsequent analysis completed in later chapters. The number of open source datasets being made available is continually expanding. This represents a significant resource, for coastal practitioners, and if the correct data sources are identified and combined effectively, this can embellish the evidence-base forming the basis of coastal planning and management processes.

Opening up the Coast

Abstract
Coastal zones attract human settlement, business and industry, and are instrumental to the functioning of societies both in coastal states and the wider global community. However, the oceans and coasts are under growing pressure as human practices change, populations rise and climate change impacts increase. In managing coastal regions, high quality data forms the basis of rational decision-making. Large volumes of 'triple bottom line' data exists representing a wide variety of environmental, social, and economic themes in coastal regions. Such data is especially crucial to development of environmental risk evaluations for the coast. The momentum driving the open source data movement across the world is accelerating and consequently, huge quantities of data are becoming freely available to the public. This presents a valuable opportunity for coastal managers, policy makers and land planners, who need to evaluate the full implications of their choices. Decision-makers frequently need to draw on many disparate datasets. However, this can be complicated by many factors, including a lack of awareness of the full range of datasets available. This paper seeks to explore this area, taking the UK as an example, to reveal how currently available open data sources relate to coastal management decision-making. Environmental risk management is a cross-cutting theme, relevant to all areas of coastal management. As such, this topic is discussed and addressed within a case study focusing on the vulnerable coastal region of East Anglia. Geographical Information Systems (GIS) play an important role in collation and analysis of coastal data; within the case study GIS approaches were used to achieve this. The case study led to development of a conceptual framework which can be applied to future coastal risk assessments, using open source data. The UK is currently at the forefront of the open source data movement and as such it is used as an example within this paper, however the issues addressed have international relevance, and the UK perspective is used to illustrate wider opportunities, resulting from freely available data sources, extending to management of coastal regions globally.

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3.1 Introduction

Coastal regions are home to the majority of the Earth's population and therefore 'much of the world's economy, is at least partly dependent upon the health and integrity of coastal resources' [1, p.9]. Coastal zones provide jobs, ports, recreation areas, energy generation and ecosystem services, and have been ranked 'among the top places in the world in terms of population and value accumulation' [2]**.** In recent times coastal regions have experienced 'amenity driven growth' [3]. Yet examples from across the world (such as highlighted by Cooper and Mckenna [4]) indicate how economic growth has also produced negative impacts for sustainability in the coastal zone, as settlements have formed in high risk areas [4]. Such risk can be seen as the product of a high probability of a hazard event and severe consequences [2,5–13]. Consequences are generally calculated in relation to potential impacts (monetary damage and human casualties) [7]. The highest risk levels are generally experienced in locations having the highest concentration of people and value, and where there is a likelihood that a threatening natural event (for example a storm surge) may occur [2]. Coastal hazards are normally associated with 'weather hazards', the most common being the storm surge, which can inundate low-lands [14]. Pollution represents another significant consequence of increased human usage of the marine environment. Rodwell et al. [15] draw attention to prominent public concern over land-based industries polluting the marine environment. Threats presented by high levels of pollution and seawater inundation are both exacerbated by catalyst factors such as climate change, increasing coastal population densities, and resource depletion. These factors can result in the consequences to humans and the environment being both more severe and extensive.

The process of managing coastal resources is fraught with challenges, due in part to the coast being an interconnected domain where stakeholders and users have competing interests which, invariably, do not align with optimal, sustainable solutions for regions. The role of data, information and knowledge within the process of coastal management is paramount. In line with the increased availability of datasets relating to the coast, 'data' has thus become a prominent theme of discussion within academe and the coastal management community. This has influenced approaches taken by governments in managing risk on the coast. In the 2000s coastal governance arrangements were often in flux (Fataleeva, 2011 in [5]). In many countries, changes occurred mirroring those in England, where the dominant approach of installation of hard adaptation measures [16] and maintenance of the current extent of sea defences, was recognised as unsustainable [4]. Publications such as *The Foresight Future Flooding report* [12], exemplified a shift to a holistic, whole-shoreline approach to understanding and addressing coastal risk [17]. Yet it is argued that a disconnect still exists between scientific evidence and decision-making at a supranational level, such as within the European Union [10]. Nevertheless open source data initiatives are now seen to be 'transforming the availability and ease of access to high quality public sector data' [18], acting as a driver for increased utilisation of such data by coastal decision-makers. This is aided by the ability to collate and manage these diverse datasets using tools such as Geographic Information Systems (GIS). Access to many datasets, relevant to coastal management, is provided online in the form of web-services, which can be accessed in real time, reducing requirements to download and store data locally. This paper further seeks to raise awareness of the range of open source datasets available related to the themes of coastal management (taking the UK as an example), revealing how these datasets can be drawn on in applications evaluating coastal risk.

Within the domain of coastal management and maritime spatial planning, the requirement to embrace a process of evidence-based decision-making has been recognised [19], as opposed to prioritisation of the interests of those actors and organisations within society who wield power and influence. Access to information enables governments to make informed choices, and to explore alternatives. The requirement for information includes ecological, scientific, social and economic data [20]. This is recognised within a dominant coastal management process, being applied across the world, termed Integrated Coastal Zone Management, ICZM. ICZM encompasses a broad range of themes, and of these the threats posed by erosion and flooding represent a dominant focus of many coastal organisations, especially those within the case study site of this paper (East Anglia, UK). Yet coastal management covers a far broader remit than these issues alone. The broader themes outlined by England's Local Government Association Special Interest Group on Coastal Issues (LGA Coastal SIG) [21] (Table 3), provide a sound thematic basis to guide an understanding of these issues. This clearly illustrates the broad range of areas which coastal managers must contend with, and necessitates their drawing upon a wide-ranging variety of data sources, to generate an expansive knowledgebase. This paper expands upon these themes; Figure 7 relates these themes to open source coastal datasets, further illustrating how adoption of a thematic approach can enable freely available information relating to these topics to be easily located. Although the main examples drawn on in this paper relate to the UK, similar data sources exist within other countries, therefore the examples given are used to illustrate wider opportunities that extend to managing coastal regions globally.

Table 3: Themes covered by the LGA Coastal SIG position statements

Coastal Management Areas
1. Integrated Coastal Zone Management
2. Energy
3. Managing Fisheries
4. Minerals and Dredging
5. Ports and Harbours
6. Marine Planning
7. Waste Management
8. Beach Management and Inshore Bylaws
9. Coastal Access
10. Marine Protected Areas
11. Marine Pollution
12. Coastal Regeneration and Economic Prosperity
13. Coastal Adaptation

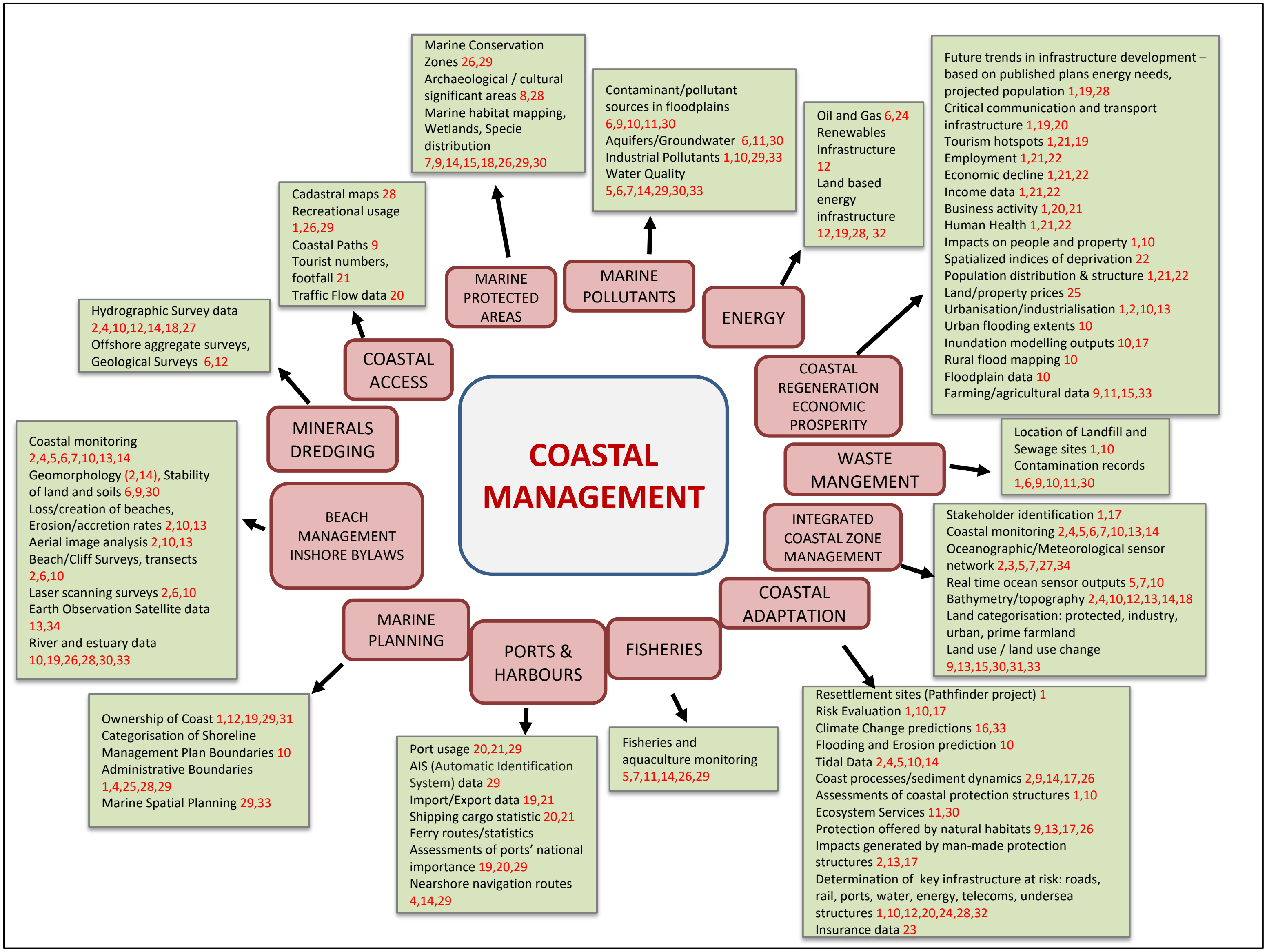

Figure 7: Coastal Management Themes related to data sources (numbers link to data sources in Table 5)

3.2 Data use within coastal risk analysis

Coastal datasets originate from a vast array of sources, the majority (90%) of reported data collection for the coast of the UK being from publicly-funded sources [22]. This is data collected by the national government, environmental bodies, national mapping and charting agencies and government (sponsored) data collectors (such as universities, private companies, local authorities and non-governmental organisations). However, not all data collection relates to public projects. On the coast of East Anglia, for example, private data gathering is also frequently undertaken. One example of this is a bathymetric survey that Bourne Leisure group commissioned of the inshore area fronting a stretch of coast owned by the company in Suffolk. This formed part of their investment in private coastal defences [23,24]. Also, many high-quality datasets are retained by energy companies, who have conducted independent surveys of inshore areas. The Crown Estate partially addresses this issue through a mandatory requirement for data and reports generated from renewable energy projects in UK waters, to be made available to the public after a specified period. The Crown Estate makes this information available to the public via its web portal, the 'Marine Data Exchange' [25]. Beyond the UK there are many organisations who collect data and make this available at a regional and international level. NOAA (the National Oceanographic and Atmospheric Administration) [26] in the USA, is one such example; others from Europe being EMODnet [27], HELCOM [28] and OSPAR [29] (more details are provided of these organisations in the supplementary material, available online). In addition to this, global coastal datasets collected using Earth Observation (EO) satellites, are available for free, from sources such as Copernicus [30], who host a Marine environment monitoring service.

Evaluation of risk in coastal regions, is a process reliant on the availability of accurate information sources. Coastal datasets generally represent raw facts and figures, whereas processing of this data generates information outputs, usable in decision-making. This information can be further transformed to encapsulate understanding, which in turn can form the basis of knowledge [31]. Coastal risk calculations involve recognition of specific hazards present on the coast, broader coastal vulnerability, the potential impacts of these to society and the environment, and the role offered by adaptation measures. Given this, information needs to be acquired detailing past and existing occurrences of coastal hazards, as well as estimations of their future probability. Data relating to human activity and use of coastal regions is also essential, as this helps determine how vulnerable an area is (in anthropocentric terms) and the consequences which can result from the occurrence of hazard events. Table 4 identifies potential types of data and information that could be included in a risk evaluation relating to a given stretch of inhabited coastline. These data types are split between the data themes typified within the 'Triple bottom line approach' [32], comprising environmental, social and economic themes. In ensuring that risk assessments are comprehensive and rigorous, it is necessary to adopt a heterodox/holistic approach to data collation and evaluation, drawing on data derived from many disciplines (including unconventional sources), to address both physical and human aspects of risk. The merits of this type of approach have been acknowledged in recent studies, such as the Tyndall Project [16]. In this work, a wide variety of data variables were incorporated within simulation models, such as those relating to: marine conditions, extreme events, damage to persons and property, and socio-economic drivers. This contrasts with other, more conventional studies such as that conducted by Villatoro et al. [33], which adopt a narrower focus, concentrating analysis on physical data, including detailed topographic and bathymetric data, and environmental modelling outputs.

Table 4: Key data types pertaining to coastal management

Category	Data Type
Environmental	• Habitat mapping, wetlands, species distribution, stocks • Climate change projections • Flooding/erosion predictions • Records of flooding and erosion (urban/rural) • Coastal monitoring: - Oceanographic/meteorological sensor networks - Real-time ocean sensor outputs - Bathymetry/topography - Offshore aggregate surveys - Geological surveys - Beach/cliff surveys, transects - Laser scanning surveys - River and estuary data - Tidal data - Loss/creation of beaches - Erosion/accretion rates derived from aerial images/EO satellite data • Coastal processes/sediment dynamics • Ecosystem services • Protection afforded by natural habitats • Inundation modelling outputs • Contaminant/pollutant sources in floodplains • Pollution threats from landfill and sewage sites • Aquifers/groundwater • Geomorphology • Stability of land, subsidence • Soils and drift geology • Water quality • Marine Conservation Zones (MCZ)
Social	• Administrative boundaries; categorisation of Shoreline Management Plan (SMP) boundaries • Future trends in infrastructure development - based on published plans, energy needs, and projected population • Critical communication and transport infrastructure • Determination of key infrastructure at risk: roads, rail, ports, water, energy, telecoms, undersea structures

	• Land use change, urbanisation derived from aerial image/EO satellite imagery • Land categorisation: protected, industry, urban, prime farmland • Urbanisation/industrialisation • Population distribution & structure • Spatial trends in human health • Location of landfill and sewage sites • Stakeholder identification • Resettlement sites for impacted coastal populations (e.g. the Pathfinder Project, UK [25]) • Archaeological/culturally significant areas • Cadastral maps • Recreational usage of the coast • Traffic flow data on roads
Economic	• Business activity • Farming/agricultural data –crop yields • Fisheries and aquaculture – resources and revenue • Tourism hotspots; tourist numbers (footfall) on beaches/coastal paths • Financial impacts on people, property, business, government • Assessment of coastal protection structures (condition and cost of repair/replacement) • Income data • Employment • Economic decline • Spatialized indices of deprivation • Oil and gas projects and infrastructure • Renewable energy projects and infrastructure • Ownership of the coast • Port usage; assessments of a port's national importance • Port import/export data • Shipping cargo statistics; AIS data • Nearshore navigation routes; ferry routes/statistics • Land/property prices
Multi- Category	• Derived information from existing risk evaluations (environmental, social and economic) • Marine Spatial Planning (MSP) • Industrial pollutants (sources and impacts) • Impacts generated by man-made coastal protection structures, change of policy

Physical environmental data can represent parameters such as water temperature, shoreline sediment grain size, tidal range, pollution concentrations, river flows and topography. Such data is deemed distinct from socio-economic data (e.g. population distributions, and social groupings). Inclusion of Environmental data within analyses, is deemed a key requirement for the protection of human health and the avoidance of ecological disaster [22]. Infrastructure is a further key area of consideration in the evaluation of coastal risk. Flooding and erosion can generate direct and severe impacts on vulnerable infrastructure, creating more complex risk and indirect impacts to populations further afield. Interdependencies between infrastructures can further compound risks which arise. For example, the complex infrastructure systems underlying modern societies comprise many interdependent components (e.g. energy, water, transport and telecommunication networks). Changes in one component can destabilise the whole interconnected and interdependent 'system of systems', potentially resulting in catastrophic failure [34]. DEFRA [35] acknowledge this with respect to transport infrastructure, noting that consideration should be made in particular, of transport networks in relation to urban flooding. Other types of infrastructure noted, that may also be especially vulnerable to coastal hazards, include electricity supply, telecom networks [36] and aquifers [37]. Environmental data can also reveal impacts from storm surges on beach recession, and enable charting of areas flooded. By combining aerial photography with Lidar data, identification of low-lying areas vulnerable to flooding is made possible. A study undertaken by researchers at Durham University [38], of a stretch of coastline in Whitby (UK) has successfully demonstrated how point cloud data generated by Lidar and terrestrial laser scanning, can be combined with other environmental data variables to increase understanding of coastal erosion and evolution, rock slope failure and wide-area ground deformation [39]. When this data is further combined with demographic and socio-economic variables, such as land use, population densities and property valuations, it can reveal the consequences expected from the occurrence of such hazards, as well as particular 'hotspots' of combined concern.

3.3 Open source data

A significant, concerted effort has been made in recent years to allow datasets held in the public domain, to become available as open source. Open source data is increasingly being made accessible, through high quality open source data portals [40]. Governments across the world have sought to make public sector data, collected using tax revenues, available for private or commercial reuse. This has partially been driven by public demand (such as The Guardian's, Free our data campaign, in the UK [41]). Private sector organisations are not usually required to make their data available as open source, however are compelled to do this in some cases, by a range of benefits this can bring. Organisations such as the Open Data Institute (ODI) (UK) [42], work with both public and private sector organisations to develop open source data opportunities, creating incentives for organisations to provide free access to their data.

The momentum of the Open Soure data movement presents new opportunities, through widening access to information [18]. This is being driven by a program to enhance information sharing between private and public sector organisations [43]. It is exemplified by some of the larger government data portals such as: Data.gov (USA) [44], Data.gov.uk [45] (UK), Data.gov.au [46] (Australia), Canada's Open Government Portal [47], Data.gouv.fr [48] (France), and Data.go.kr [49] (Korea). In June 2015, DEFRA (UK) set a target of making 8,000 datasets available open source. Within 12 months [50], this target was exceeded, with over 10,000 datasets being ultimately released in the period

[51]. Among those released were many high-resolution Lidar datasets covering UK coastal regions, published by the Environment Agency (EA). This momentum has contributed to the UK securing a leading position in the global Open Data Barometer rankings [52]. Today, much of the data required to build a risk evaluation matrix for coastal regions in the UK can be easily accessed and shared. The UK is in a privileged position in this respect, as the majority of this data was collected as a result of government funding, and recent requirements have resulted in this data being made available to the public [53]. This is unfortunately not the case for many other coastal states, which can lack publicly funded coastal monitoring programs or whose governments fail to place this information in the public domain. Many such states have been labelled 'data poor' [54,55]. The Open Data Barometer [52] reveals that for the majority of low and middle income countries open source data availability is poor. Unfortunately this is especially a problem for Small Island Development States (SIDS) [56], which invariably have highly vulnerable coasts.

The myriad of coastal datasets made available to download via open source portals presents opportunities for combining and analysing a diverse range of information, all now obtainable cost free. A listing of some of the organisational sources who host open source data portals containing data relevant to the UK coast is given in Table 5. The sources detailed in Table 5 are numbered, and within Figure 7 individual coastal issues have been assigned corresponding numbers denoting potential data sources, from where related information can be found. This is also expanded upon within the supplementary material, available on-line.

Table 5: UK open source data of key relevance in coastal management

No.	Data Source	Examples of Data Types
1	District Councils (accessed via Data.gov.uk)	Local government held datasets: condition surveys of coastal defences, land use change, extent of habitation increases, socio-economic variables
2	The Channel Coastal Observatory (CCO)	Archive and real-time coastal data, outputs from academic studies
3	The Met Office UK	Meteorological data - frequency of extreme events
4	UK Hydrographic Office (UKHO) (INSPIRE Portal)	Bathymetric charts, port and coastal data sets, navigation routes, shipping traffic data
5	British Oceanographic Data Centre (BODC)	Biological, chemical, physical and geophysical data
6	British Geological Survey (BGS)	Geoscientific, geomorphological information
7	CEFAS	Oceanographic data
8	Historic England	Cadastral, listed data sets for the coast
9	Natural England	GIS digital boundary datasets, habitat mapping, agricultural data

10	The Environment Agency (EA)	Coastal survey data: beach transects, topographic and hydrographic surveys, the UK national tide gauge network, flood risk assessments, coastal management plans, data on defences and intent, pollution
11	Department for Food and Rural Affairs (DEFRA)	Public sector food, agriculture and environmental datasets
12	The Crown Estate	Maps, GIS data –offshore aggregates and renewable energy project data
13	Copernicus, ESA	Sentinel satellite data and derived outputs
14	MEDIN	open source portal of marine environmental data
15	MAGIC	open source data repository relating to the natural environment from across UK government
16	Intergovernmental Panel on Climate Change (IPCC) [57]	Climate, socio-economic and environmental data, both past data and future scenarios
17	Academia (e.g. iCOASST [58], RISC-KIT[59], FAST)	Coastal modelling output data and data centres
18	EMODnet	European wide marine datasets
19	Data.gov.uk (web portal)	Links to all public available government data
20	Department for Transport (DFT) UK and Highways England	Traffic flow data
21	The Office for National Statistics (ONS)	UK national population, business and industry statistics
22	Datashine UK (University College London)	Spatial representations of socioeconomic datasets taken from UK 2011 Census data, by University College London (UCL)
23	Association of British Insurers (ABI)	Insurance data downloads (limited open source content)
24	UK Oil and Gas Authority (OGA)	Oil and gas fields, reserves, seismic surveys and seabed infrastructure
25	HM Land Registry	Land and property information/prices
26	Joint Nature Conservation Centre (JNCC)	Biodiversity and species data, Mapping European Seabed Habitats (MESH), marine survey data, MCZs
27	NOAA NCEI	Global datasets for coasts and oceans
28	Ordnance Survey (OS)	Cadastral survey map data
29	Marine Management Organisation (MMO)	Marine planning, fisheries, licencing, protected areas, coastal recreation
30	Centre for Ecology and Hydrology	Hosts the National River Flow Archive (NRFA), Environmental Information Centre, Environment change network, and the biological records centre
31	The National Trust	Coastal land use and land access to National Trust land

32	National Grid	Energy Infrastructure
33	European Environment Agency	Europe wide Environmental data downloads
34	CEDA Data Archive	Atmospheric and Earth Observation data

One driving force behind moves towards standardising and sharing data is the EU INSPIRE Directive (2007/2/EC) [60], which was envisioned to improve access, sharing and discovery of public sector data. The INSPIRE Directive was implemented by the EU in 2007, seeking to establish a Spatial Data Infrastructure (SDI) across European member states. The Directive applies to public sector organisations, and other organisations on a voluntary basis. Common Implementing Rules (IR) are required in areas such as: metadata, data specifications, network services, data and service sharing, monitoring and reporting. Within this, the problem of duplication of data has been identified specifically. The Marine Environmental Data and Information Network (MEDIN), a UK data repository for marine environmental data, has adopted the INSPIRE Directive, especially in relation to metadata standards [15]. MEDIN datasets are stored in a disaggregated, 'shared or distributed' manner, which corresponds to the INSPIRE objective of permitting disseminated data stores using web services. Within the domain of coastal management, as in many other sectors, data is not contained 'centrally' by any one organisation. Following the principles of INSPIRE, data can be collated dynamically from multiple sources using standardised formats and transport mechanisms (such as REST, WFS/WMS/WCS web services). In addition to enabling access to data, this can provide wider benefits to the data user community, in that it permits the relevant data 'owner' to retain the responsibility for their data and its maintenance, as well as the technological mechanisms to share it efficiently with others. Key to this process is the creation and enforcement of appropriate metadata standards, to ensure knowledge of the data is disseminated alongside the data itself. If data is accessed through web services, this allows important updates and changes to data (made by the data owner), to be incorporated within third party use of this data. This can ensure that the most up-to-date information, is continually used within projects. Given this, for many data sources, which may be incorporated in wider services, it is preferable to access these via web services as opposed to downloading and hosting them from an in-house server.

Advances such as the shift towards open source data do result in specific challenges. Restrictions on the use of datasets and intellectual property remain a potential area of concern. This corresponds to the emergence of a new generation of open source intellectual property rights terms. A range of these now exist, such as the 'Open Government Licence' (OGL) [61], used by UK public sector bodies such as DEFRA. Another significant issue relates to 'user understanding' of the available data, e.g. omissions, assumptions made, methodologies used, accuracy and other caveats. Clear limitations are imposed on datasets due to data collection methods and accuracies achieved. Many datasets, such as Lidar topography and sonar bathymetry, which have been acquired over different time periods, vary considerably in spatial density of data points and relative accuracies of data collection techniques. Direct comparisons between such datasets must therefore be approached with caution. Additionally, downloading datasets for larger geographical areas and time periods can prove more complex and time consuming (depending on which open source data portal is used). Another significant constraint imposed on the use of open source data, especially important when considering data from a range of different countries, is standardisation of data formats, which can reduce requirements to clean/process data before it becomes usable. This is a challenge which flood modelling companies, who generate flood risk evaluations for multiple countries, frequently contend with. Organisations have emerged which attempt to tackle such challenges, including Oasis Hub[62], which provides open source environmental data from different sources, but in a more standardised format.

Notwithstanding these issues, the shift towards open source data goes some way to addressing widespread demands for data sharing and standardisation. For example, many such as Rodwell et al. ([15], p.253), have argued that 'more effort is needed to standardise or harmonise access to data within the UK and Europe'. This remains an issue that many public-sector bodies (such as those listed in Table 5) are now tackling directly through open source initiatives. One crucial means to enable greater understanding of these datasets, and reduce errors in their use, is to ensure that comprehensive metadata is supplied with the data; this being descriptive data detailing data provenance and providing guideline on use of the data. Standards such as ISO19115 have been adopted as a basis for such descriptive records [63]. In accordance with the INSPIRE Directive, this should enable, data source, quality, age and original format to be determined.

3.4 Open Source Data Sharing and Mapping for the Coast

An ever-increasing number of collaborative projects seek to bring spatial datasets together for marine and coastal areas, making this data available to the public via open source portals and web-mapping tools. Details of a selection of these are provided in the supplementary material to this paper. Within the UK, the Marine Environmental Mapping Program (MAREMAP) [64], the Multi-Agency Geographic Information for the Countryside (MAGIC) [65] and MEDIN are examples of this kind of initiative. Aside from the collaborative open source data portals, numerous individual organisations make their datasets freely available to the public. Many of those who provide data related to coastal areas in the UK are listed in Table 5. Beyond the UK, the availability of open source data varies considerably depending on location. In the USA, a large number of portals exist making coastal datasets available to the public, such as those hosted by NOAA [66] and the US Geological Survey (USGS) [67]. A pan-European initiative called SeaDataNet (http://www.seadatanet.org), provides ocean and marine data for European Seas. Other data sharing/mapping projects of note, which are underway across Europe include HELCOM for the Baltic, and OSPAR for the North Atlantic. A wider initiative for Europe, including the UK, is EMODnet [27] (European Marine Observation Data network). On a global scale NOAA have established a National Centre for Environmental Informatics (NCEI) [26]. Other global initiatives are the Ocean

Biogeographic Information System (OBIS) [68] and the Marine Geoscience Data System (MGDS) [69].

The wide variety of open data sources provide a valuable resource to coastal research projects. For example, the Tyndall project has combined data successfully, from many of the sources detailed (Table 5), in the coastal models it created for East Anglia [16]. In the component of their study focusing on the coast of Devon (England), Villatoro et al. [33] drew on datasets from the BODC and from the National river flow archive. In creating flooding maps, Villatoro et al. also combined Lidar data from the CCO, with geospatial data from EDINA DIGIMAP (an academic source of geospatial data). This work also drew on a repository of re-analysis data to permit generation of future scenarios. Conventional geospatial point cloud data and satellite imagery data are deemed especially useful when creating coastal models and, as such, should form a key part of vulnerability assessments. Sources of such data include the EA [70], Copernicus [30] and the CCO [71].

3.4.1 Earth Observation (EO) satellite data

A key source of wide-area coverage geospatial data, of growing importance, derives from satellite EO data. Remote sensing has long provided a basis for terrestrial, atmospheric and marine monitoring, and geo-positioning GNSS services. However, the growing range of satellite and airborne platforms, now available with increasing spatial resolution, spectral discrimination and overflight return periods offers a range of new opportunities. This is combined with the corresponding availability of much of this data as a free and open source resource. Consequently, contemporary coastal management tools will increasingly incorporate remote sensed data and related thematic interpretations. Examples of satellite platforms providing access to free data include Landsat, EOS MODIS, Terra EOS ASTER, and the associated Space Shuttle Topography Mission (SRTM). The FAST program is a good example of an initiative which has incorporated open source EO data for coastal regions, through tools such as Google Earth Engine. This has enabled estimates to be derived, for example, of loss and gain of natural capital acting as a buffer in coastal areas. Work completed in the project can be viewed through the MI-SAFE tool (fast.openearth.eu) and their datasets are made available open source, accessible via web-services.

Perhaps the most significant provider of open source satellite data has arisen via the Copernicus programme. This is managed by the European Commission, and delivered by the European Space Agency (ESA), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), the European Centre for Medium-Range Weather Forecasts (ECMWF), related EU Agencies and Mercator Océan. The Copernicus programme comprises six Sentinel satellites currently in service, plus a growing range of fixed in-situ data and services (www.copernicus.eu). To aid the uptake of the data from the Copernicus programme, a range of interpreted thematic data services are available alongside the raw satellite data. These currently or shortly, addressing atmospheric (CAMS), marine (CMES), land (CLMS), climate (C3S), emergency (EMS) and security themes. Each theme comprises substantive data offerings, regularly updated, for a range of parameters of relevance. By example, for the Copernicus Marine Environment Monitoring Service (CMEMS), the 46 variables encompass measures of sea temperature, salinity, surface height, mixing, ice levels, wind and wave assessments, dissolved oxygen and nutrients, plankton levels and primary production, assessments of sea reflectance, transparency and turbidity. Each thematic data service is delivered by a dedicated web portal, e.g. marine.copernicus.eu/services-portfolio/access-to-products/.

3.4.2 Advances in coastal risk mapping

The exponential growth in the extent and range of datasets related to the coast, and their increasing availability as open source provides a key driver for comprehensive, advanced risk-mapping projects for coastal regions. Another driver is the rapid advance in data collection, storage and processing technologies. New remote sensing data sets are noted to reduce uncertainty significantly [72]. Recent advances in the field of remote sensing have resulted in increased data density, return period and spatial coverage, enabling visualisation and monitoring, at scales not previously possible. Improvements in measurement, observation and the establishment of extensive communication networks can increase understanding of physical processes, leading to more effective early warning systems being created, such as that implemented in Emilia-Romagna, Italy [73]. However, such innovations are not confined solely to an ability to monitor environmental variables. Hazard management has been reported to have moved from an early focus on physical hazards alone to an approach incorporating 'socio-economic, political and behavioural patterns of the affected population' ([8], p.183). This creates a requirement to combine wide varieties and volumes of data, originating in many different formats. Coupled to this, new advanced sensor technologies such as Lidar and satellite remote sensing, generate high volumes of data. Additionally, increasing quantities of data are made available as 'real-time feeds', such as those relating to ocean sensor data, provided by, for example, CEFAS and the CCO.

Given these recent progressions in the field of coastal data, the most up-to-date computing technologies need to be utilised to enable comprehensive, geospatial risk evaluation tools to be created. The rapidly developing field of Geographical Information Systems (GIS), provides one potential solution to these challenges. In the case study example which follows, GIS has been utilised to enable large volumes of open source coastal data to be collated, visualised and analysed. The aim of this was to enable fresh insight to be derived from what initially appeared an overwhelming mass of data.

3.5 Case study: open source data revealing coastal risk in East Anglia

3.5.1 Coastal Management Challenges in East Anglia

Numerous coastal risk adaptation issues in East Anglia have been introduced, and it is this English region that is selected as a case study for this paper (see Figure 8). East Anglia's coast has been recognised as highly vulnerable [5,74], yet a wealth of information relating to coastal processes exist for the area. The Suffolk and Norfolk coast is characterised by low lying land (Figure 9), soft cliffs and sandy beaches, with the

Suffolk coast (in particular) comprising a mix of soft points/embayments and hard points (natural and man-made) [74,75]. Longshore sediment transport, within sediment cells, is a dominant characteristic of the coastal processes at work in East Anglia. Past attempts to protect stretches of coast have disrupted longshore sediment pathways, resulting in stretches of coast adjacent to protected areas becoming sediment starved and more vulnerable [12,17]. Sediment loss is a common unintended consequence, on the wider coastline, resulting from implementation of ‘sea defences’, such as sea walls and groynes [76]. This has influenced government policy in England. Overstrand in North Norfolk provides an example of this, where the sea wall, timber groynes and revetments block sediment transport to downcast beaches [77]. The UK has a high number of critical infrastructure sites located on its North Sea coast [78]. Within the region of East Anglia there are many critical national infrastructure sites that are threatened, including Bacton Gas terminal [79], through which a third of the UK gas supply flows, and the Sizewell Nuclear power plant [80] (one of the largest investment areas in the UK). There are many locations in the South East of England where justification is seen to exist for continued use of hard adaptation measures [81]; this includes infrastructure choke points in East Anglia and densely populated urban areas. Yet a number of ‘softer’ measures have also been implemented in the region. Rupp-Armstrong & Nicholls ([82], p.1422) state that existing Managed Realignment schemes in the UK are mostly concentrated on the east coast of England. They outline how ‘regional assessments of Suffolk and Norfolk’ have suggested there is large potential for Managed Realignment producing a ‘net gain in inter-tidal habitats’ and that ‘the majority of Managed Realignment sites are situated on England’s East Coast in particular East Anglia’ where ‘30% of the UK salt marsh habitat’ is located. In addition to this, a soft adaptation measure, termed the ‘Sand Engine’ is currently being considered for implementation in the coastal area surrounding Bacton Gas terminal [79].

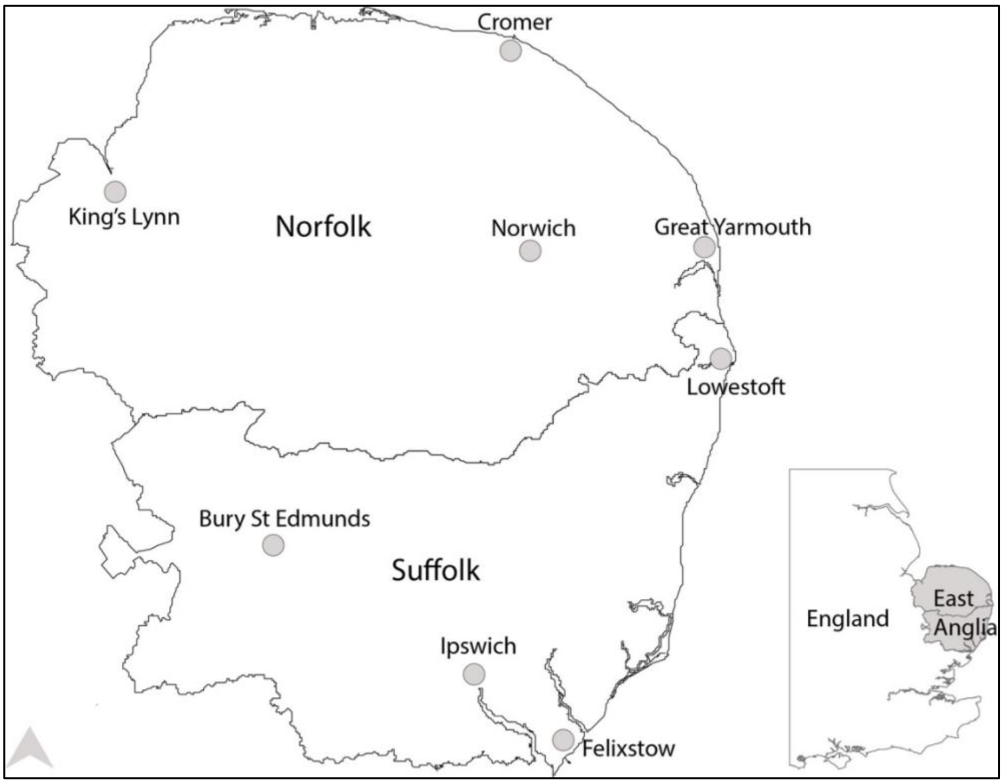

Figure 8: Map of East Anglia (courtesy of www.openstreetmap.org)

Figure 9: Low lying coastal region of Bawdsey in East Anglia (photo courtesy of www.mike-page.co.uk)

In East Anglia, a broad span of projects of note have been undertaken focusing on coastal change and risk, combining stakeholders and multiple academic organisations.

Two significant studies, which have partially focussed on the area have been the 'Tyndall Coastal Simulator' project [16] and subsequently 'iCOASST' [58]. Wider pan-European studies have been completed, incorporating the region, such as RISC-KIT [59]. A further initiative is MKEN (Marine Knowledge Exchange Network) [83]. The network focuses on knowledge and research for the coastal domain in East Anglia and is based at the University of East Anglia.

In terms of physical environmental data collection, an ongoing collaborative survey and mapping initiative exists in East Anglia, entitled the 'Anglian Coastal Monitoring Group' [84]. This group, founded in 1987, was the first regional mapping program in the UK. It includes representatives from local authorities, the EA and Natural England and has been involved with coordination of survey activities for the coast of East Anglia, resulting in accrual of 20 years' worth of data. Data derived by the group is valuable as it informs coastal management decisions. As such the rapid progress being made in making coastal data available open source can present valuable opportunities for groups such as this.

3.5.2 East Anglian Data Repository Sources and Outputs

The data repository and GIS detailed within this case study is intended to serve the production of outputs supporting both MKEN, the Anglian Coastal Monitoring Group, Coastal Partnership East (District Council level), and policy makers at a national scale (DEFRA/HM Government). Figure 10 illustrates some of the input sources and potential recipients of outputs related to this GIS data repository.

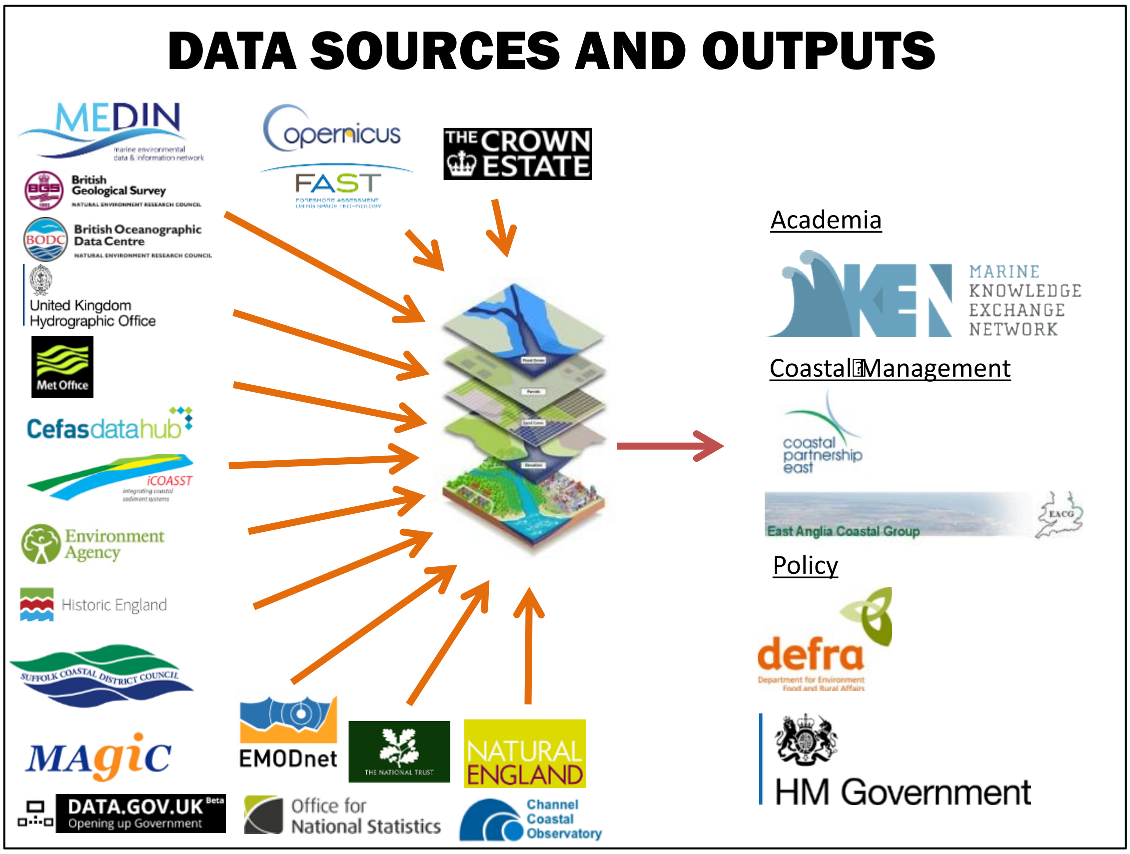

Figure 10: Data Sources and Outputs for an East Anglia Case Study

Within this case study, numerous data types have been linked to the sources outlined in Table 5 (and within the supplementary material, available on-line). This has enabled a broad range of data to be collated, representing physical environmental parameters, socio-economic indicators and demographic change, in line with a heterodox/holistic approach.

3.5.3 Risk Evaluation –Conceptual Framework

Evaluation of the various data sources outlined in Table 5, has revealed how data representing the three broad themes highlighted in Table 4 (environmental, social, and economic) is available for the case study area. Combining this data in a GIS project, enabled progressive stages of risk analysis to be undertaken. This analysis can be represented in incremental stages, characterised within a conceptual framework (Figure 11). First, data is brought together which represents a wide range of themes, enabling a holistic risk evaluation process to be initiated. The second stage involves identification of vulnerability, to infrastructure, people, property, and the environment. A third stage relates to revealing impacts, for example by comparing data for the same area but for different time periods, such as before and after storm events. Finally, a fourth stage involves identification of adaptation measures, and associated effects. These adaptation measures can relate to engineered features or natural processes. Analysis within Stage 4 evaluates the consequences of installation or removal of adaptation measures. Drawing on a wide range of data sets can reveal wider associated factors, potentially missed given a narrower focus. The conceptual framework developed in Figure 11 highlights how open source data can be used within coastal management and especially in risk evaluations. The open sources for each of the data types referred to within the case study can be found through linking coastal management themes and data types, detailed in Figure 7, with the open sources listed in Table 5.

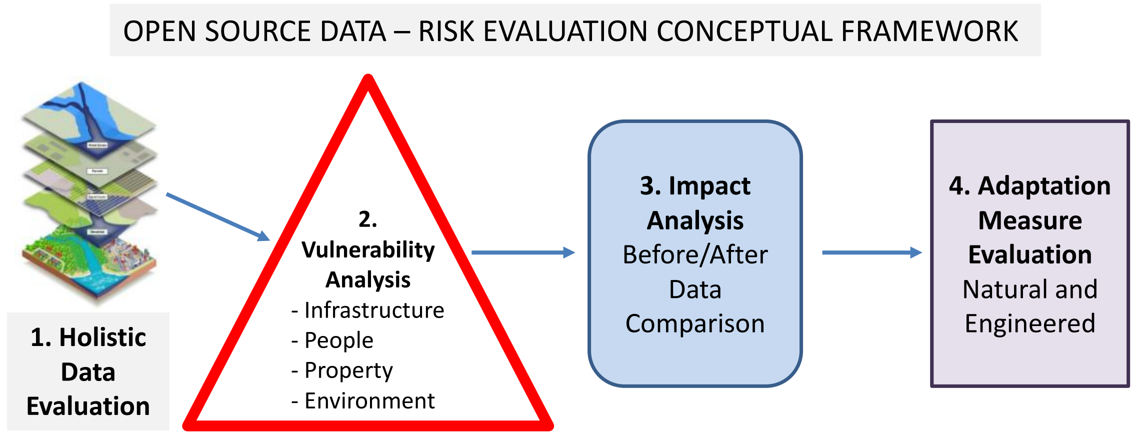

Figure 11: Conceptual Framework for Coastal Risk Evaluation using open source Data

3.5.3.1 Conceptual Framework – Stage 1: Holistic Data Evaluation

Heterodox and holistic approaches [17], outlined in Section 2, refer to collating data from a wide array of different sources, some of these unconventional, representing natural processes, society and the economy. The methodology employed in creating the East Anglian GIS involved combining data obtained from a wide range of such sources. This data has included outputs from physical environmental monitoring projects, information related to humans who live on and use the coast, and trends such as land use change. Juxtaposing such diverse datasets using a geospatial mapping tool allowed relationships to be derived between the wide range of factors present within the region. Table 6 provides an indication of some of the datasets which were included within the East Anglian GIS.

Table 6: Example of holistic data variables used with the East Anglian GIS

Data Type	Category	Source	Use
Environmental	Coastal Monitoring	CCO, EA, MEDIN (BGS, BODC, UKHO), CEFAS	Reveals geomorphological change, indication of physical changes, trends, oceanographic conditions, specie distribution, pollution
	Meteorological data	Met Office UK	Climate conditions, past and forecast
	Coastal Change Forecasts	Academia, EA	Outputs from studies and assessments giving indications of future impacts

	Natural Capital	FAST, EA, Natural England, Copernicus	Protective role offered by natural capital and change in coverage
	Land Based Hazards	BGS, EA	Location of landfill sites and other potential hazards/containments in floodplains
	Groundwater	BGS, EA	Aquifer and groundwater sources, their vulnerability to salinization
Socio-economic Factors	Population wealth and health distribution	ONS, Datashine	Financial and physical ability of populations to cope with coastal hazard impacts
	Deprivation	ONS, Datashine	Spatialized indications of vulnerability of populations
	Housing	ONS, Datashine, Aerial imagery, EO data, CEDA, Copernicus, District Councils	Enable assessments of proximity (and density) of human settlements to hazard prone locations
	Property damage	District councils	Evaluation of past impacts to local populations
	Business and services disruption	District Councils	Impacts to local economy from coastal hazards
	Infrastructure locations	OS, suppliers (such as National Grid), Copernicus, aerial imagery (CCO, EA)	Enable assessment of critical infrastructure vulnerable to coastal change and hazards
	Government Policy for the Coast (SMP)	EA, District Councils	Indication of implications of government policy in relation to future protection of coastal regions
Land Use	Agricultural Data	ONS, Natural England, MAGIC	Prime farmland, agricultural yields, exposure of food/income sources to flooding/erosion
	Planning Permission	District Councils	Reveals future land use change and vulnerability
	Land use change in coastal areas	National Trust, Copernicus, CCO, EA	Trends revealed in past changes

	Habitats	JNCC, Natural England, MAGIC, EMODNET	Natural capital, impacts and exposure of flora/fauna, provision of ecosystem services
	Archaeological and cultural significant areas	OS, Historic England, National Trust	Restrictions placed on use of land, listed areas
	Urbanisation	Aerial imagery, Copernicus (EO data), European Environment Agency)	Spread of population in to vulnerable areas, loss of natural capital, potential disruption of natural processes –increasing risk
	Energy (renewables, oil and gas, nuclear), Offshore Aggregates	Crown Estate, OGA, BGS, OS	Human use of seabed areas, presence of critical infrastructure, energy resources
	Coastal Adaptation	EA, Copernicus, District Councils, CCO	Presence of coastal protection structure, condition of these, impacts on surrounding area

3.5.3.2 Conceptual Framework – Stage 2: Vulnerability Analysis

Drawing on the foundation of a diverse range of holistic data variables, highlighted in Table 6, enables more refined analysis, with location specific themes. In evaluating coastal risk, a first stage involves an assessment of vulnerability. Vulnerability can be further divided between that to infrastructure, people, property, and the environment. Environmental datasets from the basis of vulnerability analysis. A starting point for this process is therefore, identification of environmental hazards. To do this data is required which reveals past, current and future conditions, this takes the form of environmental sensor measurement, which can include meteorological and oceanographic data, such as tide, wave heights, wind speeds, and modelling outputs giving projections of future conditions. Alongside this other important data are required detailing the stability of land, local geology, land heights, coastal processes, dominant sediment pathways, and the presence of natural barriers. This information can reveal how likely an area is to experience erosion or flooding, and allows risk hotspots to be identified. By combining this knowledge of natural processes with details of human activity (for example settlements, local populations, infrastructure, and value accumulation in coastal areas) can reveal proximity to hazards and fragile natural environments, which in turn exposes vulnerability.

3.5.3.2.1 Infrastructure

Coastal populations (and those further afield) are reliant on infrastructure, some of which is exposed to coastal hazards. This infrastructure can relate to transportation, energy, telecommunication, waste and water supply (aquifers). Varied datasets have been included within the GIS which enable critical infrastructure vulnerable to impacts from coastal hazards to be more holistically identified. In so doing, understanding potential complex and cascading risk associated with impacts to specific infrastructure. Within East Anglia some examples of such infrastructure are: Bacton Gas Terminal –sited on an eroding cliff [79]; Lowestoft's Bascule Bridge – prone to flooding during tidal surge events; Felixstowe port –the UK's busiest container port, vulnerable to flooding and erosion; and Sizewell Nuclear power plant –vulnerable to flooding. Key road transport routes such as the A12, linking North and South Suffolk, can also be identified as vulnerable, particularly in the Blythburgh area. The A149, coast road linking East and West Norfolk, is another vulnerable stretch of road identified, where many areas are low enough to be flooded by a tidal surge events, and in the past road closures have been common. Aside from transport there are a number of vulnerable aquifers within the region, these can be identified in datasets from the British Geological Survey (BGS).

Spatial representation of risk to infrastructure can aid identification of more complex risk patterns, interdependencies and causal chains, where vulnerability of one asset can destabilise the whole system, resulting in more widespread risks. For example, vulnerability to Bacton Gas terminal, in Norfolk can translate to wider risks for households and businesses across the country, who both directly and indirectly rely on gas imports routed through this terminal. Land use change is another serious consideration when assessing vulnerability. Fortunately, there are many datasets that have been created by organisations such as Copernicus and the National Trust, which reveal how coastal land use has altered. Planning permission data is also available, permitting indications of future vulnerability, given patterns of urbanisation and shifts in industrial practices. Another factor worthy of consideration is the changing pattern of transitory human usage of coastal areas, for example traffic flows along coastal roads (obtained from DFT and Highways England), and changes in recreational use of coastal areas (obtained from the MMO and other sources). This information can assist identification of emerging vulnerabilities.

3.5.3.2.2 People and property

For the case study area, large open source datasets covering the entire region are available such as Lidar topography, aerial imagery, and EO satellite data. This data has been effectively combined with statistical information (from the ONS and other sources) detailing incomes, health, property types, population densities and distribution. This process has revealed exposed populations, potentially situated in flood plains or close to the edge of rapidly eroding cliffs. Walcott in Norfolk is an example of an exposed coastal village, where poor quality housing is sited on highly erodible material. Across the region of East Anglia statistical information such as that derived from Datashine [85] and the ONS exposes large disparities in wealth. As such, residents exposed to coastal risk vary in their ability to contribute to flood defences or finance repairs of damaged properties. This divide is evident, for example, between many locations in North Norfolk and more densely populated locations such as the city of Great Yarmouth. The later has a higher proportion of households classed as deprived (Datashine [85]), as a result residents are more dependent on government support, rendering the area potentially more vulnerable.

3.5.3.2.3 Environment

Aside from vulnerability associated with human use of coastal areas, a major factor requiring consideration is vulnerability of ecosystems located in coastal regions. The hazards of flooding and coastal erosion both seriously impact natural ecosystems (and the related inherent functioning of the ecosystem goods and services). Impacts are also generated from human activity in coastal areas and the ocean. Overuse and degradation of maritime resources represents a significant concern, and land-based pollutants are a major threat to coastal ecosystems. Ultimately the coastal zone contains only a finite set of resources (Dyer & Millard, 2002) and these resources are rendered increasingly vulnerable due to a combination of unsustainable resource use and environmental degradation. In acknowledgement of this, large sections of the East Anglian coast have some form of environmental designation imposed on them. Many sources of habitat mapping data exist, which enable realisation of habitats situated in hazard prone areas. This includes land based and aquatic habitats. Coastal management groups, working in the area, represent multiple organisation which focus on stewardship of natural capital, flora and fauna. There is a wide range of datasets available (sources detailed in Figure 7 and Table 5) which enable vulnerable species and ecosystems to be identified, and thus considered within future shoreline management options.

3.5.3.3 Conceptual Framework – Stage 3: Impact Analysis

Comparison of datasets representing different temporal periods enables the impacts of coastal hazard events to be quantified. Physical impacts can be modelled by comparison of aerial imagery or EO datasets, for example. When combined with point cloud data, derived from Lidar, hydrographic and terrestrial surveys, this proves especially powerful in allowing visual representations of coastal change to be combined with quantification of change, derived from volumetric change calculations. This can indicate accurately beach loss and creation, cliff recession, loss of natural capital, and inundation by flood waters. The increasing availability of higher resolution EO data, collected more frequently, is especially powerful in enabling impacts of specific storm events (such as the 2013 East Coast Surge [86]) to be revealed. In line with the holistic approach detailed above, this information quantifying physical impacts to coastal regions, can be combined with statistical data detailing the consequences to people, property and infrastructure. Records exist of financial loss, disruptions to business and services, impacts on human health and other societal impacts. This data has been made available from district councils, the ONS and other sources, such as the EA. Historic flood extents are also available from the EA, as shapefiles, which when combined with data showing locations of properties and infrastructure, form an effective way of communicating the extent of impacts. Numerous datasets are now available as web-feeds, some of which are real-time feeds, this is especially beneficial to impact analyses and can enable live monitoring data to be incorporated into geospatial analysis.

3.5.3.4 Conceptual Framework – Stage 4: Adaptation Measure Evaluation

In managing environmental risk in coastal regions, it is crucial to understand the role which man-made and natural adaptations exert on the coast. Within East Anglia a broad range of coastal adaptation mechanisms have been identified from the datasets brought together. Some of these are naturally occurring coastal buffers, such as barrier beaches and salt marshes, whilst others are man-made, hard adaptations, such as groynes and breakwaters. A number of 'soft' adaptation measures have also been implemented. Freely available temporal data such as aerial imagery, Lidar and habitat data, covering defined time periods, can assist in identifying habitats which act as natural barriers and reveal important changes in regions where adaptations are sited, thus aiding an evaluation of the role they could play.

Future coastal strategy is reliant on information revealing the suitability of adaptation methods to specific locations. The benefits of a holistic approach to this is that consideration can be given to the wide range of factors integral to these decisions. For example, a starting point can involve consideration of data relating to current SMP designation of coastal regions (available from the EA), detailing whether the current shoreline will be maintained, left or realigned. Given present land use, there are important implications of these decisions. Therefore, it is essential to include data detailing properties and infrastructure situated in coastal areas prone to flooding or erosion. By combining this information with projections of future coastal change, derived from modelling outputs, more representative assessments can be made of the suitability of planned adaptation options.

Identification of critical infrastructure, as detailed above, is a core concern when making decisions on suitability of adaptation methods. Certain sites are deemed critical (such as infrastructure choke points) and should be defended, whilst other sites may actually benefit from processes such as Managed Realignment, (e.g. Hazlewood marshes in Suffolk [87]) which can result in the creation of valuable habitats, and restoration of ecosystem services, such as nitrogen and carbon capture [88].

Impacts arising from implementation of past adaptation measures, are also of concern, as is destruction of natural barriers, as a result of urbanisation and settlement construction. The wide range of physical datasets available for the case study area has enabled these impacts to be revealed. For example, it is possible to pinpoint where sediment loss could have resulted, from the installation of hard defences or removal of natural capital which offered protective capacity. East Anglia benefits from an extensive archive of physical monitoring data, which when brought together has exposed correlations between construction or removal of adaptations and coastal change. This final stage of the conceptual framework highlighted well, how starting with a base of holistic, varied datasets has enabled vulnerability to be revealed, impacts to be quantified and finally can allow the most appropriate adaptation methods to be selected. Given this the conceptual framework detailed in Figure 11 could prove a valuable addition to risk-based decision-making processes for coastal areas.

3.6 Conclusion

Coastal management is a complex field, which can be simplified through access to information, contributing to raising awareness of the diverse range of factors present within coastal zones. This paper has revealed how a great diversity of open source data now exists, able to address the multiple themes constituting the remit of a coastal manager. Drawing on such a diverse range of sources can remove ambiguity in judgements made on important matters in coastal areas. Data is held by a wide range of organisations; this paper has outlined 34 potential sources of open data for the UK coast. The UK is at the forefront of making public sector data available as open source (so has been used as an example within this paper). However similar data are rapidly becoming available for coastal regions globally (some of which are referred to). The process of assembling and analysing such vast stores of information encapsulates knowledge and can generate fresh insight. Through focusing on the case study of East Anglia, a conceptual framework has been developed, to assist in maximising the potential value of drawing together open source data for the coast, as part of a risk evaluation process. When attempting to apply this methodology to case studies in other part of the world, the main limiting factor, constraining its application, must be noted as the availability and quality of open source data. However, vast stores of data are rapidly becoming available open source. This has been recognised to provide decision-makers with a broader knowledge base covering environmental, social and economic factors, when formulating plans for coastal areas.

3.7 Acknowledgements

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3.9 Supplementary Material

This document provides supplementary data to accompany the article 'Opening up the Coast', and provides a table giving the content of a data repository formed as part of the case study referred to, and a glossary of abbreviations used.

3.9.1 Data Repository content

Data sources and types listed in Table 7 are those which have been included within the data repository formed as part of the case study focusing on East Anglia in the UK. Numbering of data sources corresponds to that in Table 5, and Figure 7 in 'Opening up the Coast'.

Table 7: Data Repository Content

No.	Data Source	Data Types
1	District Councils	• Stakeholder identification • Recreational use • Future infrastructure development • Planning Permission for coastal land (historic/current/future) • Impacts on people and property • Land Use Change • Population distribution and structure • Urbanisation/industrialisation • Resettlement locations (Pathfinder projects) • Ownership of the coast • Administrative boundaries • Beach cliff surveys (transects) • Critical communication and transport infrastructure • Key infrastructure at risk: roads, rail, ports, water, telecoms, undersea structures
2	CCO	• Coastal Monitoring • Aerial image analysis • Geomorphology • Loss/creation of beaches, erosion/accretion rates • Real-time ocean sensor data • Bathymetry • Topography (including point cloud laser scanning of beaches) • Outputs from academic projects (e.g. iCOASST)
3	MET Office	• Meteorological sensor network • Weather/Climate data
4	UKHO	• Bathymetry • Near shore navigation routes
5	BODC	• Water Quality • Oceanographic sensor data (real time) • Tidal data • Fisheries/aquaculture monitoring

6	British Geological Survey	• Geomorphological stability of the land, subsidence • Categorisation of coastal risk based on geological properties • Coastal Geology • Point cloud laser scanning of beaches • Aquifers and groundwater • Offshore aggregate surveys
7	CEFAS	• Habitat mapping • Species distribution • Water quality • Ocean Sensor Data (Real-time) • Fisheries/aquaculture monitoring
8	Historic England	• Archaeological/culturally significant areas • Historic coastal maps –settlement information, coastal extents
9	Natural England	• Habitat mapping, wetlands, specie distribution Species distribution • Protection offered by natural habitats
10	Environment Agency	• Coastal Monitoring • Aerial Image analysis • Real time tidal sensor network • Industrial pollutants • Location of contaminants/pollution sources in flood plains • Location of landfill and sewage sites • SMP boundaries and details • Beach Cliff Surveys (including transects/LIDAR/hydrography) • Loss/creation of beaches, erosion/accretion rates • River and estuary data • Coastal risk assessments • Assessment of coastal protection structures • Key infrastructure at risk: roads, rail, ports, water, telecoms, undersea structures • Impacts on people and property • Urban and rural flooding extents (recorded and forecast)
11	DEFRA	• Farming/Agriculture datasets • Ecosystem services
12	The Crown Estate	• Offshore Renewable Energy projects • Offshore aggregate extraction • Ownership of coast • Hydrographic survey data
13	Copernicus (ESA)	• Satellite EO data • Loss/creation of beaches, erosion/accretion rates • Land use change • Topography • Ocean properties

14	MEDIN	• Links to Marine and geological data • Hydrographic surveys
15	MAGIC	• Links to Environmental data • Land categorisation: protected, industry, urban, prime farmland • Land use/land use change • Marine habitat mapping, wetlands, specie distribution • Farming/Agriculture datasets
16	Intergovernmental Panel on Climate Change (IPCC)	• Climate change predictions
17	Academia (e.g. iCOASST, RISC-KIT, FAST)	• Aesthetic Valuations of the natural environment • Ecosystem services • Coastal processes and sediment dynamics analysis • Impacts generated by man-made coastal protection structures • Modelling Outputs based on various scenarios for the coast (inundation) • Change in protection offered by natural capital
18	EMODNET	• Repository of coastal and ocean data from many sources, for Europe • Bathymetric charts • Marine habitat mapping, wetlands, specie distribution
19	Data.Gov.UK (web portal)	• Access to public sector datasets, including: • River and Estuary data • Ownership of coast • Future infrastructure development • Critical communication and transport infrastructure • Tourism • Human health • Business activity
20	Department for Transport (DFT) UK and Highways England	• Traffic flow data/road use • Infrastructure choke points/critical transport infrastructure • Maritime and shipping statistics • Assessment of ports national importance • Key infrastructure at risk: roads, rail, ports, water, telecoms, undersea structures
21	The Office for National Statistics	• Port usage • Import/export data (ports) • Shipping cargo statistics • Ferry routes and statistics • Assessment of ports' national importance • Employment data • Economic decline • Income data • Business activity

		• Human health • Population distribution and structure • Urbanisation/industrialisation • Tourist numbers –footfall • Includes NOMIS –Official labour market statistics
22	Datashine (University College London)	• Socio-economic data related to 2011 Census • Spatialized indices of economic decline • Human health • Population distribution and structure
23	ABI	• Insurance industry datasets
24	UK OGA	• Oil and Gas data /infrastructure, surveys
25	Land Registry	• Land/property prices • Land use • Ownership of coast • Administrative boundaries
26	JNCC	• Habitat mapping • Species distribution • Industrial pollutants • River and estuary data • Protection offered by natural habitats • Marine conservation zones
27	NOAA NCEI	• Global datasets for coasts and oceans • Some limited data for case study site -East Anglia
28	Ordnance Survey (OS)	• River and Estuary location data • Administrative boundaries • Cadastral maps • Energy Infrastructure
29	MMO	• Marine Spatial Planning • AIS Data • Fisheries/aquaculture monitoring • Recreational use of the coast • Industrial pollutants • Water quality • Marine conservation zones
30	Centre for Ecology and Hydrology	• Host the National River Flow Archive (NRFA), Environmental Information Centre, Environment change network, and the biological records centre • Broad data types associated with each data centre included
31	The National Trust	• Coastal land use and land access to national trust land
32	National Grid	• Energy Infrastructure
33	European Environment Agency	• Europe wide Environmental data downloads • Land Use • Pollution • Water
34	CEDA Archive	• The atmospheric and EO data centre for NERC for the UK

		• Datasets including: climate, composition, observations and NWP data, and various EO datasets, including airborne and satellite data and imagery

3.9.2 Open source data portals

MEDIN

MEDIN [89] is an open partnership, representing government departments, research institutions and private companies. MEDIN hosts Data Archive Centres (DACs), providing long-term data management and addressing many of the data issues noted, such as data format and common metadata standards. An example of one of the accredited DACs, is the 'Offshore GeoIndex' that is hosted by British Geological Survey (BGS), for geology, geophysics, backscatter and geomorphological data [90].

MAGIC

The MAGIC website serves as a similar interactive geospatial environmental data portal as MEDIN. Its scope is broader than MEDIN and the data it makes available covers rural, urban, coastal and marine environments. MAGIC provides geographic information about the natural environment from across government; It is a public-sector collaboration, with Natural England managing the service under the direction of a steering group representing the partnership organisations [64].

MAREMAP

MAREMAP is a similar initiative to MEDIN and MAGIC, relating to the research community and marine mapping. MAREMAP combines seafloor geological, habitat mapping and model outputs with other data layers [15]. MAREMAP is jointly led by a group of research organisations including BGS and the National Oceanography Centre (NOC). The service not only presents existing maps, but also aims to create a new generation of mapping, which will be made available online. In line with INSPIRE [91], the objectives of MAREMAP's seafloor mapping activities include coordinating efforts of its associated data custodians, to avoid duplication of activities.

The CCO

The Channel Coastal Observatory (CCO) has extensive data holdings derived from environmental sensor technology**.** The CCO runs a network of regional coastal monitoring programmes and, operating in partnership with the EA and local authorities, is funded by DEFRA [17]. Their data holdings are also made available as open source, focussing on the physical attributes of the coast and near shore waters, such as: topographic, bathymetric, hydrodynamic and remote sensing data [15].

CEFAS -BODC

In addition to the CCO, the BODC and the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) also both provide a wide range of open source data relating to physical oceanographic variables; the BODC being one of the MEDIN DACs.

The Environment Agency (EA)

The EA is another significant source of coastal data and, including: Lidar topography, bathymetry, surveys of flood protection structures and flood risk assessments.

The Crown Estate

Another valuable source is the Crown Estate's, Marine Data Exchange [25], providing access to survey data and reports collated during the planning, building and operation of offshore renewable energy projects. The Crown Estate serves the role of trustee for these data, sharing the information to promote research and innovation.

HELCOM

HELCOM [28] (Helsinki Commission - Baltic Marine Environment Protection Commission) has been running for over four decades, involving an intergovernmental collaboration, tasked with protecting the marine environment in the Baltic Sea from pollution. HELCOM operates a map and data service, providing an open access portal similar to those described for the UK, containing maritime spatial data at a regional scale. The system boasts a comprehensive web-mapping interface, in which data relating to many of the coastal management themes detailed in Table 4 can be displayed and downloaded.

OSPAR

OSPAR is a comparable initiative, focussing on the North-East Atlantic, involving 15 governments from the EU. OSPAR host a Data Information Management System (ODIMS) [29], another online geospatial data access tool, making data collected through OSPAR's joint program available to the public. OSPAR view data management as critical to their work in assessing the state of the marine environment.

EMODnet

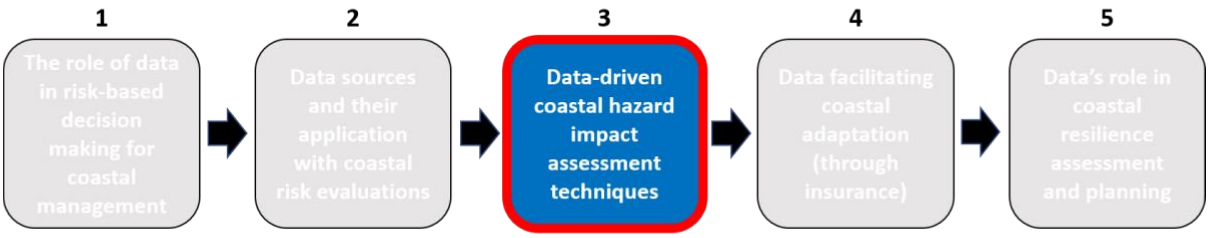
This involves more than 100 organisations, drawing on the notion of 'data stakeholders', and fostering an open source collaboration across national boundaries with stakeholders sharing their data. As in MEDIN, the project involves standardisation of marine data and harmonisation of metadata standards. The project is still in the early phases of development, with full establishment planned for 2020. Later phases involve creation of a high resolution, seamless, digital map for European waters, covering topography, geology, habitats and ecosystems. In 2015 a sub-project involving coastal mapping was initiated, involving physical mapping activities. UK partners to EMODnet include many of the organisational data sources detailed in Table 5.

NOAA NCEI

NOAA aims to realise a mission of discovery and access to data, through web-services, machine to machine services and web-mapping. As a result they hold the largest archive of marine data in the world [92]. The NCEI also offers data management expertise, including metadata training. In their combination of many different types of data, the services and expertise which the NCEI offer are worthy of note.

4 The application of data innovations to geomorphological impact analyses in coastal areas: an East Anglia, UK, case study

From Risk to Resilience: Data-driven coastal management decision making



Impacts can be considered and classified in terms of their disruption to human activity or alterations to ecological processes (Boehlert and Gill, 2008). In fact many hazards are seen only to create impacts when linked to societal interactions within ecosystems (Dodds, 2009). Impacts can occur through pathways (if taken in the context of the SPRC scheme (Reeve et al., 2012)). Attempts at adaptation can compound impacts, this has been found to be the case in certain scenarios where erosion and flooding are combined with increased human defence of the coastline (as outlined in Section 1.7.2.4). Understanding of how human activity on the coast is working to alter impacts is constantly progressing; this process is far from uniform due to the wide ranging, dynamic natural processes which operate on the coast. In some regions, such as along the coast of Devon, high energy storms can result in high levels of erosion, with beach sediment being shifted in a predominantly offshore direction (Masselink et al., 2016). By contrast, along the coast of East Anglia, human actions in modifying the coastline are reported to have significantly altered the sediment budget of beaches (Brooks and Spencer, 2010). Consideration of such processes operating in coastal zones requires an awareness of both the spatial and temporal scales over which change operates, as illustrated in Figure 12. The scale at which change is monitored and analysed can limit the relevance of outputs to determining coastal processes. Results can be misinterpreted if data for only a small section of coast is considered, as actions which minimise risk, and impacts in one location can amplify them on adjacent stretches of coast. The work presented in this chapter has adopted a regional approach to impact analysis, considering sites located across sediment cells in an effort to reveal wider scale trends. Yet, the temporal scale considered is limited. Therefore, this chapter is concerned primarily with changes taking place in the boxes labelled 'instantaneous' and 'event' (Figure 12).

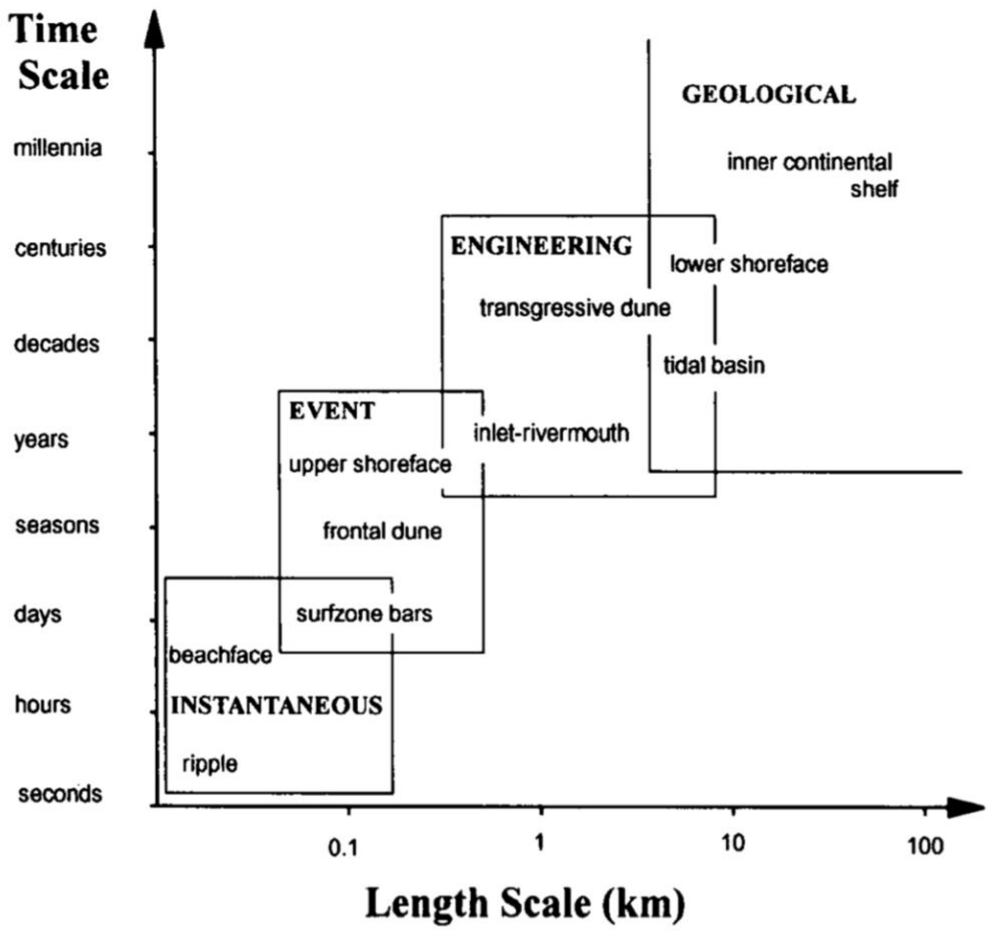


Figure 12: Definition of spatial and temporal scales involved in coastal evolution, detailing sedimentary features (Image adapted from Cowell and Thom (1994))

Storm surges occur when high tides combine with wind and wave forcing. In 2013, on the east coast of England the impacts became compounded, causing extensive damage to landforms, ecosystems and infrastructure (Spencer et al., 2015). There are clear, direct economic impacts resulting from hazards such as this, which can take the form of flooding of property, damage to agriculture, and erosion of cliff top properties and arable land (Nicholls et al., 2015a). Given this, the ability to accurately monitor and quantify physical morphological changes along the coast, resulting from hazard propagation, is vital. The coastline of East Anglia is extensive and includes varied environmental conditions and processes. Analysis presented within this chapter, documents morphological changes at 14 case study sites distributed across the region of East Anglia. The results generated reveal how events, in particular the 2013 East Coast Storm Surge (see Section 1.7.3.2), can result in varying physical consequences across the region.

The opportunities afforded by high spatial and temporal resolution point cloud datasets such as those derived by Lidar were outlined in the preceding chapters. In addition to Lidar there are many other sources of similar data, such as Terrestrial Laser Scanning (TLS) (Kromer et al., 2017), Mobile Laser Scanning (MLS) (Leyland et al., 2017), Multibeam Echosounders (Schimel et al., 2015), photogrammetry and Structure From Motion (SFM) (Westoby et al., 2018). Such datasets are increasingly becoming available, and software tools and scripts have been developed to allow comparison of such data enabling Geomorphological Change Detection (GCD) (Wheaton et al., 2010). Quantification and classification of morphological changes, now possible over extended temporal periods using point cloud coastal datasets, permit a greater understanding of coastal trends. A range of tools are available, from those which allow identification of wide scale general trends (such as linear coastal recession) (Williams, 2012), to more precise Cloud to Cloud (C2C) comparison techniques, revealing granular cliff deformations, such as individual rock fall events (M3C2 (Plugin), 2018). A more comprehensive understanding of the possibilities presented by such analytical methods is important for those seeking to make decisions based on records of past physical coastal impacts.

The previous chapter (3) adopted a wide approach and discussed the use of data within various stages of coastal risk assessments. This chapter has a narrower focus and concentrates on physical morphological impacts. In this only a limited number of data sources and types are considered. Yet despite data variety being lower, the overall volumes of data considered are still relatively high, due to the data's high spatial and temporal resolution. This chapter focuses specifically on the methodologies and analytical processes employed to derive meaning from point cloud datasets. Past assessments of GCD undertaken by practitioners, particularly for the case study region, have frequently been based on outdated processes and subjective judgements. This chapter seeks to address these issues by basing change estimates on dense, frequently updated datasets, thus reducing the requirement for manual interpolation. The main analytical technique utilised within this chapter (Triangulated Irregular Network (TIN) based differencing) is only one of the many techniques available. A review is presented in the first part of the chapter of many of the GCD methods available, this indicates the data types and contexts that each method is suited to.

The application of data innovations to geomorphological impact analyses in coastal areas: an East Anglia, UK, case study

Abstract

Rapidly advancing surveying technologies, capable of generating high resolution bathymetric and topographic data, allow precise measurements of geomorphological change and deformation. This permits great accuracy in the characterisation of volumetric change, sediment and debris flows, accumulations and erosion rates. However, such data can be utilised inadequately by coastal practitioners in their assessments of coastal change, due to a lack of awareness of the appropriate analytical techniques and the potential benefits offered by such data-driven approaches. This was found to be the case for the region of East Anglia, UK, which was analysed in this study. This paper evaluates the application of innovative geomorphological change detection (GCD) techniques for analysis of coastal change. The first half of the paper contains an extensive review of GCD methods and data sources used in previous studies. This leads to the selection and recommendation of an appropriate methodology for calculation of volumetric GCD, which has been subsequently applied and evaluated for 14 case study sites in East Anglia. This has involved combining open source point cloud datasets for broad spatial scales, covering an extended temporal period. The results comprise quantitative estimates of volumetric change for selected locations. This allows estimation of the sediment budgets for each stretch of coastline focused upon, revealing fluctuations in their rates of change. These quantitative results were combined with qualitative outputs, such as visual representations of change and we reveal how combining such methods assists identification of patterns and impacts linked to specific events. The study demonstrates how high-resolution point cloud data, which is now readily available, can be used to better inform coastal management practices, revealing trends, impacts and vulnerability in dynamic coastal regions. The results also indicate heterogeneous impacts of events, such as the 2013 East Coast Storm Surge, across the study area of East Anglia.

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Keywords

Geomorphological change detection; coastal management; open source data; point cloud data; volumetric change; impact analysis

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4.1 Introduction

Decision-making and environmental management in coastal areas requires the ability to understand and quantify the variability of change and deformation of beaches and cliffs over time. An understanding of their drivers may be gained through the quantification of such changes (Schimel et al., 2015). Typically, this involves characterisation of debris flows, accumulations and erosion rates. However, many coastal organisations, such as those in the UK, are not currently utilising the range of advanced and appropriate techniques and technologies, which are now readily available. Emergent remote sensing technologies are able to generate far higher resolution measurements for coastal areas than have been previously available, in both the vertical and horizontal planes. Such methods can allow more precise measurements of coastal retreat to be undertaken than those extrapolated from traditional topographic maps or aerial photos (Poulton et al., 2006). Analyses of such measurements can lead to the production of derivative data products that can provide, for example, retreat rates directly from volumetric change calculations (Esposito et al., 2018). Additionally, data with a higher temporal resolution is also becoming available (Kromer et al., 2017). This can reveal dynamic coastal processes with increased granularity, assisting in the identification of both vulnerable and stable locations. Furthermore, when such morphological data is combined with other measurements, causation of change can be determined (Leyland et al., 2017; Rosser et al., 2005). This can improve our ability to model coastal processes and to make informed projections on future coastal change scenarios.

Understanding the processes operating in coastal zones requires the ability to compare datasets from different epochs[15], and the consequent generation of quantitative and qualitative representation of areas where loss and gain of beach and cliff material has occurred (Earlie et al., 2015). This can enhance our understanding of processes, such as the contribution of beach sediment to littoral cells (Young and Ashford, 2006). A wide range of methods exist for geomorphological change detection (GCD), and the selection of appropriate methods requires consideration as to the local environment, context, type of output desired, i.e. volumetric change and/or linear change, output format (qualitative/quantitative), and level of detail required from the subsequent analysis. For example, the monitoring of granular deformations of hard rock cliffs (Rosser et al., 2005; Westoby et al., 2018) necessitates separate survey and analytical data approaches than do studies that are restricted to determining wider-scale cliff-top recession rates, or those monitoring beach levels (Shrestha et al., 2005), or near-shore sediment movements (Burningham and French, 2011). Airborne survey techniques can reveal cliff top retreat, however, for vertical cliffs, such approaches are not capable of revealing cliff toe erosion and overhangs which can often lead to cliff failure (Michoud et al., 2015; Obu et al., 2017). For this, survey techniques with a horizontal aspect (ground or vessel based) are required (Michoud et al., 2015; Rosser et al., 2013). Yet, to date, a comprehensive discussion on the suitability of different coastal GCD methods has not yet been completed.

The main issue addressed by this research is that of the utilisation of point cloud based GCD techniques by the coastal practitioner community. Outside academia, only limited adoption

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[15] For the purpose of this study an epoch is defined as the date and time in which a survey was completed at one specific site.

of such methods has been witnessed. Despite a large archive of morphological point cloud data existing for the many regions, coastal change analysis is most commonly based on more rudimentary methods, such as extraction of cliff edges from aerial imagery. Reasons why more advanced point cloud-based methods have been underutilised include: a lack of awareness of the available and appropriate analytical techniques, and inadequate knowledge of the potential advantages that utilisation of such GCD approaches can generate. This paper seeks to address these challenges through an initial discussion of point cloud based GCD methods, and a subsequent practical GCD for a number of case study sites in East Anglia, UK. East Anglia has a highly dynamic, vulnerable coastline, comprising soft cliffs and sandy beaches, on which extraordinary rates of geomorphological change have been experienced, (Brooks and Spencer, 2010). The region has been studied extensively, and many morphological datasets representing its coasts are now freely available. These factors combined, render this region especially suitable for analysis. As such, using a single GCD method, centred on triangulated irregular network (TIN) model creation and planar surface comparisons, datasets for 14 case study sites were combined and compared, for periods ranging between 6 to 10 years. The sites selected were identified based on consultations with those public sector bodies tasked with monitoring and managing the coastline of the region e.g. Coastal Partnership East (CPE) and the Environment Agency (EA). The sites further represent locations where a requirement exists to provide high temporal and spatial resolution change analysis.

In this study we evaluate many GCD techniques and methods to assess their application in different scenarios. A key objective was to evaluate the practical suitability of a point cloud based GCD method for coastal change detection applications. In doing so, we demonstrate how successful combination and analysis of point cloud data can reveal change and evolution of coastal environments. In line with this, a second objective was to generate increased understanding of recent morphological changes occurring at selected vulnerable stretches of the East Anglian coastline. The GCD method utilised within this study was capable of producing volumetric change estimates. Results generated through application of this technique allowed quantification of the sediment budgets at each study site. Such outputs are especially relevant to the coastal region of East Anglia and other recent studies have sought to generate similar (Brooks and Spencer, 2010; Burningham and French, 2016). It is envisaged that the outcomes generated from this study may raise awareness of the possibilities presented by point cloud data analysis for studies focussing on coastal change and deformation, and potentially assist practitioners and researchers in the selection of appropriate GCD methods. Additionally, the quantitative results may form an input to future research or decision-making processes. Many ‘state of the art’ developments in geomorphological change analysis, relevant to coastal analysis, are underway in areas of research outside the direct sphere of coastal studies, in areas such as analysis of fluvial systems (Lague et al., 2013; Leyland et al., 2017) and non-coastal rock faces (Kromer et al., 2017). Accordingly, note is given to a selection of these studies within this work.

4.2 Review of coastal GCD techniques

4.2.1 Monitoring the coast, beaches and cliffs

In attempting to understand coastal dynamics, an appreciation of processes operating across coastal environments is essential; past studies have generally divided their focus between cliffs and beaches. However, when modelling coastal cliff environments, data on the foreshore should also be included (Hobbs et al., 2010). Monitoring each environment separately can require different data acquisition techniques and processing workflows. Yet a number of studies exist that combine such techniques (Eisemann et al., 2018; Leyland et al., 2017; Seker et al., 2003). Processes operating on the near-shore seabed are linked to erosion and deposition events occurring on beaches (Sergeev et al., 2018). As such, an understanding and integration of the influence of the offshore environment, is essential when modelling future recession rates (Poulton et al., 2006). There are many drivers for monitoring the near-shore environment, resulting in datasets becoming available that are able to reveal the dynamic evolution of these areas. For example, seabed surveys can result from channel dredging requirements, marine aggregate resource monitoring, and engineering works related to undersea cables, pipelines and energy infrastructure (Schimel et al., 2015). As a consequence, monitoring of the subsea domain has progressed rapidly, and now detailed point cloud datasets are routinely generated by multibeam echosounder (MBES) surveys. Moreover, repeat MBES surveys have facilitated change analysis to be completed for near-shore environments (Kemp and Brampton, 2007; Leyland et al., 2017; Quinn and Boland, 2010; Schimel et al., 2015). Such studies can expose dynamic 'live bed processes', including the migration of seabed features (Quinn and Boland, 2010). This current study included one case study site (Case Study 10: Nearshore Lowestoft) for which MBES data from 11 epochs were analysed. Compared to topographic datasets, such as derived from airborne lidar, the number of Open Source MBES datasets available to download, are more limited. The costs associated with completion of MBES surveys is one barrier, preventing many commercial organisations who hold this data, making it available for free. However, there are initiatives in place seeking to overcome such hurdles. For the UK, the Crown Estate stipulate that datasets generated from seabed surveys related to offshore wind farms, must be made available to the public after a 2 year period, this data should then be accessible via their Marine Data Exchange (The Crown Estate, 2019).

Obtaining data for intertidal areas is challenging, there are limitations imposed on the ability to acquire MBES in these areas, due to the draft of vessels upon which MBES systems are mounted. However the growing use of unmanned surface vessels is reducing such limitations (Iwen and WAz, 2019). A number of alternative methods of acquiring intertidal data exist, and continual progress is being made in this field. Satellite derived bathymetry is one such rapidly evolving method (Kulawiak and Chybicki, 2018; Sagar et al., 2016), as is the use of X-band radar (Atkinson et al., 2018; Bell et al., 2016). However, the spatial resolution and accuracy of data obtainable by these methods is lower than that possible using MBES. Another alternative, is bathymetric Lidar (Andersen et al., 2017; Eisemann et al., 2018), this can provide higher resolution data than satellite or X-band radar, yet is limited by meteorological and ocean conditions.

The use of remote sensing data offers significant accuracy improvements over the more manual and traditional methods required to analyse historic analogue datasets, which also rely on the skills of an individual, and can lead potentially to high levels of uncertainty (Burningham and French, 2011). Furthermore, the ability to combine point cloud data, revealing the complex spatial patterns of sand redistribution (both on beaches and in the near-shore environment), is recognised as essential in attempts to represent adequately the evolution of coastal processes (Mitasova, 2015; Mitasova et al., 2002). Traditional techniques relying on manual interpretation and digitisation (Seker et al., 2003), can prove efficient in summarising change rates on a larger scale, yet can omit important site-specific details (Earlie et al., 2015; Krolik-Root et al., 2015). A number of common GIS-based analysis techniques such as the Digital Shoreline Analysis System (DSAS) (Appeaning Addo et al., 2008; Thieler et al., 2009) and AMBUR (Jackson et al., 2012), also involve manual shoreline digitisation. Yet, in comparing an approach based on DSAS, with more advanced, point cloud based methods, Leyland et al. (2017) found it to be 'error prone at high temporal resolution'. Methods used to complete morphodynamic analyses of coasts can vary widely in complexity, from simple approaches involving visual interpretation (Amaro et al., 2015), to surface comparisons based on gridded or meshed datasets (Williams, 2012), and more advanced point cloud analysis (Williams et al., 2018). It is in the field of cloud to cloud (C2C) comparison that some of the most significant contemporary advances are being made. As such, C2C analysis offers an optimal method for quantifying erosion (Lindenbergh and Pietrzyk, 2015). Automation of processes and data workflows is now becoming a common feature associated with many techniques (Esposito et al., 2018; Halls et al., 2018; Kromer et al., 2017; Kulawiak and Chybicki, 2018). In some cases this enables data to be processed at the rate of acquisition (Williams et al., 2018). Ultimately, the techniques adopted for use should be dictated by the nature of the coastline, the phenomena monitored and level of detail required (Westoby et al., 2018).

4.2.2 Coastal terrain data acquisition

There are a wide range of data capture methods available, for surveying coastal areas; a clear distinguishing factor between these is the means of their deployment: airborne, ground or vessel based. Airborne techniques benefit from their ability to cover large areas and to gain coverage of otherwise difficult or inaccessible locations (Earlie et al., 2015; Young, 2018), conversely they are hampered by drawbacks such as a decline in accuracy as the inclination of the terrain surveyed increases (Obu et al., 2017; Young et al., 2010; Young and Ashford, 2006). Additional limitations can be imposed on the use of satellite data by inconsistencies generated by rapid changes in coastal topography (Hobbs, 2008). Terrestrial laser scanning (TLS) methods and ground-based photogrammetric methods are more capable of capturing details on vertical cliff faces at higher resolution, with some allowing 10cm gridding of data (Sergeev et al., 2018). However, these approaches can suffer drawbacks associated with shadowing (occlusions) when used to survey complex cliff faces, due to scanning angles (Hobbs et al., 2010). Mobile laser scanning (MLS), undertaken from moving platforms such as boats, can partially overcome these issues, with multiple angles used to observe given points (Leyland et al., 2017; Lindenbergh and Pietrzyk, 2015; Michoud et al., 2015). Methods that generate dense point clouds are generally capable of producing more comprehensive representations of topography and bathymetry than more sparse data acquisition methods, such as GPS surveys, beach transects, and single-beam sonar surveys. Such methods can require extensive interpolation to address large areas that lack coverage (Shrestha et al., 2005). There are benefits that can arise in combining methods, for example, surfaces derived from laser scanning techniques are frequently and usefully ground-truthed using GPS transect data (Halls et al., 2018; Kaliraj et al., 2017; Pollard et al., 2019; Shrestha et al., 2005; White and Wang, 2003).

4.2.3 Geomorphological Change Detection (GCD)

Depending on which data acquisition method is employed, varying levels of complexity and interpolation are required to enable change analyses to be completed. A common option for GCD involves the use of shoreline transects (Burningham and French, 2011; Environment Agency, 2013; Gorman et al., 1998; Halls et al., 2018; Obu et al., 2017). These transects represent 2D beach and cliff profiles, generated through GPS surveys or derived from surfaces extracted from raw survey data i.e. digital elevation models (DEM) (Eisemann et al., 2018). However, high levels of uncertainty are inherent in the calculations derived through this method, as surface heights between transects are interpolated, and are often derived by multiplying profile end areas by the transect separation distance (Cantrill and Kruimel, 2013; Corbí et al., 2018; Shrestha et al., 2005). Nevertheless, transect-based methods are still frequently used in many studies and by coastal management bodies (especially for cliff retreat calculations (Young, 2018)); they have also been combined with methods such as linear regression (Appeaning Addo et al., 2008). One change comparison method (both 2D distance and volumetric) which can be used with both transect-based calculations and those involving surfaces, requires construction of a planar reference surface (or a geometric primitive) (Lindenbergh and Pietrzyk, 2015). Estimates of change are then derived by comparing the distances between survey points and the planar surface (for different epochs), along a static vector (either a horizontal or vertical distance) (Figure 13).

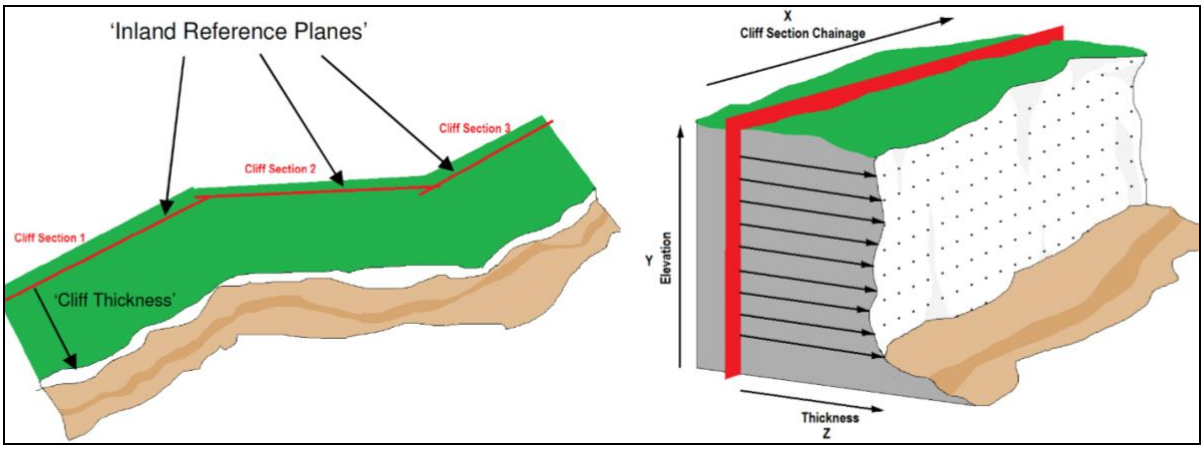

Figure 13: Planar change comparison method along a horizontal vector (image reproduced with permission from the Channel Coastal Observatory (2016))

If DEMs or topographical meshes are created from survey data, then direct comparisons can be made between surfaces (for different epochs), either by using the reference plane method, or more directly by simply subtracting elevation values of one surface from the other (Abellán et al., 2014; Mitasova et al., 2002; Sergeev et al., 2018). Volume calculations are derived through a summation of the change values of all pixels (or cells) within a given area of interest (Kemp and Brampton, 2007; Obu et al., 2017; Zhou and Xie, 2009). This can reveal a 'mosaic of morphological change' (Williams, 2012), and can also allow calculation of cliff recession rates (Esposito et al., 2018). This kind of GCD method is imperfect yet is widely used and reliable (Earlie et al., 2015). Variations of this technique have been termed DEM of Difference (DoD) (Williams, 2012).

4.2.4 Surface creation

Most contemporary studies involving GCD for the coast involve some form of DEM creation. Therefore, understanding the options for, and processes involved in DEM creation is important. Converting an irregular cloud of data points into a cohesive surface is not straightforward and requires interpolation. This can involve creation of a regularly spaced raster grid. For coastal GCD, some common methods used for this include: nearest neighbour (Michoud et al., 2015), kriging (Quinn and Boland, 2010), splining (Mitasova et al., 2009), linear interpolation (Eisemann et al., 2018), inverse distance weighting (IDW) (Halls et al., 2018), and more software-specific methods such as 'Topo to Raster' (in ArcGIS) (Burningham and French, 2011; Esposito et al., 2018), or CUBE[16] in Caris HIPS/SIPS (Calder, 2003; Schimel et al., 2015). Alternatively, DEMs can be formed from vector-based representations such as TIN models (Amaro et al., 2015). TINs have been termed the 'most common and reliable form of representing high-resolution topographic data' (Wheaton et al., 2010, p.152) and have proven popular in coastal studies as the precision of the input data is preserved. TIN models incorporate the original data points, limiting interpolation to areas between these (Aragonés et al., 2016; Dawson and Smithers, 2010). This method encompasses 'modelling the surface as a collection of small (triangular) planes' (Cantrill and Kruimel, 2013) and can account for irregular and complex geometries, and micro-topographical irregularities (Krolik-Root et al., 2015), for which a regular gridded surface proves inadequate. TIN models can also prove beneficial in allowing complex topographic surfaces with varying levels of spatial variability to be described (Gorman et al., 1998). Yet problems can be encountered where data is lacking, and where oversized polygons are created (Hobbs et al., 2010), and misrepresentation errors can contribute to surface uncertainty (Wheaton et al., 2010). Aside from DEMs, another popular surface creation method is meshing, being most commonly applied to vertical cliff faces (Rosser et al., 2005). Meshing also involves interpolation between points, but irregular meshes can allow varying levels of resolution in surfaces, thus being able to capture more complex morphologies and geometries (Zischg et al., 2018).

Analysis of DEMs using DoD was quoted to be the most popular method for point cloud comparison in earth sciences (Lague et al., 2013). Yet despite the method's popularity it holds a number of drawbacks, such as high levels of interpolation, and artefacts can be generated through the creation of surfaces (Kromer et al., 2015). It is inadequate for application to rough surfaces and ultimately the technique is not 3D (Lague et al., 2013). It can be termed '2.5D', in that only a single height value is represented in the z-coordinate plane (Williams, 2012). This can introduce bias when attempting to represent complex vertical surfaces such as overhangs (Lague et al., 2013). Tracking surface change along a static vector (which the DoD methods involve) is also regarded by Mitasova (2015) as simplistic, in that it fails to 'capture the complexity of elevation surface dynamics' such as movements which combine both vertical and horizontal components.

[16] CUBE: Combined Uncertainty and Bathymetric Estimator

4.2.5 Point cloud data

For more comprehensive 3D analytics it is necessary to consider C2C comparisons, using point cloud data which has not been triangulated, meshed or gridded. Consequently, analysis is not restricted to planar comparisons. C2C comparisons can overcome many uncertainties and inaccuracies introduced by triangulation/meshing/gridding. Using cloud-based techniques, it is possible to register vertical and overhang components of cliffs. Additionally options exist for calculating slope-dependent change vectors, or surface normals, for comparisons (Kromer et al., 2017). This can result in efficiency gains through the correct points being compared between two point clouds (Williams et al., 2018). This method is particularly suited to rough surfaces and complex geometries, where an assumption that all changes take place in the same direction can be a gross simplification, misrepresenting reality. Continual progress is being made in relation to point cloud comparison methods and novel workflows and algorithms have been devised for GCD, such as M3C2 (Multiscale Model to Model Cloud Comparison) (Lague et al., 2013). The M3C2 algorithm, first estimates surface normals (detects change orientation) then generates mean surface change distances along normal directions (including an uncertainty component), and 'assigns a level of significance to calculated changes' (Leyland et al., 2017). A number of adaptations of M3C2 (Kromer et al., 2015; Williams et al., 2018), and similar methods (Abellán et al., 2014), have been implemented in studies centring on GCD. A typical application of this type of method is where small detailed changes/deformations need to be monitored.

4.2.6 Inconsistencies and errors

In calculating coastal change, high levels of uncertainty are inherent in the methods used. However, in many studies, errors appear to be overlooked (Abellán et al., 2014). This is especially so where more simplistic, manual approaches are employed. Yet errors can act as 'the main controlling factor in the ability to detect change' (Kromer et al., 2015). As such, for change estimates to be reliable, it is important to differentiate actual geomorphic change from that generated by errors (Williams, 2012). Errors can arise through a variety of means, including: data collection methods, processing techniques, surface type, surface roughness, vegetation, variability in point density, atmospheric conditions, incidence angle, heterogeneity of point spacing, topographic complexity (Kromer et al., 2017, 2015; Williams, 2012), and (mis)registration of the surfaces compared (Miller et al., 2008). The use of remote techniques such as Lidar can necessitate establishing a minimum threshold for errors, which may thereby increase confidence in consequent change estimates (Young et al., 2010). As such, many GCD methods can involve establishment and application of volumetric confidence intervals, as well as minimum threshold values for change detection (Abellán et al., 2014). Such threshold values can be termed the limit of detection (LoD), whereby changes smaller than the LoD are discounted as they could be attributed to system errors or noise (Schimel et al., 2015). Threshold methods such as the LoD approach are not perfect solutions. There is a danger in applying LoD methods (as other error accounting techniques) of removing too much data, which can result in eliminating real geomorphological change, and potentially important features (Young, 2018; Young et al., 2010). As such, careful consideration is required in the selection of appropriate techniques. For example, for DoD methods, probabilistic approaches are reported to generate more reliable estimates than those based on LoD alone (Williams, 2012). For some DoD methods, uncertainties and errors are accounted for directly within calculations. For example, Wheaton et al. (2010) have developed a technique to account for errors that involves a ‘fuzzy inference system’[17], addressing spatially variable uncertainties (related to differing slope, point density, and point quality across a comparison area). LoD calculation are also regarded by Williams et al. (2018) to be improved through using 3D point cloud methods and by techniques allowing spatially variable confidence intervals (Kromer et al., 2017). Moreover the M3C2 algorithm (and other similar methods) directly integrates an error component within its calculations (Lague et al., 2013).

4.2.7 Temporal resolution of data

The ability to detect spatial patterns of coastal terrain evolution is directly influenced by how frequently surveys are undertaken (Mitasova et al., 2009). Generally, for change analysis to represent dynamic coastal processes more accurately, frequent monitoring is required. This can provide a ‘methodological understanding’ of change mechanisms (Rosser et al., 2005). A number of studies have successfully revealed change processes and drivers through comparison and modelling of near-continuous, high temporal resolution data (Rosser et al., 2013; Williams et al., 2018). This would be difficult to establish, with any degree of certainty, through isolated surveys, each providing no indication of change between survey epochs (Kemp and Brampton, 2007). Additionally data collected infrequently can be unrepresentative, due to it being prone to bias introduced as a result of specific events, such as those resulting from severe weather which can, for example, introduce temporary objects (Lindenbergh and Pietrzyk, 2015; Obu et al., 2017). As such, the separation between survey epochs is an important consideration. Short term variability is not captured when comparing datasets representing distant epochs. This can lead to simplification of complex geomorphological behaviour and change patterns being wrongly interpreted as episodic (Rosser et al., 2013). There are a range of novel interpretation and visualisation techniques which can be employed to represent dynamic changes, derived through comparison of high temporal resolution datasets. For example, variable spatio-temporal stability can be revealed through multi-temporal, per-cell, raster statistics (Mitasova et al., 2009) or creation of isosurfaces, used to sum elevation changes across multiple periods (Mitasova, 2015).

4.2.8 GCD technique selection

The requirements for GCDs depend on the phenomena being monitored and can range from the need to establish general trends of long term 2D coastal change, to high spatial and temporal resolution 3D morphological monitoring of cliff faces, revealing, for example, individual rock fall events. For monitoring large and obvious changes, simpler, more efficient methods can be used (Lindenbergh and Pietrzyk, 2015). Yet if granular details need to be focused on, precise *in-situ* measurement techniques can be required (Ganju et al., 2017), necessitating more complex workflows (Williams et al., 2018). In such cases, more simplistic, commonly used methods can generate errors larger than the changes or rates of retreat being measured (Ganju et al., 2017; Rosser et al., 2005). Table 8 provides an overview of the various GCD methods discussed. Ultimately though, the method selected is dependent on what datasets are already available, or can be acquired.

Many organisations responsible for managing risk in coastal areas, have been concerned primarily with generalised linear erosion rates, so have settled for basic level change

[17] This technique is freely available for download and has been utilised within this study.

comparisons centred on visual interpretation of aerial images and digitised shorelines (Stanley and Staley, 2017), and beach profile comparisons based on GPS transects (Environment Agency, 2013). In such cases, shifting to an approach deriving linear retreat rates from comparisons of DEM surfaces, such as DoD (Williams, 2012), can offer clear improvements over existing methods. In many other instances, linear retreat or analyses of change limited to one plane or vector is inadequate, particularly where small changes need to be monitored in areas of complex geometry. Furthermore, where causation of change is sought, this level of abstraction may over-simplify complex changes. In such instances, high temporal and spatial resolution C2C techniques are more applicable (Kromer et al., 2015), and can permit change detection based on dynamic surface normals, as opposed to static vectors. The scale at which changes must be monitored, also imposes restraints on GCD method selection. It may not be adequate to focus on change in one location for example, so scanning methods generating high-resolution point clouds, may not be feasible, and lower resolution techniques based on surface creation may be more appropriate.

This study seeks to address the coastal GCD requirements of a broad range of the stakeholder parties who wish to model such heterogeneous phenomena. However, the study is limited in scope, so focuses on a single aspect of GCD. Based on feedback received from coastal practitioners[18], in which their most immediate requirements and current challenges were outlined, a decision was made to focus on broad-scale general trends of morphological change. Previously reported change analyses for East Anglia have mainly focussed on linear change estimates, largely neglecting quantification of loss/gain of coastal material (Environment Agency, 2013, 2012, 2011). Yet many past studies for the region have highlighted the importance of deriving quantitative estimates of sediment budgets (Brooks and Spencer, 2010; Burningham and French, 2016). Recent analysis undertaken for East Anglia also outlines a requirement for future incorporation of volumetric analysis based on Lidar datasets (Stanley and Staley, 2017). The 14 case study sites we selected, contain varying morphological characteristics. Given this, linear change analysis was not deemed suitable by the authors, to adequately capture the diverse morphological processes operating within all study sites (not all of which were characterised by net coastal erosion). A generalised method was required, allowing quantification of net material gain or loss at each location, over multiple epochs. Therefore, for this study a decision was made to focus on the calculation of volumetric change, and based on the criteria detailed in Table 8, a TIN-based differencing, surface comparison method was selected (Cove and Lavoie, 2007). This involves calculation of surface volumes, based on elevation relative to a uniform planar surface. Prior to the selection of this method a number of other options were trialled, for example, those based on regular gridded raster surface creation, as described in Cantrill and Kruimel (2013). The method selected was considered the most suitable, given the nature of the terrain being modelled (generally complex, including steep surfaces), the data types being used (mainly airborne Lidar), and the irregular spacing of data points. The TIN models retained the original elevation at data points, thus minimising interpolation and smoothing, in which actual features could be misinterpreted as noise and so be lost from the analysis.

[18] Feedback was received from members of Coastal Partnership East (UK), the Environment Agency, and members of the Anglian Coastal Monitoring Group.

Table 8: Comparison of GCD methods

Type of GCD	Method	Benefits	Drawbacks	Area of Application
Manual Interpretation / Digitisation	2D linear retreat derived from aerial images/maps	Simple method. Not reliant on point cloud data being available; can be applied to topographic maps/aerial imagery. Easily applied at varying spatial scales.	High levels of interpolation required. Reliant on the skills of the operator. Error prone at high temporal resolution. No options for volumetric change calculation.	Where large obvious changes are present and general trends required. Wide scale linear trend identification.
	Linear retreat derived from profiles/transects	Volumetric change can be obtained through interpolation between transects. Can be based on GPS surveys. Simple.	Incomplete representation of coastal areas. Interpolation of data points between transects reduces accuracy.	General long-term trends of coastal erosion/accretion.
Surface Comparison	DEM of Difference (DoD)	Most popular and commonly used method. Simple. Variants allow error terms to be incorporated in calculations. DoD surfaces can provide visualisation of change/qualitative outputs, in addition to quantitative results.	Comparing data for multiple epochs can be time consuming and error prone. Not suitable for vertical cliff face comparisons. Interpolation required for surface creation, thus artefacts can be generated, or real data points misinterpreted as noise. Not a 3D method (2.5D), limited to only one elevation value per raster grid cell.	Beach level comparison, where simple geometry is present. Qualitative identification of patterns of sediment movement. More suited to a limited number of epochs. For aerial and subsea survey datasets. Capable of application at larger spatial scales.
	TIN to TIN Comparison	TINs account for irregular and complex geometries, and micro-topographical irregularities. Original data points preserved within calculations. Difference surfaces can provide visualisation of change. TINs are suitable where spatial variability of point density is present.	Comparing data for multiple epochs can be time consuming and error prone. Limitations imposed on the size of datasets/number of data points which can be used in TINs. TINs can be problematic where there are data gaps (occlusions).	Suitable for modelling complex topographic surfaces with varying levels of spatial variability. Suited to aerial and subsea survey methods.
	Planar Comparison (TIN/DEM)	Comparison not limited to vertical change vectors, can use horizontal, inclined and vertical reference planes. Distinct volumes obtained for each epoch; easy to compare data for multiple epochs. For TINs, the benefits listed above also apply.	Change analysis along a static vector fails to capture the complexity of elevation surface dynamics, and movements which combine vertical and horizontal components. Limited to quantitative outputs. For TINs, the drawbacks listed above also apply.	Can handle the datasets generated from survey techniques with a horizontal aspect (TLS/MLS). Can be applied where a high number of epochs are to be compared. Suited to aerial and subsea survey methods.

	Mesh Comparison (Planar/direct)	Can allow varying levels of resolution in surfaces to be compared; able to capture complex morphologies and geometries. Suitable for high density point clouds.	Interpolation required in surface creation. Time consuming. Limitations on scale of application.	For vertical and inclined cliff faces. Higher resolution data. Identification of smaller changes over multiple periods. Localised scale.
Cloud to Cloud (C2C) Comparison	Static Vector	Lower levels of interpolation due to change estimates based on original data points. Simpler and quicker to restrict change to one vector. More suited to 3D analysis than surface-based techniques, can overcome many uncertainties and inaccuracies introduced by meshing/gridding. Many options for the orientation of the static change vector.	Drawbacks associated with using a static change vector. Limitations on spatial scale of application. High density datasets required. Method required to account for any gaps between data points.	Where detailed linear retreat estimates are.
	Surface Normals	Method permits comprehensive error accounting. Direction of change given, more complete picture of change; efficiency gains through the correct points being compared between two point clouds. Potentially, lowest level of interpolation of all methods. The fact that changes occur in multiple directions is also accounted for.	Requires high density point cloud data. User expertise requirements for application. Limitations of spatial scale of application. High computation power requirements, potentially due to larger datasets.	Optimal method for precise quantification of erosion at a localised scale; monitoring of granular deformations such as that in hard rock cliffs. Suitable for determination of change causation, rough surfaces and complex geometries. Can be used to reveal individual rock fall events.

4.3 Methods

4.3.1 Application of a GCD technique to the case study region

The 14 case study sites encompassed over 24km of coastline (Figure 14). The sites are widely distributed across the region, and each site contained unique features in terms of coastal change parameters, erosion/accretion methods, geology and vulnerability characteristics. Table 9 lists the case study sites with their rationale for selection and the datasets obtained for each site.

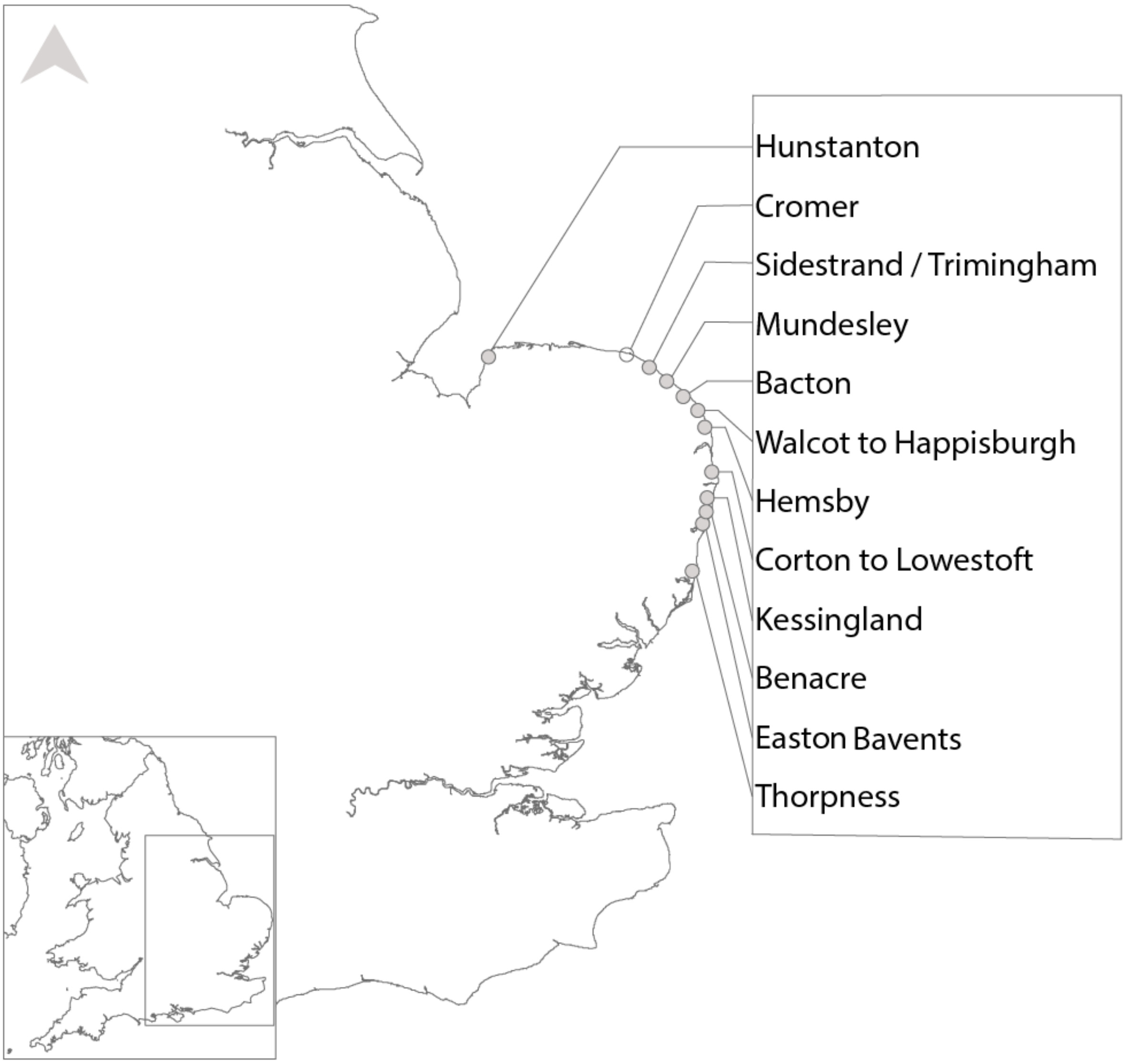

Figure 14: Location of study sites

Table 9: Case study sites

Location	Reason for Selection	Datasets Obtained (collection method and epochs)
Hunstanton North & Hunstanton South	Rapid erosion of vertical cliff faces.	Lidar:2008, 11, 12, 13, 14, 15, 16, 17 TLS: 2012, 17
Cromer	Partially defended coast. Eroding chalk cliffs fronted by sand and shingle beach.	Lidar: 2008, 11, 12, 13, 14, 15, 17, 18
Sidestrand to Trimingham	Undefended. Complex landslide, erosion, unpredictable, better information on erosion rates needed.	Lidar: 2008, 11, 12, 13, 14, 15, 17, 18 TLS: 2000, 01, 02, 03, 04, 05, 06, 07, 16
Mundesley	High water erosion trends.	Lidar: 2011, 12, 13, 14, 15, 17, 18
Bacton Gas Terminal	Eroding coast, property (critical national infrastructure) at risk.	Lidar: 2011, 12, 13, 14, 15, 17, 18
Walcot to Happisburgh	Complex landslides. Walcot - entire cliff encased in concrete. High erosion rates; partially defended; one of the few sites in the world where coastal defences have been removed and policy has shifted from 'Hold the Line' to 'Managed Retreat'.	Lidar: 2008, 09, 12, 13, 14, 15, 16, 17, 18 TLS: 2001, 02, 03, 04, 05, 06, 07, 09, 11, 16
Hemsby	Rapid erosion events resulting in houses collapsing into the sea.	Lidar: 2009, 12, 13, 15, 16, 18 MBES, Full Coverage: 2005, 11 Offshore only: 1990, 92, 93, 94, 96, 98, 99; 2000, 01, 02, 03, 04, 07, 11, 12, 13, 15
Corton to Lowestoft & Lowestoft Nearshore	Sandy coast, simple failure mechanism, rapid erosion.	Lidar: 2008, 09, 11, 12, 13, 14, 15, 16, 17 MBES: 1991, 92, 93, 94, 96, 97, 98, 99, 2000, 01, 02, 03, 04, 05, 07, 08, 09, 10, 11, 13, 15
Kessingland	High erosion rates.	Lidar: 2008, 11, 12, 13, 14, 15, 16, 17
Benacre	High erosion rates, complex processes related to migration of the 'Ness'.	Lidar: 2008, 11, 12, 13, 14, 15, 16, 17
Easton Bavents	Cliff eroding rapidly north of properties.	Lidar: 2008, 11, 12, 13, 14, 15, 16, 17
Thorpness	Defences crumbling, public hazard.	Lidar: 2008, 11, 12, 13, 14, 15, 16, 17

As with other similar contemporary studies, this study is made possible due to the extensive quantities of available open source[19] coastal datasets (Rumson and Hallett, 2018): bathymetric data was obtained from the UKHO[20]; Lidar, TLS and limited bathymetry was obtained from the EA[21]; and, TLS data was provided by BGS. From the large quantity of seabed data for the region obtained from the UKHO, only two locations had repeat bathymetry data available for multiple epochs in areas sufficiently close to the coastline to warrant inclusion

[19] Much of the Open Source data utilised has been made available to the public following a successful 2015 DEFRA initiative to place environmental datasets in the public domain (GOV.UK, 2017).
[20] Data Source: http://aws2.caris.com/ukho/mapViewer/map.action
[21] Data Source: https://data.gov.uk/publisher/environment-agency

in the subsequent analysis. These locations being in the nearshore areas close to Lowestoft and Hemsby. The horizontal coordinate system used throughout this study was OSGB 1936, and the ODN (Ordnance Datum Newlyn) vertical datum. Topographic data required no transformation, whilst bathymetric data was supplied in WGS 84 coordinates and was transformed to OSGB 1936. The main datasets used in this study were EA Lidar, for these the data acquisition dates used for each year are given within 4.4.8.1 Appendix 4.1.

4.3.1.1 Software selection

A wide range of software, tools, add-ins and toolboxes are available for GCD. In many instances, the methods selected for generating change models in previous studies are a consequence of the options within the available software packages (Hobbs et al., 2010). A common method used in many studies is GIS data analysis (Esposito et al., 2018; Jackson et al., 2012; Mitasova, 2015; Sergeev et al., 2018). Within GIS packages, tailored products are being developed. These can involve the creation of bespoke scripts, and can draw on software specific functionality such as ArcGIS Model Builder (Halls et al., 2018; Zhou and Xie, 2009) or Caris Process Designer (Foster et al., 2017). However, GIS is not suitable for point cloud comparison. It is common for C2C comparisons to involve the use of tailored scripts and task specific algorithms; many past studies have utilised Matlab for this (Kromer et al., 2017; Michoud et al., 2015; Williams et al., 2018). Examples of software used for point cloud data based GCD include Polyworks (Michoud et al., 2015), Cyclone (Corbí et al., 2018), and CloudCompare (Corbí et al., 2018; Lague et al., 2013; Leyland et al., 2017). The M3C2 algorithm developed specifically for C2C comparisons (Section 4.2.5), now comes complete with the software CloudCompare, as a plugin (“M3C2 (Plugin)”, 2018).

Although not widely utilised for this purpose, hydrographic software packages can also present opportunities for GCD analysis. A software tool produced by Teledyne Caris, termed Bathy DataBASE (BDB) has been identified as being particularly suitable, and was selected as the primary software tool utilised within this study. Caris BDB has been used previously for volumetric calculations of material removed from the seabed, such as that associated with dredging operations (Cantrill and Kruimel, 2013), and it is configured to work with a variety of terrestrial point cloud datasets and formats, in particular .laz and .las files (the format in which datasets used for this study were typically supplied). Preconfigured software functionality, such as that utilised for this study, can offer quick and efficient tools for completion of GCD. However, the software used did not provide options for including error accounting techniques within GCD calculations. Due to constraints on time and resources, and only general trends being sought, this limitation of the software functionality was deemed acceptable by the authors. However, efforts have been taken in the selection of methods within the workflow developed (Figure 15) to minimise error sources.

4.3.1.2 Software methodology

A workflow was developed in which a standardised series of operations were undertaken (Figure 15).

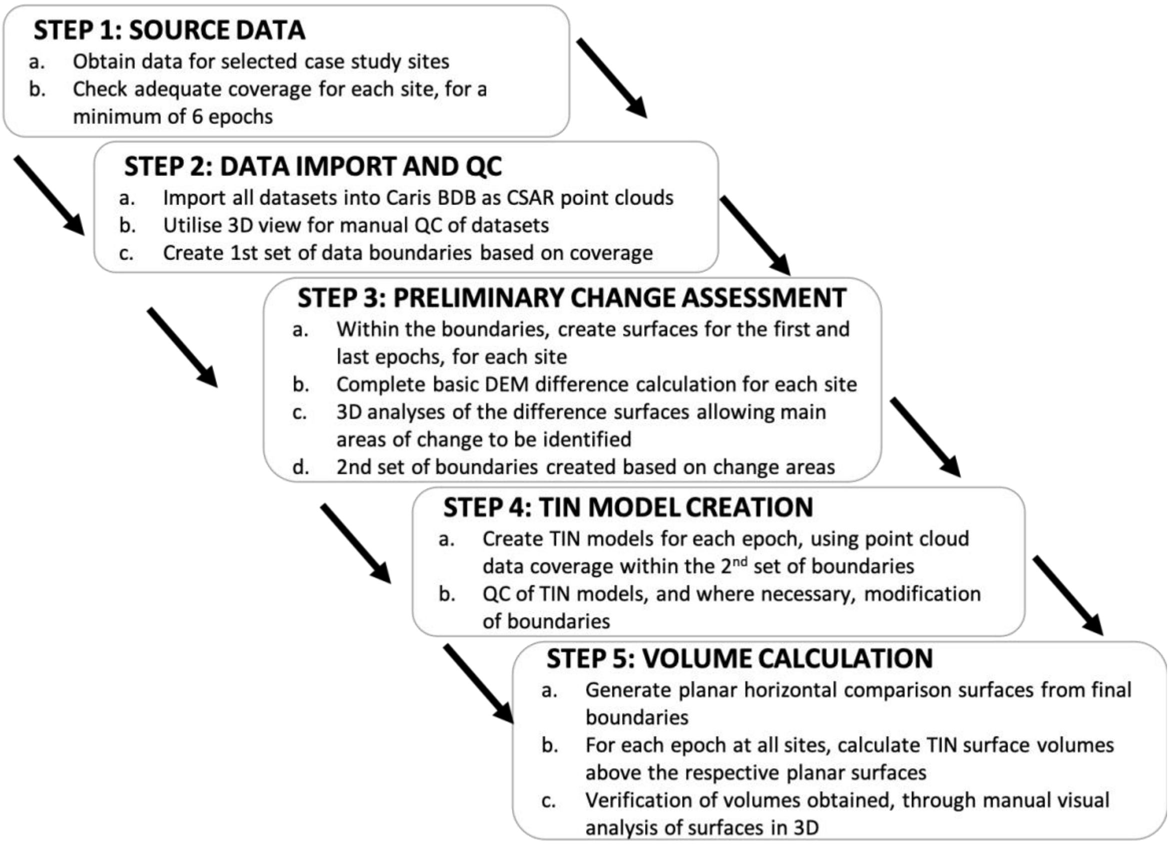

Figure 15: Software workflow for volume calculations

4.3.1.2.1 Software workflow

Step 1: Source Data

Initially, datasets covering the entire coastline of East Anglia were obtained. From this, data for the selected test sites were extracted based on the corresponding Ordnance Survey (OS) grid cells for each area. The extent of data availability varied by site and by the data acquisition method used. The minimum time period for which data was available, for any site, was 7 years and 6 epochs.

Step 2: Data import and QC

Processed point cloud data was imported as .las, .pts, .csv, or .ascii file formats. This was converted into Caris' native .csar file format, which enabled the data to be compared visually, and for its coverage to be inspected. Initially, datasets for each case study area were imported in this manner into a BDB BASE Editor project. Data varied in resolution, quality and coverage by year. Therefore, it was necessary to undertake a visual inspection of datasets available for each site, prior to deciding which datasets/epochs would be used for comparison. The 3D viewing option in BASE Editor was utilised for this (Figure 16). When areas with adequate spatial coverage and resolution were identified, a first set of boundaries were created. These were used to extract a single point cloud dataset for each selected epoch. Initially datasets derived from airborne Lidar, TLS and MBES surveys were imported. Visual analysis of the data revealed that for most TLS datasets, large data occlusions (gaps) were present, which would necessitate extensive interpolation. Also, for many of the TLS datasets, coverage was only provided for limited areas, not the entire comparison areas selected. Due to this, a decision was made not to include the TLS datasets within the volumetric change calculations, as adequate coverage and data point density was provided by the majority of Lidar datasets. Section 4.2.2 highlighted how airborne Lidar provides inadequate point density for vertical cliff faces, yet among the case study areas, only a limited number of sites contained such vertical cliffs (the most prominent being Hunstanton). Of the two sites for which bathymetric datasets were available, the only site where there was adequate quality and coverage of data, over the required number of epochs, was Lowestoft. Therefore, a nearshore site at Lowestoft was the only location for volumetric comparisons based on MBES data.

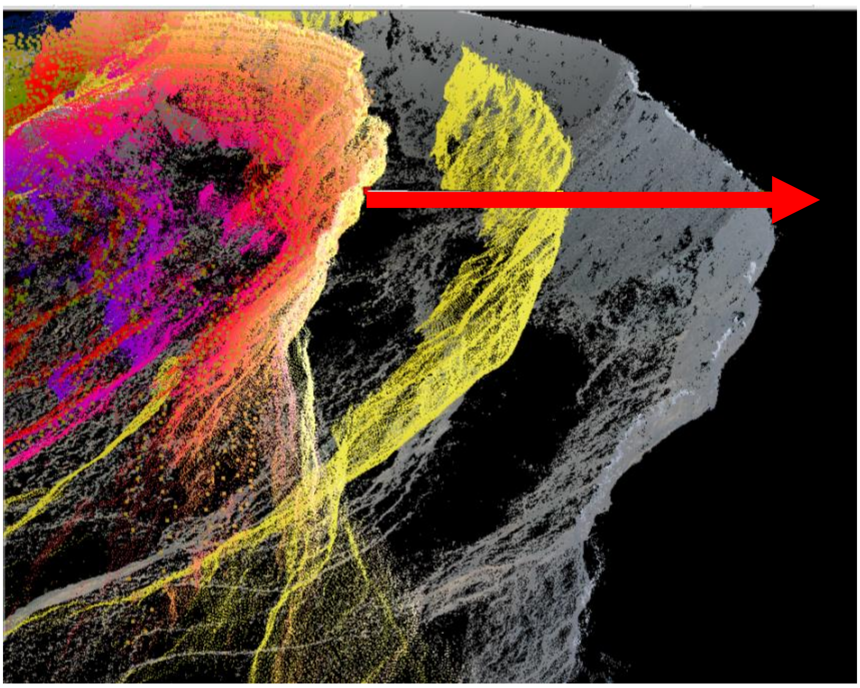

Figure 16: TLS dataset coverage/resolution comparison in BDB software, illustrating cliff retreat left to right (red arrow) for Sidestrand

Step 3: Preliminary change assessment

Using the extracted point cloud datasets, DEM surfaces were created for the first and last epoch for each site. A DEM differencing function in BDB was used to directly compare the two surfaces to generate a difference dataset. These datasets were displayed using a graduated colour schema based on elevation change, and represented change areas in 2.5D (Appendix 4.2). From this, the main areas of change and deformation could be determined. Subsequently, a second set of boundaries were created for each site, within which the main areas of change were included. Care was taken when creating boundaries to avoid including features which could generate errors in volume calculations. The resulting comparison areas formed a narrow band running along the high-water line for each site. The seaward limits of the boundaries ran as close to the coast as possible, so as to still include all areas of change identified. The reason for excluding obvious intertidal areas was that the Lidar datasets were obtained at different points within the tidal cycle for each area, so returns from the ocean surface could be misinterpreted as land and introduce errors within the calculations. The landward boundaries also did not extend far inland, past cliff edges. This minimised the inclusion of buildings, infrastructure, vegetation, and other error sources, within volume calculations. As a result, the coastline areas and lengths contained within comparison areas differ for each case study site (Table 12).

Step 4: TIN model creation
For data to be compared within the BDB software, surfaces were created using TIN models. TINs were found to be the most reliable and accurate method for surface comparison, following experimentation with other methods such as gridded raster surfaces. Additionally, working directly with TINs bypassed errors associated with the process of resampling TINs onto a regular raster grid, to create DEMs (Wheaton et al., 2010). Using point cloud data contained within the second set of boundaries, TIN models were created for each epoch at every site. The TIN models were inspected visually to identify areas where data was lacking and where large triangles with long vertices were thereby created. In some cases, this related to areas of vegetation, missing data or other errors. Where possible and necessary, boundaries were altered to remove areas where excessive interpolation had been completed, and new TIN models were subsequently created. A software function was also utilised to remove triangles with long vertices, along the outer edges of the TIN models.

Step 5: Volume Calculation
Using the Engineering Analysis Module in the BDB software, horizontal planar surfaces were created using the final boundaries for each comparison area and stored as templates (Figure 17). The BDB Triangular Volume Calculation tool was used to calculate volumes between the TIN surfaces for each epoch and the associated reference surfaces. The height of all reference surfaces, used for comparison of topographic data, was set as 2m below Mean Sea Level (MSL) with reference to ODN and for bathymetric data comparison, the reference surface height used was 10m below MSL. Prior to volume calculation a visual check was made to ensure no data points fell below the reference surfaces. Volume estimates for each epoch were stored within a spreadsheet and used to calculate volume changes between sequential epochs, resulting from surface elevation changes (Section 4.4). Once change estimates were obtained, a manual quality control process was undertaken. This involved visual inspection of surfaces associated with irregular volume changes. This enabled errors or missing coverage that might bias the change results, to be identified. In some cases, this necessitated removing datasets from comparisons for certain epochs or altering comparison area boundaries and recreating the associated TIN models. Direct comparisons between TIN models were also completed for all areas, however, the results generated proved unreliable and inconsistent, so all volume calculations were thence made in relation to a fixed planar reference surface.

4.3.1.2.2 Additional GCD Analysis Methods
The main software functionality used in this study was that allowing calculation of volumetric change. However, a number of additional analytical and visualisation features in BDB software were tested, and these assisted in analyses of the large number of datasets utilised. Simple comparisons of DEM surfaces were completed through profile or transect creation (Figure 18). Additionally, where a specific focus was required on Top of Cliff or Base of Cliff, then these were calculated roughly using an automated process, within the software, which estimates their respective positions through analysis of surface gradients. Top/Base of cliff values were then compared for two or more epochs (Figure 19). This method bypasses requirements for manual digitisation, as do other recently developed techniques (Payo et al., 2018a). Within the BDB software there is also an option to complete volume calculations

relative to a vertical or inclined reference plane. This functionality was tested and proved especially suitable to areas where vertical cliffs were present (Figure 17). However due to the heterogeneous nature of the morphology of the 14 case study sites, this method was unsuitable for adequately capturing adequately volume changes in all areas. As the main sources of data drawn upon were from airborne Lidar surveys, in which only 1 elevation point is recorded for each horizontal grid square, a 2.5D analysis method focusing on comparison of elevation changes was more appropriate. Furthermore, using the same comparison method at each site was more conducive to allowing direct comparisons of the results generated for sites across the region (such as those presented in Section 4.4).

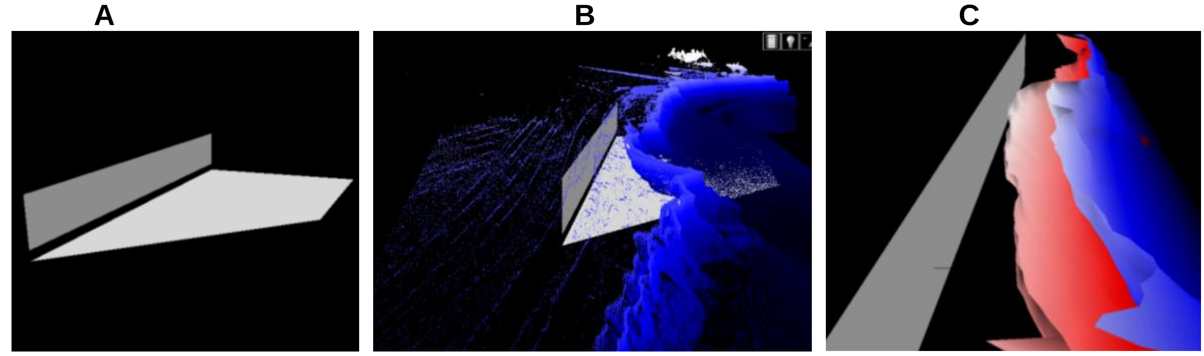

Figure 17: Planar Comparisons in Caris BDB including use of a vertical reference surface, for Happisburgh Case Study Site (A - reference surface creation; B - point cloud data for a single epoch superimposed over reference surface: C - surfaces for two epochs superimposed over a vertical reference surface).

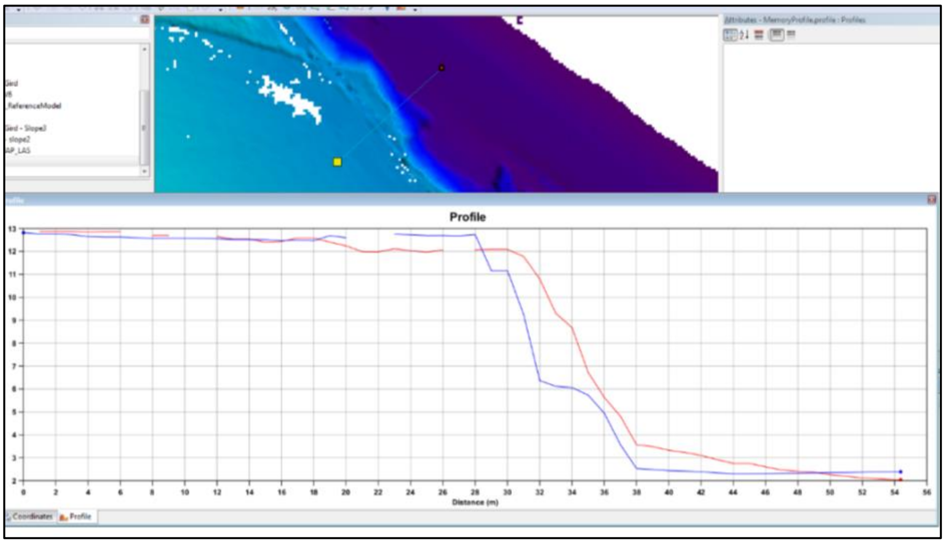

Figure 18: Profile/Transect Creation from DEM in Caris BDB

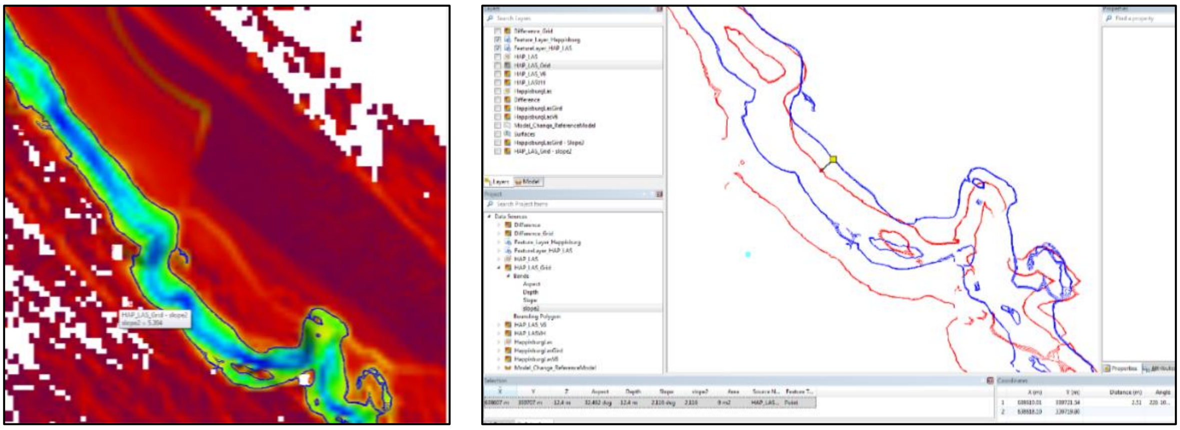

Figure 19: Top and base of cliff, change analysis in Caris BDB

4.4 Results

Surface volume estimates were generated for each epoch in which the required coverage and quality of data were available. Table 10 provides an overview of the raw results generated for each area. Cumulative change volumes obtained are presented in Table 11, with the volumes for the first epoch, at each site, listed as zero, as this represents the reference epoch. These results are represented graphically in Figure 20 and Figure 21. Results for each site are also presented individually in Appendix 4.2. This includes visual representations of the results of the initial DEM difference comparisons for each site, displayed as 2D raster images, using colours graduated by change magnitude.

Table 12 provides summary statistics for each case study area. Direct comparison between the results generated for the separate case study sites is problematic due to different lengths and areas of coastline being compared at each site, the sample period being compared, and the number of epochs used. In an effort to account for these factors, a set of summary statistics have been generated, so that comparisons can be made between the case study sites (other than cumulative net volume change). The two new statistical measures generated are labelled: ‘Average Yearly Volume Change/ metre of Coastline Sampled’, and ‘Average Height Change Across Area Sampled / Year’. Separate comparisons of change across the study sites based on these two statistics are presented in Figure 22 and Figure 23.

The raw cumulative net change results (Figure 20 and Figure 21) reveal Trimingham, Hemsby and Happisburgh as the sites experiencing the highest rates of change. However, by separately accounting for (a) length of coast, and (b) period of comparison and area of each site, the relative rates of change alter (Figure 22 and Figure 23). In both sets of statistics Easton Bavents emerges as the site with the highest rate of change, whilst when the area of each site is accounted for (b), Benacre emerges as experiencing the second highest rate of change. The change experienced at the sites, over all sample periods, generally takes the form of erosion, except at two locations, Lowestoft near shore and Hunstanton South; the possible causation of this is discussed in Section 4.5.

Table 10: Annual indicative volumes calculated for all epochs at each case study area (relative to a fixed reference plane)

Area	Volume by Year (m^3)													
	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Hunstanton North	-	-	-	193140	-	-	189203	189338	193399	186638	186981	196916	183652	-
Hunstanton South	-	-	-	138434	-	-	143976	141855	145974	148112	148862	153062	154341	-
Cromer	-	-	-	500964	-	-	505195	503427	505664	482274	482774	-	479926	-
Trimmingham	-	-	-	-	-	-	-	17902336	17848229	17610944	17577588	-	17360414	17206431
Mundesley	-	-	-	-	-	-	2345921	2352377	2340532	2298903	2302621	-	2291523	2294828
Bacton Gas Terminal	-	-	-	-	-	-	-	706013	703679	679948	686004	-	679492	679097
Happisburgh	-	-	-		1412590	-	-	1339946	1268277	1169700	1137102	1133140	1098229	
Hemsby	-	-	-		2338355	-	-	2206983	2054796	-	1979472	1992364	-	1868003
Corton to Lowestoft	-	-	-	2689242	-	-	2550845	2626298	2680332	2649146	2611697	-	2675196	-
Lowestoft Nearshore	811172	790141	814778	813311	856769	874044	861102	911558	931426	958281	980840	-	-	-
Kessingland	-	-	-	302287			299053	300549	300063	293592	291062	276659	260999	-
Benacre	-	-	-	-	-	-	504103	494043	490507	410487	405517	362777	340006	-
Easton Bavents	-	-	-	312353	-	-	308064	306538	301535	291233	262940	183715	181338	-
Thorpness	-	-	-	231833	-	-	224402	228021	219167	231502	217428	209478	174204	-

Table 11: Annual cumulative volume change for each case study area relative to a reference year

	Volume change per Year (m³)													
Area	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Hunstanton North	-	-	-	0	-	-	-3937	-3802	259	-6502	-6159	3776	-9487	-
Hunstanton South	-	-	-	0	-	-	5542	3421	7540	9678	10428	14628	15907	-
Cromer	-	-	-	0	-	-	4231	2463	4700	-18690	-18190	-	-	-21038
Sidestrand to Trimmingham	-	-	-	-	-	-	-	0	-54107	-291392	-324748	-	-541922	-695904
Mundesley	-	-	-	-	-	-	0	6456	-5388	-47018	-43300	-	-54398	-51093
Bacton Gas Terminal	-	-	-	-	-	-	-	0	-2334	-26064	-20009	-	-26521	-26916
Happisburgh	-	-	-	-	0	-	-	-72644	-144313	-242890	-275489	-279450	-314362	
Hemsby	-	-	-	-	0	-	-	-131371	-283558		-358882	-345991	-	-470352
Corton to Lowestoft	-	-	-	0		-	-138397	-62944	-8910	-40096	-77544	-	-14045	-
Lowestoft Nearshore	0	-21031	3606	2140	45598	62872	49931	100387	120254	147110	169668	-	-	-
Kessingland	-	-	-	0	-	-	-3234	-1738	-2224	-8695	-11226	-25629	-41288	-
Benacre	-	-	-	-	-	-	0	-10060	-13596	-93616	-98586	-141326	-164097	-
Easton Bavents	-	-	-	0	-	-	-4290	-5816	-10818	-21120	-49413	-128639	-131015	-
Thorpness	-	-	-	0	-	-	-7431	-3812	-12667	-331	-14405	-22355	-57630	-

Note: the first year data was available for (for each area) is taken as a reference year, and displayed as zero. The difference in volume between the reference year and that calculated for subsequent years is given for each year.

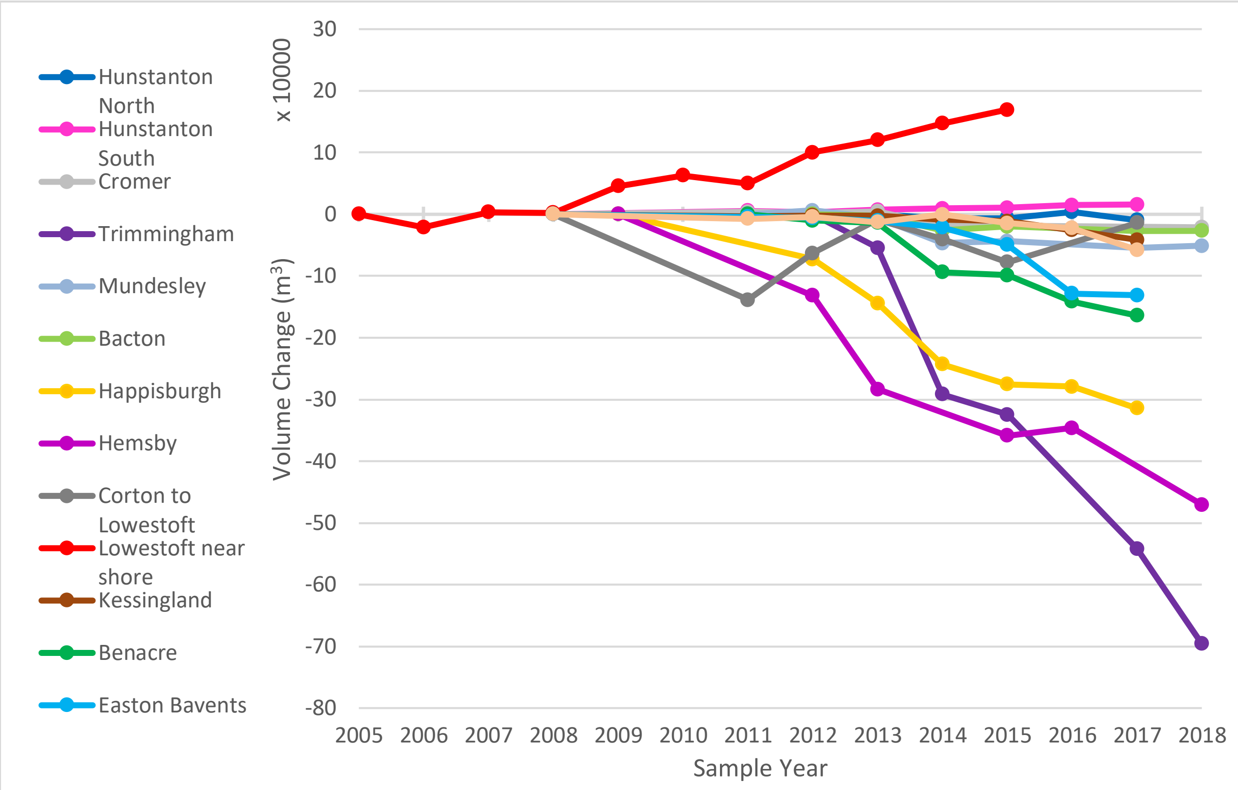

Figure 20: Cumulative net change shown for each area

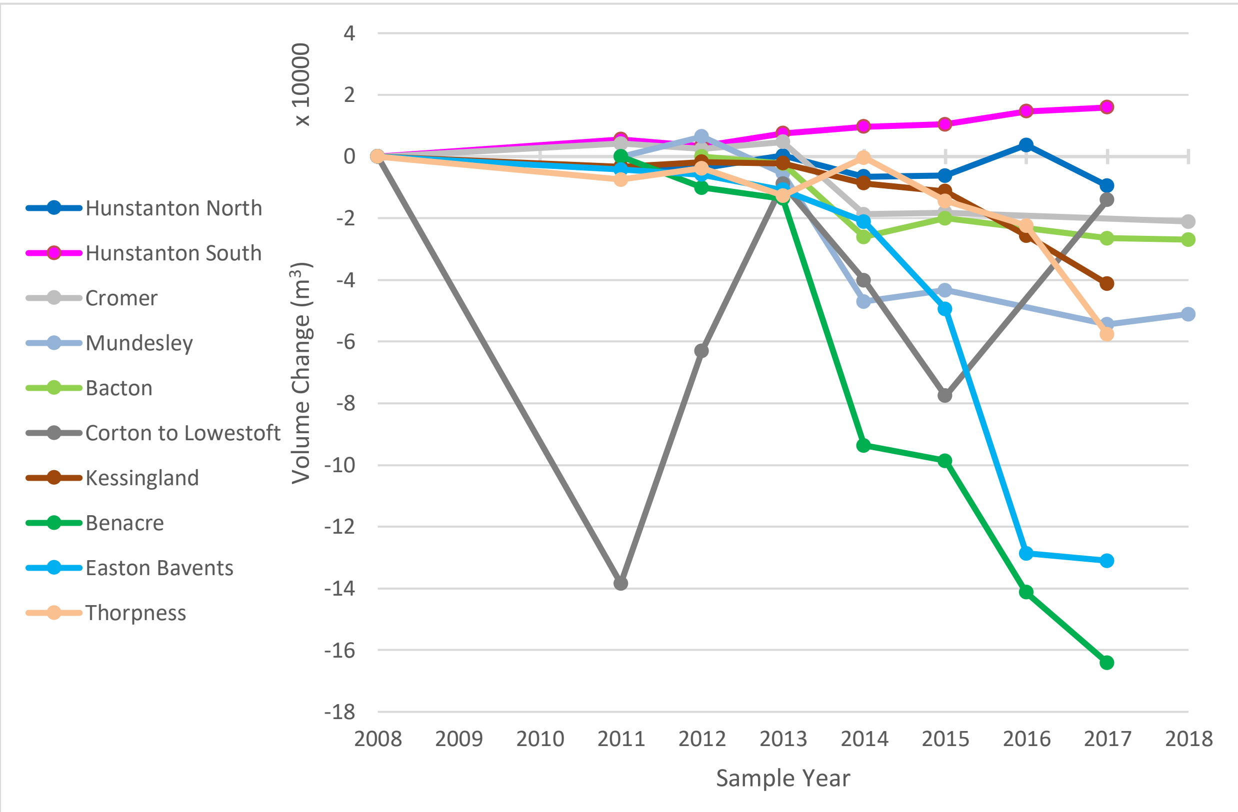

Figure 21: Cumulative net change for areas experiencing lower levels of net change (larger scale version of graph in Figure 20, excluding higher net change areas, to allow remaining profiles to be viewed in greater detail)

Table 12: Summary statistics for all case study sites

Area	Comparison / Sample Area Used		Data Sample Period				Cumulative Volume Change (m^3)	Net Erosion / Accretion	Averaged Volume Change / year	Average Yearly Volume Change / m of Coastline Sampled	Average Volume Change (per m) / year	Average Height Change Across Area	Average Height Change Across Area Sampled (m) / Year
	Area (m^2)	Length of Coast (m)	From	To	Years	Epochs							
Hunstanton North	14440	1200	2008	2017	9	8	-9487	Erosion	-1054	-7,91	-0,88	-0,66	-0,07
Hunstanton South	29594	770	2008	2017	9	8	15907	Accretion	1767	20,66	2,30	0,54	0,06
Cromer	31539	900	2008	2018	10	7	-21038	Erosion	-2104	-23,38	-2,34	-0,67	-0,07
Trimmingham	603287	4230	2012	2018	6	6	-695904	Erosion	-115984	-164,52	-27,42	-1,15	-0,19
Mundesley	222687	2570	2011	2018	7	7	-51093	Erosion	-7299	-19,88	-2,84	-0,23	-0,03
Bacton Gas Terminal	50709	1110	2012	2018	6	6	-26916	Erosion	-4486	-24,25	-4,04	-0,53	-0,09
Happisburgh	158542	2910	2009	2017	8	7	-314362	Erosion	-39295	-108,03	-13,50	-1,98	-0,25
Hemsby	265093	2340	2009	2018	9	6	-470352	Erosion	-52261	-201,01	-22,33	-1,77	-0,20
Corton to Lowestoft	196653	3280	2008	2017	9	7	-14045	Erosion	-1561	-4,28	-0,48	-0,07	-0,01
Lowestoft Nearshore	211548	660	2005	2015	10	11	169668	Accretion	16967	257,07	25,71	0,80	0,08
Kessingland	27047	650	2008	2017	9	8	-41288	Erosion	-4588	-63,52	-7,06	-1,53	-0,17
Benacre	79737	2090	2011	2017	6	7	-164097	Erosion	-27349	-78,52	-13,09	-2,06	-0,34
Easton Bavents	29208	620	2008	2017	9	8	-131015	Erosion	-14557	-211,31	-23,48	-4,49	-0,50
Thorpness	35573	640	2008	2017	9	8	-57630	Erosion	-6403	-90,05	-10,01	-1,62	-0,18

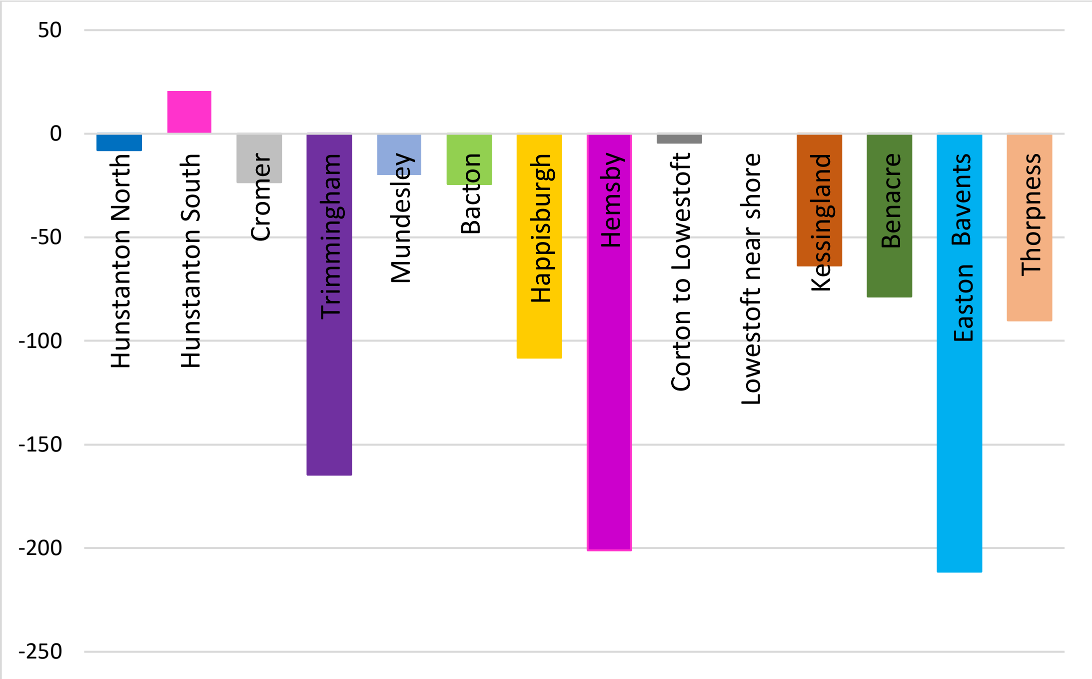

Figure 22: Mean volume change / metre of coast sampled, for each case study area

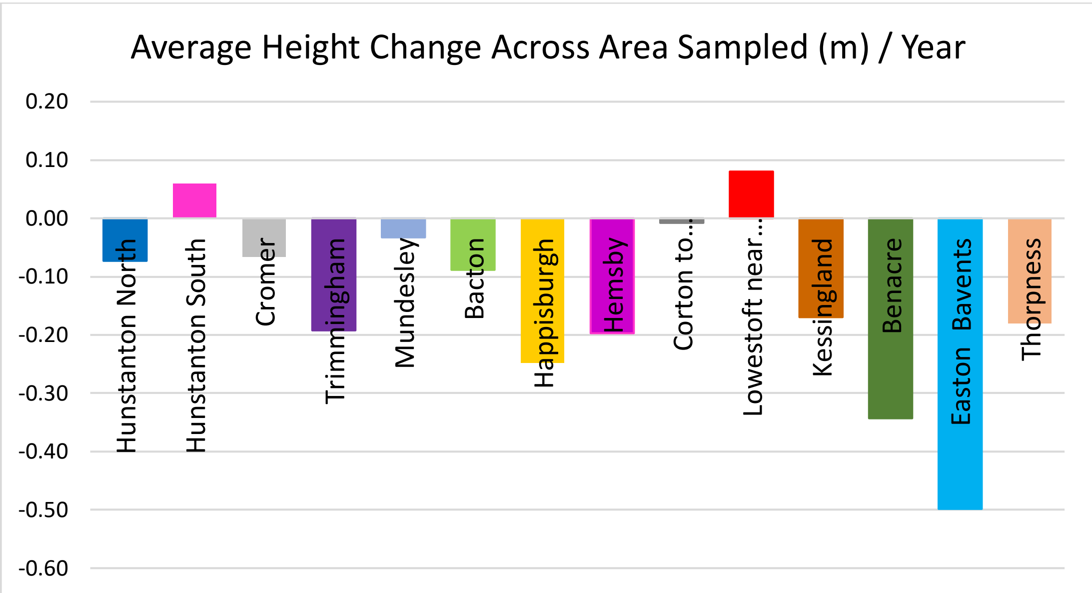

Figure 23: Mean height change across the sampled area (m / year) for each case study site

4.5 Discussion

4.5.1 GCD Method Evaluation

This study has sought to evaluate the practical suitability of a point cloud based GCD method for coastal change detection applications. In doing so the case study region of East Anglia was used, noting the approaches are of wider application. The study region benefits from an extensive archive of coastal monitoring data, much of which results from the Anglian Coastal Monitoring Programme (Environment Agency, 2016). Yet datasets available for the area have been underutilised in documented GCD studies undertaken by practitioners, and the potential benefits to coastal analysis offered by such terrain data have not been fully realised. Commonly employed methods for coastal GCD based on linear change analysis, derived from comparisons of survey data (such as that generated by topographic surveys), only incorporate a small portion of the extensive quantities of data collected for each site (which includes high resolution point cloud data). However, the volumetric change analyses, undertaken within this study has sought to incorporate all relevant and valid data points collected for a given comparison area. This enabled more comprehensive estimates of geomorphological change and deformation to be obtained, and reduces the requirement for interpolation and the associated uncertainty.

The selected GCD method used in this study, is limited to measuring change along a single vector (horizontal), yet it allows simple comparisons to be made between surface representations for different epochs at each site. This in turn enabled trends to be revealed, and comparisons to be made between sites in different locations. Application of this method seeks to address the requirements of those who need to gain a general understanding of wide-scale impacts and coastal processes. It is acknowledged that the level of detail permitted by such a technique may prove inadequate for monitoring of more granular processes (for which C2C analysis or similar techniques, using higher resolution data, may be more appropriate). Also, by limiting change analysis to measurement along a horizontal vector, the ability to accurately monitor the deformation of vertical cliff faces is greatly reduced. However, the primary purpose of applying this GCD method was not to determine linear cliff face retreat, but to estimate net volume change, allowing quantification of each case study area's sediment budget. Given this the method was deemed appropriate, and adequate given the spatial scales assessed.

Our estimates of volumetric change for each study site are indicative of levels sediment loss/gain at each location. Other studies focusing on East Anglia have generated similar results for a number of the sites we selected. We calculated the following sediment loss rates (m^3/year): Easton Bavents 14,557 (2008-2017); Benacre 27,349 (2011-2017); Thorpness 6,404 (2008-2017) (Table 12). Whilst Brooks and Spencer, (2010) focussed on a preceding time period in their study (2001-2008) and calculated sediment volumetric loss rates (m^3/year) of: Easton Bavents 16,868; Benacre 19,629. Burningham and French (2016), also completed sediment budget estimates for similar areas, and for multiple periods, one of which overlapped with that we have studied (1999-2013). They calculated the following sediment loss rates for this period (m^3/year): Easton Bavents 24,990; Thorpness 4,326. The results generated in these studies are not directly comparable with our results, given we cover a different time period, and the boundaries and shoreline lengths for each site will not be equal. However, the results are within the same order of magnitude, for each area, so this provides some assurance over the validity of our results. The methods used in these previous studies differ to what we employed, and include higher levels of interpolation, drawing on transect data, and interpretation of aerial imagery. Given this, and considering the associated issues listed in Table 8, the TIN based methodology we have used appears more robust.

The workflow developed for this study (Figure 15), involves significant levels of manual intervention and interpretation. Therefore, undertaking similar analysis on a large-scale would prove time consuming, and would be reliant on the skills of an individual operator. However, options exist to standardise and automate many of the tasks completed within the workflow by using the 'Process Designer' function in BDB or developing Python scripts to simplify and streamline processes, making execution of the workflow more efficient and reliable. The ability to work with point cloud data and surfaces in 3D was integral to the successful completion of the work. Preconfigured functionality in the BDB software, allowed rapid calculation of volumes and enabled analysis to be undertaken for the multiple sites and epochs included. Comparable functionality did not exist in other software trialled, including a number of commonly used GIS packages.

4.5.2 Data Use and Availability

The requirement for interpolation is reduced further when higher resolution datasets are used in analysis. However, there is a trade-off between data density and the scale of analysis possible. The Lidar datasets used in analyses, are on average at a 1m resolution, whilst some of the TLS data examined was under 10cm in pixel resolution. Use of higher resolution data imposes limits on the size of an area that can be analysed and was therefore deemed unsuitable given the spatial extents associated with this study. Furthermore, surface creation using TIN models was found to be problematic with large, high density datasets. For the level of detail required, the 1m Lidar data was found to be adequate to generate general trends at a wider scale. The temporal resolution of data collection was also observed as being critical in determining trends accurately. For East Anglia, the datasets available were limited to annual intervals (see 4.4.8.1 Appendix 4.1). The annual datasets proved effective for determining general trends, yet for more detailed analysis, such as studies determining causation of change, data collected over shorter intervals might be required. Also, if impacts resulting from successive high-energy events are to be compared, surveys need to be completed pre and post event. This could prove difficult though if data acquisition methods such as airborne Lidar are relied upon. However, using in situ methods such as static TLS monitoring of cliff faces (Williams et al., 2018) could provide the required temporal frequency of data. For the East Anglian datasets utilised in this study, there are examples where larger intervals are present between sequential epochs, for example, from 2008 to 2011 at Corton, from 2009 to 2012 at Hemsby, and from 2008 to 2012 at Thorpness. The only attempt at interpolation between these gaps (Figure 20 and Figure 21) is to link points by a straight line. This method, although indicative of longer-term patterns, is crude, giving no accurate indication of change within the extended interval between sample points, and if more detailed analysis was required, this interpolation could prove inadequate.

4.5.3 Evaluation of Results

This study focussed primarily on the application and evaluation of methods for GCD using point cloud datasets. Given this, the discussion does not provide extensive analysis of the significance of the results generated in relation to the local coastal management context, i.e. that relating to causation of trends, patterns, and impacts. Yet the results generated could form a valuable input to further studies focusing on such aspects. In particular, for each of the sites studied the main areas of coastal change were captured. Estimates of cumulative change over the sample periods provide some indication of the extents of net erosion or accretion occurring at each site, and furthermore, the sites contribution to local sediment cells. The stretch of coast from Sidestrand to Trimmingham stood out as experiencing the largest net loss of material and the highest rates of erosion, followed closely by Hemsby and Happisburgh. These results conform with empirical knowledge, as all 3 sites have witnessed rapid and extensive erosion over the temporal period represented in this study (Nicholls et al., 2015; Payo et al., 2018b). Yet, if the size of sample area and length of coastline for each site was considered, Easton Bavents emerged as the site experiencing the highest rates of erosion (Figure 22 and Figure 23). Again, this conforms with established knowledge, as Easton Bavents has been heavily impacted by coastal erosion and for this reason was focused on within the Coastal Change Pathfinder Programme (as was Happisburgh and Trimingham) (Defra, 2012). The emergence of Eastern Bavents as a heavily impacted area corresponds with what can be deduced from the initial DoD visual results and cross profiles generated from the TIN surfaces. These indicate large sections of coast which have eroded by over 20m laterally, at some locations, over the 9 year sample period (Figure 24). The results, presented in Figure 22 and Figure 23, should be viewed with some caution though, as for some sites, such as Kessingland, the comparison area included only a relatively small section of coast, where higher levels of erosion were concentrated, so the results were not representative of change rates across the wider area. Conversely, sites such as Corton to Lowestoft, included a longer stretch of coastline, in which areas of change were more widely dispersed.

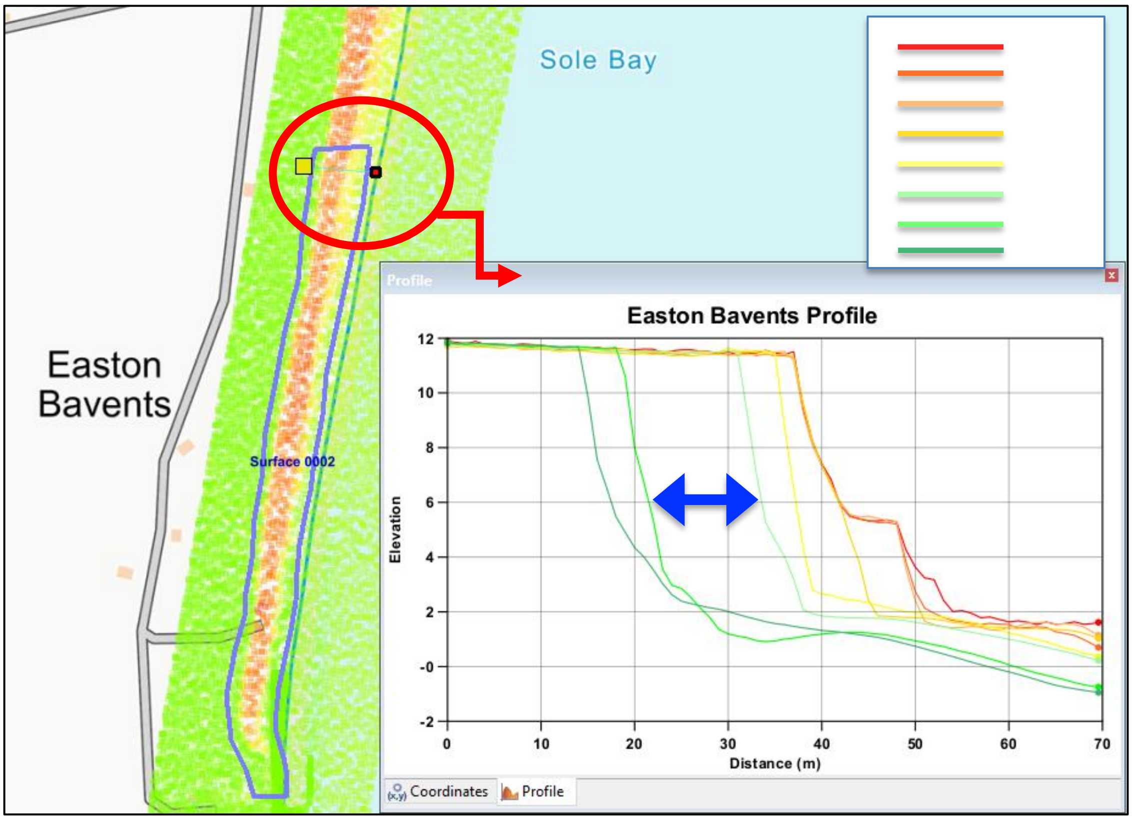

Figure 24: 2D Profile of Easton Bavents TIN surfaces from 2008 – 2017, showing over 20m horizontal cliff recession. The plan view image represents areas of accretion/erosion using a graduated colour scheme, with areas of higher erosion coloured red and stable areas green. Profiles generated for sequential years are assigned separate colours, detailed in a legend (not correlated with the plan view), these range from 2008 shown in red through to 2017 displayed as a green line. A blue arrow indicates a period between 2015-2016 where higher rates of erosion were experienced.

Net erosion was experienced at twelve of the case study sites during the period studied, yet the extent of this varied considerably, with locations such as Bacton, Mundesley, Thorpness, and Hunstanton North experiencing lower levels of cumulative material loss. However, in the period between Lidar Surveys being completed in late September 2016 and November/December 2017, Thorpness experienced a dramatic increase in erosion rates (Figure 21 and Appendix 4.2). The quantity of material removed from the Thorpness case study area (35,275m^3), in this period of just over one year, was over 150% of that removed in the preceding eight years (22,355m^3). This observation ties in with media coverage focusing on the area during that period, where in January 2017, dramatic erosion events and a subsequent cliff collapse resulted in loss of life (BBC, 2017). One site which doesn't conform with the general trend of erosion is Hunstanton South, where our results indicate net accreation. In terms of spatial orientation, this site is noticibly unique in that its coastline is west facing. Here, partial protection is provided from the full force of the North Sea by The Wash.The stretch of coastline between Corton and Lowestoft also stood out due to it fluctuating between states of net erosion and accretion. This case draws attention to how the net volume change figures obtained for the entire sample period (such as generated in the initial DoD calculations) can be misleading, and consideration of changes across all epochs sampled is necessary to gain a more complete understanding of actual trends.

The one site for which nearshore bathymetry was analysed (Lowestoft) showed a net accumulation of sediment in the area. The coastline adjacent to this section of seabed is heavily defended by concrete structures, indicating that sediment eroded from locations further along the coast, or discharged from Lake Lothing, is being deposited in this location. This case also demonstrates clearly the need to consider both visual representations of change, in addition to quantitative assessments. The visualisation generated from the initial DEM of difference calculation (Figure 25) reveals an uneven distribution of change across the site. To the east a deepening channel has emerged, in which an elevation reduction of up to 4.6m has been observed, whilst to the south west of the area, elevation increases of up to 2.6m are present. The deepening channel does not appear to align with known dredging activity in the area, or with documented shipping channels and approaches (VisitMyHarbour.com, 2019), therefore it could be attributed to local coastal processes.

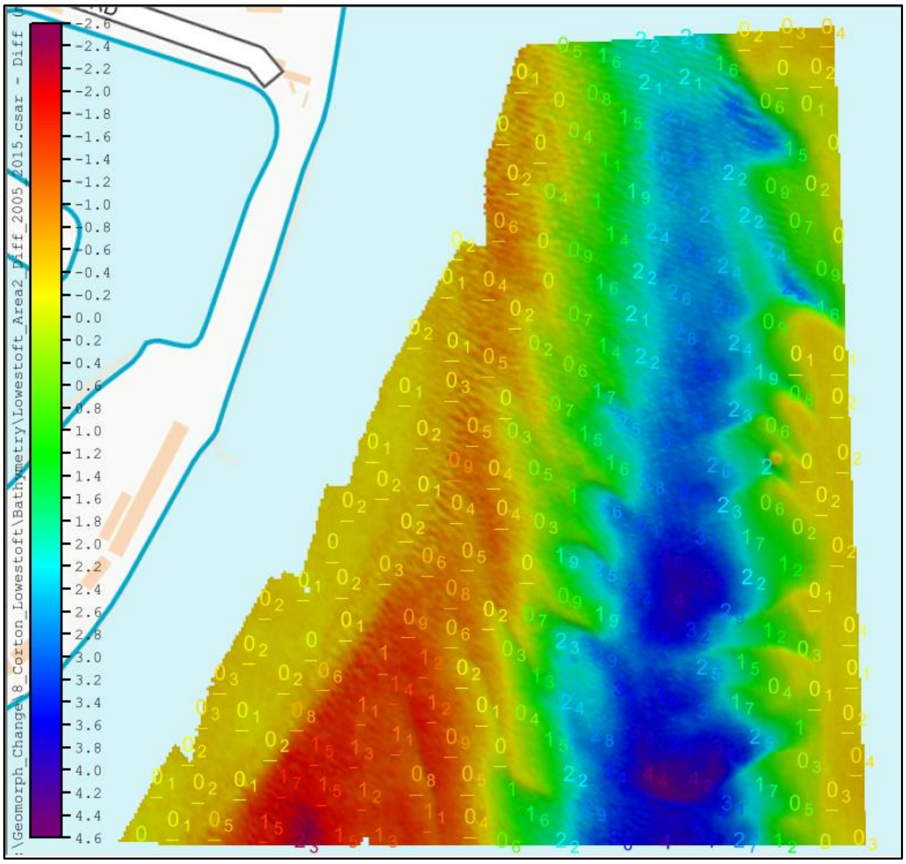

Figure 25: DEM difference surface for Lowestoft representing a comparison of data collected between 2005 and 2015. Change is displayed numerically and via a graduated colour scheme. All changes are given in metres, with areas of accretion assigned negative values, and are coloured orange/red. Numbers depicting spot change values are superimposed over the respective areas.

4.5.3.1 The 2013 East Coast Storm Surge

The most significant hazard event which impacted the case study region, during the period focussed on in this study was the 2013 East Coast Storm Surge (Environment Agency, 2016). This event took place between on 5-6 December 2013, and resulted in the highest still water levels on record being observed at many sites across the region (Spencer et al., 2015). The dates of acquisition of the Lidar data used in this study (Table 13) indicate that all 2013 datasets were collected prior to this event. Most datasets were acquired shortly before it, in October 2013, however subsequent surveys for most areas were not completed until October or November 2014. Given this, estimates of change for each area, between 2013-14, would not represent the immediate impacts of the event. The 10-11 month gap, post event (prior to resurvey), would have allowed time for sediment to be redistributed in each area. Notwithstanding this, a number of observations were made in relation to results for the period. The most prominent sharp increases in erosion, which could be attributed to this event, were witnessed at Cromer, Mundesley, Bacton Gas Terminal, and Benacre (Appendix 4.2). The shift in the rate of lateral erosion during the period between 2013 and 2014 is clearly evident in the shoreline profile for Benacre, displayed in Figure 26. A noticable difference in the volume change rate between 2013 and 2014, was not visible in the results for a number of sites. There are many possible explanations for this. One could be that coastal change on some stretches of coastline, was heavily influenced by rainfall-induced landslides, in addition to coastal processes. Another could be, that the surge redistributed sediment within the boundaries of a study area (during the interving period between surveys), resulting in minimal change to the net volume of material observed.

The 2013 storm surge is just one high energy event which can be linked to the results for selected sites within this study. Closer inspection of the change estimates generated, especially the cumulative change profiles for individual sites (Appendix 4.2), may reveal additional trends for which causation and correlation with events could be determined. For example, examination of successive coastal profiles for Easton Bavents (Figure 24) indicates a significant increse in the rate of cliff recession in the period between November 2015 and October 2016.

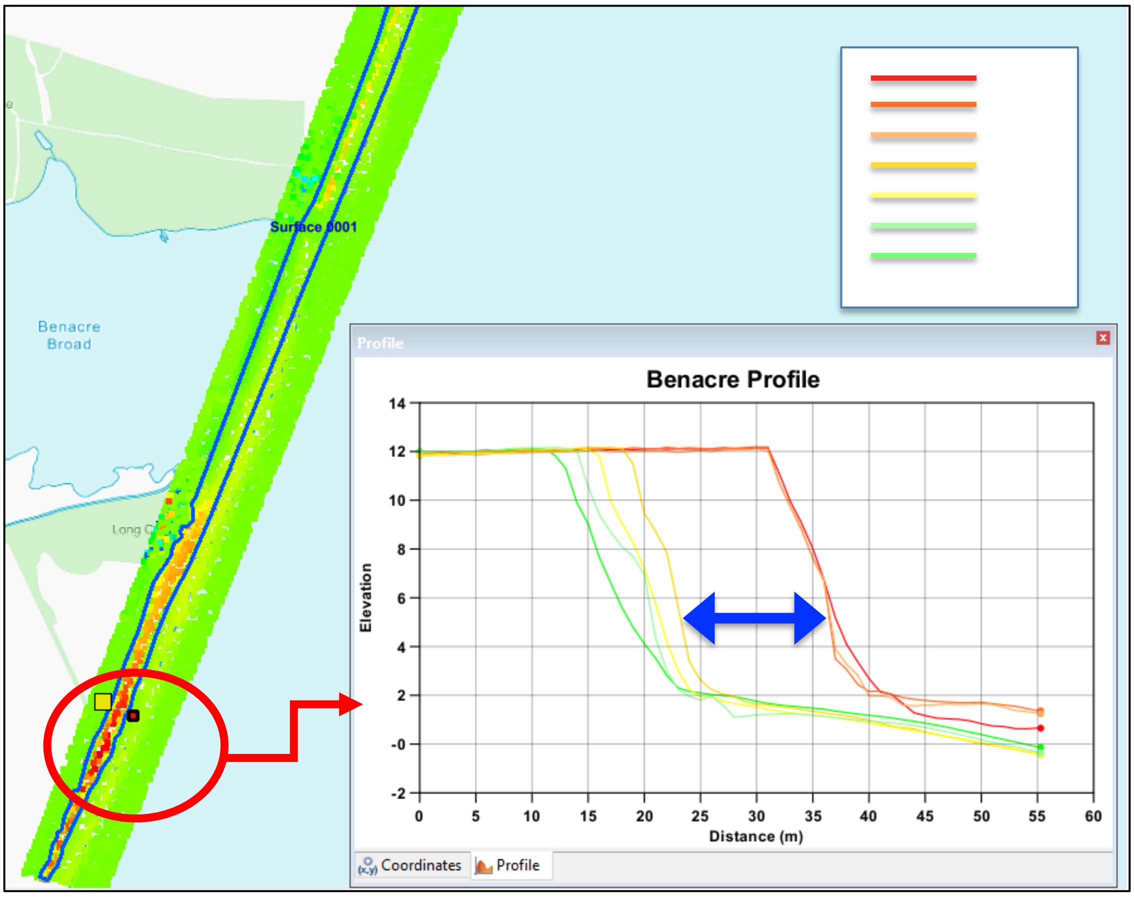

Figure 26: 2D Profile of Benacre TIN surfaces from 2011 – 2017, showing approximately 20m horizontal cliff recession. The plan view image represents areas of accretion/erosion using a graduated colour scheme, with areas of higher erosion coloured red and stable areas green. Profiles generated for sequential years are assigned separate colours, detailed in a legend (not correlated with the plan view), these range from 2011 shown in red through to 2017 displayed as a green line. A blue arrow indicates a period between 2013-2014 where higher rates of erosion were experienced.

4.5.4 Limitations

The GCD undertaken within this study is primarily based on volume calculations founded on elevation changes. Of the available methods this was deemed by the authors, the most suitable for analysis of such a wide range of datasets, yet there are limitations imposed by this method. Prominent among these is the inability to account for redistribution of cliff or beach material within the boundaries of a comparison area. Such changes could be better identified from the visual representations generated from the DoD surfaces i.e. Figure 25, or in 2D profiles (Figure 24 and Figure 26), yet they were inadequately represented in the quantitative change estimates. For example, where a cliff face has eroded, the eroded material typically accumulates at the toe of the cliff, or is deposited further along the beach. This volume of accreted material would partially offset the volume of eroded material caputured for the whole comparison area. Given this, processes operating in the area would not be fully captured within a single quantitative volume change estimate. If the results of GCD analyses were required to enable more precise impacts at specific locations and dates to be determined, then a more general overview method, could obscure important details, thus proving inadequate. A partial solution to this issue could be to isolate material change calculations to limited spatial extents such as a cliff face alone, thereby excluding beach sediment yields. Also, through combining qualitative visual representations of change, generated through DoD calculations, and the quantitative volumetric change results generated by TIN-differencing, more comprehensive change analysis is permitted.

Another limitation which needs to be noted for this study relates to error accounting. The technique we selected for undertaking GCD calculations was based on preconfigured functionality within commercial software. This limited our ability to directly account for errors and uncertainties, and placed a heavy burden on manual quality control. This proved time consuming and imposed caveats on the reliability of the results produced. For the purposes of this study, this method was deemed adequate, as the results produced are only intended to give indications of general trends. Yet it should be noted that any future attempts to implement a similar methodology should look to options for implementing more systematic and robust error accounting techniques, such as those outlined by Wheaton et al. (2010), or options allowing levels of significance to be assigned to calculated changes (Leyland et al., 2017).

4.6 Conclusions

This study presents a critical evaluation of GCD methods based on analysis of point cloud datasets for coastal and nearshore areas, involving the use of Lidar, TLS and MBES datasets. The results provide quantitative estimates of geomorphological impacts, which can be attributed to coastal processes operating across the case study region of East Anglia. 14 case study sites were included in the study, representing differing coastal geologies, morphologies, levels of hazard exposure, and types of adaptive measures in place. Cumulative change results were generated for each study site, revealing the temporal and spatial distribution of coastal erosion and accretion trends. The results presented indicate the suitability of the selected GCD methods, revealing how comparative statistics and visualisations can be generated through creation and analysis of DEMs or TIN surfaces. We also note how advances in both data acquisition and processing technology allow high spatial and temporal resolution morphological data to be combined within coastal change analyses. This can reduce uncertainty, through reducing the requirements for interpolation, which are commonplace in many traditional and in-use techniques, which demand higher levels of manual interpretation.

The methods employed, and the workflows developed, are suited to more general implementation, offering analysis at wider spatial scales. The main analysis undertaken related to cumulative volumetric change, taking place within defined case study sites. The creation of surfaces using TIN models, and volume calculations relative to a horizontal plane, proved adequate in providing quantitative estimates of each site's sediment budget. Site-specific factors influenced selection of this method; the East Anglian coast is predominantly comprised of low gradient soft cliffs, so it was possible to use a volumetric change method based on surface creation from Lidar data. However, the authors acknowledge that such analytical approaches are not optimal for estimating other types of change, i.e. linear coastline retreat. In cases where higher levels of detail and granularity are required, or where there is a requirement to precisely identify cliff edges or individual rockfall events, it may be preferable to utilise GCD methods that base calculations of change on individual data points, rather than on interpolated surfaces. The software utilised within this study also lacked functionality allowing systematic errors and uncertainties to be accounted for. Future analysis would benefit from incorporation of explicit methods accounting for spatially variable uncertainties.

The majority of datasets drawn on within this study are open source and so can be obtained with ease. The study benefitted from the required data being available for the sites selected. However, data availability, acquisition method, and frequency of collection, varies considerably depending on location. As such, these factors should be considered in any future selection of an appropriate GCD method. For the GCD method we used, the main software employed was Caris BDB, which is proprietary. However, the workflow developed involves standardised processes, such as TIN model creation and comparison, so could potentially be recreated using alternative means. One clear drawback of the method employed, is the requirement for manual intervention/interpretation. The workflow developed (Figure 15), is reliant on operator skills, and their ability to distinguish potential error sources within datasets, that need to be excluded from calculations (such as vegetation, the ocean surface, buildings, and areas of insufficient data coverage). This places limits on the ability to reproduce the results and reapply the methodology. The next logical step, following on from this work, would therefore be standardisation and automation of the operations detailed as making up our workflow. This could increase the reliability of results generated, and reduce the skills and time required for data analysis. In this study we have provided the basis of such future advances, through revealing the practical suitability of a point cloud based GCD method, for increasing understanding of morphological changes taking place on selected stretches of coastline. This reveals how more effective utilisation of a new generation of high-resolution point cloud datasets, can lead to implementation of more robust and sustainable coastal management practices.

4.7 Acknowledgements

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4.8 Appendices

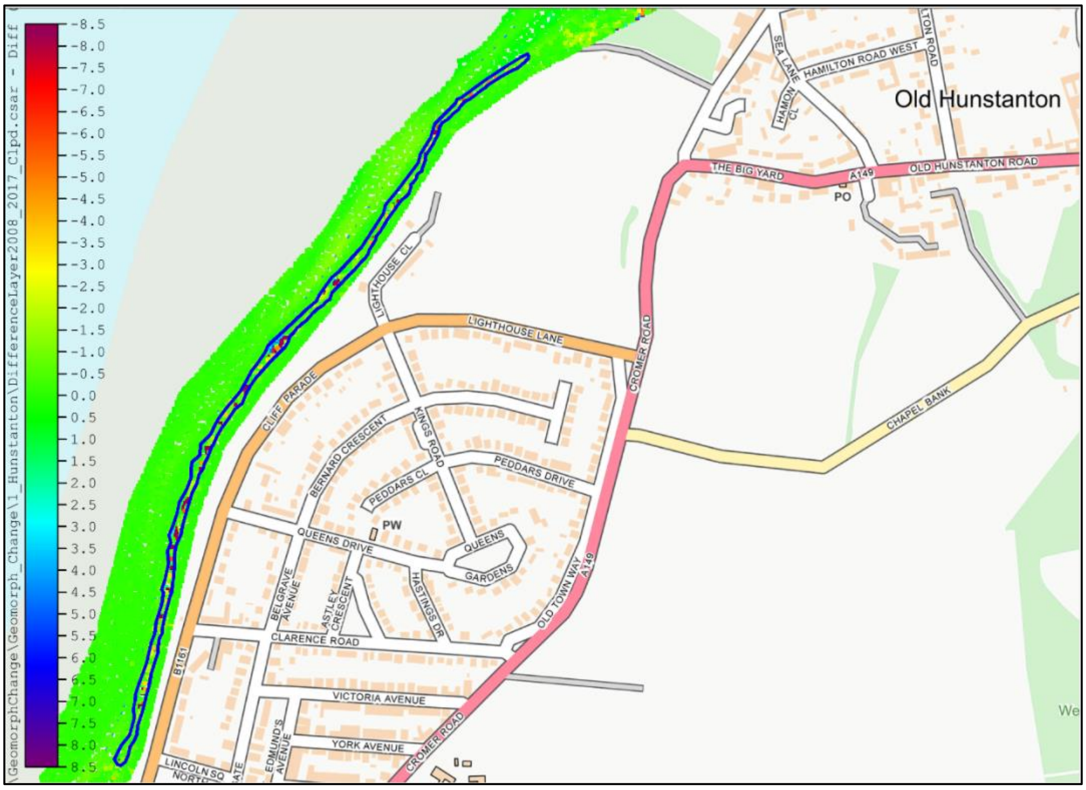
4.8.1 Appendix 4.1 Survey Data Collection Dates

Table 13: Lidar Survey Collection Dates. For each year the dates on which datasets were acquired are given in the format of day/month for the respective years.

Area	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Hunstanton North & South	20/05 17/06 09/07	-	-	04/05 26/10	26/05 27/05 13/11	03/10	27/02 28/02 09/11	05/03 07/03 11-12/11	02/11	07/11	- -
Cromer	27/02	-	-	23/11 26/11	12/11 15/11	05/10	28/10 24/11	11/11	-	28/01; 30/03; 06/11	-
Trimmingham	-	-	-	-	15/11	05/10	24/11	11/11	-	28/01	08/01
Mundesley	-	-	-	08/02	15/11	05/10	24/11	11/11	-	28/01	08/01
Bacton Gas Terminal	-	-	-	-	15/11	05/10	24/11	27/02; 11/11; 23/11	-	28/01	08/01
Happisburgh		18/01 20/01	-	-	15/11	01/04; 06/04; 05/10	24/11	11/11 23/11	27/10	28/01 05/11	
Hemsby		11/01 24/01	-	-	11/11 12/11	01/04; 06/04; 05/10	-	20/01; 27/02; 23/11	27/10	-	08/01
Corton to Lowestoft	29/06	-	-	23/11	11/11	03/10	27/10	14/01; 16/01; 23/11	-	04/11 05/11	-
Lowestoft N/S	NA	NA	NA	NA	NA	NA	NA	NA	-	-	-
Kessingland	23/05 29/06			23/11	11/11 18/11	03/10 06/10	27/10	14/01 16/01	27/10 11/11	27/10; 05/11; 02/12	-
Benacre	-	-	-	23/11	11/11 18/11	03/10 06/10	27/10 06/11	23/11	27/10 11/11	05/11 02/12	-
Easton Bavents	23/05	-	-	23/11	11/11; 18/11	03/10; 06/10	27/10 06/11	23/11	27/10 11/11	05/11 02/12	-
Thorpness	07/02 16/06	-	-	23/11	19/11	06/10	27/10	23/11	30/09	05/11 02/12	-

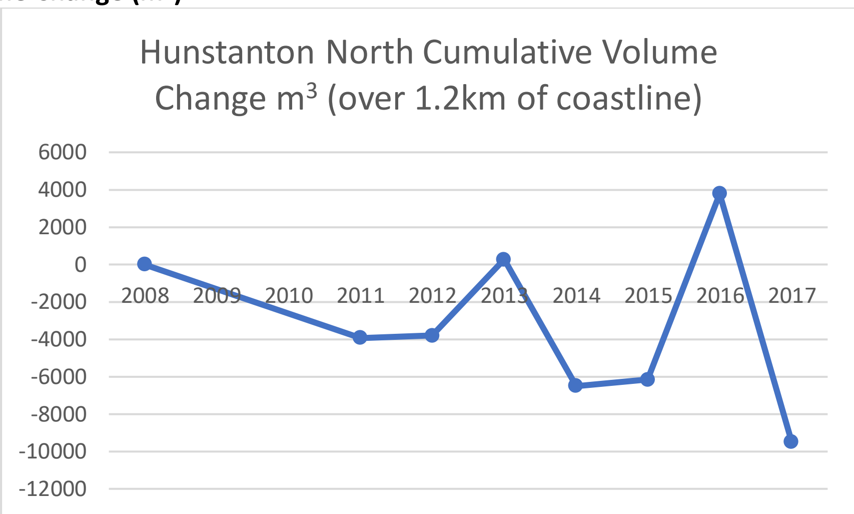
4.8.2 Appendix 4.2 case study site results

4.8.2.1 Case Study Site 1: Hunstanton North

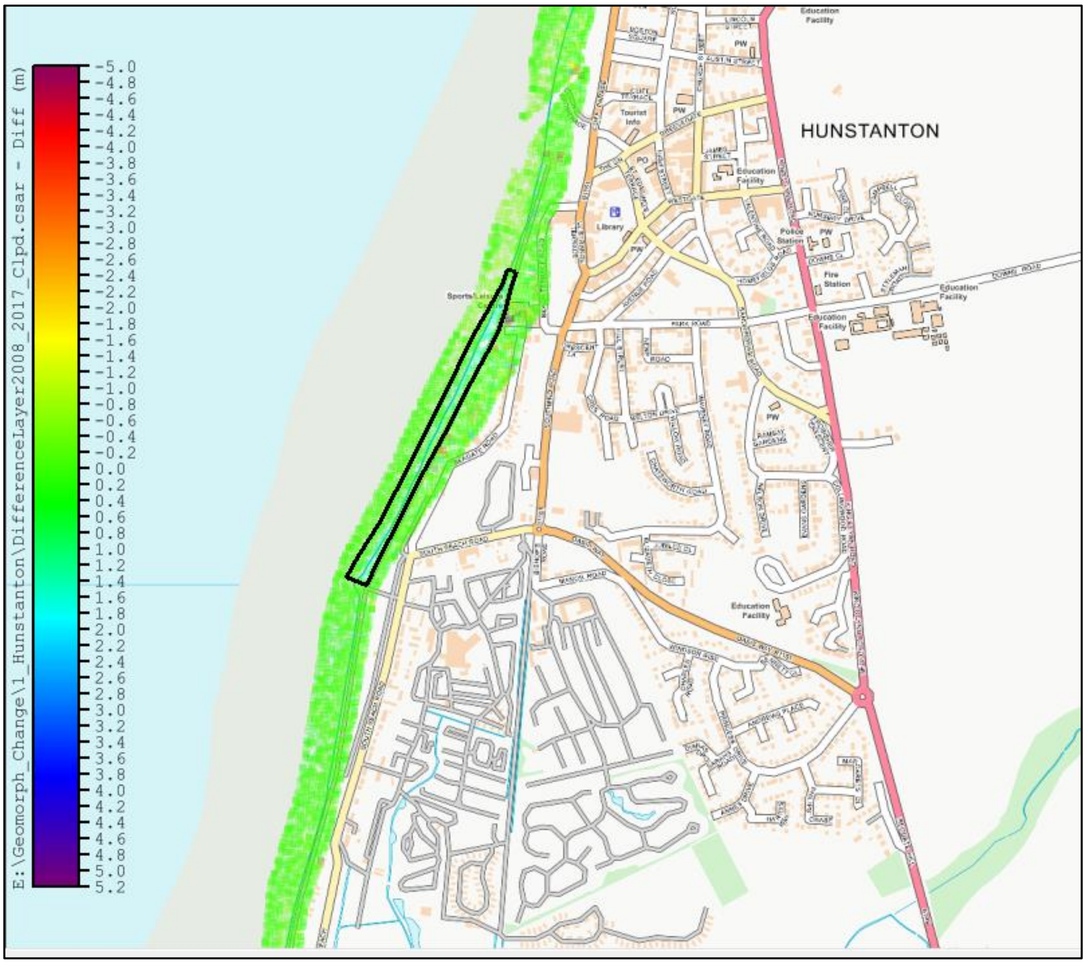


Cumulative Volume Change (m³)

2008	0
2009	-
2010	-
2011	-3937
2012	-3802
2013	259
2014	-6502
2015	-6159
2016	3776
2017	-9487

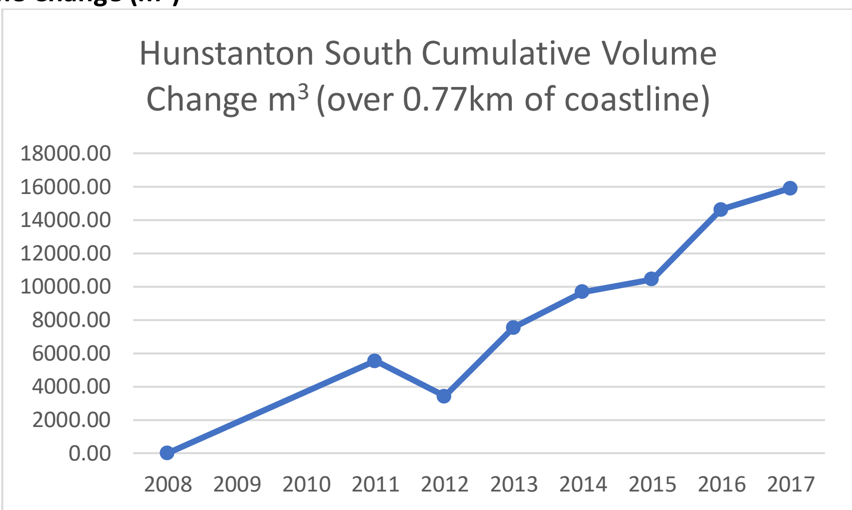


4.8.2.2 Case Study Site 2: Hunstanton South

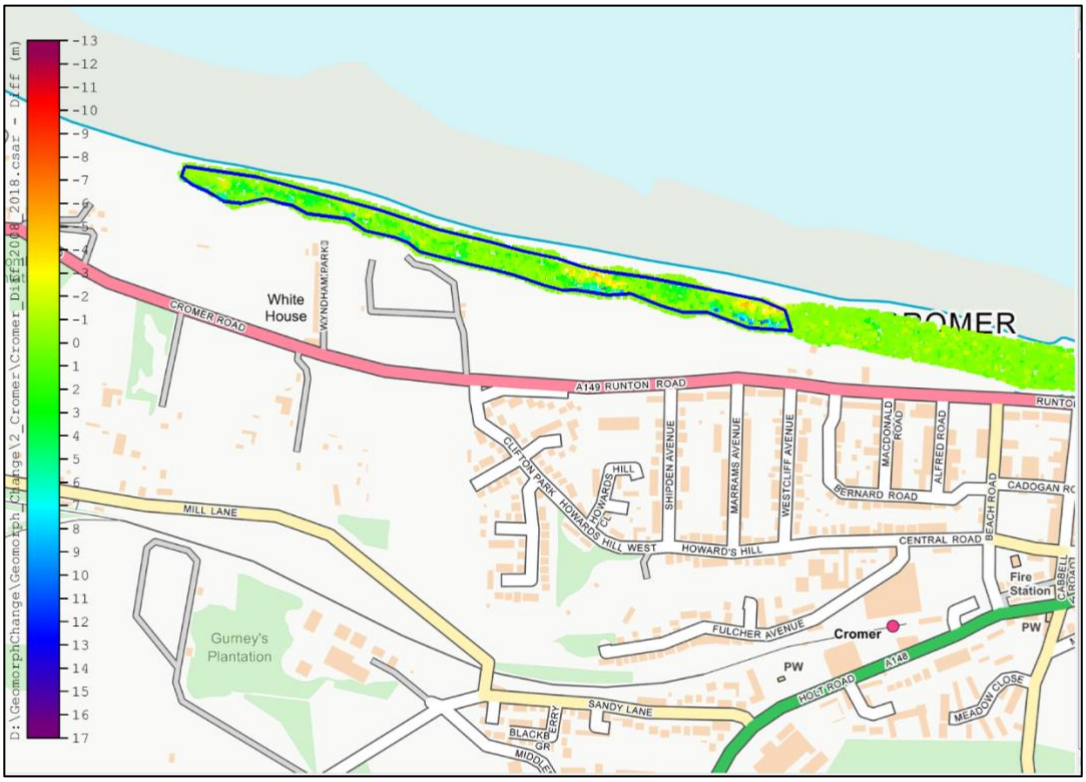


Cumulative Volume Change (m^3)

2008	0,00
2009	-
2010	-
2011	5542
2012	3421
2013	7540
2014	9678
2015	10428
2016	14628
2017	15907

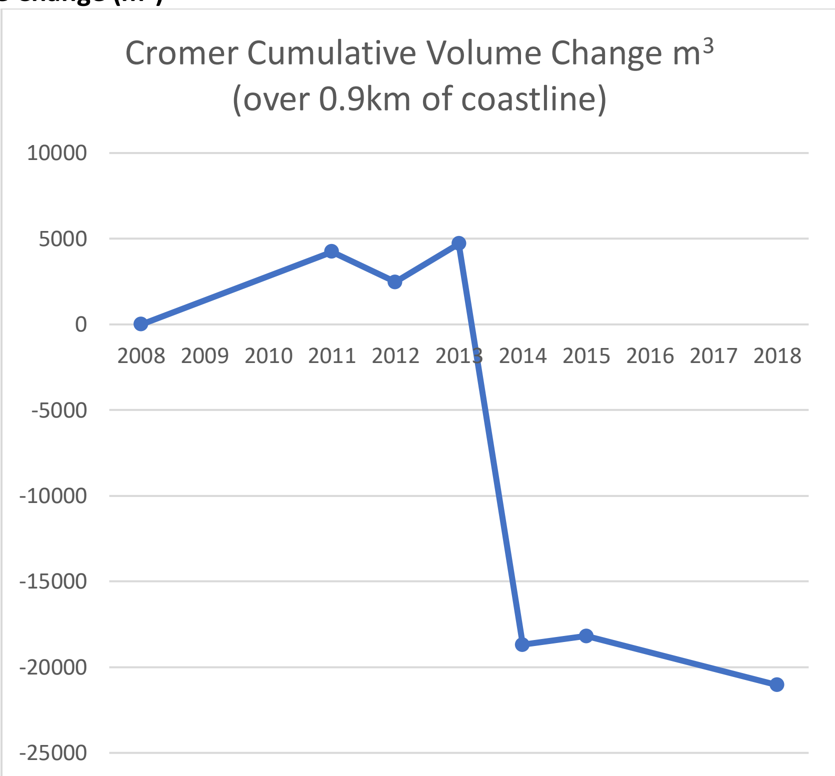


4.8.2.3 Case Study Site 3: Cromer

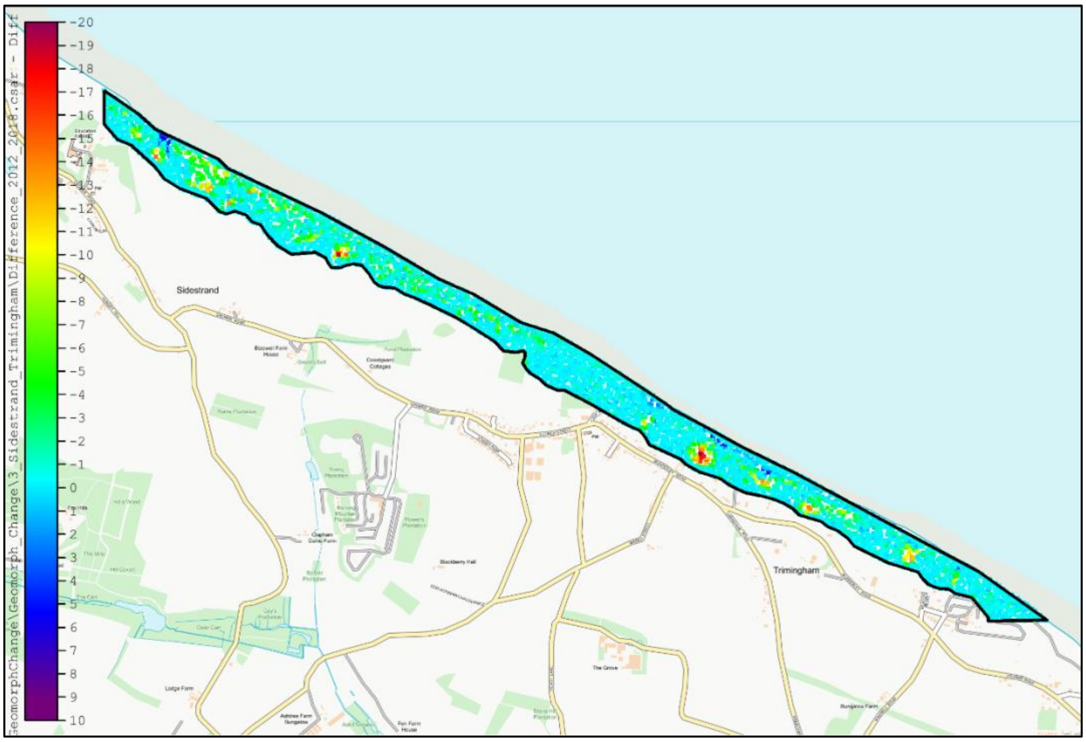


Cumulative Volume Change (m³)

2008	0
2009	-
2010	-
2011	4231
2012	2463
2013	4700
2014	-18690
2015	-18190
2016	-
2017	-
2018	-21038

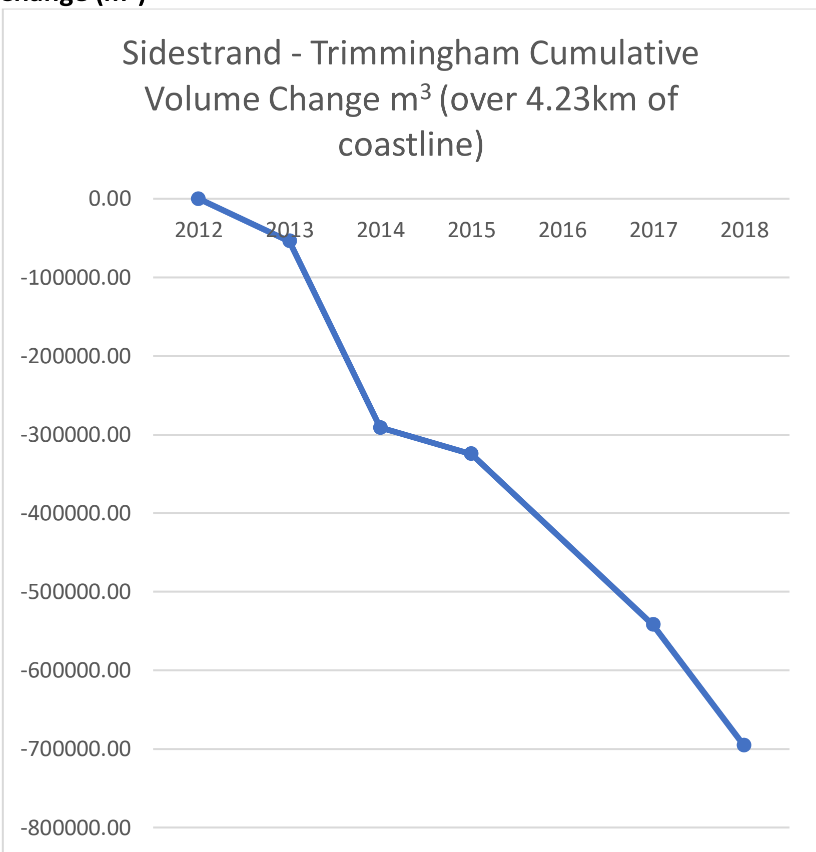


4.8.2.4 Case Study Site 4: Sidestrand/Trimingham

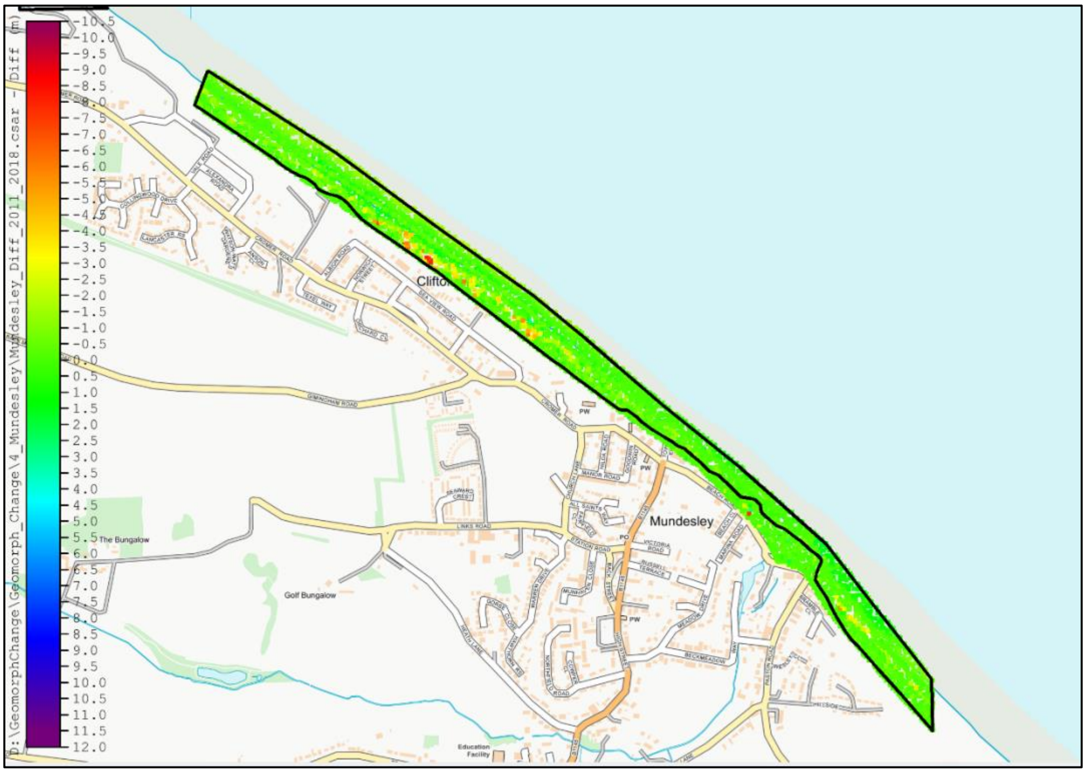


Cumulative Volume Change (m^3)

2012	0
2013	-54107
2014	-291392
2015	-324748
2016	-
2017	-541922
2018	-695904

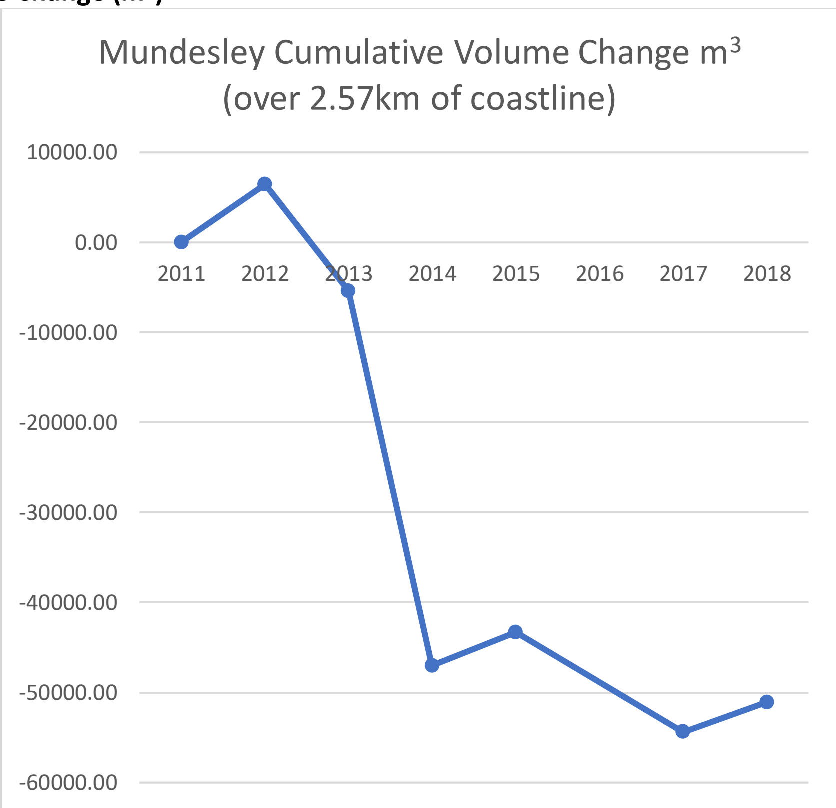


4.8.2.5 Case Study Site 5: Mundesley



Cumulative Volume Change (m³)

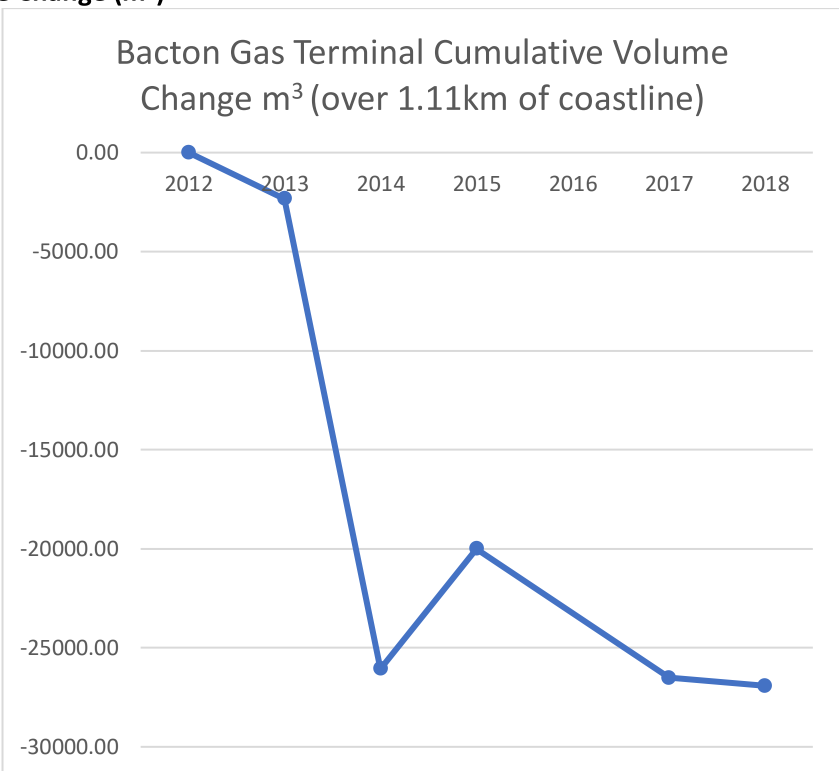
2011	0
2012	6456
2013	-5388
2014	-47018
2015	-43300
2016	-
2017	-54398
2018	-51093



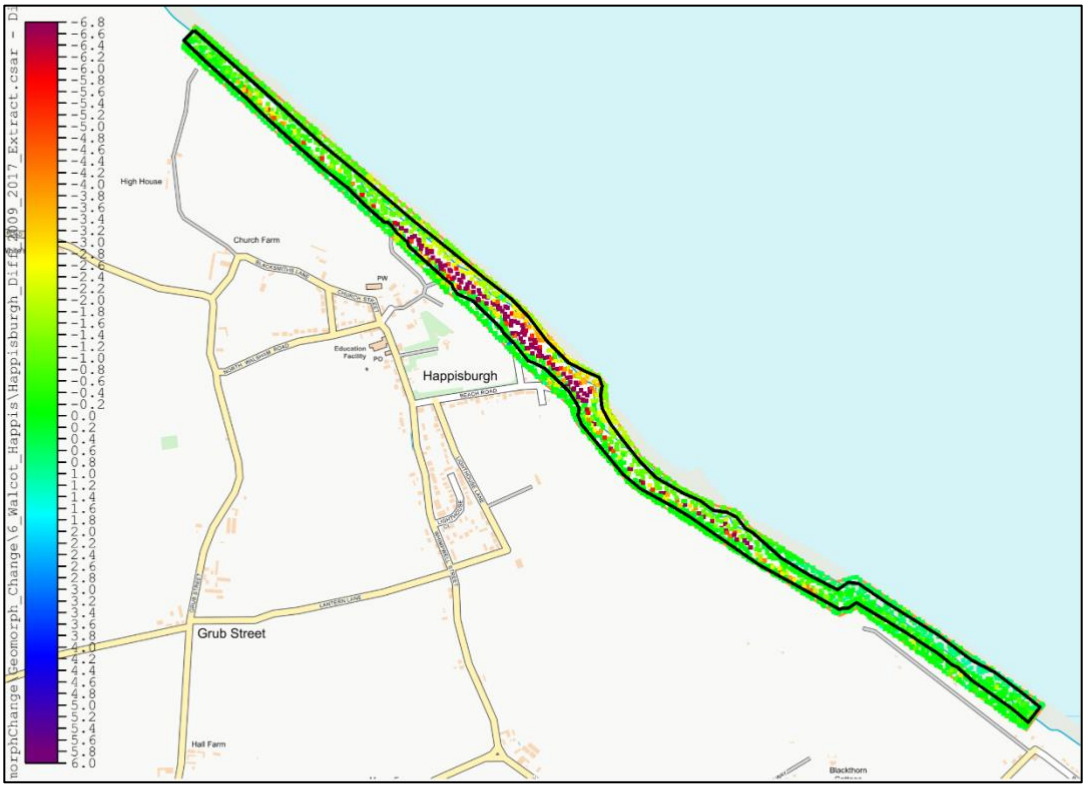
4.8.2.6 Case Study Site 6: Bacton Gas Terminal

Cumulative Volume Change (m^3)

2012	0
2013	-2334
2014	-26064
2015	-20009
2016	-
2017	-26521
2018	-26916

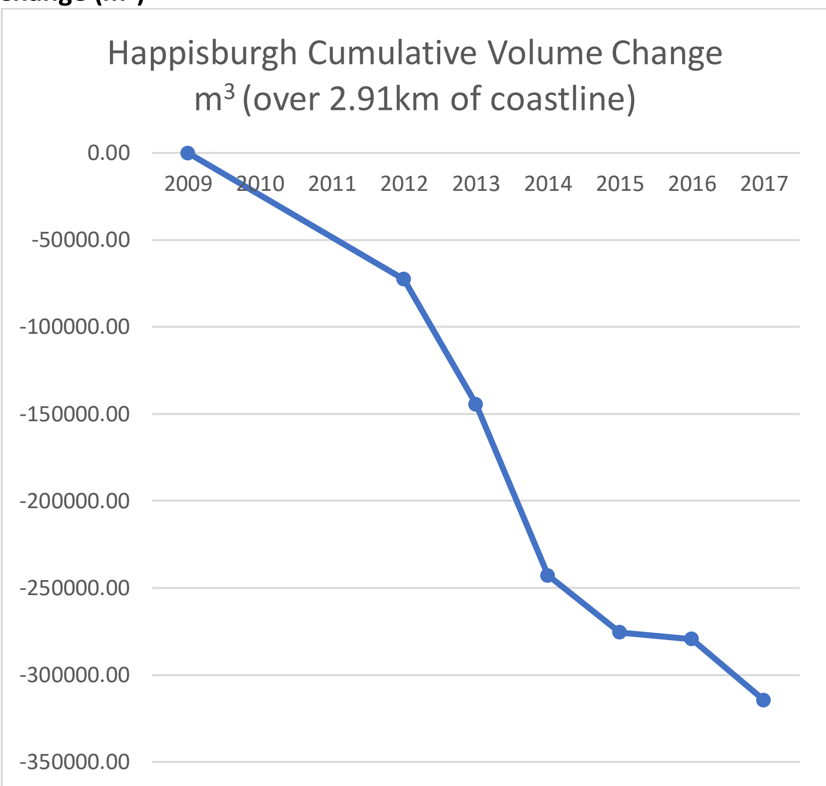


4.8.2.7 Case Study Site 7: Walcot to Happisburgh

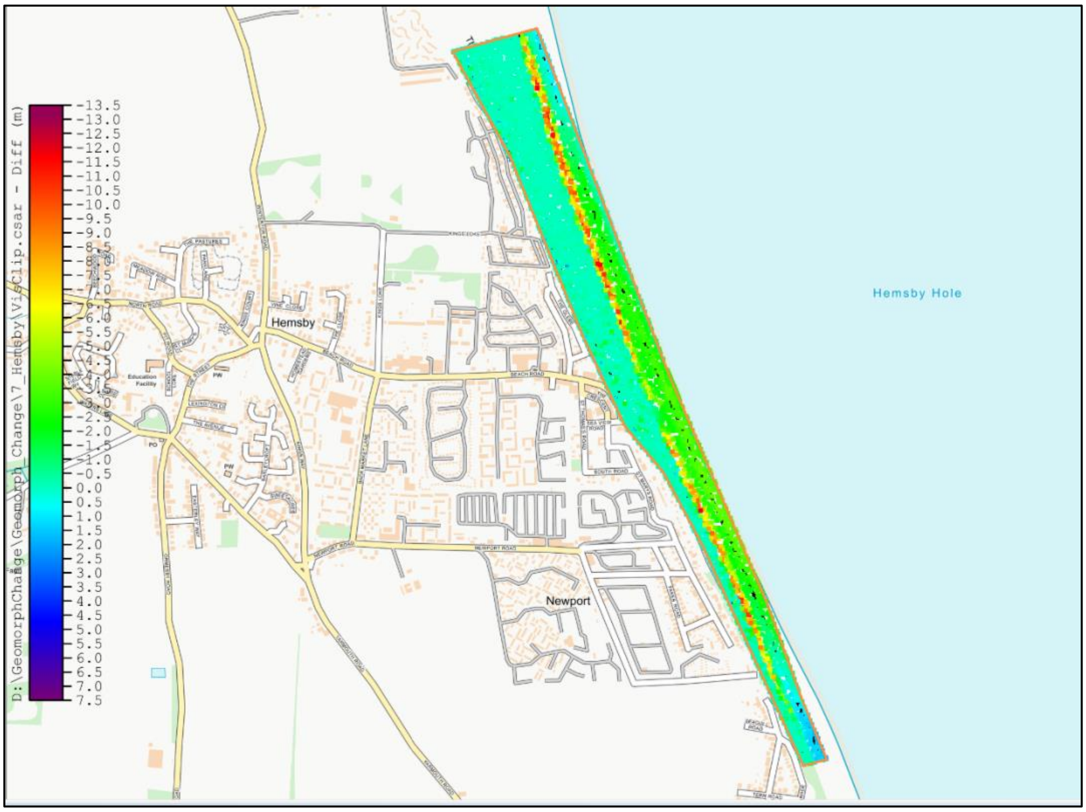


Cumulative Volume Change (m³)

2009	0
2010	-
2011	-
2012	-72644
2013	-144313
2014	-242890
2015	-275489
2016	-279450
2017	-314362

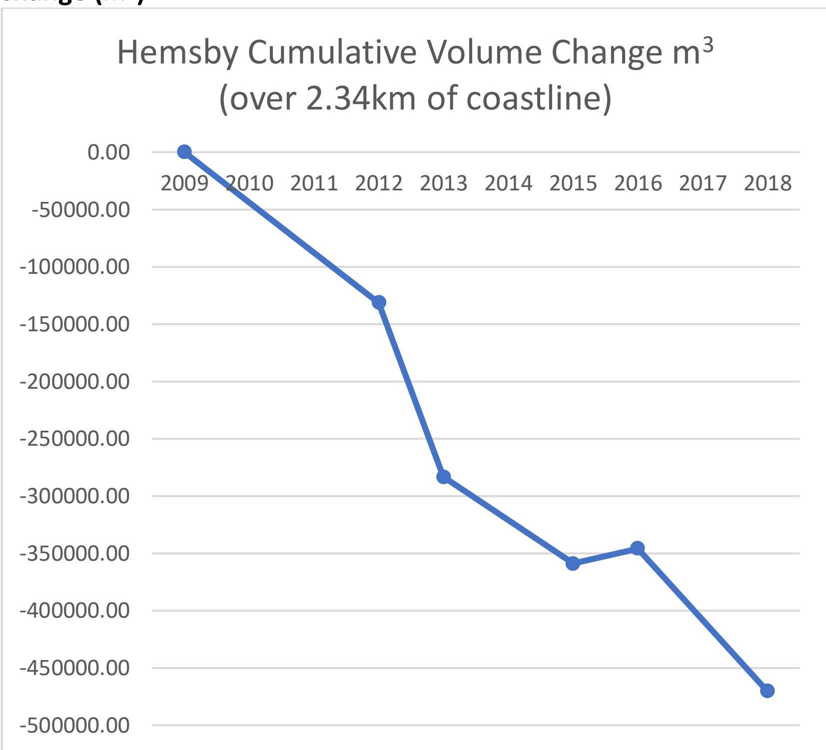


4.8.2.8 Case Study Site 8: Hemsby

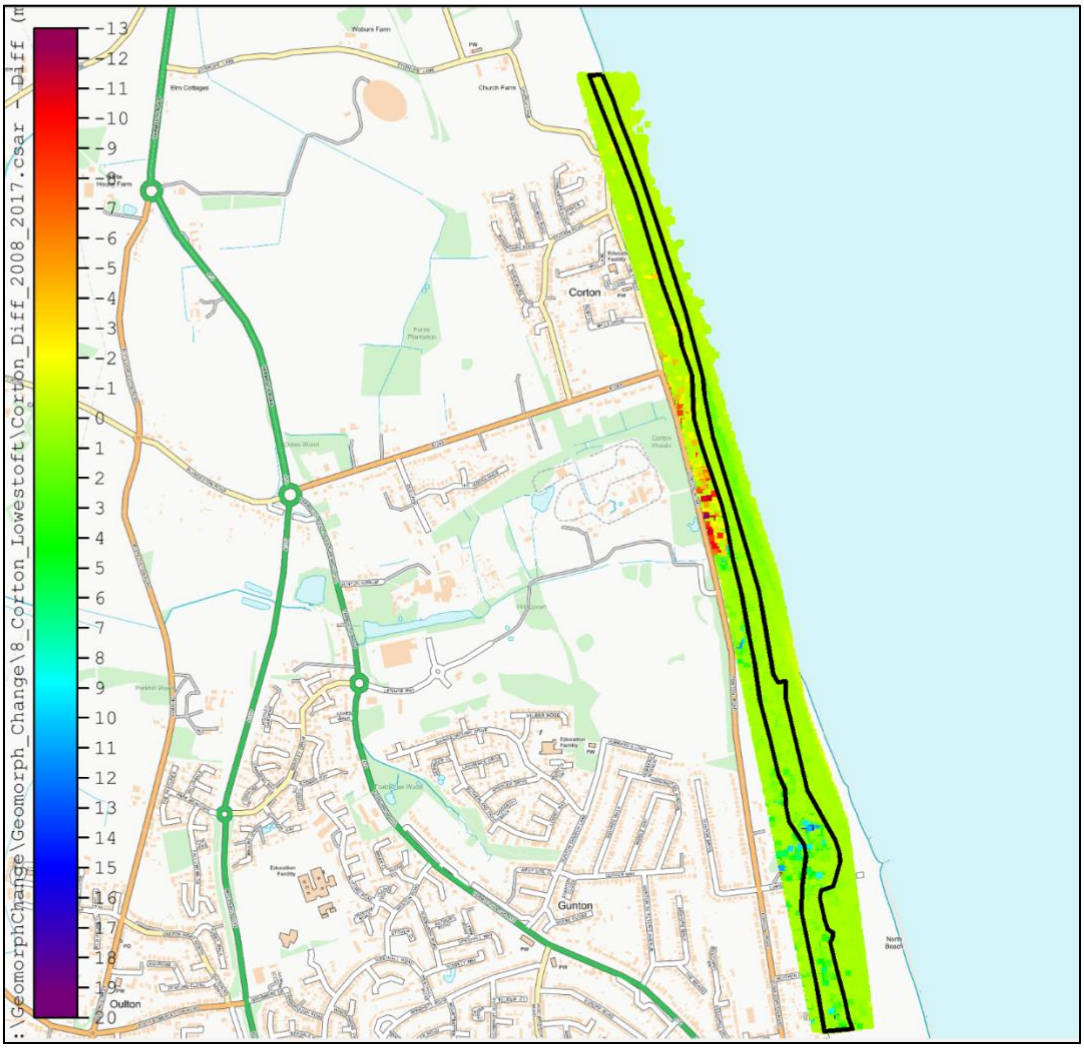


Cumulative Volume Change (m³)

2009	0
2010	-
2011	-
2012	-131371
2013	-283558
2014	-
2015	-358882
2016	-345991
2017	-
2018	-470352

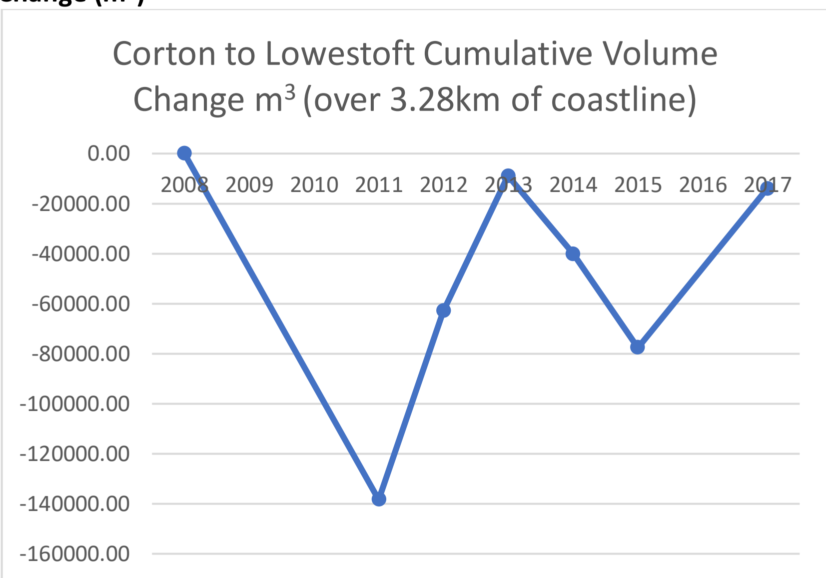


4.8.2.9 Case Study Site 9: Corton to Lowestoft

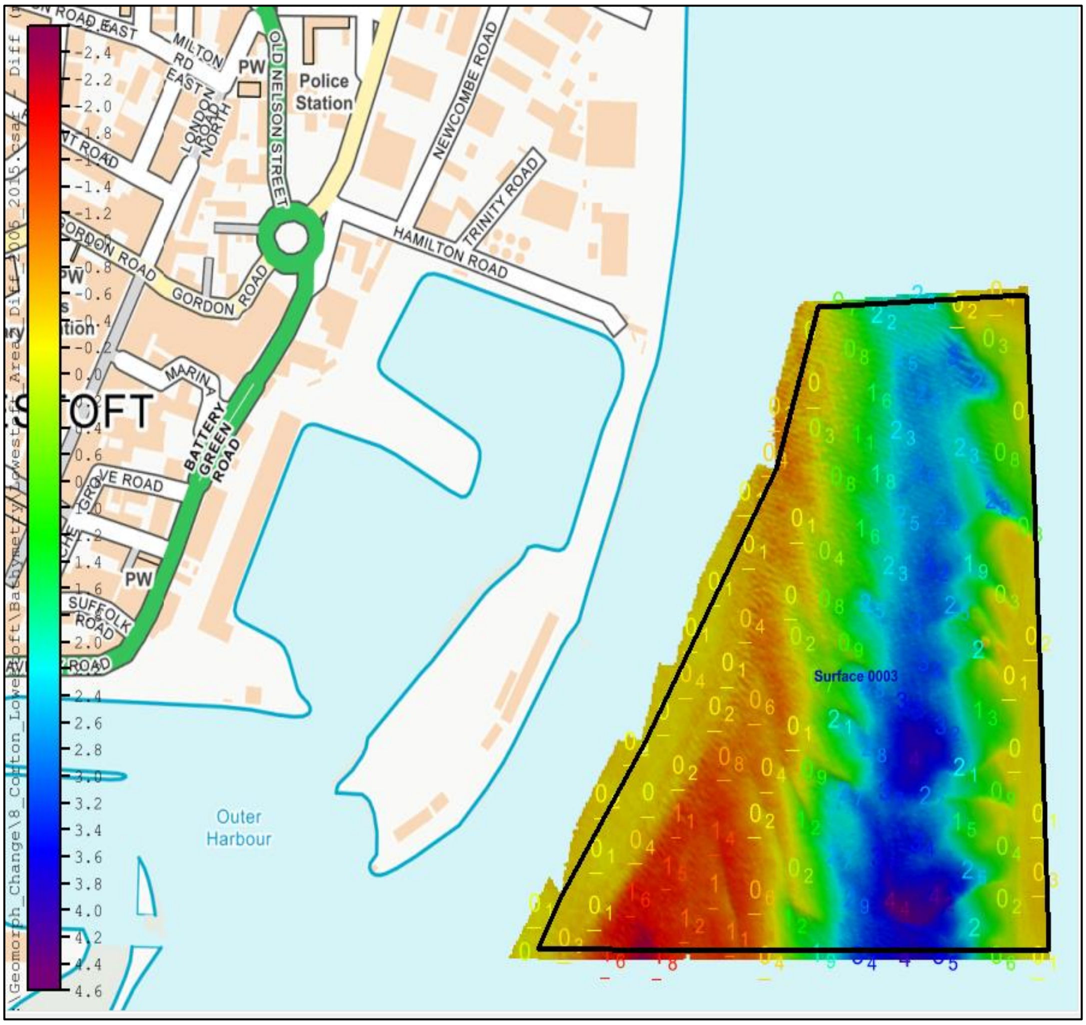


Cumulative Volume Change (m^3)

2008	0
2009	-
2010	-
2011	-138397
2012	-62944
2013	-8910
2014	-40096
2015	-77544
2016	-
2017	-14045

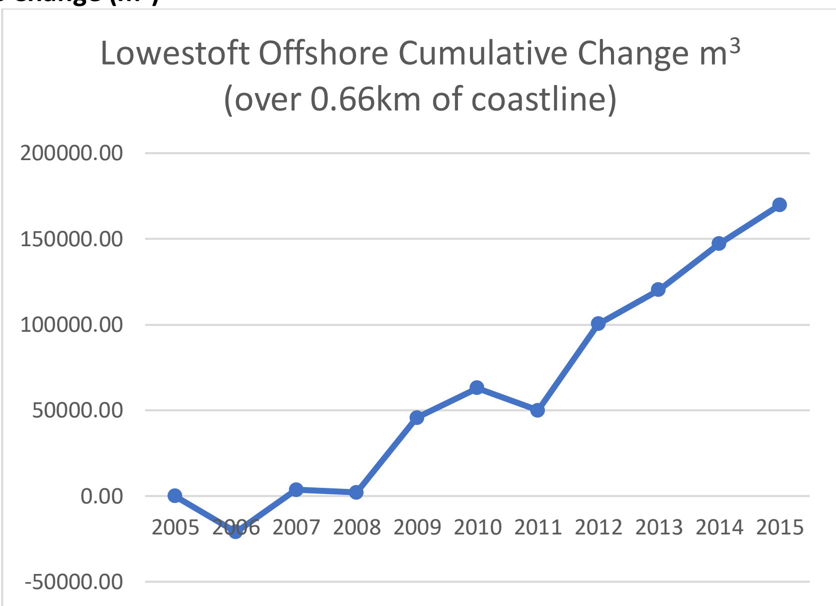


4.8.2.10 Case Study Site 10: Lowestoft NearShore

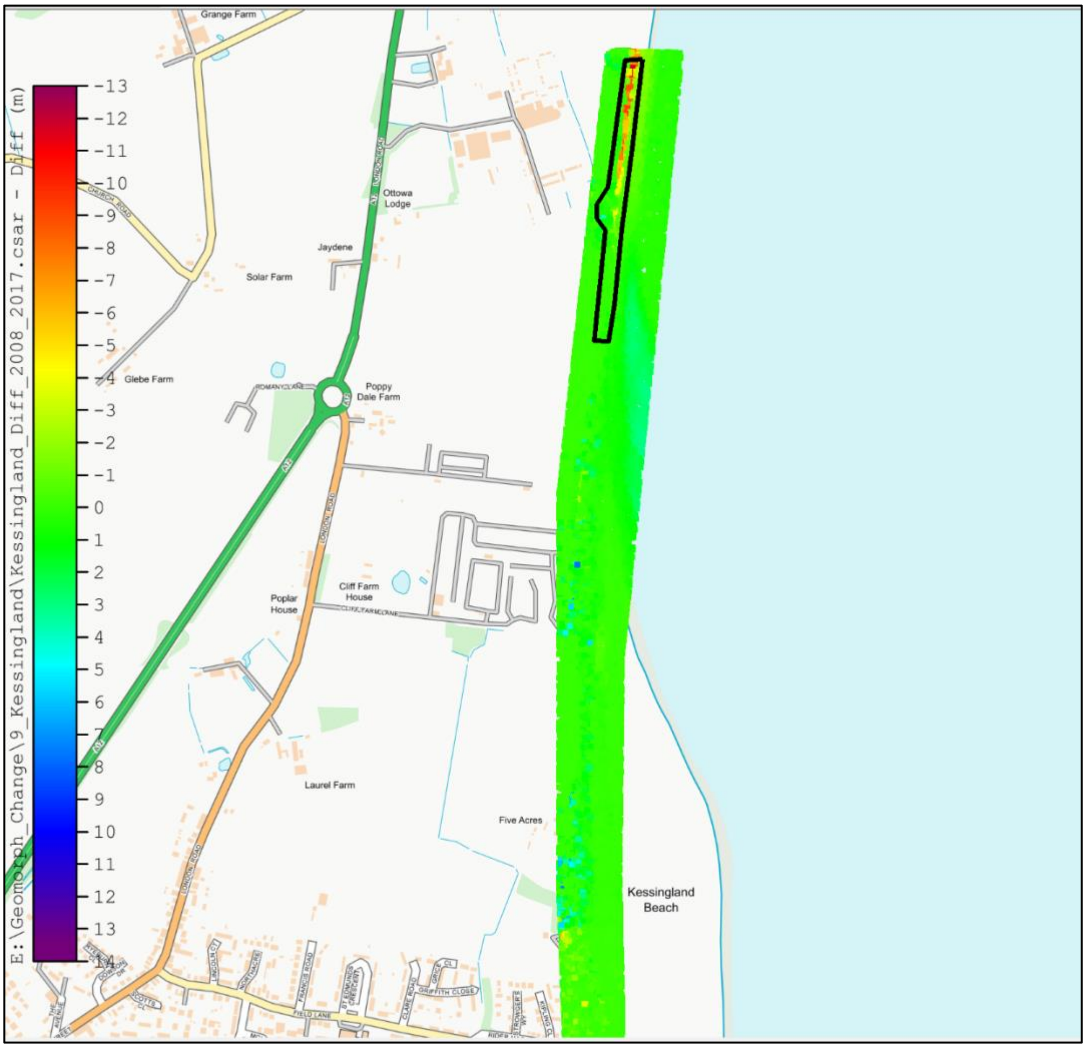


Cumulative Volume Change (m³)

2005	0
2006	-21031
2007	3606
2008	2140
2009	45598
2010	62872
2011	49931
2012	100387
2013	120254
2014	147110
2015	169668

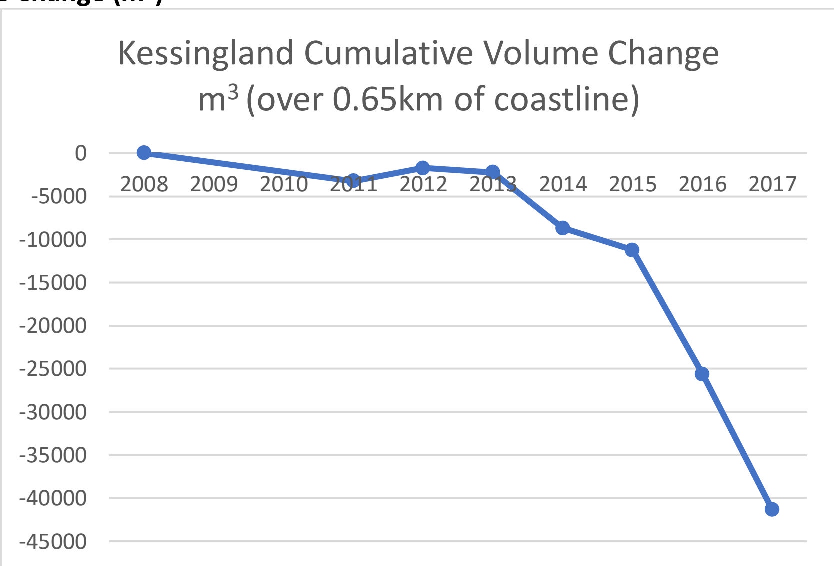


4.8.2.11 Case Study Site 11: Kessingland

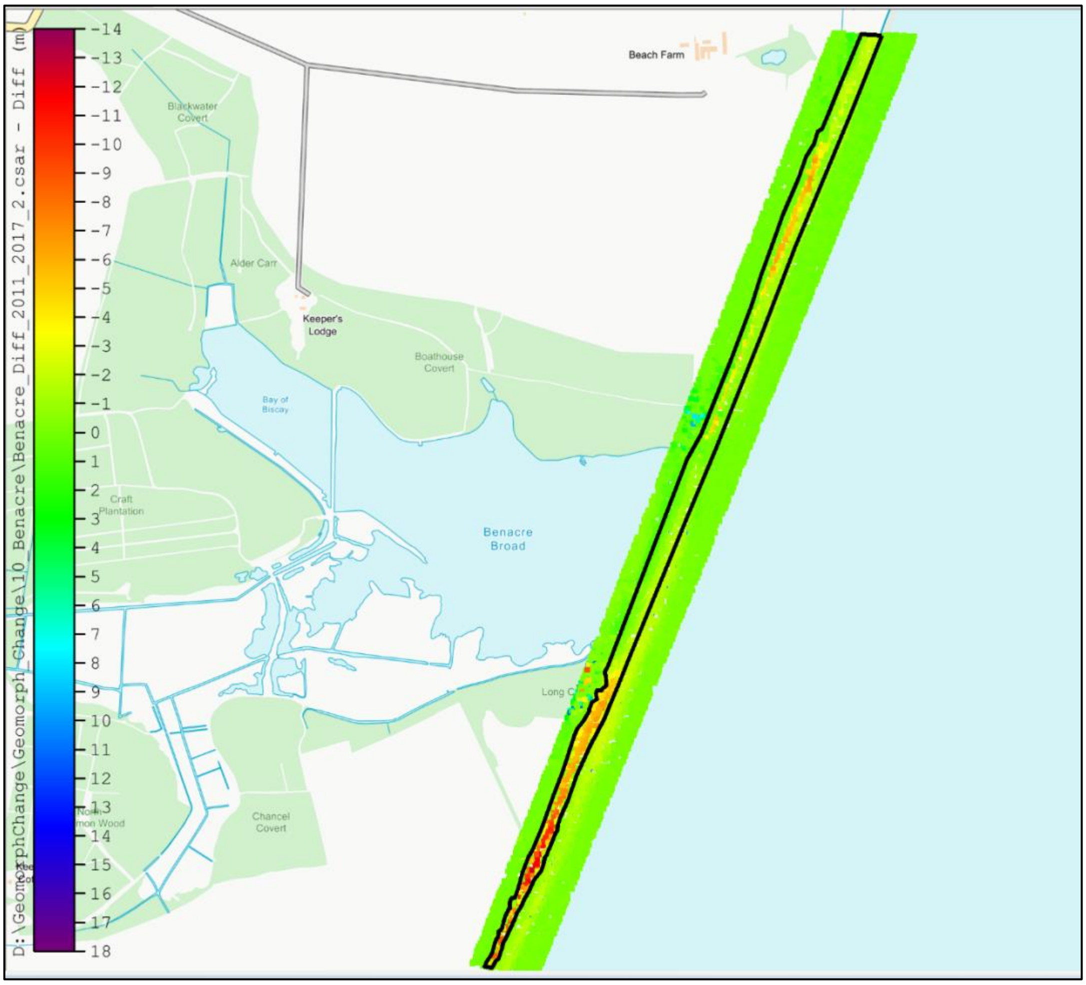


Cumulative Volume Change (m³)

2008	0
2009	-
2010	-
2011	-3234
2012	-1738
2013	-2224
2014	-8695
2015	-11226
2016	-25629
2017	-41288

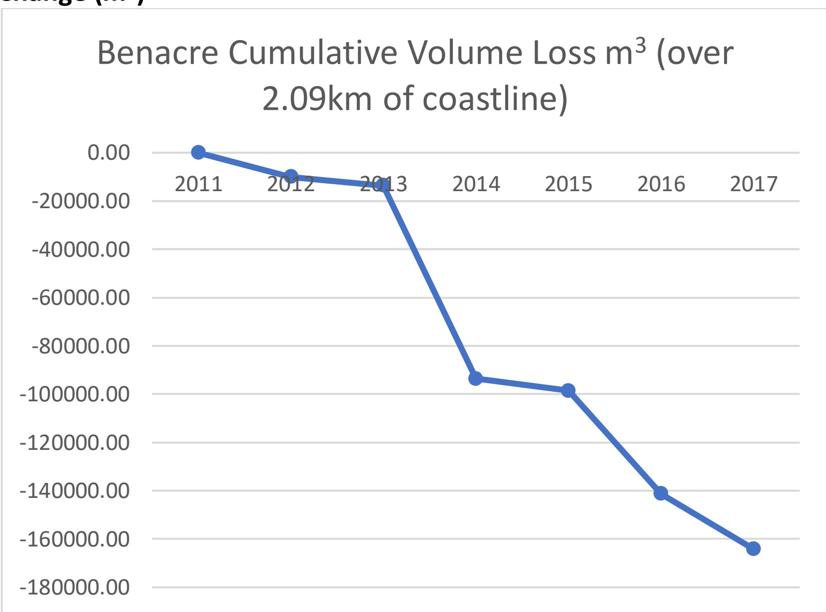


4.8.2.12 Case Study Site 12: Benacre

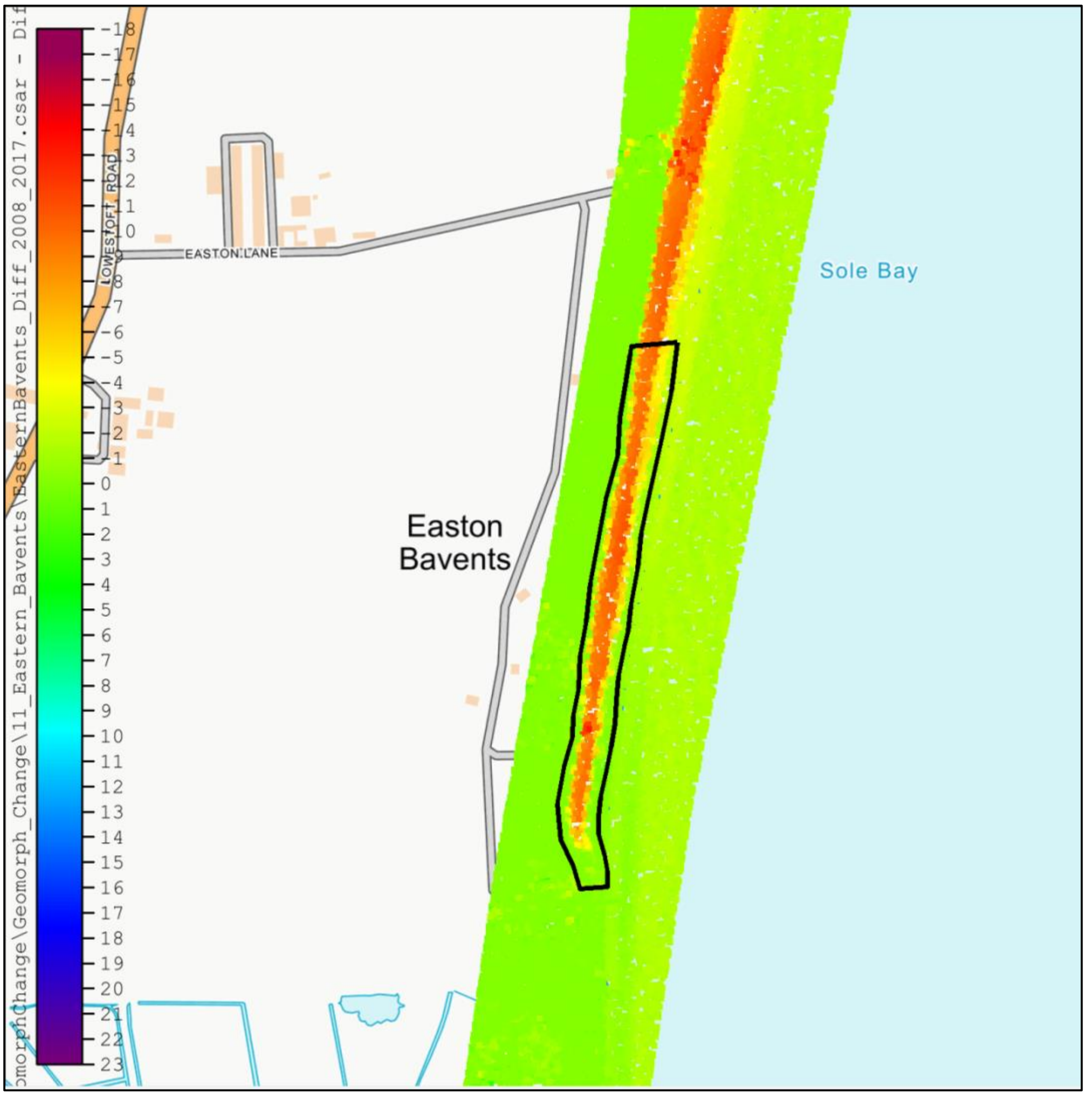


Cumulative Volume Change (m³)

2011	0
2012	-10060
2013	-13596
2014	-93616
2015	-98586
2016	-141326
2017	-164097

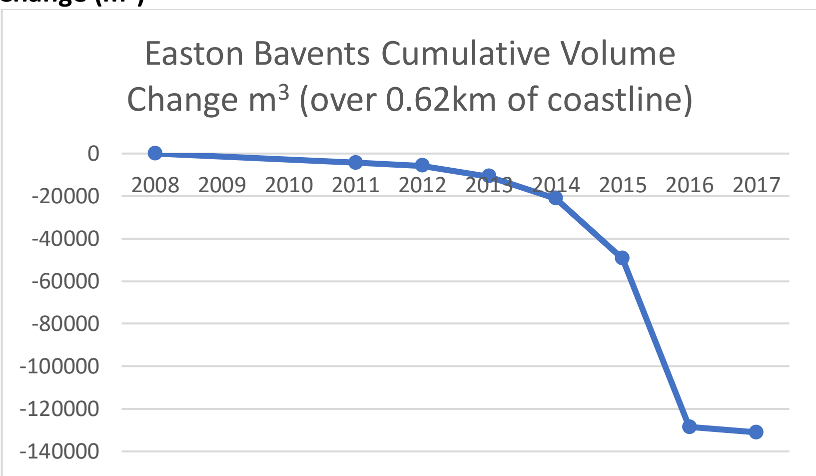


4.8.2.13 Case Study Site 13: Easton Bavents

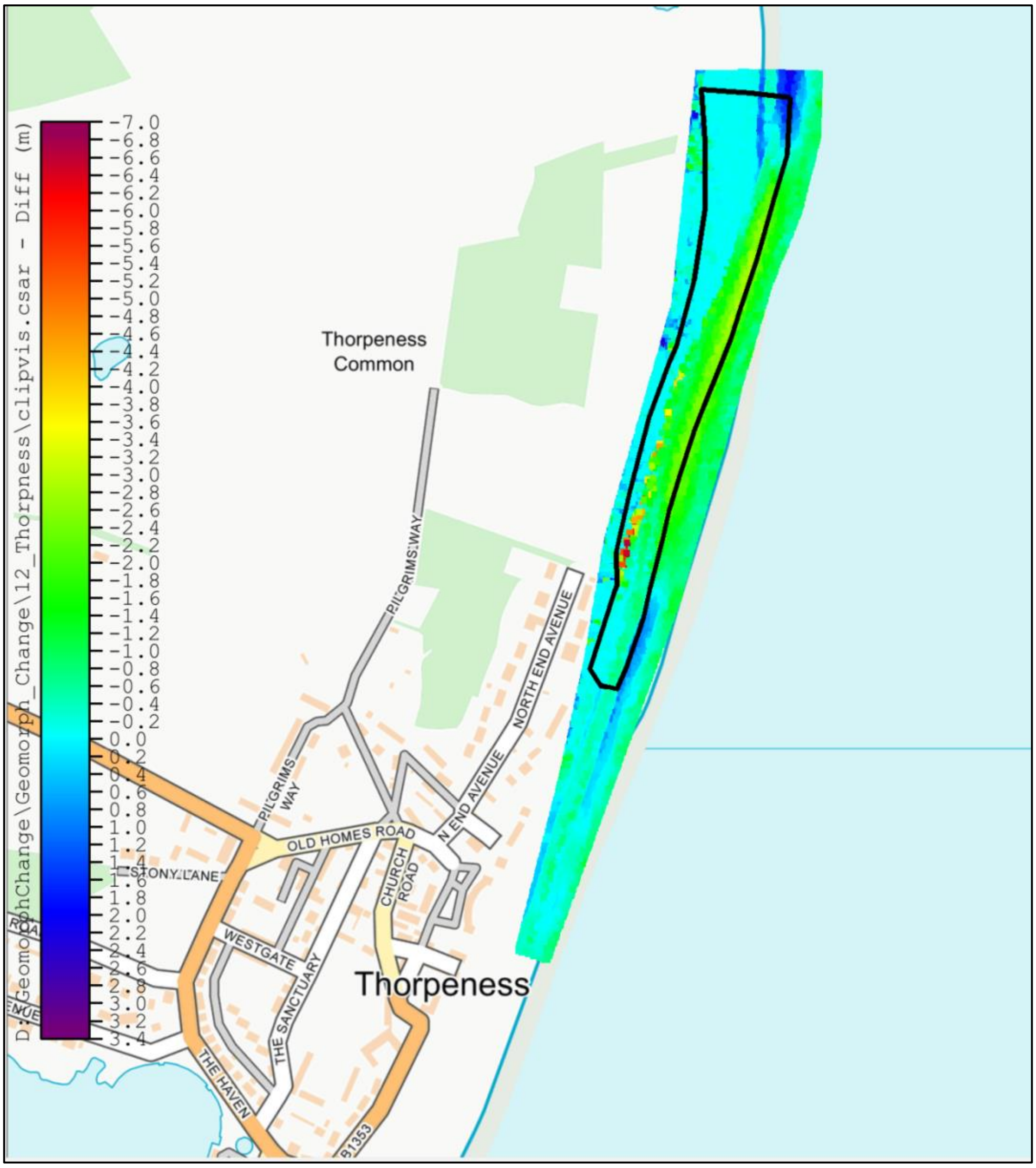


Cumulative Volume Change (m³)

2008	0
2009	-
2010	-
2011	-4290
2012	-5816
2013	-10818
2014	-21120
2015	-49413
2016	-128639
2017	-131015

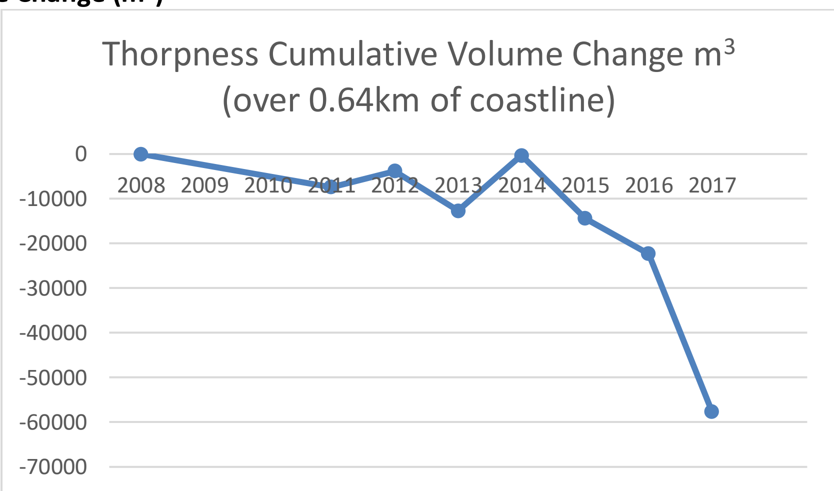


4.8.2.14 Case Study Site 14: Thorpness



Cumulative Volume Change (m³)

2008	0
2009	-
2010	-
2011	-7431
2012	-3812
2013	-12667
2014	-331
2015	-14405
2016	-22355
2017	-57630



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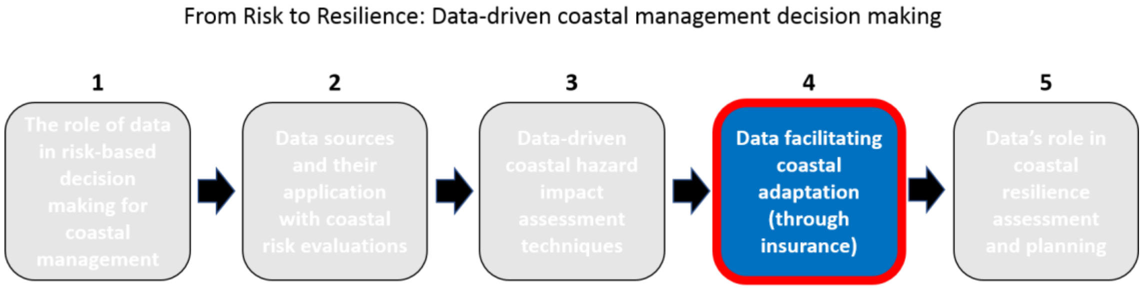
5 Innovations in the use of data facilitating insurance as a resilience mechanism for coastal flood risk



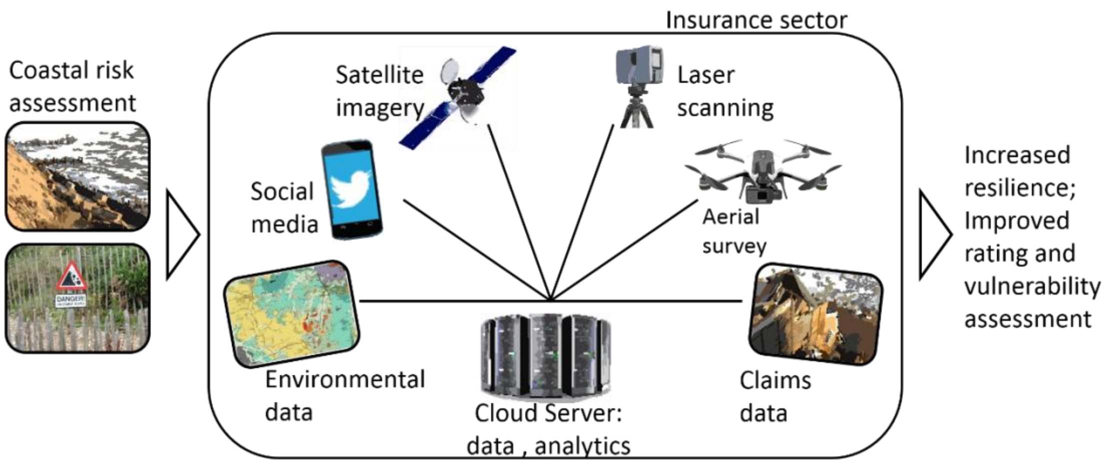
A prominent non-physical soft adaptation can be found in the provision of insurance in coastal areas. If policy pricing is risk-based, insurance holds the potential to both distribute and communicate risk. Public perception of coastal risk has been reported as inadequate in many countries (such as England) due to a lack of available clear and accurate information (Committee on Climate Change UK, 2018). Risk perception is not only important for the general public, in addition to the importance of coastal inhabitants understanding natural risk when making decisions on where to live, it is essential that land planning authorities are also fully aware of this (Roberts, 2012). As such, the capacity of insurance to raise awareness of true levels of risk, is important yet under recognised.

Accurate geospatial data analysis, incorporating granular level data sources, can allow insurers to gain a comprehensive picture of the distribution of risk within coastal regions. As a result, properties located in areas at a high risk of tidal flooding, may become uninsurable. This potentially provides a powerful message, discouraging future developments in such regions, and negatively impacting house prices. However, in areas where sustainable development has been undertaken, and mitigating measures have been implemented (at a household scale or greater), insurance policy prices may fall, potentially encouraging sustainable economic regeneration. A study by Dávila et al. (2014) considered the use of insurance as an adaptation measure, comparing the situation across Europe, in particular focussing on France, Italy, the UK and Spain. In general, the study concluded that purchase of insurance should be made compulsory in areas vulnerable to flooding, and where this has occurred, price reductions of vulnerable properties have been witnessed. Furthermore, Roberts (2012) recommended mandatory insurance for high risk properties. For insurance to provide the resilience increasing benefits mentioned, pricing of risk must be founded on accurate information. Therefore consideration is required of the evidence base commonly utilised by insurers in pricing coastal flood risk. Past assessments based on subjective judgements need to be replaced by expansive data-driven methods, utilising the best available techniques and technology. Within this chapter research is presented highlighting the potential for links to be forged between academia, coastal management bodies and insurance providers. This could facilitate increased levels of resilience through application of, what holds the potential to be, an innovative soft adaptation method.

Underpinning the work presented in this chapter is the extensive research undertaken into the role of data innovations within the London insurance market. The main contributing organisation to this research was Lloyd's insurance market. The collaboration with Lloyd's resulted in a comprehensive report (Appendix C). The report was based on inputs received through a series of interviews with insurers, data analytics firms and other associated parties. Aspects covered within these interviews, which relate to coastal flooding, formed the basis of this chapter. Chapter 4 focussed on how data and analytical methods can be used to quantify physical coastal impacts more accurately. This chapter shifts the focus to the next stage of the risk assessment framework as presented in Chapter 3 (Figure 11) and addresses the role of data in relation to adaptations. Of the many adaptations detailed in Section 1.7.3, the potential soft adaptation measure of insurance was selected due to the pivotal role data plays in facilitation of effective insurance cover. In this chapter we focus on how innovations in the use of data and analytics can allow risk-based pricing of insurance policies. This is shown to permit insurance to offer a means of adaptation through its capacity to raise awareness of true levels of risk and act as a mechanism to distribute risk, providing a financial buffer to those exposed. Provision of insurance policies covering coastal erosion is not currently recognised as feasible in the UK (Committee on Climate Change UK, 2018), given this the focus of this chapter is on insurance against coastal flooding.

The work completed within Chapter 5, marks a shift in research style from that completed within the previous chapter. This chapter adopts qualitative research methods based primarily on semistructured interview feedback, as opposed to the mostly quantitative methods employed in Chapter 4.

Graphical Abstract



Innovations in the use of data facilitating insurance as a resilience mechanism for coastal flood risk

Abstract

Insurance plays a crucial role in human efforts to adapt to environmental hazards. Effective insurance can serve as both a measure to distribute, and a method to communicate risk. In order for insurance to fulfil these roles successfully, policy pricing and cover choices must be risk-based and founded on accurate information. This is reliant on a robust evidence base forming the foundation of policy choices. This paper focuses on the evidence available to insurers and emergent innovation in the use of data. The main risk considered is coastal flooding, for which the insurance sector offers an option for potential adaptation, capable of increasing resilience. However, inadequate supply and analysis of data have been highlighted as factors preventing insurance from fulfilling this role. Research was undertaken to evaluate how data are currently, and could potentially, be used within risk evaluations for the insurance industry. This comprised of 50 interviews with those working and associated with the London insurance market. The research reveals new opportunities, which could facilitate improvements in risk-reflective pricing of policies. These relate to a new generation of data collection techniques and analytics, such as those associated with satellite-derived data, IoT (Internet of Things) sensors, cloud computing, and Big Data solutions. Such technologies present opportunities to reduce moral hazard through basing predictions and pricing of risk on large empirical datasets. The value of insurers' claims data is also revealed, and is shown to have the potential to refine, calibrate, and validate models and methods. The adoption of such data-driven techniques could enable insurers to re-evaluate risk ratings, and in some instances, extend coverage to locations and developments, previously rated as too high a risk to insure. Conversely, other areas may be revealed more vulnerable, which could generate negative impacts for residents in these regions, such as increased premiums. However, the enhanced risk awareness generated, by new technology, data and data analytics, could positively alter future planning, development and investment decisions.

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Keywords

Risk Analytics; Adaptation; Remote Sensing; Big Data

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5.1 Introduction

Insurance permits the issue of information asymmetry, between the insurer and the insured, to be addressed. In correctly rating risk, insurance can thus enable risk-transfer between clients (policyholders) and the global insurance and capital markets (Cervantes-Godoy et al., 2013; Dahlen and Peter, 2012). As a result of highly developed, globalised, reinsurance markets, risk from catastrophic (CAT) losses occurring in a single locality can be transferred across the world (Abdullayev, 2014; Dahlen and Peter, 2012). In a perfectly competitive market, the market would be price setting. However, this is rarely the case in practice, so for markets to generate risk-reflective pricing (or an actuarial fair rate (Kunreuther et al., 2016)), underwriters and actuaries require access to accurate, up to date information detailing the nature of the risks associated with each class of business (Actuaries Institute, 2016). Insurance pricing also provides a mechanism for risk signalling, which can act to raise awareness and encourage risk-averse behaviour (Bin et al., 2006; Hudson et al., 2016). If market distortions occur though, this message can become diluted, resulting in adverse societal consequences (Hudson et al., 2016). In such cases, if the risk reducing element of insurance is lost, a moral hazard could be created (Surminski and Oramas-Dorta, 2014). Governments can play a crucial role in relation to insurance. For example, for flood insurance, this can take the form of land planning, investments in adaptations, and provision of cover to some of the most vulnerable (OECD, 2016; Surminski, 2014) (which may be increasingly necessary given climate change predictions (Lamond and Penning-Rowsell, 2014; Thistlethwaite et al., 2018)). However, some government interventions, such as last resort insurance coverage, have been reported to create market distortions, preventing insurance from fulfilling its full socio-economic potential (Crick et al., 2018; Kunreuther et al., 2016), or reducing the incentive for households to take preventative adaptation measures (Surminski, 2014). Yet finding an insurance arrangement that optimises risk reduction is not simple and has been acknowledged as an international challenge (Surminski and Oramas-Dorta, 2014).

Since the 1970s losses have been growing (especially from weather-related incidents), with non-insured losses growing the fastest (Dahlen and Peter, 2012; Kunreuther et al., 2016; OECD, 2016). For insurance and reinsurance markets to function effectively, it is essential for risks to be both priced appropriately, and for coverage to be extended to those in need. Recent advances in realm of data and analytics are reported to have increased the supply of reinsurance for flood risk (The American Academy of Actuaries, 2017). For both insurance and reinsurance, it is essential for analysts to supply the information required to allow exposure management, so aggregation of risks and exposure to natural perils, can be established (Andrews et al., 2008). The opportunities presented by the vast stores of data which are continually becoming available (Actuaries Institute, 2016; Choi and Lambert, 2017; Rumson and Hallett, 2018), open up possibilities for risk to be priced more accurately (Stoeckli et al., 2018). Inevitably more accurate risk evaluations (and potentially the use of 'Big Data' (Actuaries Institute, 2016)) will create losers as well as beneficiaries, for example some geographical areas reassessed as being higher risk, may currently benefit from unrealistically priced insurance premiums. In such cases, current policy holders may be priced out of the market (Collinson, 2017). On aggregate though, this kind of outcome is socially optimal, and can result in insurers lowering their risk ratings, and premiums, for other, less vulnerable locations. This can address the pressing problem of asset underinsurance (Kunreuther, 1984; Kunreuther et al., 2016; Lloyd's, 2018a), and potentially result in increased investment and a rise in sustainable developments in more resilient areas. Positive outcomes may also be generated, such as areas previously being regarded as off limits to investors becoming an attractive option and potentially, as a consequence, regional economic regeneration occurring. This paper reveals how emergent innovation in the use of data, can improve the ability of coastal flood insurance, to facilitate adaptation and increase resilience. Literature cited within this paper reveals how the potential for insurance to increase resilience to coastal flooding has been acknowledged. However, the role of data, in ensuring the effective functioning of insurance, has been widely overlooked. This work seeks to address this issue.

5.2 Methods

In addressing the issue of how to increase the capacity of insurance to act as a resilience increasing mechanism, our research considers how data is consumed within the insurance industry and the potential role of innovations in the use of data and analytics. This has entailed researching data sources, data analytics, and methods of communicating information outputs. There are abundant suppliers of data and analytics in this field, however there is currently a lack of rigorous academic evaluation addressing the associated range of data-related challenges and opportunities. The first part of the research comprises a literature review, considering the role of insurance in relation to flood risk adaptation in coastal areas. The literature review drew on a wide range of sources including academic papers, grey literature and industry related websites. Multiple combinations of key words and phrases were used within literature searches, these included: coast*, flood*, insurance, reinsurance, adaptation, resilience, 'risk mitigation', data, 'data source*', 'data analytics', 'geospatial data', and 'flood model*'. Over 30 relevant academic papers were identified, however emphasis was placed on using more recent literature, as such, the majority of academic sources cited were published within the last 10 years.

In the sections, following the literature review, the role of data and analytics is addressed, drawing on feedback obtained from 50 semi-structured interviews with a broad range of practitioners, working in and associated with, the London Insurance market (including risk engineers, brokers, actuaries, underwriters, analysts and managers), and representatives of firms who supply data and analytics (such as CAT modellers, specialist insurance analytics firms, flood modellers, and suppliers of geospatial data). In many instances single interviews were conducted with two or more representatives of an organisation. In terms of the backgrounds of those interviewed, this can be loosely categorised as follows: 20 were from the insurance sector, 6 from data providers, 8 from insurance specific analytics firms (such as CAT modellers), 3 from more general data analytics organisations, 10 from satellite data analytics suppliers, and 3 from the field of Big Data solutions. The use of Earth Observation (EO) data, emerged as a prominent theme, as such feedback on advances in the use of EO data was provided in interviews with representatives of multiple organisations who work in this field.

All interviews were completed within a 3-month period (November 2017 to January 2018). Interviews commenced with a briefing on the nature of the research being conducted and the neutral position of interviewer, who was not connected or sponsored by any organisation linked to the insurance industry. A standardised set of questions were covered, which addressed topics outlined in Figure 27; the questions differed depending on the category of organisation the interviewee belonged to. Interviews were not recorded, however extensive notes were made from which transcripts were produced. Interview transcripts were analysed systematically, and responses given grouped into themes. The themes evolved through a process of manual comparison, and following this generation of word counts for specific terms. The most prominent themes identified have been elaborated on and led to development of the subsequent sections of this paper. The London market was selected as a case study as it is one of the oldest and most comprehensive insurance markets in the world, covering international risks, and a wide range of multinational firms are represented within it. Furthermore, it is quoted to be 'the largest global hub for commercial and specialty risk' (London Market Group, 2018). Tidal flooding is also a significant issue for London, which has led to implementation of innovative adaptations, such as the Thames Barrier (Linham and Nicholls, 2010). Lloyd's provided a focal point for this research, and assistance was provided by Lloyd's Data Lab, in selecting and securing appropriate interviewees. Details of specific contributors are omitted to protect their identities, also none of the companies mentioned have been associated with opinions expressed by their employees (who have been anonymised).

5.3 Flood risk adaptation in coastal areas: the role of insurance

Those settling, using and working in coastal locations must contend with numerous hazards. Of these, flooding is one of the most prominent and can be severe and extensive. Flood impacts are compounded by the presence of critical infrastructure in coastal areas, e.g. due to requirements for ocean access (i.e. for oil, gas, and renewables) or the need for water cooling (nuclear power plants). Additionally, most major global cities are sited on or near the coast due to needs for port and shore access. Recent events in the Caribbean and United States reveal how extreme weather-related hazards cause devastating effects in coastal areas, and how losses are transferred to insurers (Lloyd's, 2018a). Flooding is one of the major perils which generated losses from these events, resulting in calls for improvement of the flood modelling process (Lloyd's, 2018a). In many locations impacted, a primary form of defence is artificial protection, such as engineered coastal defences. However, there are a number of problems with such structural defences (Crichton, 2008). Where such measures prove inadequate in ensuring resilience in the resident populations (Kunreuther et al., 2016), devastation reaped by events such as hurricane winds and storm surges, can reach beyond what individuals are capable of covering financially. Therefore, insurance against natural perils, such as flooding, is considered a significant element within coastal management (Clark, 1998), which can facilitate recovery (Viavattene et al., 2018), and has been termed a ‘catalyst for resilience’ (Kunreuther et al., 2016). The type of risk covered by insurance is fortuitous risk, which is a risk related to accidental or chance events. In this sense the risk of flooding is more suited to insurance than erosion, which in many locations is inevitable.

Insurance is acknowledged as having a crucial role in redistributing risk (Dahlen and Peter, 2012). Insurability, or lack of this, can also serve as a tool to raise awareness of the real risks associated with settling in coastal areas, deterring investment in high risk, hazard-prone locations. In this sense, insurance has a role as a planning instrument in relation to controlling impacts on flood plain geography (Crichton, 2008). It also has a clear role within the housing market, in that market value of houses are seen to reflect perceived risk (Jongman et al., 2014; Pilla et al., 2018). In influencing asset values, insurance can also affect developers’ decisions to build in coastal areas. This is noted by Botzen & van den Bergh (Botzen and van den Bergh, 2008) who highlight how varying premiums can serve to reduce risk indirectly, by reducing the desirability to settle in high-risk areas. The application of larger more granular datasets, is highlighted to contribute to such improvements (Actuaries Institute, 2016). In fact, flood insurance premiums are said to account for up to 80% of reductions in real-estate prices in flood plains (Filatova et al., 2011). This form of house price discounting, although unpopular with real-estate owners, can lead to less overall damage arising from flooding. Furthermore, Filatova et al. (Filatova et al., 2011) conclude that when combined with building on higher ground, insurance can offer the best means of communicating risk.

Kron (Kron, 2013) describes insurance as covering a range of activities on the coast other than just real estate, including: fish farms, bio-fouling of hydraulic structures and vessels by toxic algae, and indirect impacts on hotels and resorts. Flood hazards can generate physical damage to households, businesses and infrastructure, but can also result in pollution and impacts to human health and welfare, as well as creating widespread business disruption and supply chain shocks (which can exceed direct damages) (Jongman, 2018). These risks are exacerbated by urbanisation and increasing population densities in coastal areas (Kron, 2013; Kunreuther et al., 2016). Insurance has a clear role in creation of incentives to reduce such risk (Kunreuther et al., 2016). Yet standard, static, insurance risk assessments based on a limited number of data variables can underestimate risk (Haer et al., 2017). Noting this, a wide range of data is required to enable comprehensive analysis of flood risk. This extends beyond peril data and projected hazard propagation, to data relating to human behaviour and use of areas at risk of flooding (Yang et al., 2018). Data also needs to be provided covering wider consequences of infrastructure failures, for example that related to roads, power stations, water supply, and port facilities (Kunreuther et al., 2016). One method which has been applied to understanding relationships between such data is Agent Based Models (ABM). For example ABMs have been applied to understanding disruptions generated by environmental hazards to critical infrastructure, resulting in power outages (Walsh et al., 2018). Increasing numbers of coastal flood models are also becoming available which draw on such data sources, including the CFFlood model

(Mokrech et al., 2014), which allows impact analyses, under varying socio-economic and climate scenarios (combining environmental and human datasets).

5.3.1 Adaptation through Insurance

Insurance's role as an adaptation mechanism extends beyond influencing real-estate prices and development decisions; in its ability to communicate risk, insurance can also spur and encourage investment in adaptive capacity at a household level (Filatova et al., 2011; Hudson et al., 2016). Yet, the ability for insurance to function as an adaptation mechanism depends on its availability, the resulting coverage achieved, and is based on the premise that insurers are able to operate in an open market place. However, this is not the case in many countries, as approaches to state and private flood insurance provision vary across the world (Crichton, 2008, 2004; Lamond and Penning-Rowsell, 2014), and in some instances this can create distortions. Throughout Europe a number of different approaches have been adopted in relation to insurance of coastal flood risk. In the UK a private system operates for flood risk, yet no insurance is available against erosion (Dávila et al., 2014). In France a public/private partnership exists, in which flood insurance is mandatory as a part of buildings insurance (Hudson et al., 2016). For the past 60 years in the Netherlands there has been a public flood compensation scheme, yet this has been considered inefficient, and now private schemes are being looked to (Botzen and van den Bergh, 2008). Germany has combined flood insurance within private insurance packages, resulting in only 10% coverage for flood risk (Botzen and van den Bergh, 2008). The French system can be seen as effective in that it secures close to 100% coverage, yet the method of implementation creates distortions, and the French national insurance system is regarded as not supporting reduction of individual risk (Botzen and van den Bergh, 2008). By contrast, in the UK 'insurance companies differentiate premiums based on geographical risk characteristics' which reward settlement in low-risk areas; an ethical problem exists though due to low coverage (30%) in poor households (Botzen and van den Bergh, 2008). Similar ethical challenges have been reported in other parts of the world also, such as in Australia (Actuaries Institute, 2016).

Within the UK a unique situation has prevailed, taking the shape of a 'Statement of principles'(Association of British Insurers, 2005) between the government and the insurance industry, whereby the government commits to build defences whilst insurance companies continue to provide cover for flooding (Jongman et al., 2014; Surminski and Eldridge, 2015). However, this agreement failed to take account of affordability of the insurance cover provided to those living in areas vulnerable to flooding. To address this issue, in 2015 the British government introduced a scheme labelled Flood RE ("Flood RE," n.d.). This aims to enable those who live in properties at the highest risk of flooding, to gain affordable home insurance. The current scheme, although aiming to address a serious concern for those living in areas prone to flooding (i.e. the inability to insure their real estate assets), has been found likely to generate moral hazard, due to it overlooking the risk signalling aspect of insurance, which can encourage more risk-averse behaviour (Surminski and Eldridge, 2015). This results from policy pricing being decoupled from true levels of risk, for policies underwritten through

Flood RE. Nevertheless, it does discourage future developments in high risk locations, as the scheme only applies to houses constructed prior to 2009. As such, new homes built in flood plains, wouldn't be covered by the scheme, and therefore may be uninsurable.

Similarities can be drawn between Flood RE and the French insurance system, which as a result of imposing uniform premiums (or a universal surcharge) fails to account for varying levels of risk, and has been branded an inefficient risk communication mechanism (Dávila et al., 2014). Elsewhere in Europe other challenges are faced in relation to the application of insurance to coastal flood risk. In Spain there are issues hampering effective utilisation of insurance, these relate to perceived weaknesses of the law courts and low confidence levels, due to many claims not being paid (Dávila et al., 2014). Italy also suffers from a confidence problem due to low levels of trust in national institutions and insurance companies (Dávila et al., 2014). Nevertheless in some locations beyond Europe, such as the USA, insurance is seen to be a 'primary tool of improving location choice in flood prone areas' (Filatova et al., 2011).

It is important for insurance schemes to incorporate risk reduction elements, widening their focus beyond risk transfer alone (Surminski and Oramas-Dorta, 2014). Where this aspect has been neglected, such as in an example of state backed insurance for unsustainable developments on barrier islands, the availability of insurance is reported to exacerbate problems (McNamara and Werner, 2008). As such, insurance policies which encourage rebuilding in high risk locations, as opposed to resettlement, can negatively impact future resilience. Roberts (Roberts, 2012) outlines how policies addressing coastal risks can generate an unintended outcome, whereby the burden of compensation for developments in high-risk areas can fall on society. Additionally, many countries operate cross-subsidy insurance coverage (or a bundle system, where other perils are combined with flooding (Crichton, 2008; Lamond and Penning-Rowsell, 2014)), this offers the benefit of reducing insurance premiums through further spreading risk. However, it can also prove an excuse for inaction by those settling in high risk areas (Dávila et al., 2014), as it can dilute the apparent risk posed by specific perils. In some extreme circumstances, increasing property values in areas prone to flooding (potentially resulting from increased levels of protection), can render insurance in these areas impossible (Jongman et al., 2014). In fact, a high proportion of properties in flood plains remain uninsured (Dahlen and Peter, 2012; Landry and Jahan-Parvar, 2011; Lloyd's, 2018a; OECD, 2016). This can pose a direct barrier to insurance achieving the resilience increasing function described. In order to tackle issues such as this, Roberts (Roberts, 2012) proposes a form of compulsory insurance, arguing that in practice only obligatory insurance schemes appear capable of establishing a fully functioning community of insureds. Filatova et al. ((Filatova et al., 2011), p.169) concur, stating how compulsory insurance can force homeowners 'to face the social cost of locating in a flood plain'.

5.4 The role of data in provision of insurance as an adaptation mechanism

Relevant data and information play a significant role in ensuring the desired outcomes are achieved through insurance cover. The success of flood insurance schemes is said to be reliant on how sophisticated a country's insurers are in mapping flood risks (Dávila et al., 2014). In order for insurance to function as an adaptation mechanism (through communicating and redistributing risk effectively), those who provide and underwrite insurance policies are required to use representative risk matrices for rating specific locations. For these assessments to characterise accurately the vulnerability and resilience of assets, comprehensive datasets are required, representing environmental factors, adaptation measures, past and projected impacts and consequences. Combining insurers' internal data, such as damage reports, with household level information, can reveal drivers for implementation of household adaptation measures (Osberghaus, 2017). Additionally, human behaviour needs to be accounted for. ABMs can be well suited to this task. For example, ABMs have revealed how risk averse behaviour, in response to increased risk awareness can have serious implications, altering projected risk ratings (Crick et al., 2018; Dawson et al., 2011; Dubbelboer et al., 2017; Haer et al., 2017; Jenkins et al., 2017; Yang et al., 2018). They have also been used to reveal which insurance arrangements can prove most conducive to risk reduction (Crick et al., 2018). Furthermore, through incorporating behavioural responses of humans, to hazard events such as storm surge flooding, ABMs have allowed areas vulnerable to disruption to be identified (Dawson et al., 2011).

It is deemed insufficient for insurers to merely have access to data, they require the capacity to process, analyse and communicate outputs from the data. In line with this a framework has been devised, involving four stages (represented below in Figure 27). This framework has been used as the basis to structure feedback, received from interviews undertaken. The following sections address various aspects of these four stages, from outlining data sources, to methods of accessing these, and discussions around internal data, open source data, the application of Earth Observation (EO) data, Big Data, data analytics, how data is drawn on by underwriters, and finally challenges.

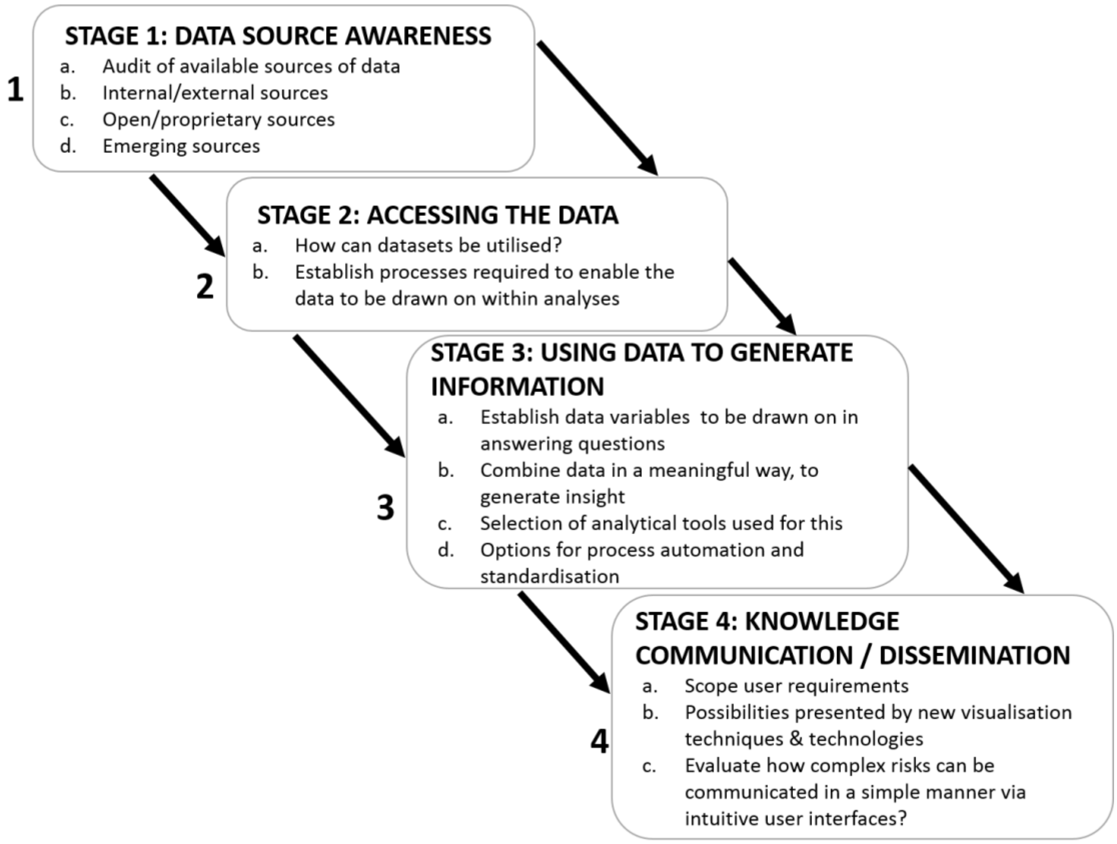

Figure 27: Data utilisation for Insurance

5.5 Data Utilisation: London Insurance Market Interview Feedback

5.5.1 Types of data

Through conversations and interviews conducted for this study, a number of datasets were highlighted as being of particular importance and interest for flood risk evaluations for the insurance industry. These datasets have been split into themes, which for simplicity have been grouped by the approximate category they belong to (Table 14). For all themes listed, direct reference was made to associated data, within at least one interview.

Table 14: Data themes commonly utilised in Insurance Flood Risk Analysis

Category	Data themes
Environmental	• Environmental risks (extreme weather events, natural disasters, climate change, loss of natural capital, air/soil/water pollution) • General information on local environments • Historical records of contamination and pollution events • Threats to natural resources (e.g. salinization of aquifers from flooding)

	• Land use change (urbanisation, industrialisation, changes in exposure) • Oceanographic records and projections (wave climates, sea temperature, water quality, marine fauna/flora, coastal processes) • Tidal data • Past storm surge events and impacts • River and estuarine data (river levels, flow rates) • Natural capital/habitats/ecosystem services (quantification, loss/gain) • Records and predictions of beach/loss creation (change calculations, modelling outputs) • Contaminant and pollution sources in flood plains • Location of landfill and sewage sites
Flooding	• Flooding records, predictions (extents taken from aerial imagery, EO data, water level gauges) • Flood risk exposure (publicly available modelling outputs) • Flood defences/adaptations (location and condition) • Flood protection offered by natural habitats • Flood damage costs (records of financial impacts to people, property, business and infrastructure) • Flood specific geotagged social media data (text, images, videos -revealing extents of flooding and impacts) • Inundation modelling outputs
Geological	• Earthquakes, subsidence, landslides -monitoring data and projections • Geological stability of urban areas • Geomorphological changes in coastal areas (derived from LIDAR, EO data analysis, Terrestrial Laser scanning)
Weather	• Archive climate data (used in claims assessment) • Records of CAT events • Predictions -short- and long-range projections of weather and climate patterns
Satellite Earth Observation	• Satellite feeds for claims (drawn on by loss adjusters to reveal extents of damage) • Derived products - change detection (revealing erosion subsidence, land use/land cover change) • Asset identification (drawing on automated processes or manual analysis) • Archive data (can form inputs to machine learning processes) • Natural capital monitoring -loss/gain/condition

Cadastral/location Data/Topographic Data	• Accurate and up to date digital maps • Geocoding data - Boundary datasets, area codes, wards • Building footprints and other relevant BIM (building information management) data • Terrain data (Digital Terrain Models (DTMs), Digital Surface Models (DSM)) • Roads, rail, and other infrastructure • Identification of critical infrastructure (through looking at traffic data and human movements, supply chains)
Corporate	• Business activity • Audit data from clients (for companies seeking insurance) • History of companies - Distribution of company assets - Value of business - Legal proceedings filed against company • Commercial properties mix in area • Lines of business (for companies seeking insurance) • Supply Chains -revealing complex risks
Insurance Specific	• Flood-related claims • Exposure data -identification of assets in flood zones • Policy insight - premiums, cancellations and gaps in cover • CAT models • Modelling inputs from clients: - descriptors - location - type of asset - policy considered - 3rd party data
Social/Economic	• Human movements -footfall, use of coastal areas • Human Health -revealing health related impacts from flooding • Costs of rebuilding houses/structures • Integration of supply chains -vulnerability to disruption of business (past impacts, claims can be used as an indicator) • Demographics • Population distribution • Property/land values • Urbanisation -population concentration in urban areas, loss of natural habitat • Economic activity -identification of core industries, how flood events have impacted these. • Road use -traffic flow data

	• Recreation and tourism data • Spatialized indices of deprivation • Human behavioural data • ABM outputs -giving indications of cascading risks, adaptive behaviour, insurance policy take-up

Risk/Hazard	• Threat data -relating to flood hazards
	• Impacts and damage levels
	• Indicators of how buildings react to peril intensity
	  - Vulnerability characteristics
	  - Vulnerability classifiers
	• Key infrastructure at risk: roads, rail, ports, water, energy, telecoms, undersea structures

5.5.2 Data Access

There are many ways of obtaining data. Open source data can be obtained free of charge, whilst proprietary data can be downloaded, if a subscription is bought or a one-off payment made. Further to this, data can be 'scraped' from web sources (one insurer and one representative of an analytics company, reported obtaining data this way). This process can draw on hash tags and geotags and even involve scraping social media feeds for information related to hazards such as floods. Data obtained through social media sites (such as Twitter) are increasingly recognised as offering a valuable input to flood risk analytics and recently a number of studies have been undertaken focusing on this area (de Bruijn et al., 2018; Jongman et al., 2015; Smith et al., 2017; Wang et al., 2018). Another method of obtaining and delivering data, is web-feeds (such as Application Programming Interfaces (API)). It is possible to embed data feeds from external websites within a user interface or webpage. This has been reported an increasingly common method for many analytics firms to provide underwriters with data.

No value is derived from holding data which cannot be drawn on when needed though, and this can result in the data providing 'DRIP' support - namely Data Rich Information Poor (Wilding et al., 2017). To avoid this, careful consideration needs to be given to how the data can be utilised effectively. It is regarded essential to focus initially on data inputs, and to transform the data into a format which can be readily worked with. In some cases, this can necessitate seeking out those with specific scientific or technical background to interpret the data. Scrutiny of data sources is also important. When drawing on multiple data sources the work required to process these extends beyond shifting data into the correct format, to more comprehensive reviewing of the source and in some cases calibration and QA of the data used.

5.5.3 Internal data

Insurers hold valuable internal data which may relate to past impacts, claims, and performance. The main type of internal data referred to by parties interviewed, was claims data. This can include simple information such as loss coordinates, which prove valuable when assessing property underwriting rates for example. Claims data can further be used for predicting claims frequency and loss, however it is restricted, not always shared across a market and can vary in resolution (as reported by analysts questioned). Exposure data can also be classed as internal data, yet it is typically derived from clients. For property cover, exposure data can include location, building type, construction type, occupancy, and year built. Exposure data can prove problematic (as reported by insurers and analysts), in that it can differ widely depending on source and be hard to obtain. It can also prove difficult to determine if exposure data is accurate, as it can be vague, incomplete or not presented in a usable form. Aside from claims and exposure, another type of valuable internal data highlighted is that termed policy insights, this can detail factors such as premiums, cancellations and gaps in cover.

A number of the data analysts and actuaries questioned suggest that in dealing with internal data, an initial step may be to focus on structuring and standardising data capture, data cleaning and archiving. Data can be fragmented, with claims data restricted to a few lines of text, frequently including slang and poor spelling. This prevents machines from being able to process it in an intelligent manner. As such, simple analytical strategies have been adopted based around typologies and manual approaches, such as counting key word frequencies. Another challenge is that industry records often take the form of narratives. This presents a particular hurdle when trying to analyse systematically large numbers of records. In order to undertake statistical analysis, such qualitative information needs to be converted into quantitative data, to enable like-for-like comparisons. This can be summed up in the requirement for structured data capture. In some instances, advanced techniques can be applied such as Natural Language Processing (NLP), for location or argument extraction, for example (de Bruijn et al., 2018; Gritta et al., 2018; Roth et al., 2018; Wang et al., 2018). Changes in the methods of exposure data capture is also regarded (by a CAT modeller questioned) as one of many factors necessitating creation of associated standards.

Representatives from data analytics firms have reported problems in sourcing data from insurance companies, particularly around claims, where varying levels of information are made available. Given this, in some instances, loss adjusters have been used for supplying claims data, including companies such as Crawford and Cunningham Lyndsey. Supply of internal data has been highlighted by multiple practitioners as an issue restraining progress, especially given that it can embellish and validate analysis using external data sources.

5.5.4 Open source data

A variety of opinions on the use and value of open source data were encountered amongst those parties interviewed. Open source data can be viewed in terms of the broad possibilities it presents for data reuse, that is data collected for one purpose, yet made freely available to use for another. Many interviewees regard open source data as beneficial to their work, this can be due to funding limitations, which necessitate the use of free data wherever possible. Others believe that not only data should be made available open source, but also methods, as the available data may not always be the specific type needed. One true evangelist (a senior-level market figure) stated that Open

Data 'should be at the core of the data types available around the world, as it enables further innovation, with it being not just a public good, but a public requirement'.

In contrast to some of these positive sentiments, many challenges have been highlighted. When considering data obtained from a wide range of countries, there can be issues relating to data source and reliability. The level of data that is provided open source, and associated standards can vary significantly depending on levels of respective government funding. In some instances, the use of open source data is reported to actually involve higher costs internally, than drawing on well calibrated and regulated sources. This can be due to the data being incomplete, inconsistent and error-bound. In many instances, the user is said to have no concept of these issues until the data has been downloaded. Therefore, to obtain something of adequate quality, and completeness, much time may need to be devoted to searching. In many parts of Europe, freely available data is limited. Conversely, in the USA there are a plethora of sources of open data, but reservations have been expressed (by one data analyst) over the quality of this data and there being a lack of associated metadata provided. Insurers are said to require a comprehensive appreciation of what they are using, so in this sense (where metadata is lacking), many open sources are deemed unsuitable. Additionally, many insurers do not have the resources to address the inherent complexity of some of the open data outputs. Yet analytics firms have overcome this hurdle by outsourcing data processing tasks to lower income countries. To add to these challenges, non-public sector organisations are reported to be slow to open up their data or just fail to make any data available for free. This can be due to issues such as the need to recoup the costs of data collection.

Despite reservations on the use of open source data, there are a large number of Open Data sources now available, and this is increasing daily. For example, in the USA there are considerable data now available which can be used by insurers, such as that relating to wind, hail, fire, and crime. The UK is seen to be improving, especially in relation to datasets made available by the Environment Agency (EA), who have for example a detailed mapping program in place involving the collection of airborne flood-plain and coastal LIDAR data, which is freely disseminated. This can be used to consider building footprints and floods. The EA dataset, the Risk of Flooding from Rivers and Seas (RFRS), has been named as a valuable input by flood modellers, as have data on flood defences, such as, 1 in 5 year event defences, recently released in 2017. Yet some modellers report this defence data to be problematic, in that it can be incomplete. Aside from the UK, a wide range of global Open Data portals exist, a selection of which can be viewed on OpenDataSoft's website (https://opendatainception.io), in which over 2,600 sources are listed (Mercier, 2015). Also, an open source data search portal (https://toolbox.google.com/datasetsearch) has recently been released by Google (Castelvecchi, 2018).

5.5.5 Application of advances in Satellite Earth Observation (EO) Data

In the interviews conducted with representatives of organisations working with EO data, emphasis was placed on gaining an understanding of how EO data can be applied to the insurance of flood risks. Over the last 10 years the cost of satellite technology has reduced significantly. As such, many opportunities are arising to draw on the data products created by a new generation of satellites (Bowler, 2018), and through web-mapping interfaces, and API feeds, it is possible to leverage vast volumes of EO data. EO missions now have the ability to generate repeat coverage of the globe daily. This is even being achieved using low cost miniaturised satellites, by companies such as Planet, using its Dove, medium resolution platforms. Terrain mapping derived from higher resolution EO data (such as through stereo imagery techniques (DeWitt et al., 2017)) is now approaching that obtained from airborne LIDAR missions, with the added benefit over LIDAR of regular repeat imagery, for vast spatial extents. In the past EO data exhibited problems such as imprecision, yet now this has been largely overcome and there are a wide range of options that can be drawn on, such as multispectral imagery (visible, infrared, and thermal), radar, and microwave. Infrared EO data was reported useful by one flood modeller questioned as it deals with problems related to cloud cover. Near-infrared is well suited to delineating water bodies (Adam et al., 2014). Microwave and SAR (such as NovaSAR-S) also bypass cloud cover issues (Lavender et al., 2016), and have been applied successfully to flood mapping. Furthermore, microwave data is being used for near-real-time flood detection and mapping in the Global Flood Detection System (GFDS) (Jongman et al., 2015).

There are many low-cost providers of this data, with the European Space Agency's (ESA) Sentinel 1 providing free and consistent SAR data for the whole of Europe. To keep costs down one company reported that their insurance related baseline product is primarily based on free-to-access Copernicus Sentinel-1 data. One example of how this data is being applied to insurance is provided in the work completed by Hénaff et al. (Hénaff et al., 2018) who combined Copernicus elevation data with historical claims data to make predictions on global insured values in flood risk areas. For flood risk analysis, there are numerous opportunities presented by Open Access remotely sensed data (from a wide range of sources), such as relating to altimetry, Digital Elevation Models (DEM), optical, and radar images, (as demonstrated by Ekeu-Wei and Blackburn (Ekeu-wei and Blackburn, 2018)). The UK Space Agency is championing many innovative projects involving application of EO data to flood risk analysis (UK Space Agency, 2017a). One company questioned, Pixalytics, has been working with the UK Space Agency, in developing Virtual Water Gauge software which uses satellite altimetry to determine water heights in estuaries, rivers and lakes, and has been used for analysis and detection of flood events (UK Space Agency, 2017b). Besides drawing on free to use EO data, many companies are also drawing on open source software where possible (Albano et al., 2017; Joseph and Kakade, 2014) (so lowering costs further). A prominent open source software drawn on for modelling flood inundation is LISFLOOD-FP (The University of Bristol, n.d.), this has frequently been combined with other free to use software in completion of coastal flood risk assessments using EO data (De Angeli et al., 2018).

Research and development in this field is continually generating innovations increasing options for application of the technology. Easily accessible user interfaces, such as Google Earth Engine, can enable a vast archive of EO data from different sources to be mixed as required (without cost). Firms also have been supplying SaaS (Software as a Service) platforms enabling clients to test the effects of new and existing insurance policies. One field advancing rapidly is interferometry. The technology can be used to assess the risk of subsidence and can monitor millimetre changes in land height (Ramieri et al., 2011). Other emerging areas such as the use of Stereo imagery techniques, are being applied to flood risk assessment (Mashaly and Ghoneim, 2018), these techniques are being used by DigitalGlobe and Terrabotics, to generate 3D images from satellite data, and can be used to look at steep slopes and build terrain datasets with sub-metre accuracy. If insurers have high-risk areas which need monitoring, they can also commission satellite missions in advance, to capture detailed, high-resolution data. Furthermore, a recent innovation implemented by the company Earth-i allows colour video to be captured from space (Werner, 2018). This may prove useful to loss adjusters, for example, in analysing disruptions generated by flood events.

Automation in the processing of EO data is resulting in huge reductions in the time spent working with the raw data. Automatic change detection is possible, for assessment of flood risk and extents (Geller, 2017), and Artificial Intelligence (AI) techniques are being used to identify flooded houses, blocked roads and bridges, and estimate depth of flood waters (Grason, 2018). Examples provided by DigitalGlobe reveal how precise damage to properties can be quantified. And in relation to their WorldView satellites, automated processes have been deployed for tasking satellites to acquire images of areas impacted by flooding, based on interpretation of social media data (Cervone et al., 2016). This is important as flood impact mapping needs to be reactive, which makes manually tasking satellites in advance difficult. Companies are moving away from manual processing of EO data, through automation possible in the cloud (Tsarouchi, 2018). Geospatial service frameworks have been developed which allow parallel processing, expandable on multiple instances within the cloud; this was reported by one firm to 'cut processing times by an order of magnitude'. One EO data analytics firm report to have developed a cloud-based parallel processing platform, drawing on a wide range of sources, including those of Airbus and DigitalGlobe. This platform is reported to cut EO data processing times significantly. Cloud-based platforms can also facilitate implementation of both traditional algorithms and Deep Learning techniques (Chen et al., 2018; DigitalGlobe, 2017).

For the insurance industry satellites can be used in disaster response, exposure management and for underwriting solutions. Satellites have been used as a remote validation tool, to contribute to audit trails and to take the place of site visits (Lloyd's, 2018a). One benefit of this is that EO data is impartial and unbiased, and just reveals what is on the ground. Furthermore, it is being combined with on the ground intelligence and Internet of things (IoT) monitoring outputs. One company, Sensonomic, is drawing together such data sources within ABMs to reveal behavioural interactions between individuals and organisations, which can generate answers as to what drives risk exposure. Such modelling processes also benefit from fusing EO data with insurers' internal data such as claims, to refine, calibrate and validate outcomes.

Within Lloyd's, claims teams have been drawing on EO data following a spate of recent hurricanes in the Caribbean and the USA, to assess damage (Lloyd's, 2018a). Analysis completed, post Hurricane Matthew (which first made landfall over Haiti on 4th October 2016), highlighted damaged properties in the wake of its path. Satellite imagery was also utilised to monitor the devastation reaped by hurricanes Harvey and Irma (Lloyd's Market Association, 2017) (which made landfall on 18th August 2018 and 5th September 2018, respectively). Similarly, firms supplied loss adjusters with imagery of the situation on the ground between hurricanes Irma and Maria, so they could check damage, and place losses appropriately (Lloyd's, 2018a). Obtaining such detailed satellite imagery, representing specific flooded locations, has proven possible, yet can be costly, due to requirements for tasking satellites to focus on desired locations. One firm (McKenzie Intelligence Service) is reported to have combined satellite imagery with CCTV footage, so street level damage could be viewed. Feedback received from the market indicated that this was useful. Combining EO data with other ground-based sources, is important and can be essential for ensuring its validity and usability. Sources such as CCTV footage, river level gauges, and images uploaded to social media platforms, have all been used to compliment and validate EO data. Many insurers have expressed interest in using EO data in the future, and satellite data has frequently been drawn on as court specific evidence given its high validity. There can be issues in application of the data though; one EO data analyst reported encountering licencing problems when providing EO data for insurance use. Yet, despite such issues, both image and radar data (in particular) are shown to provide insurers with a wide range of possibilities, involving using solely the raw data or thematic data derived through the application of automatic classification. However, to-date, the insurance industry has proved slow in adopting EO data and derived products.

5.5.6 Big Data Opportunities

A recent report by the American Academy of Actuaries stated that 'The combination of powerful computers and "Big Data" has transformed understanding of hazards such as flood'(The American Academy of Actuaries, 2017). 'Increased computing power and availability of higher detailed harmonised datasets' has also been acknowledged as enabling detailed flood analysis at various spatial scales ((de Moel et al., 2015), p.882). One CAT modeller interviewed, concurred with this, and stated that Big Data has improved their modelling work, particularly for floods, and as a result higher levels of precision are possible. The term Big Data does not only apply to large data Volumes but also large Varieties and Velocities of data (termed the 3Vs of Big Data) (Jagadish, 2015). This involves the ability to store, process and analyse structured and unstructured data, combining archive and real-time streaming data (Jagadish, 2015; Marr, 2015). The data is generated from a wide range of sources and is increasing in availability (much of it being open source). For example, these can take the form of more conventional data such as database entries, stored in Relational Database Management Systems (RDBMS) or real-time streaming data being generated by IoT sensor networks, satellites (Maier et al., 2012; Moszynski et al., 2015; SmartBay, 2017), and websites (Singhal et al., 2018). Big Data is reported as being widely applied within risk analyses (Choi and Lambert, 2017). In attempting to understand how the various fields associated with 'Big Data' can relate to an industry such as insurance, a framework is provided below in Table 15. This framework provides a chronological listing of stages associated with aspects of Big Data. These phases align with the data utilisation stages outlined in Figure 27.

Table 15: Big Data Framework

Stage	Processes	Considerations
1. Data source awareness	Data collection	• Inclusion of holistic data variables • Availability of open source data • Internal datasets -claims data (unstructured/semi-structured) • Archive/real-time streaming data • Utilisation of emerging data sources - IoT - Social media - Satellite EO - Mobile telematics - Free text (emails, web logs, transcriptions, notes) • Data source veracity
2. Accessing the data	Data Ingestions and Storage	• Database choice: RDBMS or distributed database (SQL or NoSQL) • Storage solutions: on premise/cloud/hybrid cloud • Requirements for permanent/on demand (elastic) processing capacity • Cloud vendor selection • Data Warehouse/Data Lake • Data security
	Selection of software infrastructure; data processing requirements	• Database software selection based on data types (structured/unstructured/semi-structured) • Parallel processing options and requirements (availability of compute power) • Open source/proprietary software? • Automated processes for data ingestion and collation • Streaming data processing • Processing and analysis requirements for different data formats: free text, graph, audio, point cloud, imagery, video

		• Geocoding: by address, postal delivery code, boundary, geotagged data, geoparsing
3. Using the data to generate information	Analytics and knowledge extraction	• Possibilities for advanced geospatial analytics • Options for drawing on graph, text and time series analytics • Ability and requirements to run distributed batch processing tasks for compute intensive workloads (e.g. for actuarial calculations) • Artificial Intelligence and Machine learning's role – discovering patterns (claims), feature detection, classification of land use/land cover, change detection (buildings/infrastructure) • Vast quantities of EO data stored in the cloud, used for training machine learning algorithms for flood and impact detection • Cloud based parallel processing facilitating development of Deep Learning techniques (DigitalGlobe, 2017) • Computer Vision applied to video/image analysis -to detect flood extents and damage post event • The ability to derive meaning from unstructured messy data through NLP and other techniques • The ability to combine real-time streaming data with archive data • Deployment of Artificial Neural Networks (ANN) for real-time flood inundation modelling (Chang et al., 2018) • Development of automated workflows for targeted collection, processing and analysis of data (i.e. satellites tasked to collect data for flood sites based on analysis of social media data (Cervone et al., 2016)) • Application of text analytics (e.g. NLP) to claims data • Application of predictive modelling functionality, for example involving: Linear Regression, Logistic Regression, Decision Trees, and Random Forests. • Developmental opportunities available using programming notebook interfaces such as Apache Zeppelin

		(https://zeppelin.apache.org) and Jupyter (https://jupyter.org/index.html) • Means to validate analytical outputs
4. Knowledge communication / dissemination	User interfaces and data visualisation	• Web based user interfaces • Graphical User Interfaces (GUI) • Live data feeds incorporated into interfaces • Outputs of on-the-fly analysis available to users (e.g. for analysis of impacts and claims data) • Advanced intuitive dashboards • Advances in 3D visualisations of geospatial data • Virtual/Augmented Reality • SaaS

To enable external and internal data related to insurance to be analysed and knowledge extraction to take place (Stage 3) it is necessary for data to be stored and processed in an effective way (Stage 2). Technology firms provide infrastructure and software tools to enable this, many such as Hortonworks and Cloudera base their solutions primarily on software developed by the Apache Software Foundation (The Apache Software Foundation, 2018). This software is open source and is the product of the interactions of over 30,000 contributors who commit code to Apache projects. The software tools and technologies include Hadoop, MapReduce, Apache Spark, Nifi, HBase, Hive, MongoDB and many others. The software forms an 'ecosystem' (Marz and Warren, 2015) in which different functions are performed by individual software elements, relating to distributed storage and processing, data mining, analysis and ultimately query and knowledge extraction. The analytics firm LexisNexis provide an open source alternative to some of the Apache software, in their HPCC Systems (LexisNexis, 2018).

In relation to knowledge extraction, a wide range of analytical tools are drawing on 'Big Data' in attempting to better understand risk. Techniques such as machine learning are increasingly being looked to (Peters, 2017). This is an area in which vast stores of data, now available, such as that generated by satellites, can be combined effectively with insurer's internal data. Geocalibrated claims data, for example, have been drawn on to verify and calibrate machine learning algorithms developed to make flood predictions, using EO data (Hénaff et al., 2018). There are also examples revealing how ANNs could be adopted for spotting patterns, and understanding relationships between data variables, such as those related to environmental hazards (Bezuglov et al., 2016; Chang et al., 2018; Joseph and Kakade, 2014). It is becoming increasingly possible to draw on alternative data sources in analysis of flood events. This can take the form of mining social media data, such as Tweets, using geoparsing to extract location data (de Bruijn et al., 2018). Making sense of large quantities of unstructured data is a huge challenge and techniques such as NLP, geocoding and Computer Vision, have been employed to extract flood-related data from social media (Twitter) and crowdsourced data (from Mycoast (https://mycoast.org)) (Wang et al., 2018). This field is in its infancy though, and the study by Wang using Computer Vision for urban flood modelling is reported to be the first of its kind (Wang, 2018). Other examples exist revealing how microwave EO data, has been combined with social media data to map flood impacts (Jongman et al., 2015). In fact, Twitter data is emerging as a useful source to combine with EO data, and other data inputs, to reveal extents of flooding in near real time (Li et al., 2018; Panteras and Cervone, 2018).

The emergence of modelling processes focusing on human behaviour was introduced earlier, this is an area which social media data is also forming a valuable input. Du et al (Du et al., 2017) demonstrate this in their model of individual flood evacuation behaviour, in which they also focus on transport networks. Outputs of such analysis could prove useful for revealing flood-related infrastructure stresses and disruptions. For example, this can relate to a single flood event, generating a multitude of secondary impacts, such as disruptions to business, supply chains, and utilities failures. Examples, such as that provided by Papadopoulos et al. (Papadopoulos et al., 2017) demonstrate how large quantities of unstructured social media data, can be drawn on effectively to improve resilience of supply chains and critical infrastructure. Having access to large stores of data, covering a wide range of themes could prove instrumental in understanding the factors involved in systemic risk scenarios, such as those provided within the simulated catastrophe stress tests performed by Lloyd's (the Realistic Disaster Scenarios (Lloyd's, 2018b)).

Internal data such as claims information, detailing past losses, play a vital role in the validation and calibration of new analytical techniques and models (Christie et al., 2018; OECD, 2016), and as such a lack of data relating to past insured losses can prove a factor limiting their development. Claims data has been drawn on successfully to validate flood and hydrological models such as the 2D BASEMENT simulation, by Zischg et al. (Zischg et al., 2018). EO data now available, revealing impacts, are also being drawn on to validate flood extents, and in predictive modelling of flooding (Ekeu-wei and Blackburn, 2018; OECD, 2016). This data is particularly useful for more remote and developing parts of the world where traditional datasets are lacking (Ekeu-wei and Blackburn, 2018). Lavender et al. (2016) indicate that data mining methods have been utilised to obtain the required EO data, this can be essential given the data volumes involved.

In addition to the 'Big Data' sources already mentioned, the Internet of things (IoT) is a rapidly emerging field which holds promise, to create 'Smart Insurance', in which polices can be based on detailed historical datasets generated by networks of automatic sensors embedded in homes, businesses, machinery and infrastructure. The sensors or 'things' are uniquely identifiable and connected to the Internet, with 'sensing/actuation and potential programmability capabilities', and data generated by these 'things' can theoretically be collected 'anywhere, anytime by anything' (Hassan et al., 2018). For example, the real-time data made available through IoT devices connected to cloud services, can be used to give updates on the severity of disaster events in real time. Cases, such as that provided by Koduru et al. (Koduru et al., 2018) reveal how such IoT networks could be applied to insurance of flooding and other disasters. Feedback received during interviews with insurance practitioners highlighted how insurers are currently engaging in Proof of Concepts (PoCs) with analytics firms, which involve use of IoT data and sensor deployment. These PoCs concern multiple lines of business, not just flooding, and there appears an appetite to fund future use and deployment of IoT sensors, if insight generated through their use proves effective. For example, if data feeds obtained from these sensors, proved reliable enough to be used in policy pricing or loss assessments, this could justify their utilisation.

In respect to flooding, one area of IoT application is monitoring of storm surges and water levels. In the USA this has been demonstrated through 'StormSense', which has been deployed as part of a smart cities initiative, for real-time monitoring of flood events, and has provided data inputs to subsequent inundation modelling (Loftis et al., 2018). A benefit of IoT is that the sensors can prove cheap and reliable and their outputs can be effectively combined with, social media, crowd sourced, and remote sensing data, for evaluating flood risk in densely populated locations such as 'mega-cities' (Ogie et al., 2018). However, such diverse, and dense data streams are associated with a range of uncertainties and can contain spurious and incomplete data. Given this robust methods are required to fill the gaps and to interpolate and infer values where data is missing or unreliable (Koivumäki et al., 2010). Monrat et al. (Monrat et al., 2011) set out one way of dealing with such uncertainties, for data relating to flooding, using a Belief Rule Based Expert System (BRBES) with Apache Spark, generating real time flood maps. Their Big Data platform enables replicated storage of vast quantities of data in separate nodes to ensure data integrity and fault tolerance. This allows the data to be analysed by the BRBES, which tackles inherent uncertainties. Examples, such as those detailed above, indicate how advances in collection and analysis of Big Data can potentially be drawn on to enhance flood risk analyses processes.

5.5.7 The use of Data Analytics for insurance

Of the companies involved in modelling and insurance specific data analytics interviewed, their areas of focus were: CAT risk modelling, general insurance analytics, geospatial threat analysis, flood risk modelling, and property analytics. Feedback supplied related to sources of data drawn on, methods and technologies used, and data innovations being implemented.

Analytics firms interviewed acknowledge the requirement to draw upon and fuse data from many different sources and typically state they are data agnostic. A necessary consideration is that data from disparate sources come with varying standards. In dealing with this issue, many such as one geospatial analytics firm questioned undertake extensive data cleaning. Furthermore, a CAT modeller highlighted how new standards for data capture can be required to enable so many sources to be combined: 'due to changes in exposure data capture, having standards becomes necessary'. Given the wide range of data being drawn upon, data aggregation becomes increasingly important. This was reported a goal of multiple insurance analytics firms, who build databases from insurers' internal data in addition to leveraging open source data. There are many further issues which require consideration, such as compatibility of the data being used;

it is also necessary to focus on data granularity. One CAT modeller, who engages in flood modelling, specified how they require data at an individual property level for their analysis. For example, adaptations implemented at both a regional and household level need to be accounted for in insurer's flood risk calculations (Garvin et al., 2016; Osberghaus, 2017; Thistlethwaite et al., 2018; Yang et al., 2018). This can necessitate incorporation of more granular data, enabling variations in risk exposure, over smaller distances, to be realised (Schwartz, 2018) (as illustrated by an example taken from the Netherlands (Jongman et al., 2014)). Scale was noted as a significant issue in relation to insurance risk assessments. Risk has been aggregated at the level of postcodes in England (Dávila et al., 2014), yet now flood analytics firms are producing assessments at a household level (Garvin et al., 2016). This is benefitted by advances in satellite radar and LIDAR data collection techniques, resulting in detailed terrain data now being made available by commercial suppliers, with quoted resolutions of up to 1 meter, globally (Intermap, 2018).

Many geospatial analytics firms report to be actively engaged in seeking out new sources of publicly available data including satellite imagery, LIDAR data, and private drone footage. Yet satellite EO data has not been widely drawn upon to-date, by the insurance specific modelling firms interviewed. Feedback indicated that this can be due to scepticism on its application and reliability. Insurers questioned, highlighted a requirement for line of business and peril specific use cases, demonstrating proven suitability of the technology. However, one property analytics firm stated, that in their analysis they draw on multiple kinds of EO data, such as multispectral and satellite radar imagery, to allow assessment of the impacts of flood and fire events. For the UK, publicly available data such as that made available by British Geological Survey (BGS), and the EA, are drawn on by many modelling firms. Several of these sources provide real-time data feeds (e.g. web services), these are increasingly being incorporated in models, such as those provided by one insurance analytics firm questioned. Many of the general insurance analytics firms are developing solutions for bringing together both insurer's internal data and external sources, and in doing this, harmonising data standards.

There are many similarities between the types of analytical methods employed by firms. Their methods are seen to have common goals such as enabling underwriters to screen and price risk, through provision of common loss metrics. From the responses received, location data stands out as being especially important. Many firms specialise in dealing with location data such as one property analytics firm, who host location, building, environmental and financial data. Location-based analysis also provides a prime focus of a geospatial analytics firm, who provide exposure management for underwriters. Determining the accurate geographic locations of risk is regarded as crucial by insurers, this hinges on the ability to geocode correctly, especially for accumulation calculations, for which an accurately geocoded source of data, such that relating to buildings, is deemed essential (Garvin et al., 2016). The process of geocoding aids geospatial analysis of risk and is particularly useful for flood risk analytics (as reported by a flood risk analyst). Understanding the geographic distribution of risk was reported a particularly important aspect of analysis carried out by CAT modellers, with one CAT modeller highlighting the importance of geospatial risk analysis in enabling individual locations to be focused on in calculation of risk premiums. As such, Geographical Information Systems (GIS) are a software tool widely used by many insurance analytics firms and are utilised to generate property risk profiles based on geospatial attributes.

Probabilistic modelling techniques drawing on statistical and mathematical analysis, form a central component of the methods used by most firms. These have commonly been coupled with depth damage curves (André et al., 2013; Dávila et al., 2014; de Moel et al., 2015; Hsu et al., 2011; Penning-Rowsell et al., 2013), in making predictions of financial impacts of flooding. Companies also increasingly draw on emerging techniques, for example a CAT modeller reported using Computer Vision to detect damage to an area post event, whilst one general insurance analytics firm reported making attempts to improve the underwriting process by applying machine learning to claims prediction, renewals and accumulation reporting. Open source tools are being made available by a number of firms. This includes a CAT modelling software platform (provided by a CAT modeller questioned), which draws on probabilistic methods such as Monto Carlo simulations, reporting hazard intensities, exposure and probabilities of loss at specific locations. More general open source software was also reported as being used by many firms, such as MongoDB, a NoSQL document-oriented database. Some firms have developed extensive in-house software capabilities. For example, one insurance analytics firm has created their own open source Big Data analytics platform. They report drawing primarily on their own technology, using many 'scalable automated linking technologies', which can be statistical based, incorporating probabilistic functions.

An increasing number of firms are adopting the cloud to host and deliver their solutions, and multiple analytics firms have reported migrating data currently stored in local servers to cloud environments. Many of the GIS solutions one property analytics firm operate draw on the automation and scalability possible in a cloud environment, to enable high-resolution geospatial data to be accessed in real-time via web mapping interfaces. One CAT modeller stated that all their 'future development will be completed in a cloud environment', as 'clients want to be able to access big data at scale from across the enterprise, and the cloud allows this'. Additionally, machine learning is deemed much more suited to the cloud due to the possibility for on-demand scaling of compute power. The cloud has not been adopted by all though and many such as a flood risk analytics firm, use their internal data centres to host modelling data, whilst another Insurance analytics firm reported using a conventional data warehouse. In relation to distribution and visualisation of analytical outputs, companies commonly provide their outputs as web-feeds or in the form of GUIs. Numerous analytics firms provide insurers with API feeds so that analytical outputs can be incorporated within existing dashboards. SaaS provision was also reported to be increasing in popularity as a delivery mechanism for risk analytics. This can allow firms to run their analytics solutions in a web browser. SaaS options can also allow providers to implement updates remotely, and to bypass compatibility requirements for integrating their solutions with an insurer's internal IT systems.

5.5.8 Communication of Information Outputs: Underwriting

There are a range of core roles within the insurance industry who are heavily reliant on data in analysis of risk. Among these actuaries and underwriters stand out as the most prominent. Within the feedback received during interviews, the role of the underwriter was focused on, as such, the following discussion covers some data specific aspects related to underwriting. The process of underwriting risk is a fundamental function within the insurance industry and involves risk selection and fast decision-making. However, the process is not always transparent, with underwriters regarded as utilising their own internal intelligence and idea of cover price. Some have even claimed that 'underwriters innately know risky places' (as reported by a senior insurance practitioner). Insurance cover results from interactions between underwriters and brokers. Moreover, both broker and underwriter need to have a firm grasp on how technology can be drawn on to generate answers.

The underwriter decides on the cover a client is happy doing business with. To enable them to do this they require access to tools, such as an electronic dashboard which can generate answers based on entering simple identifiers. Information supplied to the underwriter can be taken into consideration in pricing models. For example, CAT models enable underwriters to distinguish what and where to insure, geographical spreads, transfer of risk, and financial strength. Their challenge is added to by the practicalities of the underwriting process, resulting in individual underwriters not always being aware of the wider risk picture, such as that associated with cascading and systemic risks.

A challenge for underwriters and those providing them with information (which has been continually repeated by those interviewed for this report) is the lack of time underwriters have to make important decisions and to review information. One particular challenge is how data is served at the point of decision-making, given that underwriters may have only minutes to price risk and decide on cover. Such quick decisions do not allow time for underwriters to review the data in great detail. Underwriters consulted report the need to set up in excess of 500 deals per year. Given this, they are unable to devote time to navigating complex user interfaces to retrieve information. Therefore simple, intuitive dashboards are required, presenting a clear view of loss. This requirement has prevented organisations, such as one analytics firm questioned, from implementing GIS tools for underwriting, which they deem are better suited to be used by modelling teams. GIS applications have proved overly complex to be utilised for underwriting and can place constraints on teams. Abstracting this complexity is deemed a requirement, as underwriters require distilled metrics at their disposal.

One underwriter noted 'A few pieces of choice information can change an underwriters mind'. As such, more general data is required at an actuarial level, than is needed by underwriters who require more granular specific information on facilities and clients. A core requirement is for the potentially huge amounts of data available, to be turned into something useful. Provenance of data sources is also important. Underwriters questioned have stated how they draw on information obtained from internet search engines and geospatial information obtained from Google Earth. Mapping platforms such as Google Earth, are being used by underwriters to gain an understanding of properties, building materials, roof types, among other features. Yet, information in web-mapping applications aimed at the general public, can be out of date or poorly presented. Google Earth is undoubtedly a useful resource, but images can be many years out of date.

5.5.9 Challenges

Many challenges to the effective utilisation of data have been established from feedback provided from those working with and using data types such as those listed in Table 14. A number of challenges have been detailed in the previous sections, some of the more prominent of these are expanded on here.

Core inputs to CAT models have been reported as difficult to obtain, especially those with the appropriate level of detail and in a usable format. Such inputs include information on the built environment (for certain countries) and calibrated loss data. Many UK insurers and analysts are said to struggle with local authorities not providing them with the information they need. Builders have also been highlighted as not wanting to share information, with those such as flood modelling companies. Yet information relating to new housing developments (for example) is important, especially when used in response to CAT events, where environmental data needs to be merged with information about buildings, and other factors, to produce loss estimates.

Many challenges have been reported when trying to obtain datasets for a wider range of countries. Whilst the UK, and parts of the USA, have 5m resolution flood data, from which depth of water can be estimated, attempting to source data for Africa and Eastern European states was reported, by multiple flood modellers questioned, to be difficult. Insurance cover is increasingly being provided in geographical areas where policies were not written previously. These new markets can pose fresh challenges, especially in relation to data standards and availability. As such, it has been reported as difficult to obtain the required datasets for modelling risk in some lower income countries. Nevertheless, a range of opportunities are presented by emerging sources such as EO data, to obtain global datasets (Ekeu-wei and Blackburn, 2018), many of which are available open source.

States, such as the USA, who provide an extensive variety of open source and proprietary datasets, may fall down in certain areas such as provision of geological data, where experts in geology who compile the datasets may not have adequately considered how clients want to use the data. This is a common problem reported by analysts, for scientific datasets in many countries, where some government sources are said to release maps that are not usable, due to problems with complexity. Another factor reported as presenting a barrier to utilising international datasets is language, this can necessitate diverse translation requirements and additional time and resources being devoted to processing data inputs. A common problem encountered, when obtaining data for different regions, is with data existing in various formats and levels of completeness. Data needs to be transformed to regular formats, which can be a time consuming and burdensome process, although many tools are available to facilitate this. Analysts have stated that if these tasks could be pooled by a central body, it would result in time and cost savings, avoiding duplication of efforts. The London Market Target Operating Model (LM TOM) (https://tomsupports.london) is one example of such an industry wide initiative. This relates to data capture and access, involving creation of a central data repository. This was greeted with enthusiasm from those spoken with from across the market. Private initiatives have also emerged which are seeking to address these challenges, such as Oasis Hub (https://oasishub.co).

One specific problem highlighted is that many who make decisions based on data can be unaware of the limitations of the data they are using. As a result, too much confidence can be placed on the data, resulting in skewed scenario creation. Scepticism was voiced by many well-established insurance practitioners, about the use of data and reliance on models 'bought, but not understood'. In line with this, many have stated that there are ingrained attitudes held within the industry that may act as a barrier to changes being implemented. This has been cited as a factor contributing to slower take up of technological developments in the insurance industry compared with other areas of financial services, such as investment. Furthermore, one supplier of technology stated that they can use 'most of their time educating insurance syndicates, and more than actually supplying products'.

From a data-driven perspective, insurance is seen to be behind the times (Miller, 2018), in its reliance on generalised linear models, and expert opinion, such as that of warranty surveyors. This can be especially so for risk engineers, whose main tools are qualitative, with expert judgements, and surveys with clients, determining if engineers should be sent to a site. For many it may appear simpler and more reliable to resort to drawing on expert opinion instead of using unknown data analytics methods. Unfortunately, expert opinion has proven an inadequate method for capturing the dynamic nature of many risks. Drawing on larger empirical datasets in evaluations, can allow fairer pricing of risk and data signals can act to allow filtering of portfolios. Yet, a lack of knowledge sharing, across the industry, is said to pose a barrier to this.

Adoption of the most appropriate technologies by insurers has also been flagged as an issue (Libarikian et al., 2017). Data analytics firms report that many clients in the insurance industry are currently using outdated IT, and that they (the analytics firms) are not in a position to enforce change. Many firms admit to being in their infancy in the use of advanced data techniques, especially in relation to their own data (Heale, 2014). Yet consideration of advanced methods, such as those detailed in Section 5.5.6, can prove essential in understanding how complex hazards translate to loss, generating the resulting financial impacts. In line with adoption of such advanced forms of analytics, many believe that in the future data scientists and actuaries should work more closely. For example, benefits could be gained through data scientists drawing on actuarial understanding of the data, and mixing this with modern techniques, ensuring risk selection is closely aligned with risk profiles.

Innovations, such as the use of flood maps, have been reported as altering the fortunes of those covering this peril. Furthermore, underinvestment in flood modelling has been reported, by a senior figure in a flood modelling firm, as contributing to some of the highest profile losses sustained by insurers, over the last twenty years. As such the OECD have cited the lack of high-quality flood maps, in some countries, as an impediment to effective financial management of flood risk (OECD, 2016). Yet, the adoption of geospatial data analytics has altered risk ratings for many areas. Geospatial data sources are now capable of supplying insurers with high resolution datasets at an individual building scale. This can enable differentiation of risk premiums at an individual policy level. Effective use of geospatial data can potentially allow more stable areas to be identified within high-risk zones, which can allow companies to be more aggressive in pricing policies covering these areas. The opposite can also be the case with higher risk areas being identified (Collinson, 2017) and potentially avoided.

5.6 Discussion

The previous sections have presented a critique of how data is currently being used within risk analytics covering environmental perils (primarily flooding). This was primarily based on feedback received from those working in and associated with the London Insurance market. Within the London market (and Lloyd's) there is a shift to digitalisation and adoption of modern practices (Carnegie-Brown, 2017; Tischhauser, 2017). Initiatives to maximise the potential offered by data, such as the ongoing LM TOM are evidence of this. Adoption of new methods and techniques have been witnessed at various levels within organisations, data entry teams are building and adopting new tools, and it has been acknowledged that data capture and processing tasks need standardising. Many insurers are actively engaging with analytics firms seeking to apply new technologies to insurance use cases. Furthermore, the development of 'Insurtech' is evidence of the widespread impact which digitalisation is having on most aspects of the insurance industry (Stoeckli et al., 2018).

In terms of deriving value from data, four key aspects were highlighted by the authors (detailed in Figure 27): 1. knowing data is there; 2. having access to it; 3. making sense of it, and 4. using it. In the following discussion themes relating to these areas are covered in detail.

5.6.1 Data (knowing it is there and having access to it)

In evaluating insurance-related risk, the value derived from internal industry data can be maximised when it is combined with external feeds (Deshpande, 2018; Zischg et al., 2018). Furthermore, data is becoming available that can remove ambiguity in the pricing of risk, this can relate to new methods of data capture, such as that from IoT devices, satellite-based sensors, the internet (e.g. social media), and initiatives resulting in data sharing. However, an understanding of data veracity (i.e. data quality, source and validity) is essential before a decision is made to use the data. Also, the complexity of some data sources can necessitate specialist interpretation before they can be used. The increasing availability of open source data presents an opportunity to enrich analyses of risk. This open data can spur innovation, acting as a raw material to enable development of new forms of analytics. As such, many firms report to be actively engaged in seeking out new sources of publicly available data. Yet there can be limits imposed on the use of open source data, including: lack of data for some regions and countries, poor data quality, and a lack of accompanying metadata. Specific requirements which have been repeatedly highlighted are for standardisation and structured data capture. Furthermore, in some cases application of advanced methods such as NLP could enable narratives and qualitative data to be systematically analysed.

5.6.2 Analysis (making sense of the data)

Insurance data analytics should involve fusing data from many sources, providing a holistic view of risk. Techniques becoming available, can enable datasets collected for one purpose to be reused and combined and offer potential for higher-level insights to be derived. Examples have been provided illustrating how EO, IoT, and social media data have been utilised in such a way. Location data has been highlighted as important and can reveal the geographic distribution of risk. In line with this, GIS is regarded a suitable software tool and is widely used by many insurance analytics firms. For flood risk analysis it is especially important to consider the granularity of data drawn on, and if this is adequate to reveal household level risk, and to account for localised or individual adaptation measures. Furthermore, flood risk maps used by insurers need to include data on adaptations (updated regularly) (Beck et al., 2018; de Moel et al., 2015). In relation to property level adaptations, this can necessitate development and consideration of associated standards (Bonfield, 2016). Data related to human behaviour also represents an important factor, which should be included within analysis, and can alter predicted risk ratings for areas. ABMs have been highlighted as one tool which can be applied to this area.

With the volume and variety of available data sources rapidly expanding, an overview of the potential storage options, software infrastructure, and processing techniques, is required so that data can be handled and retrieved in an efficient manner. This work generated some limited findings related to the use and suitability of Big Data and cloud technologies. Open source modelling software, such as that provided by the Apache Software Foundation, is both provided and being drawn on increasingly. There is also a rise in open source flood modelling software being developed, an example of such is *FloodRisk* (Albano et al., 2017). A growing number of firms are now looking to the cloud to host and deliver their solutions, due to on demand compute power, automation, real-time data access, and options to undertake data mining and machine learning (some of which utilises vast global archives of satellite data). Automation possible in cloud environments can also reduce requirements for manual intervention, potentially lowering costs. Yet many in the industry are still wary of shifting data to the cloud, for example, due to security concerns.

5.6.3 Communication (using the outputs)

In considering how data is consumed, the work has focused particularly on the requirements of underwriters. Yet the wider issues raised also consider the needs and requirements of other key actors, such as actuaries, brokers and loss adjusters. Irrespective of user's role, a thorough appreciation of user requirements and level of domain expertise, is required, so value derived through the previous analytical steps is not squandered. A requirement has been identified for those with knowledge of how data is consumed within the industry, to act as an interface between insurers and more specialist data analysts. Also, it is important to communicate, to those making decisions based on data, the range of available data sources and their limitations. There is a heavy focus, by many analytical firms on methods of delivering their outputs; outputs are being provided as web-feeds or in the form of GUIs. Additionally, SaaS is increasing in popularity.

5.6.4 Challenges

This research highlights how progress is being made in adoption of new data sources and methods within the London market, however there are numerous challenges related to the use of data and analytics which need to be addressed. Insurers have yet to fully embrace the wide range of opportunities presented by data innovations. The industry (particularly the London market) is deemed by many to operate in an old-fashioned manner and the way data is consumed can be outdated. In many instances, a heavy reliance on expert opinion, qualitative evidence and subjective judgements, has been revealed. Nevertheless, emerging data sources have been identified, which can augment or displace some traditional methods and expert opinions. Furthermore, it is now possible to draw on large (real-time) datasets, linked to actual events, which can displace some in-use analytical methods reliant on statistical sampling. Through the application of advanced analytical processes information outputs can be generated from this data, which can replace gross assumptions, inherent in previous and current assessments of risk, and in doing so reduce uncertainty.

5.7 Conclusion

Effective insurance can act as both as a measure to distribute, and a method to communicate risk. In relation to coastal flooding hazards, insurance has been clearly identified as one potential resilience increasing mechanism. In addition to insurance providing a safety net, if premiums are risk-based, it can also serve as a signalling mechanism, communicating levels of risk. However, insurance markets need to be freely functioning in order for them to fulfil this role. Examples have been provided within this paper of how market distortions are common in many countries, which can preclude risk-based pricing of flood insurance. This can act to reduce insurance's ability to incentivise risk-averse behaviour, as can a lack of insurance coverage, and flooding being bundled with other perils. However, for insurance to operate effectively and mitigate risk, it is reliant on the provision of accurate data. Such data can also reduce information asymmetries and has a central role in revealing exposure and ensuring policies are appropriately priced. This topic formed the main focus of this paper, and extensive interview-based research was undertaken, centring on the use of data within the London insurance market. In discussing feedback received, the process of data utilisation was split into a number of stages. These were: a. data sources, b. data access,

c. data analytics, and d. communication of information outputs. Each stage was considered in turn, and associated challenges and opportunities highlighted.

Through focussing in detail on how data is utilised in insuring risks, it is deemed possible, by the authors, to optimise insurance's role as an instrument to mitigate risks associated with environmental hazards and other perils. A range of opportunities are presented by the increasing availability of 'Big Data' sources, advanced data mining and analytical techniques. Social media, EO, IoT, and crowd sourced data can be drawn on to provide more granular, higher resolution, up-to-date intelligence about environmental risks and their consequences. More traditional sources of information, such as claims data, still prove invaluable, and new techniques can be drawn on to improve how these are utilised. Advances in the field of 'Big Data' management and analytics, can allow vast bodies of archive and streaming data (in a variety of formats), to form an evidence base for insurers to draw on. This can result in empirical data forming the basis of risk pricing, which can displace more subjective methods previously relied on, and in doing so, reduce moral hazard. Moreover, findings generated through this work have revealed how the extensive range of data sources, and analytical techniques on offer, can be effectively incorporated within insurance risk analyses. This can facilitate a process of evidence-based decision-making, increasing the probability for insurance to generate socially optimal outcomes.

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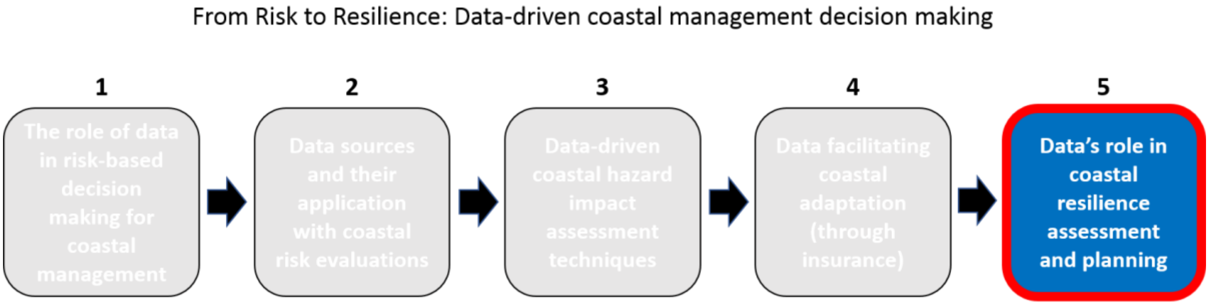
6 The role of data within coastal resilience assessments: an East Anglia, UK, case study

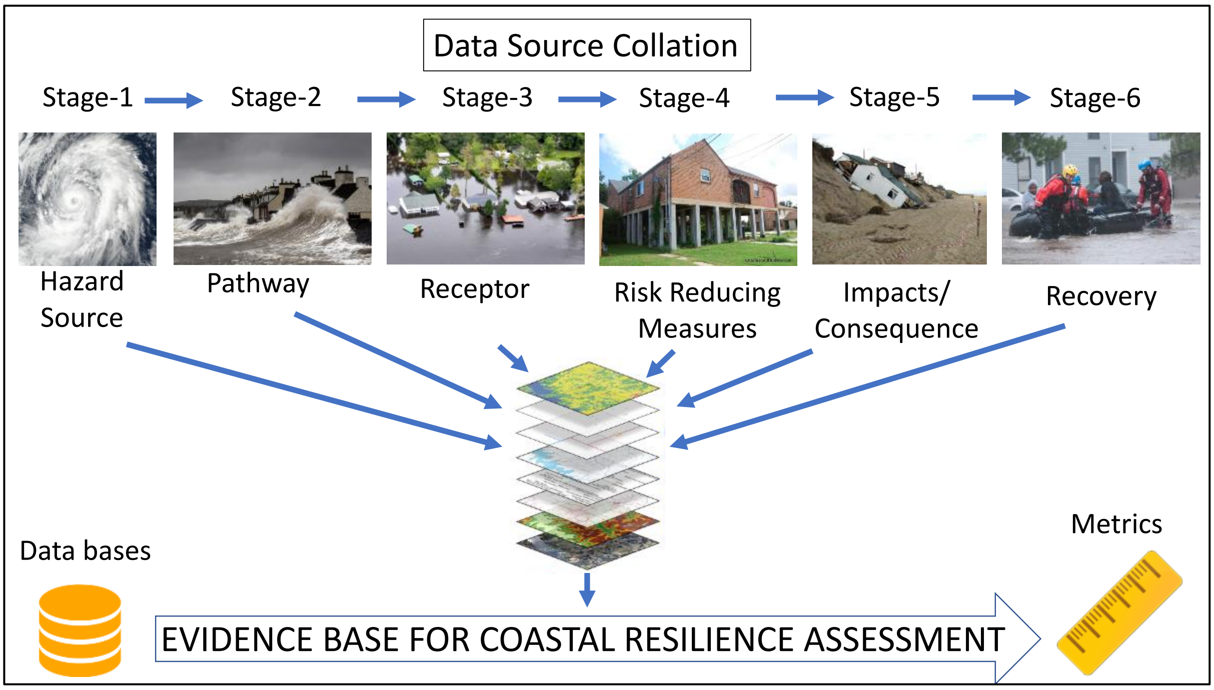


Creation of resilience in coastal areas is recognised to be a central aspect of sustainable coastal management practices (Farhan and Lim, 2011; Karavokiros et al., 2016; Kim et al., 2014; McFadden, 2010; Nicholls and Branson, 1998; Viavattene et al., 2018). Coastal risk assessments are commonplace and routinely undertaken by practitioners and academics, and in industries such as insurance (as revealed in Chapter 5). However, resilience assessments are more seldom undertaken, and can involve higher levels of complexity, depending on their focus. Yet, a substantial element involved in the evaluation of resilience, relates to identification of vulnerability and risk. So the metrics used within conventional risk evaluations can form the basis of resilience assessments, which can then be augmented by information pertaining to capacities to respond and recover from hazard events (Karamouz and Zahmatkesh, 2017).

In assessing resilience in coastal areas, a wide range of data variables need to be considered, similar to, but expanding on, those utilised for assessment of risk. The number of studies focusing on assessment of coastal resilience have increased exponentially over the last 5 years. However many forms of resilience assessment still rely heavily on subjective qualitative inputs derived from experts (Keating et al., 2017), and lack empirical validation (Cai et al., 2018). Yet there are studies which reveal how more quantitative data-driven methods can be applied to assessment of coastal resilience (Zhang et al., 2019). Furthermore, geospatial and GIS analysis of resilience indicators is a common method employed in many studies (Allen et al., 2018; Burton, 2015; Karavokiros et al., 2016; Lam et al., 2015). Resilience is a concept that is increasingly acknowledged by the UK government, in relation to long term environmental management strategies on the coast (Bonfield, 2016; Committee on Climate Change UK, 2018; Defra, 2016; National Infrastructure Commission, 2018; Twigger-ross et al., 2015). The requirement to account for the ability of communities, ecosystems, businesses, and critical infrastructure systems to continue to function following disruption by a hazard event, is being realised as crucial to sustainable management of coastal systems. Given this, new, novel data-driven methodologies need to be developed, for inclusion of factors accounting for hazard responses and recovery, and preparations and contingencies. These assessments can benefit from inclusion of emerging sources of data such as satellite derived outputs (Cervone et al., 2016), IoT sensor data (Koduru et al., 2018), alongside CCTV footage (Lloyd's Market Association, 2017) and outputs derived from social media data (de Bruijn et al., 2018; Jongman et al., 2015; Smith et al., 2017; Wang et al., 2018). These datasets can be combined using novel processes such as agent based modelling (ABM) (Du et al., 2017), which allows human behavioural responses to be revealed, or computer vision which can be used to reveal damage extents from video/image analysis (Wang, 2018). Utilisation of such sources and methods can permit inclusion of near real-time data within resilience assessments. This can address calls for dynamic assessments, and progression beyond previous static evaluations (Cai et al., 2018). A large portion of the indicator metrics required for assessment of resilience are made up of standard risk-related variables. Given the progress made in relation to the use of data, within risk assessments (as documented in the preceding chapters), this can directly benefit coastal resilience assessments.

The previous chapters have mainly focussed on the application of data within coastal risk assessments. This chapter shifts the focus from risk to resilience and explores the role of data within coastal resilience assessments. The approach taken centres on selection and combination of resilience assessment metrics, and bears similarities to the methodology adopted within Chapter 3, in that data sources available for East Anglia were paired with the factors which need to be considered within an assessment. This chapter also explores the data sources available for East Anglia, exploring how both open source and proprietary data sources could be utilised. The discussion presented also covers the role of emerging, novel data types and sources, and how derived data outputs generated through advanced analytical processes, could be drawn on to satisfy the requirements of the metrics used in resilience assessment. Resilience is shown to be a more expansive topic than risk and assessments require consideration of additional (non-risk related) factors, such as capacities to respond, recover and put the contingencies in place. Given this, the chapter contains strands of knowledge drawn from the preceding chapters, revealing how such data-driven approaches could allow a coastal resilience assessment to be based mainly on empirical evidence.

Graphical Abstract



The role of data within coastal resilience assessments: an East Anglia, UK, case study

Abstract
Embracing the concept of resilience within coastal management marks a step change in thinking, building on the inputs of more traditional risk assessments, and further accounting for capacities to respond, recover and implement contingency measures. Nevertheless, many past resilience assessments have been theoretical and have failed to address the requirements of practitioners. Assessment methods can also be subjective, relying on opinion-based judgements, and can lack empirical validation. Scope exists to address these challenges through drawing on rapidly emerging sources of data and smart analytics. This, alongside the careful selection of the metrics used in assessment of resilience, can facilitate more robust assessment methods. This work sets out establish a set of core metrics, and data sources suitable for inclusion within a data-driven coastal resilience assessment. A case study region of East Anglia, UK, is focused on, and data types and sources associated with a set of proven assessment metrics were identified. Virtually all risk-specific metrics could be satisfied using available or derived data sources. However, a high percentage of the resilience-specific metrics would still require human input. This indicates that assessment of resilience is inherently more subjective than assessment of risk. Yet resilience assessments incorporate both risk and resilience specific variables. As such it was possible to link 75% of our selected metrics to empirical sources. Through taking a case study approach and discussing a set of requirements outlined by a coastal authority, this paper reveals scope for the incorporation of rapidly progressing data collection, dissemination, and analytical methods, within dynamic coastal resilience assessments. This could facilitate more sustainable evidence-based management of coastal regions.

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Keywords
Coastal management, resilience metrics, geospatial data, open source data

6.1 Introduction

Creation of resilience in coastal areas is now commonly acknowledged to be a core requirement of sustainable coastal management practices (Farhan and Lim, 2011; Karavokiros et al., 2016; Kim et al., 2014; McFadden, 2010; Nicholls and Branson, 1998; Viavattene et al., 2018). Resilience is itself a broad concept and can be defined in different ways depending on how the term is applied (i.e. ecological resilience, engineering resilience). Ecological resilience focuses on the functioning of a system and persistence of relationships, and recognises the possibility of a resilient system shifting between stable states (Holling, 1973). Engineering resilience differs in that it relates to stability near an equilibrium state, and the ability of a system to return to an original state following a disturbance or perturbation by external stresses (Holling, 1996; Pimm, 1984). In general, resilience is associated with the capability to absorb and respond, and the existence of an internal adaptive coping capacity (Gallopín, 2006). The Stockholm Resilience Centre (2015) define resilience as the capacity to deal with change and continue to develop. There is considerable discussion concerning how coastal resilience may be defined and measured (Coastal and Environmental Research Committee, 2015). Coastal resilience relates to societal, economic and ecological factors (NOAA, 2018a). In addressing coastal resilience, this article draws primarily on the ecological definition of resilience, focusing on the persistence of relationships, and the ability to shift to alternative stable states. Our main focus is the resilience of coastal communities to environmental hazards (particularly flooding and erosion).

Planning for resilience in coastal areas extends beyond assessment of vulnerability and risk. Resilience planning can be characterized by an iterative process involving preparation for hazard events, immediate responses, and recovery (NOAA, 2018b). To achieve resilience, it is inadequate to rely solely on reactive responses to hazard events, it is also necessary to undertake proactive adaptations, increasing the ability of coastal communities to 'bounce back' following shock events (Kete et al., 2018; Leal Filho et al., 2018; NOAA, 2018a; Twigger-ross et al., 2015). Achievement of sustainable coastal management strategies therefore necessitates completion of evidence-based resilience assessments. To ensure these assessments generate usable outputs, they must address requirements outlined by coastal practitioners relating to vulnerability, impacts, and policy evaluation. This can contribute to the attainment of goals for sustainable economic development in coastal regions (DasGupta and Shaw, 2015).

There are many studies focusing on resilience which adopt a theoretical approach, developing as a result, conceptual resilience assessment frameworks. Amongst studies focusing on resilience (both theoretically based and those more practical) there is no widely agreed definite framework. This is in contrast to risk where many risk based studies are centred on approximations of the standard risk equation: *Risk = Hazard x Consequences* (Defra, 2009; Goverment Office for Science, 2004; Nicholls et al., 2015). This ambiguity surrounding the practical application of resilience assessments is a contributing factor to greater emphasis being placed on evaluation of risk, rather than resilience, by those tasked with managing vulnerable coastal regions. Yet resilience is increasingly acknowledged as a key discourse within coastal management studies and by the wider practitioner community (Cai et al., 2018a; Defra, 2016; Deutz et al., 2018; Karavokiros et al., 2016; National Infrastructure

Commission, 2018; Viavattene et al., 2018; Word Bank, 2017). Given this, a requirement exists for a standardised methodological approach to coastal resilience assessment.

In addition to the lack of a single accepted methodology for coastal resilience assessment, many existing methodologies can be difficult for practitioners to apply, requiring high levels of specialist input. Assessments can also be subjective due to a reliance on expert opinion and value-based judgements. To overcome such limitations requires application of methodologies founded on analysis of empirical evidence. Today, a data-driven resilience assessment strategy is now a realistic possibility (Bellini et al., 2016) due to the ever expanding volumes of data being made available, much of which is obtainable open source, and has already been revealed as suitable for fulfilling coastal risk assessment requirements (Rumson & Hallett, 2018). Yet, understanding coastal resilience requires consideration of a wider range of indicator variables than risk. Furthermore, general consensus is lacking, on the indicators or metrics that should be included within a resilience assessment. The requirement for such metrics, based on clear, simple data and information has been identified as forming the basis of long-term adaptation planning (Committee on Climate Change UK, 2018). In particular the need for indicators which can be based on Big Data and open source data is now being acknowledged (Jovanovic et al., 2016). In this paper, we set out to tackle the fundamental issue of the evidence base required for coastal resilience assessments. In doing so, we have drawn on a simple resilience assessment framework, populated by quantifiable assessment metrics. In addressing the requirement for empirical evidence, examples of data sources that could be drawn upon to address each metric are discussed, and example data sources are provided for a case study region in East Anglia, UK. Additionally, we identify areas where data is currently lacking, and where qualitative inputs must still be sought.

Recent, rapid progression in the methods utilised for collection and analysis of data underpin our ability to reduce uncertainty in coastal planning. This can provide opportunities to steer investment decisions on the coast towards profitable developments. The central objective of this study is to reveal how assessments of coastal resilience can be founded on smart analytics (Jovanovic et al., 2016; Lee et al., 2014; Marr, 2015) of diversified and robust datasets. Furthermore, this can allow identification of stakeholders who are vulnerable yet potentially unaware and unprepared. We explore how coastal practitioners can incorporate important missing aspects of coastal resilience within their decision-making processes at both local and regional scales. This may provide opportunities to lessen impacts, enable bounce back and identify contingencies. Moreover, it may permit future investments to be steered towards sustainable areas, creating economic development opportunities, preserving and enhancing natural capital. Overall, the study’s intention is to contribute to furthering our understanding of the poorly known aspects of how to operationalize existing coastal resilience into every day decision-making.

6.2 Case Study: East Anglia and Coastal Partnership East (CPE)

A case study region of East Anglia, in the East of England was selected for this study. The work benefited from input received from coastal practitioners tasked with managing this coastline: the key organisations being CPE and the Environment Agency (EA). East Anglia is a highly vulnerable coastal region, experiencing both high levels of erosion and regular and extensive coastal flooding (Nicholls et al., 2015). The region comprises a diverse range of coastal environments and anthropogenic activities. A number of coastal towns, such as Lowestoft and Great Yarmouth, have experienced economic decline in recent times, as a result of a declining tourism industry (Agarwal and Brunt, 2006) and significant job losses in traditional industries such as fishing (Brookfield et al., 2005). This can result in densely populated and economically deprived communities, being exposed to hazard events, and with residents lacking the capacity to take mitigating actions or to finance recovery. Previous generations have responded to coastal hazard events, such as the 1953 storm surge, by installing hard engineered coastal adaptations (Mokrech et al., 2011). In many instances these measures have been associated with disruption of natural processes, such as alongshore sediment transport pathways, often resulting in exacerbated impacts in unprotected areas (Nicholls et al., 2015).

East Anglia is also home to a range of diversified natural environments and complex ecosystems, such as the Norfolk Broads. Recent shifts in the dominant approach taken by governments in managing the coasts of England has resulted in a greater focus being placed on the importance of natural systems and ecosystems services (Defra, 2006). As such, soft adaptation measures, designed to work with nature, are increasingly being implemented (Milligan et al., 2009). Managed realignment is a prominent example of a soft adaptation measure considered in East Anglia (Myatt et al., 2003), and in the future other methods such as sandscaping are set to be implemented (Vikolainen et al., 2017). Following a second round of Shoreline Management Plans (SMPs) (Defra, 2006), sections of the coastline of East Anglia were re-categorised. This has resulted in deteriorating hard adaptation measures not being replaced, or in many locations being completely removed. Based on the reclassification of stretches of coastline as either, 'No Active Intervention' or 'Managed Retreat', projections have been made on sections of coast expected to erode, over the epochs of 20, 50 and 100 years. This has resulted in the creation of Coastal Change Management Areas (CCMAs) (Environment Agency, 2010), in which restrictions are placed on future developments due to anticipated high levels of coastal retreat. This has direct implications for resilience assessments for the region, as communities, businesses and infrastructure located within the CCMAs, may not be expected to bounce back, or fully recover, following hazard events.

Due to the range of unique contextual factors present in East Anglia, combined with high levels of vulnerability, the region has been monitored extensively. Large quantities of diversified datasets for the region are now freely available to the public, accessed via open source data portals (Rumson & Hallett, 2018). For this reason, the region proves especially suitable as a case study site for this research, as data sources associated with many of the selected assessment metrics (Appendix 6.2), can easily be located. Additionally, the major stakeholder organisation, responsible for management of the eroding coastline of the region, CPE, agreed to provide input to this study. This input took the form of unstructured interviews, and questionnaire feedback, but most importantly, a set of practitioner requirements were supplied, specifying desirable outputs sought from resilience assessments for the region (Figure 28).

Coastal Practitioner requirements outlined by CPE

1. Review and incorporate data for SMP CCMAs within an assessment to identify and aggregate what is at risk over the next 100 years (given current SMP predictions).
2. Incorporation of outputs of the most appropriate and advanced methods for measuring and reporting on coastal change.
3. Evaluate how well-prepared local authorities and communities are to respond to/recover from future coastal change and high intensity hazard events.
4. Identification of contingencies in place and adaptations.
5. Enable sustainable planning leading to resilient outcomes

Figure 28: CPE Practitioner requirements

CPE is a consortium of four coastal groups, representing Gt. Yarmouth Borough Council, North Norfolk District Council, Suffolk Coastal District Council and Waveney District Council. In 2016 the coastal management resources from these respective councils amalgamated to share their resources to manage the region more effectively (Coastal Partnership East, 2019). The aim of this wider regional focus was to foster collaboration and knowledge sharing and to pool resources for a larger contiguous area, which can promote risk and resilience assessments for larger spatial scales. As a body representing district level councils, the main hazard CPE is concerned with is erosion, whilst the EA are responsible for managing the risk of coastal flooding (Environment Agency, 2010). CPE's bias towards erosion is reflected in the requirements set out above. However, flooding and erosion in coastal areas are closely interrelated, and can occur in tandem (Defra, 2005). As such assessments of coastal resilience will generally need to account for impacts from both. The requirements listed above were deemed necessary for a coastal resilience assessment by the practitioners questioned, yet are not sufficient to account for all forms of resilience. Primarily, this study sets out to reveal how the requirements can be addressed through consideration of the framework, metrics, and data sources outlined. We also expand upon these requirements, indicating how the approach could be applied to a broader context.

6.3 Quick Scoping Review (QSR)

Standardised resilience assessment methodologies have rarely been applied directly to coastal settings. As such, agreeing on acceptable quantitative resilience assessment metrics has proved problematic and remains a challenge for the research and practitioner communities (Coastal and Environmental Research Committee, 2015). In an attempt to gain a more thorough understanding of this issue a QSR was undertaken to establish what methods, metrics and datasets have been applied within previous coastal resilience assessments. The QSR methodology and results are presented within Appendix 6.1. Through undertaking this QSR and securing an understanding of what coastal resilience assessments are being completed, and the data and information sources utilised, the most suitable metrics, and data sources could be selected. Evidence extracted from the 8 practitioner reports and 29 academic articles, which passed through the QSR screening process, is presented in Table 18 and Table 21 in Appendix 6.1. Application of this evidence is discussed in the remainder of the paper.

6.4 Simple Resilience Assessment Framework and Metrics

Following completion of the QSR an extensive list of metrics, which can be drawn on within coastal resilience assessments, was established (Appendix 6.2). This list is comprehensive yet not exhaustive. The metrics have been split into six categories, which comprise the framework presented in Figure 29. Four categories (1. Hazard Source, 2. Pathway, 3. Receptor, and 5. Impacts/Consequence) are also common aspects addressed by coastal risk assessments, in particular the SPRC (Source-Pathway-Receptor-Consequence) model (Gouldby and Samuels, 2005; Villatoro et al., 2014). However, aspects of category 4. Risk Reducing Measures, and Category 6. Recovery, are more exclusive to assessment of resilience. Stage 4.1. Adaptations, contains measures generally considered to be resilience increasing; yet it is common for adaptations to be accounted for within risk assessments, as adaptation can alter risk levels and defer impacts. However, the metrics contained within Stage 6. Recovery and Stage 4.1. Preparations and Contingencies, are not so frequently associated with risk. Inclusion of these additional metrics provides a means of progression from assessment of risk to resilience, revealing the capacity of coastal regions to continue to function and recover following hazard events.

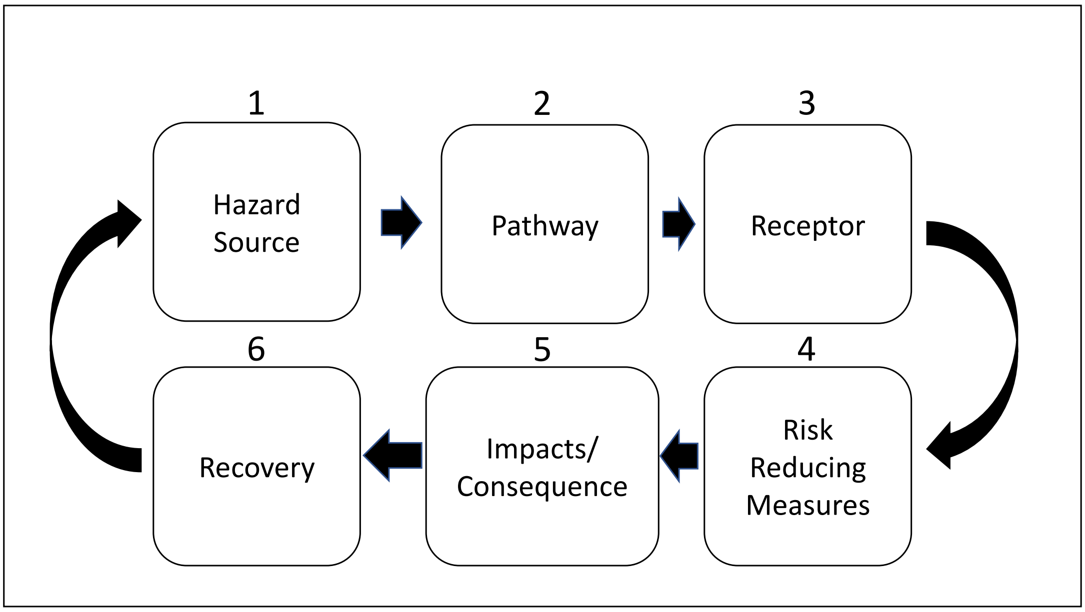

Figure 29: Coastal Resilience Assessment Framework

The metrics were grouped into categories at the discretion of the authors. This drew primarily on the SPRC model (Gouldby and Samuels, 2005), in which the coastline is divided into homogenous pathway units, based on a limited number of typologies and the hinterland divided equally into receptor units, based on features such as: land use, elevation and geomorphology. In short, the metrics falling into Stage 1, largely represent physical conditions, relating to hazard sources (i.e. environmental parameters); Stage 2, pathways through which the hazards propagate (i.e. the coastline); and Stage 3, hazard receptors (i.e. people, property, infrastructure and the environment). Those attributed to Stage 4 were split between 4.1, Adaptations and 4.2, Preparations and Contingencies. Adaptations were either physical measures undertaken by humans to lessen impacts or services afforded by the natural environment, whilst the metrics representing preparations and contingencies, are associated more with long term measures in place, potentially boosting resilience. The metrics assigned to Stage 5, represent the consequence aspect of the SPRC framework and give an indication of change associated with hazard propagation. Whilst Stage 6 metrics, represent how effectively communities have reacted to coastal hazards.

Previous studies focussing on coastal risk assessment reveal how aspects we have included within categories 1, 2, 3, and 5, such as hazard probability, intensity, and consequences (relating to land use, populations, business and infrastructure), have formed core inputs to risk evaluations (Narayan et al., 2014; Villatoro et al., 2014). Other studies, such as that of Bheeroo et al. (2016) reveal how metrics associated with physical coastal impacts have also formed the basis of risk assessments. However, reactions to coastal hazards, in the form of adaptations have been noted as being absent from many previous risk assessments, especially from those based on the CVI (Coastal Vulnerability Index) approach (Ramieri et al., 2011). The Coastal Risk Assessment Framework (CRAF) developed as part of RISCKIT (Christie et al., 2018; De Angeli et al., 2018), typifies a common approach to risk assessment, in its identification of hazards and consequences allowing classification of stretches of coast as vulnerability hot spots. The CRAF approach, does include metrics representing recovery, however it lacks the diverse range of indicators representing adaptations, preventative measures, and contingencies required by a resilience assessment. Part of the novelty of this current study, is that it identifies the means to evaluate these factors systematically, alongside the core aspects associated with risk assessments.

The data and information requirements for each metric varied. For each metric, we indicate if it is possible to obtain the required datasets based on data available for the case study region. If so, example datasets, associated with East Anglia have been listed. A list of data sources is provided in Appendix 6.3, and cross references to this are provided within a column, in each table of metrics, labelled 'available from'. The data sources detailed are only indicative and are not an exhaustive listing of those available. Both proprietary and open source datasets are listed in Appendix 6.3; issues relating to the choice of open or proprietary data are further discussed in Section 6.6. 254 separate assessment metrics are listed in Appendix 6.2. These metrics were mostly derived from the articles, reviewed as part of the QSR, listed in Appendix 6.1. For each metric, a cross reference is given in the respective table, in a column labelled 'Paper Ref.', indicating the academic article(s) which included similar metrics. This is given in the form of a letter or symbol associated with the respective paper #, as detailed in Appendix 6.1.

6.5 Metric Selection

In collating the diverse range of indicator metrics listed in Appendix 6.2 and summarised in Table 16, we aim to provide a range of options from which different groupings of indicators could be selected. The choice of metrics for a data-driven resilience assessment would depend on data and information availability, the type of area (urban/rural), at what scale an assessment is carried out (local/regional/national), and if an assessment is concerned with a specific kind of resilience i.e. community, infrastructure, ecosystem. It is not envisaged that a single resilience assessment would include all metrics, as this would prove time consuming and resource intensive. However, consideration of the large number of metrics we have presented, can allow coastal practitioners to select the factors they deem most significant for the coastal region under consideration. Many of the metrics listed cover a broad range of potential indicators, such as metric 8: Oceanographic/meteorological sensor networks, records and projections. In an effort to provide more options, and limit the number of metrics, these broad categories were not broken down further. However, during practical application, the precise indicator to be used, within such metrics, would need to be defined. Confidence levels in the results obtained for each metric would depend on data source veracity. Table 16 identifies the subcategories for each stage of the assessment framework detailed in Figure 29 with their respective metric numbers. The stages of the framework are closely interrelated, and feedback loops exist between each. This also fits with a whole systems approach (Narayan et al., 2014), which transcends the notion of impacts considered in isolation, and acknowledges the interrelated nature of the multitude of disparate factors which need to be monitored and analysed.

Table 16: Summary of metric listing. The metrics were broken down into 6 stages, these have been divided further into subcategories. The column 'Metrics' details the metric numbers included within each stage and sub-category.

Stage	Metric	Sub-categories		Metrics
1	Hazard Source	General		1-13
		Past environmental conditions during hazard events		14-16
2	Pathway	N/A		17-38
3	Receptor	General		39-44
		Public Amenities		45-54
		Economy & Business		55-71
		People		72-87
		Property		88-98
		Infrastructure		99-121
4	Risk Reducing Measures	4.1 Adaptation	Human Structural	122-127
			Human Soft	128-133
			Mitigation	134-143
			Ecosystem Services	144-157
			Planning	158-166
			Financial	167-168
		4.2 Preparation & Contingencies	Monitoring/Warning Systems	169-174
			Infrastructure	175-180
			Drainage	181-184
			Shelter/Housing	185-186
			Emergency Relief	187-197
			Societal	198-203
			Hazard Awareness	204-207
5	Impacts/Consequence	Environmental physical impacts		208-215
		General		216-220
		Business		221-223
		People		224-227
		Property		228-230
		Infrastructure		231-237
6	Recovery	N/A		238-254

6.5.1 Stage 1-3 Source – Pathway – Receptor

Stage 1 of the resilience assessment framework (Figure 29) relates to hazards. The metrics included generally represent quantifiable parameters, which can be obtained through analysis of environmental monitoring data, geostatistical datasets, or a combination of both. Hazard prediction information is paramount for assessment of coastal resilience, it can permit communities and civil protection agencies to respond and put in place hazard reduction measures (Defra, 2016). In addition to naturally occurring hazards, human actions or hazard responses, can also be looked on as hazards in their own right. These can take the form of maladaptive actions which can exacerbate impacts. For this study, the hazards are mainly weather induced, relating to coastal erosion and flooding (as is typical for many studies focusing on coastal resilience (Ellison et al., 2017; Karamouz and Zahmatkesh, 2017; Schultz and Smith, 2016). The propagation of these physical hazards through various pathways (Stage-2), such as wave overtopping and flood plain inundation (Reeve et al., 2012)), results in threats to receptors (Stage 3) (i.e. households, businesses, infrastructure (Fekete et al., 2017), and the functioning of ecosystems (Ellison et al., 2017)), and can result in adverse consequences to human health, welfare, and the natural environment. Therefore, metrics representing receptors, such as those which can be derived from population statistics, have been included in Stage 3. For East Anglia, information is readily available from the Office for National Statistics (ONS) documenting such variables (Figure 30).

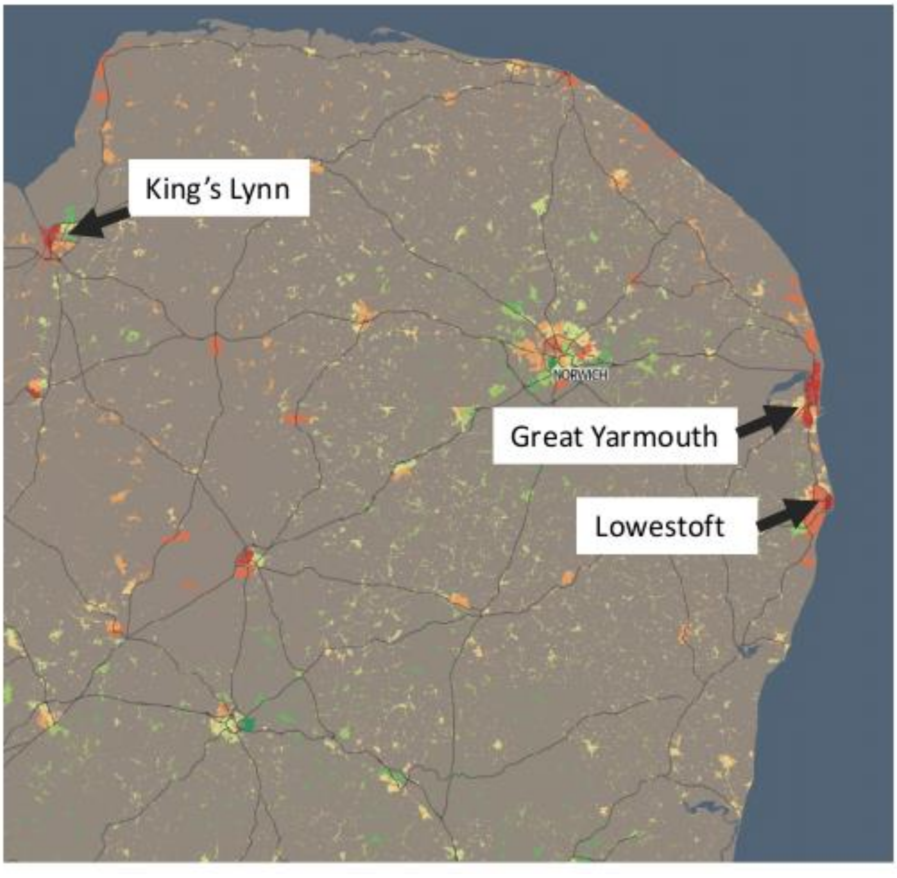

Figure 30: Example of data used to address metric 72: Poverty Levels. ONS data made available through Datashine. Households by deprivation dimension (Red – most deprived through to Green – least deprived) (University College London, n.d.)

6.5.2 Stage 4: Risk Reducing Measures

The sequential progression of the stages in the framework (Figure 29), are representative of the impacts experienced (Stage 5) being directly related to adaptations in place (Stage 4.1). These can take the form of large-scale structural adaptations, implemented through engineering projects, i.e. sea defences and dykes, or local/household level mitigation measures, i.e. retrofitting buildings or raised accommodation (as was recognised to be important by Kim et al. (2014) for Galveston, Texas). Alternatively, adaptations can involve working with nature, utilising ecosystem services, and natural capital (National Infrastructure Commission, 2018; NOAA Office for Coastal Management, 2015). This can involve salt marsh restoration or preservation of woodland areas and pervious surfaces (which can limit flood water propagation and inundation extents). Such nature-based adaptations are increasingly looked to and are commonly implemented across the case study region of East Anglia. Many of these are termed soft adaptations and can take the form of green infrastructure (Song et al., 2018), beach nourishment, and managed realignment (Finkl, 2015). Measures such as insurance can also provide mechanisms to encourage resilience practices, increasing adaptive capacity, in its ability to distribute and communicate risk (Rumson & Hallett, 2019). These various modes of adaption are recognised within the metrics included in Stage 4. Obtaining datasets to cover many of these metrics can be challenging. For example, details at a household (property) level, such as building attributes, or mitigating measures implemented, are difficult to obtain, yet are acknowledged as required (Bonfield, 2016), and are necessary to include in an assessment of resilience (Garvin et al., 2016).

The metrics for Stage 4.2 relate to preparations for hazard events and the contingencies put in place. These are biased towards flooding and disaster incidents (as in Bostick et al., 2017; Keating et al., 2017; Oladokun et al., 2017). This is reflected in a number of the sub-category groupings, including: emergency services, shelter/housing, monitoring and warning systems, and drainage (NOAA Office for Coastal Management, 2015). Not all metrics for Stage 4.2 are restricted to these forms of resilience though, and the remaining groupings of metrics (infrastructure, societal, hazard awareness), are not constrained to flooding and relate to both short- and long-term resilience (short term taken as the immediate ability to respond to hazard events, whilst long term resilience is taken to be the ability recover from the wider aftermath of many such events).

The data/information requirements of Stage 4.2's metrics, were not easily resolved (as was the case for Stage 6). Therefore, many of the required inputs would need to be derived directly from stakeholder organisations (as in Bostick et al., 2017; Keating et al., 2017). The metrics included in Stage 4 are diversified, many of these differ substantially from those commonly found in a risk assessment. These metrics seek to represent societal capacity to cope with the unexpected. This requires incorporation of varied measures, representing planning and preparations made at various levels of society, from the hazard awareness of individuals, to social groups and civil society organisations, government level planning, warning systems, emergency relief organisations and networks, and implementation of resilient infrastructure (Allen et al., 2018). The post-impact provision of basic services, such as food, water, communications, and waste removal/treatment (EPICURO, 2018), are especially important considerations within this stage of a resilience assessment, but are not factors commonly considered within coastal risk assessments. Human behaviour also stands out as an important element to include within an assessment of resilience. Human responses to recent hazard events (such as the 2013 Storm Surge in East Anglia (Brooks et al., 2016)) or hazard information can influence decisions to take mitigating actions, to undertake more sustainable practices, or to move from risk zones (Aerts et al., 2018; Jenkins et al., 2017).

6.5.3 Stage 5: Impacts/Consequence

Hazard receptors are numerous and diversified. Stage 5 includes metrics representing the consequences on receptors including: the natural and built environments, business and the economy, and coastal populations. To account for human receptors many metrics are included representing the size, distribution, and composition of coastal populations, including social indicators, i.e. health and wealth. In addition to this, more diverse receptors are accounted for in metrics representing the distribution and concentration of physical assets, business activity, infrastructure dependencies, and ecosystem services. Inclusion of such can provide a means to quantify exposure across multiple spheres. The metrics selected for assessment of impacts seek to reveal both immediate and long-term impacts (or consequences) resulting from hazard propagation. Therefore, diverse elements are represented by the metrics associated with Stage-5's subcategories (Table 16). Examples of these being: Environmental physical impacts - geomorphological change (i.e. shoreline recession such as that occurring in Norfolk, (Figure 31), and extents of flooding (Figure 32); General - physical damage and financial loss; People - human health and socio-economic feedback, i.e. job losses, and crime; Property - house prices; and, Business - business activity. Coastal hazards can result in cascading consequences (Cutter and Derakhshan, 2018) , due to disruptions to business and supply chain shocks (Papadopoulos et al., 2017). As such, identifiers have been compiled, to assist in the estimation of more far reaching effects resulting from short- and long-term hazard propagation. These can, for example, include infrastructure failures, related to roads, power stations, and water supply (Allen et al., 2018). Data detailing damages and loss can be difficult to obtain and may need to be sourced from specialist suppliers, such as those associated with insurance companies (Rumson & Hallett, 2019). Furthermore, in order for assessments to retain their validity, continually updated information detailing new developments must also be included.

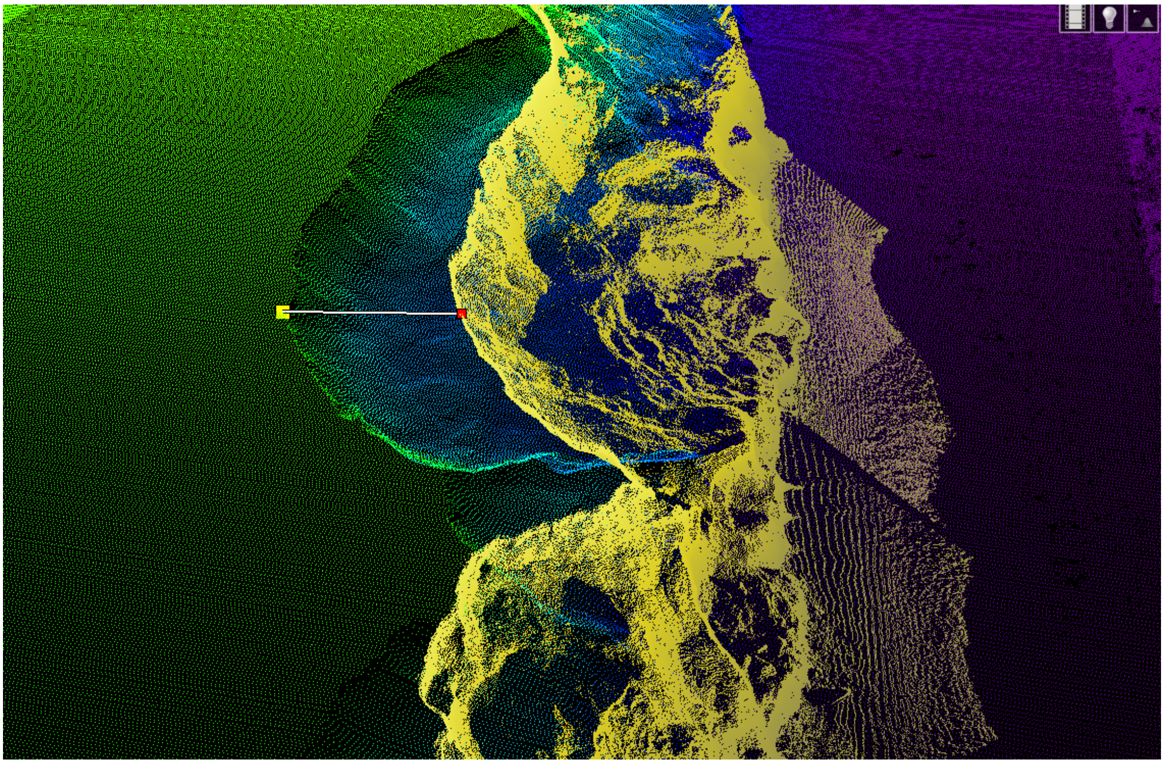

Figure 31: Example of data used to address metric 210: Geomorphological change - records of beach/loss creation. Lidar data sourced from BGS and the EA, used to estimate coastal retreat at Sidestrand between 2005 and 2018, Norfolk. Measured retreat along the white line between red and yellow points = 46m.

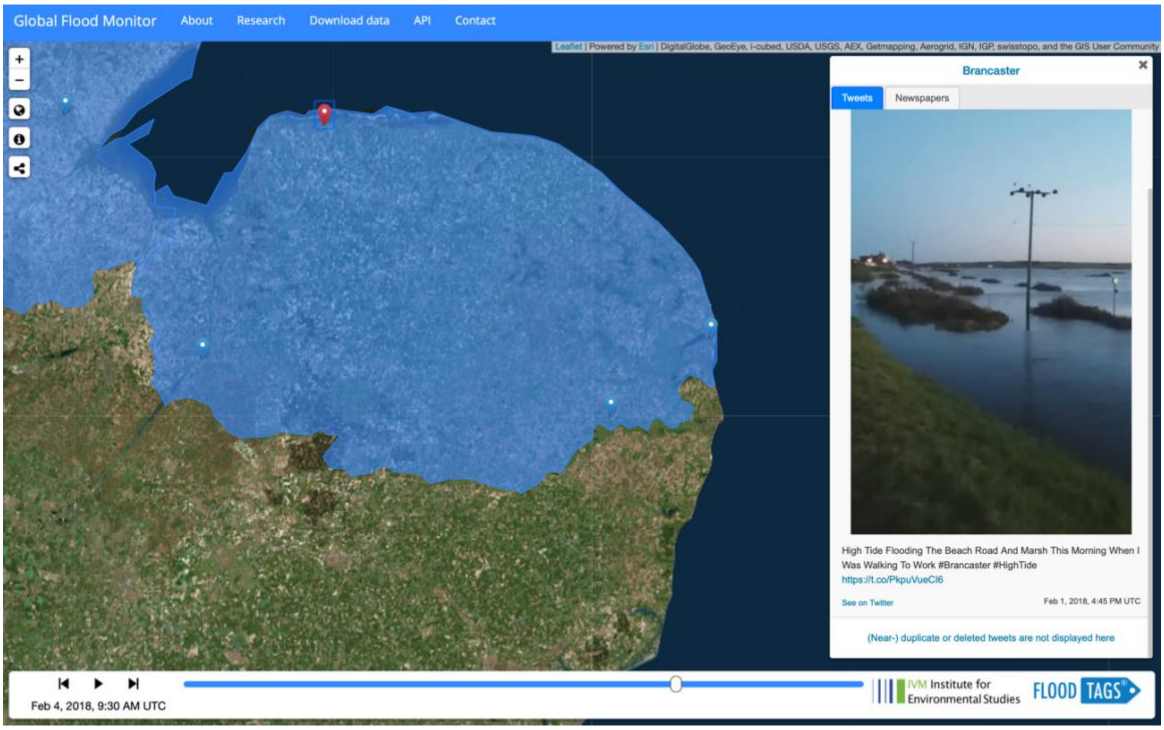

Figure 32: Data used to assess metric 216: Extents of flooding and impacts (physical and human). Geotagged flood related social media data: Tweet revealing coastal flooding extents in North Norfolk, made available by Global Flood Monitor (https://www.globalfloodmonitor.org).

6.5.4 Stage 6: Recovery

The metrics included within Stage 6 can provide an overview of how effectively communities have reacted to hazard events. These metrics cover financial recovery, functioning of warning systems, restoration of the functioning of infrastructure (Joyce et al., 2018), evacuation of homes, industrial resupply, and the performance of relief and emergency services (Papadopoulos et al., 2017). Data for the metrics included within Stage 6, were found more difficult to obtain and quantify for the case study area, than indicators associated with the SPRC model. The majority of Stage 6 metrics were deemed, by the authors, to require specialist input or derived data (such as that extracted from social media feeds revealing public sentiment in relation to government actions (Figure 32)). Practitioners questioned in East Anglia concurred with this. Indicators relating to response and recovery times are not generally published, yet this may change in the future, if demand for these variables increases.

6.6 Data Sources

Data forms the foundation of the knowledge base required for effective coastal zone management (Zanuttigh et al., 2014). The ability for coastal populations to deal with the diverse impacts resulting from environmental hazards, hinges on the availability and use of suitable datasets. This can allow appropriate planning decisions and adaptive measure to be implemented (Rumson et al., 2017). A wide range of data sources should be included within a coastal resilience assessment, this is represented in those associated with the selected metrics.

6.6.1 Evidence base for metric evaluation

In attempting to source data for so many separate metrics, we sought to provide an indication of the existing evidence base available for an assessment of coastal resilience. Of the 254 metrics selected for this study, 149 (59%) were linked with the data sources located for the East Anglia case study area (Appendix 6.3). Another 39 metrics (16%) were categorised as requiring data derived through combination or analysis of the datasets available from these sources (as detailed in Section 6.6.5). Data sources addressing the requirements of all metrics could not be located though, and 44 metrics were categorised as requiring information sourced directly from stakeholder organisations. Furthermore, the data sources required for 12 of the metrics were not defined. Of the 25% of the metrics for which more subjective, expert-based inputs were required, none were associated with aspects of the resilience assessment framework typically linked to risk assessments (Stages 1, 2, 3 & 5). Conversely, Stages 4 and 6, which are deemed more resilience specific by the authors, were revealed as the most difficult to satisfy through existing data sources. This implies that higher levels of subjectivity are associated with assessment of resilience than with risk. Nevertheless, this study indicates that the data requirements of 75% of a broad range of metrics, suitable for assessment of resilience, could be derived from empirical sources.

6.6.2 Evaluation of Data Sources

Due to the breadth of metrics selected, it was not possible to complete a comprehensive validation of all empirical data sources listed. This would need to be completed on a case by case basis. A single resilience assessment would require only a limited selection of the metrics listed, therefore at the application stage a more thorough evaluation of data source suitability would be more feasible. The data source evaluation undertaken within this study, was limited and the sources associated with the metrics (Appendix 6.3) are only indicative, not an exhaustive listing. Furthermore, the data sources which were selected for the case study area primarily act as a guide to the type of organisation, which may hold data relevant to the selected metrics. This information can potentially allow similar organisational sources to be discovered for assessments undertaken in alternative locations.

6.6.3 The cost of data

Due to the diverse range of metrics included within this study, it was not possible to obtain data satisfying all their requirements from open sources. Therefore, proprietary data sources, and services were also included within the examples provided in Appendix 6.3. There are multiple issues which need consideration when making a choice to use either open or proprietary data sources. For East Anglia, a large volume and variety of open source data is available, however, this is not the case for many other parts of the world. The veracity of open data sources is also not guaranteed, and the data may require extensive processing and preparation before it can be utilised in assessment of the respective metrics. Given this, in many cases it can prove more effective to purchase data services or proprietary datasets, than attempt to locate and prepare the freely available sources which exist for an area. This decision can also be dictated by technical operator skills, as many of the datasets associated with the selected metrics require specialist technical or scientific interpretation (especially many of the metrics associated with environmental monitoring data, included in Stage 1). Financial constraints imposed upon an organisation undertaking a resilience assessment can also affect the decision to include proprietary datasets. In such cases, using freely available data may appear logical, however, in some instances the use of open source data can actually result in higher costs internally than would be associated with using well calibrated and regulated proprietary sources. This can be due to the open sources which are available being incomplete, inconsistent, or error-bound. The majority of open source datasets identified, for the case study region, are provided by public sector organisations, given this a question arises as to the potential future role of the public sector in imposing uniform data standards, and undertaking quality assurance of the datasets made available. This could potentially generate possibilities for more widespread assessments of resilience. Nevertheless, despite the concerns highlighted, an ever-increasing number of data sources are now being made available to the public at no cost; this alone can prove a decisive factor allowing evidence-based resilience assessments to be undertaken.

6.6.4 Emerging data sources

The emergence of a new generation of unconventional data sources is another pertinent issue. In addition to data made available via open source portals or by proprietary vendors, data is now frequently acquired through mining, or scraping websites, for example, using hashtags or geotags (de Bruijn et al., 2018; Li et al., 2018). These processes can allow important information to be derived from social media data, for example (Figure 32). More dynamic sources of data can also take the form of web feeds, this can be the case for real-time ocean sensor data, and other (real-time) environmental monitoring outputs. CCTV footage is another useful source, which has been drawn on in assessment of street level damage following coastal hazard events, such as those related to a number of recent consecutive hurricanes, which impacted the southern states of the USA and the Caribbean (Lloyd’s Market Association, 2017). This is pertinent given that many resilience studies focus on such hazard events (Burton, 2015; Karamouz and Zahmatkesh, 2017; Kim et al., 2014; Lam et al., 2015).

Vulnerability arises as a consequence of what is sited in a hazard prone area, yet land use and land cover changes are frequent and continuous. Given this, images supplied regularly from earth observation (EO) satellites, can prove invaluable in revealing changes in near real-time, contributing to dynamic, accurate assessment of exposure. Associated analytical techniques such as image segmentation and object recognition can also serve to automate and speed up this process. A range of EO data outputs are commonly used in flood detection, mapping and impact assessments (Ellison et al., 2017; Jongman et al., 2015; Lavender et al., 2016). In addition to these sources, IoT sensors are capable of generating data in real-time, such as river gauge data (Koduru et al., 2018; SmartBay, 2017). Information relating to human movements and traffic flows can also be extracted from archives of mobile phone location-based service data (ONS, 2016; Ratti et al., 2006), and many applications are emerging for crowd sourced data, which are relevant to assessment of risk and resilience (Loftis et al., 2018). The high velocity of the data which can be obtained from a number of these sources, can act as driving factors, allowing resilience assessments to transgress the limitations of a static exercise, to form instead dynamic representations of the ever-changing situations on the ground. Crucial to this, is confidence in data source reliability and data quality. As such, a requirement exists for comprehensive metadata listings for each dataset, providing assurances over data veracity. Moreover, if such information is lacking, undocumented data sources should be discounted. Given the rapid emergence of so many novel data sources, which are being utilised in an uncommon manner, a requirement for national standards and guidance on the use of such data has arisen. If addressed, this could work to increase confidence and raise awareness of the possibilities presented by these new sources of information.

6.6.5 Data Derived through analytical methods

6.6.5.1 Big Data

A number of issues relating to data volume, variety, velocity and veracity, have been mentioned, these terms characterise the 4Vs of Big Data (Jagadish, 2015). The field of Big Data has been shown to be relevant to assessment of risk in coastal areas (Pollard et al., 2018; Rumson et al., 2017) and to the assessment of resilience (Bellini et al., 2016; Jovanovic et al., 2016; Papadopoulos et al., 2017). The notion of drawing from high volumes and varieties of data, available from archive and streaming sources, is central to data-driven assessments of resilience. The extensive number and diversity of metrics, which we have highlighted as applicable to coastal resilience assessments, is indicative of the high variety of data types and sources required. These can involve large volumes of data, especially if high density, attribute rich datasets are included within assessments, and where assessments are completed over large spatial scales. To permit completion of dynamic assessments, requires inclusion of both archive and streaming data sources. We have discussed a range of data sources which should be considered within a resilience assessment, and now consider a number of advanced analytical methods and processing technologies which can allow data to be combined, and to generate higher level derived outputs (which, in relation to this study, could potentially be drawn on when addressing the 39 metrics listed as requiring derived data inputs).

6.6.5.2 Advanced Analysis

The application of advanced analytical processes holds the potential to allow unconventional data sources to be utilised, this can involve graph, text and time series analytics. Natural Language Processing (NLP), for example, can be used to derive meaning from unstructured and messy data, and for argument or location extraction (Gritta et al., 2018). Application of automated machine learning processes, and Artificial Neural Networks (ANNs) can allow: pattern discovery, feature detection, classification of land use/land cover, and change detection (Bezuglov et al., 2016; Chang et al., 2018; Joseph and Kakade, 2014; Pijanowski et al., 2014). Computer vision is another emerging method, which has been applied to video/image analysis to detect extents of damage post flood event (Wang, 2018). Application of such processes can potentially generate updates on disaster events in real-time. Furthermore advanced techniques, coupled with Big Data, have been shown suitable to coastal emergency incident response (Qadir et al., 2016). This indicates potential scope for using such methods to supply a number of the inputs required to assess the metrics outlined in Stage 6 of the framework (Figure 29), relating to hazard event responses.

6.6.5.3 Agent Based Models

Agent-Based Models (ABMs) allow consideration of phenomena resulting from interactions between individual agents, with prescribed behavioural rules, in an evolving, shared spatial environment. This provides a bottom-up approach for understanding dynamic interactions in complex systems (Surminski and Oramas-Dorta, 2014), and feedback loops between humans and the environment. Outputs from ABMs can be used to add a layer of realism to assessments which have previously been based on static parameters. ABMs can achieve this through revealing hidden drivers that can alter outcomes, and in doing so uncover how human behaviour develops and evolves over time (both in the short and long term). ABMs can reveal how predictable human responses to situations and information alters behaviour in ways that affect vulnerability and resilience. For example, ABMs have been used to reveal how exposure to flood events has resulted in more risk averse behaviour, which can take the form of implementation of mitigating measures and agents moving to less vulnerable locations (Han and Peng, 2019; Crick et al., 2018; Dawson et al., 2011; Dubbelboer et al., 2017; Haer et al., 2017; Jenkins et al., 2017; Yang et al., 2018). ABMs have also been reported a useful tool for 'simulating the effects of different adaptation options on reducing vulnerability' as they allow representation of dynamic changes in climate, and of the adaptive processes of different groups (Acosta-Michlik and Espaldon, 2008). Factors such as these need to be (but in the past have not been) considered so as to ensure resilience analysis is representative.

The emergence of increasingly advanced ABM modelling processes focusing on human behaviour, can accommodate diverse 'Big Data' inputs, representing a range of phenomena relating to environmental conditions and the human world. For example, mined social media data have recently been shown to form a valuable input to ABM processes. Du et al. (2017) demonstrate this in their model of individual flood evacuation behaviour, in which they focus on transport networks. Outputs of such analysis could prove useful for revealing flood-related infrastructure stresses and disruptions impacting supply chains. Analytical outputs generated through ABM processes could form useful inputs to resilience assessments, also covering the wider consequences of infrastructure failures, for example, those related to roads, power stations, water supply, and port facilities (Kunreuther et al., 2016). In respect to this, a single flood event can potentially generate a multitude of secondary impacts, such as disruptions to business, supply chains, and utilities failures. ABMs have been used for modelling such failures, and predicting the resulting duration of power outages (Walsh et al., 2018).

6.6.5.4 Impact Analysis

Quantification of physical change to coastal landforms can now be undertaken more accurately due to advances in data collection and processing methods (Williams et al., 2018). This provides valuable inputs to the estimation of physical impacts, such as geomorphological volumetric change of cliffs, beaches and nearshore areas. This has been required in resilience studies such as that undertaken by Ellison et al., 2017, and is crucial in the region of East Anglia where high rates of coastal erosion have been experienced (Nicholls et al., 2015). A range of techniques are available, which vary in complexity and data requirements (Rumson et al., 2019). Analysis conducted using data collected from Lidar (Caroti et al., 2018) and multibeam echo sounders (MBES), allows change estimates to be generated through surface creation and comparison (Pollard et al., 2019; Williams, 2012). Alternatively, if high resolution scanning data is available, point cloud level change analysis can be completed, utilising advanced functionality (Lague et al., 2013) and automated processes (Kromer et al., 2017). Outputs generated from such analysis, can allow evidence-based assessments to be made of linear and volumetric change resulting from the propagation of coastal hazards (Figure 31). Morphological change can also be derived from analysis of EO data; application of interferometric techniques, for example, can allow subsidence monitoring (Ramieri et al., 2011). The use of EO data also allows more general change analysis to be undertaken, allowing wider impacts from a hazard event to be revealed, such as flood extents/depths, and damage to infrastructure and property (Grason, 2018; Geller, 2017). Satellites have even been tasked to acquire images of flooded areas based on automated interpretation of social media data (Cervone et al., 2016). In respect of this, and of other opportunities presented by EO data, it could be prudent for coastal management organisations to complete a cost benefit analysis in relation to the use of EO datasets, as the cost of high-resolution EO data may be substantially offset by the reductions in economic losses on the ground made possible through having the ability to complete granular, up-to-date analyses. Furthermore, a range of options now exist for obtaining EO data. Medium resolution data collected by miniaturised satellites can be obtained at a relatively low cost, whilst multiple possibilities exist for acquiring higher resolution imagery for specific locations, through tasking satellites (Rumson and Hallett, 2019).

6.6.5.5 Analysis of social media data

The range of analytical methods making use of social media data is expanding. A number of recent studies have focused on how these advances can be applied to flooding (de Bruijn et al., 2018; Jongman et al., 2015; Smith et al., 2017; Wang et al., 2018). For example, techniques such as geoparsing have proved powerful in extraction of location data from flood/disaster related Tweets (de Bruijn et al., 2018). Twitter data has also been drawn on to determine flood extents (Li et al., 2018; Panteras & Cervone, 2018). Supply chain resilience and systemic risk modelling, is another area in which social media data has been applied (Papadopoulos et al., 2017). Within the metrics listed in Appendix 6.2, a number of inputs are detailed as potentially being derived from analysis of social media data, these include tourism hotspot identification and traffic activity (Li et al., 2016), and flood extents (Figure 32).

6.6.5.6 Scale dependent data requirements

When planning a coastal resilience assessment, scale is an important consideration. Depending on the scale of analysis (household/local/regional/national), separate data sources may be drawn upon. This is apparent when contemplating the use of terrain data (Figure 31). Localised analysis of granular cliff face deformations requires the use of high-resolution point cloud data, such as that acquired using Terrestrial Laser Scanning (TLS) systems, whilst for analysis concerned with linear cliff retreat over a wider scale (multiple kilometres), data obtained through aerial Lidar surveys may be more appropriate (Young, 2018). This can also be the case for analysis using aerial photography or EO data. If granular details are required for damage assessments at a building level, then the high spatial and temporal resolutions provided by commercial EO data suppliers, such as DigitalGlobe (2017), may be required. Whilst for assessment of land use change at a smaller scale, open source EO data such as that available from Copernicus (2019) may be adequate.

Many of the variables relating to the metrics selected, are scale dependent. As a result, the availability of datasets at the required resolution may place limitations on the scale at which an assessment can be undertaken. For example, the UK Office for National Statistic (ONS) hold many statistical datasets which are only decomposed by region, city or ward (Figure 30). This precludes assessments to be undertaken at a sub-regional/city/ward level. When considering scale, it is also important to highlight how caution needs to be exercised when utilising aggregated land use data; past examples have revealed how this can prove unrepresentative (Jongman et al., 2012).

6.6.5.7 Data utilisation opportunities and constraints

Technical expertise is required for analysis of social media feeds, implementation of ABM processes, geomorphological change detection, EO data centred techniques, and application of the range of machine learning, NLP and ANN methods available. This short discussion of analytical techniques has highlighted methods which could potentially be drawn on within coastal resilience assessments, but so far it hasn't covered the feasibility of these methods being utilised within assessments completed by coastal practitioners. It is likely that those organisations seeking to undertake resilience assessments may not hold the necessary technical skills to undertake such complex analyses, nor may they have adequate budgetary means to allow outsourcing of this analysis to external suppliers. This highlights the wider issue of increasing demands being placed on organisations, due to the rapid progression towards data-driven decision-making. Nevertheless, it has been revealed that techniques and methods do exist which can allow data to be generated, potentially providing answers to questions, which in the past could only be answered through more subjective expert inputs. This marks an important progression, as expert opinion has previously proven an inadequate method for capturing the dynamic nature of many coastal risks (Rumson and Hallett, 2019). Therefore, adoption of innovative data-driven methods within coastal management decision making practices should be prioritised, as they could prove cost-effective, allowing resources to be allocated more appropriately, so enabling more effective spatial planning.

6.7 Resilience Assessment Method

Once data inputs have been acquired, satisfying the requirements of the metrics selected for a resilience assessment, the data variables must be combined and analysed to expose the spatially variable levels of resilience. The studies reviewed as part of the QSR (Appendix 6.1) employed a range of different analytical methods. These included probabilistic approaches, drawing on Bayesian techniques (Cai et al., 2018; Schultz & Smith, 2016), and Copulas analysis (Joyce et al., 2018). Many drew on 'composite indicator' methods and 'multi-variate/multi-criteria analyses (Abenayake et al., 2018; Burton, 2015; Cai, Lam et al., 2018; Hung et al., 2018; Joyce et al., 2018; Karamouz & Zahmatkesh, 2017). Geospatial analysis, using Geographical Information Systems (GIS), was the most common method utilised, and 9 of the 29 studies listed in Appendix 6.1, incorporated this approach. An extensive evaluation of the various analytical methods available is beyond the scope of this current study; however, through consideration of the data types associated with the metrics we have compiled, and of the requirements detailed by CPE (Section 6.2), the authors deem geospatial, GIS-based analysis the most suitable option for collation and analyses of the various metric datasets, and also a suitable medium for presentation of the results to stakeholders.

Most of the selected metrics are linked to data which can be spatially referenced, and many of the inputs required for a resilience assessment are frequently supplied as GIS datasets (Allen et al., 2018; Lam et al., 2015). Given this, it would be possible to represent individual metric variables as spatial attributes in vector datasets (shapefiles) or as raster layers. This would permit further geospatial analyses (Fekete et al., 2017; Lam et al., 2015), which could be used to: identify land use, natural habitats, terrain, land heights, water levels, the distribution of assets and resources, and many other features. Spatial analysis could be used to reveal vulnerable areas and populations which are unprepared (Lam et al., 2015; Szewrański et al., 2018). Also, the proximity of businesses, populations, and infrastructure, to hazards, emergency resources, and many other factors, could easily be determined (Hung et al., 2016; Johnson and McLean, 2008). This analysis could be undertaken manually through comparison of GIS layers, or through the automated application of spatial analysis tools.

Many of the resilience assessment methods highlighted within the QSR literature, rely on expert weighting of indicators (Abenayake et al., 2018a; Karamouz and Zahmatkesh, 2017), generating an index linked multi-criteria score. This is an inherently subjective process, not necessarily representative of the diverse range of interrelated factors requiring consideration. However, it could potentially be avoided through the application of a range of geospatial analytical techniques. Communication of resilience is also challenging, and the outputs generated by some purely statistical techniques, can be difficult to understand and can oversimplify complex processes. GIS tools are capable of generating a diverse range of geostatistical output, which have been shown to engage coastal stakeholders (Allen et al., 2018; Hung et al., 2016; Wadey et al., 2015). These can prove particularly suited to communicating the outputs of a resilience assessment, and can be used to generate simulations of future scenarios (Allen et al., 2018). Furthermore, resilience related outputs, generated through GIS analysis, can be simplified and supplied to practitioners via configurable user interfaces, potentially accessed using web mapping interfaces (Karavokiros et al., 2016).

6.8 Discussion

6.8.1 Operationalising the coastal resilience evidence base: Coastal Partnership East

This work has sought to reveal how the wide range of data sources and information outputs, derived through analytical processes, can be drawn on to address the multitude of factors requiring consideration when undertaking a coastal resilience assessment. In doing so, an extensive listing of assessment metrics has been compiled. This also addresses the issue of a lack of definitive metrics being agreed on for measuring coastal resilience (Burton, 2015; Cai et al., 2018). The case study approach adopted has facilitated an evaluation of how resilience assessment metrics can be selected and grouped, and how data sources can be identified addressing these metrics. The work has addressed a previously acknowledged requirement to incorporate empirical evidence within coastal resilience assessments (Cai et al., 2018a), and to embrace a dynamic approach to such assessments (Cai et al., 2018b; Cutter and Derakhshan, 2018; Lloyd et al., 2013; Martinez et al., 2017; Song et al., 2018). In Sections 5 and 6.6, we discussed metric selection, data sources, and data analytics. This section focuses on how the evidence base identified for East Anglia could be utilised. In doing so, we refer back to the set of stakeholder requirements provided by CPE (Section 6.2), and evaluate how these could be addressed using the approach discussed in this study. The approach taken has sought to address the pressing issue of inadequate information flows between scientists, policy makers and practitioners (O'Mahony et al., 2015), which can impair decision making by coastal practitioners. This has been acknowledged as a problem by those operating in the case study region of East Anglia. However, in addressing this issue we haven't constrained our scope to East Anglia, and as such we have sought to provide an indication of the relevance of the approach to other areas, countries and to varying scales of application. In the following sections we discuss how the practitioner requirements outlined in Figure 28 could be addressed using the metrics, framework, and data sources presented.

6.8.1.1 Practitioner requirement 1: Review and incorporate data for SMP CCMAs within an assessment to identify and aggregate what is at risk over the next 100 years (given current SMP predictions).

In addressing this requirement, essentially data depicting SMP predictions for the assessment area are required (metric #19) in addition to the spatial extents of the CCMAs. Following this a range of exposure data would need to be included, representing coastal populations, property, infrastructure, businesses, and local amenitites (similar analysis documented in a recent study drew on the EA's National Receptor Database and OS Mastermap datasets (Committee on Climate Change UK, 2018)). Given the need to predict vulnerability, planning information would also need to be included, along with information detailing any restrictions on land use or preservation orders. Hazardous areas sited within projected erosion zones would need to be identified, such as landfill, or other waste sites, along with any critical infrastructure. Metrics covering these information requirements are listed in Appendix 6.2, with the majority of relevant metrics contained within Stages 1 - 3.

Evaluation of this requirement using empirical sources, could also result in questioning its basis. The governance regime's requirement for using 20, 50 and 100 year time periods as an indicator of flood and erosion hazards may need to be revisited based on data revealing the extents of recent impacts. Climate change is resulting in an increased probability of extreme events occuring at more frequent intervals, and current erosion prediction methods have been associated with high levels of uncertainty (Committee on Climate Change UK, 2018). As such, the basis of predictions of change may need to alter. This could result in more immediate requirements to take action. In line with this, design criteria for critical coastal facilities may require modification, in addition to expectations of the lifespan of buildings located in exposed areas.

6.8.1.2 Practitioner requirement 2: Incorporation of outputs of the most appropriate and advanced methods for measuring and reporting on coastal change.

This requirement was interpreted to represent multiple types of change (not just physical), including: geomorphological change (Figure 31), land use change, loss/gain in natural capital and species, change in the adaptation measures implemented, socio-economic changes (population densities and distribution), change in economic activity and industry, land/house valuation changes, and change in recorded human behaviour. Again indicators addressing all these factors are contained within the metric listing. Metrics addressing the majority of such changes can be found within Stage 5, Impacts. However, other appropriate metrics are also found in Stages 3 and 4.1, such as socio-economic indicators, and the presence of structural and natural adaptation measures. EO data could prove especially useful in identifying physical changes relating to land use and land cover, however the resolution required to monitor more granular changes, may not be obtainable from open sources, so commercial EO data suppliers may need to be used. Solutions addressing this practitioner requirement would directly benefit from the increasing volumes of data now available, allowing analyses to be completed across a wider range of scales, than would be possible if only human input was relied upon.

6.8.1.3 Practitioner requirement 3: Evaluate how prepared local authorities and communities are to respond to/recover from future coastal change and high intensity hazard events.

In answering this requirement, the metrics listed in Stages 4.2 and 6 would need to be analysed. It is unlikely that this requirement could be fulfilled for East Anglia, based only on currently available datasets or analytical outputs (as described in Section 6.6.5). Input would need to be sought from stakeholder organisations, especially local authorities and other community level organisations. Given this, it is envisaged that it would prove time consuming to address this requirement and the results obtained could be more subjective.

6.8.1.4 Practitioner requirement 4: Identification of contingencies in place and adaptations.

This could be tackled through analysis of the metrics contained in Stage 4. A broad range of measures would need to be considered in addressing this requirement: household level mitigation measures, hard and soft adaptations, ecosystem services, non-structural adaptation such as insurance, and a broad range of the contingency measures outlined in Stage 4.2. CPE is primarily concerned with the eroding coast. Given this, the metrics selected should be erosion specific, i.e. covering engineered sea defences, soft adaptations (beach nourishment/sandscaping), and contingencies such as resettlement sites, rather than those more specific to flooding, i.e. drainage. There are fewer measures documented within the metrics listed, offering preparation and contingencies against erosion. This is due to impacts from erosion offering fewer options for recovery, with assets and infrastructure generally being permanently destroyed. However, flooding impacts can be temporary, with more options presented to enable systems to resume operation.

In addressing both the third and fourth practitioner requirements, an alternative approach is to draw on the notion of adaptive capacity (Gallopín, 2006; Smit and Wandel, 2006). This places emphasis on the ecological definition of resilience (Holling, 1973), which centres on systems shifting between stable states. This is particularly suited to consideration of resilience in areas prone to erosion, where the status quo cannot be maintained. In assessing resilience based on adaptive capacity, metrics need to be drawn upon which are able to represent the capabilities of a coastal community to assume some form of functioning order, in the absence of options to return to a prior state following disturbance by a hazard event. To allow this, a complex range of measures need to be in place, these must extend beyond planned or spontaneous adaptations, such as sea defences or flood barriers, which aim to resist environmental change (Cooper and Pile, 2014). Metrics contained within Stages 4 and 6 are representative of some of the factors requiring consideration. These can relate to spatial planning, i.e. siting of government offices, emergency services and critical infrastructure outside of hazard zones. Appropriate regulation and governance measures being in place, preventing maladaptive and unsustainable practices, and enforcing appropriate building codes. Long term measures such as preservation of wetlands and natural capital also factor into this, alongside installation and maintenance of sustainable infrastructure. Understanding the presence of societal capacity is also crucial, such as the presence of networks, groups and plans for coordination of the public. Public awareness of the proximity, probability, and magnitude of the hazards and potential impacts, also needs to be considered. Indicators revealing past and projected responses to hazard events could also be included. Grouping metrics representing these diverse factors, within a single assessment, could prove instrumental in revealing the long-term resilience levels of vulnerable coastal communities. The results of assessments, based on such metrics, could enable district level bodies such as CPE to greatly improve their adaptive capacity. It would also be beneficial to complete such assessments on a regular basis, allowing governance institutions and the public to track progress. Positive results, from these routine assessments, could further act as an incentive or driver for economic development.

Within this study a limited amount of time was devoted to establishing metrics which could prove relevant to a resilience assessment focusing on adaptive capacity. Given this, scope exists to refine these metrics further and to identify other, potentially more important, metrics, which could allow forward planning in the face of potential chronic or acute hazard damages. Evidence-based assessment of adaptive capacity is crucial given the widespread policy resistance to adaptation (McGuire, 2018).

6.8.1.5 Practitioner requirement 5: Enable sustainable planning leading to resilient outcomes.

This is a comprehensive objective and necessitates consideration of metrics from all stages of the assessment framework (Figure 29 and Table 16). The objective was interpreted as involving multiple aspects of planning, including spatial planning, therefore geospatial analysis, involving a GIS-based resilience assessment (as outlined in Section 6.7), is particularly suitable. Metrics which are especially relevant to this requirement are associated within Stage-4 of the framework, especially those detailed under the heading ‘planning’. Sustainable planning necessitates that all potential hazard sources and threats be considered. Given this, metrics covering hazards and environmental conditions (Stage 1) are relevant. A thorough appraisal is required of the role played by natural capital. This can potentially prevent approval of unsustainable future developments, which may result in destruction of natural systems and loss of ecosystem services. The role of structural adaptations would also need accounting for, especially their impact on natural systems, such as sediment budget distortion. Sustainable (whole shoreline) responses to erosion threats can be contentious and difficult to implement (Nicholls et al., 2015), metrics would need to be included revealing who and what would be exposed if proposed strategies were adopted. There can be options to repair flood damaged properties, so metrics related to insurance should be included, as appropriate cover could increase the resilience of those living in areas prone to flooding. Insurance covering erosion is not currently available, therefore alternative financial measures associated with erosion impacts, such as support for rollback schemes (Defra, 2012), should also be accounted for. Metrics detailing socio-economic and demographic factors should be included, as planners need to know what socio, cultural and economic gain future adaptations, mitigations and planning options may generate. This could relate to transport links, population densities, income and dependency levels, potential options for regeneration, employment levels and business activity.

6.8.2 Wider Application

Coastal flooding and erosion are global hazards, therefore the coastal management requirements addressed above, which were specific to East Anglia, are taken to be representative of the wider issues experienced in coastal regions globally. One potential key difference, in terms of assessment of resilience, is that data availability may be more limited for coastal areas in many other regions and countries. Therefore, this may result in a much higher number of metrics which cannot be satisfied using empirical data. However, alternative measures could be looked to in overcoming a lack of available datasets. For example, it may be possible to derive outputs through proxy measures or analytical methods, such as those highlighted in Section 6.6.5. This could act as a substitute for many of the preconfigured data sources listed in Appendix 6.3. EO derived datasets have been recognised as providing such an alternative for analysis undertaken in developing countries where data sources are lacking, especially in relation to flooding (Ekeu-wei and Blackburn, 2018; OECD, 2016). The literature reviewed as part of the QSR (Appendix 6.1), documented coastal resilience assessments undertaken in many different parts of the world, in varying contexts. All resilience assessment metrics listed in Appendix 6.2 were derived from these studies. Therefore, the methodology outlined in this current study, is representative of varying contextual factors, found in coastal regions across the world.

6.8.3 Novelty and limitations of the coastal resilience assessment framework, metrics, and evidence base approach

In summarising the approach adopted within this study, for selection of resilience assessment metrics and associated data sources, we have highlighted novel aspects which we believe contribute to the current academic discourse associated with this field. We have also highlighted a number of limitations of the approach employed within this paper. These are detailed in Table 17.

Table 17: Novelty and limitations of this research.

CONTRIBUTIONS OF THE DATA-CENTRIC APPROACH TO THE FIELD OF COASTAL RESILIENCE	
1.	An original approach was taken in grouping such an extensive range of indictor variables based on a simple resilience assessment framework (Figure 29); consideration of the disparate data variables highlighted as pertinent to coastal resilience can aid identification of relationships between factors not obviously connected.
2.	The approach presented within this study can form a basis for development of further, more refined, context specific, coastal resilience assessments.
3.	The framework and metrics (Figure 29 and Table 16) are founded on input parameters used in assessment of resilience in multiple contexts (as documented in previous research (Appendix 6.1)), so are internationally representative.
4.	The data-driven approach we advocate provides a means of operationalising the concept of resilience within coastal management for multiple settings.
5.	Through revealing how existing datasets can be drawn on within resilience assessments, we present options for expanding awareness of the evidence base available to coastal management practitioners.
6.	Derived data output from advanced analytical processes (Section 6.6.5) are shown to be capable of displacing more subjective methods used for obtaining the required inputs to resilience assessments.
7.	Our data-centric approach builds on progress made in assessing coastal risk (especially in relation to the SPRC scheme), incorporating this within assessment of resilience.
8.	A number of the data sources outlined and discussed are available as near real-time feeds, this potentially provides a means to allow dynamic assessment of resilience.
LIMITATIONS OF THIS RESEARCH	
1.	To date, the approach presented within this research lacks practical validation within a complete resilience assessment.
2.	The data source evaluation completed in this study was limited to one country and region.
3.	Due to the high number of metrics (Appendix 6.2) and data sources (Appendix 6.3), only a limited review was undertaken of the suitability of the data sources outlined, for each metric they were associated with.
4.	If the datasets and the associated variables, which are listed in Appendix 6.3, were to be used within a resilience assessment, additional scrutiny of metadata, and data consistency, validity and veracity, would need to be undertaken.
5.	The number of metrics listed in Appendix 6.2, could prove overwhelming, and may require significant levels of scrutiny to determine which are most suitable to any given context.
6.	A hierarchy has been established (Table 16) to aid collation of factors represented by the selected metrics (Appendix 6.2); some degree of flexibility exists in the categories assigned within this. The process of sorting the metrics into stages and sub-categories was inherently subjective.

7.	This study has identified a list of metrics suited to assessment of coastal resilience, and revealed how these could be applied, however it has not discussed benchmarks related to the variables assessed within the metrics. Such benchmarks could prove important for charting progress.
8.	The price tag associated with data sources required for evaluation of a number of the metrics may prove prohibitive for their utilisation within assessments completed by public sector/academic organisations.

6.9 Conclusions

The ability to understand, assess, and monitor resilience is essential for decision makers, tasked with management of coastal regions. In providing the capacity for such, it is possible to build on standard coastal risk assessment frameworks, which have focused on hazards and vulnerabilities, and anthropogenic and ecological exposure. However, whilst risk assessments tend to limit their evaluation of hazard responses to a focus on physical adaptation mechanisms, an assessment of resilience must also account for more incident specific details, such as recovery times, and the broad range of preparations and contingencies which have been implemented. As such, it is crucial for assessments to account for measures which minimise disruption, whilst maximising the ability of coastal systems (ecological, economic, infrastructure, and community) to continue to function following a hazard event. The concept of resilience is wide, assessment of resilience therefore requires a multifaceted approach, involving consideration of a range of holistic data and information sources. This paper has focused on the evidence base available for assessment of coastal resilience and the specific indicator metrics which should be included within a holistic assessment. Many previous examples of coastal resilience assessments have relied heavily on human, opinion-based, input (Abenayake et al., 2018a; Bostick et al., 2017; Keating et al., 2017). Reliance on such, can prove time consuming and subjective. In an attempt to address these issues, this work has sought to identify metrics which can be assessed using empirical evidence. Accordingly, a case study approach was adopted, and the region of East Anglia (UK) was focused on.

Through review of past studies covering coastal resilience, an extensive range of indicator metrics were selected. For each metric an indication has been provided of data sources, specific to the case study region, from which input variables could be obtained. It was not found possible to fulfil the input requirements of all metrics listed in Appendix 6.2, through drawing on available preconfigured data sources. However, it was considered possible to satisfy the requirements of 75% of the proposed metrics, through utilisation of empirical sources. Some 16% of these metrics would require outputs derived through analytical processes, to satisfy their requirements. A clear divide was observed between levels of data available for the metrics associated with traditional risk assessments (i.e. those related to hazard source, pathway, receptor, and consequence) and the metrics more unique to resilience assessment (representing hazard event response, recovery, preparations and contingencies). This revealed that, irrespective of data availability, assessment of resilience is inherently more subjective than assessment of risk. However, this study revealed how the number of metrics within a resilience assessment requiring such subjective inputs can be minimised.

Combining novel data sources, such as crowd sourced and EO data, can improve our ability to account for ecosystem services, land use change, impacts from hazard events, and system recovery. There are caveats associated with using information derived through such techniques, these include requirements for technical skills, time, and the ability to establish the veracity of data sources. The example data sources highlighted within this study, for the case study region of East Anglia (Appendix 6.3), include both freely available and proprietary data sources. When planning a resilience assessment, it is necessary to consider the relative benefits of both open source and proprietary data. Time constraints, budget, and the internal capacity of the organisation seeking to undertake the resilience assessment, are all factors influencing the type of data sources used.

An extensive listing of metrics is provided in Appendix 6.2, however, it is not intended that all of these metrics be utilised within a single resilience assessment. Separate indicators should be selected depending on the scale at which an assessment is undertaken (local/regional/national), the type of area focussed on (rural/urban/ mixed), and the specific form of resilience considered (long term/short term/disaster). Grouping appropriate metrics, from those proposed, can provide the opportunity to track progress in the resilience of a coastal region or district. This could expose ineffective planning and hazard responses, and a lack of adaptive capacity, and holds the potential to improve future coastal management policy responses. Selection of appropriate indicator metrics forms only one part of a resilience assessment. However, the variables considered are of crucial importance to later stages, involving analysis and communication of results. Application of the primarily data-driven mode of resilience analysis we suggest would require technical skills and an understanding of the input datasets. Stakeholder organisations, such as CPE, may not possess this. However, the main objective of this study was not to evaluate or propose a single method of resilience assessment, but to establish a set of metrics, and data sources suitable for inclusion within a data-driven coastal resilience assessment. In addressing this objective, we have presented options permitting emerging sources of data and analytics to be drawn on within a structured, holistic assessment of coastal resilience. Through careful selection of metrics that cover ecological, economic, and social aspects of resilience, this data-centric approach could assist coastal practitioners in achieving sustainable, resilient outcomes.

6.10 Acknowledgements

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6.11 Appendices

6.11.1 Appendix 6.1: Quick Scoping Review

A QSR is a type of evidence review that aims to provide an informed conclusion on the volume and characteristics of an evidence base and a synthesis of what that evidence indicates in relation to a question (Collins et al., 2015). The QSR detailed here seeks to collate evidence from academic articles and grey literature, synthesising this in order to address the following questions:

1. What indicator metrics need to be included within a coastal resilience assessment?
2. What methodological approaches have been used to combine such metrics?
3. What data sources have been associated with these metrics?

Initially a wide search was completed of websites and grey literature. From this, a number of non-academic, sources were identified as particularly relevant to coastal resilience. The most prominent among these, and those specifically relevant to the UK and the case study region, are detailed in Table 18; in this some of the most prominent metrics referred to are detailed. Together, these documents provide material detailing the key resilience initiatives currently undertaken within the UK and select studies from further afield. The data sources and frameworks utilised were also detailed. Consideration of these sources contributed to the subsequent selection of assessment metrics and data sources detailed in Appendix 6.2 and 6.3.

Table 18: Non-academic literatures sources, with prominent metrics mentioned in these detailed.

#	Author and Publication	Metrics
1	Defra (2016) National Flood Resilience Review.	Flood hazard threat, past frequency of hazard events, flooding from other sources (pluvial, fluvial), extreme rainfall, past storm surge events, climate projections, river and estuarine data, inundation zones, flood risk exposure, key infrastructure at risk - rail, highways, ports, airports-, water supply and treatment, telecommunications, energy, medical facilities, assessment of flood defences, health, temporary defences, incident response, local planning, flood risk communication
2	The Environment Agency's SMP Plans (Defra, 2006; Environment Agency, 2009);	Past frequency of hazard events, erosion prediction, flood risk exposure, main employers and sectors, land use, natural habitats, maladaptive practices, sediment supply, farming/agriculture, tourism, coastline length, urbanisation, distance from the coastline to major developments, presence/functioning of coastal defences, natural capital, habitats/specie numbers, recreational use of the coast, port usage, critical infrastructure, highways, rail, assets in flood/erosion zones, funding for resilience measures
3	The Committee on Climate Change UK's	Climate change induced hazards, assets located in flood/erosion zones, distance from the coast of developments, predictions of weather and climate patterns, exposed infrastructure, spatial

	(2018) report 'Managing the coast in a changing climate'	distribution of hazard events, functioning of coastal defences, property level mitigation, insurance coverage/availability, tidal data, salinization, flood and erosion event casualties, financial impacts of flood and erosion damage, health impacts, housing density, inundation zones, flood hazard threat, principle arterial roads and rail miles in hazard zones, landfill sites, agriculture, population age dependency ratio, natural capital, habitats and species, governance, land use and urban planning, resettlement sites, funding for resilience measures, awareness of local population
4	Twigger-ross et al., (2015), Flood Resilience Community Pathfinder Evaluation	Awareness of local population, population distribution and structure, poverty levels, age dependency ratio, disability ratio, recent immigrants, employment, incomes, insurance coverage/availability, civil society groupings, informal coordination of citizens activities, resettlement sites, volunteer networks, risk management plans, maintenance of storm sewers, availability of emergency aid, funding for resilience measures, household mitigation measures, exposed infrastructure
5	The National Infrastructure Commission's (2018) National Infrastructure Assessment	Presence/functioning of coastal defences, inundation zones, natural flood buffers, natural capital, properties flooded, insurance coverage, insured losses, financial impacts of flooding, habitat creation, predictions of weather and climate patterns, exposed infrastructure, population change, assets in flood/erosion zone, population density, funding for resilience measures, SMP erosion predictions, flooding from other sources, land use planning
6	NOAA Office for Coastal Management (2015) Coastal Community Resilience Indicators and Rating Systems;	Exposed critical infrastructure, critical facilities (i.e. emergency services) in hazard zones, assets in hazard zones, maintenance of adaptations -storm sewers etc, availability of potable water, ecosystems services, natural capital, habitats, impacts on tourism and recreation, business plans and equipment, existence of risk management plans, hazard awareness of local population, capacity of waste water treatment plants, climate change predictions, emergency services readiness, availability of flood maps, flood/erosion education, insurance cover, financial impacts of past events, early warning systems, availability of communication systems, business recovery times, population characteristics, public buildings and infrastructure locations, health impacts, evacuation plans, emergency response plans, stormwater management plans, implementation of building codes, community cohesion/social capital,
7	EPICURO (2018) European Partnership for Innovative Cities within an Urban	Spatial planning, population structure, climate and weather predictions, waste water management, solid waste management, energy security, transport exposure, transportation access -port, rail, roads-, electricity outages, availability of resilience funding, effective leadership and management, continuity of critical

	Resilience Outlook, Best practice analysis.	services, communications reliability, alternative energy sources, building codes implementation, civil society participation, social capital
8	Resilience Alliance (2010) Assessing resilience in Social-Ecological Systems - A workbook for practitioners v.2.0	Ecosystem services, salinization, specie distribution, sediment distribution, climate variables, erosion/accretion rates, health impacts, job losses related to hazard events, land cover, water quality, social networks, governance systems, incomes, soil type, funding for resilience measures

However, these reports represent a sample of only a limited body of work currently addressing issues relevant to coastal resilience beyond academia. The main body of information drawn upon in the QSR was sourced from academic journals. Yet due to the limited quantity of literature available, being focused specifically on assessment of coastal resilience, search terminologies used were extended to include wider hazards and scenarios, such as inland flooding and disaster resilience. The search of the academic literature was undertaken primarily using Web of Science (https://apps.webofknowledge.com), and SCOPUS (https://www.scopus.com).

Table 19 indicates the original search terms applied and the number of results these generated, in the respective search engines. The search strategy ensured all aspects of the QSR questions were covered. A range of possible subject descriptors for each of the keywords in Table 19 were identified in order to ensure that useful references were not missed. A wildcard (*) was also used where possible to pick up multiple word endings.

Table 19: Keywords used in the literature search (noting 'and' qualifiers where considered important to focus search).

Search Terms	# Results	
	Scopus	WoS
"coast* resilience"	130	99
"coast* infrastructure*" AND "resilience"	22	16
"coast* area*" AND "Resilience"	268	536
"coast*" AND "resilience assessment"	26	18
"coast*" AND "resilience" AND "data source*"	13	6
"coastal resilience assessment"	1	0
"coast*" AND "flood" and "resilience" AND "assessment*"	125	62
"coast*" AND "flood" AND "resilience" AND "evaluation*"	26	14
"data" AND "resilience assessment*"	72	66
"climate change" AND "resilience assessment*"	46	57
"resilience assessment*" AND "disaster*"	118	82
"information" AND "resilience assessment*"	64	54
"method*" AND "resilience assessment*" AND "coast*"	16	13

The initial web search outputs were screened using the following steps:

1. Initial review of the article titles resulting from the searches based on key words. Where this screening provided material of interest then:
2. The material was screened at abstract/contents page level to determine if the material was of further interest.
3. After passing these two screening stages (and also if any uncertainty remained regarding the material's value) then articles were consulted in full to:
    a. confirm whether or not the document was of relevance to the questions being addressed,
    b. extract the required evidence.

From the original academic literature search results detailed in Table 4, 73 papers were selected for further review (screening stage-2). Following subsequent analysis of the material covered in these articles, the list of relevant papers was further reduced to the 29 listed in Table 21 (screening stage-3). Selection of these articles was based principally on their content, covering explicit details of the methods, metrics and datasets used in resilience assessments. Efforts were made to include studies addressing a mix of spatial scales, those applied to both rural and urban settings, and those covering assessments of multiple types of resilience (including: social, economic, infrastructure, community, institutional, environmental, and structural (Burton, 2015)). The search results obtained, indicate an exponential increase in the number of papers published covering aspects of coastal resilience during the last 5 years. Furthermore, the majority of the works selected for further review (stage-2 and -3) were published during the last three years, and studies focusing on the USA represent over a third of those selected. Table 20 provides a summary of the number of works selected, by year published. No time limit was imposed on the literature searches, yet no relevant works were located which were published earlier than 1998. Evidence extracted from the 29 articles, which passed through the QSR screening process is presented in Table 21.

Table 20: Academic articles reviewed, by year published. Those relating to the second review are listed in Table 21.

Year	Number of Articles	
	First Review	Second Review
2019	1	1
2018	31	12
2017	14	8
2016	9	3
2015	3	3
2014	3	1
2013	1	-
2012	1	1
2011	3	-
2010	2	-
2009	1	-
2008	1	-
2003	1	-
2001	1	-
1998	1	-
Total	**73**	**29**

Table 21: The 29 most relevant studies identified in QSR, from which metric themes were derived. Details provided only indicate author(s) and year of study, full details of each study are found in the reference section. The table indicates study case study area (if appropriate), type of resilience or hazard focussed on, scale, nature of study, type of method used for resilience assessment, and mentions pertinent issues relating to metrics and data sources used.

#	Paper Ref.	Location	Focus	Scale/ Area	Details	Resilience Assessment Method	Metrics and data
A	Lam et al., 2018	Mississippi River Delta	Community disaster resilience	Regional	Social, economic, infrastructure, cultural and economic sectors considered.	Resilience Inference Measurement (RIM). ABM, Cellular Automata (CA)	2 main indicators: Coast hazard events -property damage; recovery- population change
B	Cai et al., 2018	Mississippi River Delta	Community resilience.	Regional, Urban and rural.	Variable identification –Population change an indicator. Complex assessment.	Bayesian Network Model: EM method – conditional probability, JT algorithm –posterior probabilities	Variables identified as important: Threat level to coastal hazards; hazard damage; employment rate; distance to coastline; % houses built before 1970; %HH containing females
C	Song et al., 2018	Busan, Republic of Korea.	Flooding damage and Socio-ecological resilience.	Urban	Green Infrastructure. Quantitative results generated in study. System resilience = system performance x cumulative value. Causal loop diagrams used.	System Resilience Dynamic Model (SRDM), 4 R model Simulation with spatial modeller in ArcGIS	Presence of impervious surfaces highlighted as important.
D	(Abenayake et al., 2018b)	Colombo Sri Lanka. Multi district	Community resilience Floods	Urban/ rural	Validation of geospatial indicators.	System Performance based method	Resilience capacities identified: transform, absorb, and recover. Metrics represents all 3 capacities. 16 indicators found to be pertinent.
E	Joyce et al., 2018	Florida, USA	Flooding and engineering resilience	Mainly Urban, local scale	Drainage infrastructure. Look at physical adaptation measures. Resilience = recovery time reduction. Exposure determined by adaptive measures	Multi-criteria method incorporating Copulas Analysis	Careful formulation of metrics around common vulnerability criteria. Hazard variables: wave, pressure, wind, rainfall, tides. Adaptive measure criteria outlined.
F	Cutter & Derakhshan, 2018	Entire USA	Community Disaster Resilience assessment	Urban/ rural National level	Cascading effect analysis flowchart. 3D visualisation. Basis of long terms spatial or development planning and emergency preparedness. Natural hazards.	Baseline Resilience Index for Communities (BRIC) (Cutter et al., 2014)	6 resilience categories represented: social, economic, environmental, housing/infrastructure, community capital, institutional. Data sources outlined.

G	Hung et al., 2018	Taiwan.	Flood, not total resilience	Household level focus, Communities	Public measures. Behaviour component. Focus on implementation of HH adaptive measures.	Multi-variate analysis. Resilience Framework of Household Autonomous Adaptation to Climate- and Weather- Related Hazard Risks (ROHACHR)	Metrics representing: Risk information; Threat appraisal; Household attributes; Social capacity and participation; Adaptation appraisal; Adaptation actions
H	Ellison et al., 2017	Tarawa, the republic of Kiribati.	physical shoreline change and ecological resilience		Satellite data used, sediment analysis, and beach surveys.	Spatial analysis using ArcGIS	Metrics including: vegetation condition, topography, spatial change analysis, sediment supply, human impacts
I	Karamouz & Zahmatkesh, 2017	New York, Bronx	Flooding Impacts from Superstorm Sandy	Urban, local	Identification and ranking of most important factors for increasing system resiliency based on decision makers' judgements.	Multi-criteria decision making techniques, linear combination of metrics; Algorithm Workflow generated, incorporating '4Rs'.	Appropriate metric to enable ranking of factors: economic, social-political, hydrological, physical
J	Bostick et al., 2017	Mobile Bay, Alabama, USA	Disasters indirectly assess resilience, Stakeholder awareness raising	Urban, local	Methodology developed addresses the stages of resilience—prepare, absorb, recover, and adapt—and integrates performance assessment with scenario analysis.	Multi-criteria decision analysis (MCDA), scenario-based preference process.	Stakeholder driven process of identifying and ranking factors impacting resilience. Problem: aggregation of data can blur vulnerability.
K	Fekete et al., 2017	Cologne Germany	Critical infrastructure, risk from flooding and blackouts.	Urban	Combined vulnerability/resilience assessment. Spatial and demographic data utilised. Analyse criticality of infrastructure. Not a static assessment.	4 R model; GIS method – inc. network analysis to determine optimal routes.	Use EO data to determine flood extents and Flood exposure maps. Critical infrastructure identified and interdependencies (i.e. Hospitals and fire stations). Criticality of rail, civil protection, electricity blackouts, routing constraints, emergency shelters, exposed population density, evacuation hotspots, use of civil protection authorities.
L	Joyce et al., 2017	Bayou watershed Florida USA	Coastal drainage infrastructure	Urban Watershed	Establishment of quantitative resilience metrics.	Informatics based Multi-scale Modelling; GIS.	Lidar Bathymetry included as data source.

M	Schultz & Smith, 2016	New York.	Response and recovery of infrastructure system following storms		Data requirements for resilience assessment addressed. Application to coastal management.	Bayesian probabilistic approach	Primary resilience indicator: time to recover system performance. 4 functional performance objectives represented by indicators: life safety, housing, utilities, transportation.
N	(Abenayake et al., 2018a)	Colombo, Sri Lanka	ecosystem flooding/ services, link to community resilience	Not coastal specific, Regional scale	Main focus is physical environment. Aggregating proxy indicators for ecosystems. Expert opinion drawn on for utility scores of land use.	Composite environmental indicators, Weighted linear combination method (WLCM)	Ecosystem services indicators included: flood regulation, climate regulation, nutrient recycling. 4 proxy indicators: soil, hydraulic properties, slope, land use, precipitation factor. Land use parameters: density of land cover, surface roughness of cover, waste assimilation capacity of ecosystem, quantity and toxicity of waste.
O	Karavokiros et al., 2016	Rethymno, Greece	Preparing for Extreme and Rare Events	City level	Documents the project outputs from PEARL, online tool developed. User self-quantifiable metrics and determined.	Pearl Flood Resilience Index Tool. Web GIS based collaboration toolbox	Filters-metrics employed in tool: flood problem type; measurement type; spatial scale; land use.
P	DasGupta & Shaw, 2015	India (Asian mega deltas).	Community Socio-ecological system.	Developing world. Rural	Framework tool. Focus on development of dimensions, indicators and variables.	Coastal Communities resilience index (Composite resilience index)	Reference given to Indicators used in other studies. Requirement identified to integrate metrics representing: social, ecological, human and natural factors
Q	Burton, 2015	Mississippi coastal counties USA.	Disaster resilience. Incident specific - Hurricane Katrine	Urban/ Rural	Assesses the ability of Composite indicators enabling distinction between non-relevant and relevant data.	Multi-variate analysis drawing on composite indicators. GIS used in recovery analysis, and to represent resilience.	Recovery process monitored using repeat photography.
R	Kim et al., 2014	Texas USA.	Disaster resilience. Flooding Incident specific Social ecological resilience to Hurricanes.		Indicators focus	Analytical Framework	Metrics identified: flood plain area; wetlands; erosion rate; impervious surfaces; biodiversity; taxation and financial incentives; conservation and restoration of natural systems; Structural and non-structural hazard mitigation (natural capital); Land use planning; local infrastructure and public services; building and structural resilience; identification of resilient infrastructure, drainage; preservation and restoration of ecosystems and ecological infrastructure.

S	Menoni et al., 2012	Sondrio, Italy.	Flash floods vulnerability of physical and socio-economic assets and systems	Local.	Informs land use planning. Metric based on judgemental selection of aspects.	Resilience assessment matrix: ENSURE Framework	Metrics covering: natural environmental, physical, systemic, social, economic and institutional vulnerability. Lack of data identified. Generic or hazard specific vulnerability indicators used.
T	Papadopoulos et al., 2017	Nepal.	supply chain networks Incident specific Nepal earthquake in 2015		Tests a theoretical framework using unstructured data (Tweets, news, Facebook, WordPress, Instagram, Google, and YouTube), and structured data, via responses from disaster relief managers	Big Data Framework	Indicators: social media responses to distribution of aid and reconstruction.
U	Oladokun et al., 2017	Not Specified	Flood	property level		Fuzzy logic (FL)-based resilience measuring model	Input factors: inherent resilience, supportive facilities and resident capacity. Property level factors, retrofitting.
V	Garvin et al., 2016	UK	Flooding. Insurers structural and building adaptation measures	property level	Combine environmental datasets on flood risk with resilience measures –allow insurance industry to account for investment in resilience	Property Flood Resilience Database	Indicators highlighted; geocoding; elevation; land use; rainfall; river geometry; flow rates; tidal data; flood depths; Flood protection work by councils, authorities, property owners (aggregated); retrofitting measures; Logistics; flood plan development, operation; post event barrier removal and cleaning site clearance, waste removal; suitable drainage; flood warning systems; local flood groups and forums, actions initiated in flood events.
W	Lam et al., 2015	Caribbean, 25 countries.	Hurricane		Based on indices of three dimensions: exposure, damage, and recovery.	Resilience Inference Measurement (RIM) model. GIS analysis.	Metric indicating: Exposure: Hurricane recurrence; Damage: per capita; Recovery: population growth post event.
X	Szewrański et al., 2018	Poland.	Environment, Social vulnerability Flood		Identification of areas populated by vulnerable social groups.	Location Intelligence System. GIS analysis.	Metrics including; Household vulnerability due to unemployment; flood hazard maps; age structure of population.
Y	Keating et al., 2017	75 communiti	flooding	Community level	Framework and tool developed https://floodresilience.net/frmc	Zurich Alliance community flood resilience measurement	Derived data used to populate metrics. Assessors assigned to collect data to grade resilience through: HH

		es across 8 countries			Comparing pre-flood characteristics, with post flood outcomes. Manual grading of resilience by an assessor	framework and tool; 4R and 5C	surveys, Community consultations, key informant interviews, interest group discussions, Third party sources deemed secondary –i.e. census data.
Z	Zhang et al., 2019	Shenzhen China.	Rainfall induced landslide resilience.	Urban	Automated method. Data-driven study, weightings derived through analytical techniques. Resilience ratings derived through machine processes not subjectively.	Support Vector Machine (SVM) (physical resilience) & Delphi-analytic hierarchy process (Delphi-AHP) (social resilience).	Datasets covering: For physical resilience -meteorology, soil, terrain, slope vegetation cover and land use; for social resilience -socio economic statistics. DEM Landsat data used to assess the capacity of urban physical system against rainstorms, and combined with feedback capacity of the human community when a landslide occurs.
Å	Allen et al., 2018	Carolina, USA.	Resilient infrastructure.		Geospatial Simulation, combined with Table top exercises. Debate on scale.	GIS based method; Resilience matrix. Strom surge simulations from SLOSH display system to ArcGIS.	Indictors for human health impacts; damage to water infrastructure: sewage overflow, loss of potable water, health facilities closure, loss of running water. Geospatial data representing water infrastructure assets. Assimilated population and health care provider data for analysis of population susceptibility.
£	Cai et al., 2018	N/A	Disaster	Multiple	Review of disaster resilience assessment methods and metrics, systematic review of 174 articles. Only 10.3% of these included empirical evaluation of indices.	Comparative study. Multi-variate regression most common quantitative method.	Metrics highlighted: income, employment, education, age, previous disaster experience, shelter capacity, social connectivity, municipal capacity, place attachment, transportation access, mitigation, housing capital, medical capacity recovery, civic involvement.
$	van Dongeren et al., 2018	10 sites in Europe's regional seas	Disaster Flood	Local, Urban/ Rural	Tools developed in project: Storm impact database, Coastal Risk Assessment Framework, Web-based management guide, Hotspot tool, Multi-Criteria Analysis	Multiple methods: storm impact DB.	Metrics highlighted: wave overtopping, flooding and shoreline erosion, land use, social, transport, utilities and economic activities, flood modelling outputs, flood depth and discharge.

6.11.2 Appendix 6.2: Resilience Assessment Metrics

6.11.2.1 Stage 1: Hazard Source

#	Metric	Available from	Paper Ref.
	General		
1	Past frequency of hazard events	3,34,35,36	M,P,Q,Y
2	Climate change induced hazards -Sea-level Rise predictions, increased frequency and magnitude of extreme events	16,33	I,P,W
3	Extreme rainfall	3,30,34	D,N,T,Z,Å
4	Past storm surge events	35,36	Å
5	Rivers, estuaries –waterbody density (waterbody area/total land area), river miles	28,30	D,P
6	Predictions, short- and long-range projections of weather and climate patterns	3,16,33,57,58	N,S,Å
7	Archive climate data	34,13,16,3	N
8	Oceanographic/meteorological sensor networks, records and projections (including real time outputs)	2,3,5,7,10,13,14,27,34	S,W,Z
9	River and estuarine data (river levels, flow rates)	10,19,26,28,30,33,55	O
10	Tidal data	2,4,5,10,14,36	M,Å
11	Water Quality	5,6,7,14,29,30,33,38	P
12	Industrial pollutants (sources and impacts)	1,10,29,33	P
13	Quantity and toxicity of waste (solid waste and water waste) – generation potential by land use	10,12,19	M,N,P
	Record of environmental conditions during hazard events		
14	Maximum storm surge elevations	36	I
15	Maximum/average flood water levels –inundation depths	10,30,62,64,65	C,I
16	Flood water chemical contaminants	9,10,11,30	Y

6.11.2.2 Stage 2: Pathway

#	Metric	Available from	Paper Ref.
17	Maladaptation practices and hazards generated through previous installation of protection structures	2,13,17	G,H,P
18	Flood hazard threat (warning zones - predictions), flood maps	10,55,62	I,O,W,Y,Å
19	Erosion prediction - SMP and academic modelling outputs	10,17	B,H,N,P,R,Z
20	Flooding from other sources pluvial/fluvial	3,6,10,30,34,62	O,N,V,X
21	Topography, slope, terrain data derived through laser scanning surveys - point cloud datasets, (Digital Terrain Models (DTMs), Digital Surface Models (DSM))	2,10,6,12	B,D,E,H,N,W,Z
22	Beach/cliff surveys, transects	2,6,10	H,M
23	Nearshore bathymetry –point cloud, or gridded data	2,4,10,12,14,18,38	Q
24	Sediment supply	2	H
25	Soil map and hydraulic properties	6,9,30,39	D,N,Z
26	Local geology	6,12	N
27	Geological stability, subsidence	6,9,30,39	A
28	Landslide subsidence areas	6	P,Q,T
29	Coastline length	28	I
30	Inundation zones –flood inundation maps (Inundation modelling outputs linked to forecasting and monitoring)	10,17,55	A,B,D,I,O,Q,Y

31	Contaminant and pollution sources in flood plains	6,9,10,11,30	J,P
32	Flood risk exposure (modelling outputs)	10,17,55,63,64,65	E,I
33	Land cover	13,30,38,67	B,I,N,Q
34	Perviousness of land cover - percent of land areas that does not contain impervious surfaces	EO Derived: 13,17,34,38,68,69,70,73,74	C,D,E,F,I
35	Surface roughness of land cover (material)	EO Derived: 13,17,34,38,68,69,70,73,74	N
36	Percent deep permeable soil per ward	6,39	D,N
37	Land area that does not contain erodible soil	6,15,39	D,N,Q
38	Distance from coastline of major developments	28	B,E

6.11.2.3 Stage 3: Receptor

6.11.2.3.1 General

#	Metric	Available from	Paper Ref.
39	Land use classification (marsh/mangrove, abandoned paddy, playground, sports ground, park, cemetery, residential, commercial, industrial, hotel/condo, institutional, road, waterbodies, agriculture, forest)	8,9,13,15,28,30,31,33,37,38,67	B,D,N,O,P,Q,R,Z
40	Urbanisation/industrialisation	1,2,10,13	B,D,P
41	Percent of developed open spaces	13,28,37	D,Q
42	Uncontrolled planning zones	1	I
43	Geocoding data - boundary datasets, area codes, wards	1,4,25,28,29,59	M,V,W,Z,Å
44	Location of waste treatment works, sewage and landfill sites (in-use and historic)	1,10,12,19,33	M

6.11.2.3.2 Public amenities

#	Metric	Available from	Paper Ref.
45	Spatial density of schools, hospitals, emergency services, hotels location	1,28	B,D,F,I,Q,S,T,Y,Å,£
46	Density of commercial infrastructure	1,28	D,Q
47	Percent of commercial establishments outside high hazard zones	Derived: 1,28	D,Q
48	Number of food suppliers (local)	1,28	F,Y
49	Child care facility locations	1,28	Q
50	Location of care homes, assisted living, mental health care, drug treatment centres, pharmacies, prisons	1,28	F,S,Å
51	Retail centres per unit population	1,28	F,Q
52	Food security	Derived: 42	F,Y
53	Doctors per 10,000 people	21,80	F,P,Q
54	Medical care capacity (number of hospital beds per 10,000 people)	Derived: 21,80	F,Q,Z,£

6.11.2.3.3 Economy and Business

#	Metric	Available from	Paper Ref.
55	Main employers and sectors	21,22	A
56	Employment rate	1,21,22	B,F,Q,R,S,U,£
57	Dependency on primary industries (farming, fishing, forestry, extractive industries) or tourism	21	B,F,P,Q,T,Y

58	Income inequality/distribution	21	A,F,G,I,Q,R,U ,W, Y,Z,£
59	Economic diversification	1,21,22	P,Y
60	Business / industrial activity	1,21,22,60	Q,R
61	Business sizes –ratio of large to small businesses	21,60	F,Q,R
62	% of population who are government employed	21	F
63	Investment in coastal areas	1	I
64	Land/house prices –stability –change	25,66	B,I
65	Availability and accessibility of financial resources	60	O,U,Y
66	Supply chains -revealing complex risks	Derived: 60	K,S
67	Farming/agricultural data –crop yields	9,11,15,33	O,P
68	Fisheries and aquaculture – resources and revenue	5,7,11,14,26,29	P
69	Tourism hotspots; tourist numbers (footfall) on beaches/coastal paths	1,21,19	T
70	Shipping cargo statistics	20,21	J
71	Number of businesses in risk zones	Derived: 1,10,17	I

6.11.2.3.4 People

#	Metric	Available from	Paper Ref.
72	Poverty levels	40,21,22	B,I,P,W
73	Spatial trends in human health	1,21,22	S,U,Y
74	Population density, distribution and structure	1,21,22	B,I,K,P,W,Å
75	Population age dependency ratio	21	B,F,I,P,Q,R,S, U,Z,£
76	Split, urban/rural population	Derived: 21,28	P
77	Population change (population stability)	Derived: 1,19,28	B,F,I,P,S,W
78	Percent of the population living in high intensity urban areas	Derived: 21,28,79	D,Q
79	Homeownership	21,22	B,F,G,P,Q,R, U,£
80	Number of disabled/handicap people	21,22	B,F,I,Q,U,Z
81	Recent immigrants, asylum seekers, non-English speakers/language competency	21,22	A,B,F,I,Q,U
82	Visitors in an area; ability to respond –hotel numbers, proximity to hazards	Derived: 21,41	K,Q
83	% population located within hazard zones	Derived: 21,10	B,I,K,M,W
84	Immigration/emigration rates	21,22	Q,R
85	Criminality	21,50	S
86	Social cohesion/social capital	21,42	P,S,U,Y,£
87	Recreational use of the coast	1,26,29	C,Å,H

6.11.2.3.5 Property

#	Metric	Available from	Paper Ref.
88	Housing density	1,67	A,B,S
89	Assets in flood/erosion zones (including the EA: National Receptor Database)	Derived: 1,10, 28,55,63,64,65	I,K,P,Q,R
90	Housing types	1,21,67,78	B,F,Q,S,U
91	Construction quality	67,78	B,F,S,T,U
92	Building age	21,67,78	A,B,Q,R
93	Bungalows	21,67	R
94	Transportation access –households with cars	19,20,21	F,Q,S,£
95	Number of multi-storey buildings	21,67,78	X

96	Vacant housing	1	Q,R
97	Building architecture –number of floors available to occupants	34,67	M,S,U
98	Households with basements	78?	S

6.11.2.3.6 Infrastructure

#	Metric	Available from	Paper Ref.
99	Transportation access and alternatives–roads, rail, ports, airports, bus routes –movement potential	Derived: 28	D,S,Y
100	Principle arterial roads in hazard zones (traffic flow data)	Derived: 20,28	A,D,Q,W,Z
101	Rail miles in hazard areas	Derived: 28	Q
102	Emergency road network accessibility	Derived: 1,20,28	O
103	Determination of key infrastructure at risk: roads, rail, ports, water, energy, telecoms, undersea structures (Identification drawing on automated processes or manual analysis)	1,10,12,20,24,28, 32	Q,S
104	Infrastructure dependencies (electricity, water, drainage, food, hospitals, daily emergency management)	Derived: 12,19,28,32,63	K,S
105	Spatial configuration of buildings and infrastructure in urban areas – which can constrict drainage	Derived through spatial analysis: 10,28,38,68,69,70 ,73,74	S
106	Existence and location of critical infrastructure (communication and transport) (from traffic data and human movements, and supply chain data)	1,19,20	S,Y
107	Water sources, fresh (potable) water	6,11,30	M,P,Y,Å
108	Water treatment works	11	S
109	Percent of building infrastructure not in flood inundation zones	Derived: 10,55,63,64,65	B,Q
110	High speed internet infrastructure	19,44	F,Q
111	Renewable energy sources	12,45,46	P
112	Energy efficiency (megawatt hours / consumer)	19	F,W
113	Efficient water use (water supply stress index)	10,30	F
114	Transformer stations	28	K
115	Operation of bridges and tunnels	28	S
116	Infrastructure condition	1,19	L
117	Strategic Water infrastructure	11	L,Å
118	Water supply, gas supply, and drains run under/along road corridors, dependency links	Derived through spatial analysis: 10,28,32,47,48,72	S
119	Sanitation facilities	1,28,11	P,Y
120	Water, gas, petroleum, storage facilities	28,47	S
121	Future trends in infrastructure development - based on published plans, energy needs, and projected population	1,19,28,48,49	R,V

6.11.2.4 Stage 4: Risk Reducing Measures

6.11.2.4.1 Stage 4.1 Adaptation

#	Metric	Available from	Paper Ref.
	Human Structural		
122	Flood proofing constructions of strategic infrastructures	Sourced from infrastructure suppliers/owners	O,T

123	Presence of appropriate/functioning flood defences/adaptations	1,10,82	I
124	Dredged canals –availability of diversion channels	52,82	E,I
125	Tidal wall (with storm water inlets)	10,82	E
126	Engineered sea defences –reef, breakwaters, groins, sea walls	10,82	O,P,R
127	Hydraulic structure limiting river discharge –installation, maintenance	1,10,82	O
Human Soft			
128	Soft adaptations –beach nourishment, sandscaping, Managed Realignment, dune rehabilitation	1	M,R
129	Green Infrastructure	1,19	C
130	Health insurance	23,75,75,77	F
131	Flood insurance coverage (% people and businesses who are covered by insurance)	23,75,76,77	F,I,U,Y
132	Crop insurance coverage	23,75,76,77	F
133	Regulations enhancing adaptation/mitigation	1,10,11	O,Y
Mitigation			
134	Low impact developments (inclusion of drainage pathways to reduce surface runoff)	63	E,G
135	Mitigation project spending/budgets	1,10,82	F,Y
136	Household mitigation measures	Undefined	G,S,U,V,Y
137	Tax Incentives for implementation of measures	1	M,R
138	Citizens adapting as a result of awareness or previous events	Derived: ABM	F,G,O,U,Y
139	Citizens involvement in flood related activities	Sourced from local organisations	F,G,O,P,Q
140	Appropriate storage of hazardous materials (above flood water levels)	Undefined	U
141	Raised accommodation	Undetermined	R,U
142	Retrofitted buildings	Undetermined	R,U
143	Electrical installation heights raised above flood level	Undetermined	U
Ecosystem Services			
144	Protection afforded by natural habitats	9,13,17,26	Q,Y
145	Percent land area that is wetland, swamp, marsh and mangrove (derived)	9,14,15,18,26,37, 67	D,Q
146	Natural capital/habitats/ecosystem services (quantification, loss/gain)	Derived: 17,11,30	H
147	Presence of forests and range land	28,15,13	D,O,Q
148	Afforestation and improvement of soil infiltration capacity	Derived: 6,54	N,O
149	Wetland diversity –proportion of flood attenuating wetlands per ward	9,10	D,R
150	Natural flood buffers (% wetland)	13,17,34	F,R
151	Vegetation condition (EO data for natural capital monitoring - loss/gain/condition)	13,17,34,38,54, 68,69,70	H,R,Z
152	Vegetation density	13,17,34,38,54, 68,69,70	N,O,R,Z
153	Human impacts –ecosystem destruction, mining	13,68,69,70	P
154	Soils ability to regulate floods and nutrient recycling	6,9,15,39	E,N
155	Waste assimilation capacity of ecosystems	9,11,30	N
156	Natural habitats maintained for their flood resilience capacity	9,26	Y
157	Preservation/conservation of wetlands and green spaces	9,26	D,M,O,Q,R
Planning			

158	Land use planning: regulated appropriate land use, controls imposed	Input from local authorities: 1,67	N,O,R
159	Incentivisation of development outside of risk zones		R
160	Flood risk accounted for in urban planning		O
161	Regulation/governance		O,P,S,Y,Z
162	Embodying flood risk in building codes		O
163	Level of implementation of building codes		O
164	Institutional relationships clear and roles and responsibilities are established and not conflicting	Undefined	P
165	Resettlement sites for impacted coastal populations (e.g. the Pathfinder Project, UK (DEFRA, 2011))	1	K
166	Moveable assets	Undetermined: Local authority?	Q
Financial			
167	Availability of insurance	23	O,P,R,U,Y
168	Funding for resilience measures (public/private)	Local authorities: 1,10,11,82	Y

6.11.2.4.2 Stage 4.2 Preparation & Contingencies

#	Metric	Available from	Paper Ref.
Monitoring/Warning systems			
169	Flood impact monitoring capacity	Require Local input	I,S,Y
170	Early Warning Systems		O,P,U,Y
171	Availability of communication systems		B,F,I,O,P,Q, W,Y,£
172	Support of enouncements (email, SMS) to targeted groups	Undefined, input from local authorities/EA: 1,10	O
173	Use of real time monitoring for hydraulic structures and urban drainage		O,S
174	Real time monitoring of river levels and flows and sea levels and conditions	10,19,30,55	O,R
Infrastructure			
175	Solid waste removal and management	Undefined, input from local authorities/EA: 1,10	O,Y,£
176	Management plans for roads susceptible to flood risk		O,T
177	Backup emergency power sources		K,P,U,Y
178	Alternative energy sources –i.e. solar panels	Undetermined	U,Y
179	Backup infrastructure at risk	Sourced from infrastructure suppliers/owners	K
180	Accessibility of roads and transportation network necessary for solid waste management	Input from local authorities	O
Drainage			
181	Storm drainage capacity and condition (length of drainage in region)	1,63	C,I,O,R,Å
182	Storm water retention tanks	1,63	O
183	Availability of resources for assisted drainage of flooded areas	1,10,82	Y
184	Maintaining storm sewers	1,10,82	R
Shelter/Housing			
185	Temporary Shelters/housing –availability/capacity	Undefined, input from local	B,F,O,P,T,Å, £

186	Number of shelters per km^2 (including, hospitals, schools, municipal buildings, and places of worship)	authorities/EA: 1,10	I,Q,Z
	Emergency Relief		
187	Emergency Services –locations, cover, backup, capacity	Undefined, input from local authorities/EA: 1,10	P,Q,T
188	Crisis management centres sited outside of risk zones		O
189	Additional resources in place supporting emergency and rescue services		T
190	Evacuation routes and plans		B,F,M,O,Y
191	Access to hospitals	Derived: 28,20	D,P,T,Y
192	Relief organisation –red cross etc.	Obtained from survey of local organisation	G,I,£
193	Availability of emergency vehicles and boats	Undefined	P,U
194	Availability of emergency aid (food, water, medicine)	Undefined, input from local authorities/EA: 1,10	G,O,P,T,U
195	Flood emergency infrastructure	Input from councils and infrastructure owners; 82	S,Y
196	Established evacuation zones	Undefined, input from local authorities/EA: 1,10	U
197	Access to high axel vehicles	Undefined	U
	Societal		
198	Civil Society grouping	Obtained from survey of local organisation	G,P,Q,T,U,Y, £
199	Resident capacity	Undetermined	S
200	Hazard event alert exercise/training for residents in vulnerable areas	Undefined, input from local authorities/EA: 1,10	F,O,P,T
201	Existence and implementation of risk management plans	1,10	I,O,R,Y
202	Informal coordination of citizens activities within communities	Obtained locally	O
203	Volunteer networks	Obtained locally	F,K,O
	Hazard Awareness		
204	Awareness of local population (recent flood events, media, education)	Survey input, or derived through ABM or similar	F,G,I,O,P,U, Y,£
205	Flood/erosion risk education and information	1,10,17,55	G,O,P,T,U,Y
206	Existence and availability of flood hazard maps	1,10	O,P
207	Flood water control and sanitation knowledge	Undefined, require local input	O,Y

6.11.2.6 Stage 5: Impacts/Consequence

#	Metric	Available from	Paper Ref.
	Environmental physical impacts		
208	Historic flood extents (taken from aerial imagery, EO data, water level gauges)	10,70	I
209	Salinization of freshwater bodies and soils	10	J,P,Å
210	Geomorphological change -records of beach/loss creation (change calculations) (derived from Lidar, EO data analysis, terrestrial laser scanning)	2,6,10,13,14	P,Z
211	Decadal loss of shoreline, permanent inundation areas (from change detection, EO derived products)	13,17,34,38	P
212	Erosion/accretion rates (derived from aerial/EO images, transects, point clouds)	2,10,13	B,N,P,R
213	Natural habitats, specie distribution and stocks	7,9,14,15,18,26,29,30	Y
214	Soil fertility (change)	39	N,P
215	Groundwater levels	55,63	J,L,V,Å
	General		
216	Extents of flooding and impacts (physical and human), as derived from flood specific geotagged social media data (text, images, videos), crowd sourced	Derived, 61, 68,69,70,71,81	P
217	Per capita damage	Derived: 1,67,77	B,W
218	Spatial distribution of hazard events and losses	Derived, 61, 68,69,70,71	K
219	Flood-related insurance claims	23,60,75,76,77	Q
220	Financial impacts of flood/erosion damage on people, property, business, government from reports and statistics	10,61	I,R,Y
	Business		
221	Impact of events on tourism and production	Derived: 21	T
222	Impacts on arable and livestock farming	9,11,15,33	F,O,P
223	Business and services disruption	Derived: 3,21	P,Y
	People		
224	Flood and erosion event casualties	1	I,M,Y
225	Health impacts from flood water contact and contamination – prevalence of post flood illness	Derived: 1,10,21,22	Y
226	Job losses related to past hazard events	Derived: 1,3,19,21,30,36	I
227	Recorded property crime and looting	50	Y
	Property		
228	Property level damage - revealed through EO data imagery an SAR, drones, social media, CCTV	Derived: 1,10,61,68,69,70, 71	B,M,R,Y
229	Property claims	61,75,76,77	M
230	Property repair costs	Derived: 51	V,M
	Infrastructure		
231	Critical infrastructure damage	13,68,69,70,71	M
232	Functioning of drainage systems and waste water removal	63	M,R,Y,Å
233	Frequency of reported defence overtopping incidents	10	P
234	Groundwater contamination in coastal aquifers –population affected	6,11,30	P

235	Drowned technical infrastructure	Derived: 10,28,32,47,48,49,51,72	K
236	Flooded roads and rail (image analysis and derived from social media, flood extent maps)	Derived: 13, 68,69,70	K,P,T,Å
237	Non-functioning basic services –water, energy, blocked roads	1	K

6.11.2.7 Stage 6: Recovery

#	Metric	Available from	Paper Ref.
238	Fraction of residents who were unable to occupy homes after a storm event	Undefined, input from local authorities/EA: 1,10	M
239	Evacuations orders issues in response to storm events		M
240	Evacuation order compliance rates		M
241	Early warning system functioning	Undefined	Y
242	Past recovery times after events	Input from local authorities	I,Q,Y
243	Time to restore housing to habitable		T
244	Utility restoration post event (% residents with potable water, wastewater and electricity services.		M,T,Y
245	Time roads out of action (Derived from EO data analytics, social media data, CCTV footage, crowd sourced data)	Derived: 68,69,70,71,73,81	T
246	Coastal land rehabilitation	10,67	P
247	Industrial resupply potential	Derived: 28,20,60	F
248	Ability to financially recover / availability of reserve funds	Undefined	O
249	Percent fire, police, emergency relief services and temporary shelters outside of hazard zones	Derived: 1,10,28	D,K,Q,S
250	Government offices outside of flood inundation zones	10,55,63,64,65	D
251	Availability of temporary flood barriers	Undefined, input from local authorities/EA: 1,10	G,V
252	Regulations governing sustainable reconstruction		O
253	Population covered by recent hazard mitigation plans		Q
254	Identification of past response problems and challenges (social media)	Derived: Social Media, 71, and local authorities	O

6.11.3 Appendix 6.3: Data Sources

Table 22: Data sources relevant to a resilience assessment for the case study area of East Anglia. Data source numbers are cross referenced in the metrics listings in Appendix 6.2. Details also provided indicating if sources are Open (O) or Proprietary (P).

#	Data Source	URL	Open (O)/ Priority (P)
1	District Councils	https://www.suffolk.gov.uk/council-and-democracy/open-data-suffolk/ https://www.norfolk.gov.uk/what-we-do-and-how-we-work/open-data-fois-and-data-protection/open-data/ https://data.gov.uk/	O
2	CCO	https://www.channelcoast.org/	O

3	MET Office	https://www.metoffice.gov.uk/datapoint	O/P
4	UKHO	http://aws2.caris.com/ukho/mapViewer/map.action/	O
5	BODC	https://www.bodc.ac.uk/	O
6	British Geological Survey	https://www.bgs.ac.uk/data/home.html	O/P
7	CEFAS	https://www.cefas.co.uk/cefas-data-hub/	O
8	Historic England	https://historicengland.org.uk/listing/the-list/data-downloads/	O
9	Natural England	http://naturalengland-defra.opendata.arcgis.com/	O
10	Environment Agency	http://apps.environment-agency.gov.uk/wiyby/151365.aspx	O
11	DEFRA	https://environment.data.gov.uk/	O
12	The Crown Estate	https://www.thecrownestate.co.uk/en-gb/resources/maps-and-gis-data/	O
13	Copernicus (ESA)	https://scihub.copernicus.eu/	O
14	MEDIN	http://portal.oceannet.org/portal/start.php	O
15	MAGIC	https://magic.defra.gov.uk/	O
16	Intergovernmental Panel on Climate Change (IPCC)	http://www.ipcc-data.org/	O
17	Academia (e.g. iCOASST, RISC-KIT, FAST)	https://www.channelcoast.org/iCOASST/pilotsites/ http://www.risckit.eu/np4/toolbox/ https://fast.openearth.eu/	O
18	EMODNET	http://www.emodnet.eu/	O
19	Data.Gov.UK (web portal)	https://data.gov.uk/	O
20	Department for Transport (DFT) UK and Highways England	https://roadtraffic.dft.gov.uk/ http://tris.highwaysengland.co.uk/	O
21	The Office for National Statistics	https://www.ons.gov.uk/; https://www.nomisweb.co.uk/	O
22	Datashine (University College London)	http://datashine.org.uk/	O
23	ABI	https://www.abi.org.uk/data-and-resources/industry-data/	O/P
24	UK OGA	https://www.ogauthority.co.uk/data-centre/	O/P
25	Land Registry	http://landregistry.data.gov.uk/	O
26	JNCC	http://jncc.defra.gov.uk/opendata/	O
27	NOAA NCEI	https://www.ncei.noaa.gov/	O
28	Ordnance Survey (OS)	https://www.ordnancesurvey.co.uk/business-and-government/products/finder.html	O/P
29	MMO	https://ckan.publishing.service.gov.uk/publisher/marine-management-organisation/	O
30	Centre for Ecology and Hydrology	https://www.ceh.ac.uk/data/	O
31	The National Trust	https://uk-nationaltrust.opendata.arcgis.com/	O
32	National Grid	https://www.nationalgridet.com/network-and-assets	O
33	European Environment Agency	https://www.thecrownestate.co.uk/en-gb/resources/maps-and-gis-data/	O
34	CEDA Archive	http://data.ceda.ac.uk/	O
35	Surge Watch	https://www.surgewatch.org/	O
36	National Tidal and Sea Level Facility	https://www.ntslf.org/	O
37	UK land cover atlas	https://figshare.shef.ac.uk/articles/A_Land_Cover_Atlas_of_the_United_Kingdom_Maps_/5219956	O

38	Tcarta (satellite derived products)	https://www.tcarta.com/products-and-services/	P
39	Cranfield University soil archive LandIS	http://www.landis.org.uk/npd_insurance/	P
40	Experian	https://old.datahub.io/dataset/poverty-in-england-experian-data/	O
41	Visit England	https://www.visitbritain.org/official-statistics/	O
42	UK Data service	https://www.ukdataservice.ac.uk/	O
43	Property Data	https://propertydata.co.uk/	P
44	Ofcom	https://www.ofcom.org.uk/research-and-data/data/	O
45	Renewable energy foundation	https://www.ref.org.uk/generators/index.php	O
46	UK data explorer	https://ukdataexplorer.com/renewables/	O
47	GIE Gas infra Europe	https://www.gie.eu/index.php/gie-publications/maps-data/bio-map/	O
48	Infrastructure and projects authority	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/520086/2904569_nidp_deliveryplan.pdf	O
49	National infrastructure commission	https://www.nic.org.uk/	O
50	Police data UK	https://data.police.uk/data/statistical-data/	O
51	Middlesex Multi-Coloured Manual	https://www.mdx.ac.uk/our-research/centres/flood-hazard/flood-hazard-research-centre-publications/	P
52	Canal and River Trust	http://data-canalrivertrust.opendata.arcgis.com/	O
53	Marine Traffic	https://www.marinetraffic.com/en/ais/home/centerx:-12.0/centery:25.0/zoom:4	O/P
54	Bluesky	https://www.blueskymapshop.com/products/national-tree-map/	P
55	Check my flood risk	https://www.checkmyfloodrisk.co.uk/	O
56	GaugeMap	https://www.gaugemap.co.uk/#!About	O
57	Weather Analytics	https://www.weatheranalytics.com/industries/insurance/	P
58	Weather Net	https://www.weathernet.co.uk/	P
59	Addresscloud	https://www.addresscloud.com/	P
60	OpenCorporates	https://opencorporates.com/	O
61	Perils	https://www.perils.org/	P
62	Oasis Hub	https://oasishub.co/	O/P
63	GeoSmart Information	https://geosmartinfo.co.uk/reports/floodsmart/	P
64	JBA	https://www.jbarisk.com/flood-services/catastrophe-models/flood-models/	P
65	Ambiental	https://www.ambientalrisk.com/	P
66	Core logic	https://www.corelogicsolutions.co.uk/products/	P
67	Verisk	http://www.geoinformationgroup.co.uk/ukbuildings/	P
68	Planet	https://www.planet.com/	P
69	Earthi	https://earthi.space/	P
70	Digital Globe	https://www.digitalglobe.com/	P
71	Social Media (mining)	https://www.globalfloodmonitor.org/	O
72	Inspire Geoportal	http://inspire-geoportal.ec.europa.eu/	O
73	NASA Worldview	https://worldview.earthdata.nasa.gov/	O
74	USGS Earth Explorer	https://earthexplorer.usgs.gov/	O
75	Crawfords	https://www.crawco.com/services/data-and-analytics/	P
76	Cunningham Lindsey	https://www.cunninghamlindsey.com/global/	P
77	LexisNexis	https://risk.lexisnexis.co.uk/	P

78	Outra	https://outra.co.uk/property-data-solutions/	P
79	City Population	http://www.citypopulation.de/UK-EnglandUA.html	O
80	NHS England	https://www.england.nhs.uk/statistics/	O
81	University of Reading Flood Crowdsourcing and CCTV sites	https://research.reading.ac.uk/dare/2017/02/20/crowdsourcing-and-cctv-sites/	O
82	RFCC Decision Support Tool	http://www.rfccobservatory.net/	O

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7 Summary and Conclusions

7.1 Summary of research

The original motivation for this research stemmed from discussions between coastal practitioners and academics on how science could be better incorporated within coastal management decision-making practices. The vast stores of data, which are now becoming available from the use of advanced sensor technologies and storage mechanisms, present a range of opportunities for furthering the inclusion of science within coastal management practices. To allow such emerging data innovations to be utilised within decision-making processes necessitates consideration of a range of new technologies to deal with the large volumes and varieties of data which are continually generated. Moreover, adoption of such technological developments offers opportunities to manage coastal hazards more effectively, and to control the associated impacts through implementation of appropriate adaptations.

This research set out to evaluate how innovations in the use of data and analytics can be applied to further the application of science within decision-making processes related to coastal risk adaptation. The methodology employed within each chapter of this thesis tackles specific issues relating to the use of data within the field of coastal management and adaptation. A number of themes have been addressed, these include: the application of Big Data technologies; the availability and utilisation of open source data; geospatial analysis and the use of GIS; the use of novel data types and sources; point cloud based geomorphological change detection (GCD), and opportunities for data to be derived through advanced analytical processes. In addressing such themes, a common objective has been to replace assumptions and subjective judgements with factually based analysis. A wide range of data sources have been identified, and discussions presented in relation to separate areas of application reveal how data collected for one purpose, can be easily reused within many other future tasks. This can maximise data value, especially where the required datasets are available as open source. To effectively exploit available data sources, a staged approach to data utilisation can be adopted as detailed in Chapter 5, Figure 27. This involves, initial identification of data sources; evaluating the preparation and processing steps needed to allow this data to be accessed; an appraisal of available and suitable analytical techniques, which can allow the data to be combined and analysed in a way, so generating the required information outputs; and, consideration as to how the ensuing knowledge can be communicated to end users. All of these stages have been addressed in tackling the objectives of this research.

In the first chapter, the central context and domain of this research was established by introducing the main coastal management challenges and available adaptation options. The discussion highlighted a gradual shift to more nature-based approaches within the UK, and the role of data was found to be crucial in facilitating this. A number of data related gaps, associated with coastal management decision-making processes, were identified and this research has addressed these issues through focusing on 5 objectives (Section 1.2). These main gaps identified were:

1. A requirement to increase coastal data utilisation, allowing informed, evidence-based decision-making to occur.
2. The necessity to increase understanding of the potential offered by geospatial analysis of existing coastal datasets.
3. A requirement to identify and catalogue open source datasets available for the coast, and to establish how these can be utilised in addressing core aspects of coastal management, through their application within coastal risk and resilience assessments.
4. A requirement to identify how holistic data variables can be acquired, combined and analysed.
5. Progress is required in combining and analysing the large quantities of point cloud data, routinely collected as part of coastal monitoring programs, so that physical coastal impacts can be more accurately modelled.
6. A requirement for identification and implementation of emerging innovations used in the acquisition and analysis of data, allowing public and private sector organisations (such as insurers) to more accurately evaluate risk in coastal areas.
7. Data sources and tools, allowing accurate representation of dynamic coastal factors, need to be identified, in addition to methodologies allowing their incorporation within future decision-making processes.
8. Methodologies need to be developed, allowing the large volumes of geospatial coastal data, now readily available for regions such as East Anglia, to be incorporated within spatially-based risk and resilience assessments.

These gaps were addressed within Chapters 2 – 6, each chapter addressing a single objective. A summary of the outcomes for each chapter/objective are provided in the following section, indicating the contributions to knowledge with respect to the research objectives.

7.2 Findings in relation to the 5 key objectives:

Chapter 2 - Objective 1: Identify and analyse challenges and knowledge gaps in relation to data-driven approaches to coastal risk evaluation.

Through an evaluation of the benefits that modern Big Data techniques offer to coastal management, the need was identified to include high resolution data in wide-scale coastal risk analyses. Big Data was revealed to enable decision support systems (DSS) to access and analyse multiple data themes relevant to coastal management. This can provide possibilities for realisation of patterns/interactions in environmental and societal factors. In line with this, geospatial Big Data analysis was revealed to hold the potential to transform coastal planning. Within a concluding summary table (Table 2), coastal management challenges were paired with potential solutions in the form of data-driven approaches and Big Data technologies.

Chapter 3 - Objective 2: Evaluate how open source data can be utilised within holistic coastal risk evaluations.

Chapter 3 revealed how the application of open source data within coastal management permits 'triple bottom line' holistic risk evaluations in coastal regions. A conceptual framework was developed for coastal risk evaluations using open source data. The East Anglian case study revealed opportunities for insight creation through combining data sources. Freely available data now exists which was shown to address the main themes of coastal management. Combining such data through the conceptual framework proposed, was shown to provide opportunities for evidence-based coastal policy creation, potentially reducing subjectivity within decision-making processes.

Chapter 4 - Objective 3: Evaluate the application of point cloud based geomorphological change detection to analysis of coastal change, in doing so generate insight on the nature of recent morphological impacts across the East Anglian region.

An evaluation of GCD methods highlighted how differing data types and methodologies are available which are suited to varying kinds of coastal change detection applications, as required for separate contexts. A methodological approach was developed which utilised high spatial/temporal resolution point cloud data to accurately reveal and quantify coastal change, at a regional scale, over multiple epochs. A TIN-based differencing method was utilised to obtain spatio-temporal patterns through analysis of open source coastal point cloud data (including both topographic and bathymetric data). This method generated volumetric change estimates, permitting wide-scale change modelling to be completed. Irregular patterns of change were found across the case study region. Prominent hazard events, such as the 2013 East Coast Storm Surge, were shown to result in higher levels of erosion in some but not all of the 14 case study sites. The results generated could form valuable input for future analysis of coastal processes, through which, it may be possible to more accurately reveal causation of change.

Chapter 5 - Objective 4: Evaluate the potential for innovations in the use of data to be utilised within coastal flood risk evaluations for the insurance industry, allowing insurance to act as a soft adaptation mechanism, distributing and communicating risk.

Research focusing on the potential role of insurance as a method of soft adaptation to coastal hazards, revealed that data-driven insurance is capable of redistributing and mitigating coastal flood risk. This function of insurance was dependent on risk-based policy pricing, founded on accurate information. Through a series of interviews conducted with insurance industry practitioners, working mainly within the London insurance market, scope was exposed for adoption of emerging data technologies. Data innovations were shown to hold the potential to allow insurance to operate an evidence-based risk advisory service. Of the various data sources evaluated, satellite-derived data emerged as a key source which holds untapped potential to enhance insurance risk analyses. Additionally, Big Data technologies are revealed capable of allowing the fusion of vast empirical datasets with claims data to generate insight. There were many challenges exposed throughout the research, these relate to requirements for structured data capture, limitations on data availability, an overreliance on subjective expert opinions, and problems with access to insurance industry datasets. Nevertheless, solutions were advanced which address these issues. Implementation and adoption of the data innovations outlined could work to improve the accuracy of insurance risk ratings, and as a consequence increase risk awareness. This could act to discourage developments in high risk areas, and incentivise sustainable practices, leading to flood resilient outcomes on the coast.

Chapter 6 - Objective 5: Explore how coastal practitioners can incorporate important missing aspects of coastal resilience in their decision-making processes at a regional scale, through a data-driven approach.

Through analysis of past coastal resilience assessments, a resilience assessment framework based on an extensive listing of metrics was created. This involved a staged resilience assessment methodology centred on the use of risk and resilience variables contained within 254 metrics. It was found possible to satisfy the requirements of 75% of the proposed assessment metrics using empirical evidence derived through utilisation of emerging data sources and analytical methods. As a result, the proposed approach limits reliance on value-based judgements, so holds the potential to increase objectivity in coastal planning processes. The research demonstrates how the proposed methodology could be utilised to address the requirements, supplied by a coastal management authority, for the case study area. The approach is revealed capable of enhancing sustainable coastal decision-making through basing coastal resilience assessments on empirical evidence. The metrics and framework which were generated through this work, could be applied to multiple coastal settings, thus forming the basis of future coastal resilience assessments.

7.3 Significance of this research

The main five chapters of this research (Chapters 2-6) are presented as standalone papers, which were submitted to academic journals. Each chapter, therefore, has generated unique outputs, potentially relevant to separate user groups or tasks. All chapters cover the common theme of how coastal management decision-making practices are reliant on access to current and accurate information, revealing how data innovations can be used to replace gross assumptions, and to incorporate uncertainty. Each chapter presents unique opportunities for incorporation of data products within an analysis of coastal systems. Application of the methods trialled and discussed holds the potential to transform the way that decisions are made in relation to managing coastal risk. In addressing a single objective each chapter highlights a separate yet interrelated means of increasing the application of science and empowering coastal practitioners. The intended outcome of which, is the reduction of uncertainty and subjectivity, through application of factual information and analysis, in situations where this was not previously possible. The methodologies presented within this work could be utilised to expose complex relationships between data variables, potentially revealing event causation, and allowing accurate predictions to be made. It is hoped that such progress could enable rigorous evaluations of land planning and coastal management policy options, and assist in selection of the most appropriate adaptation strategies.

In addressing the aim of this research, prominent issues arose around a number of themes. These themes relate to topics tackled within specific chapters, the research methods employed, or the researcher's experiences. These issues are now elaborated within the following subsections.

7.3.1 Subjectivity in decision making

Fundamentally, this work has sought to reveal how subjectivity can be reduced within coastal management decision-making processes. By challenging and replacing assumptions, opinion-based judgements, and commonly held beliefs, with information derived from empirical sources, it has been shown how uncertainty can be reduced. This study has adopted a staged approach in doing this. Essentially this is represented within the sequential stages of the diagram presented in Chapter 5 (Figure 27). This figure, is related to data utilisation within the insurance industry, however, the process can be applied more widely to coastal management applications and beyond. Despite seeking to address uncertainties created through subjective judgements, application of the 4 stages of this process (data source selection, data preparation/processing, data analysis, and communication of outputs) is not entirely objective. Each stage requires some degree of subjective judgement, in the selection of data sources, processes and software. In an effort to reduce potential selection biases, a wide range of data types, sources, and analytical methodologies have been introduced within this study. However, the familiarity of the user with these data sources and processes will impose tacit constraints on the selection and application. In particular, Chapter 6 contains a wide range of metrics but has not stipulated which specific data variables and sources must be used in the assessment of each metric. This decision must be taken by the user during the application stage. Context, scale, and data availability will ultimately determine which metrics and data sources are selected. It wasn't deemed prudent by the authors to be over prescriptive at this stage, and we recognised the requirement to evaluate the suitability of data sources and variables, on a case by case basis. Moreover, the lists of metrics, data types and data sources, presented throughout this work, only form a foundation, which can guide decision-making, and that subsequent risk and resilience assessments can build on.

Most coastal practitioners who engaged with this research, in addition to professionals from other fields such as insurance, exhibited clear preferences for consuming information in familiar formats. For example, if those who primarily work with funding and finance need to evaluate unfamiliar data sources, such as environmental monitoring data, a clear preference emerged, for dealing with a trusted intermediary, i.e. for taking advice from a perceived expert. This can also be represented in a preference to receive qualitative results in form of a conventional report, as opposed to more quantitative outputs presented in a dashboard, database or GIS. As such, many decision makers prefer to receive the more subjective advice of analysts and experts, rather than undertake interpretation and analysis manually. This was expressed in the interview feedback from insurers, documented within Appendix C and Chapter 5. The desire for information to be presented in familiar formats also imposes constraints on the willingness to embrace new, more robust methods. Many coastal engineers, for example, prefer to work with simple 2D maps, as opposed to engaging with 3D visualisations capable of allowing an enhanced perspective to be gained of a coastline. Aerial images also remain a popular medium to be used in assessing coastal change, despite the associated limitations (as detailed in Chapter 4). This study has revealed a range of advanced data-driven options, which are now readily available, and has shown how these can generate more robust, reliable and accurate answers to key environmental management questions. However, knowledge of such, does not ensure take-up of these methods. In addition to the technical capacity required of organisations and operators, there are clear hurdles barring implementation of these techniques that need to be addressed, relating to institutional culture and individual preferences, before these technologies are more widely adopted.

7.3.2 The researcher’s positionality

This research was inadvertently biased by its choice of industrial partner, and the insurance interviews being completed whilst working on a report for Lloyd’s of London. In the first instance, input was provided throughout the research from practitioners working for CPE, the EA and other public sector coastal management organisations. Limitations associated with this have been discussed within Chapter 6. The study was influenced by the concerns of the industrial partner, and this determined many of the issues focused on. If the industrial partner were a civil society group, campaigning for increased coastal protection, the study would have most probably addressed alternative areas. The researcher was aware of this bias, and took actions to ameliorate its impact on the study. Efforts were made to engage in coastal events, involving a wider range of stakeholders. Time was also devoted to speaking with, and presenting outputs to, residents and land owners who have been impacted by coastal hazards. In many cases the views of such stakeholders were opposed to those held by coastal management authorities, and those questioned deemed many of the previous technical research outputs not to be credible. This raised awareness of how the outputs generated by analytical processes need to be usable, understandable, and appropriate for a practitioner audience, but also these outputs need to address the concerns and apprehensions of the wider stakeholder community.

In relation to the researcher’s positionality, whilst undertaking the insurance industry interviews which are documented within 7.4Appendix C and form the basis of Chapter 5, a number of pertinent issues emerged. The researcher approached the potential interviewees under the banner of Lloyd’s of London. This was found to increase the probability that interviewees agreed to be interviewed, and also influenced the responses they gave. Given Lloyd’s reputation, and the number of companies working within the Lloyd’s market, there was a high chance that responses of interviewees were influenced by commercial imperatives. This was confirmed in a number of instances, when those interviewed requested the interviewer to set up meetings where they could present commercial pitches to senior figures in Lloyd’s, despite it being made explicit that this research was conducted as part of a PhD study. A clear caveat introduced by this positionality, was that many interviewees were extremely guarded in their responses to questions, overemphasising the benefits of the solutions they offered, and appearing guarded when it came to revealing any potential flaws, or disadvantages of their product. In an effort to overcome these effects, interviewees were drawn from a wide range of areas, many of whom had no desire to seek or further a commercial relationship with Lloyd's. Nevertheless, recognition of the potential constraints imposed by a researchers' positionality, is a key aspect which needs to be addressed in similar research in the future.

7.3.3 Cultural barriers to adoption of new technologies

In addition to the biases discussed, such as those introduced by familiarity with certain forms of information or technology, or technical competence, one prominent barrier encountered, which can prevent take-up of new digital technologies, relates to personal pride or a fear of being displaced/undermined. Outputs from this study have been presented to a wide range of audiences. Also, demonstrations have been given, revealing new methods of presenting and analysing coastal data. Many of the presentations/demonstrations have been greeted with high levels of scepticism by those unfamiliar with the methods used. One typical area where scepticism was expressed, by both coastal and insurance practitioners, was in relation to data storage and processing in the cloud. The concept of valuable datasets being stored in distant locations by a third party was looked on as a security concern by many of those questioned. In other instances, scepticism over the feasibility of new methods was attributed to the technology, being perceived as presenting a threat to entrenched relationships with trusted contractors, who rely on processes which could potentially be superseded by the new methods. In other instances, the new methods presented the prospect of invalidating the expertise of an individual. One senior level figure questioned within the insurance industry rejected the notion of their organisation working with Big Data, or needing to use associated technologies. When questioned on the basis of their belief, their understanding of the concept of Big Data was revealed as flawed. Given the decision-making power such individuals hold within organisations, this type of incomplete understanding of new technologies can prevent their adoption.

In short, introduction of unfamiliar, untested methods, can present a number of risks. First, the risk of uncertainty, that the method would not perform as proposed, or prove inferior to existing methods. Secondly, the risk that if the new unfamiliar method did prove superior to existing methods, then this may jeopardise an individual's standing within an organisation and they may be forced to retrain. In many instances, such as those witnessed in relation to the insurance industry, senior level figures, with potentially more to lose, were the most sceptical. However, rejection of new innovative technologies on this basis, both hinders progress, and disadvantages organisations, and in relation to coastal management, can result in suboptimal outcomes for the public. Moreover, practitioners and researchers need to be aware of the potential presence of such barriers and consider strategies for addressing these.

7.3.4 Uptake of new methods

Chapter 4 revealed the benefits of 3D GIS techniques with high resolution point cloud datasets. However the methodology adopted within this chapter involved the use of proprietary software; this imposes restrictions on the ability of others to replicate the methods utilised and developed. It also raises the question of why this method was selected given the availability of open source software alternatives . Limitations on time, technical competency, and the suitability of the alternatives, are the main reasons which prevented open source software (such as QGIS or CloudCompare) being used. In this instance, functionality utilised within the software selected (Caris BDB) is currently not present within the alternatives which were trialled. This functionality could most probably be developed, however this study sought to demonstrate, how specific datasets could be utilised to provide answers to questions relating to impact analyses, not to develop specific software tools. As such, the value of this work to practitioners and researchers, requiring GCD analyses to be undertaken, relates primarily to process selection and application. These processes can generate outputs from existing datasets allowing coastal trends and patterns (in relation to geomorphological change and sediment budgets) to be better understood. We do not envisage that coastal organisations will replicate the same processes which we undertook, however, our research in this area may act as a guide revealing options for leveraging value from existing datasets, and illustrate alternative methods for calculating coastal change than commonly used processes entailing higher levels of cost or manual interpretation. Ultimately the methodology we employed is rudimentary in its current form and requires standardisation and automation for it to prove viable for wider scale application.

7.3.5 Accountability for results

The adoption of new technologies and processes is a speculative endeavour and there is an ever present risk of the new techniques failing. If coastal management decisions are based on erroneous information, a critical question arises of who bears liability for the ensuing mistakes. Again, this introduces apprehension in the adoption of new methods, which practitioners may not fully understand. Experience gained whilst undertaking this research revealed the large number of decisions a coastal manager needs to undertake on a daily basis, and the diverse range of areas they must engage with. Moreover, a coastal manager’s available capacity to become familiar with complex methods of data analytics, is limited. Therefore, ideas, processes and outputs need to be presented in an intuitive manner. Similar conclusions were reached in relation to presentation of information to insurance underwriters in Section 5.5.8. Addressing this issue, partially tackles scepticisms over the reliability of results, yet it doesn’t settle the issue of liability. It is common for both insurers and coastal management organisations to outsource more specialist, speculative or contentious aspects of analysis, to specialist private sector firms with a proven track record and the required expertise. This can also address issues associated with an inadequate understanding of the data upon which analysis is based, which can result in too much confidence being placed on results. Therefore outsourcing to specialist firms or consultants can reduce the chance of mistakes, and can also shift or distribute liability. Yet issues of liability are complex, and require more comprehensive consideration than is possible here. However, one conclusion drawn from experience gained in this area, is that not all forms of data analysis are suitable to be undertaken internally by an organisation. Where inaccurate results could result in significant failures or losses, then those with proven competence may need to be drawn upon to undertake such analyses. If processes become more commonplace and in-house competence is developed in the respective field, it may become more feasible to conduct the analysis internally. These requirements to outsource aspects of data analytics therefore raises the important issue of financial constraints (as discussed in Chapter 6). With this in mind, the feasibility of utilising many of the techniques discussed within this thesis, would hinge on a cost benefit analysis being completed. This would need to consider the associated benefits and drawback of implementing a method internally or outsourcing, and determine if finances are available to cover either of these options.

7.4 Future work

The research presented within this thesis has been mainly conceptual, apart from Chapter 4, in which original geomorphological change estimates were generated. The main contribution of this work was to expose untapped opportunities, for the application of data-driven techniques, to improve sustainable coastal environmental management practices. In doing so a number of methodological approaches were developed and proposed. To maximise the potential impact of this work, the next logical steps would be, application of these methodologies within a practical setting. This could involve drawing together data sources and types, which were highlighted, within spatially-based risk and resilience assessments. This could facilitate creation of coastal decision support systems, or generate inputs for further modelling and analysis. Another aspect which could also be developed further, is the practical application of the advanced analytical processes reported on, such as agent based modelling, point cloud based morphological change analysis, and the range of Big Data techniques critiqued.

Coastal Partnership East, who have acted as the industrial partner for this project have expressed a desire to practically implement many of the methodologies developed within this study. Of the methods highlighted within this work, geospatial analysis of open source coastal datasets, has been highlighted as particularly relevant to work currently being undertaken in relation to quantification and assessment of assets at risk within CCMAs. Geospatial analysis of open source data has also been identified as relevant to an ongoing refresh of SMPs in England. This SMP refresh may also benefit from utilisation of point cloud based GCD methods, to allow comparisons of predicted and measured rates of coastal change.

The proposed next steps are therefore, for the author to assist coastal management authorities in applying the learning generated through this research within their practical assessments of risk and resilience. The majority of this work has focussed on the case study region of East Anglia, and the proposed methodologies have been evaluated in relation to the coastal management context in England. As such, much of this research is immediately transferrable to coastal management applications in East

Anglia and England. However, there is clear scope to expand the application of this work to coastal settings in alternative regions and countries. Also, aside from the value of this work to public sector coastal management organisations, outputs generated through application of the methods presented (especially the GCD methods), can form inputs to further studies, concerned with revealing causation of geomorphological coastal changes. This has been acknowledged by British Geological Survey who have acted as a partner in this research. Finally, the private sector could also benefit from aspects of this work, the most notable being the application of data innovations to pricing of insurance policies. The work presented within Chapter 5 and Appendix C further reveal opportunities for public/private sector collaborations centring on data analytics, insurance, and coastal resilience. A number of initiatives have been proposed, which focus on this area.

A key factor in relation to public/private collaborations, hinges on capacity within the respective organisations. This study has revealed how the majority of public sector organisations involved in coastal management, do not possess the required technical skills internally to implement some of the advanced analytical processes discussed. Furthermore, budget constraints impose limits on the IT hardware and software tools accessible to these organisations. As mentioned in Section 7.3.5, coastal management bodies frequently outsource analysis to private sector consultants. Similar options could be exercised in relation to application of the data-driven techniques discussed within this study. For many evolving methods, which are not commonly applied by coastal practitioners, such as ABMs and C2C point cloud analysis, firms who specialise in these areas could work with coastal practitioners, in developing and refining the application of such techniques. This could take the form of Proof of Concepts (PoCs) as described in Appendix C.8.1. The work contained within Chapter 4, could form the basis of one such future POC; and also illustrates how a method for impact analysis was developed to allow readily available data to be combined with existing software functionality, generating outputs relevant to future planning decisions. A POC could build on this work, looking to refine the outputs generated, and standardise and automate the tasks within the methodology developed.

In seeking to progress the work completed within this thesis, a key question relates the respective roles of the public and private sectors. The majority of the advanced forms of data analytics profiled within this study, were found to be undertaken by private sector companies, such as those listed within Appendix C. However, the coastal practitioners who need to utilise the outputs from such analysis, are usually employed by public sector organisations. Lack of funds and technical skills are key barriers preventing such public sector bodies from utilising these methods. However, if the government stipulated requirements relating to the extent of information that must be considered prior to planning decisions being made, this could incentivise the adoption of many data innovations that were discussed within this work. In addition to requiring data-driven decision-making practices, the government would also need to fund further research and development in this field, and facilitate public sector provision of data and analysis, which is currently only available from private sector firms. Government investment required to allow this, would potentially be offset by savings resulting from more sustainable management of coastal areas.

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APPENDICES

Appendix A Vulnerability and Hazards

Coastal risk arises due to the probability and intensity of hazard events combined with the presence of vulnerable people property, infrastructure, and natural environments, within exposed coastal locations (Reeve et al., 2012). As such, coastal vulnerability and hazards are central themes addressed within this research. We therefore present a short discussion focusing on these here.

Smith (2007, in Dodds, 2009) categorises environmental hazards as: those 'hazards to people (e.g. death and disease), hazards to goods (e.g. economic loss) and hazards to the environment (e.g. loss of flora and fauna)'. Defra (2009) cite flooding and coastal erosion events, as major coastal hazards, that are intermittent, variable, highly uncertain and which can relate to extreme natural phenomena. Coastal hazards have been split further into categorisations of naturally occurring or human-induced coastal processes, each with the potential to create loss (LGACSIG 2004 in Dodds, 2009). For example, specific human-induced hazards can lead to 'ground water loss/pollution, pollution from waste water, sewage, oil, marine litter and human induced impacts on coastal processes'.

Events such as Hurricane Katrina and Superstorm Sandy in the USA further demonstrate how severe flooding events can devastate urban centres (Lazarus, 2014). Furthermore, the recent losses sustained by the insurance industry, due to the impacts across the Caribbean and southern states of the USA resulting from hurricanes Harvey, Irma and Maria (Lloyd's, 2018a), reveal the widespread vulnerability of coastal communities. Climate change hazards represent a serious consideration in coastal regions. Kron (2013) argues that 'the implications for a changing climate are probably more important for coasts than anywhere else', whilst Dodds (2009) views climate change, not as introducing new risks, but as compounding existing hazards. The UK Committee for Climate Change (2018, p.23) has also outlined in detail how 'climate change threatens the sustainability of coastal communities and environments'. It is an inescapable truth that natural hazards dominate coastal regions as, essentially, 'most beaches around the world are eroding due to them being deposited at earlier geological times' (Kamphuis 2006 in Dodds, 2009).

The specific form of vulnerability focused upon in this research considers the intrinsic value of the coast to human society. It has been highlighted how a rapidly eroding coast, if uninhabited, can have no vulnerability (McLaughlin and Cooper, 2010). The term 'vulnerability' relates to both the natural and manmade environment. In assessing coastal vulnerability, it is important to recognise the interlinkages between terrestrial and ocean processes. In doing this Godschalk (2009) deems that problems facing coastal managers include: environmental degradation, marine pollution, fisheries depletion, and loss of habitats. Vulnerability related to threats posed by coastal hazards has risen in line with increased human usage of the coast. As a response to this, hard protection measures have been implemented which in some instances have actually 'increased the area of land that is vulnerable to coastal flooding' (Rupp-Armstrong and Nicholls, 2007, P.1418). Additionally, Linnenluecke et al. (2015) stress that population growth and movement into vulnerable coastal areas increase impacts from extreme weather events, due to higher levels of societal exposure.

Human practices such as residential land use and infrastructure construction in exposed coastal regions have been witnessed to have adverse effects upon natural processes in many locations (Dávila et al., 2014). In Santander, Spain, construction on the coast has directly and adversely impacted coastal processes, modifying the hydrodynamics of the estuary (Dávila et al., 2014). Incidences such as this can render coastal populations more vulnerable. For example, some areas developed in the past, where a high risk of storm surge inundation exists, can experience a resulting loss of disaster mitigating ecosystem functions (Roberts, 2012). This decline of ecosystem services due to degradation of coastal habitats is acknowledged by Nicholls et al. (2015a) as representing a significant issue in the English region of East Anglia. In this sense, human activity can contribute directly to increased levels of vulnerability, to both society and the environment. This can be evident particularly in instances where corrupt coastal practices have occurred, such as illegal seawall constructions along the south coast of Spain (Jiménez, 2016; Sanchez-arcilla et al., 2015). In this instance the decadal scale coastal evolution was reported to have been negatively impacted. Human land use choices in already vulnerable coastal locations can also act to exacerbate vulnerability in these regions. This was recognised to be the case in Westward Ho!, North Devon, where a landfill site was constructed in an area without the benefit of long-term protection from coastal flooding (Gussin, 2019). Alternatively, societal problems can also generate vulnerability. Many coastal regions of England have become economically deprived (Agarwal and Brunt, 2006) and inhabitants are increasingly ill-equipped to respond to the dynamic natural hazards that proliferate along the coastline. Additionally, as increased levels risk awareness in exposed coastal locations can result in the value of property falling (Chen et al., 2013). This can alter the demographic in such regions, acting as a disincentive to more prosperous, wealthy residents settling here, whilst encouraging poorer, more deprived families with limited budgets to move here. As such, the 2011 census for England and Wales revealed that a disproportionately high number of homes in coastal towns and cities, compared with locations further inland, were classified in some way as deprived. This is evident from the DataShine project (O'Brien and Cheshire, 2015) where the distribution of deprived households can be easily revealed by opting to classify wards by the appropriate statistic (Figure 30).

Although not covered in this study in any detail, it is acknowledged that land-based pollution is also a major hazard on the coast and as early as 1975 the Mediterranean action plan acknowledged that land-based pollution sources can account for 80% of ocean pollution (Godschalk, 2009). At a global scale, despite multiple attempts to address these problems, progress has been limited in tackling issues such as land based pollutants, illegal fishing and the consequent ecosystem impacts (IOC/UNESCO, IMO, FAO, UNDP, 2011, p.25).

Appendix B Past projects focusing on data-driven coastal management approaches

There are a wide range of studies/projects and collaborative efforts of relevance to this research, which cover the creation of vulnerability assessments, as well as approaches seeking to facilitate and optimise decision support. Some of the methods and findings are particularly relevant to this study and, therefore, an appraisal is made of selected studies/projects, what these works have involved and some of their key findings.

This research has a broader focus than solely collation of coastal data sets, with coastal risk adaptation and resilience being the key themes tackled. In respect to this there are many examples of existing pertinent studies which focus specifically on risks to coastal populations and ecosystems, relating to hazards such as flooding and erosion and tackling topics such as land planning decisions (Dávila et al., 2014; Deeming, 2008; Dodds, 2009; Filatova and Veen, 2006; Goverment Office for Science, 2004; Jongman et al., 2014; Roberts, 2012; Smith, 2013; National Trust, 2015b; Villatoro et al., 2014). Much work has been completed in relation to vulnerability assessments of coastal regions and creation of decision support systems (DSS) (Adams, 2015; Arkema et al., 2013; McLaughlin and Cooper, 2010; Ramieri et al., 2011; Natural Capital Project, 2015; Westmacott, 2001). The utility and power of GIS and associated geospatial analysis has also been well documented. A great many studies have reported on the application and capability of GIS in assessing coastal vulnerability, risk and in planning (Bheeroo et al., 2016; Brown, 2006; Brown et al., 2006; Li et al., 2016; Loader, 2011; Moszynski et al., 2015; Noll and Hogeweg, 2015; Rangel-Buitrago et al., 2015; Stavrou et al., 2011; Thumerer et al., 2000; Wheeler et al., 2010). Coastal models and maps are reliant upon the accuracy of the data they incorporate. In line with this, accurate topographic representations now widely draw on high resolution Lidar data (Pe'eri and Long, 2011), placed alongside socio-economic datasets revealing human vulnerability (O'Brien and Cheshire, 2015). Combining so many data types and formats is associated with a range of challenges, which require consideration (O'Mahony et al., 2015; Rodwell et al., 2014; Tares, 2013).

B.1 Risk Studies

Within many past studies which have focused on coastal risk, clear links are shown with coastal resilience. The two areas are thus closely interlinked. In the UK a number of academic studies have focussed on coastal risk. Dodds (2009) completed an evaluation of decision-making practices in relation to coastal risk in England, Wales and Northern Ireland. Her results reported the complexities associated with the coastal risk decision-making process, and concluded that the use of natural coastal change science within this process was constrained. Deeming (2008) focused on the relationship between risk perception and community resilience to coastal flooding. This study found that historic developments in floodplains had prevented individuals engaging with the true levels of risk in these areas; trust in authorities was another significant factor identified. A separate study undertaken by Smith (2013) also focused on community level responses to coastal hazards and adaptation measures, specifically the knowledge of, and involvement with, issues found within a small vulnerable community in Orford, Suffolk. Her study produced findings indicating a lack of engagement by the inhabitants of Orford in the coastal management process, and recommended improving participation of the public in flood management.

The Foresight review of future flooding (Goverment Office for Science, 2004) covered the entire UK, looking at both river and coastal/sea flooding, and coastal erosion. Continuing with (the then) current policies was considered likely to result in risk increasing in every scenario considered. The review can be viewed as a driver for subsequent coastal research undertaken by the Tyndall Centre and iCOASST, in that it clearly set out justifications for future research and model creation. Another project of note is the National Trust's Shifting Shores (2015b), in which they commission CH2M (now Jacobs, and formerly Halcrow), to undertake a study also looking at long time horizons and how the coastline is likely to evolve over a 100 year period. CH2M used a method of GIS dataset evaluation of coastal change. The study concluded that engineering is not a long-term solution. This is a powerful conclusion in relation to planning. It indicates a requirement for further analysis to be conducted, unpicking drivers for land use change on the coast and exploring how these relate to adaptation measures implemented. Within Shifting Shores (National Trust, 2015b), an emphasis was placed on the role of adaptive measures, especially the use of Coastal Change Management Areas (CCMAs). These areas were created to ensure that new developments do not occur in vulnerable areas. The report asserts that continued monitoring and a culture of evidence-based decision-making is necessary. One particular adaptation measure that will be a requirement in some areas, in the future, is the policy of 'Coastal Rollback', which involves moving vulnerable buildings and infrastructure out of harm's way (Defra, 2012).

B.2 Decision Support Systems and Vulnerability Assessments

Addressing coastal risk through the collation and analysis of data, can provide decision makers with the knowledge required to make judgements on the suitability of adaptation measures. Many past projects have set out to address such issues. Westmacott (2001) introduced the notion of a DSS in their evaluation of three assessment methods developed for the tropics, yet none of the methods trialled proved ultimately successful in addressing the core problem of assisting decision-making in the coastal zone. Data availability acts as an important factor when deciding on a system and scale is also considered a limiting factor. As such scale should be a core consideration for DSS, with thought given to type of data included by scale, i.e. by economic administrative unit or ecosystem.

In their study Ramieri et al. (2011) expanded on the work completed by Westmacott (2001) focusing on larger collaborative DSS methodologies and projects, and producing a critical assessment of these. They introduced the Coastal Vulnerability Index (CVI) and Multi-scale Vulnerability Index (MVI), the sector method and integrated assessment. The index method (MVI and CVI) is praised, by Ramieri et al. (2011) in its simplicity of application, being easily understood, yet they do not regard it as suitable for more detailed quantitative assessments, as factors are considered in isolation and it is unsuitable for adaptation measure selection. Contrasting with this, the sector method considers interactions between variables and non-linear effects and, as a result, allows more detailed quantitative analysis. It is the integrated assessment method though, which is the most comprehensive form of DSS, yet is difficult to apply. It involves cross-sector, dynamic interactions and can be applied to multi-scale decision-making. As in Westmacott (2001), Ramieri et al. (2011) draw attention to the need to include socio-economic factors within DSS, as these factors can produce greater impacts than both climate change and sea-level rise. It is also necessary to consider adaptation measures, however, the CVI is unable to do this and so is not recommended for wider application. The index methods produce simple numerical rankings of sections of the coastline, yet confidence levels in the results generated are not high, partially because they only consider physical factors. The MVI does include socio-economic factors, yet these do not always significantly influence the overall assessment ranking (Mclaughlin & Cooper, 2010, in Ramieri et al., 2011). For all methods, GIS is reported in these studies to aid the application of DSS, through the implementation of compound scores made through multiple GIS layers.

In terms of the sector and integrated methods alluded to by Ramieri et al. (2011), a number of projects are expanded on in more detail. RACE (Risk Assessment of Coastal Erosion) (Halcrow Group, 2007b) is a sector method, developed as part of a project funded by Defra and the EA. The project was linked to the EA's National Coastal Erosion Risk Map (NCERM) scheme, and it aimed to disseminate a consistent, probabilistic assessment of coastal risk in the UK and adopted the SPRC scheme. The RACE DSS project ended in 2006, yet its legacy is apparent in its continued use within NCERM, which is still running. Another similar project is DESYCO (The Decision support System for Coastal climate change impact assessment) (Torresan et al., 2016). This has been applied to coastal areas in the North Adriatic Sea, the Gulf of Gabes and Mauritius. The project involved an ecosystems approach to regional risk assessment, using Multi Criteria Decision Analysis (MCDA). DIVA (Dynamic Interactive Vulnerability Assessment model) (Hinkel and Klein, 2009) was an example of a large scale collaboration between European research institutions, from which an integrated DSS was produced considering biophysical and socio-economic impacts, and specifically taking into account factors such as sea-level rise and socio-economic development. The DIVA DSS enabled evaluation of economic costs in relation to a number of adaptation strategies. DIVA was criticized though due to its limited model resolution and was found not to be appropriate for local scale application. It was also found to be difficult to use, requiring technical expertise, and failed to consider ecosystem-based adaptation measures. The RegIS project (Regional Climate Change Impact and Response Studies in East Anglia and North West England) (Holman et al., 2005) was viewed in a more positive light by Ramieri et al. (2011). The RegIS project involved the creation of an integrated DSS at a regional scale in East Anglia and took a cross-sectoral approach. Key factors considered within the model were climate and socio-economic change. It enabled various responses or adaptations to be trialled. It covered a wide range of factors, such as agricultural land use, exposed populations and ecosystems, but was criticised for not accounting for economic impacts or including more detailed evaluation of adaptation measures such as cost benefit analysis. Overall it was found beneficial to the decision-making process, as it potentially allows decision makers to simulate different policy options. Of the DSS mentioned above Ramieri et al. (2011) concluded that for coastal vulnerability assessments in European seas, in relation to climate change, DIVA, RegIS and DESYCO are the approaches which held the most potential.

Index DSS methods have been widely implemented, despite the limitations outlined above. Currently a project is underway at the BGS in England focusing on developing a CVI for the coast of Britain (British Geological Survey, 2019). This draws on existing BGS datasets and expertise, and wider work through collaborations with other organisations. Scale has traditionally limited vulnerability assessments, and has been specifically highlighted as a problem for index methods (McLaughlin and Cooper, 2010). When considering scale issues, aggregation of variables can result in oversimplification and misrepresentation of the reality on the ground. Another potential flaw highlighted, in index methods such as the MVI, is that the ranking of variables within risk assessments, can be subjective. Also, the typologies selected can fail to adequately differentiate between dissimilar classifications. In a study by Mclaughlin & Cooper (2010), on the application of the MVI method, they acknowledge that greater detail is required at a local scale, but their work failed to achieve this. One setback they encountered, relates to the requirement to use high resolution Lidar data. They were limited in doing this, as at the time, Lidar data was expensive to obtain. However, for the coast of England, extensive open source Lidar datasets are now available, and so can easily be obtained, at no cost, from the EA via Data.gov.uk. or the CCO's website (https://www.channelcoast.org/). This current research drew on open source data and collaborated with data stakeholders, so availability of data did not represent a problem of similar magnitude. A further study which focuses on issues of scale is that completed by Lichter et al. (2011) used three different elevation models and two different population datasets. The study focused on land and population distribution in low elevation coastal zones (LECZ), looking at global, continental and country scales. Large differences were observed at different scales, depending on what elevation models were used. Specifically, using a global scale can result in differences of 150% in area estimates.

The Natural Capital project's index based InVEST tool is now available open source and can, in theory, be applied to any area of coastline to generate qualitative estimates of vulnerability (Natural Capital Project, 2015). The model is reported to enable greater understanding of the relative contributions to vulnerability of the variables considered, and allows identification of regions at the greatest risk to coastal hazards. It draws on data supplied by NOAA's National Centres for Environmental Information, NCEI archive. Mapped demographic data was used within the study to enable the relationship between hazards and human life/property to be realised. A highly significant, positive relationship was established between predicted estimates of exposed population and the recorded number of coastal hazard related fatalities. In terms of economic values in the coastal zone, if existing coastal habitats remain intact, the value of property, most exposed to hazards, was found to halve. In line with this the likelihood and magnitude of losses was found to fall if coastal habitats were preserved. These findings have been echoed by subsequent studies such as that undertaken by Beck et al. (2018), focusing on the protective function of coral reefs, revealing damage to increase significantly if they were removed.

Beyond academia, a tool has been developed by Adams (2015), as part of work undertaken for the Crown Estate in assessing the suitability of areas for the implementation of sandscaping. The work considers the socio-economic conditions of coastal towns in England and Wales. Findings from the work indicate that sandscaping could support regeneration or provide economic benefits in coastal areas, where high levels of deprivation combine with vulnerability to natural hazards. Yet contrary to many academic studies which focus on physical processes, and fail to adequately take account of socio-economic factors, this work does not appear to adequately account for natural processes and prioritises human factors exclusively. Given this, limitations may be imposed on the application of the work.

B.3 Coastal GIS

Due to the geographical characteristics of risk exposure on the coast, such as that relating to flooding, GIS is widely recognised as a suitable tool to apply to risk assessment in this domain (Botzen and van den Bergh, 2008). Villatoro et al. (2014) discovered that by combining GIS techniques with hydrodynamic modelling, they were able to move beyond limitations imposed on previous risk estimations based on statistical analysis of historical data. GIS was found to provide the ability to model accurately the extent of flooding and erosion, this was instrumental to the risk management process. Also, as part of their work with the Tyndall project Nicholls et al. (2015a) found GIS to offer many benefits including: the ability to archive, organise and access spatial data, analyse and interpret results, identify planning options and adaptive pathways, and act as a decision-making platform. Combining Web-based services with the functionality of GIS can also prove powerful in creating online cartographic solutions. The data exploration functionality, contained within some new web-based tools, can be embedded within online GIS, this is seen to open up many opportunities for spatial data analysis, which can complement the emerging field of Big Data (Smith, 2016).

There are many further examples of the application of GIS to coastal issues. In relation to the suitability of GIS as a platform for Decision Support Systems, DSS, Thumerer et al. (2000) created a GIS based coastal risk management DSS. Inputs included assessments of adaptation measures, land elevation and subsidence rates. Outputs related to impacts used the house equivalent concept, to represent the economic impact to an average residential property, if flooded. They concluded that GIS is an important tool, enabling evaluation of interactions between the wide range of factors present in the coastal zone. Another study, completed by Brown et al. (2006), as part of the Tyndall project, focused on the North Norfolk coast and incorporated the SCAPE model, (mentioned in Section 7.4B.5). This study looked at both assessment and communication of coastal risk, with attention paid to scenario visualisation, through creation of virtual landscapes. High resolution visualisations were created by linking scientific modelling with elevation data and other factors. GIS was found to enable the resulting visualisations to be accessible to non-specialists. The role of virtual reality GIS has been highlighted in other studies, related to the coast of East Anglia (Jude, 2003; Jude et al., 2007), and it was found to be an effective method to communicate coastal change visually and engage stakeholders and the public. A similar GIS study of the North Norfolk coast also completed by Brown (2006), in common with the aforementioned project, looked at aspects of coastal land use management. Conclusions were reached indicating that sea-level rise can have broad impacts on the human and ecological landscape, in addition to flood risk to property.

Other work of note, which utilised GIS within this domain was completed on the south coast of England by Stavrou et al., (2011). In this study GIS was used to enable risk evaluation in coastal cliff environments. Areas susceptible to recession and cliff instability were identified in the model which was created. This bears similarities to the current CVI assessment being undertaken by BGS (noted in Section 7.4B.2). The study focussed on a stretch of coastline between Brighton Marina and Portebello, East Sussex. It drew on historical maps and aerial photos for an extended period (1873-2005), in addition to geotechnical field mapping observations. The study used the ESRI Digital Shoreline Analysis System (DSAS) as part of its methodology. The results indicated the heightened risk resulting from the presence of coastal cliff top populations, and displayed how GIS can be used as a cliff management policy tool. Loader (2011) focused on the Isle of White, and the vulnerability of archaeological sites to sea level rise. This study brought together historic environmental records and mapping, aerial photographs, and Lidar data, using ArcView GIS. Coastal recession assessment techniques were evaluated, and the study generated projections of future land loss to coastal erosion. It also highlighted the potential which Lidar data holds in this domain. Wadey et al. (2015) also focused on the Isle of White, particularly the impending flooding impacts from future sea level rise. Benefits of using high resolution Lidar data were also highlighted. In line with studies relating to the Norfolk Coast (Jude, 2003; Jude et al., 2007) the application of 3D visualisation techniques, in displaying results to the public, formed an important part of the study of Wadey et al., (2015). Findings indicated that future research using these techniques could also benefit from including information relating to adaptation options.

Further afield, there are many examples of the application of GIS to coastal risk adaptation, from across the world. In Mauritius, Bheeroo et al. (2016) developed a DSAS, which revealed shoreline change rates and patterns. This was derived through GIS analysis of aerial images, spanning an extended time period (1967–2012). The use of GIS in temporal shoreline analysis proved a powerful tool to reveal shoreline evolution. One finding revealed through this study was that human intervention, in the form of hard adaptation measures, has further exacerbated coastal erosion issues in Mauritius. In Colombia, Rangel-Buitrago et al. (2015) worked on a similar study in which they combined and analysed satellite images of the coast using GIS, for a period from 1980 to 2014. In their analysis they also incorporated data from field surveys. Tying in with previous discussions, this work produced findings indicating the importance of land use planning and careful selection of adaptation measures. Rangel-Buitrago et al. (2015) also advised the use of soft adaptation measures. As in Mauritius, the use of hard adaptation measures (such as groynes) was seen to result in long-term negative consequences. Yet, it was noted in Colombia that these effects were exacerbated further by other factors such as illegal mining of sand and destruction of mangroves.

In China Li et al. (2016) investigated the consequences of rapid urbanisation in the coastal city of Haikou. In common with the analysis undertaken as part this current research, which focuses on collation of multiple types of data, they included data relating to: socio-economic indicators, DEMs, geological hazards, traffic (rail and highways) data, population census data and social media feeds. Findings indicated that land utilisation was a key human activity increasing vulnerability on the coastline. This concurs with conclusions drawn by Roberts (2012) and Villatoro et al. (2014) demonstrating how GIS can be used effectively in the analysis of coastal hazards. Similar to this, the study conducted by Newth (2014) also demonstrated how GIS can be successfully applied, more generally, to the area of risk and hazard analysis. Newth used GIS to create a multi-hazard model, enabling a better understanding to be gained of location specific risks, such as those related to natural hazards (e.g. earthquakes). The process was observed to generate easily interpretable predictions.

Despite the many benefits highlighted, which GIS have been shown to hold, in relation to coastal risk analysis and ICZM, this technology has not been adopted by coastal management professionals in many areas. This was found to be the case in Victoria, Australia (Wheeler et al., 2010). For ICZM programs in Victoria, no form of coordinated spatial information management was in place. This has also been an issue in East Anglia; within coastal management organisations in East Anglia, GIS expertise has been lacking and until recently the software has not been utilised in the form of a DSS.

B.4 Open Source Data Mapping Projects

An ever-increasing number of collaborative projects seek to bring spatial datasets together for marine and coastal areas, and make this data available to the public via open source portals, some creating online maps. Many existing, open access GIS have been created, which cover the East Anglian coast. The National Trust's, Mapping Our Shores project (Figure 33) (The National Trust, 2015) is one such example. This is the result of a survey completed in 1965 of the coasts of England, Wales and Northern Ireland. The survey involved a number of volunteers walking stretches of coast making observations, which resulted in the classification of coastal areas by use and condition. Some 350 Ordnance Survey maps were used and hand annotated, demarcating 14 categories. The Trust found that the post-war planning system had protected the coast from inappropriate development. The survey was repeated in 2014. This time aerial photography, Google Street View and digitised OS maps were used; this enabled shoreline change comparisons to be made over the 50-year intervening time period. The survey and the resulting maps focus on land use type, and also indicate areas lost to the sea. Since the original survey, the National Trust has purchased large sections of the coast of Britain (574 miles), as part of the Neptune campaign (National Trust, 2019a), and has sought to preserve this coastline for future generations.

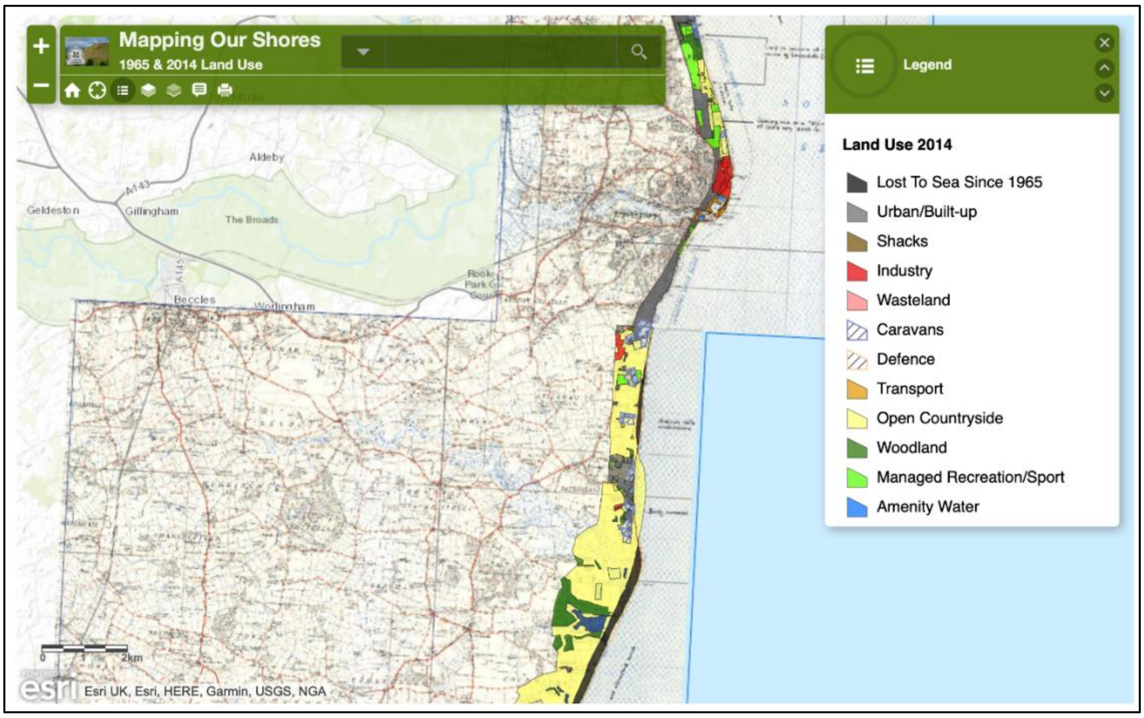

Figure 33: Image derived from the National Trust online GIS (National Trust, 2019b)

The EA have been involved in many vulnerability assessments on the coast of England. The EA are currently working on the National Coastal Erosion Risk Maps (NCERM) project, in collaboration with local authorities, aiming to generate accessible risk maps for the coast. As an output of the NCERM, interactive maps have been created and made available online (Environment Agency, 2018). These highlight SMP intent, and display the spatial NCERM coastal baseline. This baseline is split into frontages; these are defined as lengths of coast with consistent characteristics based on cliff behaviour and adaptation characteristics. The project is ongoing, and maps are continually being updated. The current stage involves changing how the data is presented and hosted. The EA alongside Defra also commissioned a report in 2005 titled: *Flood Warning for Vulnerable Groups: Measuring & Mapping Vulnerability* (Thrush et al., 2005). This report presents previous attempts at measuring and mapping vulnerability, and reviews environmental hazards. One finding from this was that emphasis should be placed upon selecting the appropriate area unit of analysis, a consideration equally valid for this current study.

As noted in Section 1.7.2.1, there are many non-departmental public body (NDPB) organisations involved with the coastal management process; Historic England is one of these. In the past, Historic England were involved with surveys of the coast of Norfolk and Suffolk. The projects focused on mapping the archaeology of the region. One key project was entitled *the National Mapping Programe (NMP)* (Historic England, n.d.). This project, as with that completed by the National Trust, used aerial photography to identify features on the coast. The mapping activities were conducted between 2001 and 2004 in Suffolk, and 2001 and 2006 in Norfolk. One recent initiative which focuses specifically on UK-wide high sea levels and coastal flood events is SurgeWatch[22] (Haigh et al., 2015). This takes the form of an online database of sea levels and severity of flood events for the UK over the last 100 years, drawing on data from the UK National Tide Gauge Network. Online mapping projects related to the coast are continually arising across the world, those profiled here are just a sample of projects which have focused on the coasts of England. However, they do indicate areas of application and issues which can be tackled by using this technology.

Private businesses have emerged which provide coastal risk assessments on demand, such as Coastal Risk Consulting (2017) in the USA. Their risk assessments use publicly available datasets relating to topography, tidal data, sea level rise predictions, land subsidence, and assessments of local conditions. The assessments are generally targeted at those working in the financial or real estate industries and homeowners. This is a good example of how the private sector can also play a role in raising awareness of coastal risk.

B.5 Collaborative Studies

Of the many collaborative studies undertaken, a recent project, highly relevant to this work and partly focused on East Anglia, is the Tyndall Coastal Simulator, which formed part of the wider work completed by the Tyndall Centre for Climate Research (Mokrech et al., 2011). This project focused mainly on a stretch of coastline, encapsulated by SMP-6 on the North Norfolk coast. The project aimed to generate simulations for future projections based on various climate change, wave, weather, demographic, and economic scenarios. Projections were made estimating environmental and economic impacts. The study drew on academic expertise from several institutions; in addition, Defra acted as a partner of the Tyndall Centre together with English Nature (now Natural England) and North Norfolk District Council (Defra, 2005). The study is comprehensive, however its main focus area is SMP-6, not covering impacts in all the study areas which this current study relates to. The Tyndall Project also focuses heavily on climate change and wave/weather scenarios and model creation, paying less attention to wider scale impacts of coastal change on society, local economies and ecosystems. Yet insight generated from the Tyndall project is significant for this current study. The SCAPE (Soft Cliff and Platform Evolution) tool (Walkden and Hall, 2005), developed as part of the Tyndall Project was continued in the form of Scape+ within the subsequent project iCOASST (integrating COASTal Sediment Systems), and the tool is now available to download via the Channel Coastal Observatory (CCO) website (Channel Coastal Observatory, 2018). An interactive version of the SCAPE tool was developed within the Tyndall project, this was a cut-down version of the original tool, and was titled iSCAPE. The tool aimed for utilisation within the decision-making process, primarily for economic valuation of coastal landscapes revealing impacts of future decisions. The iSCAPE tool was intended to act as a habitat mapping interface, providing an evidence-base for local development and supporting land use planning. The main findings from Tyndall related

[22] See: https://www.surgewatch.org/

to physical characteristics (forcing factors), such as waves (size and direction). The findings reiterated the fundamental importance of sediment supply to coastal stability, and revealed that failures are concentrated in a few areas, and in these monitoring and nourishment should occur. The project concluded that the iSCAPE model needs to be developed further and its decision support functions refined. Problems encountered in the creation of a user interface were also highlighted.

Building on work completed by the Tyndall centre, the iCOASST project set out to develop a method to predict decadal scale geomorphic evolution for coastal erosion and flood risk management, producing multiple simulations, accounting for sediment cell behaviour (Nicholls et al., 2015b). The iCOASST project brought together disparate coastal data sources and attempted to generate knowledge outputs from these. The project involved many who worked on the Tyndall Coastal Simulator and brought together expertise from the global research community. The project created a Coastal and Estuarine Mapping System (CESM) and was implemented through GIS and provides improved information relating to the seawards boundary of coastal areas (Nicholls et al., 2015b). The project came to an end in 2016, yet a legacy is sought through creation of a data repository (open source models and material), accessible via the CCO and BGS; iCOASST also identified a requirement for increased holdings of real data. An ongoing large scale UK-based project, also furthering knowledge in this area, is entitled BLUEcoast (2019). The project also aims to shape coastal protection policy, enhancing the coastal management evidence base and its focus differs from iCOASST and Tyndall in that it looks at physical and biological processes on the future evolution of the UK coastline, in particular coastal recovery following storm events. The project is led by the National Oceanography Centre (NOC) and partner organisations. Similar to the previous two projects it also looks at sediment budgets and the behavioural models developed model coastal, cliff and estuarine behaviour.

Beyond the UK, many similar projects have been undertaken. The PEARL (Preparing for Extreme events in Coastal regions) (Vojinovic et al., 2014a) is a wide collaboration between research organisations and industry, involving 24 partners from 13 countries in Europe and Asia. It has involved the evaluation of previous studies and built a knowledge base of resilience strategies (or adaptation methods). Similar to many other projects in this area an interactive web-based learning and planning platform is being developed. The project draws on seven case studies from across the EU and five from the Caribbean and Asia. Another project is THESEUS (Innovative technologies for safer European coasts in a changing climate) (Zanuttigh et al., 2014). There are some similarities between the THESEUS project and the Tyndall Coastal Simulator, yet this study focussed on creating a DSS as opposed to modelling. Vulnerability analysis and adaptation measures were considered within scenario-based analyses. A range of factors were covered in the analyses representing forcing factors, impacts and mitigating measures. At the time it was underway (2009 -2013), it was considered the largest integrated project related to coastal risk mitigation funded by the European Commission (Zanuttigh et al., 2014). GIS was used as a platform to draw together social, environmental and economic impacts, producing an open source DSS. This enabled comparison of scenarios (both hazard and management) over different temporal scales.

The focus of the DSS was limited, in that it centred on coastal flooding. The methodology used within the project incorporated the Source-Pathway-Receptor scheme. The resulting DSS is free to download (THESEUS, n.d.), and is parametric so can in theory be applied to coastal areas regardless of scale. Similar to many other DSS, which focus on coastal vulnerability it does require a high-resolution Digital Elevation Model (DEM). The system has an acknowledged weakness, in its inability to include the concept of resilience.

C-SCOPE (Combining Sea and Coastal Planning in Europe)(C-SCOPE, 2019) was a collaboration more limited in geographical reach than the THESEUS project, in that it only involved England, France, Belgium-Flanders and the Netherlands. The main collaboration was between the Dorset Coastal Forum and a centre for coastal management in Belgium. The project looked more to planning issues on the coast as opposed to coastal processes. It aimed to develop a framework and tools for integrated, sustainable, terrestrial and marine planning. The project used GIS to store and display its data, and it generated an activity 'heat map' for the coastal zone. A number of findings were generated from the project; more work was found to be required in incorporating the ecosystems approach within marine planning. Socio-economic data, at an appropriate resolution, was difficult to locate. Data, in general, proved difficult to locate, sometimes held within project 'silos'. Data formats can also prove incompatible, with inconsistent associated metadata standards adopted. However, the MEDIN project in the UK was recognised as working to tackle some of these issues.

RISC-KIT (Resilience-increasing Strategies for Coasts–toolkit) (van Dongeren et al., 2018) aimed to create an impact-oriented coastal risk database of socio-economic and physical data for various case study sites. In doing this, RISC-KIT aimed to facilitate information sharing and cooperation. It incorporated one study site located within the East Anglia region, between Old Hunstanton and Kelling Hard, Norfolk. The project looked at adaptation measures implemented and is carrying out re-evaluation of disaster risk reduction (DRR) strategies. A Coastal Risk Assessment Framework (CRAF) and DSS was developed. The DSS involved a Bayesian-belief based system (incorporating probabilities in its outcomes). The project also focused on economic damage and habitat destruction, and an early warning system was planned. The main focus of RISC-KIT differs to this research in that its central area of concern (as with PEARL) is high impact, low frequency hydro-meteorological events. As with the THESEUS and iCOASST projects, RISC-KIT represents a wide collaboration between research organisations and practitioners, and sought to make tools and methods developed, available as open source. One finding of note, from the work, highlighted by van Dongeren et al. (2014), is that GIS flood risk mapping can misrepresent coastal risk, due to 'non-stationarity of surge and flash flood events'.

Appendix C Data Innovations for the insurance industry Lloyd's of London

DATA INNOVATIONS FOR THE INSURANCE INDUSTRY LLOYD'S OF LONDON

LLOYD'S

Al Rumson

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C.1 Executive Summary

The insurance industry benefits greatly from advances being made in the domain of data and analytics. This applies to both products derived from data, as a result of applying analytical methods, and the rise in the number and complexity of sources of data, many of which are now available Open Source. However, these opportunities do not come without associated challenges; these challenges need to be understood as they impose limitations, constraining the use of data. In terms of deriving value from data, this can be split into four aspects: knowing data is there, having access to it, making sense of it, and using it. This study addresses all four of these, from the availability of data sources, to analytical methods (both currently being deployed and prospective solutions), and challenges associated with the use of data by insurers. In line with this, the overall aim of this study was to tackle the pressing question of how innovations in the use of data and analytics can be applied across the insurance industry to reduce information asymmetry and enable risk to be evaluated more accurately. The report is based primarily on first-hand accounts received during a number of meetings and interviews conducted with a variety of individuals with an interest or stake in data innovations being adopted by the insurance industry. Input was sought from those working for the Lloyd's of London insurance market, members of Lloyd's syndicates, data suppliers, analytics firms, and science and technology organisations.

A wide variety of organisations (suppliers of data and analytics) have been profiled within this report. Individual accounts of these are provided within the appendices. For the insurance industry, the value derived from data is maximised when internal insurance datasets can be combined with external feeds. However, this process is not simplistic and advanced methods need to be drawn on, to optimise any potential results and the quality of intelligence produced. Techniques coming online now, can enable datasets collected for one purpose to be reused and combined and higher-level insight to be derived from this. This report reveals many of these techniques. It also illustrated how a wide range of sources now exist, both Open Source and paid, which can address the insurance industry's data requirements. Some of these emerging data sources can augment or displace some more traditional methods and a reliance on expert opinion. However, an understanding of data veracity is a prerequisite allowing a decision is made to use the data. And with the variety and volume of data sources rapidly expanding, an overview of the potential storage options, software infrastructure, and processing techniques is required so that data can be handled and retrieved in an efficient manner. A key question for insurers is, do they have the internal expertise to implement the required analytical processes or should they draw on external expertise? Also, prior to deciding what techniques to implement a thorough appreciation of user requirements and level of expertise is required.

The Lloyd's of London insurance market was used as a case study for this research. Lloyd's is unique specialised market for insurance. Consideration of how data is utilised across this market presents a number of challenges and opportunities, beyond a focus limited to individual insurance firms. Many of the unique characteristics associated with data innovations within this market place are discussed within this report, such as pooling of data, market level analysis, and Proof of Concepts (POC), for emerging data innovations (which can involve Lloyd's, groups of companies/syndicates and analytics firms). The Lloyd's market is undergoing a process of modernisation and digitalisation of insurance processes; therefore, a study of this nature can prove pertinent.

Following an introductory section this report initially addresses challenges related to the use of data and analytics within the insurance industry. This has included challenges to both insurers and to firms supplying them with insurance specific analyses. Within this section (C.5) a number of areas have been focused on in more detail, such as underwriting, market level challenges and initiatives, and a limited number of classes of business and emerging areas of insurance. A number of challenges were highlighted including: data availability, a requirement to convert unstructured data/structured data capture, barriers to overcoming ingrained attitudes, requirements for holistic data evaluation, and knowledge sharing across the industry. Fragmentation of the data available, especially internal data, has been flagged as one barrier to progress. This needs to be tackled before internal data can be combined with external sources. Progress could be made in the way underwriters use data. This can be achieved by raising awareness of both underwriters and those supplying underwriters with data and analytics, of available data sources as well as their limitations.

At a market level there are challenges associated with risk evaluations across lines of business, which can relate to understanding more complex, cascading risks, such as that associated with Realistic Disaster Scenarios (RDS). In recent times, risk has been noted as under-priced, due to both a soft market and insufficient use of data and analytics. Market level solutions can take the form of structured data capture, market modelling initiatives, data standardisation, and pooling/sharing of data. In respect of the classes of business focused on, for the Marine class of business, data is said to be hard to obtain, and can be poor quality, yet the use of sensor and tracking technology is increasing. Cargo data is also lacking, especially data relating to the contents of containers and accumulation of cargo in ports. Application of satellite Earth Observation (EO) data and machine learning techniques is being considered to tackle some Cargo issues. For Mining and Energy, expert opinion is seen to play a large role in risk evaluations, yet emerging data sources such as the Internet of Things (IoT) and streaming data, are being realised to hold benefits. This is also the case for emerging areas of insurance, for which real-time data combined with analytics can render some new prospective technologies insurable. However, the inability to obtain good quality data for some emerging regions, where policies are looked to be written, can act as a barrier, when looking to extend coverage in these regions.

Section C.6 of the report introduces a range of data sources relevant to insurance. Commonly used data types have been grouped into 13 categories; a limited number of example sources are provided, and a more extensive listing and description of sources is provided in Appendix CC.1. A short discussion of internal sources highlights how this data can prove useful when pooled at a market level, how exposure data can prove problematic depending on source, and generally how internal data (such as claims data) is hard to obtain by analytics companies. In a discussion of data sources, a number of issues are raised. It is important for those using the data to have knowledge of the data (e.g. to prevent them being data rich insight poor). This can necessitate drawing on those with a scientific or technical background to interpret the data. Data can be obtained by many methods: bought, downloaded, through web-feeds, or scraped. Irrespective of the method used to obtain data, scrutiny and comprehensive review is important. Geospatial data is noted as particularly important for insurance; as such geocoding is a standard requirement for analyses of many perils. Yet, notwithstanding the sources listed in the report, obtaining data for a wider range of countries has been reported difficult.

The use of Open Source data has been discussed, and the possibilities this presents for reuse of data initially collected for another purpose. Open data can spur innovation, acting as a raw material to enable development of new forms of analytics. However, concerns were raised over the reliability of Open Data sources. In some cases, the messy, incomplete nature of data obtained can result in costs being higher to process and calibrate this data internally than to pay a reliable firm to supply the data in a processed/cleaned state. Also, it has been reported that for many countries (outside the UK and USA) only limited data is freely available. For the Open Source data available, metadata can also be lacking, and the data can also be supplied in complex states/formats. Many insurers do not have the required resources available to deal with this sort of data. Some of the analytics firms consulted report outsourcing data processing tasks to lower income countries in an effort to overcome this hurdle. The number of Open Data sources available is increasing daily, the report includes a selection of links to sources, that can be drawn on in insurance risk evaluations.

Section C.7 of the report provides details and evaluation of a number of organisations which supply insurance specific analytics. These are grouped into multiple themes: catastrophe (CAT) modellers; wider services –underwriting, portfolio management, multiple classes of business; geospatial threat analysis; flood; property; cyber; maritime. A short discussion is presented of these analytics firms. The analytics undertaken can involve fusing data from many sources. In this, multiple lines of business can be represented, giving a holistic view of risk, with many companies focusing on analysis across an insurer's portfolio of business. A requirement was highlighted, to consider the granularity of data and its compatibility. Those spoken with emphasise how new standards for data capture can be required and extensive data cleaning is often necessary. Up to now EO data has not been drawn on by many of the modelling firms, yet firms report to be actively engaged in seeking out new sources of publicly available data. Processes developed can enable aggregated exposure across an insurer's book of business, and many firms attempt to bring together both insurer's data and external sources.

Location data stands out being important and an understanding of the geographic distribution of risk is reported as particularly important. In line with this Geographic Information Systems (GIS) is a software tool widely used by many insurance analytics firms. Some believe that the underwriting process can be improved by applying machine learning to claim prediction, renewals and accumulation reporting. Open Source modelling software is both provided and drawn on increasingly. A growing number of firms are looking to the Cloud to host and deliver their solutions, where automation of workflows is possible. The Cloud environment can also enable high resolution data to be accessed in real-time via web interfaces. In relation to how services are delivered companies commonly provide their outputs as web-feeds or in the form of Graphical User Interfaces (GUI). Additionally, Software as a Service (SaaS) is increasing in popularity.

Section C.8 of the report covers prospective analytical solutions. Lloyd's Data Lab has engaged in multiple POCs recently, brief details are given of these. The discussion then shifts to satellite EO data sources and analytics. Over the last 10 years the cost of satellite technology has reduced significantly, and opportunities are arising to draw on the data products created by a new generation of satellites. Representatives of 9 firms supplying EO data and derived products were interviewed for this report. Notes taken during these interviews are provided in Appendix CC.3, and a comparison of the benefits, limitations and use cases for each organisation, is presented in the form of a table.

Satellites can now generate repeat coverage of the globe daily. This is possible using a new range of miniaturised satellites, which provide medium resolution imagery. Whilst repeat high resolution imagery, for vast spatial extents can also easily be acquired. Various forms of EO data products are available such as multispectral imagery: infrared, thermal visible and microwave imagery. This can be obtained from both open and paid sources. The European Space Agency's (ESA) Sentinel 1, is providing free and consistent SAR (radar) data for Europe. SAR data can be applied to many areas related to insurance such as maritime monitoring and assessing flood extents in near real-time. Google Earth Engine[23], can enable EO data from different sources to be mixed and analysed (without cost). For insurance, satellites can be used as an impartial remote validation tool and can take the place of site visits. Claims teams have been drawing on EO data for damage assessments, following recent hurricanes in the USA and Caribbean. Automated machine learning processes can be used for counting cars and containers and other assets. Satellites can even be used as IoT devices, and automatically tasked to acquire imagery for specific locations. For high risk locations, it is also possible to commission missions to capture detailed satellite imagery in advance. There are many emerging techniques such as satellite interferometry, which can be used to look at terrain and for subsidence, mining and earthquake monitoring. Another method is the Stereo techniques, used to generate 3D imagery. There are many options available, to draw on this valuable data source. Insurers can use just the raw data or look to applying automatic classification to predict future events. Fundamentally though, before deciding on which source of EO data to use insurers need to evaluate their data and information requirements

In Section C.8.3, the report briefly discusses the field of 'Big Data'. A framework has been developed which takes the form of a chronological listing of stages associated with aspects of Big Data. The framework is discussed in relation to information provided within this report. To understand how innovations in the use of data and analytics can be utilised within the insurance sector, it can be helpful to look at five core areas (which are detailed in the Big Data framework): 1. Data Collection, 2. Data Storage, 3. Infrastructure and automated processing, 4. Knowledge extraction and analysis, and 5. Visualisation and communication. A number of firms associated with fields of Big Data were profiled, this included interviews with representatives of some of these firms. Details of the techniques and technology provided by these organisations is provided in Appendix CC.4.

To summarise the report a number of conclusions have been drawn. The industry is deemed by many to operate in an old-fashioned manner and the way data is consumed can be outdated. There appears to be heavy reliance on expert opinion, qualitative evidence and subjective judgements in risk evaluation processes. There are a number of challenges with working with internal insurance data, such as it being unstructured, and it can take the form of narratives. External data can easily be acquired representing a wide range of insurance related themes, which can potentially be used to replace gross assumptions, inherent in previous and current assessments of risk, and in doing so reduce uncertainty. A range of new methods of data capture have been identified, such as IoT devices, satellite-based sensors,

[23] https://earthengine.google.com

drones and wider initiatives resulting in Open Source data sharing. EO data presents many, largely untapped, opportunities for the insurance industry. Data from small satellites can prove more affordable, and thus accessible. In collating data derived from diverse sources or time periods, standardisation of formats, content and QA is required. The increasing availability of Open Source data presents an opportunity to enrich analyses of risk, yet there are limits imposed on the use of Open Source data, and it can be more cost effective in some instance to purchase more reliable data. Open Source data is also lacking for some regions and countries, or there can be problems with poor data quality, and a lack of accompanying metadata. At a market level a centralised body capable of sourcing commonly used data, and carrying out QA/QC of this, would be valuable.

The wide range of data (internal and external), available to insurers needs to be stored in an appropriate way; consideration should be given to selecting the most appropriate software for handling data management and storage. More firms are looking to Cloud solutions, this is deemed advantageous due to negating the requirement to purchase IT hardware, the high levels of automation possible in the Cloud and on demand compute power available. Yet there is scepticism of the Cloud by some insurers. In terms of Big Data software tools for storing, processing and accessing data, there are a range of Open Source options, such as those provided by the Apache Software Foundation and LexisNexis (HPCC Systems). These should be considered, and depending on internal expertise, the software could be implemented locally first, then potentially scaled up using Cloud services. A range of companies can assist with this, if insurers lack the required expertise. The POC method, which Lloyd's have adopted, appears well suited to testing some of these more prospective technologies and data types, especially analytics based on EO data and the application of Big Data software tools. For example, options exist for drawing on EO data analytics platforms (such as those supplied by Planet, DigitalGlobe or Google Earth) to access and analyse EO data archives. Again, if companies require specialist assistance or lack expertise in this area, there are a growing number companies operating in this domain who could be worked with to develop POCs (a selection of these are detailed in this report). Ultimately, there is a heavy requirement for those with knowledge of how data is consumed within the insurance industry, to act as an interface between insurers and more specialist data analysts.

C.2 Abbreviations

ABI	The Association of British Insurers
AI	Artificial Intelligence
AIS	Automatic Identification System (Vessel)
ANN	Artificial Neural Networks
BGS	British Geological Survey
CAT	Catastrophe
CCTV	Closed-circuit television
CEFAS	The Centre for Environment, Fisheries and Aquaculture Science
CEO	Chief Executive Officer
DEFRA	Department for Environment Food and Rural Affairs
DEM	Digital Elevation Model
DFT	Department for Transport
EA	The Environment Agency
EC	European Community
EMODnet	European Marine Observation Data network
EO	Earth Observation
ESRI	Environmental Systems Research Institute
Flood RE	Flood Reinsurance scheme (UK)
GIS	Geographical Information System
HPCC	High Performance Computing Cluster
IoT	Internet of things
IT	Information Technology
LIDAR	Light Detection and Ranging
LMA	Lloyd’s Management Association
MAGIC	Multi-Agency Geographic Information for the Countryside
MEDIN	The Marine Environmental Data and Information Network
MIS	McKenzie Intelligence Services
NCEI	National Centre for Environmental Informatics (NOAA, USA)
NERC	The National Environmental Research Council
NLP	Natural Language Processing
NOAA	National Oceanographic and Atmospheric Association (USA)
NOC	National Oceanographic Centre (UK)
ODI	Open Data Institute
POC	Proof of Concept
QA	Quality Assurance
QC	Quality Control
RADAR	Radio Detection and Ranging
RDS	Realistic Disaster Scenario
RMS	Risk Management Solutions
SaaS	Software as a Service
SAR	Synthetic Aperture Radar
UK	The United Kingdom
USA	The United States of America

C.3 List of Contributors

Table 23: Listing of those who provided input to this report -and their then current company/job title

	Name	Company	Job Title
Insurance industry			
1	Craig Civil	Lloyd's	Data Innovation Lead
2	Albert Kuller	Lloyd's	Research Manager
3	Anna Bordon	Lloyd's	Associate, Innovation
4	Nick Blewden	Lloyd's	Head of Business Intelligence and data products
5	Philip Norwood; Neil Roberts	Lloyd's LMA	Senior Technical executive, underwriting; Head of Marine Underwriting
6	Peter Griggs; Peter Holdstock	Lloyd's LMA	Head of IT; Senior Executive – market processes
7	Richard Rodriguez	Lloyd's	Head of MRC and Lloyd's Actuary
8	Paul Mang	AON	Senior Advisor
9	Matt Wheeler	XL Caitlin	Group Catastrophe Research Manager
10	Parth Patel	Ascot UW	Chief Actuary
11	Steve Harris	Marsh	Assistant Vice President
12	James Garratt	Talbot	Head of Digital Underwriting
13	Sian Fleming	Talbot	Head of Exposure Management
14	Mathew Wells	Allianz	Underwriter Yachts and Marine Hull
15	Delioma Ormas-Dorta	Guy Carpenter	Catastrophe Risk Analyst (Vice President)
16	John Munnings Tomes	Navigators	Chief Risk Engineer
17	Alex Wilmot	Navigators	Energy Underwriter
18	James Fryer	CAN Hardy	Class Manager, Mining, metals and minerals
19	Nick Chalk	MSP	Class Underwriter
Data information provider			
20	Mike Ackroyd	BGS	Commercial Manager
21	Pottengal Mukundan	International Maritime Bureau	Director
22	Dr Tim Farewell	Cranfield University	Senior Research Fellow
23	Ellen Casey	Satarla	Project Manager
Open Data			
24	Orsola De Marco	ODI	Head of Startups
25	Dr Dave Tarrant	ODI	Head of Learning
Insurance Risk Analytics			
26	James Poole	Geospatial Insight	Sales
27	Jan Tlaskal	Galytix	Chief Actuary

28	Dan Chicchetti	LexisNexis	Head of Sales Insurance
29	Alan O'Loughlin; Ricard Toomey	LexisNexis	Senior Statistical Modeller; Manager GIS Analytics
30	Shane Latchman	AIR -Verisk	Assistant Vice President
31	Jill Boulton	JBA	Director
32	Dickie Whitaker	Oasis Loss Modelling Framework	CEO
33	Ross Franklin	RMS	Senior Director, Strategy and Partnerships
Data Analytics			
34	Rotem Abeles	Windward	Business Development
35	Scott Beckstrom	Geodata	Technical Advisor
35	Dr Adan Santander Lopez	Geared	Managing Director
Data Analytics Satellite Data			
36	Dr Samantha Lavander	Pixalytics	Managing Director
37	Anders Gundersen	Sensonomic	CEO
38	Andrew Iwanoczko	Harris	Earth Observation Specialist
39	Richard Flemmings	Tcarta	Operations Director
40	Charlotte Bishop	Terrabotics	EO Technical Business Development Lead
41	Matthew Stevenson	Planet	Sales Development Representative
42	Gareth Crisford	Earthi	Sales and Business development
43	Forbes Mckenzie	McKenzie Intelligence Solutions	Managing Director
44	Dr Boris Snapir	Cranfield University	Research Fellow in Remote Sensing
45	Dr Toby Waine	Cranfield University	Lecturer in Applied Remote Sensing
46	Matt North	Cranfield University	PhD Researcher
47	Luca Perletta; Dave Benson	DigitalGlobe	Sales Engineer Manger; Regional Sales Director
Big Data			
48	Cindy Maike	Horton Works	VP Industry Solutions & GM – Insurance and Healthcare
49	Dan Grorud	Hortonworks	Global Account Manager, Hortonworks
50	Richard Harmon; Richard McIntyre	Cloudera	Financial Service Industry Leader Enterprise Account Executive
51	Milan Grita	Cambridge University	PhD Researcher –Natural Language Processing (NLP)

C.4 Introduction

This report is the product of a 3-month study undertaken by a PhD Researcher from Cranfield University. The study focused on the Lloyd's of London insurance market. The purpose of the study was to establish data sources and innovations in the use of data analytics, which can be used within the insurance industry, with a focus on risk evaluation. Input was sought from those working for the Lloyd's market and members of Lloyd's syndicates, to provide a background understanding of the challenges faced across the industry, related to use of data in this domain. This enabled the scope of the study to be refined, and those with, potentially the most relevant input, to be targeted, and where possible to be interviewed.

The report is based on primary research which took the form of first-hand interviews. A wide range of individuals provided input to this study; those spoken with represent Lloyd's, the Lloyd's syndicates, insurance risk analytics firms, and various fields of science and technology. Table 23 provides a listing of all those who have provided input drawn on in this report.

The study centred on Lloyd's of London insurance market, yet the majority of findings pertain to the insurance industry in general. Lloyd's is the world's leading market for specialist insurance, and both Lloyd's and companies operating within the market are keen to adopt emerging data innovations at various levels within their businesses. As such a case study focusing on the use of data innovations within Lloyd's is deemed representative of the wider insurance industry.

The way Lloyd's operates offers a number of unique opportunities for implementation of data innovations within various areas of the insurance sector. Examples of ways data innovations can potentially be implemented at Lloyd's are:

1. Innovations implemented internally by Lloyd's. This can be by the Lloyd's Data Lab or other departments/bodies such as the Lloyd's Management Association (LMA). These initiatives can relate to how internal market data is managed and analysed and how external data sources can be combined with internal data, to generate value.
2. At a market level –in the form of services provided by Lloyd's to its syndicates.
3. Innovation implemented in partnership between managing agents, Lloyd's and external data analytics providers. This can take the form initially of Proof of Concepts (POC). POC are discussed further in Section C.8.1.
4. Innovations implemented by individual insurance companies operating within the Lloyd's market.

The work presented within this report relates to innovations implemented in all four of the areas listed above. The study deals with problems and requirements that can be met through application of data innovations and provides details of solutions currently being implemented or considered. Common challenges associated with the use of data have been established from a wide range of consumers of data sources. In-depth feedback has been sought from both users of data and information outputs, and data and analytics practitioners who provide services to the insurance industry.

The research has been limited in its scope, both by time and resource constraints. Therefore, the sources of data and analytics outlined within this report are not comprehensive, yet it is hoped that the methodology developed within this study provides a framework to enable further work to be completed in this area in the future. Those interviewed as part of this study represent only a sample of interested parties or stakeholders in the Lloyd's market and beyond.

Data analytics and sources of data are rapidly evolving, as such input to this report has been sought from organisations who may not be currently supplying the insurance industry (or at least the Lloyd's market). However, accounts included within this report are from those who have identified opportunities where the technology they are using and processes they are developing/implementing, can generate actionable insight relevant to the insurance industry. The next Section (C.5) of the report presents industry feedback, laying out data related challenges, demands and requirements. The following Section (C.6) highlights some data types and sources relevant to the industry, then moves to discuss issues surrounding the use of data, especially Open Source data. Section (C.7) looks at insurance specific analysis currently being drawn on. Section (C.8) moves to review some prospective techniques which have been identified and Section (C.9) attempts to draw some conclusion from this work, in relation to where innovations in the use of data and analytics can be deployed in the insurance industry in the future.

C.5 Industry challenges and requirements

C.5.1 Lloyd's and insurance fundamentals

The Lloyd's insurance market is over 325 years old. The market exists fundamentally to tackle the problem of information asymmetry, between the insurer and the insured and to enable risk-transfer between clients (policyholders) and underwriters. Lloyd's has a strong international focus and through syndicating risk placement it is deemed possible to achieve agreements which are half the price of single deals. In a perfectly competitive market the market would be price setting, however this is rarely the case, so underwriters and actuaries require access to accurate information detailing the nature of the risks associated with each class of business. Insurance pricing can be viewed as a risk signalling mechanism, which can act to raise awareness and encourage risk adverse behaviour. Therefore, if market distortions occur, this message can be diluted, resulting in adverse societal consequences. Schemes such as the USA government NFIP[24] flood insurance program, which bypasses conventional market mechanisms, has been associated with big failures, such as incentives being created for construction to occur in high risk areas. Since the 1970s losses have been growing (especially from weather related incidents), with non-insured losses growing the fastest. For insurance markets to function effectively, it is essential for both risks to be priced appropriately, and for coverage to be extended to those who need it. Insurance is believed to be under-priced in some instances, due to the existence of reinsurance. Given this the use of data analytics, for assessing reinsurance portfolios can be more important than for insurance. For both, it is essential for analysts to supply the information required to allow exposure management, so aggregation of risks and exposure to natural perils can be established by insurers. This can be to fulfil internal company risk management requirements and is a regulatory obligation of the Lloyd's market. To enable exposure management and Catastrophe (CAT) modelling, the most

[24] https://www.fema.gov/nfip-reinsurance-program

advanced analytical techniques should be drawn on. This report will reveal many of these techniques, and innovations in the use of data analytics which can enhance this process.

C.5.2 Future directions for Lloyd's and the industry

The current Chairman of Lloyd's has made statements in which he advocates a shift to digitalisation and adoption of modern practices, moving beyond hearsay and subjective judgements in the pricing of risk[25]. This sentiment is echoed by the current CEO, who backs initiatives to maximise the potential offered by data driven initiatives[26], such as the ongoing Target Operating Model (TOM)[27]. There is said to be a focus within the market, currently, on underwriting, this report acknowledges that in discussing data related requirements of the underwriter, and looking at tools and data sources which can improve the underwriting process. The world is changing, and technological advances are creating new risks, in addition to new opportunities. It is deemed necessary for new ideas outside the industry to be embraced, allowing innovation to be adopted. This can result in fresh ways of looking at aggregations, and the ability to evaluate new emerging perils. These processes need to be driven from the ground up, with data entry teams building and adopting new tools, standardising data processing tasks, making them quicker and more robust. Processes such as the use of Artificial Neural Networks (ANNs)[28], for example, are being looked to as a means to enable broking to become more of an evidence-based risk advisory.

C.5.3 Challenges in the use of data

As the insurance industry has developed, the importance of access to information has become ever more apparent. Demands are made for more data, yet it is important that those using the data understand what it represents. One problem highlighted is that many who make decisions based on data can be unaware of the limitations of the data they are using. As a result, too much weight can be placed on the data, resulting in skewed scenario creation. Then irrespective of the quantity of data which is incorporated within models, their reliability does not necessarily increase. This sort of scenario can bolster scepticism about the use of data and reliance on models 'bought, but not understood'. In overcoming such challenges, it has been said that the old-fashioned nature of processes currently drawn on in the industry, needs to be acknowledged, and generally the use of technology needs to increase. The evolving digital domain presents both opportunities and threats, which must be faced. Data analytics firms have cited as a problem, that many clients in the insurance industry are currently using outdated IT, and that they (the analytics firms) are not in a position to enforce change. Another issue highlighted is that insurance companies have too many different computer systems, which all need continual updates and can become incompatible with new software.

Industry records often take the form of narratives. This presents a particular challenge when trying to systematically analyse a large number of these records. In order to undertake

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[25] https://www.lloyds.com/news-and-risk-insight/speeches/2017/london-market-conference-2017
[26] https://www.bcg.com/publications/2017/insurance-market-new-destinations-inga-beale.aspx
[27] https://www.lloyds.com/market-directory/london-market-group/target-operating-model-tom
[28] http://home.ijasca.com/data/documents/ID38_Pg160-172_Predictive-Modelling-for-Motor-Insurance-Claims-Using-Artificial-Neural-Networks_2.pdf

statistical analysis, this qualitative information needs to be converted into quantitative data, to enable like for like comparisons to be made. This can be summed up in the requirement for structured data capture. Modern techniques can be applied such as Natural Language Processing (NLP), however this does not negate the requirement to undertake modernisation drives, to standardise methods of data capture and archiving. There are many options to achieve this, and currently there appears to be widespread interest within the industry in the use innovations such as Block Chain distributed ledgers[29]. However, there are other widely established processes which could be more readily adopted. There are vast opportunities to take advantage of emerging forms of data analytics that are being used globally. Decisions to use data can be driven by individual team or management imperatives. Many firms freely admit to being in their infancy in the use of advanced data techniques, especially in relation to looking at their own data.

The use of data can appear more suited to certain lines of business, for example motor insurance. This has not always been the case, apparently 'no one' created models for this sector in the past, yet now models exist incorporating over 50 factors, and it is said to be common for modelling tools to be shared for this field. There are emerging streams of data analytics which can be applied to multiple classes of business and perils. For example, it is reported that ANNs are not currently widely used, yet could be adopted for spotting patterns, and understanding relationships between data variables. This kind of understanding is essential for realisation of how hazards translate to loss, and generate the resulting financial impacts. The outputs of models can even determine the future direction for a business. Models can reveal the real risks and potentially indicate lines of business currently held on a company's books which should be dropped. Intuitive modelling processes can also increase insurers' understanding of aggregations, for example. Many believe that in the future data scientists and actuaries should work much closer. Benefits can be gained through data scientists drawing on actuarial understanding of the data, and mixing this with modern techniques, ultimately to ensure risk selection is closely aligned to risk profiles.

Some of those questioned for this report, regard the use of Geographical Information Systems (GIS) within the industry is inadequate, despite the fact that many firms are willing to provide this service. Many larger insurance companies have GIS teams, yet more modestly sized companies could also benefit from this expertise. A barrier some have cited, as preventing technology take-up is the overwhelming amount of tech companies, now trying to gain a foothold in the industry. Some of those questioned within the Lloyd's market receive emails from multiple companies daily, who are touting their new techniques. There can be an overreliance by these companies, on using buzz words, such as Artificial Intelligence (AI), Big Data, and Machine Learning (for example), yet without adequate explanation of the underlying processes. In cases such as this, it may appear to be simpler and more reliable, to resort to drawing on expert opinion instead of unknown data analytics methods. Unfortunately though, expert opinion has proved an inadequate method for capturing the dynamic nature of many risks, especially for emerging areas of risk, where experts are hard to find. It is therefore necessary, for those providing access to data and analytics to address some of the prominent concerns from the user community, for example: security of data

[29] http://www.ey.com/Publication/vwLUAssets/EY-blockhain-in-insurance/$FILE/EY-blockhain-in-insurance.pdf

stored in the Cloud, and addressing what lies within the 'black box' of machine learning algorithms.

C.5.4 Functional challenges

From conversations with those working in, using and associated with the Lloyd's market, a number of functional challenges have been established. Of these, resistance to change appears an issue, acting as a barrier to progress. Many have stated that there are ingrained attitudes held within the industry acting as a barrier to changes being implemented. This has been highlighted as a factor contributing to the slower take up of technological developments in the insurance industry compared with other areas of financial services, such as investment. One supplier of technology has stated that they use 'most of their time educating syndicates, and more than actually supplying products'. The Lloyd's market is regarded as very personal, where background can dictate which processes are used, making it difficult to implement new modelling technology, for example. Some believe that there is too much focus on loss records, whereas it would be better to search for route causes and drivers. Representatives from mining insurers have stated that the London market can lack innovation in its insurance products, resulting in a lack of market penetration in new territories, contributing to the majority of the developing world remaining uninsured. Simple innovations, such as the use of flood maps, have been cited to alter the fortunes of those operating policies covering this peril. Underinvestment in flood modelling has been reported as contributing to Zurich RE and the NFU sustaining the biggest losses on flood claims, every year since 2000.

From a data driven perspective, insurance is seen to be behind the times, in its reliance on generalised linear models, and expert opinion, such as that of warranty surveyors. This can be especially so for risk engineers, whose main tools are qualitative, with evidence based expert judgements, and surveys with clients, determining if engineers should be sent to a site. In this area, in particular, data could be used to create a more targeted approach, so that surveys are focused on the correct areas. Subjectivity and bias can too often influence assessments made by risk engineers, this could be addressed through using holistic evaluation methods and sharing of information, from other locations and events. Drawing on larger datasets in evaluations, can allow fairer pricing of risk. Data signals can then act to allow filtering of portfolios. A lack of knowledge sharing, across the industry, is said to pose a barrier to this though. Effective use of data can potentially allow more stable areas to be identified within high-risk zones, this can enable companies to be more aggressive on price for policies in these areas. An example of how more granular data is available for such geospatial risks, can be seen in the case of earthquake data which was only available at a zip code level but now can be millimetre-specific.

Other functional challenges include, general insurance (not life) being so diverse, and given that many insurers' books of business cover many territories, languages used are not always English. So, diverse translation requirements add to the burden of making sense of the associated qualitative data. In lines of insurance such as maritime and energy (especially Oil and Gas), near miss scenarios are not accounted for, so it is difficult for credit to be given to companies taking appropriate measures to prevent such incidents. Developments in data sources now becoming available, such as associated with streaming sensor data and the Internet of Things (IoT), may present opportunities to address such issues.

C.5.5 Internal data

The insurance industry has very valuable internal data which many believe should form the basis of risk management. Lloyd's internal datasets can relate to past impacts, claims, and performance of syndicates. Claims data is typically stored internally within an organisation. This can present an organisation with a competitive advantage, especially when its data are combined with external data sources. However, the first step may not be to bring in external data sources, but to focus on structuring and using internal data in a better way. Advanced analytics made possible, using for example Hadoop libraries[30], could be drawn on to make better sense of internal data. The value of using such proprietary data, especially for a large market such as Lloyd's, cannot be readily replicated by competitors. Given this, a first step in data analytics, for an insurer could be to focus on claims data, from within their extended archive, and to establish how this process could be standardised going forward. Portfolio data is also deemed valuable, and this data can readily be embellished by external sources, generating a greater understanding of risk. Simple information such as loss coordinates, can prove valuable when looking to underwrite properties for example. This points to the necessity of understanding available sources of data and analytics (which will be covered in a subsequent sections of this report). Syndicates such as Talbot are actively looking at the provision of external data. There are many barriers to success in this area though, the data available can be fragmented, with claims data restricted to a few lines of text, frequently including slang and poor spelling. This prevents machines from being able process this in an intelligent manner. As such, simpler analytical strategies have been adopted based around typologies and manual approaches such as counting frequency of words. Irrespective of what technique is adopted though, a better understanding of what is required from the data, is fundamental, to make it actionable for insurance companies.

C.5.6 Underwriting

The process of underwriting risk is a fundamental function within the insurance industry and involves risk selection and fast decision-making. Underwriters typically have a technical background and rely on their technical expertise. The process is not always transparent though, with underwriters commonly regarded as having their own intelligence and idea of cover price. Some have even claimed that 'underwriters innately know risk places'. Insurance cover results from interactions between underwriters and brokers. As part of this process specific key questions need to be asked, which require an understanding of companies' records and the ability to compare companies to their peers. This is a requirement for each client, in addition to the ability to answer questions such as what do they do, where do they do it, and have they done it before? Ideally it is the job of the broker to provide such information. Therefore, both broker and underwriter need to have a grasp on how technology can be drawn on to generate answers.

The underwriter decides on the cover a client is happy doing business with. To enable them to do this they require access to tools, such as an electronic dashboard which can generate answers based on entering simple identifiers. Information supplied to the underwriter can be taken into consideration in pricing models. Catastrophe (CAT) models, for example enable

[30] http://hadoop.apache.org/

underwriters to distinguish what and where to insure, geographical spreads, transfer of risk, and financial strength. Emphasis is said to be placed on underwriters looking for what isn't working as opposed to what is. In terms of the standard risk equation (Risk = Hazard Probability X Consequence), the insurance industry is said to focus on consequences, before probability. Yet the willingness of underwriters to insure, can be dependent on the hazard and risk. A challenge is for this process to be completed consistently across an enterprise. How risks are assessed by underwriters, is a concern, as is how risks are assessed as part of a portfolio for higher level decisions, such as those undertaken by actuaries. Problems have been highlighted in the process of pricing risk, due to underwriting teams in insurance companies not communicating. This problem is added to by the practicalities of the underwriting process, resulting in individual underwriter not always being aware of the wider risk picture, such as that associated with cascading and systemic risks.

A challenge for underwriters and those providing them with information (which has been continually repeated by those interviewed for this report, from across the industry) is the lack of time underwriters have to make important decision and to review information. So, a particular challenge is how data is served at the point of decision-making, given that underwriters may have only minutes to price risk and make a decision on cover. Such quick decisions do not allow time for underwriters to review the data in great detail. Underwriters consulted report the need to set up in excess of 500 deals per year. Given this, they are unable to devote time to navigating complex user interfaces to retrieve information. Therefore simple, intuitive dashboards are required, presenting a clear view of loss. This requirement has prevented organisations such as LexisNexis from implementing GIS tools for underwriting, which they deem are better suited to be used by modelling teams. GIS applications have proved overly complex to be utilised for underwriting and can place constraints on teams. Abstracting this complexity is deemed a requirement, as underwriters require distilled metrics at their disposal.

'A few pieces of choice information can change an underwriters mind'. As such, more general data is required at an actuarial level, than is needed by underwriters who require more granular specific information on facilities and clients. Different levels of engagement with clients can necessitate drawing on different levels of data. Given this, it is necessary for data scientists and data analytics companies to recognise where their data is being used, and the amount of information required. At a brokerage level, a different level of data is required, than for underwriting, yet brokers do need to respond to underwriters. A core requirement is for the potentially huge amounts of data available, to be turned into something useful. Provenance of data sources is also important; underwriters questioned (for this report) have stated how they draw on information obtained from internet search engines and geospatial information obtained from Google Earth. Mapping platforms such as Google Earth, are not intended for use in insurance, yet underwriters are using this to gain understanding of properties, building materials, roof types, among other features. Information in web-mapping applications aimed at the general public, can be out of date or poorly presented. Ultimately, effective use of data and analytics within the underwriting process can increase operational efficiency and generate a competitive advantage.

C.5.7 Market level challenges (Lloyd's)

Aside from the granularity required at an underwriting level, a broader approach is required at a market level. Lloyd's (for example) needs to understand the performance of its syndicates. This can necessitate a focus on class of business, building an understanding of which classes of business are not profitable and in effect are subsidised by profitable classes. Energy have been reported to have proved profitable in recent years, whilst marine, accident, health, casualty, aviation, and yacht are said to have contended with structural issues. Motor has been highlighted as an attritional class, where there are many small claims, yet policies are simpler to price given ready access to higher quantities of information about the insured. This contrasts with aviation and cargo, which are said to be difficult to price. The market for motor insurance is regarded to be more competitive due to the availability of information. For other classes, if information were more freely available, risk could potentially be priced more effectively. For ships and yachts, not all operators collect and share information with insurers. This contrasts with aviation, where complete accident records can be obtained. For many classes of business, pricing is highly dependent on insurer or the current state of the market.

There is a necessity for data to be made available crossing lines of business, and this not only for evaluation of market performance. Incidents such as Super Strom Sandy, resulted in huge losses across multi classes; impacts to properties, subways, cargo (New York just offloaded cars), fine art and specie[31]. Wider indirect impacts were also experienced across the country which related to supply chains and contingent risk. Similar was true for the Thai floods of 2011[32], where high insurance losses were experienced, related to contingent business disruption, even in the USA, indicating how downstream consequences can be international. For past incidents such as this, there was reportedly inadequate analysis of supply chains completed. In light of this, it is essential for companies to understand how their portfolios stack up. The Lloyds realistic disaster scenario (RDS)[33], is a regulatory market requirement, involving deterministic modelling of incidents such as hurricanes, collisions and aviation incidents. The RDS involves running a hypothetical scenario and looking at what impact this would have on a company's book of business, and if a company could withstand such an event. Analytics firms such as RMS are said to be involved in an active dialogue with Lloyd's in connection to RDS, where a bottom up approach is being taken, involving managing agents. Business interruption is a major source of claims in such scenarios, with financial losses from property damage dwarfed in comparison.

At the time of writing, the insurance market is regarded to have been very 'soft' for a considerable time, resulting in insurance being a 'buyer's market'. A common problem when the market prices risk, is that there is little leeway in repricing policies following events. In this context a problem with increasing premiums, is a subsequent choice to not insure. This may have contributed to hurricane risk being under-priced, despite the damages resulting from previous hurricanes such as Matthew, so impacts from Harvey, Maria and Irma inflicted larger

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31 https://www.lloyds.com/cityriskindex/threats/wind_storm/case-study

32 https://uk.reuters.com/article/uk-lloydsoflondon/lloyds-faces-third-biggest-loss-from-thai-flood-idUKTRE81D0C420120214

33 https://www.lloyds.com/market-resources/underwriting/realistic-disaster-scenarios-rds

losses on the industry, due partly to under-priced risk. This may have resulted not only from the soft market, but also from the insufficient use of data and analytics. The Lloyd's market of syndicated risk is said to be powerful, this should be exploited in terms of opportunities offered by utilising data and analytics.

C.5.8 Market level initiatives

In relation to the use of data and analytics there are a number of market level initiatives taking place at Lloyd’s, which were detailed during interviews. These have been associated with the Lloyd’s Data Lab, the LMA, and others. Of these market level initiatives, a prominent challenge being grappled with is dealing with messy, unstructured internal datasets. In an ongoing initiative, which is part of the London Market Group Target Operating Model (LM TOM), which is titled Structured Data Capture (SDC)[34] the LMA has been tackling the problem of standardising data related to the Market Reform Contract, a service provision at a market level. A clear requirement exists for data to be formatted and cleaned in a consistent way. This project relates to structured data capture and shared market services. This involves formatting data and placing rules around the transfer of data into coding. So, data can be extracted directly by an organisation, not constrained by proprietary formats. A driver for this is that brokers are not providing data in a consistent manner. High levels of automation (80%) are reported as being incorporated in this project. Another more detailed, separate requirement, which has been mentioned, is for machine read claims to be augmented with standardised information such as geography, year, and peril. The LMA is an advocate of improvements in the way data is handled, they have stated that ‘we should be doing everything possible to ensure that the customer experience and claims service are prioritised within market modernisation initiatives’[35]. Modernisation efforts are essential to maintaining advantage in a highly competitive market. Therefore, it is deemed necessary for organisations such as Lloyd’s to understand how emerging technologies can be used to automatically process data into a usable schema that is ready for analysis. Processes to achieve these results, which are currently undertaken manually, can be expected to become automated in the near future.

When looking at providing services at a market level, many considerations are necessary. One of these must be avoidance of replication of functions completed by organisations operating within the market; value needs to be offered with what is provided. However, inefficiencies in the London market, have been flagged, due to the many of the same basic operations being repeated separately by individual companies. This could be improved by specific core datasets, which many syndicates and companies draw on, being made available centrally. This can relate to Open Source data, scraped data, and paid datasets. This could pave the way for Lloyd’s or another organisation to provide options for a potentially paid and free data service. A comment about this was received from an underwriter at Allianz, who stated that ‘information pooled should not just be anecdotal, it needs to be quantifiable, if it will be of value to the end user’. A centralised data sharing system could also enable non-restricted internal data to be pooled between companies. Furthermore, a representative from Ascot has expressed enthusiasm (which has been echoed by others) for a system to be developed

[34] https://tomsupports.london/structured-data-capture

[35] http://www.lmalloyds.com/LMA/News/Blog/Hurricanes_Test_Satellite_Imagery_Service.aspx

where information related to claims fraud can be shared by the Lloyd's market (or even wider). This would require collaboration between syndicates and companies but could potentially benefit all. However, concerns have been expressed relating to loss of intellectual property rights, opening up firms to competition.

In relation to a dashboard provided at a market level, by Lloyd's or another organisation, a suggestion was received by an underwriter from Navigators, that it could be useful for a two-tier dashboard to be implemented, one industry specific focusing on a single (selectable) class of business, the other tier at a top level, giving overall market conditions and containing relevant external data; 'this could be the sort of things we'd log in to in the morning when we come in'. With respect to services provided by external organisations, a representative from RMS stated that they were open minded about making exposure data available at an industry level. A core benefit of market or industry level initiatives is they can address common problems encountered with data existing in various formats and levels of completeness. This has been said to be especially the case when data is obtained for different countries. Data needs to be placed into a regular format, which is a time consuming and burdensome process. If these tasks could be pooled by a central body, it would result in time and cost savings, avoiding duplication of efforts. The London Market Group Target Operating Model (LM TOM) is one example of such and industry wide initiative. This relates to data capture and access, involving creation of a central data repository. This was greeted with enthusiasm from those spoken with from across the market.

A centralised body such as Lloyd's or large-scale data analytics organisation can take a lead role in enforcing data standards, and ensuring quality checks have been performed on standard core datasets. Profound benefits are believed to be possible by standardising the way that property risk (for example) is modelled. Change in exposure data capture is also regarded a factor necessitating creation of associated standards. Additionally, if requests for better quality data become common, this can result in changing norms in the industry. Centralised data provision has been suggested by many, especially in relation to CAT modelling. Many of the core inputs to CAT models are difficult to obtain, especially with the appropriate level of detail and in a format that can be used. Such inputs include information on the built environment (for certain countries) and calibrated loss data. Furthermore, the ability for CAT data to be entered centrally onto a slip, can drive improvements in the CAT modelling process. A recently formed company, Oasis Hub (associated with Oasis Loss Modelling Framework) is working to address this problem, drawing on Open Source data, which it makes available via its website[36]. Many reinsurers are completing the same base level, routine tasks in parallel. So, if these operations can be completed at a higher level and made available to individual insurers, this can increase efficiency. Individuals from firms using such data, have expressed an interest to pay for these services. One other question, which has been raised, is that relating to the possibility for Lloyd's or an external organisation to obtain a single, centralised licence for many datasets that multiple syndicates/firms are drawing on.

[36] https://oasishub.co

C.5.9 Sector/Class of business specific challenges

Some limited details are presented below of individual sectors or classes of business, and risks faced within these, and associated data related challenges. Selection of these classes of business was arbitrary and was based on access to/input from those working in these fields.

Marine

Marine is a wide category, covering vessels (Liability, Hull, Cargo, and Casualty), including inland trading vessel, freight, ports, and offshore installations. Huge losses have been felt recently following impacts from hurricanes Irma and Maria. Marine is regarded by many as an old-fashioned class of business. The maritime industry is currently weathering challenging times, due to freight rates being down, as a result of depressed trade rates in the world economy. Many ships are therefore making a loss, which translates to insurers making a loss. Costs are therefore a key concern for the industry. A problem flagged within the maritime sector, is that of ship owners not trusting each other, resulting in a lack of data sharing. Marine data is generally regarded to be poor quality, and hard to find, with a lack of centralised sources for casualty statistics, loss causation, trends and reporting from officers of the watch. Many people are involved in the maritime trade, from many different countries, therefore no one data source can solve all insurance related issues. This can pose a problem for assessing certain types of risk. Expert elicitation is commonly combined with whatever data is available.

Data sources drawn on are generally conventional, with companies not looking at tracking every single ship, as the overhead would be prohibitive, and the value added over standard data, is said not to justify this. Nevertheless, an increased use of sensors and tracking technology has been witnessed. Industry experts have expressed a need for monitoring vessels. This is especially the case when vessels' AIS identifiers are being switched off, so accessible records could be used to address safety concerns. A suggested form of analysis is to check global vessel traffic compared to AIS activity, these are predicted not to tie up, this being the case, recorded analysis could be used to increase awareness in this area, and highlight issues. There are many ocean regions of perceived enhanced risk, if vessels enter these waters, insurers need to be informed. This can result in calculation of an additional risk premium or advise being issued on actions to be taken. Examples of known risk areas include waters off Iran, Venezuela, and sections of the Indian Ocean. The presence of pirate attacks can also contribute to areas being deemed high risk, alongside political instability of coastal states, war and terrorism. Lloyd's have been involved in a number of studies and a Proof of Concept (POC), relating to marine risk. It has been expressed by those working in this domain that any product supplied at a market level still needs to be granular and specific enough, so it could be used to track a fleet of vessels.

One issue highlighted by marine experts from the LMA, was that it could be useful for more details to be provided relating to pollution claims. Data and analysis on the duration oil spills persisted, if chemical were used, and did this alter the time the oil persisted? Also, does it help to accelerate spills using man made dispersants? Data and analysis related to these issues is reported to not currently be drawn on, but it is believed that it could form a valuable input. Data could potentially be acquired from advanced sources such as Earth Observation (EO) Satellites. The more general requirement for real-time information, for marine insurance, is debatable, there are those who feel that this is not a requirement, yet most are unaware of the full range of sensor feeds that could be drawn on and how data from these sources could be used. This is an area where the IoT may hold benefits. Another source of data is hydrographic depth data, and charts of the seabed. This reported to be of prime concern to vessel owners, but of questionable relevance for insurers. However, this data may be more important when considering new shipping routes in areas where there is no up to date charting. Advances are being made in this domain, both in terms of coverage and availability of data. Companies have emerged who can supply satellite derived bathymetry, which can be accessed on demand more easily than conventional sources. Other sources of data that have been highlighted as useful include details of laid-up vessels.

Cargo

Cargo premiums have grown in recent years. The value of global exports is predicted to continue increasing, this in part explains the growth in premiums. Another contributing factor to growth in premiums is that the loss ratio increased in recent years. Big Data and machine learning have been identified to hold benefits for Cargo insurance. Data variables focused on have been: past shipping routes, seasonality, and goods in port (at any particular time).

Problems with cargo data

Risk is posed by the infrequent accumulation of cargo in ports. There is therefore a requirement for current listings of ports where there are accumulations. Details of average values running through ports is also sought, particularly access to cargo manifests. Problems have been encountered obtaining this information though, especially definitions of what is transported and stored within containers, not just the number of containers in port. Value and weight of imports is commonly under reported to customs, especially for high value cargo. Differences have routinely been observed between invoice value of goods imported and that reported to customs. Ports are inadequately sharing data, such as the origin of containers. A recent example came from the chemical explosion in Tianjin, in China, where the numbers of cars reported to be stored in the port did not relate to the real exposure. There is a disparity in processes globally, with information hard to obtain or non-existent in some areas. An issue flagged is that it is only possible to obtain access to information after the risk has been written in many cases.

Mining

Mining insurance is a niche field - there are only limited number of mines in operation. Policies are available which cover property, for all mining, in all territories. Mining is regarded: highly volatile, high hazard, polluting, and loss making for insurers, therefore the appetite is low for underwriting mining risk. Mining is exposed to a high number of hazard (some of which are not found in other places): fire, explosion, Natural CAT perils, human error, machinery, underground geotechnical hazards, and open pit flooding. Consequences can be: environmental -pollution, human casualty, liability, cascading risk –river/sea pollution, and loss of income or disruption of business. There is a high requirement for expert involvement in understanding and pricing risk. Companies such as Strategia[37] provide qualitative risk analysis. Mining insurers have highlighted how the analysis which is carried out of the mining industry is less rigorous than that in the energy sector, and risk assessors (for energy) spend less time on the ground and involved with operations, whilst this is not so common for mining. Many risks in the mining industry are connected with wider sustainability issues.

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[37] http://www.strategiaworldwide.com/strategia-worldwide-hosts-mining-risk-event-johannesburg/

Mining is generally regarded as low-tech and there is a lack of data associated with the mining industry. However, innovations in sensor technology, being adopted in other fields is also filtering through to the mining industry. IoT monitoring technology can result in risks being flagged earlier. This can include the use of quantum devices that can detect small movements, and rely on streaming analytics. There is a mining insurance group, this is a technical group, helping the mining industry make improvements, and it produces a loss database. There are areas where data can be collected which can provide some assurance to insurers. Data is needed, not just on hazards but also relating to the nature of operations, and internal risk aversion measures implemented. Knowledge of any risk mitigating actions can result in reductions of premiums, thus enabling the insurer to be more competitive on price. Different risks are associated with new types of mining, such as new processing techniques, not crushing, but oxidisation. These new methods are hard to price due to the lack of prior experience and data. Other experimental techniques such as deep sea and asteroid mining are deemed too far away to consider, from an insurance perspective. Generally, attitudes to mining alter when commodity prices are good.

Energy

Feedback received related to the class of business Energy, has mainly been confined to the offshore Oil and Gas industry. Through the life cycle of an oil and gas project, risk generally increases as the project develops. Risk assessments are site specific with risk quality and exposure focused on by insurers. Cover is provided against property damage, consequential loss, liability and disruption of business. Risk analyses can incorporate various sources of data; however, the main emphasis is on ground based assessments by experts. Analysis can involve looking at a client's risk quality as a whole, at a site level. For example, if a client has 20 oil platforms in a region or distributed globally, it is still necessary to look at the client at a detailed level, to gain an understanding of the client's approach to risk management at a corporate level. Inspectors who pay visits to client assets produce models to generate an understanding of how a company is mitigating risk. They look for documented evidence that procedures for risk management are being implemented. This can involve attending hazard identification (HAZID) meetings prior to commencement of operations, and involvement in subsequent infield operations, such as the sail away of a drilling rig top side (which can involve Warranty Surveyors, for example). Industry specific data can form a valuable input to analysis, usually undertaken by specialist insurers, such as Navigators. Detailed data inputs derived by advanced streaming sensors can be drawn on by insurers; for example, in drilling operations different premium prices are charged by per metre drilled, due to risk of the drill bit breaking. In assessments of oil and gas projects, data revealing high reservoir pressures, can act as a sign of good yield potential. Insurers questioned have expressed their interest in sustainable, profitable use of assets. Declining reservoir pressure results in reduction of the insured asset, given this continually updated data inputs are required from the field. Oil and Gas is regarded a better prospect for insurers than mining, due to a core problem with mining being, that a higher concentration of value is sited in a single location, whilst a large oil field may comprise of many satellite platforms, which can result in lower business interruption exposure should a loss occur at one location.

C.5.10 Data use in emerging areas of insurance

The nature of risk is evolving, insurance cover originally focussed on returns to physical assets, yet now intangible assets make up bulk of modern day balance sheets. Contemporary businesses operate with tight supply chains, as a consequence, small changes result in disruption of production. This can alter the nature of what is insured. In line with this, the complexity of policies has developed accordingly. When insuring new technologies and methods, not used before, and for which no past track record exists, the availability of information which can document processes and performance can potentially render these technologies insurable. This is an area where streaming data feeds, cloud computing and Big Data analytics can prove beneficial. The operation of autonomous machinery is one example. It may not be possible to obtain historic claims data for these new technologies, however, if data exists which can demonstrate how the machinery operates under various conditions, it may be possible to evaluate the risk of its failure. Data alone is not adequate to assess emerging risks, there is a clear requirement for people with industry specific knowledge to assist in assessing each emerging risk. This can enable premiums to be written on these. An example of such an emerging technology is autonomous vehicles, these are associated with a unique set of risks; proof is needed to establish pricing and deductibles. In addition to these considerations for land based autonomous vehicles, autonomous vessels pose separate questions, for example how can these vessels deal with threats posed by pirate attack?

Emerging areas of insurance can also relate to cover provided in geographical areas where policies were not written previously. Lloyd's largest market is said to be the USA, where over half the Lloyd's premiums are reportedly written. However emerging markets are a target for future growth. These new markets can throw up a new set of challenges, especially in relation to data standards and availability. It has been reported to be difficult to obtain the required datasets for modelling risk in some lower income countries, in which Lloyd's syndicates currently write policies, however these problems may be compounded if Lloyd's targets the Least Developed Countries which house the 'Bottom Billion'. Overall though the nature of risk is changing both in terms of the increase in man-made risk such as Cyber, and the geographic distribution risk.

C.6 Data sources

This section discusses data types and sources currently drawn on by insurers and risk analysts, and highlights a limited number of potential sources for future use. A more extensive listing of sources can be found in C.10.1 Appendix CC.1. Feedback has been obtained on prominent issues surrounding the use of data within the insurance industry, this is captured within a discussion. Open Source Data is prominent theme addressed, and many sources detailed are Open Source; feedback on the use of Open Source data is also included.

C.6.1 Types of data

Through conversations and interviews conducted for this study, a number of datasets were highlighted as being important or of interest for risk evaluations in the insurance industry; a selection of commonly referred to data types are listed below, in Table 24 and detailed in Figure 34. These data types have been grouped in to 13 categories. This is far from an exhaustive schema and only a limited number of classes of business are detailed within this.

The examples serve primarily to demonstrate the wide-ranging data types which are relevant to the insurance industry and acts as a framework which has allowed sources of these data types to be identified and grouped. A number of these data sources have been reviewed within this report; a listing of external data sources is given in Table 25. Details/review of these data sources are presented in C.10.1 Appendix CC.1, alongside additional sources of data for each category.

Table 24: Data Types

Category	Types of Data
Maritime	• Collision avoidance reports • History of vessels - insured and uninsured losses - if previous owners have run high deductibles • Vessel traffic in ports • Data on new shipping lanes -including charts • Data detailing high risk ocean areas -terrorism, piracy • Data on offshore operations -Oil and Gas, renewables • Vessel Financial data - arrests - payment of yard fees • Customs data - numbers through ports (such as Dover) - how many checked • Indicators used to inspect containers?
Aviation	• Aeronautical and flight data • Airport flight traffic • Reporting of incidents/near misses
Environmental	• Environmental risks • Fire accumulation, wildfires • General information on local environments • Records of contamination and pollution events • Threats to natural resources • Land use change • Tree data • Air Quality
Flooding	• Flooding records, predictions. • Flood risk exposure • Flood defences • Flood costs
Geological	• Earthquakes, subsidence, landslides • Geological stability of urban areas
Weather	• Archive climate data (claims assessment) • Records of CAT events • Predictions
Satellite Earth Observation	• Satellite feeds for claims

	• Derived products -change detection • Archive data
Cadastral/location Data/Topographic Data	• Accurate updated digital maps • Geocoding data • building footprints • Terrain data • Roads, rail, infrastructure • Boundary datasets

Corporate	• Audit data from clients
	• History of companies
	    - Distribution of company assets
	    - Value of business
	    - Criminality
	• Commercial properties
	• Lines of business
	• Supply Chains

Insurance Specific	• Loss Data • Exposure data • CAT models • Modelling inputs from clients: - descriptors - location - type of asset - policy considered - 3rd party data
Social/Economic	• Human movements • Crime statistics • Societal data • Integration of supply chains -vulnerability to disruption of business • Demographics
Risk/Hazard	• Political risk & Terrorism incidents • Cyber risk • Threat data • Impacts and damage levels • Indicators of how buildings react to peril intensity - Vulnerability characteristics - Vulnerability classifiers • key infrastructure at risk: roads, rail, ports, water, energy, telecoms, undersea structures
National/International	• National government Open Source data portals • International sources of information

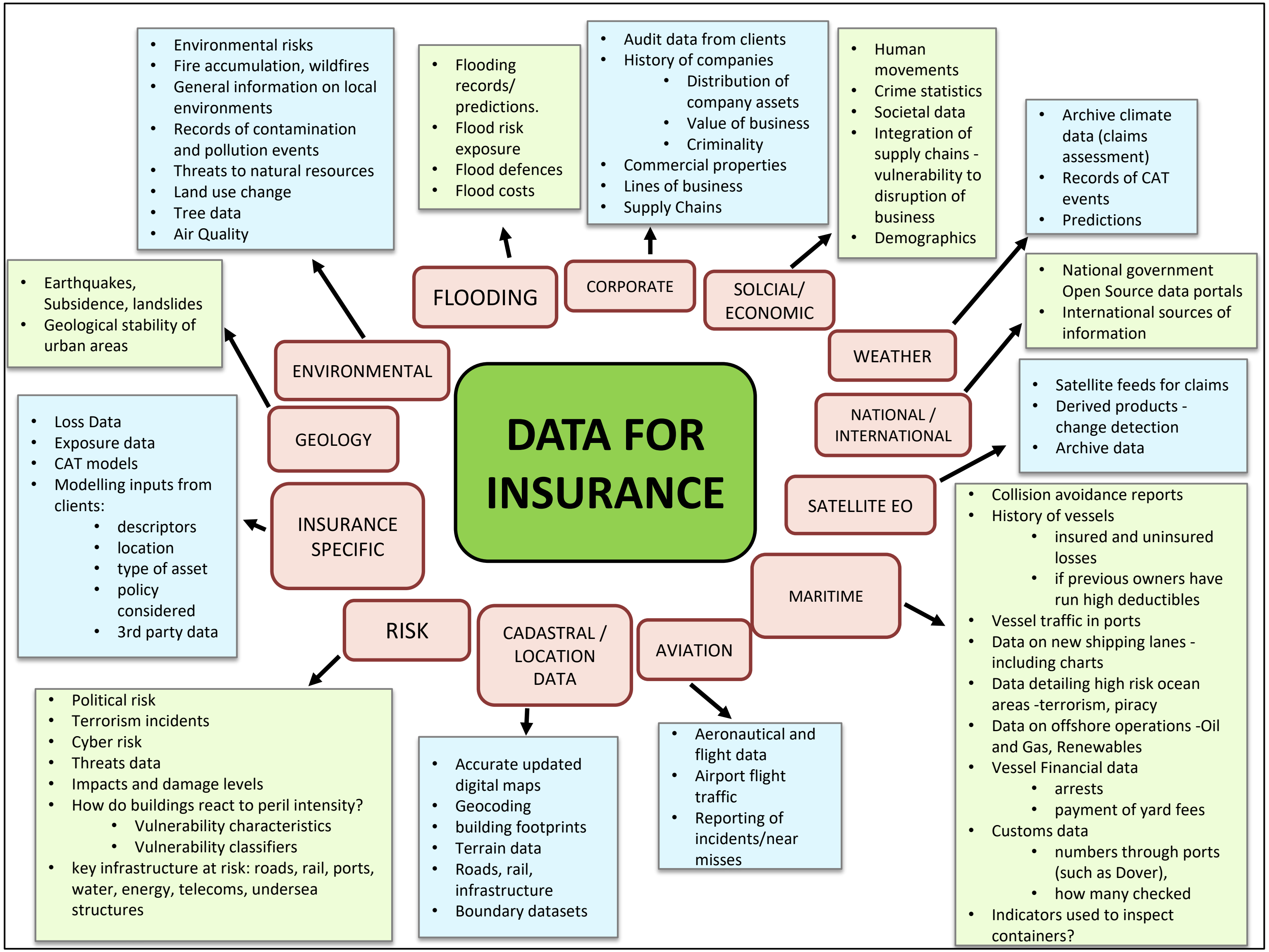

Figure 34: Data Types Diagram

C.6.2 External data sources

Examples of data sources addressing the 13 themes listed in Table 24 and Figure 34 are detailed in Table 25 below. These are both Open Source and proprietary data sources, which range from raw data, to derived data with a substantial value-added component. A description of each of these data sources is provided in C.10.1 Appendix CC.1. Appendix CC.1 also provides a more comprehensive listing of additional sources for each category. Data sources outlined in this report are a mix between Open Source and paid services. Emphasis was placed on seeking out examples of Open Source data, where available. Each data source in Table 25 is detailed as being either Open Source (O), a closed paid service (C), or a combination of both (O/C).

Table 25: External Data Sources

Open/Closed	Source	Description
Maritime		
C	Sea-Web (https://ihsmarkit.com/products/sea-web-maritime-reference.html)	Maritime datasets and intelligence
O/C	Marine Traffic https://www.marinetraffic.com	AIS vessel data
O	USCE National Coast Watch UK https://www.nci.org.uk/	Records of maritime incidents for the UK
O	US Army core of engineers (USCE): US Waterways Data: http://www.navigationdatacenter.us/	The U.S. Waterway Data is a collection of data related to the navigable waters in the United States
O	NOAA NCEI https://maps.ngdc.noaa.gov/viewers/bathymetry/	Bathymetric database global
O/C	IMB –Piracy data https://www.icc-ccs.org/index.php/piracy-reporting-centre/live-piracy-map	Piracy incident reporting
Aviation		
O	Open AIP https://www.openaip.net	Worldwide aviation database
Environmental		
C	Bluesky- https://www.blueskymapshop.com/products/national-tree-map	National tree map UK

O	NERC http://www.nerc.ac.uk/research/sites/data/	National Environmental Research Centre UK. 7 Databases Environmental monitoring and science
C	Skytruth https://www.skytruth.org/what-we-do/roles/	SkyTruth use Earth Observation data to identify and monitor threats to natural resources
O	World Air Quality Index http://Aqicn.org	Global air pollution data
Environmental: Flooding		
C	Middlesex multi-coloured manual https://www.mcm-online.co.uk/	Flood Impact damage Costs
O	Shoothill: Check my flood risk http://www.checkmyfloodrisk.co.uk	UK Flood risk
O	Shoothill: Gaugemap http://www.gaugemap.co.uk	River gauge data UK
Geological		
O	USGS https://data.usgs.gov/datacatalog/#fq=dataType%3A(collection%20OR%20non-collection)&q=*%3A*	Real-time events: Weather, GIS, Wildfire, Flood and Earthquake. Being used as real-time risk overlay and data stored for historical analysis
O	USGS Advanced National Seismic System ANSS https://earthquake.usgs.gov/data/comcat/	Contains earthquake source parameters (e.g. hypocentres, magnitudes, phase picks and amplitudes) and other products
C	BGS UK Geosure http://www.bgs.ac.uk/products/geohazards/geosureInsurance.html	Insurance related Geological data products
C	Cranfield University - http://www.landis.org.uk/npd_insurance/	Modelling outputs of subsidence and six other geohazards for the UK
Weather Data		
C	Weather Analytics https://www.weatheranalytics.com/industries/insurance/	Threat information related to weather events
C	Weather Net https://www.weathernet.co.uk/	Post coded weather information for claims verification
Satellite Earth Observation Data		
C	Tcarta https://www.tcarta.com/products-and-services	Satellite derived bathymetry, topgraphic bathymetry, habitat mapping, vector shorelines
Cadastral/location Data/Topographic Data		

O	Natural Earth http://www.naturalearthdata.com	Global map datasets
C	Address cloud - https://addresscloud.com/#/?_k=4w1y6j	Detailed location information from address matching
C	Pitney Bowse: https://www.pitneybowes.com/uk	Location Analytic
O/C	Ordnance Survey (OS) UK https://www.ordnancesurvey.co.uk/business-and-government/products/opendata.html	A set of free digital maps of Great Britain, including higher resolution services such as building outline data
C	OS Mastermap https://www.ordnancesurvey.co.uk/business-and-government/products/mastermap-products.html	OS Detailed maps, including change detection provided at a household level
C	Geoplan https://www.geoplan.com/product/data/index.html	Postcode data -including boundaries (global)
Corporate		
O	Open Corporates https://opencorporates.com	Relationships between branches of companies in different countries - reveal where majority of business is located Facebook of companies
C	Dun and Bradstreet http://www.dnb.com/about-us/our-data/data-depth-and-breadth.html	Corporate Database of companies
Insurance Specific		
C	Perils https://www.perils.org	Insurance industry exposure and loss database
O/C	Oasis Hub https://oasishub.co	Open Source data inputs for insurance analysis –data cleaned and structured
C	ImageCat http://www.imagecatinc.com/	Insurance related Exposure, Hazard and disaster damage data
Risk/Hazard Data		
O	Global risk map http://globalriskmap.nicta.com.au	Global natural disasters and impacts, insurance penetration and density
O	Lloyd’s City Risk index https://www.lloyds.com/cityriskindex/	Predicted potential impact on the economic output of 301 of the world’s major cities from 18 manmade and natural threats.
National/International Open Source Portals		

O	USA Government Open Data https://www.data.gov/	Includes data and tools, census data, climate data, agriculture, consumers, ecosystems, education energy, finance, health, local government, manufacturing, maritime, ocean, public safety, and science and research.

C.6.3 Internal insurance industry data

The main type of internal data referred to, by those spoken with for this research, is claims data. Claims data is restricted, and not always shared across a market. Claims data varies in resolution by country. It can be used for predicting claims frequency and loss. This can prove additionally useful if claims data is pooled across lines of business or at a market level such as Lloyd's. Exposure data can also be classed as internal data, yet it is typically derived from clients. For property cover, exposure data can include: location, building, building type, construction type, year built. Exposure data can prove problematic, in that it can differ widely depending on source. It can be difficult to determine if exposure data is accurate, as it can be vague, incomplete or not presented in a usable form. Another form of internal data is termed policy insights, this can detail factors such as premiums, cancellations and gaps in cover. Problem have been reported by data analytics firms, when trying to obtain data from insurance companies. This can relate to both internal and market data. On the claims side, varying levels of information is available. Loss adjusters have been looked to for supplying claims data, such as Crawfords[38] and Cunningham Lyndsey[39]. The Association of British Insurers holds industry data, yet the quality of this has been questioned.

C.6.4 Discussion

As mentioned above for internal data, there are problems with data supplied to insurers from clients and claims data is usually restricted to insurers and not readily shared. The real value derived from this internal data is said to be when it is combined with other sources. A key challenge is how to make it available at the point of impact. No value is derived from holding data which cannot be drawn on when needed, this can result in the data providing 'DRIP' support - Data Rich Insight Poor. To avoid this, knowledge of data sources is needed. It is easy to underestimate the difficulty of working with insurance related data. First of all, it is essential to focus on data inputs, and to transform the data into a format which can be readily worked with. This is a mundane yet essential task, which companies can complete internally. If this step is bypassed a situation of 'garbage in - garbage out' can prevail. Data drawn on varies by peril under consideration; in some cases this can necessitate seeking those with specific scientific or technical background to interpret the data.

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[38] http://uk.crawfordandcompany.com/
[39] https://www.cunninghamlindsey.com/global/.

Many of the data sources detailed in Table 25 and C.10.1 Appendix CC.1 come with a substantial price tag. There are ongoing discussions, between data providers and organisations such as the Open Data Institute (ODI) in the UK, over which derived data should be made available for free, a topic which is expanded upon below. There are many ways of obtaining data; Open Source data can be downloaded free of charge, whilst proprietary data can be downloaded if a subscription is bought or one-off payment is made. Otherwise data can also be scraped from web sources. A number of insurers and analytics companies are obtaining data through scraping sites. Data scraped on a daily basis, has been shown to provide information on sanctions, regulatory environments, negotiations, the compliance side, bribery, and corruption. This can draw on hash tags and geotags and even involve scraping social media feeds for information related to hazards such as floods. It is also possible to embed data feeds from external website into a user interface or webpage. This is a common method for many analytics firms to provide underwriters with data. Some simple data feeds being drawn on (in real-time) by those operating in the Lloyd's market include exchange rates and market data (taken from sources such as Bloomberg).

Scrutiny of data sources is important. When drawing on multiple data sources the work required to process these extends beyond shifting data into the correct format to more comprehensive reviewing of data sources and in some cases calibration and QA of the data used. Many UK insurers and analyst are said to struggle with local authorities not providing them with information they need. Builders also have been highlighted as not wanting to share information, with those such as flood modelling companies. Yet this information is important, especially when used in response to catastrophe events, where environmental data drawn on from sources such as NOAA needs to be merged with information about buildings, and other factors, to produce loss estimates. Nevertheless, access to some data sources such as address information, which is currently sold at high prices, will be relaxed in the future, according to a source interviewed. Geospatial data is an important source for the insurance industry. Determining the accurate geographic locations of risk is regarded crucial by insurers, this is said to hinge on the ability to Geocode correctly, especially for accumulation calculations, for which an accurately geocoded source of data, such that relating to buildings, is deemed essential.

Geospatial data is especially important for claims relating to flooding. Within the UK, the Environment Agency make a number of flood maps available Open Source, in the form of shape files, or web feeds. The Risk of Flooding from Rivers and Seas (RFRS), has been named by flood modellers as a particularly useful input. However, problems are encountered when trying to locate flood data for other countries. Whilst the UK has 5m resolution flood data, from which depth of water can be estimated (and reliable sources are also available for the US), attempting to source data for Africa and Eastern European states is reported to be difficult. For the UK, the Environment Agency also recently released more extensive defence data in 2017 (E.g. 1/5 year defences). However, this data is not regarded as problem free. The EA flood defence data is not deemed complete by some flood modellers. There is also a problem with the EA not being property specific in their data.

Generally, many challenges have been reported when trying to obtain datasets for a wider range of countries. In particular Israel is nation for which data can be problematic to obtain. Other states, such as the USA, who provide an extensive variety of Open Source and proprietary datasets, may fall down in certain areas such as provision of geological data, where experts in geology who compile the datasets may not adequately consider how clients want to use data. This is a common problem though for scientific datasets made available in many countries, where some government sources are said to churn out maps that are not usable, due to problems with complexity. Another factor which has been reported to present a barrier to utilising international datasets is language, this can necessitate additional time and resources being devoted to processing data inputs.

C.6.5 Open Source data

A variety of opinions on the use and value of Open Data were encountered from those interviewed for this report. Open Source data can be viewed in terms of the possibilities it presents for data reuse, that is data collected for one purpose, yet made freely available to use for another. Many regard Open Source data as beneficial to their work, this can be due to funding limitations, which necessitate the use of free data wherever possible. Others believe that not only data should be available Open Source, but also methods, as the available data may not always be the specific type needed. One true evangelist, stated that Open Data 'should be at the core of the data types available around the world, as it enables further innovation, with it being not just a public good, but a public requirement'. In relation to the insurance industry some believe that certain basic forms of insurance data should be made Open Source. And to enable this, incentives should be offered from, say, an underwriter's point of view. This could enable a point to be reached in the future, where everyone is sharing data, so this becomes the norm, and potentially those who don't share are penalised. Others have taken a more measured view and stated that only certain types of industry data, such as cyber breaches should be made available free.

In contrast to some of these positive sentiments, many challenges have been highlighted also. When looking at data from a range of countries, there can be issues relating to data source and reliability. The level of data provided Open Source, and associated standards can vary significantly depending on government funding. In some instances, the use of Open Source data can actually involve higher costs internally, than drawing on well calibrated regulated sources. This can be due to the data not being as complete, it being messy, and lacking consistency. In many instances, the user is said to have no idea of these issues until the data has been downloaded. So, to obtain something of adequate quality, and completeness, a lot of time may need to be devoted to searching. In many parts of Europe and other locations, only limited data is freely available. In the USA there are a plethora of sources of open data but, reservations have been expressed over the quality of this data and there being a lack of associated metadata provided. Insurers are said to require a greater appreciation of what they are using, so in this sense (where metadata is lacking), many Open Sources are unsuitable. Additionally, many insurers don't have the resources to deal with the complexity of some of the open data outputs. Yet some analytics firms overcome this hurdle by outsourcing data processing tasks to lower income countries. To add to these challenges non-public sector organisations are reported as slow to open up their data or just fail to make any data available for free. This can be due to issues such as the need to recoup costs of data collection.

Despite reservations on the use of Open Source data, there are a large number of Open Data sources now available, and this is increasing daily. For example, in the USA there is much data available which can be used by insurers, such as data relating to wind, hail, fire, and crime. The UK is seen to be improving, especially in relation to datasets made available by the Environment Agency, who have for example, a detailed mapping program in place, involving the collection of Lidar data, which is freely disseminated. This can be used to look at building footprints and floods. A wide range of global Open Data portals can be viewed on the Spatial Reserves website[40], in which over 3,600 sources in total are listed. Appendix CC.2 (C.10.2) contains a listing of various Open Data Portals for the UK and beyond.

C.6.6 Advanced data sources - IoT

The Internet of Things (IoT) has been mentioned earlier in this report. The technology is being adopted widely to support risk analysis in the insurance industry. Vast sensor networks generating real-time data streams can enable processes to be monitored in real-time. For example in running a gas terminal, many client have access to real-time data being fed back to them. This can be taken as a credit to the client, but insurers have not had real-time access to this sort of data in the past. In fact, insurers do not require real-time access to the data, as the data needs to be managed by a third party and identified against a model, yet the outputs could be hugely advantageous to the insurance industry. The sort of information being generated does not just relate to data for individual machines. For example when drilling a complex well real-time data can be fed back due to innovations in sensor technology, this enables risks to be flag sooner. Nevertheless, there are barriers to IoT being taken up readily, this can relate to costs of the sensor technology being implemented; this is a less significant factor when considering satellite data, which will be discussed in more length in Section C.8.2.

C.7 In-use, insurance specific company supplied analysis

Interviews have been conducted with a wide range of representatives from companies involved in modelling and insurance specific data analytics. Table 26 below includes the names of firms questioned for this report and other associated companies who supply similar forms of analytics. These are grouped by the main area in which they work. Notes taken during meetings with these firms are presented in C.10.2 Appendix CC.2, this includes feedback on sources of data they are drawing on and data innovations being implemented. Appendix CC.2 (C.10.2) also includes a short overview of the other companies detailed who complete work related to each specific areas of data analytics listed.

[40] https://spatialreserves.wordpress.com/2017/10/22/a-one-stop-shop-list-of-all-open-data-portals-around-the-world/

Table 26: Data Analytics Companies

#	Company Name	Description
Catastrophe (CAT) Modellers		
1	RMS	CAT
2	Guy Carpenter	CAT and other
3	AIR Verisk	Geospatial analysis, CAT
4	Validus group	Wide ranging, including CAT, supply Talbot
5	Oasis Loss Modelling Framework	CAT
6	AON Benfield	CAT and other services
7	CATRisk Solutions	CAT
8	KAT Risk	CAT
Wider Services –Underwriting, Portfolio Management, Multiple Classes of Business		
9	LexisNexis	Portfolio, quote, underwriting, Claims
10	Urban Stat	Underwriting –full suite
11	Europa technologies	Assessing risk across a portfolio
12	Russel Group Alps connected risk	Multiple classes of business: aviation, offshore energy etc.
13	Business Insight	Analysis across classes of business
14	Cytora	Wide ranging, AI, using internal and external data.
Geospatial Threat Analysis		
15	Spatial key	Geospatial, war, terrorism
16	Global Earthquake Model: Open Quake	Earth Quake
Flood		
17	JBA	Flood
18	GeoSmart	Flood, ground water
19	Ambiental	Flood
Property		
20	Core logic	Property and casualty insurance risk
21	Geodata	GIS –Property risk
Cyber		
22	Cyenes	Cyber risk
Maritime		
23	Right Ship	Maritime, environment

Evaluation of analysis currently being undertaken

A short discussion is now presented based on feedback received from interviews with representatives of the analytics firms detailed in Table 26 and C.10.2 Appendix CC.2. Those spoken with have provided details of methods, data and technology they are working with, mention is also given to techniques used by other similar firms, also listed in Table 26, who were not spoken with directly. More extensive details for each firm listed in Table 26 can be found in Appendix CC.2 (C.10.2).

It is common for analytics firms to acknowledge the requirement to draw on and fuse data from different sources. RMS state that the data underlying their models is multidisciplinary, with multiple lines of business being represented in their data schema. This can allow insurance to gain a holistic view of risk across lines of business. In drawing on so many types and sources of data RMS have highlighted that new standards for data capture can be required. In dealing with data with different standards, many such as Windward undertake extensive data cleaning of the various sources they draw on. For Windward these sources include AIS, EO and IoT data. These data feeds can provide information in real-time, this is increasingly being drawn on in models, such as those provided by UrbanStat. EO data is emerging as a valuable source of information for insurers but has not been drawn on by many modelling firms, such as JBA, up to now. Many geospatial analytics firms such as Geodata (Norway) are actively engaged in seeking out new sources of publicly available data including satellite imagery, LIDAR data, and private drone footage, which is deemed useful in many scenarios. For the UK, publicly available data such as that made available by British Geological Survey (BGS) and comparable organisations, are drawn on by many modellers, including GeoSmart.

Given the wide range of data sources and types which firms are now drawing on, data aggregation becomes important. This is a goal of LexisNexis, who build databases from insurers internal data in addition to leveraging Open Source data. Europa Technologies also focus on aggregated exposure across a company’s book of business. Galytix is a company (mentioned in Section C.8.1) who is currently engaged in developing a solution for bringing together both insurer’s data and external sources, harmonising data standards in doing this. SpatialKey is another firm who is fusing internal and external data sources with the aim of deriving fresh insight. It has been noted however, that when drawing together disparate data sources it is necessary to focus on the granularity of data being considered and compatibility. AIR Verisk, have detailed how they require data at an individual property level for their analysis. Across the analytics firms spoken with, location data stands out being important. Certain firms specialise in this area such as CoreLogic, who host location, building, environment and financial data. Location based analysis is also a prime focus of SpatialKey, who provide exposure management for underwriters.

There are many similarities between the type of analytical methods employed by firms profiled in this report (detailed in Table 26). The analytics is seen to have common goals such as enabling underwriters to screen and price risk, drawing on common loss metrics. Geocoding has been highlighted as especially important in understanding risk, in particular by RMS, LexisNexis, KATrisk and Verisk. The process aids geospatial analysis of risk and is particularly useful for flood risk analysis, such as that carried out by JBA, Geosmart and Ambiental. AIR Verisk highlight geospatial analysis of risk as being a core part of what their work, in which individual locations are focused on for calculation of risk premiums. This can require access to hazard data such as that relating to storm surges, flooding and earthquakes. Understanding the geographic distribution of risk is reported as a particularly important aspect of analysis carried out by the CAT modellers detailed in Table 26. Probabilistic modelling techniques drawing on statistical and mathematical analysis, are used by most firms. Guy Carpenter, for example, takes on and assesses models developed by many firms and refines these and applies them to specific areas. Verisk and others, use their models to look at capital held by insurers in respect of certain perils. These models can be validated using impact analyses. Economic capital models can also be drawn on when looking at portfolio optimisation, AON Benfield are one company who use this approach. Economic impact is a consideration of the solution developed by Cyence which focuses specifically on cyber risk. Many companies focus on analysis across an insurer's portfolio of business, such as the Russel Group in their Alps platform, as do Galytix. Companies are also increasingly drawing on advanced techniques, for example RMS report using Computer Vision to detect damage to an area post event, whilst UrbanStat are attempting to improve the underwriting process by applying machine learning to claim prediction, renewals and accumulation reporting.

Open Source tools are being made available by a number of firms. Oasis Loss Modelling Framework is one such company, who provide a CAT modelling software platform, which draws on probabilistic methods such as Monto Carlo simulations, reporting hazard intensities, exposure and probabilities of loss at specific locations. Another Open Source software, concentrating on one specific hazard, is GEM's Open Quake, which focuses on earthquake hazard. More general Open Source software is also being used by firms, including Galytix and Windward who are using MongoDB, which is a NoSQL document-oriented database. LexisNexis have also developed 'HPCC Systems', an Open Source Big Data analytics platform. Lexis draw primarily on the own technology, using many Scalable Automated Linking Technologies (SALT), which can involve statistical based, linking technologies drawing on probabilistic functions (e.g. specific density).

An increasing number of firms are looking to the Cloud to host and deliver their solutions. The Russel Group provide Alps Remote a Cloud based risk management software, modelling connected risk across multiple classes of business. Windward similarly operate a Cloud based system hosted in AWS. AWS is also used by Geodata in many of the GIS solutions they operate which draw on automation possible in a Cloud environment, to enable high resolution geospatial data to be accessed in real-time via web mapping interfaces. The Cloud has not been adopted by all though and many such as JBA use their internal data centres to host modelling data, and LexisNexis currently use a conventional data warehouse, but are looking to migrate this to the Cloud. GIS is a software tool widely used by many insurance analytics firms concerned with geospatial data, including LexisNexis, Europa Technologies, and AIR Verisk who use Touchstone software integrated with ESRI ArcGIS, and Geodata who are a distributor of ESRI products. Geodata use GIS to generate property risk profiles based on spatial attributes. In their analysis they draw on multiple kinds of EO data such as multispectral and satellite radar imagery (further discussion of EO data in Section C.8.2) to assess impacts of flood and fire events.

In relation to distribution and visualisation of analytical outputs, companies can commonly provide their outputs as feeds or in the form of Graphical User Interfaces (GUI). Software as a Service (SaaS) is increasing in popularity as a delivery mechanism for risk analytics. This can allow firms to run analytics solutions in web browsers. SaaS is being drawn on, for example, by Windward, Europa Technologies, RightShip, and LexisNexis in their Map View product. The SaaS option allows providers to implement updates, and bypasses compatibility requirement for integrating their solutions, with insurer's IT systems. Numerous analytics firms, such as RMS, SpatialKey, Oasis, Windward and Ambiental provide insurers with API feeds so that analytical outputs can be incorporated in to existing dashboards.

C.8 Prospective solutions

Technological developments and innovations in the use of data present a sea of opportunities to the insurance industry. Many of these innovations are being adopted by the organisation that provided input to this report, detailed in Table 23. In this respect, market level initiatives such as Lloyd's are well placed to partner with innovators who have already acquired knowledge and experience relating to application of valuable techniques to improve how data is utilised within the insurance industry. A number of companies have already engaged with Lloyd's over the last year, in such endeavours. These have been termed Proof of Concepts (POC) and have involved not only Lloyd's staff, but a selection of representatives from Lloyd's syndicates. Some of the recent POCs are detailed below. Following this. Within this section, there follows a discussion of how Satellite EO data can be used in the insurance industry. A range of practitioners drawn from this industry have been interviewed for this study. Some of the companies profiled are operating at the forefront of this domain. Comments received have fed into the discussion presented below. Notes from the associated meetings/interviews are also provided in C.10.3 Appendix CC.3. A comparison is presented in Table 28, which highlights the benefits and limitations of the solutions provided by each organisation profiled. In addition to looking at how EO data can be used, a number of meetings have been conducted with organisation supplying Big Data analytics and software. Notes from these meetings are provided in C.10.4 Appendix CC.4 and a short discussion of some of the main points is presented Section C.8.3.

C.8.1 Disruptive technologies – Proof of Concepts at Lloyd's 2017-2018

Marine POC Windward

A marine POC has been undertaken, working with the Israeli company Windward, this has involved development of a web-based interface for tracking fleets of vessel in real-time. More details are provided about this proof of concept in notes related to Windward in C.10.2 Appendix CC.2.

Galytix

An ongoing proof of concept is underway in which the company Galytix is developing a system for drawing together external data sources. Again, more details are provided of this POC in C.10.2 Appendix CC.2.

NLP (LITA)
Natural Language Processing (NLP) for Lloyd's International Trading and Advice (LITA). This POC looked at how NLP could be used to assist in the evaluation of risk and policy valuation, to deal with unstructured text, enabling performance to be improved, such as the speed of services delivered to the market, and reducing time for teams to answer questions. NLP can answer questions quicker than an individual. Limitations were imposed on the solution by how messy the input data was. The output from the POC, was shown to save time, and was due to be introduced in February 2018. Lloyd's is also currently looking at how this NLP technology can be applied in other areas, such as tax.

Claims Insight –Unstructured-
This POC focuses on Cargo trains. Records for looking at trains is poor and involves a lot of unstructured data. There is a requirement for inside knowledge to deal with this information. This project looks at running AI over data to look for trends. Data quality is reported to have imposed barrier on the success of this project.

Property Data - Verisk
The POC involves using additional data items now being collected by Verisk, for example by drones, and using AI technology to understand information contained within the data, such as tiles on a roof, pitch, height, condition and other factors. When added to traditional datasets, the information can be used in the market. The POC is looking at how this can alter underwriting behaviour, choice of risk, and underwriting models. 8 managing agents are taking part. Lloyd's also plays a central role in this, in purchasing data on behalf of managing agents who currently buy it individually (which may be inefficient).

IoT Sensors for cargo tracking
The POC involves a plan to send out 20 packages, then track these using IoT enabled sensors. The robustness of the sensors will be tested, cost of sensors reviewed, and efforts made to determine which data items it is possible to send back.

Energy and Insurance
This involves an idea similar to that used in the cargo tracking POC. Plentiful asset data is available at a granular level. This can provide insurers with the ability obtain data about a power plant (for example) and the way it operates. The POC hopes to generate improvements in data processing and risk assessments.

C.8.2 Satellite earth observation data

No current proof of concept is operating within Lloyd's Data Lab that is focused primarily on the use of Earth Observation (EO) Satellite Data. However, the LMA have recently been working with McKenzie Intelligence Service (MIS) on a number of initiatives. And there are other firms such as Geospatial Insight that have some market penetration. Further initiatives are on the horizon, which could build on rapid developments currently being made in this domain. Over the last 10 years the cost of satellite technology has reduced significantly, as such many opportunities are arising to draw on the data products created by a new generation of satellites. This is made easier in the current era where there is widespread familiarity, among the public, with web-mapping products such as Google Maps. Through web-mapping interfaces it is possible to leverage vast volumes of data. Through feedback gained from insurance practitioners during this study, there appears to be an appetite within the industry to draw on EO data to reduce costs and enable mapping over wider areas.

Earth Observation missions now have the ability to generate repeat coverage of the globe daily. This is even being achieved using low cost miniaturised satellites, by companies such as Planet, using its Dove, medium resolution satellites. Higher resolution satellite EO data is now approaching airborne LIDAR, with the added benefit over LIDAR of repeat imagery, for vast spatial extents. In the past EO data was plagued by problems such as imprecision, yet now this has been overcome and there are a wide range of options that can be drawn on, such as multispectral imagery: infrared, thermal visible and microwave imagery. Infrared EO data deals with problems related to cloud cover and infrared missions can generate an image for the same location every 6 days. Microwave and SAR also bypass the cloud cover issue, with the European Space Agency's (ESA) Sentinel 1 providing free and consistent SAR data for Europe (Open Source outputs generated by the ESA's Copernicus program are detailed in Appedix A). It is not possible to fit SAR on the new generation of small satellites (e.g. CubeSat) though. SAR data is being applied to the field of maritime monitoring, this is because boats appear as easily distinguishable bright pixels in SAR imagery. SAR can encounter problems in some instances though, such as when obtaining images where rough sea conditions are present. Satellites are also being looked on as IoT devices, which can be called on automatically by devices. Automation in the processing of EO data is resulting in huge reductions in the man hours which need to be spent working with raw EO data. And easily accessible user interfaces, such as Google Earth Engine, can enable satellite images from different sources to be mixed as required (without cost).

For the insurance industry satellites can be used as a remote validation tool to contribute to audit trails and take the place of site visits. One benefit of this is that Earth Observation data is impartial and unbiased and just reveals what is on the ground. EO data can be used to embellish work, making reports easier to understand. Within Lloyd's, claims teams have been drawing on EO data following a spate of recent hurricanes in the Caribbean and the USA, to assess damage. Satellite data is also used extensively for assessing flood extents in near real-time for live events. Radar is particularly suited to scientific measurements, especially of floods. Satellite radar missions are expensive to book, but lower cost flights are becoming available. Another example can be seen in the use of EO data in conjunction with automated processes. For instance, in relation to health insurance, air quality can be assessed indirectly method through counting cars. In relation to IoT, satellite can be brought into automatically monitor oil pipelines. A loss in pressure in a pipeline can trigger a satellite image to be captured. This is a good example of a future vision for the industry and how rapid the pace of change is. If insurers know of high risk areas, which need monitoring they can commission missions to capture detailed satellite imagery in advance. The use of Interferometry has also been advancing rapidly. The technology can be used, for example, to look at areas with mining activity and tunnelling, as it is possible to distinguish subsidence when mines are left and also uplift when land swells again; it can also be used to view earthquakes, with cm changes in land height being detected. Other emerging areas such as the use of Stereo techniques, are being used by DigitalGlobe and Terrabotics, to generate 3D images from satellite data, and can be used to look at steep slopes.

Satellite imagery was utilised by Lloyd's to monitor the devastation reaped by recent hurricanes Harvey and Irma[41]. MIS was used for this. Feedback received from the market indicated that this was useful, however one drawback was the inability to obtain images in conditions of extensive cloud cover. This posed a problem for use of the data in the hurricane response efforts that were provided in first 24 hours, and impacted the ability to use the data to make assessments on exposure. Notwithstanding this, many insurers have shown interest in using EO data in the future. Both image and radar data (in particular) are shown to provide insurers with a wide range of possibilities, this can involve using just the raw data or applying automatic classification to predict future events. However up to now, the insurance industry has proved slow in adopting EO data and derived products. Yet underwriters frequently draw on images presented in Google Earth. This is undoubtedly a useful resource, but Google Earth images can be 3-4 years out of date. For high risk areas where insurance cover is provided, it may be a prudent move in the future, for insurers to consider commissioning EO monitoring programs focussing on these specific locations. Data is generated on a daily basis for most areas of the globe in medium resolution. However, for more detailed analysis one cannot assume that a satellite data provider would have collected data for the area of interest. A wide range of options now exist in the EO data market, this can relate to detailed products from well-established commercial providers to lower resolution alternatives from newer entrants to the industry. Essentially, in establishing which source to use insurers need to evaluate their data and information requirements.

C.8.2.1 Satellite Data and Analytics Providers

Input was gained from each of the providers listed in the Table 27, during meetings and interviews. This is presented in C.10.3 Appendix CC.3.

Table 27: EO Data and analytics Suppliers

#	Company Name	Description
	Owner/Operators of Satellite Hardware	
1	Planet	Operator of miniaturised satellites, Flock CubeSats -Doves-, and RapidEye and Skysat. Partner with external organisations to provide analytics
2	Earthi	Operates satellites: DMC3/TripleSat Constellation and the KOMPSAT series. Supplies analytical products
3	DigitalGlobe	Largest commercial satellite data provider. Operate a range of satellites (EarlyBird-1, IKONOS, QuickBird, GeoEye-1, WorldView with up to 0.3m resolution. Partners with external organisations to supply analytics.
	Insurance Specific EO data service	
4	Geospatial Insight	Collects remote sensing data, which is combined with EO Data in analytical products

[41] http://www.lmalloyds.com/LMA/News/Blog/Claims_Imagery___Intelligence_Service_-_4_September_2017.aspx

5	McKenzie Intelligence Solutions	Analysis of EO image data, which is combined with IoT data feeds and video
Wider Earth Observation Data Analytics		
6	Harris	Host ENVI geoprocessing infrastructure for analysis of EO data
7	Pixalytics	EO data and remote sensing company, work with a range of satellite derived products
8	Terrabotics	EO data analytics company, host large quantities of data in the Cloud, specialist products in altimetry
9	Sensonomic	Use EO data combined with ground-based data sources, in an Agent based modelling process to derive insight about natural capital and agriculture

Table 27 above does not provide an exhaustive list of the firms working in this domain however, these firms were focused on as they are either already supplying data and analytics to the insurance sector or are producing outputs that have been identified as relevant. The services and outputs of each firm differ; to provide a means to gain a better understanding of how they could potentially be utilised by insurers a comparison is provided in Table 28. More extensive details are given in C.10.3 Appendix CC.3 of technological methods being used, and of potential use cases identified by these organisations. However, the comparison in Table 28 can provide a starting point for realising how these technologies can be drawn on in the future.

Table 28: Comparison of EO data/analytics providers

Company	Benefits	Limitations	Technology	Use Cases highlighted
Planet	• Own Satellites • Coverage of globe daily, 3-5m resolution. • Application developer program where companies can access data at a fraction of the cost (5%) • Can task a satellite to collect higher resolution images - only problem cloud cover. • Provide a global API that can allow image delivery within 10 minutes for locations dating back to 2009 • Comparatively low price	Only providing the data, not analytics Medium res. limitations for looking at individual buildings. Only visible imagery provided, Problem cloud cover.	• Nano Satellites • Medium res. 3-5m visual imagery. • Skysat higher res. 0.8m (sub weekly) • Panchromatic • Pansharpened multispectral • Video • Night imaging • Off-nadir imaging • Stereo imaging	• Automatic change detection • System for monitoring particular assets, system to look at changes, can send alerts. • Agriculture their biggest market, look at crop yields • Counting cars stored in docks. • Monitoring of oil and gas storage tanks -how much volume. • Application for pricing of development (construction) insurance. Repeat daily imagery can allow equipment to be brought on site just in time.
Earthi	• Own Satellites • 5m data subscription • Can provide 1m or better, using	Limited analytical capability Only recently own satellites,	• Prototype • Video satellite - 3D imagery • Working with partners on machine learning	• Can provide shadows of containers in port to calculate the height of containers stacked • Can monitor vehicles to see if vehicles are moving, monitor activity -used for disaster scenarios

	capability to task satellites • Capability to supply SAR data, infrared • Lower price options	limited constellation/coverage	**DMC3/TripleSat Constellation** • 1m, 80cm pixel size • Multispectral RGB, near infrared and panchromatic **KOMPSAT** • Optical: 40cm -1m • SAR – 85cm **Vivid-i Constellation (in development)** • 60cm, 1m GSD & full motion, full colour video	• Catastrophic event data -supplied loss adjusters imagery between hurricanes Irma and Maria - check damage, so place loss appropriately • Provide evidence related to natural disasters CAT Modelling • New construction of power plant -can enable insurers to give better costed proposal. If 80% of high value items not on site until the build, risk reduced. • For an incident at an airport can realise how many planes are affected
DigitalGlobe	• Own Satellites • The largest commercial provider of satellite data • DG Imagery and derived solutions have been used extensively in the mapping, monitoring and analysis of events for more than a decade. • Highest spatial resolution and spectral capabilities available in the	Entry price point is higher - currently using conventional satellites so price point higher. Solutions up to now have been limited to visible wavelengths, but now have access to SAR data (due to being part of	• Provides world imagery, spectral & elevation data • Global archive, on demand – in the Cloud • Machine Learning applied to extract information • Stereo imagery • Cloud Based imagery service • Satellites: EarlyBird-1, IKONOS, QuickBird, GeoEye-1, WorldView series	• Tornado in Oklahoma, sat. imagery revealed destroyed properties to help companies estimate their exposure a few hours from the event • Identified settlement location unknown to local government, over 100,000 km^2 area within hours from the earthquake that occurred in Nepal • Analysis done post the Hurricane Matthew highlighted damaged property in the wake of its path. • Effect of Hurricane Irma on the International Airport in St Martins was revealed • Hold spatial database with building attributes - roof material extraction possible, using machine learning • High-resolution land cover map • Building footprint extraction

	commercial environment • only provider of 30 cm imagery – with an archive going back 16 years. • Platform -GBDX -can be used to develop algorithms -then pull results	Maxar Technologies)		• Automatic extraction of information for assessment of flooding risk or impact (Hurricane Harvey images) • Can identify flooded houses, blocked roads and bridges • Can be used in disaster response and underwriting solutions
Geospatial Insight	• Use a wide range of techniques, combine many data sources • Company has a number of drones • Rapid response drones access distressed properties that conventional teams cannot access • Arrangement with satellite owners for supply of data. Draw on a wide range of satellite data with different price points.	Doesn't own Satellites, new company, shorter track record, technological solutions still being developed.	• Use Big Data, machine learning, remote sensing EO data and LIDAR • Multi variate regression analysis • Use radar enabled satellites and interferometric signatures	• Loss estimation, claims management and loss adjustment • Depth of flood waters - precise damage to properties quantified • Car counting in Brazil, 40,000 in 2 minutes • Car counting data to Guy Carpenter • Big Data -crop yield -infrared and near infrared data for crops in America eventual yield, soil porosity and other details • Cargo vessels in ports -number vessels, cargo containers, amount of coal stored, details of fuel stored • Satellites Data used to compare heights of floating oil drum containers -calculate oil stored in specific place on date • Interferometric capability contributes to assessing the risk of subsidence -can monitor mm changes in land height over years
McKenzie Intelligence Solutions	• Satellite imagery analysis service,	Reliance on visible imagery	• Purpose-built portal to deliver the imagery	• Provides Lloyd's with satellite imagery following major catastrophes: storm, earthquake, flood or fire.

	drawing on military expertise • Provides extent and type of damage at a post code level, can look at individual properties • Draw on a wide variety of data sensors to provide information to supplement EO data	Reliance on analyst interpretation not using automated processes (yet will consider in the future)	alongside other forms of intelligence. • Radar • Google Earth Engine has been used for processing SAR - Sentinel 1 data	• Use radar to reveal the extent of flooding • Use CCTV footage from Houston, so street level damage could be viewed • Maria and Irma, managing agents were able to quickly assess the damage footprints and severity of the storm damage in urban areas • Underwriters were able to establish which storm caused particular damage • Provide tool for exposure management • Work for loss adjusters, creating a database used to model risk • Potential analysis for insurance of Maize crops in South America • Property on/off temperatures -inform underwriters at a property level • Validation of situation on the ground -when claims made • EO data can be used to reveal the scale of damage from wild fires -property burnt or not
Harris	• Developed an advanced Cloud based EO data platform drawing on a wide range of EO data sources, including Airbus/DigitialGlobe • Working with traditional algorithms and Deep	Do not have own data sources. Haven't targeted insurance market because specific products not developed so far	• Use analytics to create solutions that extract information from all types of remotely sensed data. • Developed software ENVI, an advanced hyperspectral image analysis package. • Geospatial services framework -allows to run parallel processing	• Working with partner analytics for flood mapping • Flooding risk run through archive -run a multivariate model • Outcomes of analysis can be used as a trigger in internal systems of underwriters • Use cases can be developed with insurers (examples of existing use cases on website: http://www.harrisgeospatial.com/IndustrySolutions.aspx

	Learning -have a high success rate • Various data options and price points. • Deal with all remote sensing data • ENVI SARScape: processing and analysis of SAR data acquired from all platforms	Limited experience with insurance applications	expandable on multiple instances within AWS Cloud • Deep learning tools used on point cloud data • Software ENVI SARscape for image processing of SAR data • Machine learning	
Pixalytics	• Wide experience of dealing with a range of satellite data products and outputs. • Insurance related baseline product is primarily based on free-to-access Copernicus Sentinel-1 data, so that the cost is not prohibitive • Lower cost solution - small company	Do not have own data sources. Small company more limited capacity Not currently working with techniques such as machine learning Limited experience with insurance applications	• Scientific advice on the use of EO data and services • Scientific R&D in the field of Earth Observation (EO), which includes: collection of remotely sensed data, analysing EO data.	• The Virtual Water Gauge software uses satellite altimetry to determine water heights in estuaries, rivers and lakes, used for analysis of flood risk. • Detection of flood events. • Space for Smarter Government' funded proof of concept project[42] to provide the Environment Agency (UK) with flood mapping capabilities • Happy to work with developing proof of concept ideas into demonstration models and beyond. • Developing new products and services from available satellite data. Identifying, and developing, new methods for in-situ data recording. • Green vegetation mapping can provide an indication of vegetation health, important for both agriculture and contamination mapping, and natural versus unnatural surfaces

[42] (http://www.spaceforsmartergovernment.uk/case-study/pixalytics-optical-and-microwave-extension-for-floodwater-mapping-omef/)

Terrabotics	• Cloud based parallel processing used, cuts processing time down by an order of magnitude • Draw on many open source software where possible (lowering price) • Can rapidly process historical and current data • Rapidly transform volumes of Earth Observation imagery, video & sensor data into actionable terrain intelligence • Training datasets used for improving reliability of algorithms	Do not have own data sources. Limited experience with insurance applications Small company more limited capacity	• Develop & deploy smart proprietary algorithms & analytical services. • Use existing machine learning algorithms, which generate outputs very quickly • Draw on historical data sets -various levels of feature detection • Move away from manual processes using AWS • Deal with and combines new methods, sources and types of EO data • 'Terrain Intelligence Platform, TIP'. Beta version -visual GUI, with data analysis function and FTP download facility. Used to push data out to clients, links with AWS	• Recognise that rapid delivery and object detection are applicable to the insurance market. • Terrabotics -stereo satellite imagery (visible) being used to build terrain datasets sub metre accuracy. Taken from two high resolution images -one looking forward, one back. Used for generating 3D models • have been used for mine monitoring. • Carry out object detection, flood risk analysis
Sensonomic	• Draw on a wide range of EO data sources • Combine data with on the ground	Do not have own data sources. Small company more limited capacity	• Agent based modelling • Machine learning • EO data combined with different sources, • Combine statistics, predictive modelling,	• Agent Based Models can reveal behavioural interactions between autonomous and interrelating individuals and organisations and can generate unexpected answers as to what drives risk exposure.

	intelligence and IoT monitoring outputs • Unique solution using EO data outputs within Agent Based models • Low cost solutions • Solution incorporates human behavioural dimension • User interface supplied as simple SaaS	Limited experience with insurance applications	data mining, financial time series data, and advanced analyses of remote sensing data, to generate insight into natural capital behaviour and risk.	• Can be used to address claims made by insurance objects and specialised insurance companies, and challenge assumptions, based on emergent properties. • SaaS platform enables clients to test effects of new and existing insurance policies • Monitoring for regional, country and local risks across a complex portfolio can be enhanced by the opportunity to make satellite derived insight available in near real-time • Combine internal data with Agent Based Model – draw on internal expertise with NLP • Can combine industry data with EO data, other ground info, data on people and business • Look at disruption of business following CAT or other events • Used in relation to Realistic Disaster Scenarios

C.8.3 Big Data

The term Big Data does not only apply to large data Volumes but also large Varieties and Velocities of data (termed the 3Vs of Big Data). This involves the ability to store, process and analyse structured and unstructured data, combining archive and real-time streaming data (Jagadish, 2015; Marr, 2015). This data is generated from a wide range of sources, these can take the form of more conventional data such as database entries, stored in Relational Database Management Systems (RDBS) or real-time streaming data being generated by IoT sensor networks, satellites, and websites, for example.

Why is Big Data relevant for insurance, do insurance companies generate Big Data or need to draw on the tools and technologies associated with this emerging field? In light of the details presented in earlier sections of this report the answer is deemed to be yes. In attempting to understand how the various fields associated with 'Big Data' can relate to an industry such as insurance, a framework is provided below in Table 29. This breaks aspects of Big Data technology into chronological stages: data capture, storage, processing, knowledge extraction and communication. This characterises the process of data forming the basis of information and ultimately knowledge (Anderson, 1991).

C.8.3.1 A Big Data Framework

Table 29: Big Data Framework

#	Stage	Description
1.	Data Collection	• Wide ranging data sources • The Internet of Things • Role of Satellite EO datasets • Real-time streaming data -the role this can play in hazard alert • Open Source Data
2.	Data Storage	• Distributed Storage and processing of data • Cloud based on demand infrastructure
3.	Infrastructure and automated processing	• Automated processes for data ingestion and collation • analysis of different data types -video, text, audio, point cloud, imagery
4.	Knowledge extraction and analysis	• Advanced geospatial analytics • Machine learning role -identification of change, classification of land use (buildings/infrastructure) • Change detection from high resolution point cloud data and feature detection from EO data

		• The ability to derive meaning from unstructured messy data through NLP and other techniques • The ability to combine real-time streaming data with archive data • Data mining of a wide variety of data types
5.	Visualisation and Communication	• Web based user interfaces • Advanced intuitive dashboards • Augmented Reality

Within this report stage one (of Table 29) is captured in Section C.5 and C.10.1 Appendix CC.1, where various data sources, potentially relevant to risk analysis for insurance, are introduced. Other satellite data sources are also presented in Section 0. Various aspects of stages 2, 3, 4 and 5 are being undertaken by companies outlined in Section C.6. To enable external and internal data related to insurance to be analysed and knowledge extraction to take place (stage 4) it is necessary for data to be stored in an effective way (stage 2) and for automated processing of this data to be completed (stage 3). Technology firms such as those detailed in Table 30 provide infrastructure and software tools that can enable this to be completed. Some of these firms such as Hortonworks and Cloudera base their solutions primarily on software developed by the Apache Software Foundation[43]. This software is Open Source and is the product of the interactions of over 30,000 contributors who commit code to Apache projects. The software tools include Hadoop, MapReduce, Apache Spark, HBase, Hive, MongoDB and many others. The software has been said to form an ecosystem (Marz and Warren, 2015) in which different functions are performed by individual software, relating to distributed storage and processing, data mining, analysis and ultimately knowledge extraction. LexisNexis provide an Open Source alternative to some of the Apache software, in their HPCC Systems[44].

The last category outlined in Table 29, Visualisation and Communication, is a final yet essential step in the Big Data framework presented. Within this report much has been said in relation to communication of data and information outputs to users. Insurers have internal mechanisms/dashboards for making data available to underwriters, actuaries, and brokers. These can draw on visualisation mechanisms provided by external parties (including that provided by some of those detailed in Table 26 and C.10.2 Appendix CC.2). There are many options for communicating information derived from the data to insurers, this warrants an extensive discussion which is beyond the scope of this report. However, Section C.5 of this report has outlined some of the requirements of those using the data, and interview notes are presented in C.10.2 Appendix CC.2 which include feedback from analytics firms spoken with, some of which gives mention to data visualisation and communication mechanisms.

[43] https://www.apache.org
[44] http://hpccsystems.com

C.8.3.2 Big Data Technology and Software Providers

Many of those met with in connection with this report were keen to discuss how advances in the use of Big Data technology may benefit the insurance industry. A number of companies who work more specifically in this area were selected. These are detailed in Table 30 below and notes from meetings with representatives of some of these companies are presented in C.10.4 Appendix CC.4, alongside details of the work undertaken by the firms not spoken with.

Table 30: Big Data Technology Suppliers

#	Company Name	Description
1	Hortonworks	Distributor and contributor of Open Source Big Data Platforms (Apache Software Foundation projects). Provide Hortonworks data platform for management and analytics, which is 100% Open Source. Provides support and training. Focus on distributed processing on large clusters.
2	Cloudera	Distributor and contributor of Open Source Big Data Platforms (Apache Software Foundation projects). Provide enterprise data management and analytics platforms, support and training. Focus on distributed processing on large clusters. Products contain more proprietary content than Hortonworks and have a higher focus on security. This may be reflected in pricing.
3	Teradata	Enterprise software company, providing server and cloud database and data warehouse storage solutions. Provides business analytics and consulting services. Offers Hybrid Cloud and Multi-Cloud options. Provides Aster Big Data solutions.
4	RMS	A CAT risk modelling company, operating solutions in a Cloud environment, drawing on Big Data functionality.
5	LexisNexis	Provider of digital legal, business and risk solutions. Hold the largest database of public-records and legal information. Provider of Big Data system -LexisNexis HPCC Systems –alternative to Apache Software Foundation products, drawing on software 'Thor' and 'Roxie'.
6	Microsoft Azure	A Cloud computing service. Provides Software as a Service (SaaS), Platform as a Service (PaaS) and Infrastructure as a Service (IaaS). Pay as you use pricing plan.
7	Amazon Web-Services	A Cloud computing service. Provides SaaS, PaaS and IaaS. Variable pricing plans with on demand services and options to bid on Spot instances.

C.9 Conclusions

The aim of this study was to tackle the pressing question of how innovations in the use of data and analytics can be used within the insurance industry to reduce information asymmetry and enable risk to be evaluated more accurately. In attempting to tackle this question, the report initially addresses challenges related to the use of data and analytics within the insurance industry. This has included challenges to both insurers and to firms supplying them with insurance specific analyses, such as CAT modellers. Data forms the foundation of risk analysis, yet the industry has yet to fully embrace the wide range of opportunities which are presented by innovations in this realm. For many lines of business there is a heavy reliance on expert opinion, qualitative evidence and subjective judgements. Data is becoming available which can enable a more accurate understanding of both hazards and consequences. This can relate to new methods of data capture, such as IoT devices, satellites-based sensors, and wider initiatives resulting in data sharing, many of which generate a range of disparate data sources, which are made available Open Source. Figure 34 is a basic diagram illustrating data types associated with 13 separate areas of insurance. The framework has allowed sources of data associated with these themes to be identified and grouped (See Appendix CC.1 (C.10.1)). This process indicates how data can easily be acquired representing a wide range of themes, and can potentially be used to replace gross assumptions, inherent in previous and current assessments of risk, in doing so reduce uncertainty.

For both internal and external data a core challenge is quality assurance. To enable data derived from diverse sources or time periods, to be collated and analysed requires standardisation of formats and content. This can necessitate structured data capture initiatives. Another problem highlighted is that much data is unstructured and can take the form of narratives. Knowledge extraction from such data is difficult, however there are a range of techniques which can be drawn on to assist in this process, such as NLP. Application of these techniques can require, as a starting point, the data to be stored in an appropriate way, in this respect it is helpful to consider options offered in the realm of Big Data. Table 29 outlines various areas associated with field of Big Data, which could be looked to. Prior to selecting which analytical processes will be applied to the data (i.e. machine learning, NLP), it is necessary to select the best storage location (local server/data warehouse/Cloud) and what software program will be used to structure and retrieve the stored data (for example many companies are using MongoDB for unstructured data).

The increasing availability of Open Source data presents an opportunity to enrich analyses of risk, by allowing companies to draw on additional information relating hazards and consequences. For example, in relation to flooding, it is possible to obtain Open Source flood maps, river gauge data and also satellite derived imagery of areas impacted by floods. However, there are limits imposed on the use of Open Source data, these can relate to a lack of data for some regions and countries, poor data quality, and a lack of accompanying metadata. A result can be companies being required to devote substantial resources to processing data derived from many open sources, before they are able to work with them. Some questioned as part of this study, have reported that this can actually mean that it would be more cost effective to pay a reputable firm to supply the data, rather than attempt to processes it internally. This issue highlights how it could be valuable for a centralised body to source data commonly used within the industry and to carry out QA/QC on this data, before making it available to individual companies.

Opportunities arising from the use and analysis of satellite EO data have been apportioned a substantial amount of space in this report. The field is deemed to hold immense, largely untapped opportunities for the insurance industry. There are a wide range of sources of EO data, both paid and Open Source. A number of these are listed in C.10.3 Appendix CC.3. The price of EO data has been falling, whilst the number of companies operating in this field (both data providers and analytics firms) has increased dramatically over the last decade. A new range of small satellites now orbit the earth, operated by companies such as Planet and Earthi. These can provide medium resolution imagery of the entire globe on a daily basis. These outputs can be more affordable, and thus accessible for a wider range of applications. Companies such as Planet and DigitalGlobe operate developer programs, which enable companies to draw on EO data archives and current imagery, and to develop industry specific use cases, which can employ machine learning techniques, for example. There are a wide range of EO data outputs that can be drawn on, visible, infrared, microwave, interferometric, and radar, for example. These can be utilised through a host of processes depending on the data's intended use. Options such as Google Earth Engine can also be used for free in research and development to gain an understanding of the 'art of the possible', enabling users to draw on a 30-year archive of public EO data from a range of satellite missions. Aside from the high-profile suppliers of satellite data and analytics, there is an abundance of smaller start-ups working in this domain who can provide more tailored products at lower prices. A selection of these have been reviewed within this report. Additional value can also be leveraged from EO data when it is combined with other data sources. This can be IoT data, human movements, CCTV footage, ground sensors, data collected by drones and other sources. Automated routines applied to this data can enable more than just imagery, this can be change detection, classification of features, and a deeper understanding of emerging trends, for example, through applying novel techniques such as Agent Based Modelling.

A wide variety of companies have been profiled within this research. Individual accounts of these are provided in the Appendices (Section C.10). This has revealed how there are many organisations willing and able to provide analytical services to the industry, however the choice of suppliers can prove overwhelming. The methods used by data analytics firms and the data sources they draw on are also evolving. Many firms are moving to the Cloud, both to store data, and to host their services. These services are increasingly being supplied to clients as Software as a Service (SaaS), enabling users to access analytics platforms/dashboards via web-browsers, negating the requirement to install and update software locally. Cloud hosting can also accommodate altering usage demands and allow batch processing of data during off-peak hours (so optimising costs). High levels of automation can also be built into processing of data in Cloud environments, such as AWS, increasing redundancy, and reducing the requirement for manual intervention. This can involve automated GIS workflows, optimising Geocoding tasks. However, awareness of IT developments is noted to act as a barrier to implementation and take up by insurers, in some areas. The Cloud is one such area, where there is much scepticism relating to data security issues. Analysts questioned, have stated that they can use a large amount of time educating syndicates. The general lack of technological awareness, which has been reported, can also relate to inappropriate use of technology and data sources, such as an over reliance of Google Earth, or an inadequate appreciation of how the resolution at which data is sampled can limit its use.

Section C.8.3 revealed some of the companies who currently provide 'Big Data' services, many of these draw on Open Source Software such as that developed within the Apache Software Foundation (Hadoop, for example). This new wave of advanced analytics, potentially accessible to all, is a good starting point for those who are interested in exploring Big Data opportunities, and have the required programming skills. Specialist companies (such as those detailed in Table 30) provide more tailored solutions built on Open Source software. However, the only barriers preventing direct user implementation of software such as Hadoop and Apache Spark, are lack of familiarity or technical competence (which can be learnt) and access to compute power. So, for those who are not ready to sign up to agreements with data management providers, attempting to implement the software locally first, may prove a good starting point. Then depending on requirements to scale up, Cloud services may be the next consideration.

The insurance industry is deemed by many to operate in an old-fashioned manner, and lag behind other finance sectors such as investment, in adopting digital technologies. The way that brokers, underwriters, actuaries and risk engineers consume data can be outdated. Yet the differing needs of those who fulfil these roles is a necessary consideration when looking at how data should be presented and communicated. Underwriters, for example, require distilled risk metrics, which are intuitive and self-explanatory, due to a lack of time available to analyse these. Data visualisation and presentation is not a topic covered extensively in this report, however the discussion in previous sections has revealed the importance of this final stage of analysis. It becomes even more essential when considering the increasing quantity and resolution of data variables, which need to be incorporated into models. This can necessitate those with knowledge of how data is consumed within the insurance industry, to act as an interface between insurers and data analysts, to ensure outputs are fit for purpose and usable by those who need them. In speaking with companies who are proposing more prospective solutions this becomes especially apparent. With this in mind, the Proof of Concept (POC) method which Lloyd's have adopted, appears well suited. The method would be ideally suited to testing some of the more prospective technologies and data types, such as analytics based on EO data and application of Big Data software tools, such as those developed by the Apache Software Foundation.

A final takeaway message from this study relates to the framework presented in Table 29. To understand how innovations in the use of data and analytics can be utilised within the insurance sector, it can be helpful to look at five core areas: 1. Data Collection, 2.

Data Storage, 3. Infrastructure and automated processing, 4. Knowledge extraction and analysis, and 5. Visualisation and communication. In terms of data collection, this report has illustrated how a wide range of sources now exist both Open Source and paid, which address some of the insurance industry's data requirements. These data sources can increase insurers' understanding of both insured assets and perils. Emerging data sources can augment or displace traditional methods and expert opinions. Yet an understanding of data quality, source and validity is essential before a decision is made to use the data. To maximise value derived from these data sources it is necessary to combine external data sources with internal insurance data. Combined, the volume of these datasets can become too large to store locally, so an awareness of is required of what storage options are now available, e.g.: local/Data Warehouse/Cloud. This ties in with the need for an understanding of what options exist in terms of software infrastructure, which can be implemented to structure the stored data so that it can be processed and retrieved in an efficient manner (options for this were presented in Section C.8.3 and Appendix CC.4 (C.10.4)). To enable actionable insight to be extracted from this data requires the use of analytical processes; many firms specialise in using specific types of analysis, examples of these are listed in Table 26. Insurers need to decide if they have the expertise to implement the required analytical processes internally or if they need to draw on external expertise. Finally, once answers have been generated from the input data variables, these need to be communicated to those making decision. This final stage requires a thorough appreciation of user requirements and level of expertise, so value derived through the previous steps is not lost.

C.10 Appendices

C.10.1 Appendix CC.1: Details of external sources

Maritime

IHS Sea-Web (https://maritime.ihs.com)

Sea-web is a maritime reference tool, with more than 600 data fields on over 200,000 ships of 100 GT and above. Quoted as the industry's largest maritime database, Sea-web features multiple, separate modules that integrate detailed information on ships, companies, builders, ports, movements, fixtures, casualties, performance, security into one online platform. It features seven levels of ownership and more than 290,000 owners, 240,000 companies, 15,500 ports and 116,000 ship photographs.

Comment from the market:

- For maritime data, Ascot are using Sea-web and Windward and other platforms (more important for insurance than reinsurance, to know where vessels are in real-time).
- IHS –Source of data and analysis for most Marine insurers

Marine Traffic (https://www.marinetraffic.com)

MarineTraffic is a maritime information service that allows you to track the movements of any ship in the world. Founded in 2007, it builds technology-based solutions that deliver actionable intelligence to shipping professionals, hobbyists and provides a link between seafarers and their families. An advocate for the democratisation of data, MarineTraffic is an open, community-based project that creates online solutions, data services and mobile apps to leverage global real-time and historical ship positional data. It has databases of information on the vessels which includes details of where they were built, the dimensions of the ship, gross tonnage and International Maritime Organisation (IMO) number. Users can submit photographs of the vessels which other users can rate. Vessel locations can be seen on different layers, including Google Maps (using the Google Maps API), Nautical Charts and OpenStreetMap The basic MarineTraffic service can be used without cost; more advanced functions are available subject to payment.

National Coast Watch UK (https://www.nci.org.uk/)

The National Coastwatch Institution (NCI) is a voluntary organisation keeping a visual watch along UK shores. The website contains Records of maritime incidents for the UK.

US Army core of engineers, US Waterways Data:
(http://www.navigationdatacenter.us/)

The U.S. Waterway Data is a collection of data related to the navigable waters in the United States, including inland waterways, off-shore waters, the Great Lakes, and the Saint Lawrence Seaway. Data on commerce, facilities, locks, dredging, imports and exports, and accidents are included along with the geographic waterway network.

Bathy Database NOAA (https://maps.ngdc.noaa.gov/viewers/bathymetry/)

Global open source seabed bathymetry.

IMB Piracy data
(https://www.icc-ccs.org/index.php/piracy-reporting-centre/live-piracy-map)

The IMB live map shows all maritime piracy and armed robbery incidents globally, which have been reported to IMB Piracy Reporting Centre. The IMB map is restricted by massive under reporting of piracy events and no reporting of effective antipiracy measures. The IMB report to have close connections with the Lloyd's committee that looks at Piracy and war risk, who receive reports on a regular basis to enable evaluation of the piracy risks for underwriters. This information provided publicly is deemed by the IMB adequate for insurance. The IMC do not currently supply this data as a web-feed, but are willing to consider this. Incident data included within the live map is derived from ship masters, owners, flag states, navies (not from the media, only official parties).

Additional Sources

Data Source	Area	Description
The Channel Coastal Observatory (CCO) https://www.channelcoast.org	UK	Archive and real-time coastal data, outputs from academic studies
UK Hydrographic Office (UKHO) (INSPIRE Portal) http://aws2.caris.com/ukho/mapViewer/map.action	UK	Bathymetric charts, port and coastal data sets, navigation routes, shipping traffic data
MEDIN (The Marine Environmental Data and Information Network) http://www.oceannet.org	UK	Open source portal of marine environmental data
NOAA NCEI https://www.ncei.noaa.gov	Global	Global datasets for coasts and oceans
Marine Management Organisation (MMO) https://www.gov.uk/government/organisations/marine-management-organisation	UK	Marine planning, fisheries, licencing, protected areas, coastal recreation
UK Oil and Gas Authority (OGA) https://www.ogauthority.co.uk/data-centre/	UK	Oil and gas fields, reserves, seismic surveys and seabed infrastructure

Additional data sources (listing from https://publicwiki.deltares.nl/display/DDP/External+Portals)

Name	Area	Description
EMODnet Central Portal	Europe	EMODnet: European Marine Observation and Data network. This is the central web page

		containing all EMODnet portals. The portal categories are: bathymetry, geology, seabed habitats, chemistry, biology, physics, human activities, and coastal mapping.
EMODnet Bathymetry Viewer	Europe	A web viewer application to EMODnet bathymetry data.
EMODnet Bathymetry	Europe	EMODnet: European Marine Observation and Data network. Bathymetry, coastlines, and geographical location of underwater features: wrecks.
EMODnet Geology	Europe	Seabed substrate, sea-floor geology, coastal behaviour, geological events and probabilities, and minerals.
EMODnet Seabed	Europe	Modelled seabed habitats based on seabed substrate, energy , biological zone, and salinity.
EMODnet Chemistry	Europe	The concentrations of chemicals (pesticides, heavy metals, antifoulants) in water, sediments and biota.
EMODnet Biology	Europe	Temporal and spatial distribution of species abundance and biomass from several taxa.
EMODnet Physics	Europe	Salinity, temperature, waves, currents, sea-level, light attenuation.
EMODnet Human Act.	Europe	The intensity and spatial extent of human activities at sea
US Ocean Data	United States	The place to search for data on US marine, coastal, and Great Lakes environments.
MATROOS	North Sea	MATROOS (Multifunctional Access Tool foR Operational Oceandata Services): recent and historical model and monitoring data relevant to storm surge forecasts
SeaDataNet	Europe	SeaDataNet infrastructure links oceanographic data centres and marine data centres from 35 countries riparian to all European seas.
OBIS	World	OBIS (Ocean Biogeographic Information System) allows users to search marine species datasets from all of the world's oceans.
NDBC	World	NDBC (National Data Buoy Centre): get wave measurements for model input & calibration
Coastdat	North Sea	Wind, wave, current and water level data of the North Sea (hindcast database)
ICES	World	ICES Oceanographic

CMEMS	World	Copernicus Marine Environment Monitoring Service (CMEMS)
Marine Geoscience Data System	World	The Marine Geoscience Data System (MGDS) provides a suite of tools and services to marine geoscience research data acquired throughout global oceans and continental margins
Informatiehuis Marien	Netherlands	Background data for various projects and reports. A selection of the basic data for wind projects and Environmental compensation.
Schelde Monitor	Netherlands-Belgium	ScheldeMonitor is a Flemish-Dutch information portal for research and monitoring in the Scheldt estuary and offers an overview of the research landscape and an extensive literature collection. Includes measurement information and data products from various data sources.
Cefas Data Hub	United Kingdom	Cefas is a world leader in marine science and research. Various data available for download.
Plymouth Marine Laboratory (PML)	World	Marine science datasets.

Aviation

OpenAIP - Worldwide aviation database (https://www.openaip.net/)

openAIP has the goal to deliver free, current and precise navigational data to anyone. openAIP is a web-based crowd-sourced aeronautical information platform that allows registered users to add, edit and download aeronautical data in many common formats used in general aviation.

All available data is instantly shown on the openAIP map where it is possible to view airports, airspaces, navigational aids, thermal hotspots and many other datasets.

Environmental

Bluesky (https://www.blueskymapshop.com/products/national-tree-map)

Bluesky hosts the national tree map for the UK. Created using up to date aerial photography and colour infrared datasets combined with detailed height models, the map provides an assessment of tree heights and canopy cover.

NERC Databases (http://www.nerc.ac.uk/research/sites/data/)

The UK National Environmental Research Council's data centres. These centres hold data from environmental scientists working in the UK and around the world. The data centres are responsible for maintaining environmental data and making them available to all users. NERC supports five data centres covering a range of discipline areas:

- British Oceanographic Data Centre (Marine) http://www.bodc.ac.uk/
- Centre for Environmental Data Analysis http://www.ceda.ac.uk/ which includes:

    - British Atmospheric Data Centre (Atmospheric)
    - NERC Earth Observation Data Centre (Earth observation)
    - UK Solar System Data Centre (Solar and space physics)
- Environmental Information Data Centre (Terrestrial and freshwater) http://www.ceda.ac.uk/
- National Geoscience Data Centre (Geoscience) http://www.bgs.ac.uk/services/ngdc/
- Polar Data Centre (Polar and cryosphere) https://www.bas.ac.uk/data/uk-pdc/
- Archaeology Data Service http://archaeologydataservice.ac.uk/

Skytruth (https://skytruth-org.carto.com/datasets)

SkyTruth use Earth Observation data to identify and monitor threats to the planet's natural resources such as offshore drilling and oil spills, urban sprawl, fracking, mountaintop removal mining, and overfishing of the oceans. Their data outputs are made available open source. Data outputs can incorporate many inputs such as vessel AIS data, data derived from machine learning.

World Air Quality Index (http://waqi.info/ and http://aqicn.org/)

The World Air Quality Index project is a social enterprise project started in 2007. Its mission is to promote Air Pollution awareness and provide a unified Air Quality information for the whole world. The project is proving transparent Air Quality information for more than 80 countries, covering more than 10,000 stations in 800 major cities.

Flooding

Middlesex multi-coloured manual (https://www.mcm-online.co.uk/)

Flood and Coastal Erosion Risk Management: A Manual for Economic Appraisal' is a successor to, and replacement for, the highly respected manual on the benefits of flood and coastal risk management, produced by the Flood Hazard Research Centre at Middlesex University, with support from Defra and the Environment Agency. It provides methods and data which can be used for the practical assessment of schemes and policies. Secondly, it describes new research to update the data and improve techniques. Thirdly, it explains the limitations and complications of Benefit-Cost Analysis, to guide decision-making on investment in river and coastal risk management schemes. It enables one to convert depth of flooding to cost.

Shoot Hill -Check My Flood Risk (http://www.checkmyfloodrisk.co.uk)

The Check My Flood Risk map is designed to increase awareness among the public of the likelihood of flooding from rivers or the sea. The map shows the Environment Agency's assessment of the likelihood of flooding from rivers and the sea across England. The information is based on the presence and effect of all flood defences, predicted flood levels, and ground levels. The data is available under Open Government Licence V2.

Shoot Hill -Gaugemap (http://www.gaugemap.co.uk/)

This contains British and Irish river level, flow, groundwater and camera data from the Environment Agency, SEPA, the Irish Office of Public Works, and Farson Digital. Data displayed is recorded at 15 minute intervals.

Additional sources

Data Source	Area	Description
Natural England https://data.gov.uk/publisher/natural-england	UK	GIS digital boundary datasets, habitat mapping, agricultural data
The Environment Agency (EA) https://data.gov.uk/publisher/environment-agency	England	Coastal survey data: beach transects, topographic and hydrographic surveys, the UK national tide gauge network, flood risk assessments, coastal management plans, data on defences and intent, pollution
Department for Food and Rural Affairs (DEFRA) https://data.gov.uk/publisher/department-for-environment-food-and-rural-affairs	UK	Public sector food, agriculture and environmental datasets
The Crown Estate https://www.thecrownestate.co.uk/energy-minerals-and-infrastructure/downloads/maps-and-gis-data/	UK	Maps, GIS data –offshore aggregates and renewable energy projects
MAGIC http://www.natureonthemap.naturalengland.org.uk/home.htm	Great Britain	Open source data repository relating to the natural environment from across UK government
Joint Nature Conservation Centre (JNCC) https://data.gov.uk/publisher/joint-nature-conservation-committee	UK	Biodiversity and species data, Mapping European Seabed Habitats (MESH), marine survey data, MCZs
Centre for Ecology and Hydrology https://www.ceh.ac.uk/data	UK	Hosts the the National River Flow Archive (NRFA), Environmental Information Centre, Environment change network, and the biological records centre
The National Trust http://uk-nationaltrust.opendata.arcgis.com	England and Wales, Northern Ireland	Coastal land use and land access to National Trust land

Additional data sources (Listing from https://publicwiki.deltares.nl/display/DDP/External+Portals)

Name	Area	Description
INSPIRE Geoportal	Europe	INSPIRE (Infrastructure for Spatial Information in the European Community) contains European spatial data that may have an impact on the environment.
European Environment Agency	Europe	Large collection of European environmental datasets
Atlas Leefomgeving	Netherlands	Contains maps with information over health aspects of the (Dutch) environment
Atlas Natuurlijk Kapitaal	Netherlands	Maps with information about the services that the natural environment delivers, such as forest, food, energy sources.
Environmental Information Platform	World	Dataportal of the Centre for Ecology & Hydrology. Includes WATCH Forcing data.
SWITCH-ON	Europe	SWITCH-ON (Sharing Water-related Information to Tackle Changes in the Hydrosphere for Operational Needs) explores the potential of Open Data for water security and management.
Rijkswaterstaat Geodata	Netherlands	Direct download of many important Dutch geodatasets, such as Top10, (vaar)wegen, AHN, DTB, coastal maps, vegetation.
Water Kwaliteits Portaal	Netherlands	The Water Quality Portal (WKP) collects, manages data for the Water Framework Directive (WFD) and makes it possible to present a consistent image of the Dutch water quality. In addition, their surface water quality data administrators each year as part of the National Water Quality Survey in the Import WKP.
Fresh Water Metadata	Europe	Information on existing freshwater datasets. The metadatabase on freshwater related datasets was built as part of the EU BioFresh project to centralise such information and provide free and universal access to it
Watergegevens RWS	Netherlands	Projected and historical measurement data on water quality and water quantity.
Water Info RWS Waterhoogte	Netherlands	Overview of the water levels in the Netherlands measured by Rijkswaterstaat. You can view the history and predicted water levels at a given point by clicking on the measuring point.

Flusshydroligischer Webdienst - Bundesanstalt für Gewässerkunde	Germany	The FLYS system is an instrument of the BfG (Germany) for processing model results against the background of measurement data. The tool interpolates between the results, visualizes and interprets together with further information and so compiles the appropriate sections: Measurement and model, federal and district data, historical and current, geodetic, hydrological and morphological data.
United States Geological Survey National Water Information System	United States	The types of data collected are varied, but generally fit into the broad categories of surface water and groundwater. Surface-water data, such as gauge height (stage) and streamflow (discharge), are collected at major rivers, lakes, and reservoirs. Groundwater data, such as water level, are collected at wells and springs.
River Gages	United States	River gauge data.
Geo Dataportaal van Provincie Limburg	Netherlands (Regional)	This Geo Data Portal provides the necessary current geographic files in open form. These files can be edited and processed in a GIS environment.
Nederlands Hydrologisch Instrumentarium (NHI)	Netherlands	Dutch Hydrological Instrumentation (NHI) is the toolbox of software and data for the development of groundwater and surface models on a national and regional scale.
Florida Department of Environmental Protection Geospatial Open Data	United States	Includes spacial and raster datasets, tables, and documents.

Geological

USGS (https://data.usgs.gov/datacatalog/#fq=dataType%3A(collection%20OR%20non-collection)&q=*%3A*)

Contains a wide range of scientific data sources, including National Map Data, Earthquakes Hazards Program, Energy Resource Program, Water Resource.Real-time event data: Weather, GIS, Wildfire, Flood and Earthquake. Being used as real-time risk overlay and data is stored for historical analysis.

The USGS Advanced National Seismic System (ANSS) is being used by many reinsurance companies to supplement Catastrophe models. The ANSS Comprehensive Catalogue (ComCat) https://earthquake.usgs.gov/data/comcat/ contains earthquake source parameters (e.g. hypocentres, magnitudes, phase picks and amplitudes) and other products (e.g. moment tensor solutions, macro seismic information, tectonic summaries, maps) produced by contributing seismic networks. Important digital catalogues of earthquake source parameters (e.g. Centennial Catalogue, Global Centroid Moment Tensor Catalog) are loaded into ComCat. New and updated data is added to the catalogue dynamically as sources publish or update products.

BGS GeoSure Geohazards Insurance Product (http://www.bgs.ac.uk/products/geohazards/geosureInsurance.html)

The BGS GeoSure: Insurance Product gives an index level assessment of the potential for a geological deposit to create financial insurance loss due to natural ground movement. It incorporates the combined effects of the six BGS GeoSure hazards on (low-rise) 2-storey buildings and links these to a postcode database — the Derived Postcode Database. This database contains a normalised hazard rating for each of the six BGS GeoSure themes hazards (i.e. each BGS GeoSure theme has been balanced against each other), and a combined unified hazard rating for each postcode in Great Britain (rating A-E). A series of GIS (Geographical Information System) maps show the most significant hazard areas. The ground movement, or subsidence, hazards included are landslides, shrink-swell clays, soluble rocks, running sands, compressible and collapsible deposits. Three output vector formats are available: statistical analysis, postcode version, total score for postcode polygon (postcode look up database). This has resulted from extensive liaison with insurance industry to address their needs.

Cranfield University Subsidence Data (http://www.landis.org.uk/npd_insurance/)

Cranfield University's Natural Perils Directory (NPD) uses the best available spatial data on soils, weather and trees to models subsidence and six other geohazards for the UK. The NPD also provides geohazard potential maps for cavitation, peat shrinkage, frost heave, soft and compressible soils, natural flood extent and wind exposure. Cranfield University's National Soil Map provides a foundation depth (70-120 cm) assessment of shrink-swell potential. The NPD uses measured and UKCP09-modelled weather data to provide a suite of climate models to identify hazard levels under current, extreme and future weather scenarios. Also uses Bluesky's National Tree Map in calculations of subsidence potential. Enables insurers to look at address-level for tree and topographic risks, so can identify high and low risk properties and price accordingly.

Additional sources

Data Source	Area	Description
British Geological Survey (BGS) Non insurance specific data products http://www.bgs.ac.uk/data/home.html	Great Britain	Geoscientific, geomorphological information

Additional data sources (taken from https://publicwiki.deltares.nl/display/DDP/External+Portals)

Name	Area	Description
OneGeology Portal	World	OneGeology is an international initiative of the geological surveys of the world to

		create a dynamic digital geological map data for the world.
DINO Ondergrondmodellen	Netherlands	The 'DINOloket Ondergrondmodellen' contains a viewer where you can visualize and access data from the DGM, REGIS and GeoTOP geological models.
DINO Ondergrondgegevens	Netherlands	Contains an extensive collection of soil and groundwater samples.
EarthChem	World	This web site gives you access to data systems and services for geochemical, geochronological, and petrological data.
National Oceanic and Atmospheric Administration (NOAA)	United States	NCEI is responsible for hosting and providing access to one of the most significant archives on Earth, with comprehensive oceanic, atmospheric, and geophysical data. From the depths of the ocean to the surface of the sun and from a million-year-old sediment records to near real-time satellite images, NCEI is the USA's leading authority for environmental information.

Weather Data

Weather Analytics (https://www.weatheranalytics.com/industries/insurance/)

Weather Analytics fuse event data with high resolution topographical information to provide insights about threats to the property, casualty, crop, and specialty markets, the world over. This can relate to perils such as hurricanes and tornado damage paths.

The service is said to be used by actuaries to price better with statistically-stable, gap free weather and peril data, and assess risk and changing exposures for CAT and subCAT events. For claims validation the high-resolution hail, rain, and wind data helps assess and triage claims caused from property or crop damaging weather conditions. Can enable brokers to provide specific weather conditions and alerts to policy-holders and aid in their weather mitigation activity. For reinsurers, used to optimize portfolios across sectors, programs, and geography. Calculate MPL, leverage landfall probabilities from the hurricane and tropical storm ensemble forecast. Can be used to measure attritional losses over time – including those caused by convective systems, floods, and hail.

Weather Net (https://www.weathernet.co.uk/)

WeatherNet provides historical weather data reports and online applications. WeatherNet is a subsidiary of Cunningham Lindsey, and specialises in supplying online weather applications, weather data sets, weather reports, consultancy and advice. WeatherNet was established in 1995 to provide post coded weather information to UK insurers to help verify claims for storm, freeze and flood.

Additional sources

Data Source	Area	Description
The Met Office UK https://www.metoffice.gov.uk/services/industry/data	UK	Meteorological data - frequency of extreme events

Additional data sources (listing from https://publicwiki.deltares.nl/display/DDP/External+Portals)

Name	Area	Description
Climatic Research Unit (CRU)	World	Past climate history and climate change.
Copernicus atmosphere	World, Europe	The Copernicus Atmosphere Monitoring Service (CAMS) provides data on the composition of the atmosphere and solar radiation.
Copernicus climate	World, Europe	The Copernicus Climate Change Service (C3S) will combine observations of the climate system with the latest science to develop authoritative, quality-assured information about the past, current and future states of the climate in Europe and worldwide. *Note: service is development / pre-operational*
earth2observe	World	Contains hydrometeorological data of 10 global hydrological models including forcing data for a period of 34 years. Also includes a large amount of EO data including soil moisture, precipitation etc.
ECMWF	World	The European Centre for Medium-Range Weather Forecasts (ECMWF) is an independent intergovernmental organisation supported by 34 states. Provides forecasts, climate reanalysis and atmospheric composition.
IPCC Data Centre	World	The IPPC provides climate, socio-economic and environmental data, both from the past and also in scenarios projected into the future.
KNMI Data Centre	Netherlands	The KNMI Data Centre (KDC) provides access to weather, climate and seismological datasets of KNMI.
MERRA - NASA	World	MERRA is a NASA reanalysis for the satellite era using a major new version of the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5). The Project focuses on historical analyses of the

		hydrological cycle on a broad range of weather and climate time scales and places the NASA EOS suite of observations in a climate context.
Met Office - Hadley Centre	World	Researchers at the Met Office Hadley Centre produce and maintain a range of gridded datasets of meteorological variables for use in climate monitoring and climate modelling.
NCAR/UCAR	World	Contains a large collection of meteorological and oceanographic observations, operational and reanalysis model outputs, and remote sensing datasets.
Weather Underground	World	Weather conditions worldwide (measurements). *Note: Includes unvalidated personal weather stations.*

Satellite Earth Observation Data

Tcarta (https://www.tcarta.com)

Tcarta provide bathymetric and seafloor mapping data for marine applications, and now offers onshore and offshore geospatial solutions. Traditionally supplied the data which has driven analysis, rather than perform this internally.

EO derived data that could be used within the insurance/reinsurance sector:

Satellite Derived Bathymetry - currently available at 2m, 10m and 30m resolution (based on DigitialGlobe, Sentinel-2 and LandSat imagery), with different price points depending upon resolution. Useful for a wide range of applications (e.g. accurate storm surge modelling).

Topographic Bathymetry - recently been supplying seamless land/shallow water surface models at varying resolutions dependent upon satellite images used.

LULC/Habitat Mapping - delivered several projects classifying the coastal, inter-tidal and shallow water regions using satellite imagery. The end use of the data often drives how the image is classified (e.g. for environmental classification, a more ecologically driven approach would occur).

Vector shoreline - available at different map scales, depending on the satellite source. Useful for understanding coastal erosion and associated change detection.

Additional data sources (listing from https://publicwiki.deltares.nl/display/DDP/External+Portals)

Name	Area	Description
NASA Worldview Earthdata	World	Satellite web application that allows you to interactively browse global satellite imagery within hours of it being acquired.
Satellietdataportaal	Netherlands	Satellite data from various instruments of multiple satellites, free, registration required.
Earth Explorer	World	Multiple global satellite datasets, from multiple instruments (e.g. MODIS,

		Landsat, ASTER, SRTM). Free, registration required.
Earth Engine	World	Google Earth Engine brings satellite imagery online with tools to mine this data to detect changes, map trends and quantify differences on the Earth's surface.
Sentinel Data Hub	World	The Sentinel Data Hub is a web-based system designed to provide EO data users with distributed mirror archives and bulk dissemination capabilities for the Sentinels products.
Sentinel Data Access Service (SEDAS)	World	Useful Sentinel data portal by UK Space Agency. Registration required.
LSA SAF	World	The scope of Land Surface Analysis Satellite Applications Facility (LSA SAF) is to increase benefit from EUMETSAT Satellites (MSG and EPS) data related to: Land, Land-Atmosphere interaction and Biospheric Applications. The LSA SAF performs: R&D Programs and Operational Activities (Generation of land surface products, Archiving long time series and Dissemination to users)
Comprehensive Large Array-data Stewardship System - NOAA	World	The Comprehensive Large Array-data Stewardship System (CLASS) is an electronic library of NOAA environmental data. This web site provides capabilities for finding and obtaining those data. CLASS is NOAA's premiere on-line facility for the distribution of NOAA and US Department of Defence (DoD) Polar-orbiting Operational Environmental Satellite (POES) data, NOAA's Geostationary Operational Environmental Satellite (GOES) data, and derived data.
Landsat-8 tile selector	World	Libra is a browser for open Landsat 8 satellite imagery. Use it to browse, filter, sort, and download images.
Satellite imagery - vito	World	A product distribution portal containing various types of satellite imagery: free satellite imagery, commercial satellite imagery, derived products and APEX.

TRMM near-real time satellite based rainfall	World	ftp server with near-real-time satellite-based rainfall.
GSMaP research and NRT products (MVK+ known to perform excellent over the Zambezi in Southern Africa)	World	Users can download surface rainfall products of the GSMaP Standard (post-processing, 1998-2006) version here!
GRACE Tellus	World	GRACE TELLUS provides user-friendly Level-3 data grids of monthly surface mass changes, with most geophysical corrections applied, to analyze changes in the mass of the Earth's hydrologic, cryospheric, and oceanographic components.
CU GRACE	World	This website allows visitors to perform basic data analysis on publicly available Level-2 GRACE data. Computations are performed in real-time, producing downloadable maps or time series.

Cadastral -location data-

Natural Earth (http://www.naturalearthdata.com)

Natural Earth is a public domain map dataset available at 1:10million, 1:50m, and 1:110m scales. Featuring tightly integrated vector and raster data, with Natural Earth one can make a variety of maps with cartography or GIS software.

Address cloud (https://addresscloud.com/#/?_k=4w1y6j)

Detailed location information from address matching. A geocoding service for the UK and Ireland. Includes datasets from rich datasets from the Ordnance Survey, Royal Mail and Eircode.

Pitney Bowse (https://www.pitneybowes.com/us/data.html)

The company provides a range of business, geographic, and industry-specific data featuring global coverage across 250 countries and territories. Data includes worldwide points of interest, demographic information and fully-attributed street products, and boundary products, including: community, administrative, postal, risk and telecommunication. The company also provide an insurance specific risk data suite.

The Ordnance Survey (UK) (https://www.ordnancesurvey.co.uk/business-and-government/products/opendata.html)

Ordnance Survey (OS) is Great Britain's national mapping agency. The OS supply a range of cadastral information, building outline data and other products. They offer these as paid services and also have a range of open source data products. OS OpenData is a set of free digital maps of Great Britain, available for anyone to use, for any purpose.

OS Mastermap (https://www.ordnancesurvey.co.uk/business-and-government/products/mastermap-products.html)

OS MasterMap is a source of highly-detailed geographic data for Great Britain. Offered in layers – topographic, imagery, networks. Topography Layer is a detailed view of Great

Britain's landscape – from roads to fields, buildings and trees, fences, paths and more. This can be used to assess change related to houses for example. OS MasterMap Highways Network provides a common and authoritative view of the whole road network in Great Britain. The Water Network layer is the only detailed, heighted water network of Great Britain showing the flow and course of rivers, streams, lakes and canals. It supports flood risk management.

Geoplan (https://www.geoplan.com/product/data/index.html)

The Geoplan Maps data range delivers demographic, point of interest and boundary data for a range of countries. Geoplan map data is available as data packs for GIS data formats. The data is sorted by country. This includes postcode data and boundaries (global).

Additional sources

Data Source	Area	Description
Historic England https://historicengland.org.uk/listing/the-list/data-downloads/	England	Cadastral listed data sets for the coast
HM Land Registry https://www.gov.uk/topic/land-registration/data	England and Wales	Land and property information/prices

Additional data sources (listing from https://publicwiki.deltares.nl/display/DDP/External+Portals)

Name	Area	Description
Geoweb Rijkswaterstaat	Netherlands	GeoWeb is a Web GIS with geo-information from multiple, distributed sources which can be combined.
Publieke Dienstverlening Op de Kaart (PDOK)	Netherlands	PDOK enables users to access digital geographical data via official PDOK web services. About 250 web services (aimed at digital mapping) are available to the general public, private companies, organisations and the public sector.

Topographic Data

Name	Area	Description
ASTER and SRTM data	World	Portal for downloading ASTER and SRTM Global Digital Elevation Model (DEM) data. Free data, but registration required.
AHN1 and AHN2	Netherlands	Instructions and links to download and visualize the detailed Dutch digital elevation model.

ALOS World 3D	World	Global DEM with a 5 m resolution created by the Japanese Advanced Land Observing Satellite (ALOS); paid service.
ALOS World 3D - 30m	World	Global DEM with a 30 m pixel resolution and 5m vertical accuracy created by the Japanese Advanced Land Observing Satellite (ALOS).
Copernicus Land	World, Europe	Includes digital elevation model of Europe and various 'land' data geospatial datasets.
Viewfinderpanoramas dem3	World	Void filled and 'cleaned-up' global elevation data based on SRTM; particular improvements in some mountain regions

Corporate

OpenCorporates (https://opencorporates.com)

OpenCorporates is the largest open database of companies and company data in the world, with in excess of 100 million companies in a similarly large number of jurisdictions. Mission of the site is to tackle the use of companies for criminal or anti-social purposes, for example corruption, money laundering and organised crime. The ODI (UK) worked with the company to help develop their business model. The site looks at relationships between branches of companies in different countries and can reveal where the majority of business is located. Termed the Facebook of companies. Enables employees to look at corporates and their business structure. Used as a tool to force companies to Open up their data, ‘Share a like licence’ -to use data on site, companies need to open up their internal data.

Dun and Bradstreet (http://www.dnb.com/about-us/our-data/data-depth-and-breadth.html)

Corporate Database. The database includes insights on the top 43,000 global companies, both publicly traded and private, with a database of more than 285 million company records. De-duplicated records, additional company and contact information, and related businesses linked in corporate families. Derived data include: Inquiry Data, Purchase/Spend Data and Commercial Property data.

Insurance Specific

Perils (https://www.perils.org)

PERILS offers industry exposure and event loss data and an associated industry loss index service for Australian, European and Turkish natural catastrophes. The service incorporates anonymised data, which is resold to the insurance market. The PERILS Industry Exposure & Loss Database is based on data directly collected from insurance companies writing property business in the covered territories. The service provide loses for events, at a country and company level.

Feedback has been received that this is an expensive service and the impacts data provided is not comprehensive.

Oasis Hub (https://oasishub.co)

The Oasis HUB is an online portal/marketplace for the publishing and purchasing of environmental data, adaptation planning tools, models and services, formed to increase the availability of information on catastrophe and climate change risk. Reported to be a way that several insurance clients are obtaining data. GUI front end modelling, relies on Cloud based storage, also contains metadata links. Datasets incorporated are cleaned up -problem with headers etc. are dealt with prior to making the data available. Incorporates both commercial and non-commercial data. Ambition to drive down prices for data.

ImageCat (http://www.imagecatinc.com)

ImageCat supply insurance related exposure, hazard and disaster damage datasets. They host a library of post-event damage data layers for global events dating back to 2005. This includes a number of independent data sources containing building attributes and replacement cost valuations. Their disaster damage datasets, are developed using image analysis and field reconnaissance. These datasets cover damage to buildings and infrastructure using aerial and satellite imagery, data mining and geospatial field survey techniques. Their archive data includes: flood boundaries, storm surge damage, hurricane wind damage, earthquake building damage, wildfire damage. These damage datasets cover major catastrophes in US, Europe, established and emerging Asian insurance markets and selected humanitarian catastrophes (e.g. 2010 Haiti earthquake). Recent applications of their data archive include understanding the past performance of high-value facilities such as refineries for making underwriting decisions. Their data has also been used to validate catastrophe model results, update vulnerability functions and event sets and provide expert witness following major catastrophic events. Datasets are provided in GIS-ready shapefile and kml formats.

Additional sources

Data Source	Area	Description
Association of British Insurers (ABI) https://www.abi.org.uk/data-and-resources/industry-data/industry-data-and-subscriptions/	Great Britain	Insurance data downloads

Social/Economic

Data Source	Area	Description
Department for Transport (DFT) UK and Highways England https://data.gov.uk/publisher/department-for-transport	UK	Traffic flow data
The Office for National Statistics (ONS)	UK	UK national population, business and industry statistics

https://data.gov.uk/publisher/office-for-national-statistics		
Datashine UK (University College London) http://datashine.org.uk/	England and Wales	Spatial representations of socioeconomic datasets taken from UK 2011 Census data, by University College London (UCL)

Risk/Hazard Data

Global risk map.com.au (http://globalriskmap.nicta.com.au)

The Global Risk Map covers major natural hazard events over the past 115 years. The map highlights the social and economic devastation caused by cyclones, floods, earthquakes and related perils, and identifies the regions/countries most vulnerable to these natural hazards. The map achieves this by assessing relevant core data such as available disaster statistics, social and economic variables, and insurance penetration and density.

The website includes a databased titled EM-DAT. EM-DAT contains core data on the occurrence and effects of over 18,000 global disasters from 1900. The database is compiled from various sources, including UN agencies, NGOs, insurance companies, and research institutes.

EM-DAT data calculates costs on the following basis:

- Deaths: The number of people who lost their life because the event happened.
- Missing: The number of people whose whereabouts since the disaster is unknown, and who are presumed dead (official figure when available).
- Total deaths: The sum of deaths and missing.
- Estimated Damage: The amount of damage to property, crops, and livestock. In EM-DAT estimated damage are given in US$ ('000). For each disaster, the registered figure corresponds to the damage value at the moment of the event, i.e. the figures are shown true to the year of the event.

Lloyd's City Risk index (https://www.lloyds.com/cityriskindex/)

Lloyd's City Risk Index predicted potential impact on the economic output of 301 of the world's major cities from 18 manmade and natural threats. Based on original research by the Cambridge Centre for Risk Studies at the University of Cambridge Judge Business School. Those from the Lloyd's market who have been using this website have provided positive feedback, and would like to see more information included within this (or a similar application) and higher levels of transparency, such as more details provided of where the numbers came from and what is the basis of the ratings?

National/International Open Source Portals

USA Government Open Data (https://www.data.gov/)

The USA's national open source data portal. Includes data and tools. Including Census Data, climate data, agriculture, consumers, ecosystems, education energy, finance, health, local government, manufacturing, maritime, ocean, public safety, and science and research.

Additional sources

Data Source	Area	Description
Data.gov.au	Australia	Australian Government
http://open.canada.ca/en/open-data	Canada	Government of Canada, Open Government Portal
Data.gouv.fr	France	Open platform for French public data
https://www.data.go.kr/e_main.jsp#/L21haW4	South Korea	Korea

Additional data sources (listing from https://publicwiki.deltares.nl/display/DDP/External+Portals)

Name	Area	Description
Nationaal Georegister	Netherlands	Dutch national spatial data catalogue
NEDData Hub	Netherlands	Dutch open data portal, including historical data.
Data.gov.uk	United Kingdom	UK national data portal
gob.es	Spain	Spanish national data portal
ign.es	Spain	Spanish national geographic data portal. Includes high resolution DEMs.
OpenGeoCode.org	World	Extensive list of Open Data Portals, containing: census/demographics, climate, health, education, commerce, agriculture/food portals.
European Data Portal	Europe	The European Data Portal harvests metadata of public sector information available on public data portals across European countries.
re3data.org	World	re3data is a global registry that covers research data repositories from different academic disciplines
Geopunt.be	Belgium	Geopunt is the central gateway to geographic government information. The geoportal makes geographic information accessible to government agencies, citizens, organizations and companies.
PhilGIS	Phillipines	GIS data for the Philippines. Includes Mangroves distribution maps.

C.10.2 Appendix CC.2: Insurance specific data analytics companies

CAT Risk

RMS (http://www.rms.com/about) [Notes from Interview]

- RMS is used extensively in Lloyd's
- 30 years providing risk model managing transferring CAT risk
- Carry out analysis of 200 perils across 100 countries
    - Class focused on -anything exposed
- Models created are probabilistic
    - Look at how (the insured) is exposed -frequency of expected losses
- Latest Model RMS (One) platform
- Consider both hazard and vulnerability
    - For property look at building structure, use, built details, combine this with loss and contractual details of policy
- Data underlying models is multidisciplinary
- Geocoding used to understand risk locations
- Hazard data
    - geographic distribution
    - intensity
- loss data
- Recent examples: Location intelligence API-
    - Agnostic of systems to be integrated
    - Outputs from analysis can be fed into spreadsheets if no other means available, yet most clients have this fed into their desktop systems or dashboards
    - Initiative -data from many sources made available via an API
    - Information on risk and analytics enables underwriters to screen and price risk -includes risk scores, tailored products, loss metrics
    - RMS does not enforce change in IT systems used, can use client existing IT interface. API can accommodate this
    - Built on RMS 1 platform
- Data sources: mixture depending on region and government policy -agnostic approach depending on region.
- Data sources cover 100 million properties in the USA -many details related to loss, construction type, etc.
- Global Exposure Accumulation and Clash initiative -development initiative with 12 clients and Cambridge Risk Framework (Judge Business School)
    - Multi line of business data schema -new standards for capture of information, allow insurance to gain a holistic view of exposure across lines of business (understand clashes)
    - natural CAT and also manmade CAT -war in Asia involving a superpower –
    - implement on RMS 1 and other systems
- Unlock risk management and modelling

- produce new models, iterate -models can be old (20 years), constantly searching for data sources and technologies
    - Computer vision used to detect damage to an area post event
    - IoT sensor networks used to ground truth analysis
- Engaging with start-ups and public agencies in the USA
- Big Data:
    - RMS 1 has new exposure risk management capability
    - built and delivered in the Cloud
    - agreement with Microsoft
    - Reviewed 90 different technologies prior to coming to a decision to use Microsoft

Some feedback on RMS by others:
RMS is involved in statistics-based work -problem they rely on statistics which they don't really understand. In some cases, they serve 2m resolution data -yet data is only sampled at 30m.

Guy Carpenter (http://www.guycarp.com/content/guycarp/en/home/the-company/gc-analytics.html) [including interview notes]

- Guy Carpenter delivers a combination of broking expertise, strategic advisory services and industry-leading analytics to help clients achieve profitable growth.
- GC are not underwriters -analysis completed to support the brokerage process
- Preparation of insurance and finance tools for use in risk management.
- Guy Carpenter as a broker assesses models.
- Guy Carpenter takes on general models, refines and applies to specific areas.

Disaggregation Model
About exposure, probabilistic techniques based on land cover -land use type
Damage Model
Can be linked to engineering methods, statistical -work out costs based on past statistics
Financial Model
What is the loss to insurer, standard model, policy conditions, socio-economic and environmental data
GIS -Digitisation -for built environment and hazards, land use.

AIR Verisk (http://www.air-worldwide.com/Industry-Solutions/Reinsurers/) [Notes from Interview]

- Perils Concerned with include:
    - Wind
    - Coastal flood
    - Inland flood
    - Earthquake
    - Terrorism
- CAT models generated
- Serve clients in Lloyds and the wider insurance market

- Models they generate are used for pricing, solvency (calculate capital held in respect of perils)
- GIS used by company
    - Touchstone (software) integrated with ESRI
- Geospatial analysis
    - Individual locations -calculate risk premiums
    - Hazard maps -storm surge, flooding
- Have a flood team based in the USA
- 10 year probability commonly focused on (flooding)
- Flood maps, hydrological models, generate flood footprints
        - Validation using impact analysis data (helps inform the way flood footprints are clipped)
        - After event geotagged images obtained from on the ground
- Outputs of modelling tools can be dollar loss -average annual loss- probabilities (by peril)
- Outputs -video on website
- Interested in top cities in the world in terms of specific risk
- Try to go for open source data where possible
- Less focus on Climate Change in insurance -policies are only for 1 year
- Some climate change research -impacts of climate change certain scenarios
- Data Verisk is concerned with needs to be granular, at an individual property level.
- Many data attributes focused on: age of building, occupancy, height

Comment from others in the industry
AIR/Verisk only has good data only for the UK/USA and specific cities
- Problem the lack of information for emerging markets
- Part of Verisk, - former company GeoInformation Group
http://investor.verisk.com/news-events/press-releases/press-release-details/2016/Verisk-Analytics-Inc-Acquires-The-GeoInformation-Group/default.aspx
Validus Research (https://www.validusholdings.com/about-us/our-companies-homepage/validus-research/) [including interview notes]

- Validus has created a specialist team to provide risk analytics. Validus Research Inc. ("VRI") is dedicated to catastrophe research, risk modelling and development of analytical tools. Provides services to other companies in the Validus Group such as Talbot.
- Validus Research -natural catastrophe -informs how risks are selected and priced
        - Exposure management and CAT modelling overlap -analysis of exposure and using prior research to inform risk
        - Exposure management -look at risk aggregation and exposure to natural perils
- Big research capability, research division, data scientists, geologists, actuaries
- Includes a Crop Risk Service

Oasis Loss Modelling Framework (http://www.oasislmf.org/) [including interview notes]

- Provide an open source CAT modelling platform
  - An architecture for catastrophe modelling
- In field expertise
- Simulations -insurance company exposure
- Result: expected loss -probability of loss = exposure
- Models report hazard intensities at separate locations
- Considerations - severity, frequency, coverage
- Realistic disaster scenario (RDS) -used to test models against
- Insurance companies concerned with simultaneous exposure
    - Hazard intensity
    - Peril intensity
- Oasis -standardise calculation method, use retrocessionaires, probabilities, Monte Carlo Simulation
- Use relational database structure, with keys so data remains on the original tables (dictionaries)
- Damageability matrix -combined footprint
    - Outputs: av. annual loss, event loss, period specific loss, loss exceedance
- Oasis don't provide models, just provide software
- Two perils: wind and storm surge -modelled separately then combined
- Insurance industry collectively invests £1m/year funding in Oasis, but Oasis remains open source
- How users run Oasis software
    - Hazard model -events, intensity
    - Vulnerability -exposure, damage
- Data transformation tools -generate GUI (graph user interface) API (application user interface)
- Oasis, R allows reports to be converted quickly
- Oasis Kernel can be downloaded from github -front end can be supplied on demand
- Now Oasis hub (separate data service hosted by Oasis) has analytical tools embedded in it

AON Benfield (http://www.aon.com/reinsurance/analytics-(1)/catastrophe_management.jsp)

AON Benfield has been highlighted by those interviewed as a source of CAT modelling. Aon Benfield Analytics offers clients catastrophe management, actuarial, rating agency advisory and risk and capital strategy expertise. Working with brokers on risk transfer products and engaging on broader analytic and modelling engagements. Help structure optimal risk transfer programs for placements. Provide solutions for risk and concentration analysis, portfolio optimization, catastrophe modelling, pricing and cost recovery, and economic capital modelling.

CATRisk solutions (http://www.catrisks.com/Home.html)

CATRisk Solutions has been highlighted by those interviewed as a source of CAT modelling. They are a scientific company, providing natural hazard and risk modeling software and consulting services to the engineering community, insurance companies, enterprises and governments. Founded in 2005 and worked on projects globally.

KATRisk (http://www.katrisk.com/)

KATRisk has been highlighted by those interviewed as a source of CAT modelling. KatRisk is a catastrophe modeling company focused on flood and wind risk. The company was formed in 2012 by ex-RMS modellers.

Wider Services –Underwriting, Portfolio Management, Multiple Classes of Business

Lexis Nexis (https://insurancesolutions.lexisnexis.com/idslogin/) [Notes from Interview]

- The companies ultimate goal is data aggregation
- Start from building data bases from insurance companies
- High risk factors can be highlighted in this database, such as gaps in cover
- Lexis acquired -map view -geospatial -perils data -on a geospatial platform
- host data for insurers but not pooled
- Can provide products for underwriters -visual aids for underwriting a risk
- Risk score generated for specific location searched for
- Mapview:
  - platform to deliver many datasets
  - acknowledge geospatial character of question
  - started as underwriting tool, taking spatial coordinates
  - correlate to perils especially flood
- Lexis have capability to geocode -looking up polygons -dealing with realities of geospatial scoring
- customer feed internal data to enhance perils data scores
- risks are global therefore datasets looked at are global
- Lowest resolution for flood globally is 30m
- Look at a customer's book of business then geocode -can give accuracy rating on addresses
- Map View Front End originated as underwriting tool for portfolio management
- Accumulations important for underwriting -can use Map View to take an overview of a book of business
- Perils scoring and accumulations -can optimise insurance workflows
- Backend -currently in servers -looking to migrate to Cloud
- Map View delivered as a service
  - Tool runs in the browser
  - monthly reports from Map View -what users are reporting -risk underwritten in high risk areas -own book of business can be uploaded to application -geo-locate and give results file. Gives ability to evaluate a book of business and assess it.
- Machine Learning currently being considered

    - USA -wind storms, hail -deriving a roof complexity score -leveraging open source data, LIDAR, photo
    - Use data from insures
- Lex ID (one of their most powerful tools). Involves a stack of information stored for everybody in the UK (and USA)
- Technology used in company -mostly own tech. -a lot of open source -SALT -scalable automated linking technology -statistical based linking -probabilistic specific density
- HPCC -use own distributed tech. -very fast -built -in-house technology
- Has bespoke datasets -want to host everybody's data
- Has a specific contract with each insurer -involves not giving away any IP, yet certain information can be used

Galytix (Currently working with Lloyd's on a POC) (https://www.galytix.com/web.html) [including interview notes]

'Insurance Professionals are struggling to harness increasing volume of external data. Galytix aims to help professionals distil actionable insights from external data - by bringing together Intelligent Search, Granular Insights, Powerful Analytics, Deep Data, News & Messaging - in the world's first fully integrated smart analytics solution for insurance.' Platforms developed for drawing on internal data to improve the performance of the market and companies. Looking at exposure to risk by class of business\country, creation of an exposure index. Host macroeconomic data. Aim to provide single source for external data for the insurance industry. Catering for different user groups: scientists and actuaries. Mongo DB used as a back end for the data warehouse, due to unstructured nature of the data dealt with. Data can be used to form base of CAT models. Underwriter benefits: more context, more risk factors than normal.
In Brief:

- Application depending on level of granularity required
- Aim to create an environment/platform where data can be served and published
- Aim to harmonise data quality and standards, recognised by insurance industry
- High level analysis possible of country, to performance of market and performance of companies
- Users scientists and actuaries

Urban Stat (http://www.urbanstat.com/)

- Aims to improve the underwriting processes, using machine learning, generating real-time reporting capabilities.
- full-suite solution specifically for underwriting

Claim prediction uses Integrate AI identify customers at the time of underwriting. AI used to analyse current customers as their renewal times approach, so insurers have the right risks covered. Customer data can be accessed, filtered, and download policy and claim file data without any limitations on time or geography. Provide risk analysis for catastrophic and non-catastrophic perils with accumulation reporting. Enables rules for user generated custom regions based on time, accumulations, and expert opinions, to be implemented. System draws on live data feeds to access current weather, forecasts, and visualise recent earthquakes.

Current users: Sompo Japan, Ageas, Allianz.

Europa technologies (https://www.europa.uk.com/industries/finance-and-insurance/)

Provides Risk Insight for assessing risk across an insurer's portfolio, providing underwriters, brokers and senior managers with an understanding of individual risks and aggregated exposure. Implemented as SaaS (Software as a Service), this can enable the Risk Insight to be integrated with existing systems.

Address level risk assessments. UK oriented solution, yet platform has the capability to incorporate global datasets.

Russel Group: ALPS Connected Risk (https://www.russell.co.uk/)

The ALPS platform is an integrated process for single and multiple classes of business. It consists of a connected risk framework, an integrated risk management approach which rationalises the risk classes into a platform that supports the similarities and differences whilst delivering data, analytics and visualisation for risk and solvency management. A typical process being portfolio and underlying industry data, naming convention and analytics. The platform utilises a connected risk framework to enable corporates to better manage increasing event complexity. Core areas of functionality:

- Integrated Data – data ready platform
- Connected Risk Framework – multi-class architecture for actual and modelled events
- Integrated Analytics
- Exposure Management - portfolio exposure analysis
- Pricing –simulation of risk pricing
- Portfolio Modelling – simulation of portfolio profitability and capital utilisation
- Visualisation – geographic visualisation of portfolio exposure
- Remote – cloud-based hosting

Business Insight (http://www.business-insight.net/)

Business Insight is a UK based independent company specialising in providing perils risk models, quote enrichment data and premium analysis software to the insurance industry. Applies mathematical and statistical analytics coupled with understanding of insurance. Help insurance organisations find and implement new insights through their products that are aimed at the core insurer business processes of pricing, underwriting and marketing.

Geospatial Threat Analysis

Spatial key (http://www.spatialkey.com/insurance-technology-solutions)

Provide enterprise-class solutions for risk management. Delivers self-serve analytics for underwriting, exposure management, and claims. SpatialKey delivers a geospatial analytics solution using insight derived from many disparate data sources. Insurer's internal portfolio data can be used and overlaid with external content. Provide on-demand applications and APIs.

Global Earthquake Model (GEM): Open Quake
(https://www.globalquakemodel.org/oq-getting-started)

OpenQuake is a suite of open source software that allows the GEM community to use data, best practice and applications being developed collaboratively. The Platform is comprised of the engine, and a great variety of online and offline tools for modelling, accessing and exploring GEM products, as well as uploading and sharing data and findings. The OpenQuake Engine is the GEM's state-of-the-art, free, open-source and accessible software collaboratively developed for earthquake hazard.

Flood

JBA (http://www.jbarisk.com) [Notes from Interview]

- Risks focussed on wind and floods
    - A few models for different countries -crop etc. on a consultancy basis
- Usually provide basic product (JBA to insurance)
- Rating risk category 1-53
- Assessments based on a 5x5m grid with 10m buffer (25x25m total)-for private domestic dwellings
- Look to move to commercial -wider footprint 200m
- Building outline -buffered by 2m
- Matrix created -type of flooding
- Rating given in the form of Black/Red/Amber/Green
    - Assessments at address level -can be postcode
    - Address based licence +plus premium
- When housing development raised -details required by JBA
- Launch new UK Cat Model /annual damage ratio
- Update Hazard maps
- Looking at wind data (400m annual)
- Hazard maps globally -surge -global coverage for rivers -main rivers modelled -surface water -surface stream
    - UK and Ireland coverage 5m (aim for world at this resolution) -World currently 30m
    - Adding Lidar
- Granularity -property level data -can take global
    - UK good address level data
    - Not the case for the whole world
    - Work on variable level grids
- Currently looking at -using AI for data from different sources
    - Try to train AI
    - QC process
    - Use internal Server, not Cloud -data centre
- Big Data -parallel processing
    - Jflow allows to run in tandem (V.9)
- Global Hazard maps Cat model produced fast -most for the Far East
- Look at global data deals -for height maps

- Satellite data has not been a major source -start to look at
- Coastal flood map -not a big issue -so well defended -model look at wave overtopping
- JBA Look at internal drainage boards -other companies don't -client driven to reduce flooding

GeoSmart Info (http://geosmartinfo.co.uk/about-us/customers/insurance/)

- UK groundwater flood risk information and forecasting services for the insurance market, provides an early alert to groundwater flood events.
- GeoSmart's map provides assessment of risk across England, Wales and Scotland. It combines science, quality assured models and data from the British Geological Survey (BGS) and other organisations. It provides property and address level flood risk data across the UK and can be incorporated alongside other river and coastal flood data to provide a complete picture of flood risk.
- Provide a 30 day flood forecasting service, giving daily alert to groundwater levels and the risk of flooding.

Ambiental (https://www.ambientalrisk.com/)

Ambiental combine flood modelling, predictive analytics, machine learning to give insight into flooding and flood risk. Provide analytics to support risk managers, underwriters and reinsurers, through tools, dashboards and integrated systems. Flood information is provided accounting for all major floodwater sources. Portfolio-wide analysis tools and property-level flood risk analyses supporting underwriting decisions.

Property

Core Logic (http://www.corelogic.com/industry/insurance-solutions.aspx)

Company focuses on property and casualty insurance risk.

- Aggregate risk and construction cost data, enable users to gauge the accuracy of that information and use it in a way that's optimized for a company's workflow. Property imagery helps underwriters validate property characteristics and conditions. Host a database with detailed information on over 28 million building permits, such as relating to new construction, remodels, room additions, roof changes.
- Deterministic models calculate the likelihood of a natural disaster such as a severe storm, flood or earthquake; probabilistic models give loss estimates; forensic models show the actual frequency, severity and location of severe weather - to a specific property within a portfolio.
- Assess a property's roof using aerial measurement reports, pre-fill data, change detection, weather verification and disaster intelligence. Possible to determine the probable age, condition and characteristics of a roof so to price the risk. Pinpoint the precise location and severity of damage from severe weather, including high-resolution aerial imagery.
- Proprietary hail, wind and lightning verification services used to determine where and when the impact happened, how severe it was and which properties were directly impacted.

- Host location data, building data, occupant data, environment data, financial data

Geodata (https://www.geodata.no/artikkel/forsikring) [including interview notes]

Geodata provide an automatic service which accepts an address, coordinate, or parcel-ID (from cadastral registry) and returns a risk profile-based a on property's spatial relationship with authoritative risk data

This particular service examines a policy or potential policy's exposure to the following risks:

- Flood – 10, 20, 50, 100, 200, 500, and 1000-year probabilities
- Fire and spreading risk – areas with densely packed wooden structures or fire-prone areas
- Landslide probability and consequence
- Mudslide (quick clay) risk
- Historical or culturally protected properties
- Underlying geology
- Ground contamination and pollutants

The service is said to drastically improves internal data quality

Can be used as an independent tool or the service can be integrated into existing systems

In addition to this type of risk profile, Geodata also use GIS in the following areas:

- Disaster response – exposure and coordination with claims adjusters
- Sales – Demographic and consumer analysis, market penetration, prospecting for private and business markets
- Case handling – Automatic quality control and validation of customer data against central cadastral registers. Possible for integration with other systems such as Salesforce
- Detailed modelling and portfolio assessment for Solvency risk scenarios

Geodata are also looking at alternative sources of data, such as publicly available satellite imagery, LIDAR data, or private drone footage, which is deemed useful in many scenarios. For example, using multispectral and radar satellite imagery to better quantify the impact of flood and fire events or to assess crop or forest yields and health over time.

Cyber

Cyence (https://www.cyence.net)

Cyenes deal with threat assessments for cyber security. They look at 8 cyber factors on a monthly basis. Produce reports allow susceptibility of clients to attack be realised and look at motivation of attackers. Cyence combines data science, cybersecurity, and economics into an analytics platform that quantifies the financial impact of cyber risk. Cyence is used to prospect and select risks, assess and price risks, manage portfolio risk accumulations, and bring new insurance products to market.

Maritime

Windward (Currently working with Lloyd's on a POC) (http://www.windward.eu)
[Notes from Interview]

Marine Real-Time Data (POC)

Solution sets out to help insurers with the claims Investigation process and to identify vessel navigation in high risk areas. Lloyd's is being asked to evaluate the business value of using the data, smart analytics and the technology. The POC looks at benefits on shared service basis -group together syndicates in relation to what focussed on. Data included in the Windward solution: AIS data, satellite EO data and other environmental parameters. Smart analytics are being drawn on + data visualisation software and associated user engagement techniques. Machine Learning and artificial intelligence technology, which is Cloud based, is also being used.

- For the claims investigation process -value of use in the market to speed up the claims process, deemed better than waiting for a claims adjuster, or for images to come through
- Use satellite imagery to show vessels at the time when incidents happened -combine with other information, such as weather and sea conditions
- Vessels operating in high risk zones can result in additional premiums -when vessels are entering into a war risk zone can attract addition premium outside normal policy -so need data in real-time. Can enable insurers to provide alerts when vessel enter high risk zone
- When vessel turns off their AIS -this can trigger alarms -can provide details of this
- Volume of external data realised by Windward
- Windward tool takes raw navigational data -uses a Cloud based analytical platform -structuring data, so it can answer questions. Tool provides quick access to lots of contextual information.
- Information in the system for all ocean-going vessels for the last 5 years
- Possible to track vessel which could have grounded -used for claims investigation
- API in and out of system -can generate CSV exports
- Alert System can trigger if vessel heading into storm
- Each of market participants able to upload fleet into system
- Windward cleans data and fuses data from different sources
- 1st priority to clean AIS data
    - Low quality data inputs -what data, what vessels
    - Implement algorithm -for vessel determine what should be (i.e. Loading of oil -draft change)
    - Identity resolution
- Enrich data by creating derivative datasets -total mileage
- Because of the way data is structured can enable to understand context of an accident
- Archive -own data -derived AIS data
    - A lot of data frequently acquired
    - Dates back to 2013
- Target variables -accident all sources

- Insurers who give access to archive -they can in return use the model based on own fleet
    - increase confidence
- Predictive function focus on Hull and machinery
    - Visual analytics
- Run processes in the Cloud on AWS
    - Repurpose software to do georeferencing
- 2 Million data points per day
- SaaS used -allows new features to be implemented on a weekly basis -avoid on site updates
- Mongo Db used -Best in class solution - open source
- GIS infrastructure -mostly coordinates -integrate satellite imagery -these are used to compliment AIS data -find dark vessels [feature new in the last couple of months]
- Machine learning -Deep learning project
- Claims investigation -knowing about vessels in the area -cannot use extrapolation
- Can look at a vessel -where it has been through lifetime
    - Determine time in dangerous depths

Right ship (https://site.rightship.com/)

Right Ship provide a maritime and environmental management system, giving risk scores. This take the form of a predictive online ship vetting platform, RightShip Qi. Banks, insurers and P&I clubs are reported to be using RightShip Qi to supplement their internal risk processes. Insurance brokers use RightShip data to deliver premium relief across multiple lines of cover to their customers in recognition of the superior nature of the vessels they engage. RightShip's Ship Vetting Information System complements internal risk management procedures during the vessel loan underwriting process. SVIS can provide an instantaneous risk rating of the vessel under consideration and the star rating of the owners' fleet and ship manager associated with the vessel can be evaluated.

C.10.3 Appendix CC.3: Satellite earth observation data and analytics providers

Owner/Operators of Satellite Hardware

Planet (https://www.planet.com/markets/insurance/) [notes from interview]

- The idea to set up Planet came from a group of NASA scientists, wanting to see changes to the earth on a daily basis -not on an adhoc basis. They started development of Nano satellites, at first a garage project, now only recently achieved their goal of being able to view the whole planet on a daily basis. It has been around 5 years from the launch of planet scope to obtaining this goal in 2016.
- Planet are interested in people looking to effect change from their data, they are also interested in finding new use cases for the data

- A lot yet to be discovered -analytics, algorithms
- Lots of use cases for insurance -automatic change detection -system for monitoring particular assets -system to look at changes -send alerts -so can send person to look at features
- higher resolution satellite data available
- Largest target market for Planet: America a lot with Crop insurance -because an image is generated every day -so planet is most likely to get before and after pictures, whilst other sat. companies only take an image every week
- Digital Globe has a problem with price point -you either want or not. Planet's background, scientists,
- Product development schemes possible. Planet R&D people can provide access to Million km of data, give a period to ingest data for testing then look for future partnership.
- Can come to the table with use cases already thought of, but Lloyd's may come with different use cases
- Planet taking an image anyway, so data is there at medium resolution -for all areas.
- Skysat used for higher resolution data
- Planet is a young company. Only providing the data not analytics; need another company to provide analytics.
- 50p / square kilometre
- Minimum execution price per year $10,000.00
- Claim to be the most flexible scientific company
- Agriculture biggest market
- 3m daily resolution used by all agricultural clients (not so good if looking at individual buildings)
- Clients using data for car manufacture -counting cars stored in the docks.
- Have Skysat -tasking satellite, $8 /km2 ≤0.8m resolution
- Have an application developer program where companies can access data at a fraction of the cost -5%, just can't sell on the data used in this period
- Various examples of use: car counting, Florida parking facilities monitoring; using algorithms to work out how many cars are parked. Oil and gas tanks -how much volume.
- Look at making new usage cases together with companies, Look at Crop Yields for example
- Looking at insuring development (construction) bringing equipment on site just in time.
- Can help company by giving global access to an API- can be used to look at remote locations -Tesla factory, Apple building. This can use a combination of medium and high resolution data.
- Users can log in to an API and within 10 minutes have images of a location dating back to 2009.
- Because of reactive nature cannot set up a system to look at a floods in advance.

- Testing coastal -automatic change detection. In theory can set up an algorithm to watch the whole of the UKs coast on weekly basis. An alert can be generated when something has changee
- Can task a satellite to collect higher resolution -only problem cloud cover.

Earthi (http://earthi.space) [notes from interview]

- Earthi vision for own data source, from own satellites
- Prototype, test the use of video -capture motion in detail
- Prior to using own satellites, distributed outputs of three high resolution satellites
- looking at areas hard to get to on a regular basis
- Huge datasets (2 million km^2)
- Good use in insurance
    - 5m data subscription
    - Can provide 1m or better, need to task satellites
- Can provide shadows of containers in port to calculate the height of containers stacked
- Can task satellite to cover an area multiple times a day anywhere on earth, so can monitor change.
- Introducing burst mode to define how many images captured
- Telespazio partner Cosmo Skymed
- Can monitor vehicles to see if vehicles moving -see activity -used for disaster scenarios
- Focus on visible range data
- Catastrophic event data -supplied loss adjusters imagery between hurricanes Irma and Maria
    - check damage, so place loss appropriately
- Useful evidence related to natural disasters CAT Modelling
- Looking at clubs of insurers, easier to build relationships with individual companies though
- Data used for pricing of premiums
    - Example: new construction of power plant -can enable to give better costed proposal. If 80% of high value items not on site until the build, risk reduced.
    - So can be smarter about how pricing the risk -save $100,000s, cost of satellite imagery only a small part.
    - Data would be controlling the checks -state of the build -show up in the imagery -life cycle of big build: clear land, flatten, bring in equipment (keep really expensive stuff off site until the end of project).
- Video satellite -many different angles contribute to better detailed 3D imagery
- Current launch of satellite -http://earthi.space/press/earth-i-launches-prototype-worlds-first-full-colour-full-motion-video-satellite-constellation/
- Tianjin warehouse explosion -manufacturers of cars scramble to understand value of cars lost.
- Satellites benefits over drones -don't need permission, higher frequency images obtained, can get anywhere fairly rapidly.

- Satellite images used in court specific evidence -validity is high, use for investigation of claims
- Data best with small target areas
  - Incident at an airport how many planes affected
- Machine learning: working with partners, looking at in house and using open source data
  - Free data + open source code = commercial service
- Earthi works across several industries and is well financed
- Big plus point of Earthi is they control the satellites

DigitalGlobe (https://www.digitalglobe.com/industries/insurers) [Partially from interview notes]

- DigitalGlobe is the largest commercial provider of satellite data
- DigitalGlobe Imagery and derived solutions have been used extensively in the mapping, monitoring and analysis of events for more than a decade.
- Highest spatial resolution and spectral capabilities available in the commercial environment
- DG is the first and still only provider of 30 cm imagery – with an archive going back 16 years.
- Following a tornado in Oklahoma, sat imagery revealed destroyed properties to help companies estimate their exposure a few hours from the event happening
- DG has identified settlement location unknown to local government, over 100,000 km^2 area within hours from the earthquake that occurred in Nepal
- analysis done post the Hurricane Matthew highlighted damaged property in the wake of its path.
- the effect of Hurricane Irma on the International Airport in St Martins was revealed.
- Satellite technology is best suited to addressing these types of events
- Man-made or natural catastrophes exposure can vary significantly, areas of high insurance concentration need to be monitored as they pose the highest exposure in the event a disaster occurs
- DG provides world imagery, spectral & elevation data
- Global Archive, on- demand – in the Cloud
- Identification, extraction, change detection, measurement & prediction
- DG hold spatial database with building attributes
- Roof material extraction possible
  - Using machine learning -roof types -also determine if a tree close to house falls
- Digital Surface Model—Elevation map
- High-resolution land cover map
- Building footprint extraction
- Automatic extraction of information for assessment of flooding risk
- Automatic classification of flood areas for Hurricane Harvey images
- Can id:
  - Flooded Houses
  - Blocked Roads

    - Blocked Bridges
- Can be used in disaster response and underwriting solutions
- Integrated processes to allow crowd-based solutions to either validate or identify information.
- Volunteer -identifying features
    - Crowd sourcing
    - Identification automated
- Understand change -urban risk
- Platform -GBDX -can be used to develop algorithms -then pull results
- DigitalGlobe is now part of Maxar Technologies, which includes MDA who owns and operate a SAR satellite. This ability to combine high res optical and high res SAR, allows DigitalGlobe to reduce the negative effects of cloud presence during disaster response, providing faster information to insurances in all weather conditions.
- DigitalGlobe has developed a network of information partners who specialize in different fields of satellite image processing. Capabilities: analysing water bodies through satellite derived bathymetry, apply configurable deep-learning algorithm to extract specific feature of interest (solar panels, swimming pools, cars, planes, ships, water tanks, oil tanks etc).

Insurance Specific EO data service

Geospatial Insight (https://www.geospatial-insight.com/industries/insurance/) [interview notes]

Geospatial Insight is a provider of services to the insurance sector, based upon the acquisition, integration and analysis of a range of spatially-enabled data sets. Working with a range of insurers, reinsurers, reinsurance brokers and loss adjustors, Geospatial Insight provides data and intelligence to assist their understanding of risk and the impact of events, particularly in the fields of loss estimation, claims management and loss adjustment.

- Use Big Data, machine learning, remote sensing EO data and LIDAR
- Ability to predict -assurance- use multi variate regression analysis to enable insurance buyers to develop strategies for managing risk
- Enable dynamic risk modelling
- Company has a number of drones
- Drones can get to parts of distressed properties that conventional teams cannot access
- Main opportunity pre-risk, more up to date data, enable accurate analysis of risk
- Agreement with FloodRE -syndicated arrangement -pool of insurers
- Arrangement with satellite owner.
- Enable rapid response post event

Use cases

- Rapid response post loss

- Depth of flood waters - precise damage to properties quantified
- Rapid response capabilities of drones and drone pilot -generating precise data
- EO data analytics used to count cars in Brazil, 40,000 in 2 minutes
  - Provided car counting data to Guy Carpenter
  - Counting cars in supermarket every 3 hours
- Taking crop data for North America (Kansas) -look at relative levels of green - proxy for biomass during growing season. Also use soil data, wind speed, predictive analytics for yield
- Big Data -crop yield -infrared and near infrared data for crops in America eventual yield, soil porosity and other details
- Provide details of cargo trading vessels at ports -number vessel -number of cargo containers, amount of coal stored, details of fuel stored.
- Satellites Data used to compare heights of floating oil drum containers - calculate oil stored in specific place on date
- Hurricane Maria -data obtained from Virgin Islands 5 days before first support arrived
  - Could be used for loss adjusting
- Use radar enabled satellites and interferometric signatures
  - contribute to the risk of subsidence -can monitor mm changes in land height over years

Mckenzie Intelligence Solutions (http://www.mckenzieintelligence.co.uk) [inc. interview notes]

LMA Claims Committee (LMACC) and Lloyd's agreed to support and fund the satellite imagery service provided by McKenzie Intelligence Services (MIS) in March 2017. The service provides Lloyd's underwriters and claims professionals with satellite imagery following a major catastrophe, such as a storm, earthquake, flood or fire. It uses a purpose-built portal to deliver the imagery alongside other forms of intelligence. This includes intelligence from radar to reveal the extent of flooding. Cloud cover delayed the availability of more conventional satellite imagery, yet their portal also gave underwriters access to CCTV footage from Houston, so street level damage could be viewed. For Maria and Irma, managing agents were able to quickly assess the damage footprints and severity of the storm damage in urban areas. Able to manage and assess damage remotely. Underwriters were able to establish which storm caused particular damage. Reported to be a valuable tool for exposure management. Provides extent and type of damage at a post code level, giving intelligence in the immediate aftermath of a catastrophic event. Lloyd's market seen to trigger their satellite Imagery and intelligence service.

- Natural Catastrophe analysis -imagery to support exposure claims teams
- Work in house -data agnostic -work with whatever is available
- Have over 300 users on their portal
- Services provided to every managing agent and syndicates
- What they want is beyond EO, requirement to incorporate data from:
  - Ground Sensors
  - IoT -

        - Aerial imagery
- Bringing in ground sensors from in N. America
- Work for loss adjuster
- Creating a database adjusters are using to model risk
- R&D work with Block Chain -personal profiles generated
- Looking at claims workflow
- Has used Google Earth Engine for processing SAR -Sentinel 1 data
    - Outputs supplied to MS Amlin
- Started out catering for 250 users in insurance market, now can service over 1000
- Staff have a military background-are able to recognise what industrial processes look like
- At the moment all outputs are a result of analyst interpretation
- Look at automatic classification in the future
- Looking at the Tabaco industry in Australia -Google Earth Engine
- Similarities with insurance of Maize crops in South America
- Sceptical on use of Machine Learning with EO data
    - Maritime container counting -problem data in the nadir can be out by 33%
- Everything MI are doing is driven by the market
    - Harvey, Irma, Maria
    - Wild Fires California
    - Mudslides -California
- Hurricane Harvey -very thick cloud couldn't obtain adequate images from EO data
- Need to draw on whatever can find on the ground
- Make sure data sensors are automatic -temperature, hydro (N. America) sensors
- Look at individual properties
- Property on/off temperatures -inform underwriters at a property level
- Validation of what is going on the ground -claims made
- EO data
    - Wild fires -property burnt or not, damage scale

Wider Earth Observation Data Analytics

Harris (http://www.harrisgeospatial.com) [notes from interview]

- Harris Geospatial use scientifically-proven analytics to create solutions that extract information from all types of remotely sensed data.
- Main software is ENVI, an advanced hyperspectral image analysis software package written in IDL (Interactive Data Language).
- Harris has developed a geospatial services framework
    - This takes rest requests
    - populates a job list
    - allows to run parallel processing expandable on multiple instances with Cloud computing which is available

    - disseminate data using this tooling
    - data array processing
    - Watcher on data on Amazon archives in AWS
        - pull data auto when reaches requirements
        - pulled in to job manager
        - executes jobs
- working with partner analytics for flood mapping
    - Connecting data to sentinel 1 archive from ESA
- Haven't targeted insurance market because specific products not developed so far
- Flooding risk run through archive -run a Multivariate model
    - Outcomes of analysis can be used as a trigger in internal systems of underwriters for example
- Harris is well placed to support processing
- Utilise Cloud processing environment and delivery over web service
- Can work with the insurance sector -need to define a use case –
- Current work undertaken to identify datasets
- Have a data platform drawing on Airbus/DigitialGlobe data
- Also have involvement with company aerial surveying contaminated land - putting together a hyperspectral solution
- Deep learning tools used on point cloud data
    - identify rail infrastructure
    - plates between tracks
    - 'crocodiles'
- Work with traditional algorithms and Deep Learning -have a high success rate
- In the future further work to identify most important spectral bands
- Harris machine learning
    - pick up open source data
    - not about facial recognition
    - used to processes spatial cube
    - technology allows higher confidence rate on average with fewer training samples
- Software ENVI SARscape for image processing, allows processing and analysis of SAR data acquired from all existing space borne and selected airborne platforms. Generates products, and integrates information with other geospatial products.

Pixalytics (https://www.pixalytics.com) [including interview notes]

Pixalytics Ltd works in collaboration with its customers to determine whether solutions can be answered with Earth Observation (EO) data. An example related to the insurance industry is the detection of flood events. Pixalytics worked on a 6-month 'Space for

Smarter Government' funded proof of concept project[45] to provide the Environment Agency (UK) with reliable and accurate operational flood mapping. Since then, the developed product has been taken forward in a UK Space Agency funded project helping to support the Ugandan Government in terms of Droughts and Floods (https://www.gov.uk/government/case-studies/rhea-uganda-drought-flood-monitoring), and a commercial click-to-buy product is being launched shortly (http://www.pixalytics.space). The baseline product is primarily based on free-to-access Copernicus Sentinel-1 data, so that the cost is not prohibitive, but can also be run using commercial data when there's a need for a higher spatial resolution analysis or guaranteed timeliness and delivery via the tasking of a satellite.

Terrabotics (http://www.terrabotics.co.uk) [Notes from Interview]

Terrabotics makes sense of a new wave of Earth Observation imagery, at scale. They develop & deploy smart proprietary algorithms to rapidly transform volumes of Earth Observation imagery, video & sensor data into actionable terrain intelligence & useful analytical services.

- Have been involved in some peripheral work with Lloyds both recently and in the past and they understand there is a lot of appetite for these types of services. Recognise that rapid delivery and object detection are applicable to the insurance market.
- In terms of use of data, can be a problem licencing EO data for insurance use. Clients want interpreted layer of information (involve royalties). Challenge overcoming this barrier. Had chats with others operating in the insurance market and working with Lloyd's, they have encountered similar barriers. Requirement for purchase of underlying data, traditional methods make it difficult to change approach.
- What is it that insurers want? What do they want to get from data? What data is needed to get this?
- Syndicates want to share data, and don't want to pay for vast amounts of data that they can't show anybody.
- Company need to establish an understanding of how high-resolution data can help insurance?
    - Looking at Land Cover change?
- Potential to use existing machine learning algorithms
    - Can rapidly process historical and current data
    - Generate outputs very quickly
    - Historical data sets -various levels of feature detection
    - Training Datasets -improving reliability of algorithms
    - Move away from manual processes
- Use AWS to store all of data -Also use Cloud Services, to process models, draw on spot instances and on demand services
    - Some processes are continually running -process data in multiple parts

[45] (http://www.spaceforsmartergovernment.uk/case-study/pixalytics-optical-and-microwave-extension-for-floodwater-mapping-omef/)

    - Especially the case for extracting elevation
- Project time series based or time sensitive -high spec, high grade, process run quickly in 48 hours
    - QA/QC is necessary
    - Cloud based parallel processing cuts processing time down by an order of magnitude
- Also have a web platform 'Terrain Intelligence Platform, TIP'. Beta version -visual GUI, with data analysis function and FTP download facility. Used to:
    - Push data out to clients
    - Carry out object detection, flood risk analysis
    - Links with Amazon -AWS
- Using an open source GeoServer solution -coding for what they want
- Use a range of software -internal proprietary and open source
    - Using commercial sweets for image processing -Global Mapper used for image processing -used extensively -low cost
- Combine different sources of EO data together
- Terrabotics -stereo satellite imagery (visible) being used to build terrain datasets sub metre accuracy. Taken from two high resolution images -one looking forward, one back
- Terrabotics have been used for mine monitoring.

Sensonomic (http://sensonomic.com) [including interview notes]

Sensonomic builds digital representations of business environments using multiple data sources and advanced analytics. In this, high temporal and spatial resolution Earth Observation data is combined with computational simulations, particularly Agent Based Modelling. Digital models are populated with information about people, organisations, infrastructure and assets. This information can relate to agriculture, transport routes and storage locations, for example. Thousands of simulations are run, drawing on this data, under varying conditions. These combine statistics, predictive modelling, data mining, financial time series data, and advanced analyses of remote sensing data, to generate insight into natural capital behaviour and risk. Machine learning is utilised to continuously improve the models, using predictive power to provide real-time insight into complex dynamic systems.

Sensonomic's Agent Based Models can reveal behavioural interactions between autonomous and interrelating individuals and organisations and can generate unexpected answers as to what drives profitability and risk exposure. In doing this, fundamentally their systems establish what is important, not humans. The Agent based modelling approach also allows users' input to shape their design (where factors can be weighted depending on scenario), and they are driven by intuitive guidelines, which can handle varied data and behaviours. The Modelling outcomes emerge from bottom-up rules. This Agent Based Modelling approach is believed to be a more powerful method to reveal correlation, than causality alone.
Insurance applications
Due diligence

The Agent Based Modelling approach can be used to address claims made by insurance objects and specialised insurance companies, and challenge assumptions, based on emergent properties.

Key performance indicator monitoring

Through combining simulations with remote sensing and in-situ verification, live KPI monitoring is possible, for risks related to climate change, ecosystem integrity, biodiversity, and socio-economic impacts.

Predictive analytics

Sensonomic's dynamic SaaS platform enables clients to test effects of new and existing insurance policies

Portfolio overview

Monitoring for regional, country and local risks across a complex portfolio can be enhanced by the opportunity to make satellite derived insight available in near real-time.

Potential Use Cases

- Class of Business Agriculture
- Combine internal data with Agent Based Model –draw on internal expertise with NLP
- External data which can be combined with industry data –EO data, other ground info, people, business
- Look at disruption of business following CAT or other events
- Realistic Disaster Scenarios

C.10.4 Appendix CC.4: Supplier of Big Data technology and software solutions

Hortonworks (https://hortonworks.com/solutions/insurance/) [including interview notes]

About

Hortonworks (HW) is a Big Data software company. The company develops and supports Apache Hadoop (an independent open source software created by the Apache Software Foundation, which HW is a sponsor of), for the distributed processing of large data sets across computer clusters. HW was formed in 2011 as an independent company, funded by $23 million venture capital from Yahoo. HW create, distribute and support enterprise-ready open data platforms and modern data applications. HW's mission is to manage the world's data. Their focus is on driving innovation in open source communities such as Apache Hadoop, NiFi, and Spark. The Hortonworks Data Platform, powered by Apache Hadoop, is a massively scalable and 100% open source platform for storing, processing and analysing large volumes of data.

- HW deals with
    - Streaming processing
    - Data analytics
    - Data storage at scale

- 30,000 contributors to Apache Software Foundation (whose products form the base which HW draw on), they are leaders in this sphere, and these contributors commit code as agreed on by peers
- HW staff make up 1/3 of committers of their code to the Apache code base - HW seeds foundations steering committee
- Within Hadoop are Hbase and Hive for data warehousing, include graph databases
- HW provide an underlying data management platform (for both data at rest and data in motion) this draws on the Hadoop platform
- Strategy of Horton Works -100% open source
    - Not locked into proprietary software
    - Open source development provides more and faster innovation simply because more engineering resources are utilised
- Because the Apache Software used is entirely open source it also means that HW have much deeper partnerships with the key players in the Hadoop 'ecosystem' – and especially with the three big cloud vendors Amazon, Microsoft, and Google so that our customers can truly manage data assets across data centres and clouds.
- Clients have reported problem when all their data is residing in AWS
    - HW draws on a combination of Cloud and on-premise solutions
- Strategy to give big companies the opportunity to work with multiple Clouds
- HW understands the correlation between data Science and machine learning
- Hadoop can do better than traditional relational databases (RDBS) in challenging modern data management challenges
- Modern companies from Silicon Valley do not have RDBS at their core -Hbase and Hive, for example are at their core
- New infrastructure enables insight to be captured from data
- HW Business Model: Subscription support, define what a cluster can do, provide support
    - Professional services -20% revenue –install, configure, provide resident architects, ongoing maintenance
- Proprietary software can sit on top of Hadoop
- Infrastructure -Schema on read
    - System picks up on what data is uploaded
    - Can provide metadata
    - Add maps to data
    - Apache Foundation seen to steer innovation where it happens -providing the next generation data science libraries -apply to data sets

Use cases

- New paradigm in insurance and data science
- HW works with lots of big insurance companies and banks
- Have an insurance group -GM spent a long time with insurance
- Currently working with 45-60 insurance companies
- Zurich is building a data lake, containing all their legacy data (data warehouses phased out)

- Markel -insurance syndicate in Lloyd's use their technology https://hortonworks.com/customers/markel/
- Working with Munich RE -who are reported to be best in best in 'connected home'
- Enterprise Data Warehouses are being offloaded
  - Insurance firms have been moving away from the traditional EDWs onto a modern data architecture that can handle bigger data volumes, streaming data, unstructured data, embracing a new paradigm in data sources, as well as providing the opportunity to implement modern libraries and methods for Machine Learning and AI.
- Distributed ledgers (Block Chain) is one area being looked at -surrounding app built on Hadoop
- Zeppelin platform can enable companies to pull in interesting data, build up profile of people or firms (considering insuring), can enable them to ask more questions than possible directly
- HW working with 'Risk Listening': this involves insurers monitoring, analysing, and integrating external data sources in real-time (weather feeds, news and stock feeds, and satellite imagery, for example). By integrating and injecting these new data sources into their risk models and underwriting, insurers are better able to identify their risk appetites and effectively price.
- Data Plane management of data applied to insurance data
- Edge resources drawn on –certain types of sensors IoT

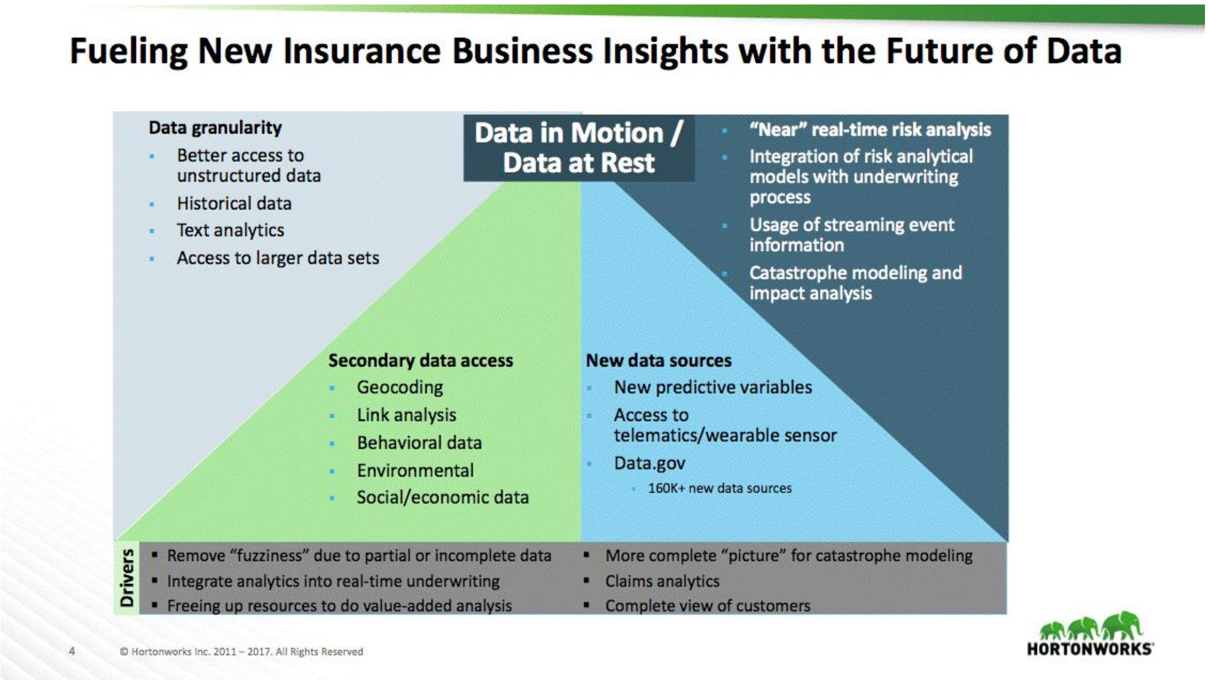
Hadoop opportunities for insurance

- Schema on Read vs. Schema on Write
  - Processing of Streaming Data
  - Application of machine learning for claims
- audit, fraud and subrogation identification
- Usage of text analytics to analyse unstructured data
- Usage of 'graph database' for related entity -fraud analytics

MUNICH RE'S JOURNEY TO THE BIG DATA & ANALYTICS SELF-SERVICE PLATFORM INCLUDING A

CENTRAL DATA LAKE

Munich Re is relying on SAS Analytics and Hortonworks Data Platform (HDP) for its big data initiative. Together with its technology partners, the reinsurer has installed a platform capable of analysing extraordinarily large quantities of data. Using the platform, it is possible to analyse semi-structured and unstructured data – from paper documents to emails and video files. Munich Re also wants to integrate external data such as weather information or sensor data from vehicles, machinery and other networked devices.



Fueling New Insurance Business Insights with the Future of Data
Data granularity
Better access to unstructured data
Historical data
Text analytics
Access to larger data sets
Data in Motion / Data at Rest
"Near" real-time risk analysis
Integration of risk analytical models with underwriting process
Usage of streaming event information
Catastrophe modeling and impact analysis
Secondary data access
Geocoding
Link analysis
Behavioral data
Environmental
Social/economic data
New data sources
New predictive variables
Access to telematics/wearable sensor
Data.gov
160K+ new data sources
Drivers
Remove "fuzziness" due to partial or incomplete data
Integrate analytics into real-time underwriting
Freeing up resources to do value-added analysis
More complete "picture" for catastrophe modeling
Claims analytics
Complete view of customers
4
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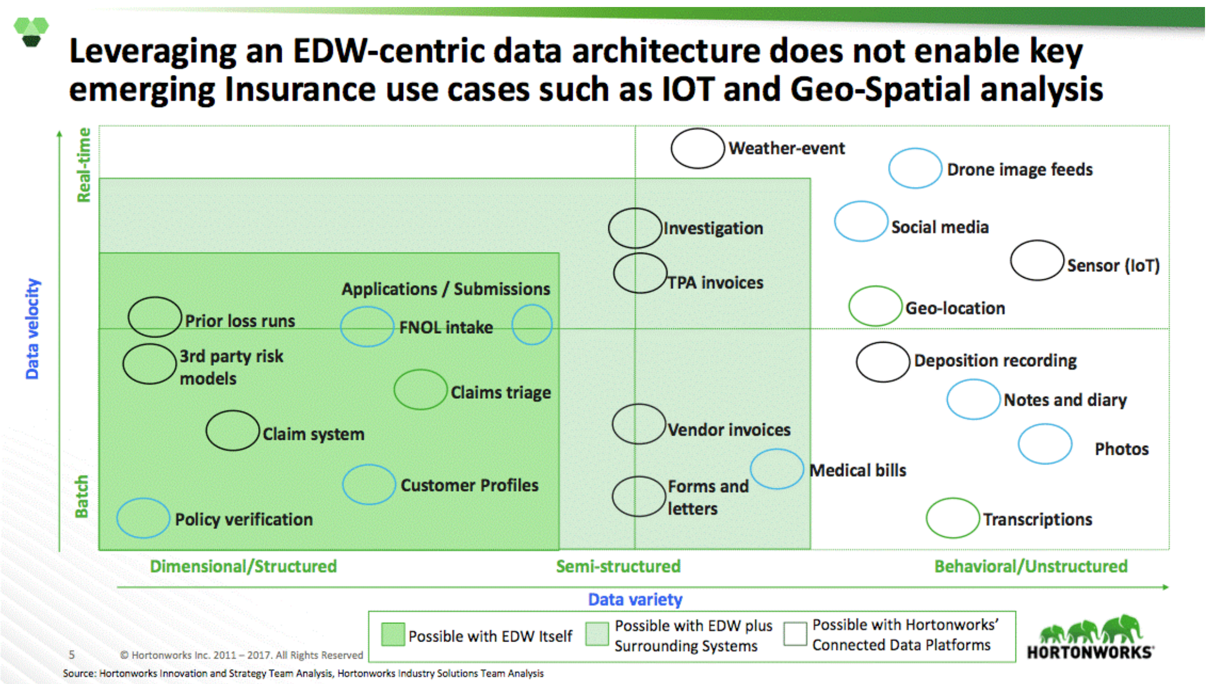

Leveraging an EDW-centric data architecture does not enable key emerging Insurance use cases such as IOT and Geo-Spatial analysis
Data velocity
Real-time
Batch
Weather-event
Drone image feeds
Investigation
Social media
Sensor (IoT)
TPA invoices
Geo-location
Applications / Submissions
Prior loss runs
FNOL intake
3rd party risk models
Claims triage
Deposition recording
Notes and diary
Claim system
Vendor invoices
Photos
Medical bills
Customer Profiles
Forms and letters
Policy verification
Transcriptions
Dimensional/Structured
Semi-structured
Behavioral/Unstructured
Data variety
Possible with EDW Itself
Possible with EDW plus Surrounding Systems
Possible with Hortonworks' Connected Data Platforms
5
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Source: Hortonworks Innovation and Strategy Team Analysis, Hortonworks Industry Solutions Team Analysis
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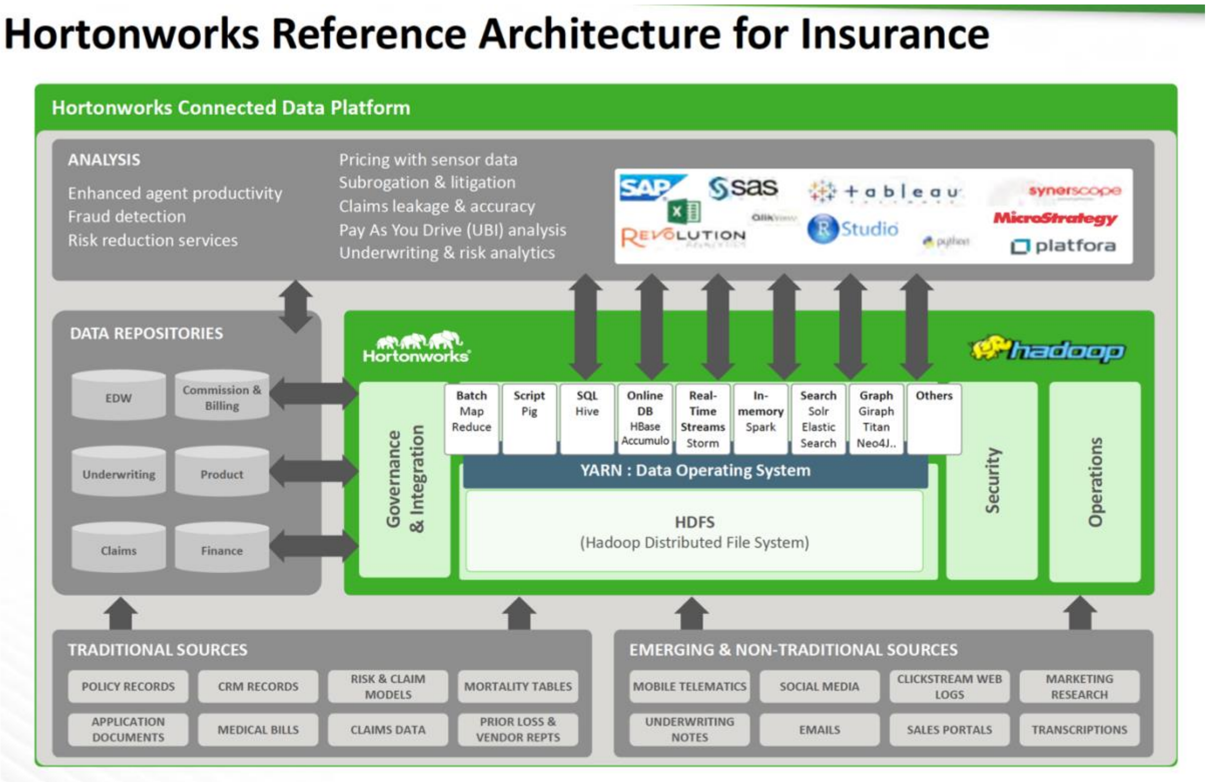

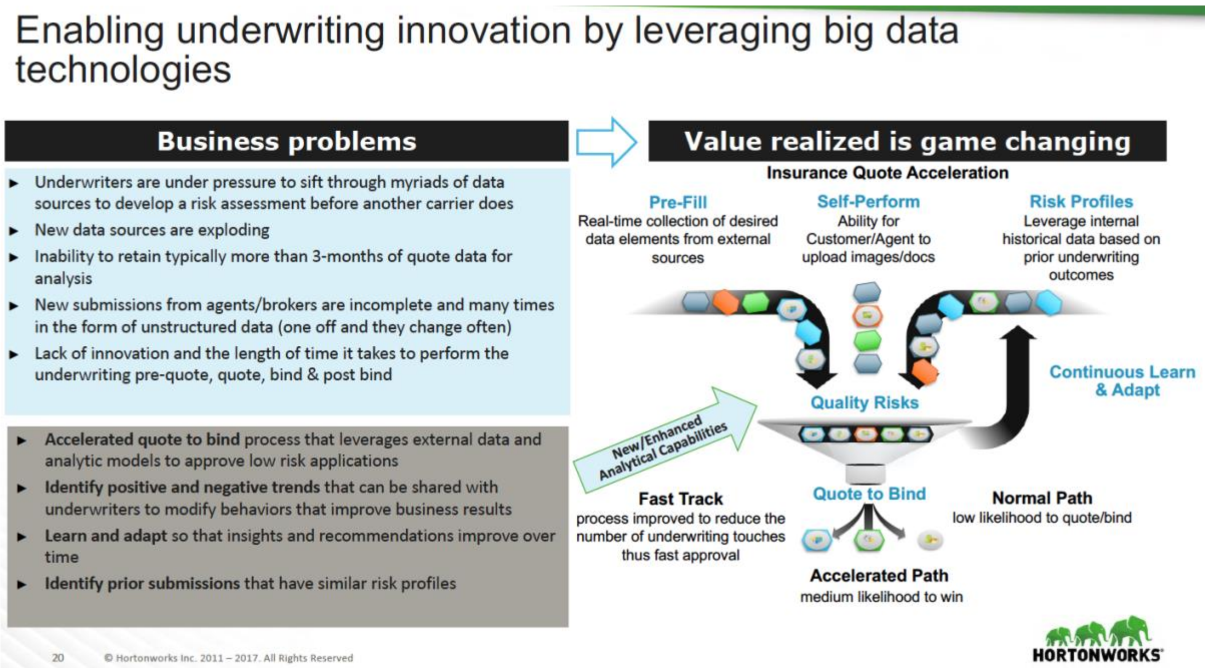

Cloudera (https://www.cloudera.com/solutions/insurance.html) [including interview notes]

Cloudera is a data platform company. The platform is built on open source technology, the same way as Hortonworks (drawing on the Apache Software Foundation products. Pedigree reported as financial services. Cloudera Enterprise provides data processing, machine learning and advanced analytics for both historical and real-time data. Cloudera Enterprise can work across AWS, Google Cloud Platform and Microsoft Azure to support on-premises, hybrid-cloud and full cloud deployments for customers. Through the Data Science Workbench (DSWB) Cloudera can deliver machine learning, AI, deep learning and other techniques natively on the platform

- Data security is a paramount feature of the Cloudera Solution
- Shared data experience - secure access to those across organisation to data when they need it. Secure -all data together –make available to all
- In its proprietary software -Enterprise grade functionality
- Enterprise data management raps around open source components
- 19 of the top 30 banks use Cloudera
- Main banks use Cloudera due to security, data governance
- Using Cloudera platform to combine internal and external data
- Resonates with how Cloudera operates
- Framework of Big Data -Where Cloudera can fit in
    - Process different data sources –structure/unstructured data
    - Single platform -not silos separate databases
    - Cloudera is platform -Enterprise data hub
    - Platform flexibility of schema
    - Scalable
    - Platform provide all data governance, management, security that open source community does not
    - When data is in the platform -multiple different use cases possible
    - Many ways to consume data
    - Can deliver advanced analytics, plug in BI, machine learning
- Cloudera Engineers are committers of code to the Apache Foundation
- Cloudera Enterprise provides the security, governance & management capabilities that enterprises demand - these aren't met by the open source tooling alone and so Cloudera provides proprietary software to deliver this necessary functionality
- The core of the platform (everything that stores and analyses the data) is 100% open source
- Cloudera continues to be a significant contributor to the open source community and has 100+ committers to the Apache Software Foundation
- When the data is in Cloudera's platform, customers can serve that data to many different consumers of the data through a variety of applications - that could be BI tools, semantic search, SQL, data science tools etc. etc.
- All of this is done in a secure and governed fashion
- Cloudera is optimised for the cloud, but many customers run on-premise, or in a hybrid environment of both

Insurance use case

A Challenge highlighted: ‘Having traditionally relied on structured data to make decisions, insurers are now faced with a rapidly expanding wealth of unstructured data from internal and external sources. With the amount of unstructured data growing faster than structured, managing this new complexity is a key challenge for insurers.'

- Machine learning is creating many new opportunities for insurers
- One way it's improving on the performance of traditional analysis or human judgement is 'submission prioritisation'
- helping insurers to predict premiums, conversion and how much a policy is likely to cost them more accurately.
- machine learning is helping to power smarter decisions is when a claim has been made and a settlement needs to be reached. Insurers could save millions by reaching settlements faster, carrying out smarter, more targeted investigations and managing cases more effectively
- Cloudera helped a leading UK-based general insurance company to improve the performance of its insurer hosted rating hub, enabling it to access 95% more quote data
- Accurate assessments of risk -require access all data from all sources
- Historically problem for insurers to access this
- Cloudera Platform enables access of data at scale
    - Put all data in a single place
    - To leverage risk
    - What Cloudera does for most insurers -typical use case
- Use cases on Website
- Experience in the insurance industry
- Lloyd's was a Cloudera customer until 2015
- Use case in Cargo industry, Cargotec used an IoT-as-a-Service solution using machine learning to derive insights from streams of data across the thousands of cargo handling equipment and machinery to enable remote monitoring and predictive maintenance
- Octo Telematics are using Cloudera to ingest 11 billion data points daily to improve customer experience

Teradata (https://www.teradata.com)

Teradata is an enterprise software company that develops and sells database analytics software, using Cloud and hardware-based data warehousing. In relation to Big Data, Teradata acquired Aster Data Systems in 2011 for the company's MapReduce capabilities and ability to store and analyse semi-structured data. They have applied an SQL backbone to Hadoop environments to enable multi-user scaling, this has led to development of proprietary software on top of Apache open source software, such as SQL-MapReduce. Teradata provide three main services: business analytics, Cloud products, and consulting. Their solutions are reported to use massively parallel processing across both its physical data warehouse and Cloud storage, such as AWS, Azure, and VMware. Teradata provide a managed Cloud service and one of their server solutions is IntelliFlex is described as having multidimensional flexibility allowing in-memory processing. Teradata offers both Hybrid Cloud and Multi-Cloud storage options.

Teradata provides insurance companies with a number of services. This can include risk management analytics to identify and mitigate emerging risk and exposure management, and:

- Data-driven finance –data integration and proactive analysis,
- Claims and fraud analytics –service and settlement provided to catastrophe claimants
- Underwriting and pricing analytics – standardise pricing across an acquired book of business.
- Customer analytics – understand customer demographics
- Data-driven marketing – use a 360-degree view enhance customer knowledge
- Next generation analytics –digital and mobile opportunities, telematics, SAS in-database processing

Insurance Specific Use Case

Text Analytics for Insurance: Aster Big Data analytics solution

Used for identifying and analysing target communications for customer insight, regulatory compliance, fraud identification, claims efficiency, and litigation discovery. Used by Property & Casualty (P&C) and Life & Retirement (L&R) insurance companies, who have used it to improve the identification of targeted voice and text communications. Aster Analytics enables a series of iterative analytic steps to be executed in a work flow integrating multiple analytic genres. The Aster analytics solution includes more than a dozen NLP and machine learning algorithms that enable insurers to easily determine how communications are taking place and identify the content. It automatically analyses every message, chat, email or post. Combining this with other unstructured data types, such web logs and voice recordings, using the graph and visualisation functions. Aster Analytics delivers multi-genre analytic capabilities supported by NLP, machine learning, MapReduce, graph, statistics, time series, path, and pattern analytic engines in an ANSI SQL environment. It does so using a common optimizer and execution engine and with a unified interface creating capabilities to solve business problems. The solution can simultaneously utilise graph analytics, text analytics, and time series analytics.

RMS (http://www.rms.com/blog/2017/08/10/data-analytics-fueling-the-future-of-insurance/) (From Interview Notes)

RMS Are running operations in the Cloud. It is not deemed effective to port existing code and tech into the Cloud, therefore RMS deem it paramount that future developments should be made in the Cloud environment. One of the drivers for RMS switching to the Cloud is that client want to be able to access big data at scale from across the enterprise, the Cloud allows this. Machine learning is also deemed much more suited to the Cloud due to the possibility for on-demand scaling of compute power. Big Data technology is seen to have a big impact on progress possible in modelling work. In relation to flood modelling, the combination of high-resolution data now available and the increased compute power accessible has had a profound impact on levels of precision possible.

Block chain is also increasingly being looked to by insurers, one reason is that it allows security in workflows.

RMS Risk Modeler is an application developed which is said to incorporate Big Data functionality. http://www.rms.com/software/risk-modeler

LexisNexis (High Performance Computing Cluster) HPCC Systems (http://cdn.hpccsystems.com/pdf/HPCC-Systems-Brochure.pdf)

An open source high performance computing cluster technology. Uses a programming language called Enterprise Control Language (ECL). The system is uses high-performance, parallel processing and delivery for applications using big data. Used by developers and data scientists to process and analyse data at scale. Allows horizontal scalability from one node to thousands of nodes.

HPCC Systems has in place predictive Modelling Tools (supporting distributed linear algebra). The predictive modelling functionality can be used to perform Linear Regression, Logistic Regression, Decision Trees, and Random Forests. For data visualisation one option is the HPCC Systems/Tableau Web Data Connector.

Thor Cluster

The system uses a clustering tool (Hadoop alternative) called Thor. This is designed to execute big data workflows including extraction, loading, cleansing, transformations, linking, and indexing.

- Thor uses a master-slave topology in which slaves provide localized data storage and processing power, while the master monitors and coordinates the activities of the slave nodes and communicates job status information.
- Thor was invented in 1999 by LexisNexis specifically to solve large graph problems.
- Thor enables consumption of large volumes of structured and unstructured data and can convert it into a social graph of people and businesses (for example).
- Thor data can be indexed and deployed to ROXIE for high performance real-time query.

ROXIE Cluster

- Roxie is an index-based search engine to perform real-time queries.
- The ROXIE rapid data delivery cluster provides separate high-performance online query delivery for big data. ROXIE (Rapid Online XML Inquiry Engine) utilizes highly optimized distributed B-tree indexed data structures conceived for high concurrent use.
- Roxie enables query and Search -using SOAP, XML, REST, and SQL interfaces.

Microsoft Azure (https://insurance.azure.com)

Microsoft Azures Cloud environment allows insurance risk modelling workflows to be run on multiple machines in the cloud drawing on additional processing power as required. Azure boasts a 'virtually limitless capacity and unlimited infrastructure resources', enabling workloads to be run faster and more frequently. This enables workflows to be run during off-peak times; unlike on premise server solutions, Azure operates a pay as you use policy.

Use cases

Improving risk, pricing, and reserving through unlimited compute power in the cloud

- insurance firms are turning to high-performance computing grids in the cloud
- This gives actuaries access to elastic compute power
- Ability to run more models and simulations more often, 'the cloud will become mainstream in the insurance industry across multiple workloads'
- Microsoft work with regulators to deal with compliance and to ensure that appropriate security standards are met
- Cortana Analytics and PowerBI can deliver mapping visualisations and analytics to carry out catastrophic risk modelling, enabling measures to be put in place to minimise losses and manage the amount of claims related to an event
- Insurance companies around the world use Willis Towers Watson's MoSes and RiskAgility Financial Modeller actuarial projection systems (https://www.towerswatson.com/en/Services/Tools/riskagility), and the company saw that it could help them to automate scheduling in the cloud.
- Milliman Case: access to information in an almost real-time basis
- FIS CASE: automating and outsourcing production of the numbers, insurers are freeing up human capacity to focus on analytical and planning activities. Can increase the productivity of an actuaries
- Tagetik Case: Tagetik automates and controls the regulatory and risk management reporting process with a single solution that provides built-in financial intelligence and collaborative workflow

Cortana Intelligence Suite and Azure Machine Learning

Event Hubs can ingest millions of events per second and stream them into multiple applications, enabling insurers to process and analyse the massive amounts of data produced by connected devices and applications. Results can be presented on interactive dashboards and visualisations generated through PowerBI. In addition, Cognitive Services and Bot Framework give insurers new cognitive capabilities in vision, speech, text and conversations.

Amazon Web Service (AWS) (https://aws.amazon.com/financial-services/insurance/)

The AWS Cloud includes tools and capabilities to enable a scalable infrastructure and reduce total cost of IT ownership. It provides on demand services and is possible to run SaaS in the Cloud and develop automated workflows. High levels of redundancy can be incorporated in solutions. Possibilities to implement IT infrastructure in code. AWS has been applied to the insurance lifecycle – including underwriting, policy, billing, and claims. Many different option for data storage in the Cloud depending on access requirements, for example S3 storage allows real time access to data and is elastic so that compute power can be scaled as needed allowing users to drawn on the AWS Spot market for processing data at times of lower demand, thus reducing costs. Whilst Glacier storage is a lower cost alternative used for storing archive data.

Insurance Use cases:

- AON run ‘5 million policies in minutes, instead of the standard overnight run times.’
- Radian -draw on infrastructure as code to enable rapid responses to changes in the market.
- MSG Global run their SAP insurance solution on AWS
- IHS Markit use AWS analytics, and enterprise data management solutions
- Guidewire InsuranceSuite offers applications that optimize the insurance lifecycle — through policy, billing, to claims.
- Cognizant Unified Insurance Platform includes core functionalities and integrated features to migrating platforms

Insurers have been utilizing AWS grid computing engines to power actuarial calculations, determine capital requirements, model risk scenarios, price products, and other business operations. Compute-intensive workloads can be taken out of the data centre and into the AWS Cloud. It is possible to run batch processing tasks at scheduled times reducing costs. Grid computing draws on Amazon Elastic Map Reduce (EMR) for data processing through a managed Hadoop framework to distribute and process large amounts of data. Amazon EC2 is also being drawn on. EC2 provides resizable compute capacity. Different EC2 instance types offer varying combinations of CPU, memory, storage, and networking capacity for all workloads. Grid processing using EMR and EC2 instances can be used to run many of the Apache Foundations software and other open source software such as Hadoop, HBase, Spark, Presto and Flink.
AWS can provide the ability to optimize data lifecycles, including collection, ingestion, processing, analytics, short-term storage, and archiving. It supports real-time streaming and analytics, petabyte-scale warehousing, business intelligence tools, and machine learning.