CRANFIELD UNIVERSITY

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Soil-related geohazard assessment for climate-resilient UK infrastructure

School of Energy, Environment and Agrifood

PhD

Academic Year: 2015- 2016

Supervisors: Dr. Stephen Hallett and Dr Timothy Farewell

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This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

ABSTRACT

UK (United Kingdom) infrastructure networks are fundamental for maintaining societal and economic wellbeing. With infrastructure assets predominantly founded in the soil layer (< 1.5m below ground level) they are subject to a range of soil-related geohazards. A literature review identified that geohazards including, clay-related subsidence, sand erosion and soil corrosivity have exerted significant impacts on UK infrastructure to date; often resulting in both long-term degradation and ultimately structural failure of particular assets.

Climate change projections suggest that these geohazards, which are themselves driven by antecedent weather conditions, are likely to increase in magnitude and frequency for certain areas of the UK through the 21st century. Despite this, the incorporation of climate data into geohazard models has seldom been undertaken and never on a national scale for the UK. Furthermore, geohazard risk assessment in UK infrastructure planning policy is fragmented and knowledge is often lacking due to the complexity of modelling chronic hazards in comparison to acute phenomenon such as flooding. With HM Government's recent announcement of £50 million planned infrastructure investment and capital projects, the place of climate resilient infrastructure is increasingly pertinent. The aim of this thesis is therefore to establish whether soil-related geohazard assessments have a role in ensuring climate-resilient UK infrastructure.

Soil moisture projections were calculated using probabilistic weather variables derived from a high-resolution version of the UKCP09 (UK Climate Projections

2009) weather generator. These were then incorporated into a geohazard model to predict Great Britain's (GB) subsidence hazard for the future scenarios of 2030 (2020-2049) and 2050 (2040-2069) as well as the existing climatic baseline (1961-1990). Results suggest that GB is likely to be subject to increased clay-related subsidence in future, particularly in the south east of England.

This thesis has added to scientific understanding through the creation of a novel, national-scale assessment of clay subsidence risk, with future assessments undertaken to 2050. This has been used to help create a soil-informed maintenance strategy for improving the climate resilience of UK local roads, based on an extended case study utilising road condition data for the county of Lincolnshire, UK. Finally, a methodological framework has been created, providing a range of infrastructure climate adaptation stakeholders with a method for incorporating geohazard assessments, informed by climate change projections, into asset management planning and design of new infrastructure.

This research also highlights how infrastructure networks are becoming increasingly interconnected, particularly geographically, and therefore even minor environmental shocks arising from soil-related geohazards can cause significant cascading failures of multiple infrastructure networks. A local infrastructure hotspot analysis methodology and case-study is provided.

Keywords: *UKCP09, Soil geohazards, Geoinformatics, Infrastructure, Climate Change, Resilience*

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But in the end, thanks also to you the reader. If you are reading this line after the others, you at least read one and a bit pages of my thesis!

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LIST OF ABBREVIATIONS

BGS	British Geological Survey
CAPEX	Capital Expenditure
CREW	Community Resilience to Extreme Weather
CVI	Coarse Visual Inspection
Defra	Department for Food, Environment and Rural Affairs
EPSRC	Engineering and Physical Sciences Research Council
FAO	Food and Agricultural Organisation (of the United Nations)
GB	Great Britain
GIS	Geographic Information Systems
ICE	Institution of Civil Engineers
IPCC	Intergovernmental Panel on Climate Change
ITRC	Infrastructure Transitions Research Consortium
IUK	Infrastructure UK
NATMAP	National Soil Map
NPD	Natural Perils Directory
NPS	National Policy Statements
NRR	National Risk Register
NSRI	National Soil Resources Institute
OPEX	Operational Expenditure
UK	United Kingdom
UKCP09	United Kingdom Climate Projections 2009
PET	Potential Evapotranspiration
PPT	Precipitation
PPS	Planning Policy Statement
PSMD	Potential Soil Moisture Deficit
SSWELL	Shrink/swell susceptbility
WG	Weather Generator

1 Introduction

Chapter synopsis

This chapter introduces the research undertaken. The work is presented in respect of the wider auspices of the Infrastructure Transitions Research Consortium project (ITRC). Also described are the research contributions, dissemination activities, and aims and objectives, as well as the overall structure of the thesis.

'The soil varies from place to place, and many of its properties vary in time too. This is what makes the soil so fascinating'

(Heuvelink & Webster, 2001)

1.1 Background and Context

Infrastructure is the backbone of the UK's (United Kingdom) economic, social and physical wellbeing (Defra, 2013). The Department for Environment, Food and Rural Affairs (Defra) vision for infrastructure is: '*An infrastructure network that is resilient to today's natural hazards and prepared for the future changing climate'* (Defra, 2013).

A number of soil properties, when impacted upon by climatic factors, can manifest into a range of geohazards. The term geohazard is defined here as an environmental phenomenon capable of causing damage or risk to people and the built environment (Forster & Culshaw, 2004). Soil-related geohazards in the UK include; clay-related subsidence (shrink/swell), corrosion (to buried ferrous metal), erosion and landslides.

To enhance resilience, infrastructure operators, owners, designers, engineers and policy-makers require an awareness of the potential impacts that soil geohazards and climate change can exert on UK infrastructure. However, the impact of climatic change on the frequency and magnitude of soil-related geohazards is as yet far from understood and has been subject to relatively little research to date. Although soil-related subsidence, for example, was highlighted in Defra's recent climate change risk assessment (Defra, 2013), in some instances the UK construction industry and the bodies maintaining infrastructure assets demonstrate a lack of awareness concerning ground movement and potential climate change issues. Often, this results from their compliance with standards that are devoid of climate adaptation methods (Vivian et al. 2005).

The use of soil information for predicting the likelihood of soil-related geohazards in the UK has been established by several studies (e.g. Brink et al. 1982; Simonson 1974; Hartnup & Jarvis 1979) and one national soil-related geohazard dataset exists (Hallett et al. 1994). Moreover, the previous CREW (EPSRC 'Community Resilience to Extreme Weather' EP/F036795/1) project demonstrated the feasibility of using probabilistic climate data (UKCP09) together with appropriate soil information to provide estimates of the likelihood and spatial occurrence of clay-related subsidence, for a range of future scenarios (e.g. 2030 and 2050) (Blenkinsop et al. 2010).

This thesis aims to investigate the role of soil-related geohazard assessments in planning, delivering and maintaining climate resilient infrastructure. A version of the UKCP09 (Jenkins et al. 2009) spatially correlated weather generator is used to create a probabilistic estimation of UK climate for the time periods of current baseline (1961-1990), 2030 (2020-2049) and 2050 (2040-2069). This data is then incorporated within an existing geohazard model to provide a novel estimation of future geohazard risk for the entirety of England, Scotland and Wales.

1.2 Scope and ITRC

Funding for this doctoral research was provided by the EPSRC-sponsored, Infrastructure Transitions Research Consortium (ITRC, EP/I01344X/1). ITRC is a 5-year research project (concluding in late 2015) which has developed a new generation of infrastructure system simulation model and tools, informing the analysis, planning and design of National Infrastructure. The ITRC work streams are presented in Figure 1-1, with this research falling within Work Stream 2, 'Understanding future risks of infrastructure failure'.

The main purpose of this doctoral project was to establish the current risks posed by a range of soil-related geohazards to UK infrastructure networks, and subsequently, how these risks may change for future climate scenarios. Climate models have been applied and incorporated into soil-related geohazard models to assess the future risks that infrastructure may face over a range of future climatic scenarios with the principal aim of ensuring a climate-resilient UK infrastructure network.

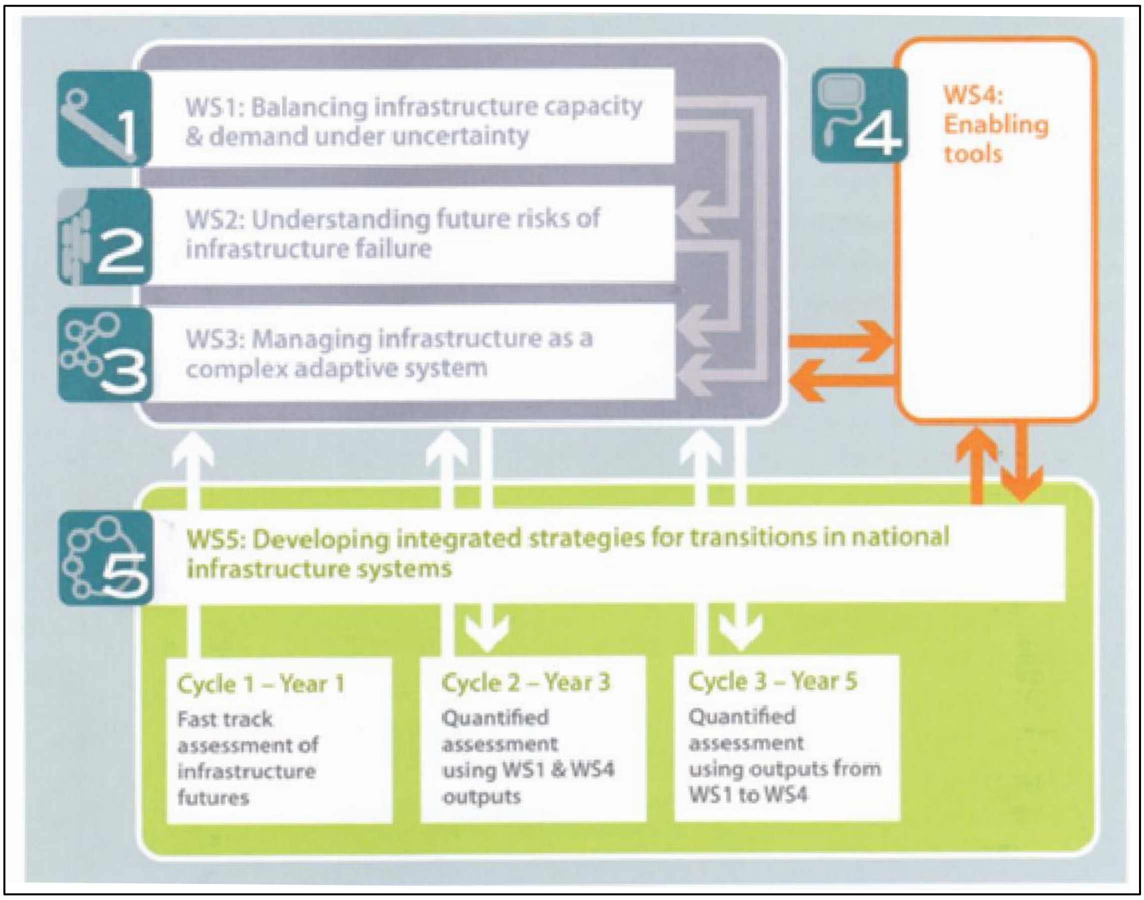


Figure 1-1: Overview of the ITRC Work Stream (WS) Structure (Source: Hall et al. 2012)

1.3 Research Objectives

1.3.1 Aim

Based upon the literature review (Chapters 1.5 & 3), it was established that little prior research exists regarding forward-looking semi-quantitative assessments of soil-related geohazard risk. There is also a consequent lack of understanding as to how such assessments could help inform the planning, development and maintenance of UK infrastructure networks for future scenarios.

The aim of this research is therefore:

To establish the role of soil-related geohazard assessments in delivering, planning and maintaining climate-resilient infrastructure

1.3.2 Hypotheses

The research takes two hypotheses:

UK infrastructure networks are currently susceptible to the perils of soil-related geohazards

and;

Climate change will likely increase the impact of these soil-related geohazards on UK infrastructure.

1.3.3 Objectives

In order to explore and test these aims and hypotheses, a series of objectives have been developed:

1. To undertake a critical review of the soil-related geohazard processes which impact upon UK infrastructure.

2. To incorporate UKCP09 climate projection data within soil geohazard models for assessing future spatial geohazard distribution.

3. To investigate the current failure and degradation of infrastructure networks, as well as future probability as a result of soil-related geohazards through a case-study analysis.

4. To establish the impact of soils on national infrastructure fragility.

5. To develop a national framework methodology to support mitigation of the impacts of soil-related geohazards on UK infrastructure.

1.4 Summary of thesis structure

The thesis is written in a traditional format. However, several papers and articles have arisen from the findings of this research (Section 1.4.1). The thesis is subsequently divided into seven chapters with the following synopsis providing a summary of each chapter's contents:

Chapter 2 – Soil impacts on UK infrastructure: Current and Future Climate;

This chapter presents a critical review of the literature regarding the impacts of soil on UK infrastructure networks; both considering current and future weather and climate scenarios. It addresses the need for a national framework methodology to be developed in order to help policy-makers and infrastructure asset managers better understand the future impacts of soil-related geohazards to the UK infrastructure network under a changing climate. This chapter is based upon a publication in *Proceedings of the ICE: Engineering Sustainability* (Pritchard et al. 2014a).

Chapter 3 – Application of soil-related geohazard modelling to civil engineering, planning and development: Past, present and future;

This chapter discusses the history and development of soil-related geohazard assessments in the UK. It provides a background to the soil surveys of England

and Wales, and Scotland. Finally it introduces the role of soil-geohazard maps in planning and policy and the datasets which are currently available.

Chapter 4 – Probabilistic soil moisture projections to assess Great Britain's clay-related subsidence hazard;

This chapter presents the methodology for creating a novel, future-outlook clay-related subsidence hazard map for Great Britain. A UKCP09-derived version of the 5 km grid resolution spatial weather generator is used to derive probabilistic estimates of potential soil moisture deficit. This data is then incorporated into an existing geohazard model. This chapter is based upon a publication in *Climatic Change* (Pritchard et al. 2015a).

Chapter 5 – Soil geohazard mapping for improved asset management of UK local roads;

This chapter develops and assesses the use of a soil informed maintenance strategy for the asset management of UK local roads. It considers the impact of soil-related geohazards to the local road network, drawing on a case study from the UK administrative county of Lincolnshire. This chapter is based upon a paper accepted in *Natural Hazards and Earth System Sciences* (Pritchard et al. 2015b).

Chapter 6 – Making UK infrastructure resilient to chronic geohazards under climate change: A framework for governance;

This chapter brings together information from the prior chapters of the thesis to provide a framework methodology to inform policy-makers and planners in identifying UK infrastructure networks that are likely to be affected by soil-related geohazards under climate change scenarios.

Chapter 7 –Synthesis and Conclusions;

This chapter presents a synthesis of the thesis, drawing on conclusions and contributions to knowledge. This is approached through revisiting the aims and objectives, discussing how each have been addressed in the course of the thesis research. Finally, recommendations as well as directions for further research are provided.

1.5 Definitions

A number of definitions exist for the principal terminologies adopted in this thesis. Below are definitions, selected from the literature, with interpretations that this thesis has adopted:

- *Adaptation* – Adjustments in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (McCarthy et al. 2001).
- *Hazard* – A condition with the potential for causing an undesirable consequence (Fell et al., 2008).
- *Geohazard* - an environmental phenomenon capable of causing harm to both life and the built environment.
- *Vulnerability* – degree to which a system (or network) is likely to experience harm due to exposure to a hazard (Füssel 2007)
- *Exposure* – the extent and value of infrastructure affected by a named hazard (Fedeski & Gwilliam 2007).
- *Risk* – A function of the probability and severity of an adverse effect to health, built environment and environment (Fell et al., 2008).

$$Risk = \int (exposure, hazard, vulnerability)$$

- *Clay-related subsidence* – the volumetric shrinkage and swelling of susceptible clay soils under differing moisture contents.

- *Soil corrosion* – the corrosion of buried metallic objects (e.g. pipelines) caused by a range of soil properties.
- *Sand-washout* – The erosion of sandy soil under movement of water which can lead to cavitation.

1.6 Research Contribution

From the literature review (Chapters 2 & 3), this thesis revealed a lack of current forward-looking approaches, incorporating climate projections, as a means to assess UK infrastructure vulnerability to soil-related geohazards. Furthermore, a suitable methodological framework for both policy and industry decision-making is required.

As such, the novel contributions of this research to the topic area are as follows:

1. From the literature review, this thesis found that forward-looking approaches as a means to assess UK infrastructure vulnerability to soil-related geohazards are currently lacking. Furthermore, a suitable methodology for both policy and practice is required.

2. Creation of a novel assessment of clay-related subsidence hazard, incorporating high-resolution UKCP09 climate projections for the entirety of Great Britain.

3. The creation of a risk assessment methodology for assessing the impact of geohazards on UK local roads both now and in future climate scenarios. The methodology was tested on the local road network of Lincolnshire. This approach has now been fully implemented within the County asset management planning, and the approach also has applicability for all UK local authorities.

4. Development of a framework methodology, for both policy and practice, which outlines areas of potential vulnerability to UK infrastructure networks as a result of soil-related geohazards under a changing climate.

1.7 Dissemination from PhD thesis

This section provides the reader with an indication of publications, conference presentations and other relevant dissemination of the research presented in this thesis.

1.7.1 Journal publications

The following peer-reviewed journal publications have arisen from the research conducted in this thesis, subsequently forming various chapters. O. Pritchard has been first author on all papers, having written content, undertaken analysis and presented conclusions. S. Hallett and T. Farewell have contributed by editing papers, preparing selected figures and aiding with data processing. All papers at the time of writing of this thesis have been accepted and are published in the respective journals. There is a further intention to adapt and submit Chapter 6 to the *Journal of Environmental Policy* following thesis submission. A bibliography of the published papers is presented below:

Pritchard, OG., Hallett, SH., Farewell, TS. 2014. Soil impacts on UK infrastructure: current and future climate. Proceedings of the Institution of Civil Engineers: Engineering Sustainability. 167(4): 170-184. doi: 10.1680/ensu.13.00035

Pritchard, O., Hallett, S., Farewell, T. 2014. Cracking up in Lincolnshire. *Geoscientist*, 24(2): 14-19

Pritchard, OG., Hallett, SH., Farewell, TS. 2015. Probabilistic soil moisture projections to assess Great Britain's future clay-related subsidence hazard. *Climatic Change*.133(4): 635-650 doi: 10.1007/s10584-015-1486-z

Pritchard, OG., Hallett, SH., Farewell, TS. 2015. Soil geohazard mapping for improved asset management of UK local roads. *Natural Hazards and Earth System Sciences*. 15(9): 2079-2090. doi: 10.5194/nhess-15-1-2015

1.7.2 Conference presentations

A number of conference, seminar and technical group talks have been provided which relate directly to the research undertaken in this thesis, including:

Pritchard, OG., Hallett, SH., Farewell, TS. *Effects of extreme hazards on infrastructure*. Responding to and mitigating the impacts of extreme weather. Policy Knowledge. Bristol Hotel, Bristol, April 9th 2014

Pritchard, OG., Hallett, SH., Farewell, TS. *The impact of soils and changing environment on buried water infrastructure*. Association for Geographical Information (AGI) Asset Management Special Interest Group Seminar: Water Sector. Arup, Bristol, September 9th 2014

Pritchard, OG., Hallett, SH., Farewell, TS. *Soil-related geohazard assessments for maintaining the UK's minor road network*. European Geosciences Union, General Assembly 2015. Vienna, Austria, April 16th 2015

Pritchard, OG., Hallett, SH., Farewell, TS. *Soil-related geohazard assessments for maintaining the UK's minor road network: a Lincolnshire case study*. Midlands Service Improvement Group, Leicestershire County Council Offices, Leicester, July 7th 2015

Pritchard, OG., Hallett, SH., Farewell, TS. *Geohazards to infrastructure*: *Cracking up in Lincolnshire*. The future of national infrastructure: Outcomes from the ITRC. Institution of Civil Engineers, London, October 15th, 2015

1.7.3 Other dissemination and impacts

A number of working papers arising from the initial literature review process can be found on the ITRC website at: http://www.itrc.org.uk/category/theme/geohazards/. A selection of papers and reports were submitted as evidence to the Department for Transport's, 2014 *Transport resilience review: a review of the resilience of the transport network to extreme weather events* (DfT, 2014).

A journal paper arising from Chapter 4 (Pritchard et al. 2015a) was submitted to the 2015 *Lloyd's Science of Risk Prize*, where it was shortlisted and awarded *Special Merit* in the category "Big Data Analytics and Machine Learning". The research presented in Chapter 5 was selected to form an EPSRC case study in 'Big Data' research, demonstrating the practical impacts of funded research. This case study was entitled *'Big data research prevents cracking up'*, dated 12 June 2015, and is available at: https://www.epsrc.ac.uk /newsevents/casestudies /bigdata1/.

2 Soil impacts on UK infrastructure: current and future climate

Chapter synopsis

This chapter undertakes a critical review of the literature concerning mechanisms and impacts of soil-related geohazards to UK infrastructure. Conclusions presented form the recommendation for a national framework methodology to manage future risks posed by soil geohazards to UK infrastructure. This chapter is based upon a publication in the *Proceedings of the Institution of Civil Engineers: Engineering Sustainability (Pritchard et al. 2014a)*.

2.1 Introduction

The UK's critical infrastructure forms the backbone of economic, social, and physical wellbeing (Defra, 2013). Infrastructure provision in the UK is threatened by climate change and extreme climatic events (Defra, 2011; Hall et al. 2006; Hall et al. 2013), and is comparable with other immediate threats including international terrorism, cyber-attacks and major accidents (HM Government, 2010). The UK Department of Environment, Food and Rural Affairs (Defra, 2013) vision for infrastructure is to create '*an infrastructure network that is resilient to today's natural hazards and prepared for the future changing climate*'.

The majority of the UK's physical infrastructure assets have foundations within the soil (i.e. not resting on bedrock), predominantly within a depth of 1.5m below ground level (Busby et al. 2012), and are often co-located (Figure 2-1). However, the impact of climatic change on soil-related geohazard processes and consequently on infrastructure networks were previously far from understood in both research and existing policy. Climate and infrastructure resilience is the basis of many UK national infrastructure assessment reports (HM Treasury, 2013; Cabinet Office, 2011; Royal Academy of Engineers, 2012; CST, 2009). Hall et al. (2006) argue that infrastructure systems (often extensive and linear) are not ‘static artefacts constructed in a stable environment’, but are instead at the mercy of diverse ground conditions and hazards.

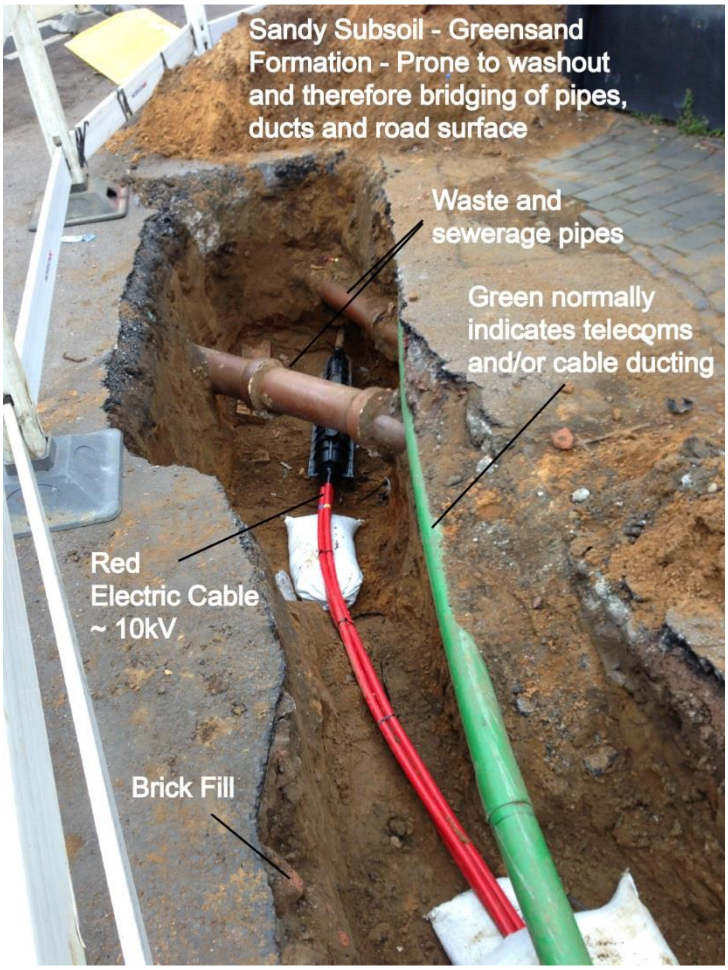


Figure 2-1: Complexity of underground assets, Ampthill, Bedfordshire

This review concerns the *natural* soils within this upper 1-1.5m of the ground surface, rather than *anthropic* engineered soil systems (‘*technosols*’); albeit that the same mechanisms can exist and develop in the latter. *Natural* soils are inherently varying and complex and, in the UK, comprise some 700+ soil types (Keay et al. 2009).

Infrastructure operators, designers, engineers and policy makers need to be aware of the impacts that soil geohazards and climate change may exert upon UK infrastructure networks. In some instances, the UK construction industry and the bodies maintaining infrastructure assets demonstrate a lack of awareness concerning potential climate change issues. Often this is due to their reliance on standards that are often devoid of climate adaptation methods (Vivian et al. 2005).

Section 2.2 of this chapter reviews the principle soil geohazards impacting upon UK infrastructure, specifically that operated by the utilities (i.e. water, wastewater, energy) and transport sectors. Discussion of infrastructure resilience to geohazards is considered, including the observation that it is often a combination of soil factors that lead to actual asset failure. Section 2.9 describes the impact of projected climate change on these soil processes, highlighting how this may affect the magnitude and frequency of soil-related geohazards, and also considering the inherent uncertainty in probabilistic geohazard modelling. Finally, Section 2.10 discusses the need for a national framework methodology, allowing knowledge sharing and mitigation against soil-related geohazards for future projected climatic scenarios.

2.2 Soil geohazards

The UK is not subject to large-impact geohazards, such as high magnitude earthquakes and volcanoes. Landslides represent the highest magnitude geohazard typically impacting UK's infrastructure. The most prevalent soil-related impacts on UK infrastructure include ground movement, corrosivity and mass movement, or solifluction Table 2-1. This section aims to provide a brief interpretation of each geohazard mechanism and its potential impact upon UK infrastructure.

Table 2-1: Summary of key mechanisms, responses and consequences of soil-related geohazards to UK infrastructure (after Farewell et al. 2012 and Hallett et al. 1994)

Mechanism	Response	Consequence
Shrink-swell	Ground Movement	Subsidence
Sand washout		Pipe failure
Bearing strength and Compressibility		Instability on minor roads
		Instability in clay-rich embankments
Salt concentration	Corrosion	Pipe failure
Soil redox potential		Failure of concrete structures
Waterlogging		
pH		
Erosion	Mass Movement	Electricity network disruption (e.g. pylon damage)
Landslides		Interruption of transport infrastructure

2.2.1 Ground movement

Soil-related ground movement is recognised as a potential hazard to national infrastructure (Cabinet Office, 2011). Table 2-1 identifies the processes resulting in soil-related ground movements in the UK, including clay shrinkage and swelling; sand washout; soft (compressible) soil movement; and peat shrinkage (Farewell et al. 2012; Hallett et al. 1994).

2.2.2 Clay-related shrink-swell

The volumetric shrinkage of susceptible silicate clays is considered to present the most prevalent and damaging soil-related geohazard to infrastructure, commercial buildings, and domestic dwellings (Culshaw & Harrison, 2010). The amount of shrinkage is controlled by clay mineralogy and seasonal moisture flux (Reeve & Hall 1978). Shrink-swell susceptible clay minerals (i.e. smectite, montmorillionite and vermiculite) have high surface areas, with a 2:1 layer lattice onto which water bonds (Brink et al. 1982). Increased water content results in significant inter-layer expansion (swell) and with water loss, subsequent contraction (shrinkage). However, not all 2:1 clays are susceptible to shrink-swell, i.e. Illite (mica) and chlorite (Brady & Weil 2002). During spring and summer months, when evapotranspiration progressively exceeds rainfall, soil moisture deficits (SMD) develop as soils dry out from the surface downwards. Typically, UK SMD affects the top 1.0-1.5m of soil, but in particularly dry years or during drought conditions, this can reach greater depths (Clarke & Smethurst, 2010; Corti et al. 2009; Hawkins, 2013).

SMD can be exacerbated by the presence of large vegetation, particularly high water demand trees (Biddle, 1998; Sanders & Phillipson, 2003). Cracks in clay soils allow roots to penetrate deeper, consequently resulting in deeper soil drying and further shrinkage (Clarke & Smethurst, 2010). Surface soil and debris falling into wedge-shaped shrinkage cracks may lead to subsequent heave and lateral pressure on re-swelling of clays in wetter winter months, this can potentially result in further damage to infrastructure assets (Forster et al. 2006; Brady & Weil, 2002) (Figure 2-2).

2.2.3 Sand washout

Sandy soils, which contain more than 70% by weight sand sized particles (0.06 to 2.0mm) are particularly susceptible to erosional processes or washout, with excess water resulting in running-sand conditions (Brink *et al*. 1982).

2.2.4 Soft and compressible soils – Bearing Strength

If the soil is not strong enough to support the loads applied from infrastructure (e.g. buildings, roads or buried pipes), or the presence of overburden (e.g. embankments), then compression can lead to settlement, deformation and ultimate failure of the infrastructure (Kechavarzi et al. 2010; MacKellar & Stott, 2011). Compressible soils include alluvium (of fluvial, marine and lacustrine source), organic clays and peats. Organic soils (i.e. peats) are known for their poor bearing capacity due to large pore structure and high water content, which can be up to ten times the solid soil weight (Hall et al. 1977; Page, 1998). Alluvial clays often have a firm crust which is not representative of the clay beneath, often causing settlement under loading (BRE, 1993).

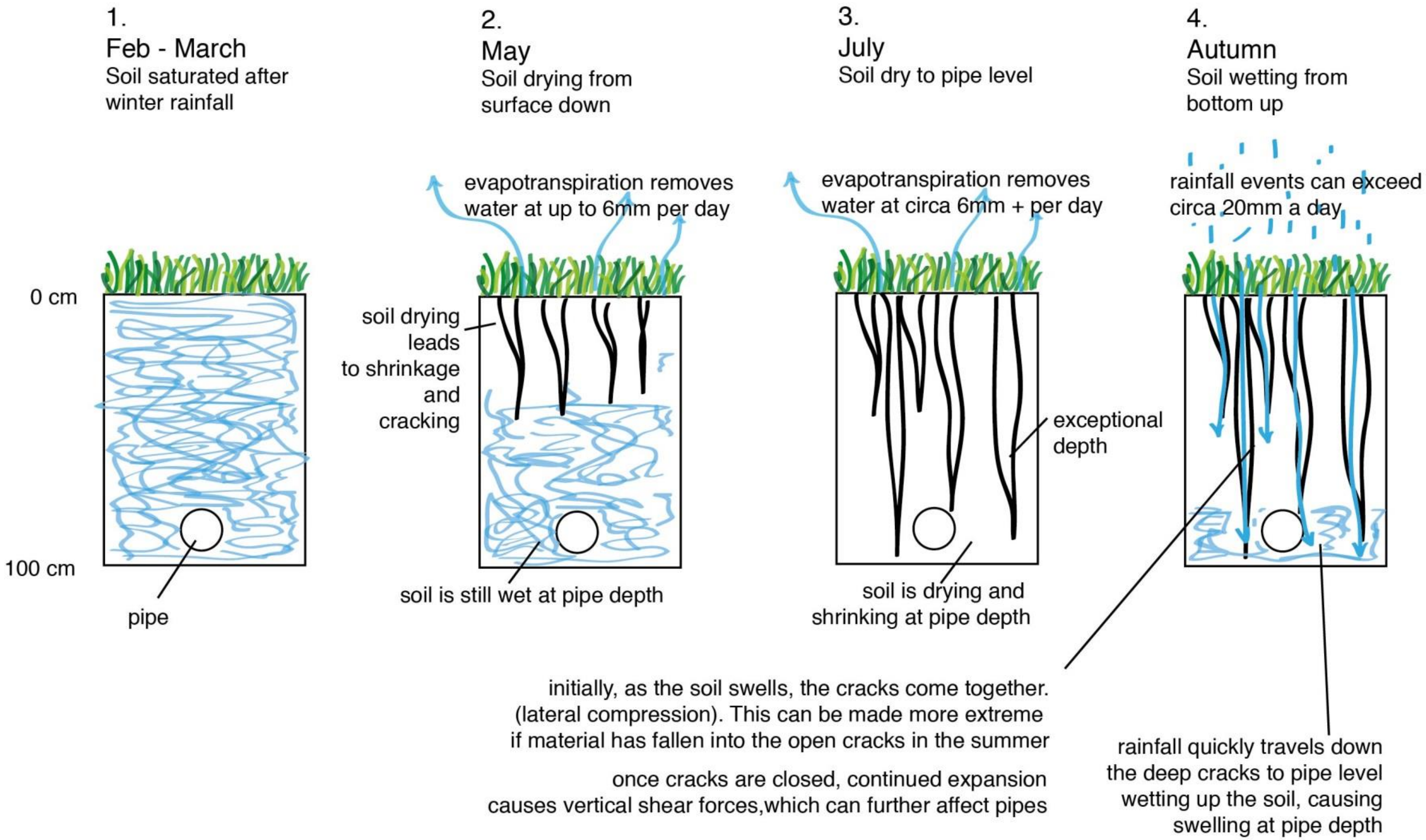


Figure 2-2: The seasonal processes affecting soil movement and pipe failure

2.3 Ground movement impact on infrastructure

Shrink-swell susceptible clays are the cause of the most damaging form of ground movement, estimated to cost the UK between £300-400 million per year (Forster et al. 2006). Approximately 80% of domestic subsidence claims arise as a result of susceptible clays (Page 1998). The south-east of England is at highest risk due to the geographical combination of shrinkable clays in these areas, together with commonly high SMDs.

2.3.1 Built structures

Most damage from ground movement occurs on light, brittle structures, such as 1 or 2 storey buildings (Jones & Jefferson, 2012). Here, swelling soils have the potential to exert high (~200 kN m^{-3}) pressures on foundations (Johnson 1982). Infrastructure assets, particularly those with strip foundations at shallow depths, are at the greatest risk of soil-related subsidence. Such structures include, pumping stations, sewage treatment works, recycling facilities, distribution network substations, and telephone exchanges.

2.3.2 Utilities

The wetting of shrinkable clay soils can lead to considerable and rapid volumetric expansion, which can fracture pipes carrying water, wastewater, oil, natural gas or other substances, such as CO_2 for carbon capture and storage (Koornneef et al. 2009). There are numerous mechanisms by which buried utilities fail and, of these, fractures are the most contributory to water leakage (Clayton et al. 2010).

The failure of drains and water mains can lead to the egress of water, that when sustained, or at high pressure can result in ground movements affecting other proximal buried services. Often pipes are located extremely close to one another (~10-50 cm), especially in congested urban areas (Burton 2001). Hawkins (2013) argues that utilities entering structures are likely to suffer differential settlement as a result of the building's influence on local soil moisture regimes. Failure of utilities could then result in further/additional damage to structures (e.g. escaping water wetting cohesive soils and reducing bearing strength, or forming washed out cavities).

In coarse-grained soils (i.e. sand/gravel), escaping water originating from a fractured pipe can form a highly abrasive soil-water slurry. In one example, a high-pressure water pipe failed in close proximity to two 6 month old [PVC] gas pipes. The resultant abrasive soil-water slurry led to a rapid thinning of the PVC gas pipes, causing their eventual rupture (Majid et al. 2010). Failure of gas/oil pipes, especially those routed through urban areas can pose significant secondary risks to human life (Jo & Ahn, 2005).

The UK's water industry regulator Ofwat (2004) reported the UK sewer network to be significantly cracked or deformed, resulting in higher vulnerability to future ground movement. Studies argue that between 23-33% of sewer to manhole connections are faulty (Davies et al. 2001). Maintenance activities (e.g. drain jetting) can also lead to local infrastructure failure with subsoils being washed out, damaging other nearby services, e.g. water mains (BBC, 2013b).

Overhead electricity and telecommunication transmission lines can also be susceptible to ground-related movement, especially wooden, singular pylons (Figure 2-3).

Figure 2-3: A section of the A1011, Bates Drove, Norfolk, showing leaning telecommunications pylon (left) and undulating road surface due to soil shrinkage.

2.3.3 Transport

Highways are particularly vulnerable to ground movement, due to their light construction and potential to become brittle after road-material oxidation (Wu, 2009). Major highways in the UK (motorways and 'A' classified roads) are well engineered and are designed to cope with potential geohazards (Chaddock and Roberts, 2006; TRRL, 1984). However, minor roads, representing 98% of the UK's highway network (Defra, 2013) are more susceptible to soil hazards due to their direct proximity to unengineered soils. Soil subsidence and surface water run off present the main geotechnical risks, both likely to be exacerbated by projected climatic change (ADEPT 2009).

Following droughts in 2003, a significant deterioration in road quality was identified by several East Anglian council authorities. The East Anglian region has a high proportion of shrink-swell susceptible clay and low bearing capacity peat soils. Many of the roads on these soils have been subject to differential settlement, resulting in severe cracking and undulating morphologies, necessitating speed restrictions or road closures. Addressing these issues has led to maintenance costs totalling millions of pounds (ADEPT 2009). Figure 2-4 presents the mechanisms leading to road failure as a result of shrink-swell susceptible clay soils.

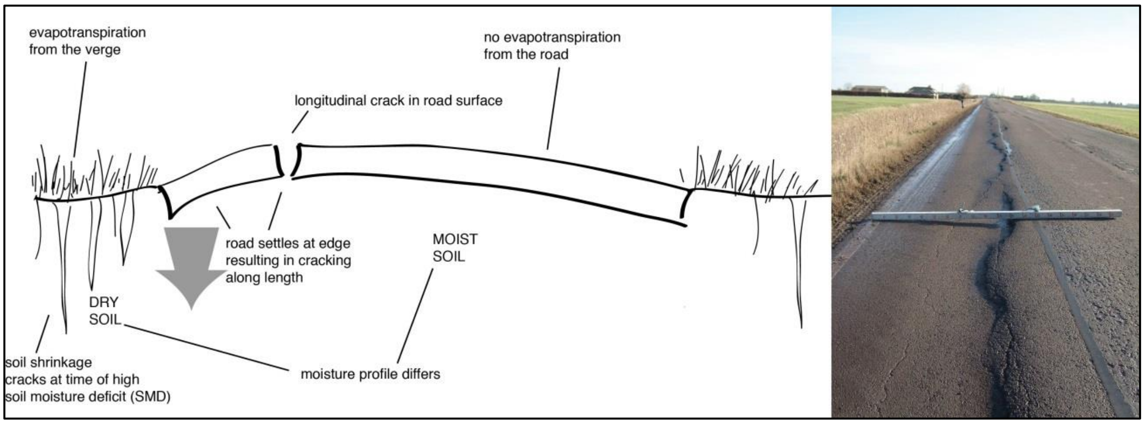


Figure 2-4: Soil processes leading to longitudinal road cracking and with photo example from Fodderdyke, Lincolnshire (Photo: Lincolnshire County Council)

Railway embankments and cuttings are at risk from the cyclical swelling of clay soils, resulting in undulating tracks and landslip initiation. Where railways rest on soft and compressible soils, for example, peat bogs, track deformation can lead to a necessary imposed reduction in train speeds (Hendry et al. 2010). The Stainforth Landslide in 2013, caused by colliery waste spoil surcharging compressible (saturated) alluvial deposits, followed a significant period of extreme rainfall and caused closure of a main railway line for five months with consequent revenue losses to the rail operator (Network Rail, 2013; BGS, 2013).

2.4 Soil corrosivity

Corrosion affects almost all metals, as they react with their environment (Bradford, 2001). The predominant deterioration mechanism on the exterior of cast and ductile iron, representing much of the UK's water infrastructure, is electro-chemical corrosion at the soil-metal interface, resulting in corrosion pits (Rajani & Kleiner 2001) that enlarge to the point of failure.

Contributing factors to soil corrosivity include: the concentration of soluble salts in the surrounding soil (sulphates and chlorides); pH; soil resistivity; temperature; and soil redox potential (Rajani et al. 2012; Md. Noor et al. 2012; Jiang et al. 2011). However, moisture content is the most consistent factor regulating soil resistivity (Cole & Marney, 2012; Laver & Griffiths, 2001). Soil resistivity is indicative of the ability of a soil environment to carry corrosion currents, being regarded as the most common indicator of soil corrosivity (Bradford, 2001). The prevalence of moisture and mineral salts in soils mean they act as good electrolytes (Payne, 1999), essential in the redox reactions that occur during the corrosion process.

In anaerobic (oxygen depleted) soil environments, it is generally assumed that microbial activity is the main influence on corrosion. Microbial activity of sulphate-reducing bacteria (SRB) produces hydrogen sulphide (H_2S), during the reduction of soil sulphates (Pankhania, 1988). Knowledge of localised soil conditions therefore plays an important and cost-effective role in determining routes and materials for pipe laying, as well as in the design of cathodic protection schemes for buried infrastructure.

2.4.1 Impacts of soil corrosivity on infrastructure

The cost of all corrosion in the UK is estimated as 2.5-3.5% of the gross domestic product (GDP) (Francis, 2006). Specifically, soil-related corrosion in the UK impacts on buried (metallic) pipelines serving the water, wastewater and gas sectors (Cole & Marney, 2012).

2.4.1.1 Impacts of soil corrosivity on Transport

Soil *nailing* is a technique undertaken on highway and rail embankments to prevent movement, using closely spaced steel nails (Yean-Chin & Chee-Meng, 2004). However, the nails themselves are often unalloyed or low-alloyed steel (Nurnburger, 2012), making them prone to subsequent attack from aggressive soils (Prashant & Mukherjee, 2010). Concrete encapsulation has been applied to prevent this, but inherent cracking in concrete can leave exposed-metal surfaces vulnerable to attack (Phear et al. 2005). However, most metallic corrosion occuring on the transport network is derived from exposure to de-icing salts, and is therefore not a wholly soil-related issue.

2.4.1.2 Impacts of soil corrosivity on Utilities

Hembara & Andreikiv (2012) state that soil corrosion is a major factor in decreasing the reliability of buried pipelines. The particularly aggressive nature of the London Clay formation (e.g. Windsor soil series) means cast-iron pipes are particularly susceptible to corrosion processes (Schmidt et al. 2006).

The impact of soil excavation can also alter localised corrosion potential. Soil disturbance allowing oxygen, through formed pore spaces, to reach exposed metal surfaces, as well as introducing foreign materials and organisms, both altering the soil chemistry (i.e. pH) (Burton, 2001; Bradford, 2001).

Angular soil particles can score or pierce passive, protective layers around metallic pipes, having a profound effect on corrosion rates and leaving pipes exposed to potentially aggressive soils (Sjogren et al. 2011). Corrosion-resistant PVC pipes are also subject to the abrasive action of angular particles, leading to possible failure of the service (Figure 2-5), especially when using trenchless installation methods in abrasive soil types.

A gas explosion in 2010, resulting from cast iron pipe corrosion in Bridge Street, Shrewsbury, highlighted the consequence of asset failure. This particular event culminated in the destruction of six commercial town centre properties, along with proximal telecommunications and traffic light cabling (HSE, 2010; BBC, 2010). The sandy-gravel soil at this location was recorded as being moderately to very corrosive and, due to its loose texture, allowed escaped gas to migrate from the severed pipe into the buildings which were then destroyed in the subsequent explosion.

Stray currents passing into the soil, originating from mass transit systems and overhead electricity pylons and substations can result in severe corrosion of underground assets (Wang et al. 2013; Flounders & Danilyak 1995). Zhu et al.

(2011) have suggested that soils with a higher resistivity can counteract the issue of stray currents by limiting the soils current carrying capacity. The drying of soils leads to a corresponding decrease in soil resistivity, decreasing the soils earthing potential, affecting substation earthing systems (Busby et al. 2012; Laver & Griffiths, 2001).

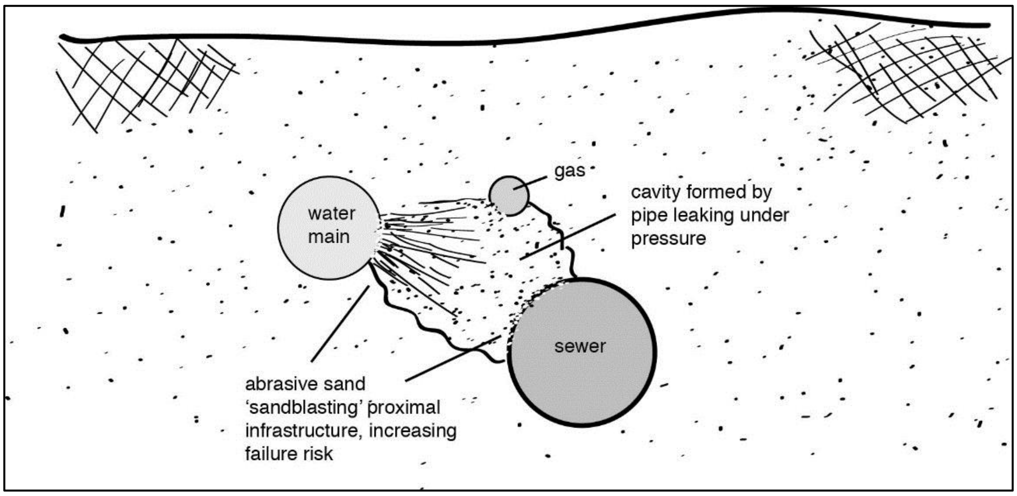


Figure 2-5: Forming of abrasive 'slurry' on pipe failure in coarse-grained soils

Oxidation of drained peats and pyritic soils (acid sulfate soils) can lead to the formation of ochre. This can lower pH values to less than 3.5, causing corrosion of metallic structures (e.g. drain culverts) (Stuyt et al. 2005).

Often telecommunications and electricity cables are wrapped in corrosion-resistant materials and are placed in plastic ducting so preventing their direct contact with potentially corrosive soils.

2.5 Erosion

Soil erosion is the '*wearing away of the land surface by physical forces such as rainfall, flowing water, wind, ice, temperature change, gravity, or other natural or anthropogenic agents that abrade, detach and remove soil or geological* *material from one point on the earth’s surface to be deposited elsewhere*’ (Huber et al. 2008). Sandy soil is particularly susceptible to erosional processes or *washout*, with excess water resulting in *running-sand* conditions (Brink et al. 1982; Walsby, 2007). Erosion represents a significant soil threat in both upland and lowland areas in the UK (Brazier, 2004), with water being the main driver. However, it is generally anthropogenic activity that results in *accelerated* soil erosion (Álvarez-Mozos et al. 2014; Verheijen et al. 2009).

Rivers are a cause of rapid erosion, particularly on meandering sections where saturation of the riverbank can lead to soil structural failure, exacerbating bank undercutting. This can cause considerable damage and may lead to failure of infrastructure in close proximity (i.e. electricity pylons and roads).

Deposition of eroded material in reservoirs can reduce the volume of water which can be stored (Palmieri et al. 2001). Rowan et al. (1995) have shown that Abbeystead Reservoir in Lancashire has been reduced to 6% of its original capacity as a result of soil sedimentation over a period of 140 years. Similarly, Foster & Walling (1994) documented sedimentation rates varying between 1.7-4 cm yr^{-1} in a Devon reservoir. This can also exert consequent impact on related hydro-electric generation capacity, with ongoing effects on the wider economy.

The movement of fine material (i.e. clay/silt) can impact significantly on perforated drainage systems. This, together with silting up of drainage pots, can result in increased surface water flooding, causing particular concern near major highways (Navid 2011). Wind-induced erosion in the East Anglian fenlands, also termed ‘fen blow’, has led to major traffic disruptions, consequent to poor visibility, reduction in agricultural potential and soil deposition on highways (BBC, 2013a).

2.6 Landslides

Landslides, mass movements and solifluction are collective terms for a mass of rock, soil, debris, artificial fill or earth passing down a slope under the force of gravity (Cruden & Varnes 1996). Landslide classifications are further detailed in Cooper (2007) and Cruden & Varnes (1996).

Soil-related landslips represent a significant proportion (53%) of landslips in the UK, compared to those originating in underlying geology (37%) (Mansour et al. 2011), often being the result of landslide reactivation (Forster & Culshaw, 2004; Dixon & Bromhead, 2002). However, recent debris flows on the A83 'Rest and Be Thankful' pass are largely associated with soil-derived deposits and heavy rainfall events (Pennington & Harrison, 2013). Such conditions highlight the potential for activation of previously undeveloped landslides. Similarly, a survey of 570 km of motorway embankments, often composed of constructed fill, documented that 81% of failures occurred between 0.5-1.5 m bgl with only 5% of failure surfaces below 1.6 m bgl (Table 2-2) (Perry 1989).

First time slope-failures are a result of formed pre-failure mechanisms, such as a continuous rupture/shear surface, their full development defining the failure point (Fell et al. 2007). Pore-water pressure is an important factor impacting on slope stability (Abramson et al. 2002), whereby increasing pressures result in a decrease of a soil's shear strength, causing shear surfaces to move relative to one another.

Table 2-2: Percentage of slips with different depths of failure for 570 km of motorway embankment (after Perry, 1989). © TRL (Transport Research Laboratory)

Depth of failure surface (m)	Percentage of total slip length
0.2-0.4	14
0.5-0.9	35
1.0-1.5	46
1.6-2.0	4
2.1-2.5	1

A low soil moisture deficit (i.e. saturated soil) has been regarded a likely triggering factor for landslides on infrastructure embankments (Dixon 2008). This is supported by peaks in railway earthwork failures in winter when moisture contents are high; by contrast peaks are seen in late summer following desiccation caused by high temperatures (RAIB 2008). Moore et al. (2010) have described landslide behaviour prediction as a '*poorly developed and applied*' science. However, accurate forecasting has clear benefits to managing risk to infrastructure assets by encouraging proactive maintenance and ensuring continuation of the assets service.

2.6.1 Impacts of landslides on infrastructure

2.6.1.1 Utilities

Buried utilities are particularly susceptible to damage in landslide-prone soils, as they are designed as composite structures in conjunction with the ground. A landslide in St Dogmaels, Pembrokeshire in February 1994 caused disruption to an 11kV electricity and mains water supply (Gibson et al. 2012). Above-ground structures such as energy pylons, substations and pumping stations can also be affected by landslides and mass-movement of soil.

2.6.1.2 Transport

Landslides have had a significant impact on the transport sector in the UK, particularly in 2012 (BGS, 2014). Approximately 1.2% of the main transport networks (motorways, A roads and railways) are situated in high-risk landslide areas, with a further 6% at moderate risk (Dixon, 2008). A series of superficial debris flows in 2004 significantly impacted upon the Scottish highways network, resulting in key roads being closed for a substantial period (Winter et al. 2005).

On average, some fifty embankment failures occur on the UK rail network per year (Loveridge et al. 2010), often leading to major disruptions (Bromhead, 2013). For example, an embankment landslide on the 17th October 2012 prevented trains from travelling between Barrow and Carlisle, adding 60 minutes to passenger’s journeys for two days (North West Evening Mail, 2012).

2.7 Interconnectivity of soil geohazards

Soil geohazards often do not occur in isolation, but rather as a sequence of processes, that can culminate in overall, consequent infrastructure asset failure.

Cohesive soil shrinkage cracks, sometimes propagating to depths of 1.0m or more, can have the effect of allowing oxygen to reach exposed metal surfaces, increasing corrosion rates (Brady & Weil, 2002). In this instance the combination of shrink-swell soil and metallic corrosion can lead to premature pipe failure.

Shrinkage cracks present a significant factor in slope stability, causing progressive failure during repeated shrink-swell cycles, but also allowing rainfall to reach shear surfaces more easily (Figure 2-6). The latter causes a sharp increase in pore-water pressure at the shear surface, which during intense rainfalls can result in slope failure (Hughes et al. 2009; Dixon, 2008) (Figure 2-6). Cracks can also act as preferential pathways for soil contaminants, originating from a pipe breakage or other external sources which, in areas of highly permeable soils or in shallow aquifers, can cause significant environmental issues (Oostindie & Bronswijk, 1995).

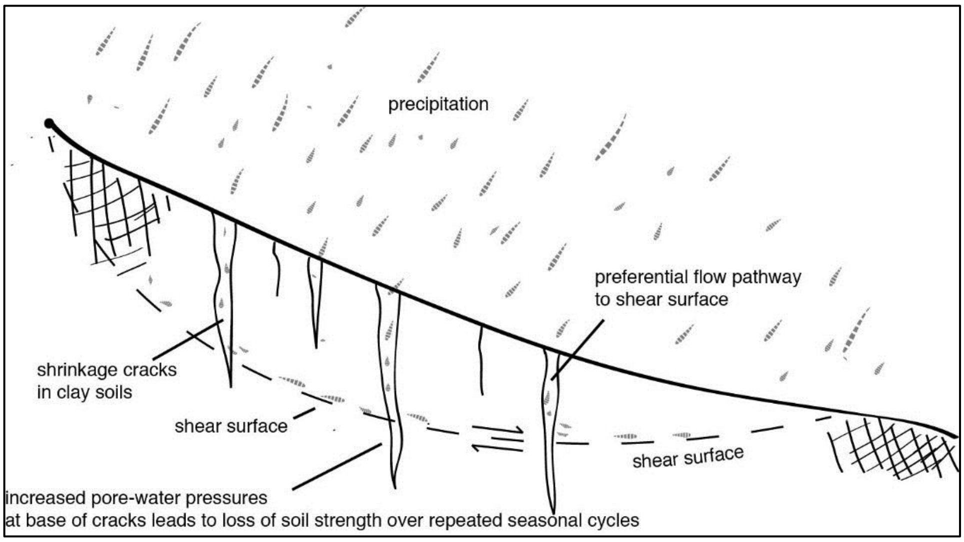


Figure 2-6: Relationship between crack formation in shrink-swell susceptible clay soils and land instability

2.8 Infrastructure resilience to geohazards

Infrastructure resilience to extreme weather impacts is defined as *the ability to prevent, withstand, recover from and learn from the impacts of the hazard(s*) (Hallett, 2013). The resilience of national infrastructures to soil-related geohazards is therefore a function of how mechanisms in the soil system respond to environmental perturbations, and how such impacts can be continually assessed and managed into the future.

Much of the UK's infrastructure, especially water, wastewater and railway networks, are of Victorian origin (e.g. a third of Thames Water's mains are in excess of 150 years old (Greater London Authority, 2003)) and are less-well engineered when compared with modern day installation practices and design standards. To upgrade its ageing infrastructure, Network Rail recently announced a planned investment of £37.5 billion, the largest investment since the inception of the railways (BBC, 2013c). During 2007/08, Network Rail spent approximately £80 million on earthwork maintenance alone, with a large proportion spent on preventative measures (RAIB, 2008).

Like humans, infrastructure assets become increasingly susceptible to external impacts as they age. However unlike humans who *wind-down* in old age, infrastructure assets are often subjected to greater increases of required performance and extended service in their later life and indeed well beyond their design life, often due to increasing population demand (D'Agata, 2003).

Investigating and/or replacing existing ageing infrastructure can result in negative impacts, leading to repeated failure in other parts of the network and to adjacent assets. For example dry clay soils transfer the forces acted upon them to structures buried within them, especially when mechanical excavators and pneumatic drills are used, resulting in damage to proximal services.

Responsibility for infrastructure resilience lies with owners and operators. The infrastructure regulators (i.e. Ofwat, Ofgem and Ofcom) play an important role in ensuring asset replacement occurs at a sufficient rate without pushing considerable expense towards consumers (Cabinet Office, 2011). varying levels of resilience are found acceptable across different industries. The severe consequences of gas pipe failure, for example, has resulted in the HSE (2001) enforcing statutory replacement of cast iron gas pipes with corrosion-resistant PVC. Often the condition of the gas pipes being replaced are significantly better than many of the water mains currently deemed fit for service. In such cases, the consequences of failure outweigh the likelihood of failure in the risk assessment.

HM Government regards infrastructure as a key basis for economic growth in the UK, and is seeking to make relatively short-term investments to result in maximum financial gain (HM Treasury, 2013). It is therefore imperative to understand the risks posed by soil geohazards when replacing and upgrading infrastructure assets.

2.9 Impact of climate change on soil processes

The climate is a driver of the seasonal changes in soil conditions, which consequently exert effects on infrastructure, as identified in Section 2.2. Soil strength is fundamentally determined by its water content (Bohne & Lessing, 1988), with wetter soils generally being weaker (Dexter, 1988). Therefore, future impacts of climate change require a sound knowledge of soil geohazard processes in their current environmental setting (Forster & Culshaw, 2004).

UKCP09 probabilistic climate projections indicate the likelihood of hotter, drier summers; milder, wetter winters, more extreme rainfall events; and increased

UV radiation in summer (Jenkins et al. 2009). Projected climate change and extreme weather conditions are therefore likely to cause significant, but varying impacts on soil geohazards in the UK.

Hotter, drier summers will remove more soil water, up to 20-40% in the South East of England (Sanders & Phillipson, 2003). Wetter winters will lead to significant fluctuations in soil moisture over the future annual cycle. These conditions are likely to result in potentially damaging differential movement at pipe/foundation depth (<1.5-2 m below ground level).

Higher soil moisture contents can increase corrosion rates (Ahmed, 2011; Norin & Vinka, 2003) with a seasonally-fluctuating groundwater level changing the reducing-oxidising state of the soil; increasing the soils aggressiveness to metallic, buried infrastructure (Kleiner et al. 2012).

Cracked, shrinking clays are likely to contribute to an increased probability of progressive slope failure. When coupled with high-intensity rainfall events, leading to rapid increases in pore water pressure at potential shear surfaces, causing inevitable slope failure (Hughes et al. 2009).

Erosional processes will increase with projected climate change (Jones et al. 2009), especially in non-cohesive soils. These soils are more likely to initiate overland water flow during extreme rainfall events, ultimately preventing re-wetting of soils and so promoting erosion and localised flooding of proximal infrastructure.

Infrastructure assets can themselves exert a profound impact on soil moisture regimes. Sealed surfaces and structures can prevent moisture from readily entering the underlying soil. In times of drought this can lead to further moisture deficits and shrinkage leading to damaging differential settlement (Hawkins, 2013; Pritchard et al. 2014).

Regional climate modelling will allow future predicted changes in SMD to be calculated, which can then be employed to aid probabilistic soil-related geohazard modelling. Currently only limited research has been undertaken in modelling soil geohazards for future scenarios (Harrison et al. 2012; Blenkinsop et al. 2010; Loveridge et al. 2010; Clarke & Smethurst, 2010), the main focus often being on evaluating existing historic datasets (i.e. Crilly, 2001).

2.9.1 Climate modelling uncertainties

Flooding represents an acute hazard, its likelihood and consequence(s) are assessed using probabilistic modelling (Sene et al. 2009). However, the chronic nature of soil-related geohazards makes their frequency and response difficult to quantify. Furthermore, sparse data leads to a greater uncertainty in threshold responses. Nevertheless, work is ongoing to establish the relationships between soil geohazards and related infrastructure failure (Hall et al. 2006; Free et al. 2006).

The inherent uncertainty in probabilistic climate modelling means that infrastructure risk analysis is generally qualitative in nature. However, UKCP09 probabilistic projections allow a number of scenarios (i.e. high, medium and low emissions) to be evaluated. The UKCP09 assessments for future climate differ from its predecessor UKCIP02, which gave only a single estimate of change.

Instead UKCP09 allows the user to incorporate probabilities of differing amounts of change (Jenkins et al. 2009).

The quantification of uncertainty is paramount in the utilisation of geohazard models in infrastructure risk management (Royse, 2011). Sanders & Phillipson (2003) agreed, but suggested that uncertain predictions will prevent regulators from making significant adaptations. Certain efforts have been made to model physical changes in soil-biological systems to aid probabilistic modelling methods, e.g. the 'BIONICS' embankment experiment (Hughes et al. 2009).

2.10 Towards a sustainable framework

The increased threat to UK infrastructure from soil-related geohazards in the last decade has resulted in this issue becoming embedded in the wider concept of sustainable development (White et al. 2001), especially within spatial planning approaches (Wilson & Piper, 2010). Soil geohazards are well understood in the UK but they still catch many by surprise and with land pressures increasing developers and infrastructure owners are looking now to land which was considered previously as being unsuitable due to hazardous ground conditions. Inevitably, this will increase the vulnerability of infrastructure(s) in future years if these newer installations are not appropriately designed and maintained.

Brook & Marker (2008) state that awareness of geohazards is greatest in areas subject to high frequency events, where understandably experiences in dealing with these issues are more established. However, climate change could result in areas that have previously been unaffected becoming more prone to geohazards in the future. Similarly, geohazard mechanisms may change; i.e. landslides lying previously dormant could be reactivated by climatic perturbations (Pennington & Harrison, 2013).

There is therefore, a need for both infrastructure operators and earth scientists to share knowledge as to how the potential impacts that may arise from increasing vulnerabilities to soil-related geohazards may be understood and mitigated. Current asset inspection regimes have an apparent inability to detect deterioration not yet visible (ICE, 2013). This is particularly so with soil-related hazards, including landslides and shrink-swell clays which represent chronic processes that manifest over (many) seasons, in contrast to acute flood events. Geohazard impacts are poorly recorded, for example the Highways Agency does not routinely record the impact of landslides, making it difficult for engineers to understand the causes of failure (Gibson et al. 2012). Similarly, local authorities (e.g. highways) and many other infrastructure operators make decisions in the absence of earth-science expertise.

The need for a framework methodology, providing practitioners with best-practice approaches for avoiding the future risks posed by soil-related geohazards is apparent and clear. Flooding, due to its high economic impact and public visibility has spawned a number of reviews (Pitt, 2008; Stern, 2006) considering how society can more efficiently manage this geohazard. However, currently little information in the civil engineering sector exists on how to manage soil-related geohazards, particularly considering the interconnected 'systems-of-systems' approach to UK infrastructure (Hall et al. 2013).

It is suggested that a case-study approach is required to assess both expert and practitioner knowledge on a range of soil geohazards across different sectors (e.g. water, transport and energy) and over a range of geographical areas in the UK. An understanding of the current impact of soil geohazards and how they have been dealt with will then enable an analysis as to how future climatic predictions and soil-geohazard modelling can be incorporated into sustainable designs and maintenance regimes. A multi-disciplinary approach to infrastructure planning and design is argued as a necessity (Hall et al. 2013).

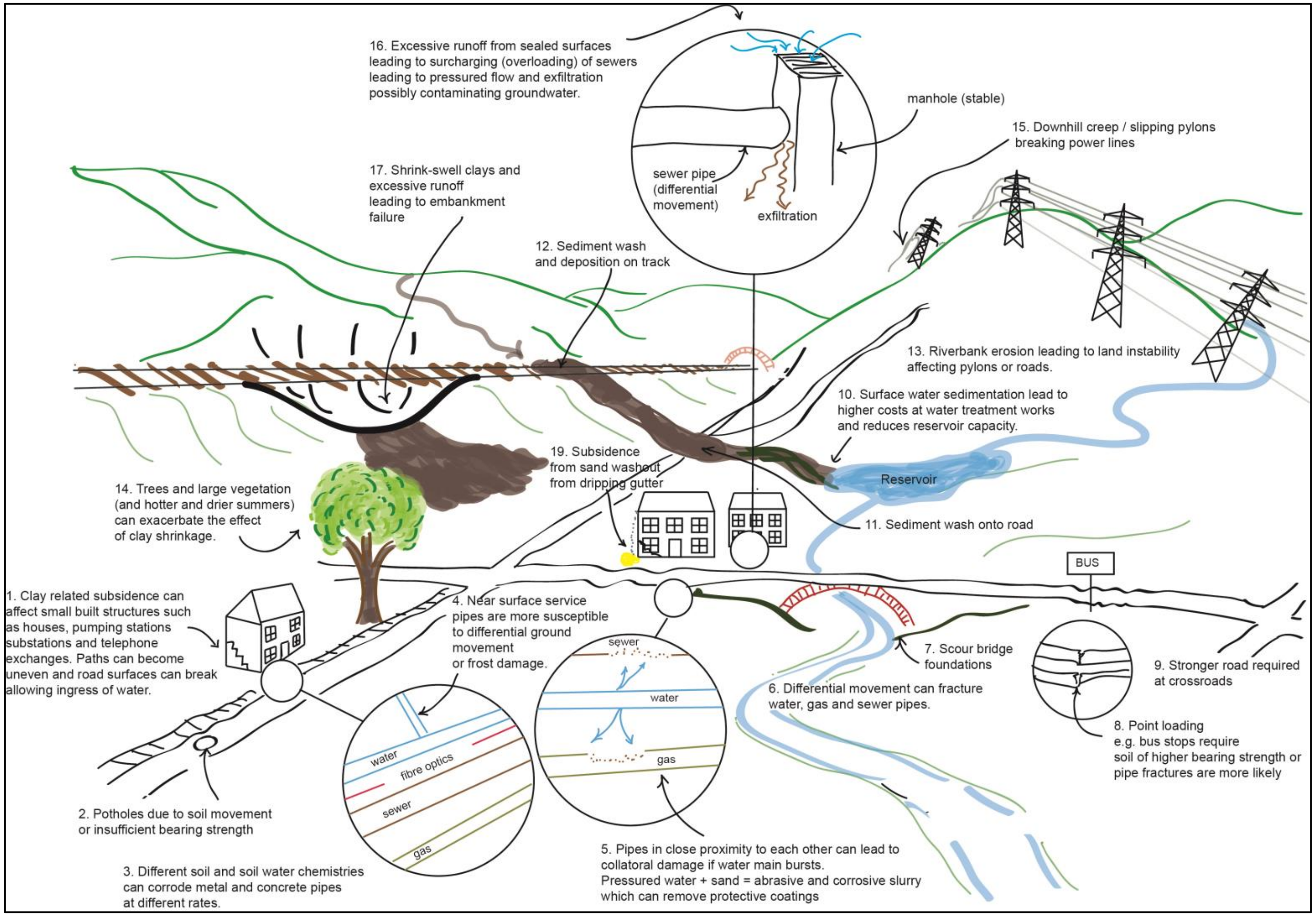


Figure 2-7: Scenarios of soil-infrastructure interactions

2.11 Conclusions

UK infrastructure faces a range of soil-related geohazards, many of which are likely to be exacerbated by climatic change (Figure 2-7) as a result of the climate regulation of the moisture content of soils, fundamental to the occurrence of many soil geohazards.

Significant future geohazards are likely to comprise: (1) cyclical shrink-swelling of clays due to large seasonal differences in SMD; (2) shallow landslides as a result of repeated shrink-swell cycles and high intensity rainfall events; and (3) higher erosion rates (non-cohesive soils) due to overall drier soils and intense rainfall events.

However, research to date has focused principally upon assessing current/historic geohazard distribution and its impact on UK infrastructure. Although this is essential in understanding the fundamental processes, to ensure a sustainable future for the UK's infrastructure, a probabilistic approach to soil-geohazard infrastructure interactions is now required.

Projections from the UKCP09 climate model suggest the UK is not likely to face any unseen soil-related geohazard threats. However, the magnitude and frequency of existing soil-related geohazard events is likely to increase and previously unaffected areas could be susceptible to an increased vulnerability.

The sharing of best practice for the management of soil related geohazards amongst civil engineers is required through a suitable framework methodology. Ideally this will incorporate existing collections of geohazard assessments, climatic projections, and infrastructure network asset locations and condition assessments. Together, these have the potential for highly visible benefits, enabling the infrastructure sector to prioritise ground investigations, design sustainable assets, and to encapsulate expert knowledge to interpret risk.

3 Application of soil-related geohazard modelling to civil engineering, planning and development: Past, present and future.

Chapter synopsis

This chapter explains the background of the soil survey in Great Britain, and the collection of data over the last 80 years. It then discusses the need for soil information and how thematic soil maps have been applied within civil engineering to date. Lastly, the chapter discusses what is required to further integrate soil thematic maps into infrastructure design and how we can incorporate projections of climate change into existing models.

3.1 Introduction

The previous chapter stated that the UK's built environment, predominantly founded in the soil (<1.5 m bgl), faces a range of challenges posed by soil-related geohazards, likely to become exacerbated by climatic change (Farewell et al. 2012). Desk studies, comprising field reconnaissance and mapping of the subsurface, are often the first steps in identifying potential ground hazards for civil engineering projects (Free et al. 2006). Identification of potential ground-related hazards allows engineers to design effective ground investigations (Griffiths, 2002). Glossop (1968) notably stated that '*if you do not know what you are looking for in a site investigation, you are not likely to find much of value*'. Ground investigations form a small part of a project's time and costs, rarely exceeding 1% of overall project costs (Whyte, 1995). Adequate site investigations can reduce unnecessary costs arising as a result of unforeseen ground conditions during any consequent construction phase.

Soil surveys, which classify the uppermost (0-1.5 m bgl) layer of the earth's surface, provide an understanding of soil properties and their spatial distribution. However, the application of pedological soil surveys in civil engineering is seldom undertaken within the UK, with geological mapping being the preferred and often solely recognised option. In contrast, in the USA (Bauer, 1973; Santi & Martens, 2003; Allemeier, 1974; Lee & Griffiths, 1987; Beatty & Bouma, 1973), Netherlands (Westerveld & Van Den Hurk 1973) and Australia (Murtha & Reid, 1976), soil surveys have an established role (Hartnup & Jarvis, 1979).This is likely the result of few published works regarding the use of soil survey for application in UK civil engineering with the exception of Brink et al. (1982), Hartnup and Jarvis (1979) and Reeve (1989); these publications being also now dated with regards to their interpretation and application. In any case, a lack of knowledge transfer between soil scientists and civil engineers, planners and developers regarding the application of the UK's soil survey data over the last two decades is apparent. This review is therefore considered timely, if not overdue.

Recent (i.e. post 1990) technological developments in Geographic Information Systems (GIS) have provided means for rapid development of a range of thematic soil-related geohazard maps incorporating UK soil survey data. Thematic maps provide a mechanism for succinct applicability and knowledge transfer in civil engineering practice, their relative simplicity having the ability to aid non-earth-science specialists.

Soil-related geohazards is defined here as phenomena having potential to result in harm to life, properties and infrastructure networks (Forster & Culshaw, 2004).

This chapter provides a historical background to the UK's soil survey data collection. Reference is made as to how soil survey data have been interpreted and applied subsequently to civil engineering practice to date. Finally, future needs and applications of soil-geohazard modelling are considered. Particular emphasis is placed upon the need for climate-driven probabilistic mapping, accounting for changes in soil processes, with an assessment as to how this can be applied in relation to hazard and risk planning for a range of future scenarios (i.e. 2030 and 2050). The latter are then explored in more detail in subsequent chapters.

3.2 Soil survey in the UK

Firstly, it is important to provide the reader with a definition of soil. Within the UK, soils are defined in soil science as; '*the natural, unconsolidated, mineral and organic material occurring above bedrock on the surface of the earth; it is a medium for the growth of plants';* and from an engineering [geological] perspective as comprising '*any loose, soft, and deformable material, e.g. unconsolidated sands and clays*' (Allaby and Allaby, 1996). This review will refer predominantly to the former whilst simultaneously drawing upon similarities and comparisons identified between the two disciplines.

Soils in the UK are typically recorded from the surface to a mean depth of 1.5m below ground level (bgl), although the British Standards Institution (British

Standards Institution, 2015) regard the average soil depth as 1.2m bgl. There are approximately 700+ recorded soil types in Great Britain (Busby et al. 2012; Hartnup and Jarvis, 1979). The science of pedology, which studies soils in their natural environment, was historically incorporated into the discipline of geology (Clayden & Hollis, 1984). However, the emergence of Russian soil literature during the 1920's led to the recognition of pedology as an independent discipline. Following this, the Soil Survey of England and Wales (SSEW) was created, officially coming into existence in 1939 (Thompson et al. 2005).

Pedological soil surveys, based upon soil science classifications, are precious sources of data, and in the UK represent a definitive source of spatial soil information (Zhu et al. 2001). The UK is fortunate in that it has much detailed information regarding its underlying soils, collected over the past eighty years.

The National Soils Inventory (NSI) is a systematic nationwide survey of UK soils, begun in 1979 and completed by 1984. This inventory was undertaken alongside the creation of the National Soil Map (*NATMAP*) (Figure 3-1). The culmination of *NATMAP* was a 1:250 000 scale map of the soils of England and Wales (Bullock, 1991; Keay et al. 2009), with a legend comprising some 296 geographic soil associations. These associations identify groupings of the most frequently occurring soil series and ancillary series. Prior to 1979, the Soil Survey of England and Wales (SSEW) had mapped almost 20% of the two countries, amounting to 154 maps and the creation of 1,080 soil series (Clayden & Hollis, 1984). Soil series are that 'group of soils similar in the character and arrangement of horizons of the profile, and developed under similar conditions from one type of parent material’(Robinson, 1943; Avery, 1980).

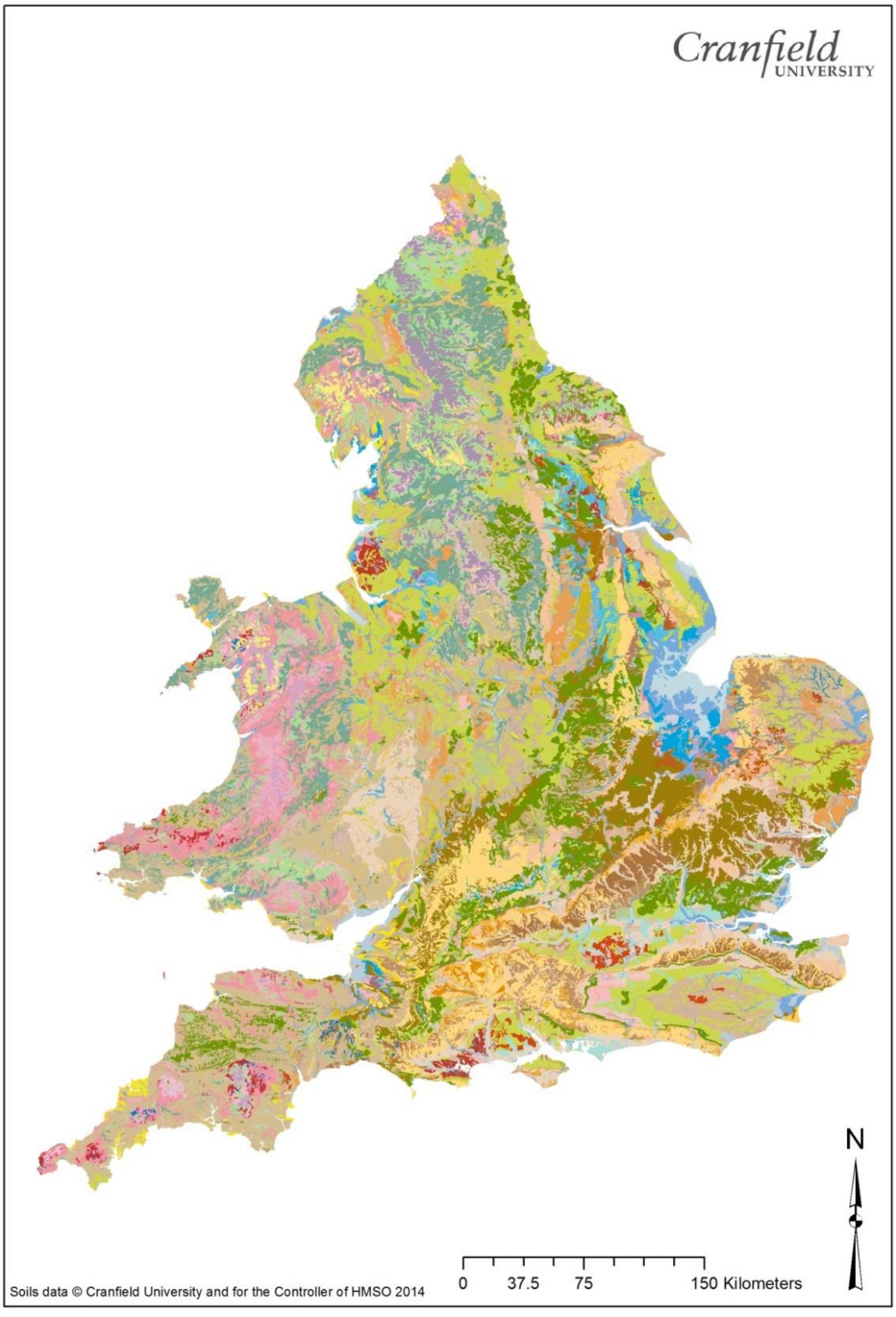


Figure 3-1: National Soil Map (NATMAP) of England and Wales (Soils data © Cranfield University and for the Controller of HMSO 2015)

The NSI consisted of approximately 3 auger borings or small pits per square kilometre, totalling 6,125 sampling points. Of these, 5,692 samples were further analysed for a range of chemical and physical parameters, including pH, organic carbon and numerous elemental analyses (Table 3-1) (Thompson et al. 2005). In the mid 1990's, a proportion of NSI sites were revisited to allow assessments of changes in the soil characteristics (Bellamy et al. 2005). The NSI survey, due to its precise geo-referencing and systematic sampling, will enable accurate future resampling, deducing changes in soil processes and formation over time (Keay et al. 2009). The National Soil Inventory Scotland (NSIS) (1978-87), a sister project to that of NSI and subsequently NSIS 2 (2007-10) jointly obtained 43,000 samples of Scottish soils from approximately 13,000 locations.

The agricultural [research] impetus of the soil survey(s), as a means of improving food security and production post World War Two, meant that urban areas were generally not included in the survey. Hazelton and Murphy (2007) have argued that in any case, urbanisation and surface modification make the mapping of soils difficult in these areas, with urban areas often constructed on what is termed 'made-ground' (Craul, 1985; Rosenbaum et al. 2003). However, in contrast, some urban areas subject to intense human activity may still have recognisable soil profiles (i.e. below roads), suggesting that knowledge of near surface soils in urban areas can indeed be of value (Burton, 2001). Hollis (1992) derived a system of soil classification for urban soils, however, to date little additional survey work has been undertaken in urban areas due to probable limited funding opportunities and property access difficulties, with the exception of some geochemical analyses (i.e. Lark and Scheib, 2013).

Table 3-1: National Soil Inventory (NSI) Data (After Bullock, 1991).

Recorded Field Properties	Measured Soil Properties
Slope	pH
Rock outcrops	% carbon
Erosion	Lime requirement
Land-use	Extractable P, K, Mg
Soil-class	Total P, K, Ca, Mg, Na, Fe, Al, Mb, Co, Mn, Ba, Sr, Zn, Cu, Ni, Cd, Cr, Pb
Litter thickness	
Particle size	
Stones	
Organic matter	
Rock	
Water state	
Soil Structure	
Porosity	
Roots	
Carbonate	
Horizon notation	

Unfortunately, no active systematic national soil survey for the UK currently exists, additional survey and data collection is now undertaken on an *ad-hoc* basis. This has necessitated the need for further interpretation and re-interpretation of existing maps and data (Bui & Moran, 2001).

3.2.1 Soil survey and advances in GIS

The availability and increasing sophistication of Geographic Information Systems (GIS) together with advances in information technology have gifted the soil surveyor with a powerful set of tools, allowing the display and statistical analysis of regional as well as national-scale data for soils and other environmental themes. This has spawned a branch of science known as *geoinformatics*, a discipline that ‘seeks to promote the utilisation and integration of complex, multidisciplinary data in seeking solutions to geoscience-based societal challenges’ (Sinha et al. 2010).

Contemporary GIS allows greater flexibility than paper based map information (Bishop et al. 2001), allowing addition and upkeep of new information as it becomes available (Smith & Ellison, 1999). These technologies also allow for integration and fusing of digital elevation models, climatic data, remote sensing and geophysical data sets, resulting in improved evaluation of soil properties (Bui, 2004). For modern applications, the necessity of fieldwork is negated by the availability of GIS and incorporated expert knowledge (Thompson et al. 2005).

The National Soil Resources Institute (NSRI) at Cranfield University is the custodian of the soil survey data of England and Wales. Similarly, the National Soil Archive at the James Hutton Institute, Aberdeen is custodian of Scottish soils data. Within NSRI, soil information is stored within the Land Information System (LandIS), the largest [environmental] database of its kind in Europe, considered by the Department for Food and Rural Affairs (Defra) as the principal source of UK soil information (Keay et al. 2009). LandIS provides the basis and repository for holding the digital representation of the soil survey data for England and Wales, together with a series of thematic remote sensing datasets, including those depicting soil-related geohazard risks, to be explored in this chapter.

3.3 Application of the soil survey to civil engineering

3.3.1 A need for soil information

Infrastructure networks are predominantly located within the soil mass, as opposed to the underlying geological formations. Most buried infrastructure networks are found within the top 1.0-1.5 m of the soil surface, excepting major construction projects (e.g. motorway, railways) where foundations can often extend to many metres below ground level. Typically, electricity cables are placed 0.45-1.0 m bgl (below ground level); gas pipes 0.3-0.9 m bgl; and water pipes 0.75-0.9 m bgl (HSE, 2000). Current guidance also places domestic house foundations at a minimum depth of 0.9 m bgl (NHBC, 2008). However, much of Britain's historic housing stock and indeed infrastructure assets in Britain are found at shallower depths. Therefore, knowledge of the soil and its underlying, potentially hazardous processes are required to ensure the continuation of the country’s infrastructure networks which contribute to the UK's economic, social and environmental functions. Rogers et al. (2012) argue that infrastructure assets are particularly under threat from ‘deterioration through (often extreme) ageing, exacerbated by adverse ground conditions’.

The use of soil survey data in civil engineering practice has been examined by Hartnup and Jarvis (1979) who posit that this data can supplement geological information by showing conditions for: house construction, light industrial and commercial premises, drains and soakaways, pipelines and roads. Whereas Hartnup and Jarvis (1979) primarily focus upon soil mapping being used in land-use planning, this chapter also discusses its use in infrastructure asset management incorporating hazard and risk assessment, and its potential benefit.

Soil surveys have been regarded as being majorly disadvantaged for civil engineering applications due to their relatively shallow survey depths (<1.5m) (Hartnup & Jarvis, 1979). However, the importance of their applicability to shallow-founded structure(s), as identified previously cannot be understated. Soil surveys distinguish 'areas of thin peat, high water tables, acid, sulphate-rich or highly expansible subsoils not shown on any other type of earth science map' (Reeve, 1989). They more clearly represent areas subject to glacial and alluvial processes (Hallett et al. 1994), such as peat deposits (less than 1 metre thick), colluvium and some loess deposits which are not readily included on geological maps (Farewell, 2010). Winter et al. (2013) note that a landslide assessment of Scottish roads encountered difficulties in assessing areas of peat accumulation, although no reference to soil survey data was mentioned. Santi and Martens (2003) argue that using soil survey maps in 'engineering-based' mapping may be preferable to comprehensive engineering geology maps, at least during the scoping phase of construction.

An increasing need for housing development could potentially lead to a further 1.3% of England's soils disappearing under construction by 2016 (Environment Agency, 2004). Additionally, the Department for Communities and Local Government (2013) identified that in 2011, 22% of dwellings were built on agricultural land, compared to 18% in 2010. The encountering of agricultural soils, which historically have not been engineered or undergone significant anthropic disturbance is therefore, more likely. Harrison *et al.* (2012) suggest that areas previously considered unsuitable due to potentially hazardous ground conditions are likely to face construction as increasing pressure for land develops. Inevitably, this will lead to the greater applicability of soil survey within these potential development areas.

A number of physical laboratory tests are available for establishing soil engineering properties (e.g. plastic and liquid limits) (BS1377-2:1990). However, these tests are both expensive and time consuming (van der Meer, 1999; Gogé et al. 2014), especially for large, geographically distributed projects (i.e. roads and pipelines). Therefore, pre-requisite soil information used for screening purposes can allow for prioritisation of limited funding often associated with physical testing on geotechnical projects, or perhaps even the re-routing or re-siting of a development. However, this thesis is not suggesting that soil maps are an alternative to comprehensive site investigation, which is advised for any localised development.

3.3.2 Combining pedological and geological disciplines

Planning Policy Guidance: Note 14 (DTLR, 2002) states that the combined 'examination of topographical, geological and soils maps, together with any specialised mapping or databases' form the basis of *desk-study* investigations. Harris et al. (2005) argue that soil surveys, often limited to a fixed depth (i.e. 1.0-1.5 m), lead to 'inaccurate and disjointed depiction of soils on the landscape'. Geologists and civil engineers often disregard the upper reaches of the earth's surface, with trial pit and/or borehole logs regularly representing the top 20-50cm under one collective term of 'topsoil' (Lee & Griffiths, 1987).

There is an advantage of integrating pedological and geological interpretations in near-surface materials for both engineering and general scientific purposes. Both the pedologist and geologist can learn much from each other and greatly assist the civil engineer if greater collaboration takes place, helping to derive a *fuller* picture of the soil profile and soil-rock interface (Wysocki et al. 2005). Other branches of science, such as hydrology, do not abide by these definitive depths, instead branching over pedology and geology (Schoeneberger & Wysocki 2005), giving them a significant advantage in analysing the entire subsurface system. In conjunction, soil and geology mapping can act as a 'first sieve' (Hartnup & Jarvis 1979), where areas for development are screened either to eliminate areas or identify where further advice is sought when planning site investigation and testing regimes.

3.3.3 Soil properties important to the civil engineer

British Standard BS5930 (British Standards Institution, 2015) and more recently Eurocode 7 (BS EN ISO 14688-1 and 2) are the standard(s) to which soils (civil engineering classification) are classified in UK civil (and geotechnical) engineering. Problematically, pedology and civil engineering have differing approaches to soil classification. Hodgson (1997) provides a detailed description of soil classification in pedology, identifying methods utilised during the NSI soil survey. Ideally, co-operation between civil engineers and soil scientists would be sought prior to the soil survey being undertaken to ensure a more harmonious classification system. However, this was not undertaken in the UK, as the soil survey's impetus was primarily agriculturally focused.

Lee and Griffiths (1987) undertook a comprehensive comparison of soil survey and civil engineering approaches to soil classification which identified a number of similarities and subsequent advantages of the soil survey method of classification. Encouragingly, pedological descriptions were considered more detailed in their classification approach, as compared to BS5930 and so properties considered by the latter are recorded in detail during the soil survey – ensuring some harmoniousness. Soil properties considered important to the civil engineer include:

- Nature of soil grains: *Particle size; shape; texture; plasticity; organic and carbonate content*
- State of soil grains: *Packing; water content; strength; relative density; stiffness*.
- Structure of soil grains: *Fabric/microfabric; features, i.e. layering/fissuring/shearing/cementing*.

Similarities between the two disciplines identified by Lee and Griffiths (1987) include:

- Clay, silt and sand classes in both pedological and BS5930 classification schemes share similarties and are thus compatible, and that;
- Plasticity shares a close similarity in both approaches.

Advantages of pedological descriptions identified and recommended for inclusion in BS5930 were:

- Pore size and description – providing insights into potential drainage of soil.
- Field Strength – using standardised methods (i.e. crushing a 3 cm cube of soil between finger and thumb) compared to BS5930.
- Ped description – not used currently in BS5930, but allowing drainage characteristics and compaction susceptibility to be evaluated.
- Soil boundaries – detailed [stratigraphic] boundaries being given in pedological description, however this is not used within BS5930, where often a diffuse boundary is only noted as a dashed line on a borehole/trial pit log.
- Colour – Soils are classified according to the Munsell colour classification scheme (Munsell Color Company, 1954), whereas BS5930 is based on a minimal number of set colours.

Soil series information can also provide engineers with detailed spatial insights, if appropriately interpreted, into climate, vegetation, topography, geographical position and both internal and external drainage characteristics. Knowledge of these properties can then allow for minimal impact of engineering activities upon long-term environmental effects (Hazelton & Murphy, 2011).

3.3.4 Limitations of soil survey to civil engineering

It is argued that although particle-size grades are the same, particle-size classes differ for each classification system (Hodgson & Whitfield, 1990). Furthermore, soil scientists do not classify particle size alongside plasticity

(Hodgson and Whitfield, 1990), unlike civil engineers, further stifling comparison of surveys.

Often, the sampling intensity of soil surveys can be such that contrasting/merging soil types are present over a particular site. Soil properties are often continuous in their distribution, especially if the area is extensive (Hengl et al. 2004; Hodgson and Whitfield, 1990; McGown and Iley, 1973; Reeve, 1989), therefore a detailed site survey is recommended for any such development. Often however, intrusive soil surveys will not be undertaken until relatively late in the planning timeframe. Therefore, extant soil survey data can act as a valuable screening medium for initial planning considerations and establishing potential cost-estimates of construction.

3.4 Thematic soil mapping

The late 1980's/early 1990's saw the development and creation of a number of applied thematic datasets and maps, where information was reinterpreted from previous SSEW soil surveys. Hodgson and Whitfield (1990) undertook some of the early attempts at applications of soil-related thematic data that improved the accessibility of soil data to the non-specialist user.

Soil geohazard maps are used by a wide range of construction, planning and regional/national authority professionals, as well as insurers, albeit not to the extent that they could be. Planners and earth scientists share common ground, in that they can both utilise maps (Dearman, 2002). However, for planners who often lack earth-science expertise, the interpretation of complex geological or pedological maps, where data is stored within a series of complex tables, can be difficult (Wysocki et al. 2005).

Since this time, advances in GIS and an increased knowledge base has led to more user-friendly soil data and targeted interpretations. NSRI currently holds several thematic datasets that are particularly relevant to civil engineering, planning and development practice in the UK, which include the Natural Perils Directory (NPD) and Leakage assessment from corrosivity and shrinkage (Leacs), both of which are discussed in the following sections.

3.4.1 Soil-related subsidence - Natural Perils Directory

The Natural Perils Directory (NPD) is a thematic dataset representing specific soil materials and their ground movement effects (Hallett et al. 1994), including: clay – shrink-swell (Figure 3-2); sand – erosion; silt – frost heave; soft soils (alluvium and peat) – compressibility; and peat – shrinkage. Of these, clay related shrink-swell is by far the most damaging soil process impacting upon the built environment in the UK, often totalling £100-500 million of damage per annum and accounting for over 70% of valid insurance claims (Plante, 1998). The tolerance of buildings and infrastructures to ground movements varies greatly, and is ultimately dependent on their foundation design, depth and property/asset age. An increase in soil volume of between 3-7% is considered potentially damaging (Godfrey, 1978). Domestic buildings generally having a tolerance of up to 25mm settlement (Boden & Driscoll, 1987).

The Underground Foundation Stability (UFS) model, forming the core of the NPD, uses data derived from the soil surveys of England and Wales, and Scotland, together with expert knowledge, climatic and laboratory data to interpret subsidence hazard. The laboratory data includes representative testing of specific soil types for their shrink-swell characteristic’s at depths of 1.0 m below ground level.

Figure 3-2: Horizontal shrinkage crack in clay soil, Northamptonshire, UK (Photo: O. Pritchard)

The climatic element of the clay-related subsidence model is the mean Potential Soil Moisture Deficit (PSMD) value, calculated from the 1961-1975 baseline of climatic data (Figure 3-3) derived from the Met Office weather stations (Jones & Thomasson, 1985). Standard deviations around the calculated mean annual PSMD act as representations for calculating the probability of subsidence of the driest year in 3, 15, 45 and 150 years respectively. Currently the UFS model and subsequently NPD are unable to offer probabilistic subsidence risk in respect to projected climatic change (e.g. Jenkins et al. 2009).

Erosion is important to the civil engineer, particularly when construction acts to rapidly increase the process, a causal effect of removing the binding surface layers of soil and vegetation. The process of erosion can result from a variety of physical mechanisms including; water, wind, mass movement, dissolution of carbonate rich material, translocation and mechanical processes. Sunken lanes in southern Britain are an example of infrastructure networks susceptible to erosional processes, themselves being a product of soil erosion through stock and later vehicular movements. Barton (1987) argues that it is often difficult, due to topography and land access, to undertake thorough site investigations in these areas. The *washing-out* of sand sized material, during water flow can cause gullies, voids and cavities to form. Related to infrastructure, the burst of a high-pressure water pipe can lead to rapid sand-washout causing bridging of adjacent buried utilities and the road surface, ultimately leading to their failure (e.g. Majid et al. 2010).

Construction practice is likely to impact on the compaction of the ground surface, either through the placement of structures or vehicular movements around a particular site. As a process, soil compaction is generally irreversible and affects the subsoil, often not remediated after re-emplacement of topsoil (Randrup & Dralle, 1997). Soil compaction can lead to the inability of roots to penetrate the soil and a loss of soil volume causes accelerated run-off resulting in erosion and possible flash-flooding together with a lessened ability for the soil to absorb contaminants (Jones et al. 2003). The latter is an important factor in the use of 'on-site' waste disposal systems, where soil acts as a cheap 'biological feature' (Beatty & Bouma, 1973).

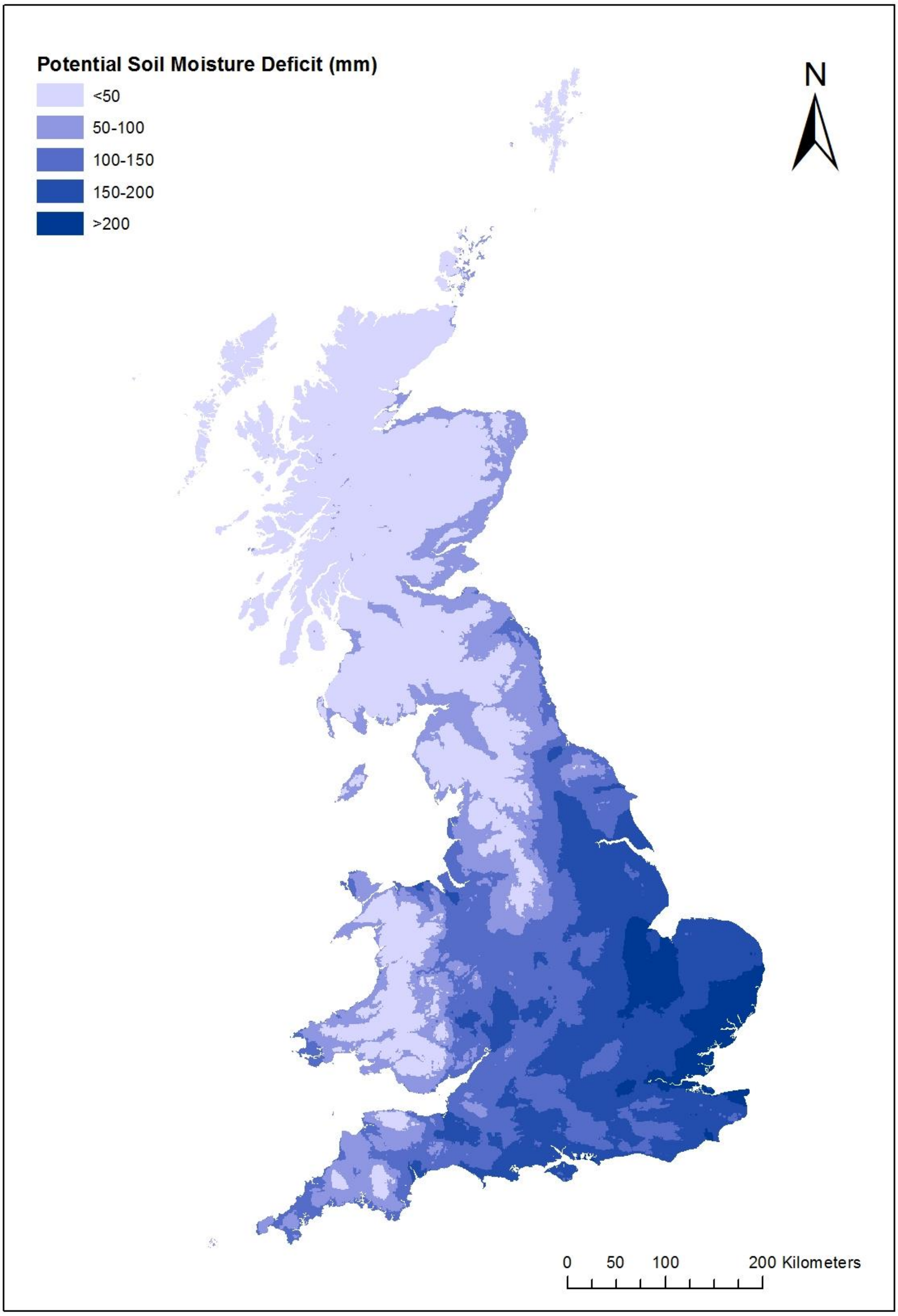


Figure 3-3: Average annual maximum potential soil moisture deficit (PSMD) for the 1961-75 climatic baseline (data from UK Met Office)

3.4.2 Leacs (Leakage Assessment from corrosivity and shrinkage)

NSRI's geo-spatial tool, Leacs (Leakage Assessment from Corrosivity and Shrinkage) enables those companies operating buried ferrous infrastructure to assess the surrounding soil's corrosivity potential. Leacs is regarded as the main source of soil corrosion information within the UK (Royse et al. 2009).

Corrosion is the degradation of a metal by a reaction with its environment, and affects almost all metals (Bradford, 2000). The corrosion of ferrous objects in soils are a significant problem for the water, sewer, oil and gas distribution networks (Figure 3-4) (Cole & Marney, 2012). A number of soil properties influence corrosivity, including: moisture content, resistivity, soluble salt concentration, pH, temperature, and soil redox potential. From these variables, Leacs calculates six classes of risk based upon the soil properties at depths of 0.4 and 1.0 m. (Figure 3-5).

Figure 3-4: Characteristic pitting in water mains pipe due to soil-water corrosion (Picture: S. Hallett)

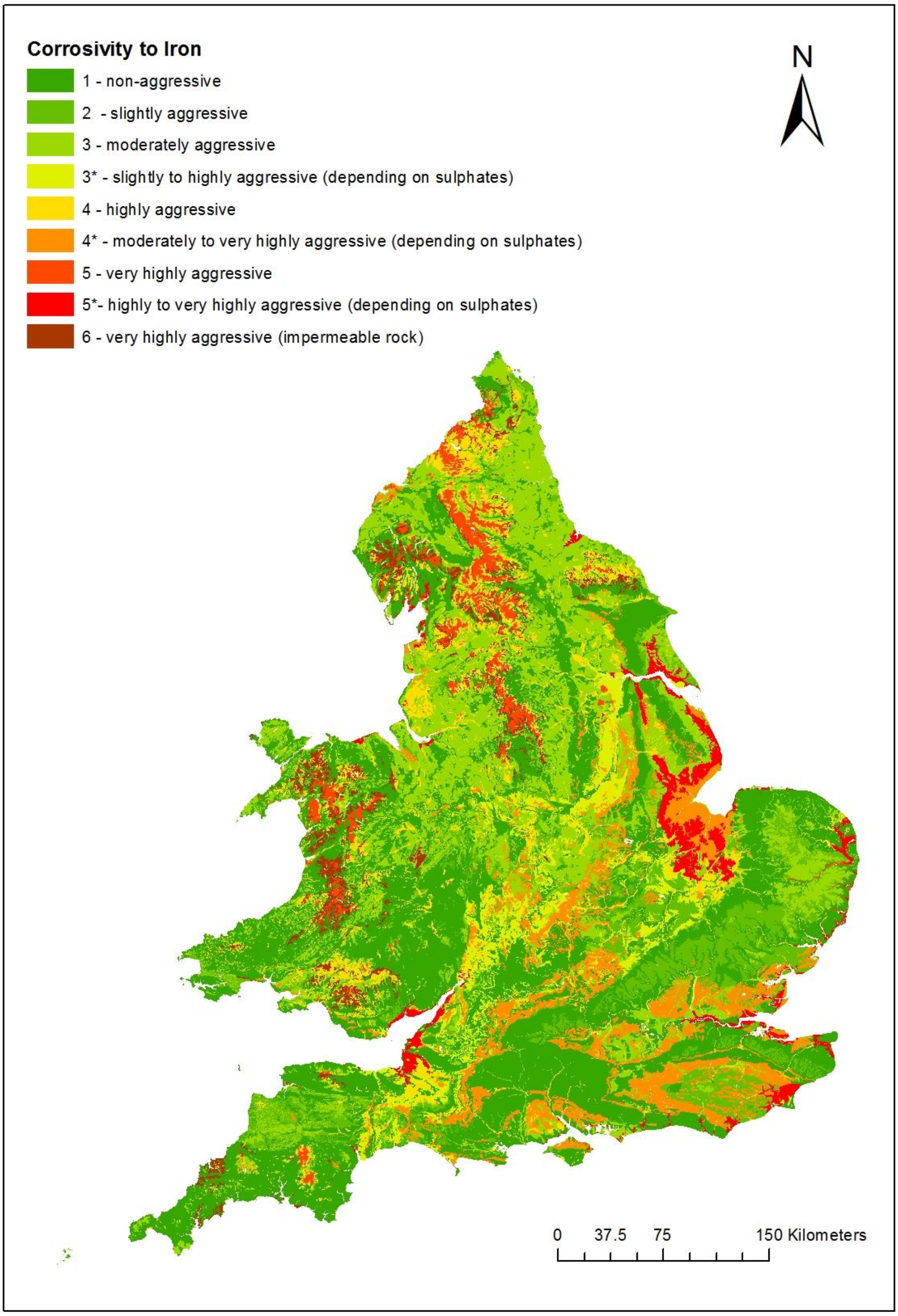


Figure 3-5: Corrosivity to Iron in England and Wales (Soils data (England and Wales) © Cranfield University and for the Controller of HMSO, 2015)

Soil data use in corrosivity assessment was first adopted when pipeline risk assessments required improvement, helping to reduce the likelihood of asset failure (Jarvis & Hedges, 1994). Soil corrosivity mapping provides a clear visual interpretation for regional characterisation, of a complex system resulting from the heterogeneity of UK soils (+700 series). They can also be used alongside and provide focus for *in-situ* measurements of soils during the scoping/design phase of pipeline construction (Gimelfarb, 1990).

Soil maps are often better able to distinguish the potential degree of corrosiveness, in shallow depths, compared to geological mapping. Corcoran et al. (1977) surveyed soils in an area of south Oxfordshire where geological maps interpreted the study area as underlain solely by the Oxford Clay formation. By contrast, local soil maps for the area identified three distinct soil series (Evesham, Denchworth and Langley) which possessed significant lateral variations in corrosivity. Boundaries between soil types are particularly important for pipeline engineers, as differing soil chemistries result in electrical potential differences that promote the development of anodic/cathodic sites, forming a corrosion cell, which accelerates corrosion.

However, Penhale (1971) argued that soil corrosivity mapping based upon soil characteristics alone will likely be subject to error due to the number of soil-related factors influencing corrosion. Infrastructure operators and soil scientists are constrained by the time consuming and financial pressures associated with soil testing, therefore existing data is utilised (Jarvis & Hedges, 1994). For example, the current spatial representation of sulfates in the UK, critical in corrosion potential, is at present limited. Royse et al. 2009 have suggested that the BGS’s G-BASE (Geochemical database) could be used to statistically assess sulfate levels across UK soils.

Projected climate change, causing rain and temperature fluctuations is likely to influence and alter soil conditions, predominantly moisture (Cole & Marney, 2012). Cole and Marney (2012) argue that soil moisture content is the only prolific control on the corrosion of ferrous materials in soil, therefore this change needs to be accounted for (Kumar & Imam, 2013).

3.4.3 Soil water regime and drainage evaluation

The role of the soil water regime is important when considering geohazards and is defined as the cyclical seasonal variation of wet, moist or dry soil states. The magnitude and frequency of the soil-related geohazard processes identified in this thesis are controlled by soil moisture variation.

A soil's natural water regime is controlled by its permeability (Ragg et al. 1984) which is a function of soil texture. This inherently impacts upon drainage characteristics, a clay soil having a lower permeability by comparison with a sandy soil.

Soil survey data offers a qualitative approach to changes in soil moisture regime through the identification and description of mottling (Hodgson, 1997). Mottling suggests fluctuating water tables, where ferrous iron in the soil is oxidised to give a characteristic brown or ochre colour, contrasting with the surrounding anaerobic grey and olive colour (Fitzpatrick, 1974). Such soils have grey layers and distinctive orange mottles where poorly and better aerated parts of a soil layer show the differential effects of gleying (Reeve, 1989).

However, Boucneau *et al.* (1996) argued that using soil survey for assessing groundwater depths can be problematic, especially where anthropic drainage practices have been adopted since the original survey, the same applying to geological mapping (Dearden et al. 2013). Site-specific ground investigations, dependent on their temporal setting can also mislead interpretation of groundwater levels; a result of sparse data collection and economic constraints.

In construction the emplacement of impermeable surfaces, whether this be in the form of a highway, building or other structure results in soils not being able to take up rainfall as easily (Craul 1985), therefore appropriate drainage systems are required. Soakaways which allow on site storage and gradual drainage of waters are often constructed in soils that have an effective permeability coefficient (BRE Digest 365). Recently the introduction of permeable paving has limited the impact of sealed surfaces on new developments (InterPave, 2008).

3.4.4 Benefits of soil-related geohazard mapping

The benefits of mapping soil-related geohazards are clear. They allow planners, developers and engineers to design appropriate mitigation strategies and formulate suggestions as to where to reinforce or even divert infrastructure networks. Moreover, they prompt engineers to ask the right questions at the geotechnical investigation stage, leading to reduced costs in terms of having to deal with unforeseen ground conditions during the construction phase. Much of the UK's infrastructure assets are aging and under increasing demand from customers. For example, 70% of the UK's rail network and a large percentage of Thames' Water network is greater than 100 years old (CIRIA, 2009; Costello et al. 2007). Insurers also seek to identify which domestic and commercial properties could be at potential risk from soil-related ground movement and flooding, so as to correctly price the risks.

The relationship between highway condition (particularly local road networks) and the shrink-swell susceptibility of soils has been recognised by authorities in recent years (ADEPT, 2009). Pritchard et al. (2014) have discussed the application of soil geohazard assessment (NPD) in asset management of the rural road network of Lincolnshire, discussed in Chapter 5. Biggs and Mahony (2004) state the need for engineers and soil scientists to collaborate in respect to road infrastructure operations. Often engineers understand the physical nature of soils but not their chemistry and/or environmental settings.

3.5 Geohazard mapping and UK planning

The UK Planning system has an important role to play in the mitigation and prevention of the adverse impacts of soil-related geohazards and future climatic change (Wilson 2006). The Office of the Deputy Prime Minister (2004) stated the obligation of planning authorities in England and Wales to identify areas at risk of flooding and unstable land (i.e. erosion). Flooding has often been at the forefront of planner’s minds, a result of the large associated economic losses and policy implications, this is in contrast to soil-related hazards. Wilson's (2006) study surveyed a number of climate impact studies undertaken by local authorities where only 1 in 14 respondees recognised soil subsidence as a threat to the built environment similarly no links were made between climate change and infrastructure services.

Planning policy and subsidence issues in the UK has been reviewed by Brook and Marker (2008), who noted that the wide availability of spatial geohazard information (i.e. through British Geological Survey and Cranfield University) is only beneficial where planning authorities understand the need for such information. When understood, a combined pedological and engineering geological approach provides added scope for planners to base their decisions upon, especially when considering alternative land uses (Lee and Griffiths, 1987).

Planning Policy guidance note 14, Annex 2 (DTLR, 2002) advises that 'local planning authorities should identify areas where due consideration is required for the potential impact of subsidence on development'. This means that planning departments must advise where site-specific ground investigation is required; if for example clay-related subsidence is likely to be a hazard in the vicinity of development. By contrast, building regulations within the UK are designed to prevent and mitigate the impact of subsidence 'in so far as the risk can reasonably be foreseen, [and] will not impair the stability of any part of the building'.

Operators of infrastructure and utilities are required by the Health and Safety Executive (HSE) to protect citizens from any impacts that their operations and systems could have in exacerbating landslide activity. Planning authorities do not have a legal obligation to understand the distribution or potential for landslide hazards to impact on new developments in their planning decisions (Gibson et al. 2012), and instead this risk falls to the owner/developer of the site (DCLG, 2012).

3.5.1 Uncertainty in soil mapping

In flood risk research, the use of broad scale hazard maps for soil-related geohazards offers a powerful tool for policy analysis, particularly for infrastructure projects (Hall et al.2003). The Stern Review (Stern, 2006) advises that the integration of land-use planning and climate data can provide insight for risk management, yielding encouragement of investment in buildings and *long-lived* infrastructure networks.

The clarity of soil thematic data that is presented both visually and spatially is of importance, and is where these maps provide value. Thematic maps aid understanding as to the impact that soil properties have upon structures/infrastructure assets when placed in a particular location and/or route. Likewise, hazard/risk zoning maps identify areas where mitigation measures are required. Furthermore, the potential impact of asset onthe surrounding environment is also of importance. For example, such information may reveal where a water burst may result in erosion of the subsurface leading to a cavity.

Oversimplification of data however, can lead to hazards being missed, over-complication of data can have the same effect, making a balance critical. Deck and Verdel (2012) describe the many uncertainties facing geohazard risk analysis, including: resources uncertainty; expertise uncertainty; model uncertainty; and data uncertainty.

Risk and hazard evaluation are inevitably subject to uncertainty (Hall *et al*. 2006). This is especially so with soil-related applications, as there are over

700+ soil types within the UK, making thematic interpretation of soil extremely complex. Handling uncertainty is crucial when mapping soils and associated geohazards (Bishop et al. 2001), and represents an inherent feature in contemporary Spatial Data Infrastructures (SDI) (Clementini et al. 2000). Soil mapping is also often based on limited survey activities having some form of limitation, for example, due to economic or time constraints. Soil field observations are consequently often extrapolated across landscapes using expert knowledge. Finke (2012) argues that uncertainty is often overlooked, despite the number of tools available to the environmental modeller to address this. Applications from the finance sector require calculated probabilities and consequences of risks posed; therefore these approaches must be integrated when developing applications with soil-related factors in their modelling approaches. However, much like no quantification, the precise quantification of geohazard probability is ultimately uninsurable (Tol, 1998).

It is argued that soil scientists are in danger of reducing their physical understanding of soils, resulting from increased reliability of computer models to predict soil spatial properties (Hartemink & Sonneveld, 2013). This is exacerbated in the UK by further resampling and field studies of soil properties not being undertaken on both a national or regional level. This is important, at least on a national scale to aid spatial predictions and models. However, Beucher et al. (2013) argue that geostatistical spatial modelling allows for soil interpretation and calculation of uncertianty in areas where little or no knowledge exists. The process still requires validation by expert knowledge assessment, however a considerable amount of resources (time and costs) are saved through not undertaking extensive fieldwork activities. The wide availability of GIS systems may however, allow users particularly those outside of the research community to underestimate uncertainty through their misunderstanding of the data (Foody, 2003).

3.5.2 Future-proofing geohazard assessment

The probabilistic climate projections suggested by UKCP09 (Jenkins et al. 2009) indicate that the UK is likely to encounter hotter, drier summers and warmer, wetter winters. It is argued that civil engineers and infrastructure operators often show a low-level of awareness to climatic change and its potential implications. Planners are concerned with the relative uncertainties that climatic change brings (Arkell et al. 2004).

The inherent process of undertaking pedological soil surveys allows for only a *snapshot* in time, exemplified in the UK where there is no active soil survey. Soils are highly dynamic and continually changing (Tugel et al. 2005), their conditions and processes predominantly linked to climate-driven moisture content (i.e. shrink-swell, bearing strength, corrosivity and resistivity). Remembering Jenny's (1941) equation regarding soil formation, climate and time are two of the major functions of soil formation.

An improved understanding of the connection between meteorological and pedological processes is therefore required and is currently lacking (Hertin et al. 2003; Royse, 2011). To this end, Harrison et al. (2012) and Blenkinsop et al. (2010) have undertaken preliminary studies integrating climate projections (UKCIP02 and UKCP09 respectively) within geohazard models, the former using geological and the latter using pedological data. These studies both focus upon London and the south-east of England, where vulnerability from clay shrinkage susceptible soils are considered most at risk. Peaks in subsidence related insurance claims in this area are a testament to this (Page, 1998).

Probabilistic geohazard models have the potential to aid the asset management, assessment of mitigation measures and ultimately the resilience of civil engineering projects and infrastructure networks (Jaedicke et al. 2008). This will be of particular importance in respect of the likely higher frequency soil-related geohazard events in the coming decades.

Availability of *off-the-shelf* and *open-source* GIS software has not only increased accessibility, but has also permitted the interpolation of climatic data together with a wide range of environmental data (Chapman & Thornes, 2003). GIS has also provided utility companies with enabling tools, allowing more precise mapping and recording of their assets (Costello et al. 2007). Alongside this, currently both NSRI and the BGS are able to provide licenced geohazard data in GIS format, allowing easy interpolation alongside other data layers (i.e. infrastructure data), simplifying the creation of vulnerability and risk-assessments (Fedeski & Gwilliam, 2007). Combining both environmental datasets and infrastructure networks has the potential to improve and streamline asset management systems, especially in the context of long-term climatic change.

3.6 Conclusion

Although geohazards in the UK do not always pose a direct threat to life, they pose significant risks to infrastructure which is key to ensuring the continuation and wellbeing of the UK's society and economy. Application of soil-related geohazard datasets have where adopted, provided a key role in aiding UK planners, developers and engineers design more resilient infrastructure.

The emergence of GIS systems has facilitated the '*unlocking*' of soil data previously embedded within complex data tables to be visually displayed and easily interpolated with other geospatial datasets (i.e. asset locations/failures and meteorological data).

With the concept of sustainability becoming an ever increasing part of modern civil engineering projects, thematic geohazard models themselves need to evolve and become more usable in light of climate change. Until now (Chapter 4) no national-scale geohazard model has incorporated climatic change projections, the only offer being those of preliminary studies at a regional scale (e.g. Blenkinsop et al., 2010; Harrison et al., 2012). However, in doing this the uncertainties that probabilistic projections bring must be communicated clearly to potential users. Further research on the effects of meteorological conditions on soil processes has been identified as a research need. Therefore, soil scientists, engineering geologists and other branches of earth sciences have a role to play in ensuring the climate resilience of the UK's built environment.

In summary:

1. Advancements in GIS and geoinformatics have allowed for novel applications of soil survey data for civil engineering.
2. Data collected during UK soil survey is relevant to civil engineers and infrastructure asset managers.
3. Soil survey can supplement geological mapping and aid prioritisation for geotechnical investigation and physical testing of soils.
4. Mapping soil geohazard future spatial trends (i.e. subsidence, corrosivity and resistivity) has been lacking and could aid both civil engineers and planners in both the construction of new and existing infrastructure networks to increase asset climate change resilience.
5. Soil scientists should compliment spatial predictions with field and laboratory data.
6. Ideally, further integration of soil survey data with geological surveys would allow a ‘whole-system’ view of the earths subsurface.

4 Probabilistic soil moisture projections to assess Great Britain's clay-related subsidence hazard

Chapter synopsis

This chapter presents a framework for incorporating probabilistic projections of potential soil moisture deficit (PSMD), derived from a version of the UKCP09 stochastic weather generator, into a clay subsidence model. This has provided a novel, national scale thematic model of the likelihood of clay-related subsidence, related to the top 1-1.5m soil layer, for three time periods; baseline (1961-1990), 2030 (2020-2049) and 2050 (2040-2069). This chapter is based upon an article published in *Climatic Change* (Pritchard et al. 2015a).

4.1 Introduction

Clay-related subsidence is the most damaging soil-related geohazard in Great Britain (England, Scotland and Wales) costing up to £500 million per annum (Forster and Culshaw, 2004; Plante, 1998; Pugh, 2002). Here a geohazard is defined as an environmental phenomenon capable of causing harm to both life and the built environment. This form of subsidence is a result of specific clay soils shrinking and swelling in response to dry and wet conditions, respectively (Corti et al. 2011). This leads to both vertical and horizontal ground movement, caused by volumetric change of the soil mass, which can cause significant damage to infrastructure and property founded within the soil. The susceptibility to which these clay soils shrink and swell is controlled by their mineralogy and seasonal moisture flux (Reeve & Hall, 1978). It is the magnitude and frequency of this seasonal moisture flux, or potential soil moisture deficit (PSMD), which governs the damaging nature of clay-related shrink-swell cycles. PSMD reflects the balance in flux between rainfall, potential evapotranspiration (PET) and drainage, high PSMD values characterising drier soils and low values wetter soils. PSMD is therefore key to modelling clay-related subsidence. However, unlike acute geohazards (e.g. flooding and landslides), the impacts of clay-related shrinkage and swelling are chronic processes, with PSMD developing over many months or seasons (Corti et al*.* 2011).

Ground movement, which incorporates clay-related shrinkage, is recognised as a hazard to the built environment (Cabinet Office, 2011). Chapter 2 identified several impacts of clay-related subsidence on UK infrastructure networks, including; pipe and shallow foundation failure, road instability, and potential embankment instability (Pritchard et al. 2014). The United Kingdoms' (UK) Climate Change Risk Assessment posits that under anticipated future climate projections, the susceptibility of the built environment to ground-related subsidence will increase (Defra, 2012; Jenkins et al. 2009). An ability to anticipate future spatio-temporal trends of this geohazard therefore have the potential to notably advance the field of geohazard modelling and awareness (Royse, 2011). Geohazard information is valuable to both public and private sectors, with its increasing availability driven by HM government planning policy and the insurance industry (Royse, 2011). Sectors using geohazard information include: finance, central and local government, residential property markets, utilities and infrastructure operators.

The UK Climate Projections 2009 (UKCP09) represent the UK's first probabilistic assessment of climate change for the 21st century, providing a sample of possible climatic changes that incorporate inherent climatic uncertainty. Importantly, it provides results not dissimilar to specific climate models (Burton et al. 2010). UKCP09 climate projections, based upon a large perturbed physics ensemble (PPE) of the Met Office Hadley Centre's HadCM3 GCM, suggest that parts of the UK will be subject to increasingly hotter, drier summers and warmer, wetter winters through to 2080 (Murphy et al. 2009; Jenkins et al. 2009). As a result, soil moisture levels are predicted to decrease by 20-40% in the south-east of England (Sanders & Phillipson, 2003). This will cause marked changes to the spatio-temporal patterns of clay-related subsidence.

Shrinkable clay soils in wetter regions, having low PSMDs, currently exhibit *low* to *medium* subsidence potential, yet such areas potentially face increased subsidence potential under hotter, drier climate scenarios. Moreover, it is likely that these areas, having been previously unaffected by clay-related subsidence will lack appropriate mitigation measures (e.g. deeper foundations or more flexible material for buried utilities). This was observed in areas of France where the incidence of several years of extreme drought resulted in widespread soil subsidence causing extensive damage, with costs exceeding those of flooding (Corti et al. 2011). By contrast, areas having long-standing incidence of subsidence often have local practitioners (e.g. planners, developers, etc.) having both experience and expertise in the adaptation and mitigation of such geohazards (Brook & Marker, 2008).

To-date, GB clay subsidence models have been predominantly based upon historical and empirical climate data (Figure 3-3). A number of studies discuss the qualitative relationship between climate and clay-related shrinkage, arguing that UKCP09 climate projections indicate an increase in clay-related subsidence hazard for specific areas of GB (e.g. Forster & Culshaw, 2004; Sanders & Phillipson, 2003; Rawlins et al. 2013). UKCP09 is accompanied by a weather generator (WG) that provides downscaled climate projections encompassing a range of climate variables. Projections are provided on a 5km grid, as opposed to the traditional 25 km grid offering of UKCP09. These downscaled projections give higher spatial resolutions which are more suitable for studying the varying effects of climate change across heterogeneous physical landscapes. The WG is based upon a stochastic process, calibrated to the present day climate, providing statistically plausible realisations of daily climate (Borgomeo et al. 2014). The adoption of the WG and UKCP09 climate projections in climate change risk assessments and applications is well-established in other disciplines; for example, in the implications for water resources planning (Christierson et al. 2012; Borgomeo et al. 2014), agricultural risk planning (Knox et al. 2010), geomorphological modelling (Coulthard et al. 2012) and building overheating studies (Jenkins et al. 2014). Nonetheless, few studies incorporate probabilistic projections of climate into soil geohazard models, and none have attempted a national-scale assessment to date. Blenkinsop et al. (2010) fused UKCP09 climate projections with soils data to estimate clay-subsidence hazard for an area of south-east London based upon modelled annual mean PSMD. Similarly, Harrison et al. (2012) applied the earlier UKCIP02 projections to model shrink-swell in bedrock and superficial geology for the south-east of England. For the latter, UKCIP02 projections were chosen over UKCP09 due to resolution and formatting issues at the time of the study. Clarke & Smethurst (2010) used UKCIP02 projections to assess the impact of climate change on infrastructure embankment stability. However, the examples presented by Harrison et al. (2012) and Clarke & Smethurst (2010) are at a relatively low resolution (25km^2 grid cells), being deemed unsuitable for understanding local and regional climatic changes.

The aim of this chapter is to develop medium-high resolution (5km^2) UKCP09 WG-derived projections of PSMD for GB over three time periods: baseline (1961-1990), 2030 (2020-2049) and 2050 (2040-2069). The approach incorporated these PSMD data within a clay subsidence model for GB only, as soil data for Northern Ireland were unavailable for this study. Projections of the spatial and temporal likelihood of clay-related subsidence for all three time periods are presented. Section 4.2 discusses the existing and modelled data required for the assessment of clay-related subsidence. Section 4.3 explores the methodological approach used for processing and incorporating UKCP09 climatic projections within an existing soil-related geohazard model. Section 4.4 presents the results of the climatic modelling for the three scenarios, describing the future soil moisture fluxes (PSMD) and the changing clay-related subsidence geohazard susceptibility for GB. Finally, Section 4.5 discusses the findings and implications of this research, offering conclusions and suggestions for future study.

4.2 Natural Perils Directory (NPD)

There are over 700 taxonomic soil series in England and Wales (Keay et al*.* 2009) and approximately 1,000 in Scotland (A. Lilly *Pers. Comm*.). Soil series in England and Wales represent a taxonomic classification of soil characteristics based upon precisely-defined particle-size subgroups, parent material type, colour and mineralogical characteristics (Clayden & Hollis 1984). Scottish soil series represent soils of similar horizons which have developed on similar parent material (Soil Survey of Scotland, 1984); differing from the England and Wales soil series classification. Soil series data is often less useful to non-soil-scientists than the many thematic interpretations of soil and its functions, especially considering the different classification approaches. Some models arise from the fusion of soils data with other data (e.g. meteorological and climate change projection data). Since the early 1990's, a range of spatial soil-related geohazard models have been developed for GB (Hallett et al. 1994). The *Natural Perils Directory*™ (NPD) is a geohazard thematic dataset providing detailed information on GB soil-related hazard, of which clay-related subsidence is included. NPD is used widely within the finance, insurance and water utility sectors, with recent applications in the asset management of local highways (e.g. Pritchard et al. 2015 and Chapter 5).

This chapter's methodology focuses principally upon modelling the *hazard* (extent, severity and probability) that clay-related subsidence presents. However, in order to present a *risk*, the built environment needs to be both exposed to the physical geohazard (i.e. clay-related subsidence), as well as being vulnerable to damage (i.e. shallow foundation). This is best represented by the following function, after (Crichton, 2001):

$$Risk = \int (exposure, hazard, vulnerability)$$

Equation 4-1: Risk calculation (after Fedeski and Gwilliam, 2007)

4.2.1 Potential Soil Moisture Deficit (PSMD)

Soils generally lose moisture throughout the spring and summer, as a result of evapotranspiration exceeding rates of rainfall, resulting in the formation of soil moisture deficits. A [potential] soil moisture deficit (PSMD) is defined as the amount of water required (in mm) to return a soil to its 'field capacity' (Earl, 1997). Field capacity is the point at which any further addition of water into the soil will not add to the overall water volume of the soil mass, instead leading to run-off of excess water (Robson and Thomasson, 1977; Smith, 1967). However, soils with high groundwater tables will be little affected by a soil moisture deficit. Field capacity therefore represents a PSMD value of '0'. PSMD has been calculated, starting at '0', annually from January 1st of each year using Equation 4-2 below. Further detail is provided on the calculation of accumulated PSMD in Section 4.3.2.

$$PSMD = \sum (PPT - PET)$$

Where: PSMD = Potential Soil Moisture Deficit (mm)

PPT = Daily Rainfall (mm)

PET = Daily Potential evapotranspiration (mm)

Equation 4-2: Calculation of Potential Soil Moisture Deficit (PSMD) (After: Smith 1967; Jones & Thomasson, 1985)

4.2.2 Soil shrink/swell susceptibility (SSWELL)

The propensity of a soil to shrink and swell has been determined through laboratory assessment of volumetric soil shrinkage at a range of moisture contents (Avery and Bullock, 1977; Reeve et al. 1980; Reeve and Hall, 1978). In addition, multiple linear regression analysis was undertaken to determine the specific soil properties contributing to clay-related shrinkage. Reeve et al. (1980) found that bulk density, liquid limit, clay content, organic carbon content and cation exchange capacity provided good correlations with volumetric shrinkage measurements. The bulk density, derived from GB soil databases (i.e. Cranfield University's LandIS and James Hutton Institutes ISIS systems) was subsequently used to predict clay-subsidence hazard potential for the full range of substrate types upon which soil is classified in GB (Clayden and Hollis, 1984). Assessments represent conditions in the subsoil at approximately 1 to 1.5 m depth, the typical foundation depth for much of the UK's built and buried infrastructure. GB soils are allocated to six volumetric shrink/swell (SSWELL) classes, ranging from very low (0) (<3% volumetric shrinkage) to very high (6) (>15% volumetric shrinkage) (Table 4-1). The 'High*' SSWELL class represents soils with alluvial clay or peat at 1m depth, but being prone to shrinkage only when drained to at least 2m depth. Soil criteria relating to other SSWELL classes are described in Table 4-1.

Table 4-1: SSWELL Classes in relation to volumetric shrinkage (%)

SSWELL class	SSWELL	Shrinkage (vol) %	Soil Characteristics
Very Low	VL (1)	<3.0	Lithoskeletal, gravelly, sandy, light loamy or silty
Low	L (2)	3.0 - 5.0	Medium loamy or medium silty unless derived from clay-with-flints/platueau drift
Moderate	M (3)	5.001 - 12.0	Medium loamy or medium silty and derived from clay-with-flints or clayey on soft shales, Reddish Marl, clay and sand, non-swelling clay, or any till or head deposits
High	H (4)	12.001 - 15.0	Clayey and on swelling clay, clay-with-flints/plateau drift or glaciolacustrine clay
Very High	VH (5)	>15.0	Clayey and on brownish swelling clay
High*	H*(6)		Alluvial clay or peat – very high SSWELL potential that is not realised unless effective drainage installed to at least 2m depth.

4.2.3 NPD clay subsidence model

NPD's clay model combines PSMD and SSWELL data in order to predict the spatial likelihood of clay-related subsidence under different prevailing weather conditions; this will be further explained in Section 4.3. To date, climatic extremes within NPD have been modelled through the addition of standard deviations around the mean PSMD, drawn from the temporal run of observed data (1961-75) (Figure 3-3). Weaknesses of this approach include both the currency of the now historical time series of the data, and the fact that no effective probabilistic element is employed in the modelling allowing for the management of potential future uncertainty.

4.3 Approach and methods

The methodology presented demonstrates how probabilistic climate information can be applied in the long-term assessment of clay-related geohazards. A modified version of the UKCP09 stochastic weather generator was used to derive projections of daily rainfall and potential evapotranspiration (PET). These values were then processed to provide values of PSMD for the three time periods. The methodology is summarised in Figure 4-1. The approach outlined facilitated the probabilistic analysis of PSMD as well as providing the basis for an assessment of the underlying climate model uncertainties. The future PSMD datasets were analysed using the software tool ESRI ArcGIS v.10.2. The selected PSMD scenarios were subsequently intersected spatially in turn with the SSWELL data (Figure 4-2) and reclassified using NPD principles to ascertain a clay-subsidence hazard assessment (Figure 4-12). The methodological approach is discussed in detail for the remainder of Section 4.3 below.

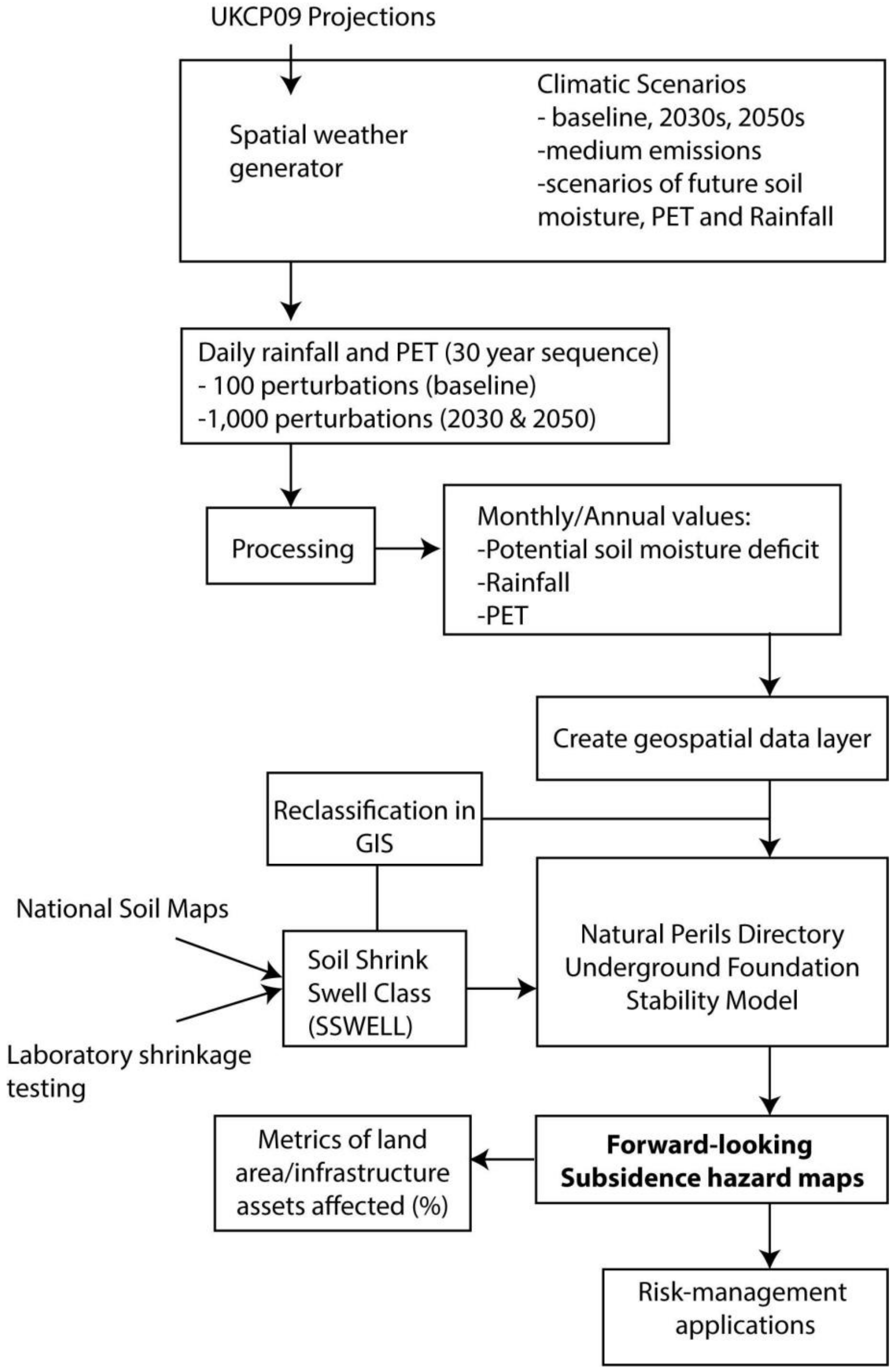


Figure 4-1: Methodological framework

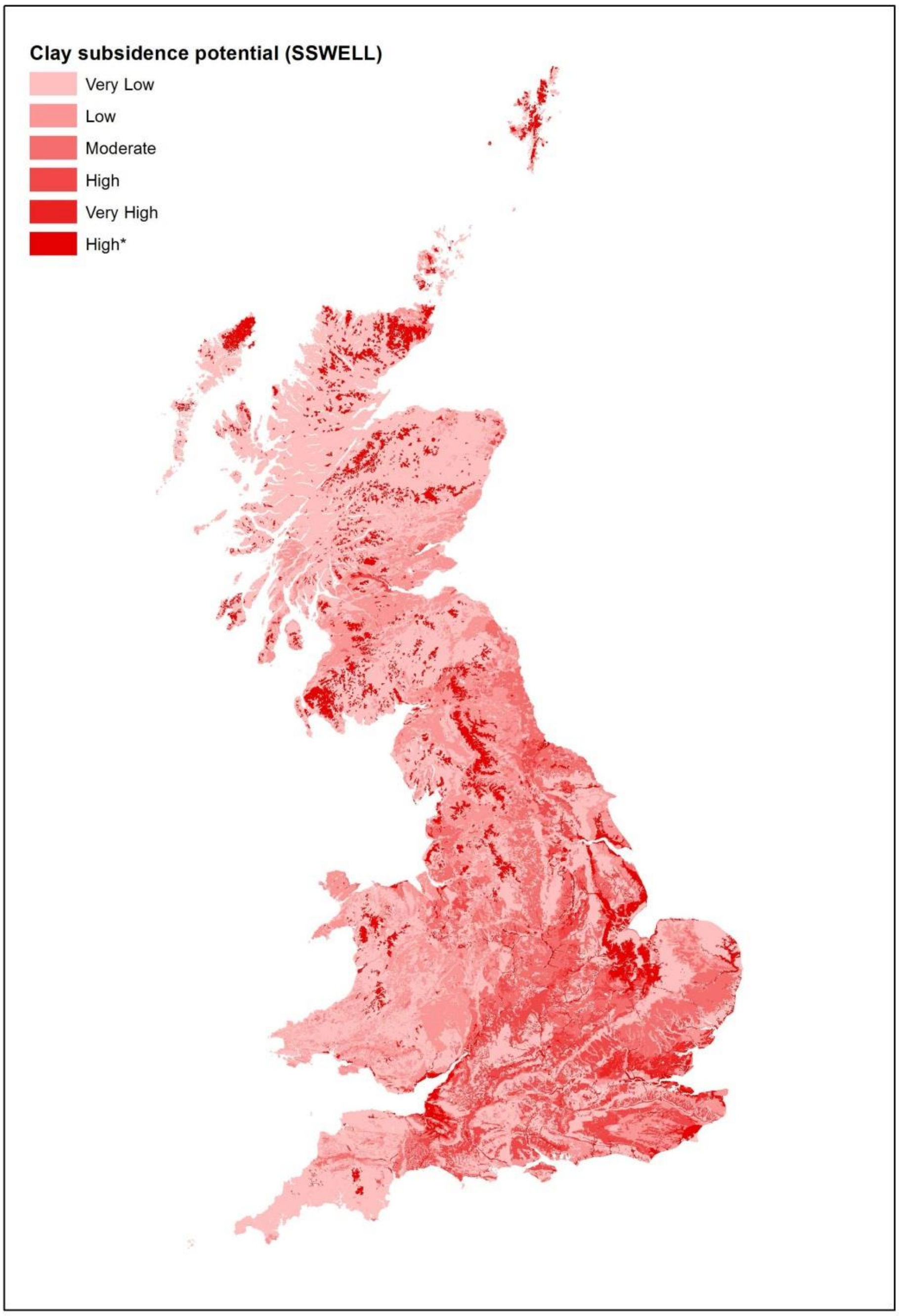


Figure 4-2: Clay-related subsidence potential (SSWELL) values for Great Britain (Soils data England and Wales © Cranfield University and for the Controller of HMSO 2015; Scottish soils data © James Hutton Institute 2015)

4.3.1 UKCP09 Weather Generator

The standard UKCP09 WG provides simulations of weather sequences on a site-by-site (i.e. 5km cell) basis, and so lacks spatial consistency in time over neighbouring grid cells (Jones et al. 2009; Jenkins et al. 2014). Due to specific soil properties extending beyond the 5km resolution a decision was taken to adopt a modified version of the UKCP09 stochastic weather generator (WG) (Burton et al. 2013) (whose interface is shown in Figure 4-3). The WG used builds upon the earlier EARWIG WG (Kilsby et al. 2007) in order to compile a set of spatially-coherent daily climate values (Table 4-2) over a 30 year stationary sequence at a 5 km^2 resolution for GB (see Appendix A for example output tables and processing strategy).

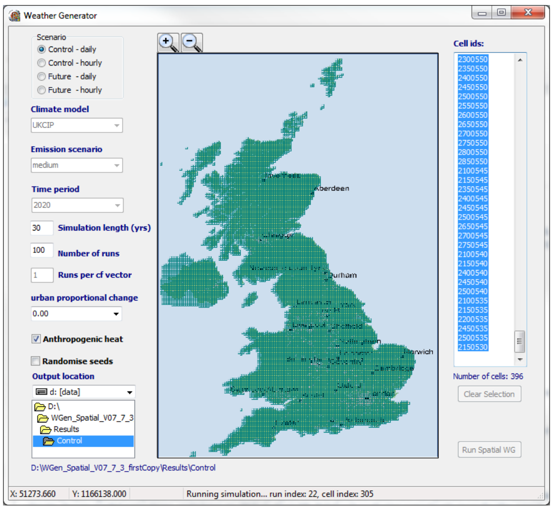


Figure 4-3: The Newcastle University UKCP09 spatial weather generator graphical user interface

The 30 year sequences included in each of the three scenarios are referred to hereafter as ‘baseline’ (1961-1990), ‘2030’ (2020-2049) and ‘2050’ (2040-2069). The future projections were drawn from a medium emissions scenario, equivalent to the IPCC’s (Intergovernmental Panel on Climate Change) SRES

A1B scenario (IPCC, 2000). This scenario was chosen as it is contiguous with other analyses which have applied the UKCP09 WG datasets; analysis of the high and low medium emissions scenarios have been undertaken for a representative case study area and results are shown in Section 4.4.5. As with UKCP09, scenarios did not use urban land-use corrections.

UKCP09 baseline data were produced to reveal the extent to which the WG is able to match baseline climate calculations with known empirical data (Eames et al. 2012). An example is given in Figure 4-4, which presents annual average totals of precipitation and potential evapotranspiration for the UKCP09 WG-derived baseline (1961-1990) (Figure 4-4a) and 2050 (2040-2069) scenarios (Figure 4b) which are compared with observed baseline (1961-1990) data for GB. In baseline comparisons (Figure 4-4a), both the observed and UKCP09 WG-derived data show the same spread. Appendix D and E present the spatial outputs of rainfall and potential evapotranspiration from the WG for GB.

Table 4-2: Climate variables output by the spatial weather generator

Variable	Field	Unit
Daily Precipitation Total	precip_dtotal	mm/day
Daily Minimum Temperature	temp_dmin	degC
Daily Maximum Temperature	temp_dmax	degC
Daily mean Vapour Pressure	vapourpressure_dmean	hPa
Daily mean Relative Humidity	relhum_dmean	%
Daily mean Wind Speed	wind	m/s
Daily Total Sunshine	sunshine_dtotal	Hours
Diffuse daily radiation	diffradt_dtotal	kWh/m^2
Direct daily radiation	dirradt_dtotal	kWh/m^2
Daily mean Potential Evapotranspiration	pet_dmean	mm/day

However, for the 2050s, Figure 4-4b points to higher average annual potential evapotranspiration and reduced rainfall. Met Office 5km gridded data was used to analyse annual average rainfall and potential evapotranspiration (Perry & Hollis, 2005). The 30 year WG baseline series was run 100 times based on a different randomly sampled vector of change factors, providing the basis for probabilistic analysis. The future scenarios of 2030 and 2050 represent a higher factor of uncertainty as compared with the baseline. Therefore, these scenarios were run 1,000 times, based on a differently randomly sampled vector of the 10,000 UKCP09 change factors available to provide the probabilistic analysis. Some reported studies have only undertaken 100 runs of scenario series for futures studies (e.g. Gupta, 2013; Jenkins et al. 2014).

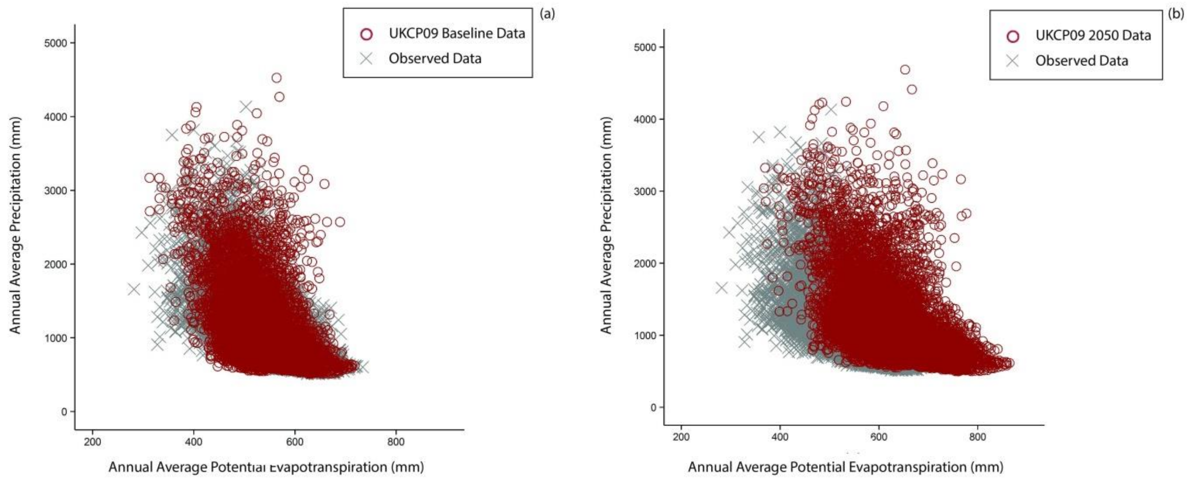


Figure 4-4: Variability of Great Britain annual average precipitation and PET (potential evapotranspiration) for the observed historical (1961-1990) data compared to (a) UKCP09 baseline and (b) UKCP09 2050 projections. Observed data is derived from 5 km gridded datasets made available from the UK Met Office (Perry and Hollis, 2005)

Unlike its predecessors (UKCIP98 and UKCIP02), UKCP09 does not provide projections of soil moisture. However, the WG does provide daily outputs of rainfall and potential evapotranspiration (PET), fundamental for calculating PSMD (Equation 4-2). PET is calculated in UKCP09 using a variant of the Penman-Monteith method, known as the FAO56 Method (Equation 4-3) (Allen et al. 1998).

$$Potential\ Evapotranspiration = p(\alpha T + \beta)$$

Where:

P = mean daily percentage (for the month) of total annual daytime hours

α = empirically derived 0.456

T = temperature in ^{o}C

β = empirically derived 0.416

Equation 4-3: FAO-modified version of the Penman-Monteith equation for calculating potential evapotranspiration, as adopted by the spatial weather generator

The following section discusses how projections of PSMD were derived from the raw output WG data. Discussion then focuses on how projected PSMD data were processed and incorporated within the clay-related subsidence geohazard model.

4.3.2 Computation of soil moisture deficit

The WG produced substantial output data (≈50 Terabytes). Custom software tools were therefore required to process the raw WG files to produce the necessary summary data products required for geohazard modelling purposes. A series of programs were prepared using the *Perl* scripting language in order to automate the calculation of PSMD values (script is provided in Appendix B and C). The process is presented graphically in Figure 4-5, and shows an example of the processing steps for a future UKCP09 scenario (1,000 perturbations). The same approach is undertaken for the baseline scenario however, the baseline data is only representative of 100 perturbations.

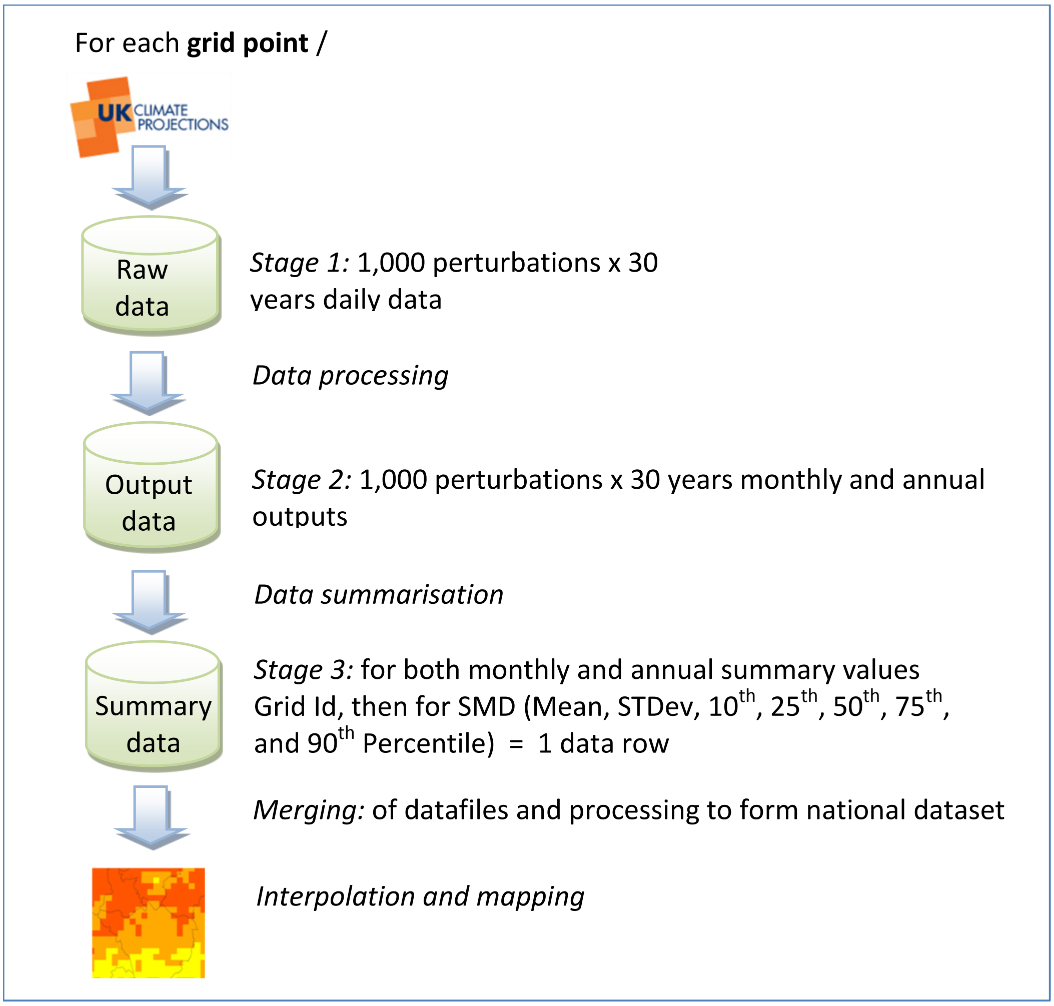


Figure 4-5: Graphical representation of PSMD processing steps

Soil moisture accumulation and loss oscillate over the course of a year. Therefore, a temporal resolution of monthly and annual PSMD were deemed more appropriate than the raw daily data format of the WG outputs produced in Stage 1. Future scenarios represented 1,000 daily realisations of climatic parameters which, over a 30 year time series, provided 30,000 realisations of daily climate. In effect the resultant future raw climate projection data has 30 x 1000 = 30,000 'January 1st' values and so on.

Stage 1 of the process (Figure 4-5) involved the production of raw climate data from the UKCP09 weather generator, which output the variables identified in

Table 4-2. On production of this data, in its daily format, the Perl script (Appendix B) was used to calculate PSMD. During computation, PSMD was set to 0 mm each January 1st and subsequently each day's PSMD (Equation 4-2) (if not a surplus) was added to the previous days' PSMD to give an accumulated value. If a surplus of water existed (i.e. PSMD > 0) then it was subtracted from the previous days accumulated PSMD. Soil moisture surplus (SMS) was computed and retained; however, SMS was not required for this geohazard model, except in its use for calculating accumulated PSMD. However, SMS data could form the basis for future flood response modelling. On calculating accumulated PSMD at a daily resolution, this was summarised to monthly and annual values for each perturbation's 30-year synthetic time periods (Stage 2 in Figure 4-5). Data was subsequently output to a relevant file format. Further statistical analysis and summarisation of the dataset (Stage 3) is discussed below.

4.3.3 Statistics

Stage 3 of PSMD processing (Figure 4-5) involved calculating the mean, standard deviation and a range of percentiles (10, 25, 50, 75 and 90th) for the monthly and annual soil moisture data over the WG change factors; the Perl code used to derive this is presented in Appendix C. This resulted in one monthly and annual accumulated PSMD value for each 5km grid cell at the percentiles and mean shown above. To provide consistency with UKCP09 outputs, the 10th, 50th and 90th percentiles were selected to represent data uncertainty; the 90th percentile being taken as 'unlikely to be more than', the 10th percentile being 'unlikely to be less than', and the 50th percentile representing the ‘central estimate/tendency’. Adopting a standardised approach in the representation of UKCP09 uncertainty allows users, who are likely to be familiar with the UK climate projections, to incorporate these modelled data within climate adaptation schemes.

4.3.3.1 PSMD distribution analysis

Over 10,000 5km UKCP09 weather generator grid cells were modelled for PSMD over the entirety of Great Britain. To better undertand PSMD distributions for the scenarios presented, ten grid cells were selected for further statistical analysis (Figure 4-6). These cells were chosen on the basis that they represent the broad range of climatological and topographical areas of Great Britain.

As discussed in Section 4.3.2, model runs for the 'Baseline' consisted of 100 perturbations, with future model runs of '2030' and '2050' consisting of 1,000 perturbations. Therefore, to provide the same number of observations for easily comparable analysis, future scenarios were randomly sampled to provide a subset of 3,000 observations; the same as provided by the 'Baseline'.

Statistical analysis was then undertaken to show the PSMD distributions for the three time periods for the ten chosen locations (Figure 4-11). If the data were not normally distributed, established through a Shapiro-Wilks test and supported by Quantile-Quantile plots (Appendix G), then the non-parametric Mann-Whitney U-test was undertaken to establish whether a significant difference existed between the yearly values of accumulated PSMD for each of the respective time periods. If the data were normally distributed, then a parametric test was used; the two sample T-test was used in this instance.

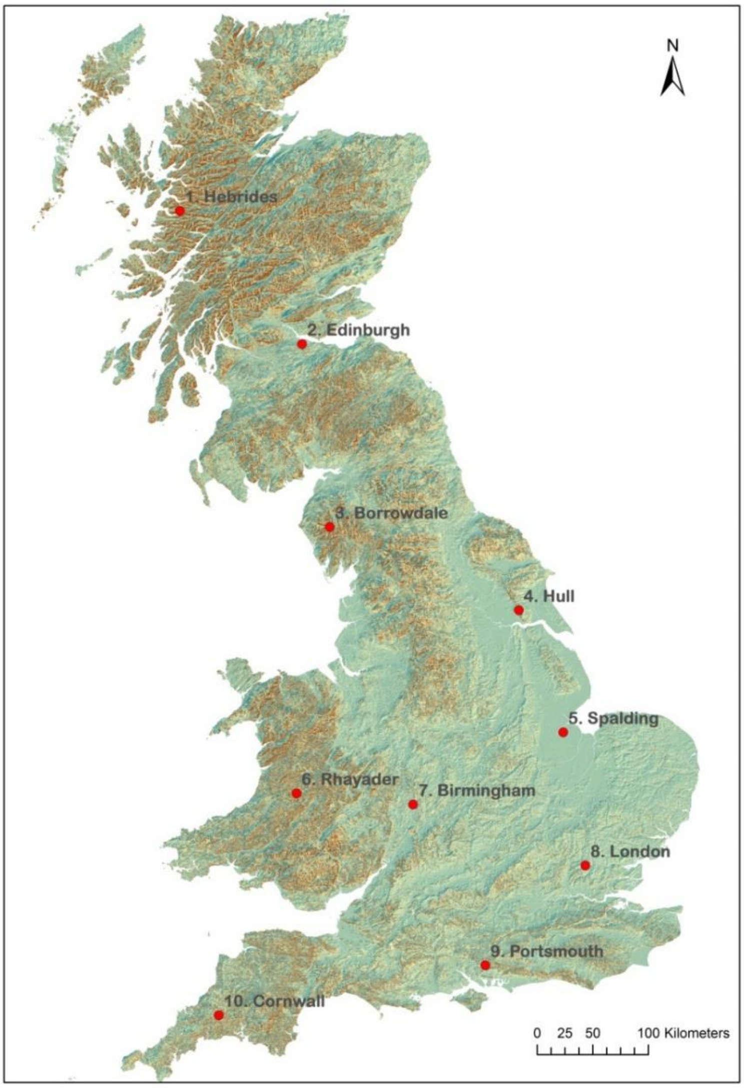


Figure 4-6: Location of selected 5km UKCP09 grid cells for further analysis (Contains Ordnance Survey data © Crown copyright and database right 2016).

4.3.4 Integration of climatic and geohazard models

Currently, the NPD model uses the empirical 1961-75 accumulated maximum annual mean PSMD as the climatic component to estimate potential clay-related subsidence hazard. The aim of this study was to supplant this empirical data with projections of PSMD computed from WG data. To achieve this, the WG-derived PSMD data was spatially referenced to the 5km WG grid cells (see http://ukclimateprojections-ui.metoffice.gov.uk/ui/docs/grids/wg_5km/index.php) and intersected with the SSWELL data.

Clay subsidence hazard was then calculated from the maximum accumulated PSMD and SSWELL using a Python script in ArcGIS's field calculator function (Appendix F) using the relationship defined in Table 4-3. This process was undertaken for each climatic scenario and for the 10, 50 and 90th percentiles as well as the mean and standard deviation PSMD.

Clay subsidence hazard potential in NPD is portrayed with nine classes (0-8), ranging from *extremely low (0)* to *extremely high (8)* (Table 4-3). PSMD is divided into 8 classes, where '1' is representative of field capacity (i.e. saturated ground with a PSMD of approximately 0 mm) and '8' is where the soil would be classed as having lost all available water (Table 4-3). For the latter, a particularly dry year may see PSMDs reaching 300 mm, however for most soils this is well beyond the available water reserves (Jones and Thomasson, 1985). The relationship between PSMD and SSWELL, established through laboratory-based shrinkage testing of each soil substrate type for each representative of soil series in GB, is tabulated in Table 4-3; this table represents the basis of the Python code provided in Appendix F. Specific PSMD values (i.e. mm) for each of the 8 classes have not been defined due to the intellectual property rights associated with the NPD model operated by Cranfield University.

Additionally, a series of clay subsidence vulnerability class change maps have been produced to show the projected change in clay subsidence hazard between (1) baseline and 2030 (Figure 4-16) and (2) baseline and 2050 (Figure 4-17). Similarly to the clay subsidence hazard maps (Figure 4-12), these are also presented as changes in respect of the 10^{th}, 50^{th} and 90^{th} percentile projections. To create these maps, the baseline clay subsidence map was intersected spatially with the 2030 and 2050 clay subsidence maps, respectively. New fields were then created, and the 'field calculator' function in ArcGIS v. 10.2 was used to calculate the difference in clay subsidence vulnerability class, presented in Figure 4-16 and Figure 4-17.

Table 4-3: Matrix for calculating clay-related subsidence potential

		Potential Soil Moisture Deficit (PSMD)							
		1	2	3	4	5	6	7	8
Soil Shrink Swell Potential	1 (VL)	0	0	0	0	0	0	0	1
	2 (L)	0	1	1	1	1	1	1	2
	3 (Mod)	0	2	2	3	5	5	5	5
	4 (H)	0	3	5	6	6	7	7	7
	6 (H*)	4	4	4	5	6	7	8	8
	5 (VH)	0	4	6	7	8	8	8	8

0 –Extremely Low

1 – Very Low

2 – Low

3 – Medium Low

4 – Medium

5 – Medium High

6 – High

7 – Very High

8 – Extremely High

4.4 Results

It is envisaged that the maps resulting from this study will be used at a range of scales. Therefore, as well as providing the GB view, a region of eastern England (Figure 4-18) was highlighted for further analysis. This area was selected due to the region's diverse range of soil types, varying topography and significant changes in PSMD for the different UKCP09 climatic time periods. This area also encompasses the full range of SSWELL values. The probabilistic nature of UKCP09 means that the daily weather variables produced by the spatial WG are able to display the uncertainty inherent in the climatic modelling outputs. Analysis of the full range of UKCP09 emissions scenarios was also assessed for the UK administrative county of Worcestershire, and information is presented in Section 4.4.5.

4.4.1 Potential soil moisture deficit

Results indicate that PSMD is likely to increase significantly from the baseline through to 2050. The south-east of England is set to undergo the biggest changes, with annual PSMDs based upon the central estimate (50th percentile) set to increase by up to 100mm by 2030, and 160mm by 2050 (Figure 4-7). By contrast, the upland areas of the UK (i.e. Wales, Dartmoor, Exmoor, Lake District and Pennine regions) are unlikely to be affected by projected climate change scenarios. In these upland areas, PSMD change is not likely to exceed 20-40mm through to 2050. However, during extreme events (i.e. 90th percentile PSMD), higher PSMDs may result (Figure 4-7). Monthly estimates of PSMD for the representative scenarios (Figure 4-8, Figure 4-9 and Figure 4-10) suggest that the highest rates of PSMD are likely to occur in late summer/early autumn

(August-October) which is consistent with present conditions. However, by 2050 these high PSMD's (i.e. > 300 mm) are likely to persist into November (Figure 4-10), which could lead to a temporal change in clay subsidence hazard, especially in the south-east of England.

It is apparent from Figure 4-7 that what may be regarded at the current time as an extreme event (i.e. baseline 90th percentile) is likely to represent PSMD values of a *central estimate* (50th percentile) by 2030, especially in the south-east of England. Moreover, modelled baseline *central estimate* (50th percentile) PSMD values are likely to represent the lower 10th percentile (*not likely to be less than*) by 2030 and 2050 respectively. Both the 2030 and 2050 scenarios at the 50th and 90th percentiles also indicate that PSMDs are likely to persist through the winter months, carrying the deficit across into the following year (Figure 4-9 and Figure 4-10); projections of monthly PSMD for the 10th and 90th percentiles for 2030 and 2050 are presented in Appendix E. However, the data produced by the WG is representative of an independent model year, based upon specific change factors. Therefore, the analysis cannot take into account consecutive years: PSMD being reset to zero in January. It is therefore possible that the models are under-predicting the future PSMD and consequent impacts over consecutive model years.

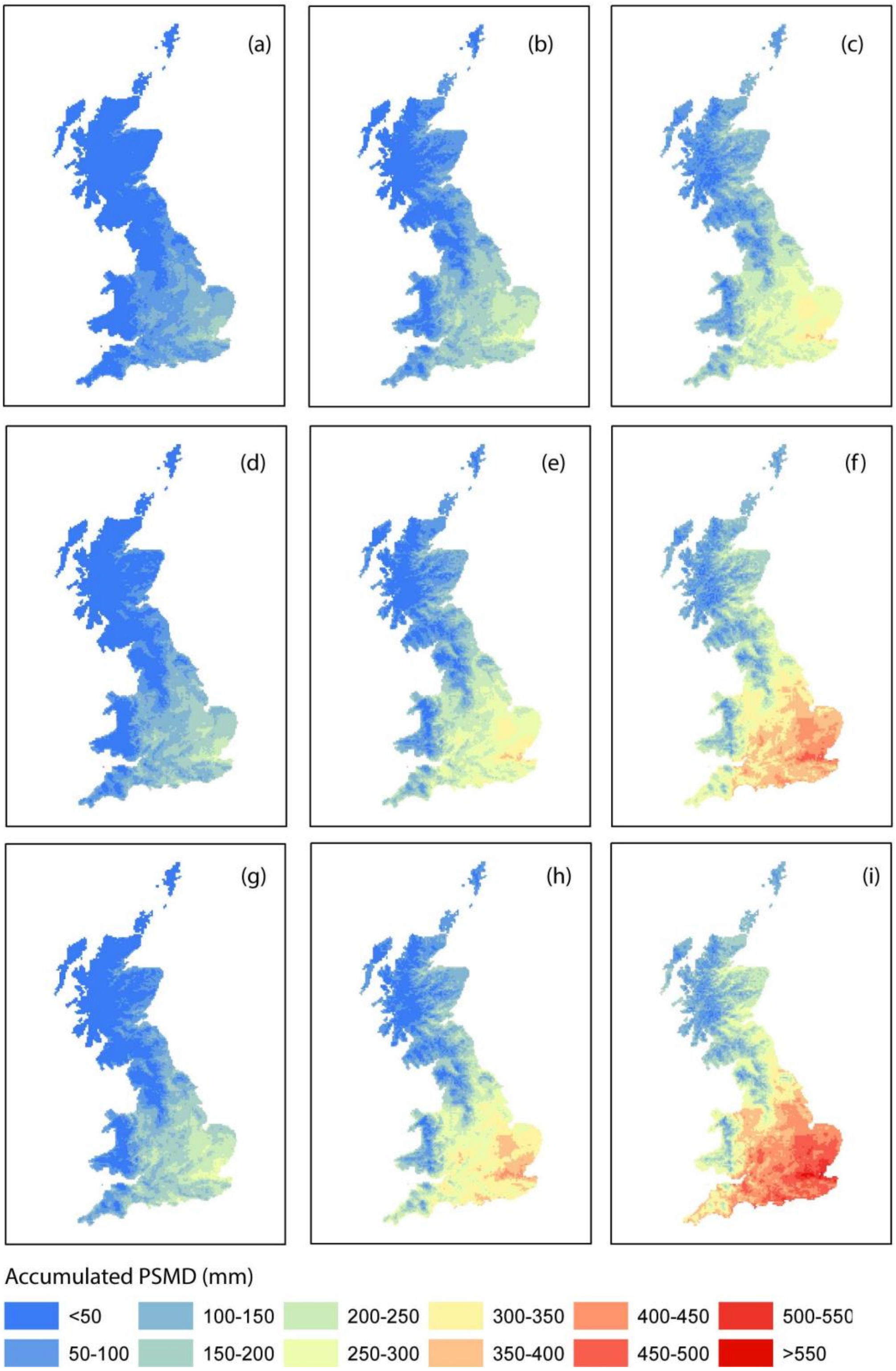


Figure 4-7: UKCP09-derived projections of accumulated annual PSMD for Great Britain Baseline (1961-1990) (a) 10th, (b) 50th and (c) 90th percentiles; 2030 (2020-2049) (d) 10th, (e) 50th and (f) 90th percentiles; 2050 (2040-2069) (g) 10th, (h) 50th and (i) 90th percentiles

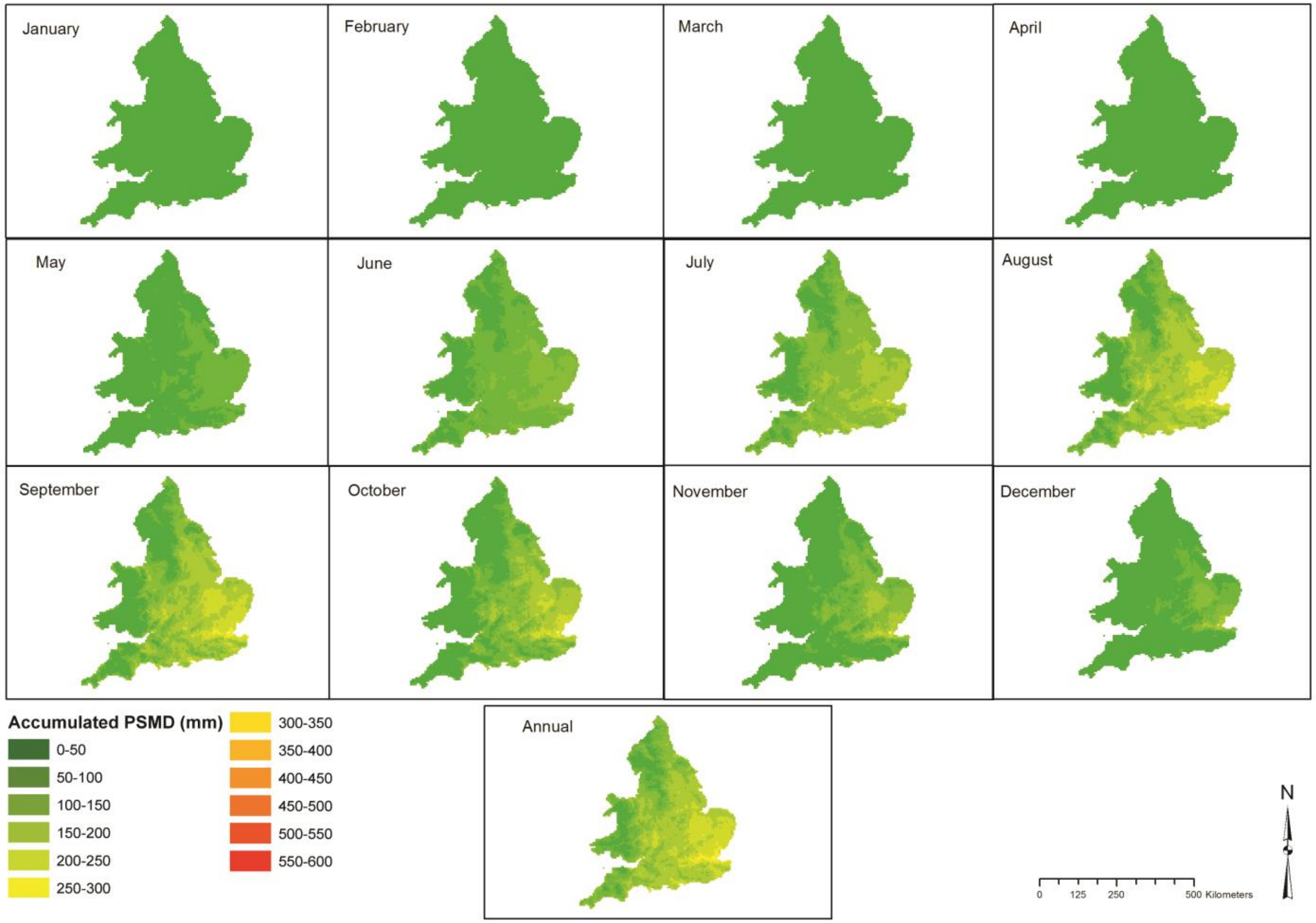


Figure 4-8: A 'central estimate' (50th percentile) monthly and annual UKCP09 baseline (1961-1990) Accumulated Potential Soil Moisture Deficit (PSMD)

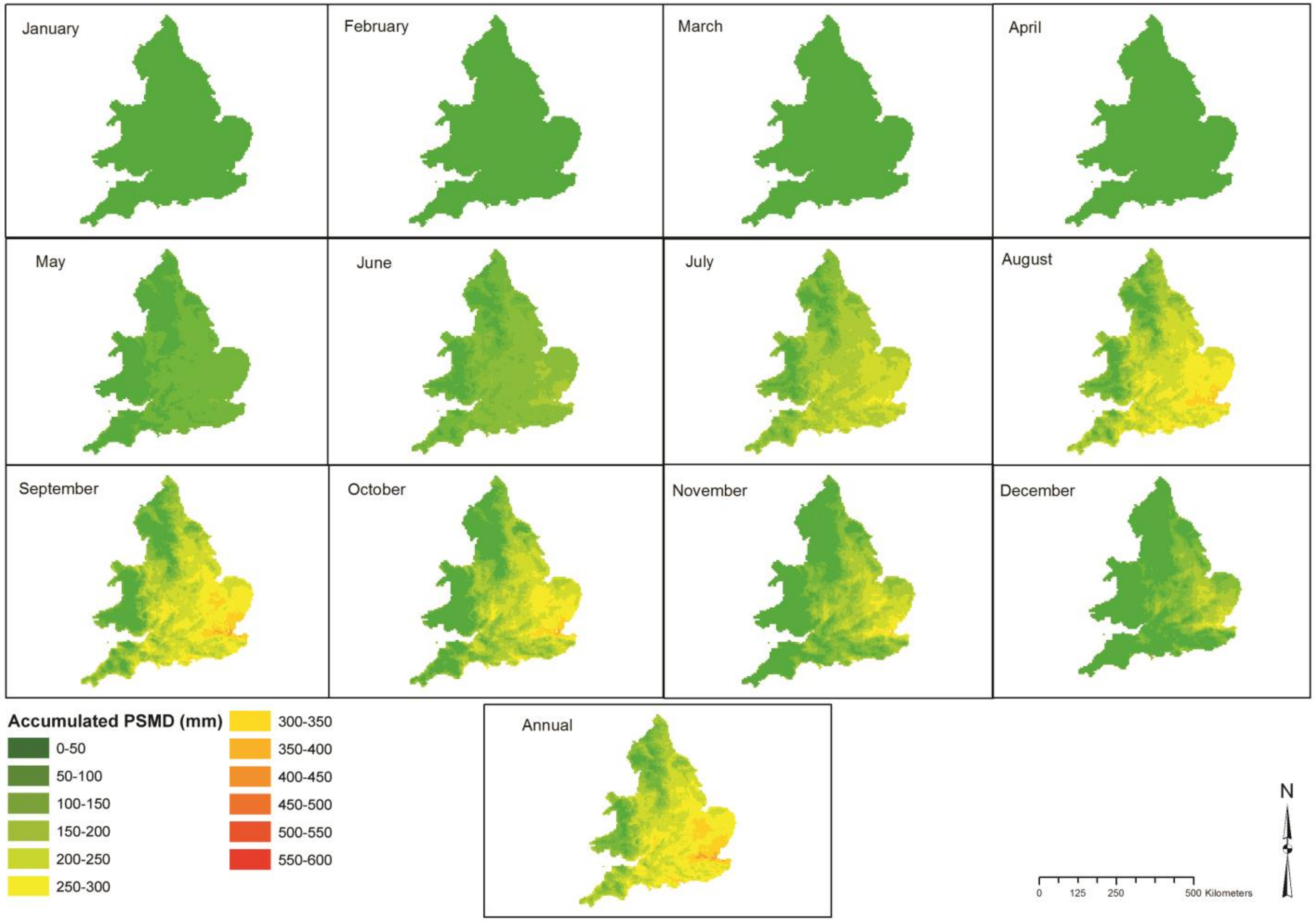


Figure 4-9: A 'central estimate' (50th percentile) monthly and annual UKCP09 2030 (2020-2049) Accumulated Potential Soil Moisture Deficit (PSMD)

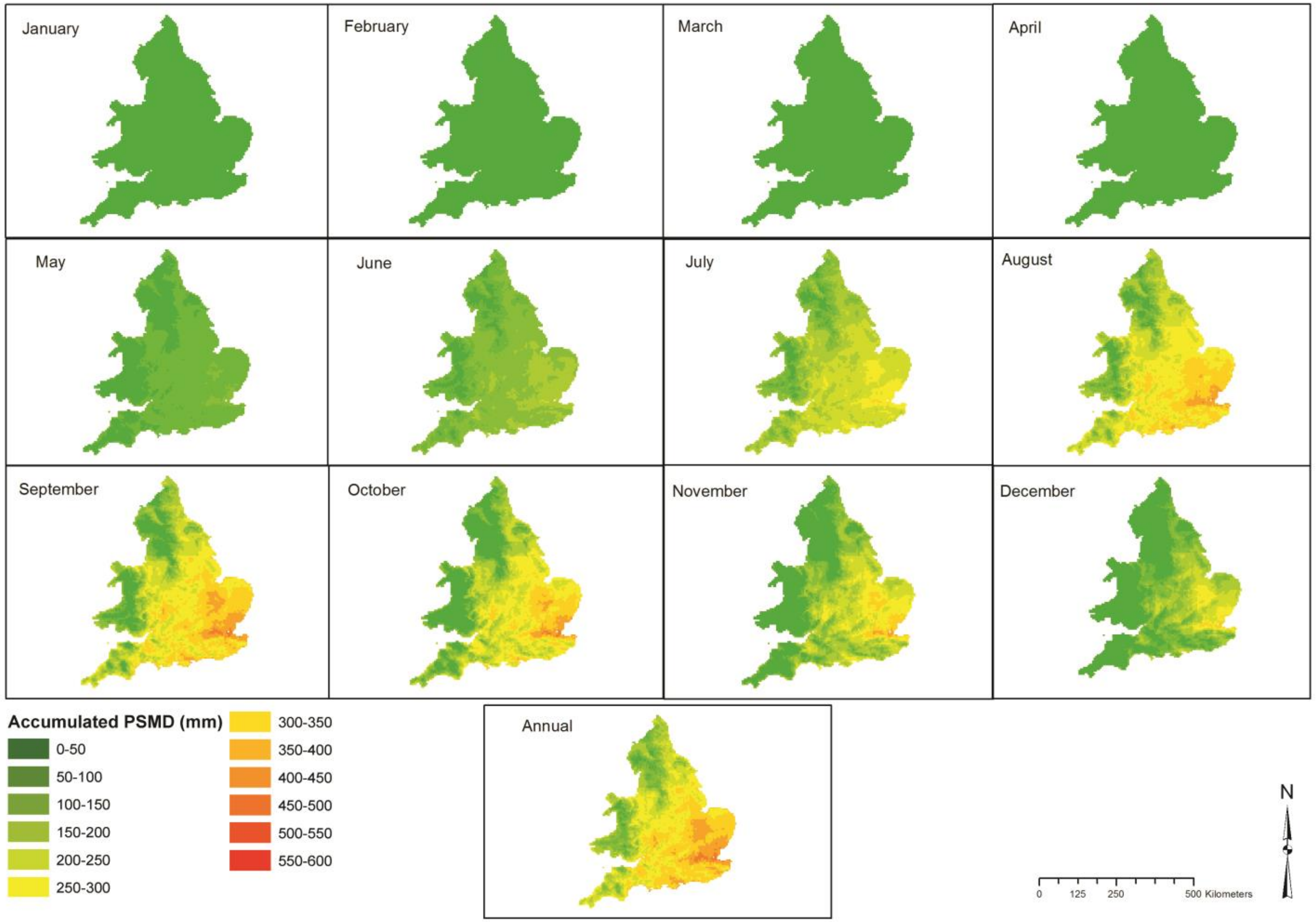


Figure 4-10: A 'central estimate' (50th percentile) monthly and annual UKCP09 2050 (2040-2069) Accumulated Potential Soil Moisture Deficit (PSMD)

4.4.2 PSMD distributions

PSMD projections shown in Figure 4-7 suggest that significant changes in PSMD are likely to occur across certain areas of Great Britain. However, in-depth analysis of ten selected UKCP09 weather generator 5km grid cells, which are representative of GB's climatic regions (Figure 4-6), further supports the theory that this change will not be equally proportionate across Great Britain. Frequency distributions of PSMD data for the baseline, 2030 and 2050 scenarios are provided in Figure 4-11; the reader is reminded that the 2030 and 2050 distributions represent a subset of the full modelled dataset of 1,000 perturbations. Summary statistics of the datasets for the ten selected gridcells are shown in Table 4-4.

Statistical analysis using a combination of a Mann-Whitney U-test (MWUt) and two sample T-test (2Tt) showed that data distributions for all ten selected sites were significantly different (Table 4-5). This supports the frequency distributions shown in Figure 4-11. The choice of statistical test was based upon whether the data was classed as normally distributed, the Shapiro-Wilks test was used to derive this and results are provided in 4-4; Quantile-quantile plots were also created to support the Shapiro-Wilks test and are provided in Appendix G.

Those grid cells in upland areas (i.e. Hebrides and Borrowdale) show that there is likely to be little change in PSMD from baseline to 2050. Conversely grid cells in the south-east of England (e.g. Birmingham, London and Spalding) suggest a significant change in PSMD distribution between baseline and 2050. However, PSMD exerts a greater magnitude of change between the baseline and 2030 compared to that between 2030 and 2050 (Figure 4-11).

Table 4-4: Summary statistics for the ten selected UKCP09 5km grid cell locations for Baseline, 2030 and 2050 PSMD as labelled (S-W: Shapiro-Wilks Test; * indicates statistically significant to 0.05 confidence level)

	Baseline (1961-1990)				
Location	**Min**	**Median**	**Mean**	**Max**	**S-W Test**
1. Hebrides	0	2.96	18.27	197.3	2.20×10^{-16}
2. Edinburgh	0	120.4	122.3	324.1	9.18×10^{-12}
3. Borrowdale	0	0	7.304	117.7	2.20×10^{-16}
4. Hull	0	137.5	138.1	348.9	1.39×10^{-08}
5. Spalding	4.59	198.6	199	407	0.00098
6. Rhayader	0	40.84	47.74	229.7	2.20×10^{-16}
7. Birmingham	12.56	190.7	190.5	398.8	0.01442
8. London	42.97	231.8	230.9	470.5	0.5674*
9. Southampton	11.94	164.3	165.2	375.9	8.38×10^{-05}
10. Cornwall	0	36.2	43.09	207.1	2.20×10^{-16}

	2030 (2020-2049)				
Location	**Min**	**Median**	**Mean**	**Max**	**S-W Test**
1. Hebrides	0	17.44	29.93	255	2.20×10^{-16}
2. Edinburgh	4.46	167.2	167.3	402	4.74×10^{-07}
3. Borrowdale	0	0	17.06	162.4	2.20×10^{-16}
4. Hull	0	199.6	199.8	498.3	0.000547
5. Spalding	22.43	278.2	275.3	588.4	0.1853*
6. Rhayader	0	81.3	90.27	329.5	2.20×10^{-16}
7. Birmingham	21.04	266.2	264.9	569.6	0.06208*
8. London	51.57	319.9	318.1	597	0.07404*
9. Southampton	12.48	256.9	257.9	609.2	0.0005407
10. Cornwall	0	80.96	92.01	365.8	2.20×10^{-16}

	2050 (2040-2069)				
Location	**Min**	**Median**	**Mean**	**Max**	**S-W Test**
1. Hebrides	0	24.1	37.03	362.8	$2.20x10^{-16}$
2. Edinburgh	7.97	195.8	195.4	420.4	0.000703
3. Borrowdale	0	9.23	25.61	272.5	$2.20x10^{-16}$
4. Hull	11.86	239	238.3	542.4	0.000163
5. Spalding	24.14	314.9	314.3	652.5	0.4605*
6. Rhayader	0	114.1	122.1	401	$2.20x10^{-16}$
7. Birmingham	29.83	317.9	318.5	629	0.1932*
8. London	39.03	377.3	373.8	746	0.00881
9. Southampton	2.92	311.7	312.6	767.7	0.00209
10. Cornwall	0	120.3	133.2	470.5	$2.20x10^{-16}$

Table 4-5: Test for significant differences comparing 'baseline', '2030' and '2050' scenarios at the 95% confidence level for all the ten selected 5km grid cells (MWUt – Mann-Whitney U Test; 2Tt – 2 sample T-test)

Location	Statistical analysis		2030	2050
1. Hebrides	MWUt	**Baseline**	$2.20x10^{-16}$	$2.20x10^{-16}$
		2030		$4.92x10^{-09}$
2. Edinburgh	MWUt	**Baseline**	$2.20x10^{-16}$	$2.20x10^{-16}$
		2030		$2.20x10^{-16}$
3. Borrowdale	MWUt	**Baseline**	$2.20x10^{-16}$	$2.20x10^{-16}$
		2030		$2.20x10^{-16}$
4. Hull	MWUt	**Baseline**	$2.20x10^{-16}$	$2.20x10^{-16}$
		2030		$2.20x10^{-16}$
5. Spalding	2Tt	**Baseline**	$2.20x10^{-16}$	$2.20x10^{-16}$
		2030		$2.20x10^{-16}$
6. Rhayader	MWUt	**Baseline**	$2.20x10^{-16}$	$2.20x10^{-16}$
		2030		$2.20x10^{-16}$
7. Birmingham	2Tt	**Baseline**	$2.20x10^{-16}$	$2.20x10^{-16}$
		2030		$2.20x10^{-16}$
8. London	2Tt	**Baseline**	$2.20x10^{-16}$	$2.20x10^{-16}$
		2030		$2.20x10^{-16}$
9. Southmapton	MWUt	**Baseline**	$2.20x10^{-16}$	$2.20x10^{-16}$
		2030		$2.20x10^{-16}$
10. Cornwall	MWUt	**Baseline**	$2.20x10^{-16}$	$2.20x10^{-16}$
		2030		$2.20x10^{-16}$

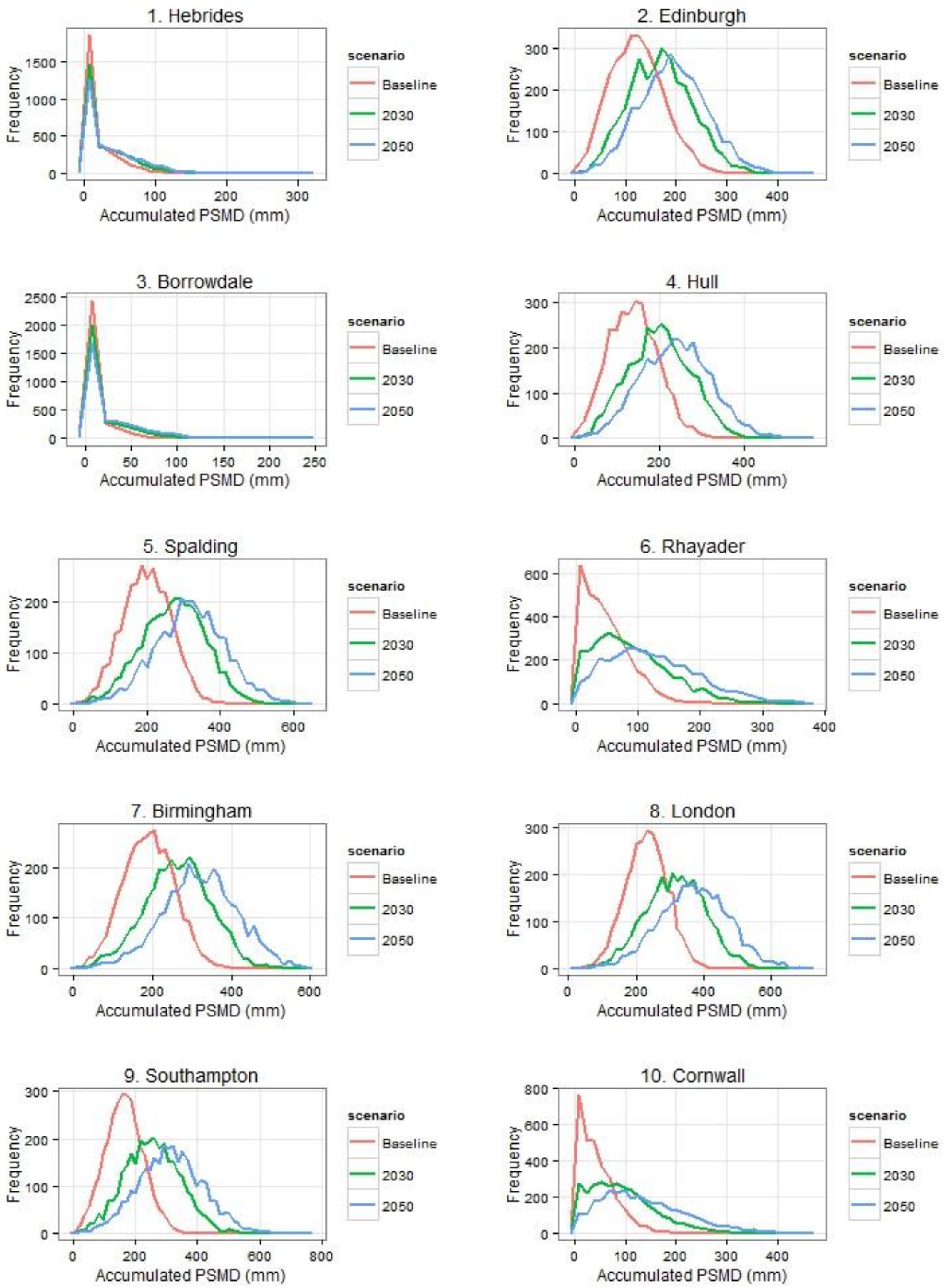


Figure 4-11: PSMD distributions for Baseline (1961-1990), 2030 (2020-2049) and 2050 (2040-2069) UKCP09 scenarios for selected Weather Generator 5km grid cells

4.4.3 Weather generator limitations

Climate models possess a degree of uncertainty, and the downscaling of global circulation models to regional and local-scale models can result in a further layer of uncertainty (Coulthard et al. 2012). The usability of climatic projections has been questioned by numerous articles, and remains a key issue when using projections in model applications. Without trusting the WG outputs how can assurance be gained that, in this instance, the computed assessment of clay-related subsidence hazard potential is likely to occur? Dessai & Hulme (2008) argue that prior to UKCP09, climate projection models in the UK broadly fell within the range of observed climate with the biggest ambiguity occurring for summer rainfall.

Ekström et al. (2007) argue that the determination of PET is an imperfect science, resulting from a limited knowledge regarding atmosphere-soil feedbacks. Furthermore, PET can be affected by a number of soil properties including, porosity and soil depth. Seneviratne et al. (2010), in their extensive review on this matter, regard the ability to model accurately the soil-climate feedback as being limited by empirical, observed data on the ground. This is likely to become increasingly apparent as weather station numbers decline (Prior & Perry, 2014; Perry & Hollis, 2005). Ultimately, an improved knowledge in this subject area will reduce the inherent uncertainty in climate models.

The use of any WG-derived outputs must be treated with caution. Kay and Jones (2012) argue that comparison of WG outputs and empirically-derived baselines will likely not show close agreement as the WG is unable to capture natural climate variability. Moreover, Harding et al. (2014) argue that the interpolation of empirical weather data presents its own uncertainty and biases. Uncertainty inherent in the WG is addressed by providing a range of probable scenarios for clay-subsidence hazard (Figure 4-12).

4.4.4 Outlook for clay-related subsidence potential

Figure 4-12 shows clay-related subsidence hazard modelled for the baseline, 2030, and 2050 time-periods at the 10th, 50th and 90th percentiles. Clay subsidence hazard potential ranges from *extremely low* to *extremely high* making it contiguous with the current NPD classification. The south-east of England will likely become increasingly prone to clay-related subsidence through to 2050. This is a result of high PSMDs coupled with extensive clay-rich soils with mineralogy prone to shrink-swell activity. The north-east of England is also likely to incur increased susceptibility. Conversely, Scotland and Wales are unlikely to see any substantive increase in clay-related subsidence hazard. Although a number of soil types known to be prone to moisture–related shrinkage exist (Figure 4-2), PSMD values are not set to change significantly through to 2050. This is supported by the PSMD distributions analysis in Figure 4-11. Exceptions to this are the areas around the Firth of Forth and the River Tay estuaries in Scotland where the hazard potential of the shrink-swell prone alluvial soils changes from a *medium low* to a *high*/*very high* class. The PSMD distribution for Edinburgh (Figure 4-11) supports this change in PSMD and therefore subsidence hazard. The land area of each subsidence hazard class for the baseline, 2030 and 2050 scenarios is detailed in Figure 4-14. By the 2050's, 12% of the land area of GB will be at *extremely high* or *very high* hazard potential for clay related subsidence, comparable to the 7% of land area for the 1961-1990 baseline. The apparent diminishing of the *high* class is a consequence of higher PSMDs, causing redistribution of values to the *very high* and *extremely high* classes.

Figure 4-12: Projections of Great Britain clay-related subsidence hazard for the baseline (1961-1990) (a) 10th, (b) 50th and (c) 90th percentiles; 2030 (2020-2049) (d) 10th, (e) 50th and (f) 90th percentiles; 2050 (2040-2069) (g) 10th, (h) 50th and (i) 90th percentiles. (Soils data (England and Wales) © Cranfield University and for the Controller of HMSO 2015; Scottish soils data © James Hutton Institute 2015)

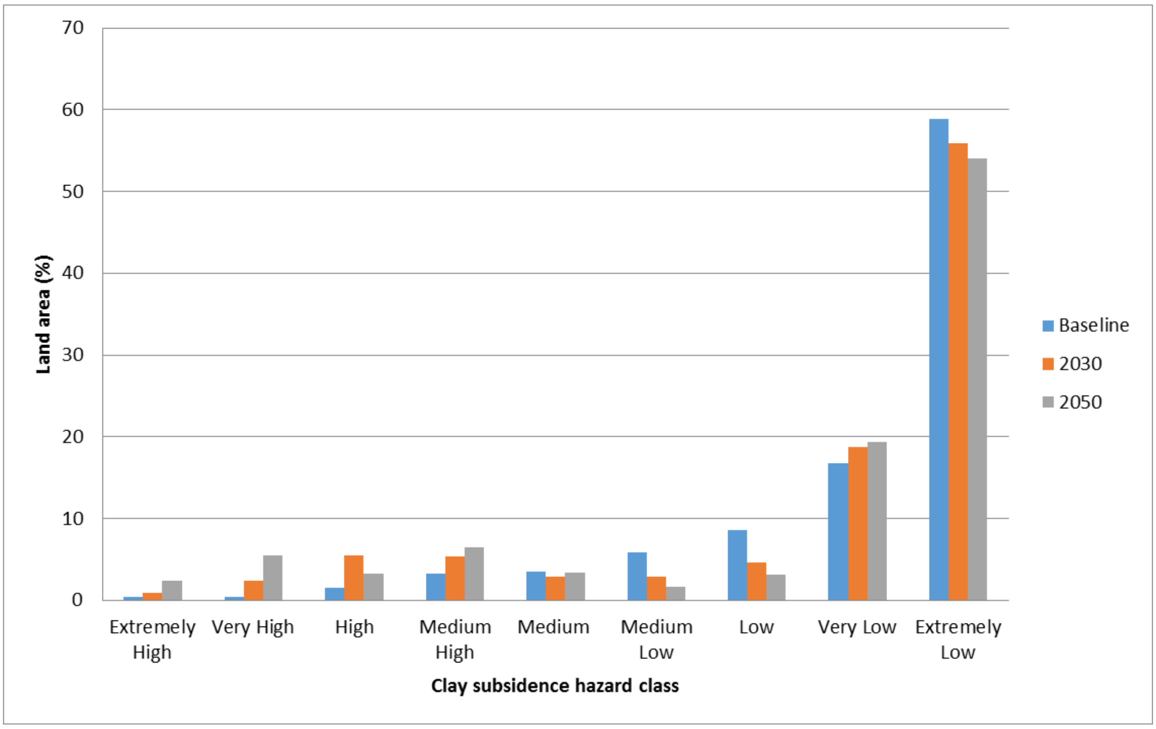


Figure 4-13: Percentage of Great Britain land area by clay subsidence hazard class (10th percentile)

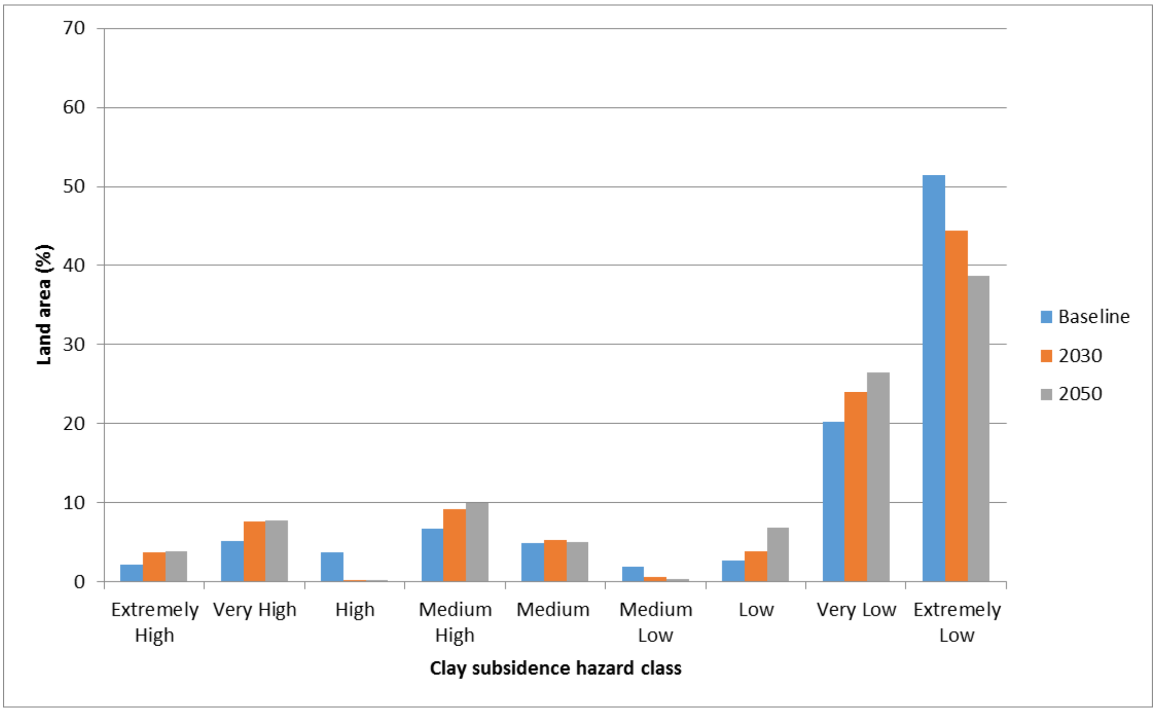


Figure 4-14: Percentage of Great Britain land area by clay subsidence hazard class (50th percentile)

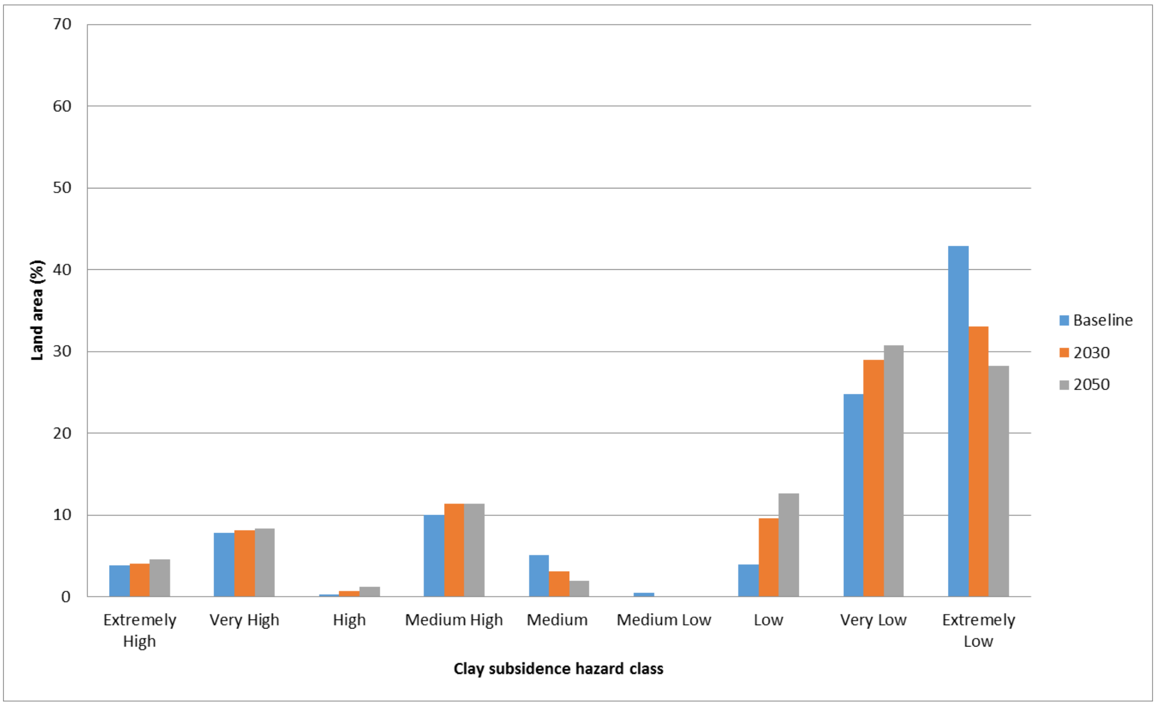


Figure 4-15: Percentage of Great Britain land area by clay subsidence hazard class (90th percentile)

Approximately 75% of the land area in England and Wales is underlain by soils of *low* to *extremely low* likelihood of clay-related subsidence hazard for the baseline period (i.e. <5% volumetric shrinkage potential) and is only set to decrease to 73% by 2050 (Figure 4-14); percentage values for the equivalent 10th and 90th percentiles are provided in Figure 4-13 and Figure 4-15, respectively. These subsequent figures show that in the 10th percentile, clay subsidence hazard will be heavily weighted with a greater percentage being in the lower risk classes (Figure 4-13). Conversely, in Figure 4-15 subsidence hazard although heavily weighted in the lower hazard classes, a spreading of the land area into the higher clay subsidence hazard classes will potentially be realised.

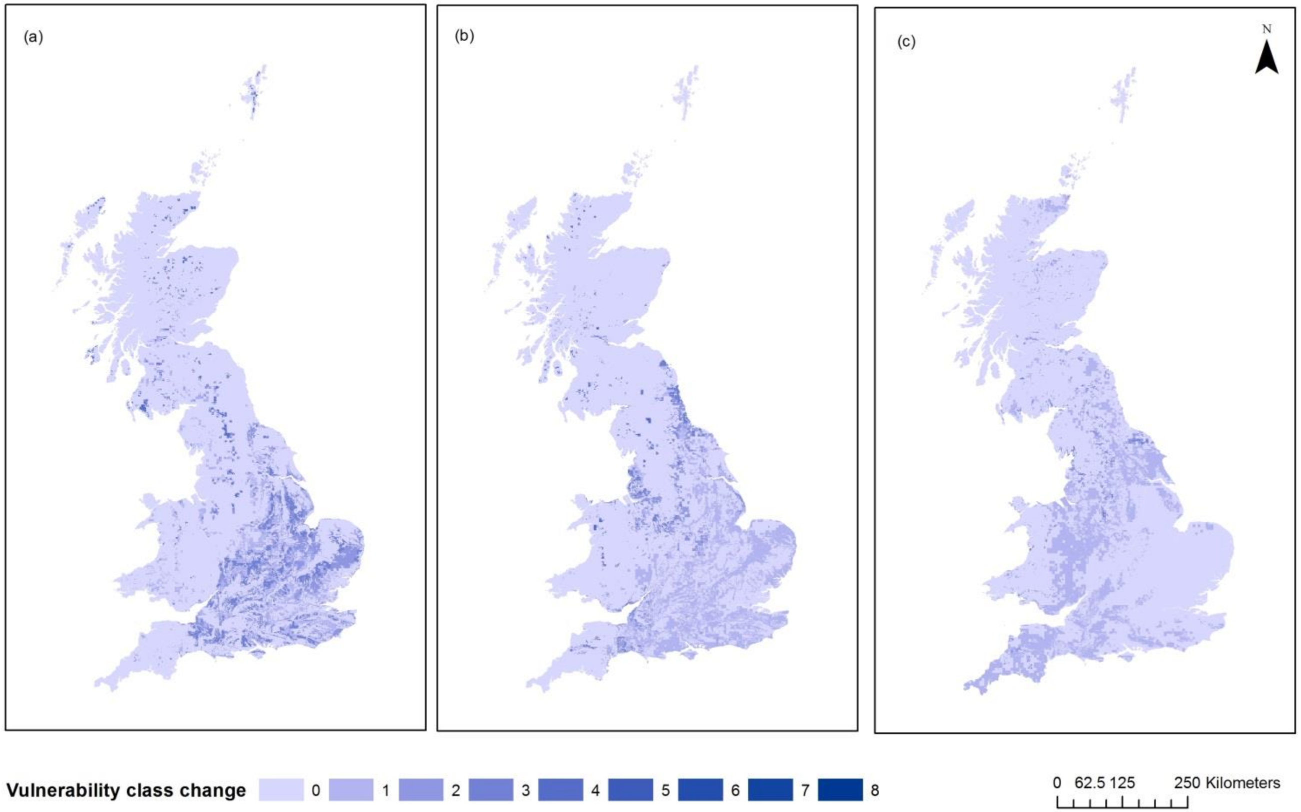


Figure 4-16: Clay subsidence vulnerability class change between Baseline (1961-1990) and 2030 (2020-2049) for (a) 10th, (b) 50th and (c) 90th percentile

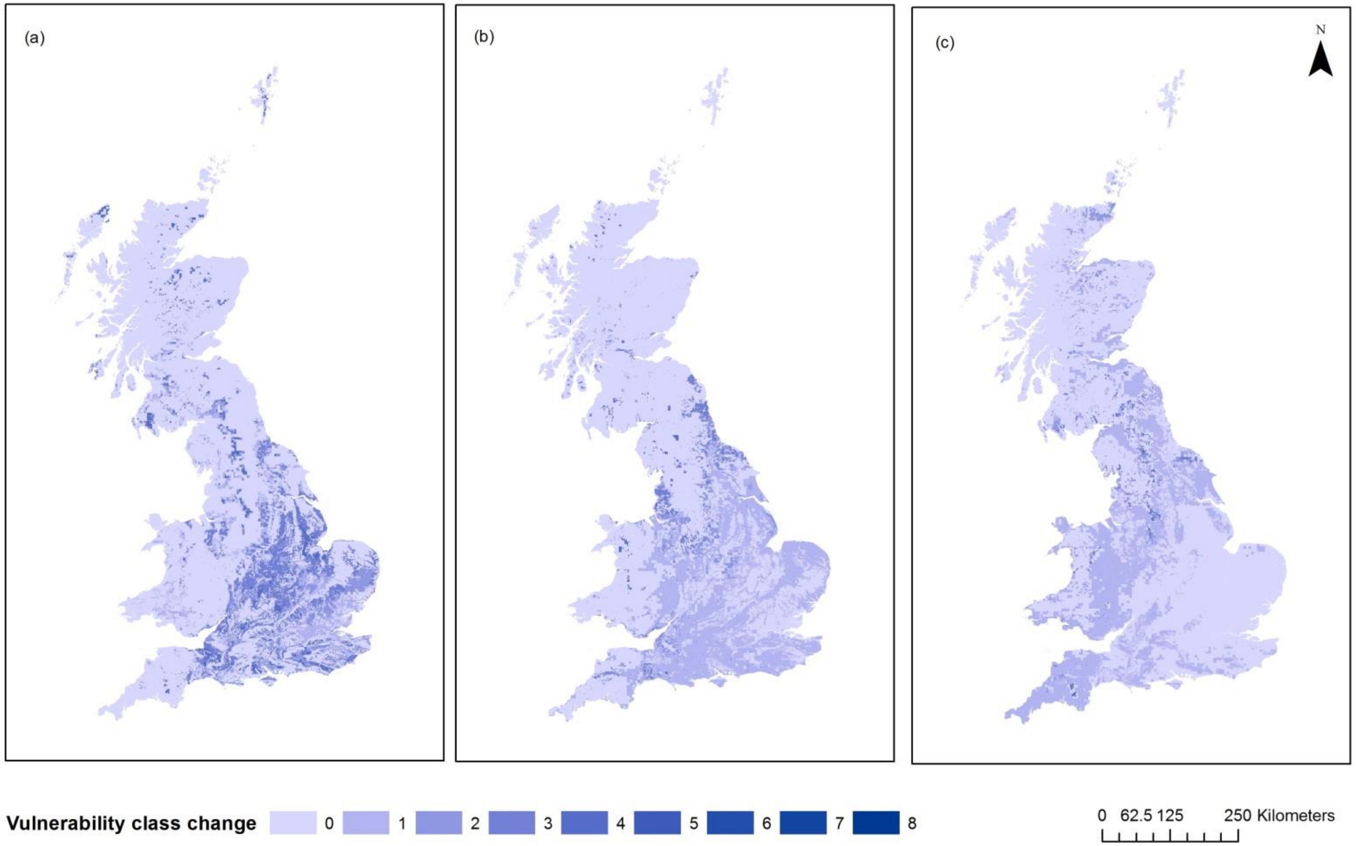


Figure 4-17: Clay subsidence vulnerability class change between Baseline (1961-1990) and 2050 (2040-2069) for (a) 10th, (b) 50th and (c) 90th percentile

For a number of soils, their texture and mineralogy will mean that they will not undergo volumetric change under differing moisture conditions as PSMD changes occur. Significant mineralogical change in the context of this thesis (i.e. up to 2069) will not occur and, therefore, these soils will remain at a lower potential hazard as a result of clay-related subsidence.

Figure 4-18 shows the selected study area of the mid-eastern coastal area of England. This area reveals a general increase in the susceptibility to clay-related subsidence through to 2050. Map (d) in Figure 4-18 shows the hazard class change. Of particular note is the large change in the Derwent valley just south of Scarborough. In some areas, a movement of 4 subsidence hazard classes between the baseline and 2050 is observed, indicating a large increase in susceptibility. In contrast the upland areas are predominantly unaffected due to the underlying geology not giving rise to clay-bearing soils and with PSMDs remaining comparatively low.

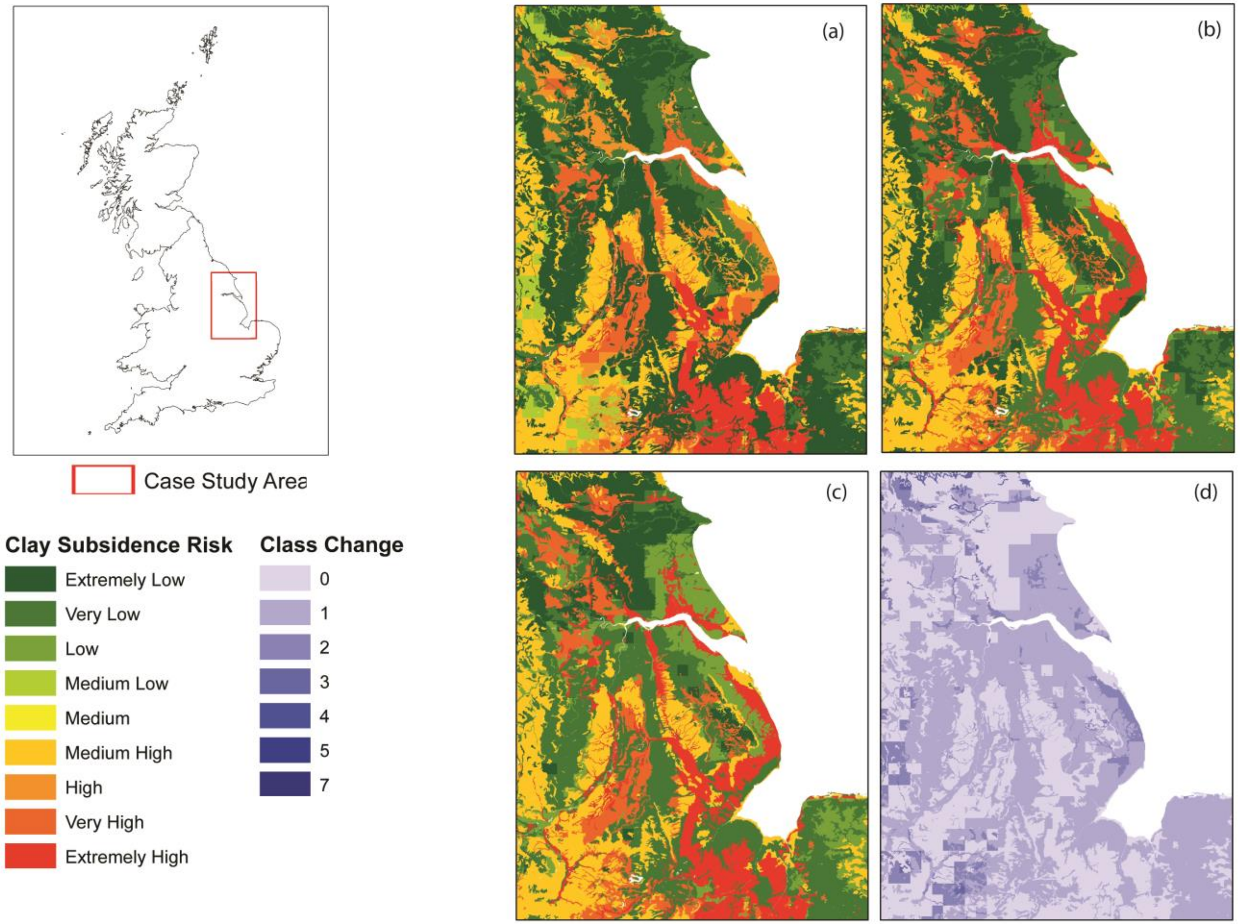


Figure 4-18: Case study area (a) 50th percentile clay subsidence hazard Baseline (1961-1990); (b) 50th percentile clay subsidence hazard 2030 (2020-2049); (c) 50th percentile clay subsidence hazard 2050 (2040-2069); (d) Difference in hazard class, Baseline to 2050 (Soils data © Cranfield University and for the Controller of HMSO 2015)

4.4.5 Exploring the full range potential of the UKCP09 emissions scenarios

For comparative purposes, the WG was also run to obtain low, medium and high emissions climate scenarios for calculation of PSMD. However, due to modelling time and data storage constraints, the entirety of Great Britain could not be modelled. As such, a case-study area forming the UK administrative county of Worcestershire was chosen for the additional analysis of emissions scenarios.

Situated in central western England, Worcestershire has a diverse range of soil types (Figure 4-19), with predominantly clay-rich soils in the south-east of the county, and more sand-rich soils to the north; a factor of the respective underlying geology. This made it a suitable area for establishing the effect of the full range of emissions scenarios on clay-related subsidence potential. Furthermore, Worcestershire County Council and Sustainability West Midlands have already undertaken a simplified analysis of clay subsidence risk to infrastructure assets and therefore this analysis was presented to Worcestershire County Council to help inform their infrastructure planning strategy (Sustainability West Midlands, 2012).

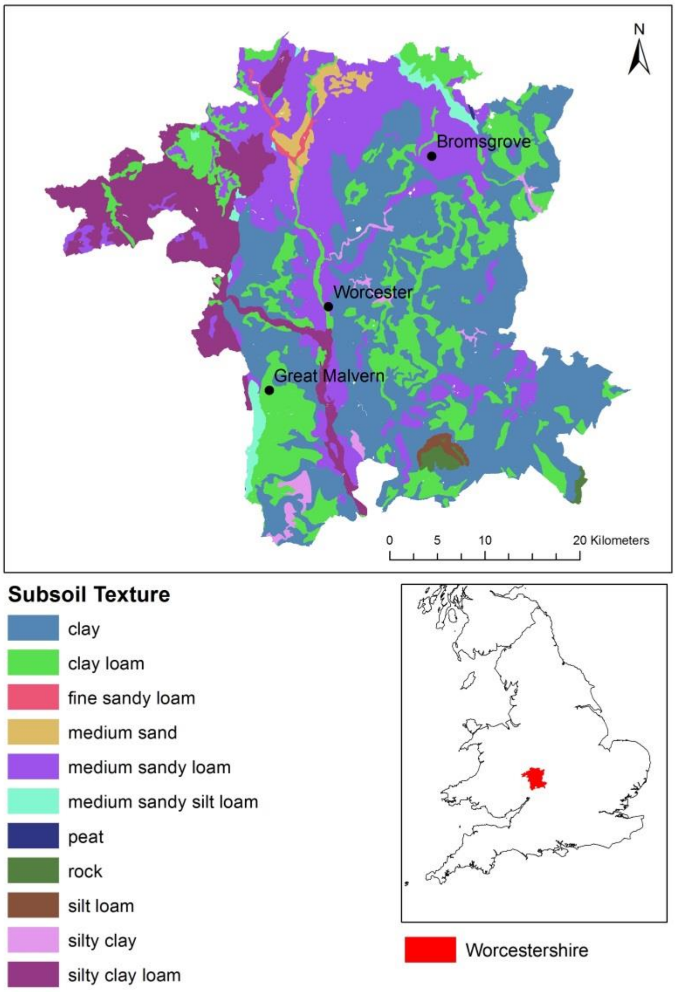


Figure 4-19: Subsoil textures for the county of Worcestershire, England (Soils data © Cranfield University and for the Controller of HMSO, 2015)

4.4.5.1 Worcestershire PSMD projections

Using the methodology described in Section 4.3.2, projections of PSMD were calculated for each of the respective emissions scenarios;the low emissions scenario being equivalent to the IPCC's (Intergovernmental Panel on Climate Change) B1 scenario; the medium emissions with that of A1B; and high emissions with that of A1F1 (IPCC 2000). Figure 4-20 provides a visual representation of these PSMD projections for the county.

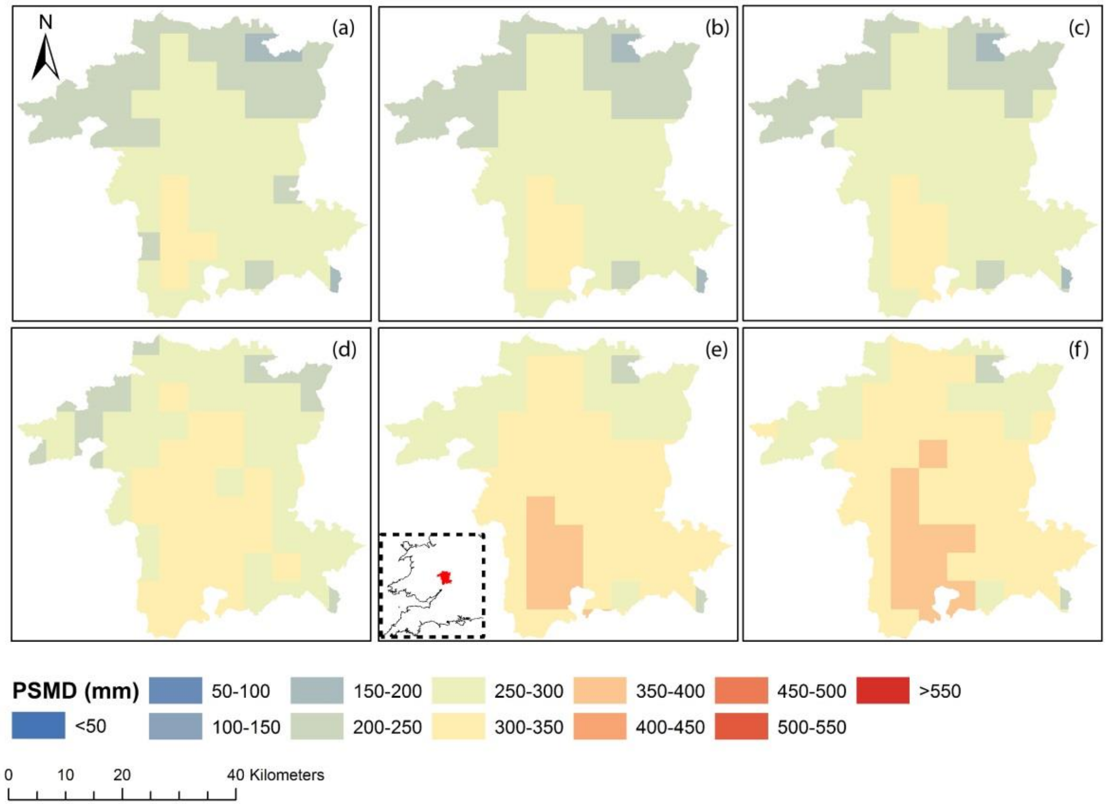


Figure 4-20: Projections of accumulated annual PSMD for Worcestershire, UK, for 2030 (2020-2049) (a) low emissions 50th percentile, (b) medium emissions 50th percentile, (c) high emissions 50th percentile; 2050 (2040-2069) (d) low emissions 50th percentile, (e) medium emissions 50th percentile, (f) high emissions 50th percentile

4.4.5.2 Worcestershire clay-related subsidence projections

From the PSMD data derived for Worcestershire (Figure 4-20), projections of clay-related subsidence hazard, using the methodology described in Section 4.3.3, have been produced for the same area. Figure 4-21 shows that there appears to be little change between the projections representative of the low, medium and high emissions scenarios for 2030 and 2050. This is likely to be due to the PSMD having reached a limit where, even if soils are susceptible to clay-related subsidence, the soil has no more available water and therefore subsidence hazard will not increase beyond the *Very High* or *Extremely High* classes.

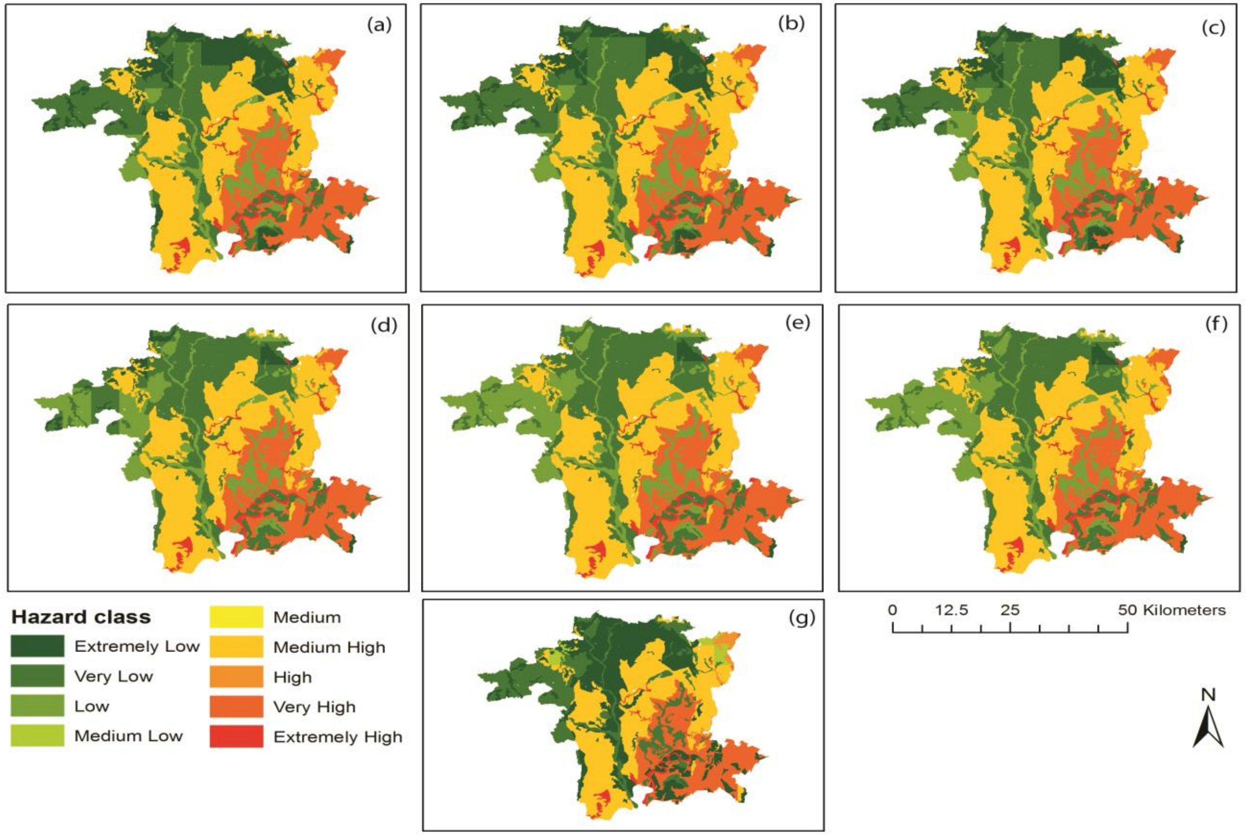


Figure 4-21: Projections of clay-related subsidence hazard for 2030 (2020-2049) (a) low emissions 50th percentile, (b) medium emissions 50th percentile, (c) high emissions 50th percentile; 2050 (2040-2069) (d) low emissions 50th percentile, (e) medium emissions 50th percentile, (f) high emissions 50th percentile, (g) Baseline (1961-1990) 50th percentile. (Soils data (England and Wales) © Cranfield University and for the controller of HMSO 2015)

4.5 Discussion and conclusions

A method for processing UKCP09 high-resolution climate projection data to produce probabilistic scenarios of PSMD based on a medium emission (SRES A1B) scenario for GB has been developed; low (SRES 1B) and high (SRES A1F1) emission scenarios have also been investigated for the UK administrative county of Worcestershire (Figure 4-20). Resultant PSMD scenarios have been incorporated within a soil-related geohazard model. The outcome has been the production of a novel, national-scale, thematic dataset revealing the spatial and temporal distribution, alongside inherent uncertainty, of potential clay-related subsidence for a range of future time-periods. This advancement in the spatio-temporal understanding of clay-related subsidence hazard potential will bring benefits to organisations and stakeholders with long term interests. Projections suggest that future clay-related subsidence will become more common in GB. Particular concerns centre on the southeast of England, where modelled PSMD indicates a substantial increase through to 2050 (Figure 4-7) compared to the baseline. This could indicate that areas at a current *medium* hazard of clay-related subsidence may potentially become exposed to *very high* and *extremely high* hazard by 2050 (Figure 4-12). This is supported by the PSMD distributions in Figure 4-11, which show that there is likely to be a significant shift in PSMD between the baseline (1961-1990) and that of 2030 (2020-2049) for the south-east of England. Similarly, certain areas of north-eastern England will see localised changes in clay-relted subsidence class, as shown in Figure 4-18. Changes in the mean and extremes of PSMD become apparent, and is represented both hypothetically (for temperature) in Figure 4-22 and in the

PSMD distributions shown in Figure 4-11. However, analysis has shown that for certain areas of GB, this change will not be comparable. For example, the selected grid cells (Figure 4-6) of the Hebrides and Borrowdale indicate that there will only be subtle changes in PSMD in these upland areas and the area will likely remain with low PSMD (wet) through to 2030 and 2050; as such, clay-subsidence risk won't be realised.

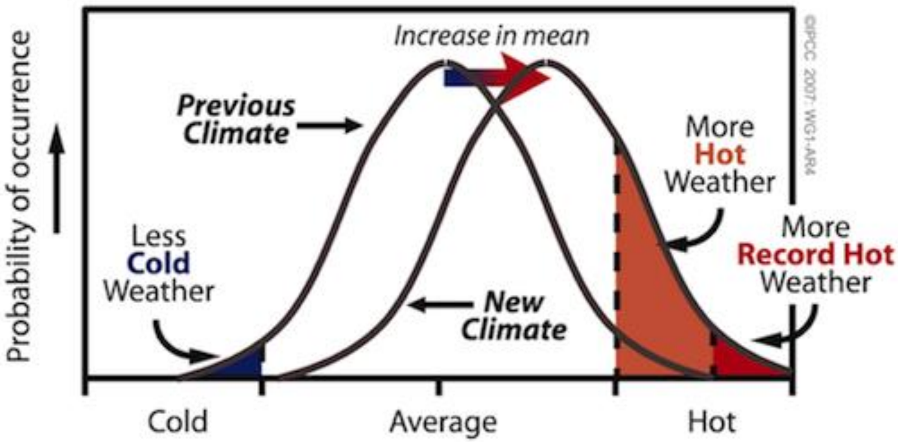


Figure 4-22: Changes in mean and extremes of climate under climate change (Source: Solomon, 2007)

France's drought of 2003 resulted in a number of subsidence claims arising from a lack of preparedness and adaptation (Corti et al. 2011). The fact that GB's built environment suffers currently from degradation and/or failure as a result of clay subsidence means that, as a society, GB is not wholly resilient to this hazard. The projections shown in this chapter suggest that the built environment and critical infrastructure of England, Scotland and Wales are likely to become further exposed to clay-related subsidence at higher frequency and magnitude, through to 2050 and beyond. However, Figure 4-11 suggests that the largest potential clay-subsidence hazard and changes in PSMD will likely occur between baseline and 2030 with clay subsidence hazard likely to have reached the highest possible hazard classes (i.e. Very High and Extremely High) by 2030 in areas of south-east England. This is reflected in the analysis of the low and high emissions scenarios (Figure 4-21) which shows little difference in clay subsidence hazard between the scenarios. This is likely to be a result of both the presence of non-suscpetible soils and in areas where soils are susceptible there being PSMD values which reach a saturation point in which clay subsidence hazard cannot increase.

Damage is likely to ensue particularly to shallow-founded structures and buried infrastructure networks, and particularly where mitigation practices are not in place and/or understood. Subsidence hazard could also affect the material consideration of house valuations (Wynn & Hardiment 2001). Crilly's (2001) analysis of a subsidence damage database argues that there '*are no reasons to be concerned over current minimum depth requirements'* of building foundations. However, Hawkins (2013) argues that in drought years, evidence of shrinkage can reach depths >2.5m below ground level which is beyond current minimum foundation depth recommendations of 0.9m (NHBC, 2008). Moreover, in Rodda & Marsh's (2011) assessment of the 1975-76 drought, the future projections of PSMD in both 2030 and 2050 (Figure 4-7) show similarities to previous events, that resulted in extensive damage. This is especially so where PSMD, even at the 10th percentile, is still present in the winter months (i.e. November and December) allowing it to be carried over into the following years (Figure 4-7, Figure 4-9 and Figure 4-10). Similarly, in an analysis of the UK drought of 2003, Marsh (2004) argued that modelled values of PSMD are likely to be much higher than those of the 1962-2003 average depicted. Therefore, perhaps such assessments as those detailed in this chapter will provoke consideration as to whether to reassess construction practices regarding foundation and civil engineering standards and help facilitate significant changes in risk-management-based approaches to clay-related subsidence.

It may be noted that, since the 1975-76 drought, extensive reforms in UK planning policy have led to better design practices related to the construction of new domestic and commercial property foundations. This has helped to mitigate the risk of clay-related subsidence on properties since this time. Planning Policy Guidance 14 (PPG14) is one example of this, advising local planning authorities to identify areas where the potential impact of subsidence on development could be realised (DTLR, 2002). Similarly, the National House Building Council (NHBC) has provided recommendations for minimum foundation depths in clay soils (NHBC, 2008). Despite this, Wilson (2006) identified that only one of fourteen local climate impact studies surveyed recognised subsidence as a threat to the built environment, perhaps due to its chronic rather than acute characteristic.

Current planning policy applicable to UK infrastructure development appears fragmented in addressing both climate change and geohazards. A series of National Policy Statements (NPS) are available (see: http://infrastructure.planninginspectorate.gov.uk/legislation-and-advice/national-policy-statements), covering a range of infrastructure sectors, including: energy, transport and water, waste water and waste. However, water supply in itself currently does not have an NPS, with no stated plans to implement one. For example, the wastewater NPS discusses the impact of leaks on soil quality, but not the impact that soil processes could have on fracture rates of this infrastructure as reported by Owen et al. (1992). Conversely, both the gas and electricity NPSs provide more detail on potential soil effects to the respective infrastructure networks. GB infrastructure represents extremely complex networks that are aging, some assets reported as being >100 years in age, and which are constructed from a range of materials. Consequently, networks are susceptible to climate change and geohazards, which is further exacerbated by ever increasing public demand (Pritchard et al. 2014). Moreover, the increasing interconnection and spatial proximity of networks can mean that the failure of a particular infrastructure asset can lead to failure(s) in another (Rogers et al. 2012). The high-resolution of these projections can enable stakeholders at the local, regional and national scale to identify where clay-related subsidence may affect their (and others) assets going forward to 2050. The incorporation of climate change adaptation strategies and tools, relating to infrastructure asset management, is prudent for long-term asset risk management and ultimately reducing costs and disruptions caused by asset failures. Therefore, it is recommended that the NPSs for infrastructure resilience be amended to more fully incorporate potential climate change and environmental vulnerabilities.

Harding et al*.* (2014) argue that end-users of climate model data are predominantly interested in the magnitude of change that is likely to be experienced. The probabilistic projections of clay subsidence provided (Figure 4-12) should therefore be used in their entirety (i.e. mean, 10th and 90th

percentiles) when forming part of resilience planning and/or climate risk assessments. Investigation of the likely impact of the low and high emission scenarios would also be recommended for a more detailed analysis of the potential for clay subsidence hazard. This study has shown however (Section 4.4.5) that there appears to be little effect in terms of increasing potential subsidence hazard for the reasons identified earlier in this section. Local factors such as significant vegetation can act to modify these projections. An understanding of all the factors at play will help ensure the resilient construction of a built environment that can cope with the majority of extreme events, but is ultimately dependent on individual risk appetites. A forward looking risk management approach to clay-related subsidence will require a range of subsidence scenarios to avoid potential *surprises* in future climates. As climate models evolve and improve, our method can facilitate the integration of new data when assessing clay-related subsidence hazard. Mastrandrea et al. (2010) argue that decision makers are interested in information which clearly depicts climate change risks. The thematic results presented here, are aimed primarily at non soil-scientists and are presented in an easily understandable format, to encourage evidence-based decision making.

Due to time and data constraints we have not been able to assess the entire range of scenarios available in UKCP09 for the entirety of Great Britain. Future work would consider the impact and uncertainty of the UKCP09 low and high emissions scenarios (further to that in Figure 4-20& Figure 4-21). It is further anticipated that the integration of real-time soil-moisture monitoring data, for example, through remotely sensed data (e.g. SMOS and the recently launched

SMAP) could provide users with a predictive tool for where clay-related subsidence and subsequent failure(s) or degradation is likely to occur in real-time. This predictive nature would prove particularly important for asset management and the scheduling of maintenance for more *fragile* pieces of the built environment and critical infrastructure. For this national assessment, the effects of local vegetation were not taken into account, for example high water demand trees. However, when using these maps, users should be aware of the potential for proximal high water demand trees to result in higher PSMD's and therefore higher clay subsidence hazard than that reported here. Furthermore, although the research scope of this chapter has been primarily directed at clay-related geohazard modelling, the implications of soil-moisture modelling have many other research applications. For example; water resource management, flood control, domestic building construction and other agricultural sector applications.

5 Soil geohazard mapping for improved asset management of Great Britain's local roads

Chapter synopsis

This chapter assesses the use of soil-related geohazard assessments in providing soil-informed maintenance strategies for the asset management of the locally important road network of the UK. The chapter utilises the clay-related subsidence maps produced in Chapter 4 to undertake a national susceptibility of GB's unclassified roads, both current and in future scenarios (i.e. 2030 and 2050). A specific case study then draws upon the UK administrative county of Lincolnshire, where road assessment data have been analysed against mapped clay-subsidence hazard. This chapter is based upon an article published in *Natural Hazards and Earth System Sciences* (Pritchard et al. 2015b).

5.1 Introduction

UK minor, or non-strategic, roads which are owned and managed by local authorities represent 98% of the overall network (Defra, 2013). As a subclass, the unclassified road network represents 60% of this minor network (DfT, 2011) supporting local communities, society and the wider economy.

The Institution of Civil Engineers (ICE, 2014) regards one-third of the UK’s road network as being in urgent need of maintenance, stating that the immediate action required to improve road conditions is its' top priority. A number of factors can lead to road deterioration, including (but not restricted to): traffic volume, road works, poor construction or reinstatement after repair of buried infrastructure, cold weather, tarmacadam oxidation and underlying ground conditions. Several authorities have argued that during drought conditions, changing moisture contents in underlying soils, particularly in those clay soils prone to volumetric shrinking and swelling, have resulted in considerable structural damage to their highway networks (Figure 5-4). Highways assets themselves exacerbate developing drought conditions by prohibiting the permeation of water into the underlying soils (Harrison et al. 2012b).

A number of drivers of soil-related ground movement impact on UK highway networks, including: clay shrinkage and swelling; sand-washout; compression of soft soils; and peat shrinkage (Pritchard et al. 2014a). As clay-related shrink-swell is the dominant form of ground movement in the UK, this chapter examines the impact of clay-related shrink-swell on road infrastructure.

Road damage resulting from expansive clay soils is reported to be problematic for a number of countries' highway networks, including: USA, Israel, India, South Africa, Sudan, Saudi Arabia, Nigeria, Australia and Algeria (Wanyan et al. 2014; Abam et al. 2000; Alexander & Maxwell, 1996; Daffala & Shamrani, 2011; Zumrawi, 2015). It is argued that expansive soils are one of the most problematic foundation materials faced in many of the countries identified in the studies above, often leading to annual replacement and maintenance costs running into the US$ millions (Sapkopta et al. 1997).

Longitudinal cracking is the predominant mechanism of road failure recorded in the majority of studies (Puppala et al. 2011). Cracking of the road surface can often lead to a 'vicious cycle' of successive shrink-swell episodes within the substrate, resulting in rapid deterioration of road surfaces and in the worst-case scenario car accidents and fatalities (Jegede, 2000). Wanyan et al. (2014), reporting on a Texas roads survey, found that substrate moisture fluctuations represent the main perceived reason for longitudinal cracking of road surfaces, further exacerbated by poor drainage (Zumrawi, 2015).

Soil surveys, which classify the uppermost layer (0 to c.1.2 m) of the earth’s surface, provide an understanding of soil properties and their spatial distribution. However, despite the intimate link between the soil and the infrastructure it supports the application of soil surveys in highways asset management has seldom been undertaken within the UK. Elsewhere, this is not the case, examples including: USA (Bauer, 1973; Santi & Martens, 2003; Allemeier, 1974; Lee & Griffiths, 1987; Beatty & Bouma, 1973), Netherlands (Westerveld & Van Den Hurk, 1973) and Australia (Murtha & Reid, 1976; Biggs & Mahony, 2004). Whereas it is recognised that soil surveys have an established role (Hartnup & Jarvis, 1979), the UK still tends to look only to deeper geological maps for indications of ground movement (e.g. clay-related subsidence).

Highways engineers and asset managers often have a civil engineering background, and many possess only general knowledge of earth sciences, geology and geotechnics. Clear spatial information which describes the risk of hazardous ground conditions, without the need for geological interpretation, is therefore potentially of great benefit to practicing engineers (Royse, 2011). Thematic soil-related geohazard maps, derived through reinterpretation of traditional soil maps and fusion with meteorological data, can provide decision makers with a clear view of the potential hazards affecting their assets.

This chapter aims to demonstrate how soil-related geohazard assessments can serve within a decision support tool in the asset management of local highways. Many tangible associations have been posited with regard to the impact of geology/soils on road condition (Willway et al. 2008), especially in light of climatic change. However, quantitative analyses are currently lacking, providing this study with its novel approach.

This chapter is presented in the form of two distinct analyses. Firstly, Section 5.2 undertakes a national-scale assessment of clay subsidence risk to Great Britain's minor road network. Secondly, Section 5.3 presents a detailed case-study, incorporating road condition data provided for the county of Lincolnshire to establish the impact of clay-related subsidence on local road infrastructure. Both of these analyses have utilised the clay subsidence projections created in Chapter 4. Finally, discussion and conclusions are drawn from these previous sections to understand what risk Great Britains minor road network will face from the threat of clay-related subsidence both now (i.e. baseline) and in the future scenarios of 2030 and 2050.

5.2 Risk of clay subsidence to Great Britain's minor road network

5.2.1 Minor road classification

Great Britain's minor road network is defined in this thesis as roads classified B, C and U. Road classes in the UK are defined by the Department for Transport (DfT, 2012); classes and definitions assessed in this chapter are provided in Table 5-1.

Table 5-1: Great Britain minor road classes and definitions (Source: DfT, 2012)

Road class	Definition
B	Roads intended to connect different areas, and to feed traffic between A roads and smaller roads on the network.
C	Smaller roads intended to connect together unclassified roads with A and B roads, and often linking a housing estate or a village to the rest of the network. Similar to ‘minor roads’ on an Ordnance Survey map and sometimes known unofficially as C roads.
U	Local roads intended for local traffic. The vast majority (60%) of roads in the UK fall within this category.

5.2.2 Analysis of clay subsidence risk to the GB minor road network

For this assessment, the Ordnance Surveys 'Open Roads' dataset was used, which uses the same road classification as the Department for Transport (Table 5-1). Roads in classes 'B', 'C' and 'U' were subsetted from the main dataset, which also included motorways and 'A' roads. This data was intersected spatially with the clay subsidence hazard datasets produced in Chapter 4 for baseline, 2030 and 2050 scenarios, respectively.

The combined road and clay subsidence hazard dataset was then attributed to each European electoral region, chosen as these regions broadly align with the UKCP09 climatic regions; these regions were derived from the Ordnance

Survey's Boundary Line open dataset (see Appendix I for European Electoral Region map). The percentage of roads on ‘High’ to ‘Extremely High’ clay subsidence risk was then calculated as a percentage of the overall road length (kilometres) per European region for the entirety of GB.

5.2.3 GB minor road assessment results

The results of the analysis of GB minor roads (B-U class) at risk of clay-related subsidence for the baseline, 2030 and 2050 scenarios are presented in Figure 5-1. The analysis shows a distinct north-west, south-east divide of road sections which are at potential risk of the highest bands of clay-related subsidence hazard from present day (baseline) through to 2050. The biggest percentage change of roads ‘at risk’ occurs between the baseline and 2030. This is consistent with results presented in Chapter 4, where PSMD distributions (Figure 4-11) show the largest changes in climate occurring between these time periods. Moreover, Figure 5-1 also shows that in both 2030 and 2050 scenarios, clay subsidence risk at the 10th percentile PSMD level will represent almost equivalent conditions to that of an extreme event (i.e. 90th percentile) presently at the baseline.

Although this analysis shows a clear distinction between the north-west and south-east of GB, the assessment of roads at this spatial scale is not suitable for analysis of county and intra-county assessment of roads potentially susceptible to clay shrinkage; this is reflected in the subtle changes in road percentage affected at the European Region scale (see table presented in Appendix J). Furthermore, the UK’s minor roads are managed at the local authority (i.e. county level) and as such additional analysis at this scale would be particularly beneficial to highways asset managers looking to understand more local issues. It would also allow inclusion of road condition data, through surveys undertaken by local highway authorities. The remainder of this chapter therefore presents a detailed case study of the Lincolnshire road network as a means for testing such a methodology to assess the impact of clay-related subsidence on road condition. Results at the national and county-scale are then discussed in concluding sections.

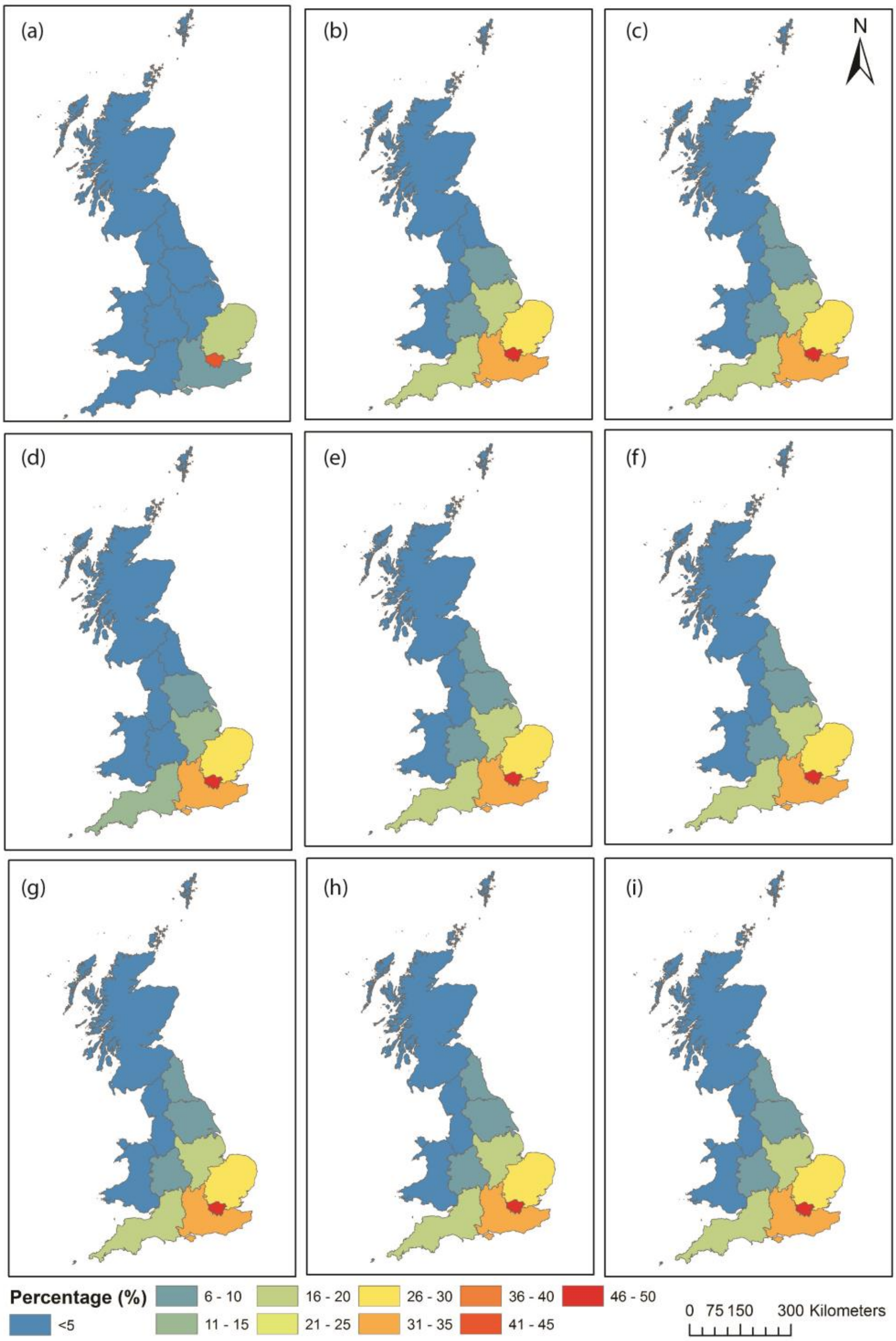


Figure 5-1: Percentage of road network (B-U class) overlaying 'High' to 'Extremely High' clay subsidence risk zones: Baseline - (a) 10th percentile, (b) 50th Percentile, (c) 90th percentile. 2030 - (d) 10th Percentile, (e) 50th percentile, (f) 90th percentile. 2050 - (g) 10th percentile, (h) 50th percentile, (i) 90th percentile PSMD. (Contains Ordnance Survey data © Crown copyright and database right 2016).

5.3 Lincolnshire case study area

The county of Lincolnshire reported the largest impact of drought conditions on its highways in 2003 (Table 5-2), indicating that it is particularly prone to ground movement due to the county's abundance of shrink-swell (or expansive) susceptible clay soils.Empirical road condition data provided by Lincolnshire County Council (LCC) has been intersected spatially with an existing soil-related geohazard model to understand the statistical and spatial relationship between the two datasets. Furthermore, the use of UKCP09 climate projections to understand future clay-related subsidence risk (derived from Chapter 4) to the county of Lincolnshire's road network are investigated. Subsequently, suggestions and recommendations resulting from the use of this approach for planned operational maintenance in Lincolnshire are described. Finally, it is considered how this can form a framework for other local authorities to follow, both in the UK and internationally.

5.3.1 Climatic, topographical and geological setting

The administrative county of Lincolnshire is situated in mid-eastern England, spanning from the Humber Estuary in the north, to the Wash in the south of the county (Figure 5-2). As a result of its flat, fertile lands, a large area of the county is devoted to high intensity agriculture The county's relief is predominantly low-lying (0-50 metres above sea level), excepting the Lincolnshire Wolds in the central-northern area of the county; a chalk outcrop, where heights range between 50-200 metres above sea level.

Table 5-2: Drought damage to roads in England in 2003 (data sourced from Wilway et al. (2008))

Authority	Reported Drought Damage (£000)
Lincolnshire	7,397
Essex	5,614
East Sussex	5,568
Kent	4,167
Cambridgeshire	3,522
Hampshire	3,030
Peterborough	2,400
West Sussex	2,221
Isle of Wight	1,500
Wiltshire	1,302
Buckinghamshire	1,200
Surrey	1,000
Suffolk	750
Norfolk	650
Bedfordshire	300
Total	**40,621**

This area of Eastern England has a relatively mild, temperate climate. Annual rainfall is relatively low, for example in Lincoln it is 577 mm. Consequently, it is one of the driest areas in the country (Hough & Jones, 1997). This low rainfall, coupled with high evapotranspiration rates, contribute to some of the highest soil moisture deficits (driest soils) in the UK in an average year (Hodge et al. 1984; Robson, 1990).

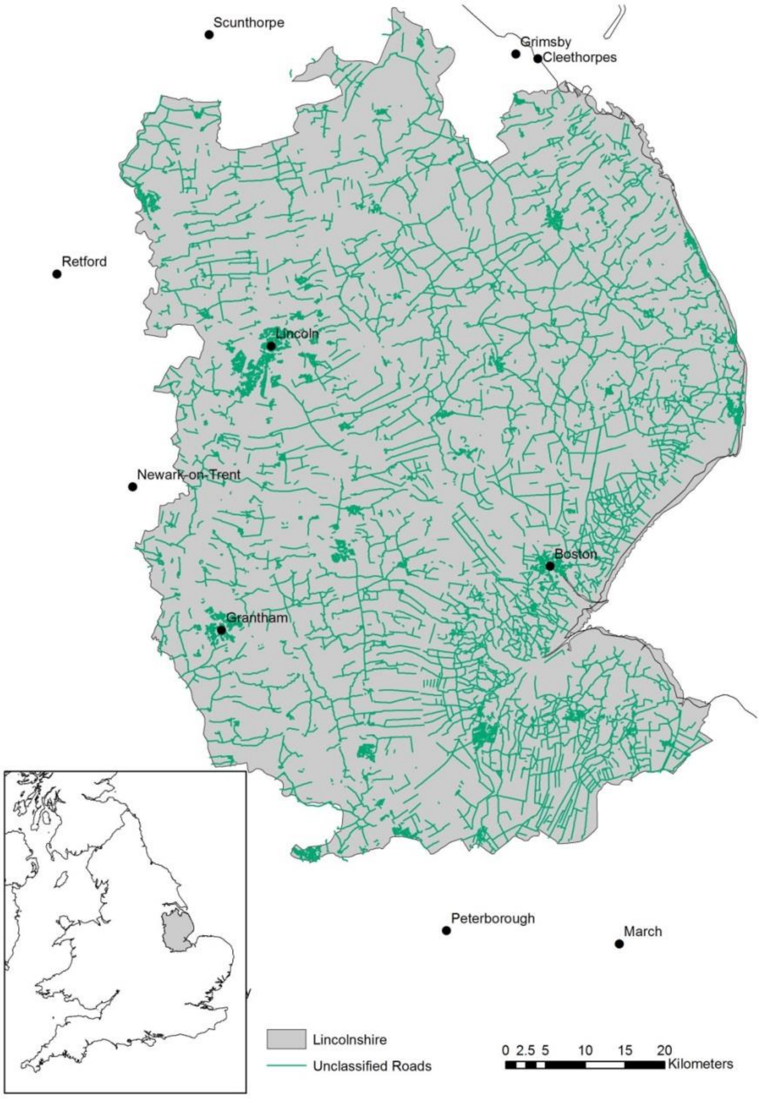


Figure 5-2: Lincolnshire location map and the distribution of unclassified roads

The superficial geology and subsequently the soil parent material of Lincolnshire is predominantly derived from Pleistocene and more recent deposits (Hodge et al. 1984). The influence of previous glaciations and regressions and transgressions of the North Sea around the Wash have led to extensive deposits of silts, clays and the formation of peat material (Chatwin, 1961). Marine and riverine alluvium and glacial till represent a large proportion of the deposits, with glaciofluvial deposits dominating the Lincolnshire Wolds. As a result, Lincolnshire contains a broad range of soil types, encompassing 73 soil associations (Cranfield University, 2015) (Figure 5-3). Further details of soil types and their distribution in Lincolnshire can be found in Hodge et al. (1984).

Industrial drainage in the fenlands of Lincolnshire since the 1600’s have caused such extensive peat wastage that previously underlying clays and silts are now exposed at the ground surface. Substantial thicknesses of peat are therefore now confined only to the edge of the fens or to areas remaining undrained (Hodge et al. 1984). In 1985 it was recorded that only 16% (240 km^2) of the pre-drained peatland remained (Burton & Hodgson, 1987). The presence of large areas of predominantly clay soils and their susceptibility to volumetric shrinkage, combined with high soil moisture deficits, means that Lincolnshire is particularly affected by clay-related subsidence.

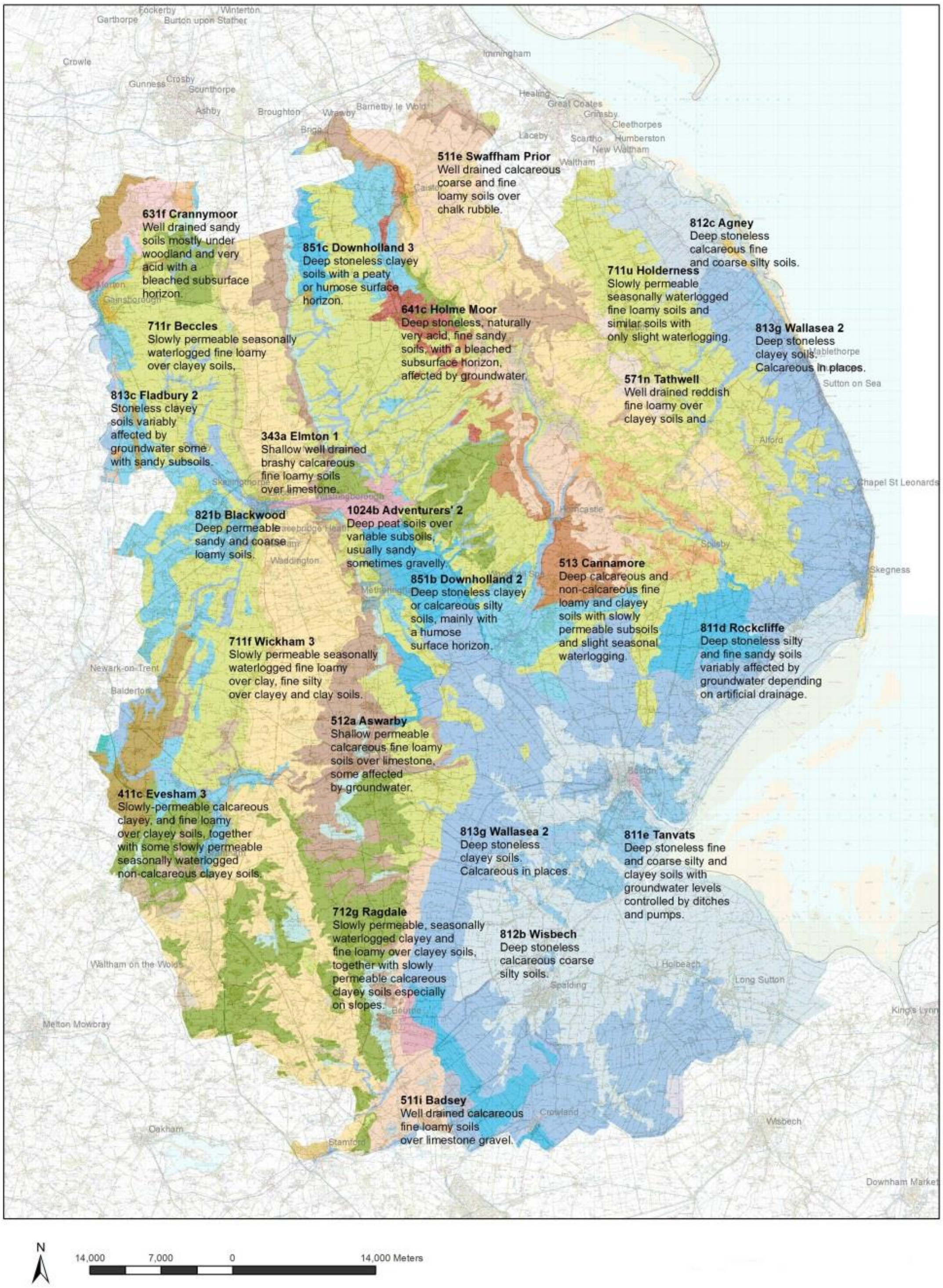


Figure 5-3: Soil Associations of Lincolnshire (Soils data (England and Wales) © Cranfield University and for the Controller of HMSO, 2015; contains Ordnance Survey data, Crown Copyright and Database Right, 2015)

5.3.2 Unclassified road distribution

This section considers the 'C' and unclassified road network of Lincolnshire (Figure 5-2), representing 66% of the county's highways (Table 5-3), 85% of Lincolnshire's unclassified roads being in rural areas.

The majority of unclassified highways in Lincolnshire, as with many other UK counties, are deemed to be *evolved*. Evolved roads have not been designed to modern engineering standards and have instead evolved from historic or even ancient roads, even dating in some specific instances to the Roman and Bronze Age eras (Astbury, 1958).

Table 5-3: Road classification in terms of length and percentage of network in Lincolnshire

LCC Hierarchy	Road Class (DfT)	Length (km)	Percentage
1	A (Principal)	888	10
2	A, (some) B	560	6
3	B, (some) C	1,458	16
4 & 5	C, all unclassified	5,808	66

A Coarse Visual Inspection (CVI) is a nationally defined standard of assessing road defects and is principally used on the UK's minor road networks. Further technical information regarding this survey can be found in Wallis (2009). CVI surveys revealed that Lincolnshire's unclassified road network has been subjected to severe drought-related subsidence, particularly during 2003 (Table 5-3) (M. Coates, *Pers. Comm*.). Moreover, during the 2010-11 period, approximately 154 road sections were highlighted by the CVI survey as having been damaged as a direct result of drought conditions realising the shrinkage potential of clay rich soils (Figure 2-4). It is likely that subsequent wetting events, over winter months, exacerbated road damage through swelling of clay soils, as reported in other studies (e.g. Puppala et al. 2011). These two event years led Lincolnshire County Council (LCC) to place a bid to central government for additional emergency road funding.

Figure 5-4: Examples of Lincolnshire road subsidence; (a) Childers Lane, Spalding; (b) Cowbridge Road, nr Bicker (Photos: Lincolnshire County Council)

LCC highlight several safety hazards arising from soil-related drought damaged roads, which are often unclassified, and have speed limits of up to 60 mph (miles per hour).

Specific risks include:

- Increased deterioration of the longitudinal profile of roads, requiring drivers to reduce speeds below those that would normally be appropriate for the width and alignment of the road;
- Severe localised transverse depressions, which require drivers to slow to speeds below 20 mph;
- Longitudinal differential settlement and cracking, requiring supplementary road signs to warn drivers and allow roads to remain open;
- Defects which are not easily seen at night or in adverse weather conditions, increasing risk to motorists.

5.4 Data

5.4.1 Natural Perils Directory (NPD)

The Natural Perils Directory™ (NPD) geohazards thematic dataset, developed and maintained by staff at Cranfield University, provides a detailed and comprehensive assessment of the environmental vulnerabilities to building structures and infrastructure posed by soil-related geohazards (Jones et al. 1995; Hallett et al. 1994). NPD represents a thematic reinterpretation of the national soil map (NATMAP) which shows the spatial distribution of all ~700 soil series in England and Wales (Cranfield University, 2015) (Figure 3-1). This soil data, alongside climatic data and expert knowledge are encompassed within a 'Land Information System' (LandIS) (Keay et al. 2009). LandIS is regarded as the principle source of soil information for England and Wales by Defra (Department for Environment, Food and Rural Affairs).

A core component of the NPD is the clay-related subsidence model, or the underground foundation stability (UFS) model. Based upon a pedo-climatic approach, UFS assesses the likelihood of a soil to undergo shrink-swell and subsequently, whether a potential soil moisture deficit (PSMD) is present for shrink-swell potential to be realised. Once classified, a 9 point vulnerability class, ranging from *Extremely High* to *Extremely Low* is assigned. The NPD model output is expressed in GIS (Geographical Information System) format on a vector polygon basis across England, Wales and Scotland. The reader is directed to Chapter 4 for a more detailed interpretation of how clay subsidence hazard is derived for GB. This GIS format makes it suitable for easy integration with other geospatial data (e.g. infrastructure networks). It is predominantly used by the insurance, reinsurance and water sector. However, its use in highways asset management has not been explored until now.

5.4.2 Highway condition data

CVI assessment data for ~4,400 km (75%) of unclassified roads, collected between the years 2007-2014, was supplied in a GIS vector-polygon format by Lincolnshire County Council's highways department (M. Coates, *Pers. Comm.*). Data were supplied for 4 survey periods, 2007-11, 2011-12, 2012-13 and 2013-14. CVI is expressed as a series of indices, including assessments for wearing course, edge effects and structural condition. Following discussion with LCC, it was identified that the '*structural condition index*' provided the most suitable index in understanding the effects of soil on the network, also incorporating edge defects. Conversely, wearing course degradation is a factor of traffic use, direct climatic effects and road surfacing techniques and so therefore soils do not exert a direct effect.

Each structural condition index GIS vector polygon represents a 50 m rolling average survey area, where increasingly higher values indicated a worsening structural condition of the highway (P. Shevill, *Pers. Comm.*); values ranged between 0-93. Generally, a value of <40 represents a road in a good state of repair, whereas values >40 require further investigation and likely treatment options; Figure 5-4 represents such conditions of the latter. To avoid any potential survey bias, Lincolnshire is divided into 10 distinct sub-regional operational areas where a percentage of each of these areas is surveyed each year. Moreover, the current 2-man surveying team, who have undertaken the survey for a number of years, remain independent from maintenance scheme selection and are not influenced by budgetary constraints (M. Coates, *Pers. Comm.*).

5.4.3 UKCP09 future climate projections

UKCP09 climate projections (Jenkins et al. 2009) indicate that the UK is likely to experience hotter, drier summers and warmer wetter winters, especially in the south-east and east Anglian region of England, for the forthcoming century. Such weather patterns will exacerbate clay-related subsidence.

The long lifespan of road infrastructure in the UK leads to particular susceptibility to hazards under future climates (Willway et al. 2008). Model parameters of daily rainfall and potential evapotranspiration were derived from a spatially coherent, 5km resolution gridded output from the UKCP09 weather generator (Burton et al. 2013; Jenkins et al. 2014); See Chapter 4 for detailed methodology.

PSMD represents the fundamental climatic control on clay-related subsidence and so has been incorporated within the NPD geohazard model (Pritchard et al. 2015a) (see Equation 4-2). Future projections of clay subsidence risk for Lincolnshire are presented in Figure 5-5. These enable assessment of future risk from ground movement for Lincolnshire’s unclassified road network.

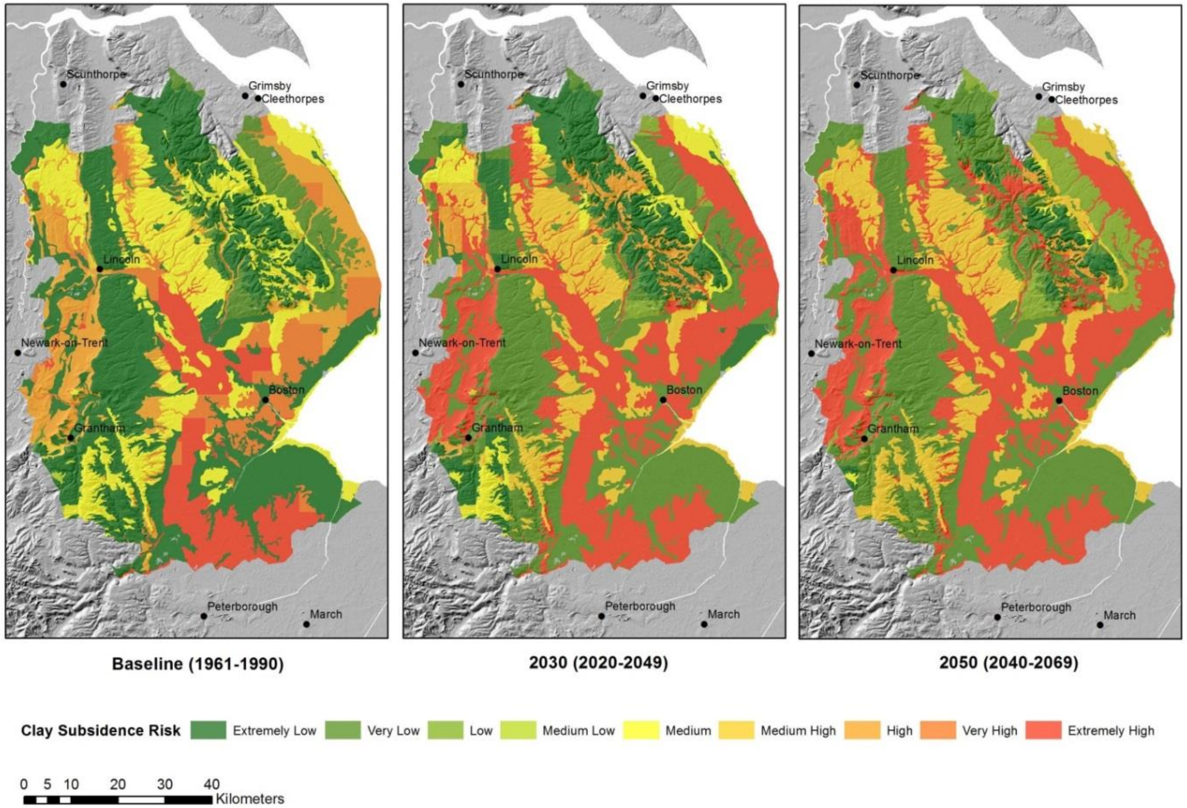


Figure 5-5: Modelled clay subsidence risk at the central estimate (50th percentile) for Baseline (1961-1990), 2030 (2020-2049) and 2050 (2040-2069) UKCP09 scenarios for the administrative county of Lincolnshire (contains Ordnance Survey data, Crown copyright and database right, 2015; Soils data (England and Wales) © Cranfield University and for the Controller of HMSO, 2016)

5.5 Risk assessment

5.5.1 Overview

The relationship between CVI value and clay-subsidence hazard class from NPD for each survey period has been determined statistically. This section describes the GIS and statistical framework used to assess the impact of clay-related subsidence on Lincolnshire's unclassified road network which is illustrated in Figure 5-7. GIS software was employed to provide a platform for rapid analysis and handling of spatial data (Fedeski & Gwilliam, 2007), including CVI and clay subsidence hazard class.

CVI data provided by LCC required processing to make the data suitable for intersection with the NPD data (Figure 5-5). The provided CVI data polygons were often not spatially representative of the actual road width, some being in excess of 40 m in width, whereas unclassified roads are often less than 3 m wide (Figure 5-6). Where multiple boundaries exist between clay subsidence hazard classes, this may have given false results as to the underlying soil condition when intersected spatially. To improve the data, the supplied CVI polygons were converted to points using ESRI's ArcGIS (v. 10.2) polygon centroid tools. The open-source software, Geospatial Modelling Environment (www.spatialecology.com) was then used to snap the CVI points to the particular road section (vector line feature) which presented a representative analysis of the particular road section; this is represented graphically in Figure 5-6. Road sections (GIS format) for the entire Lincolnshire network, classified by road hierarchy, were provided by LCC. Processed CVI data was then spatially intersected with the NPD geohazard dataset and the resultant GIS shapefile attribute data imported directly into the statistical package, R (R Core Team, 2014) for further statistical analysis. The number of CVI points assessed per subsidence risk class is presented in Table 5-4. Similarly, future subsidence projections have been intersected with the Lincolnshire unclassified road network within the GIS in order to understand the change in potential exposure throughout these scenarios.

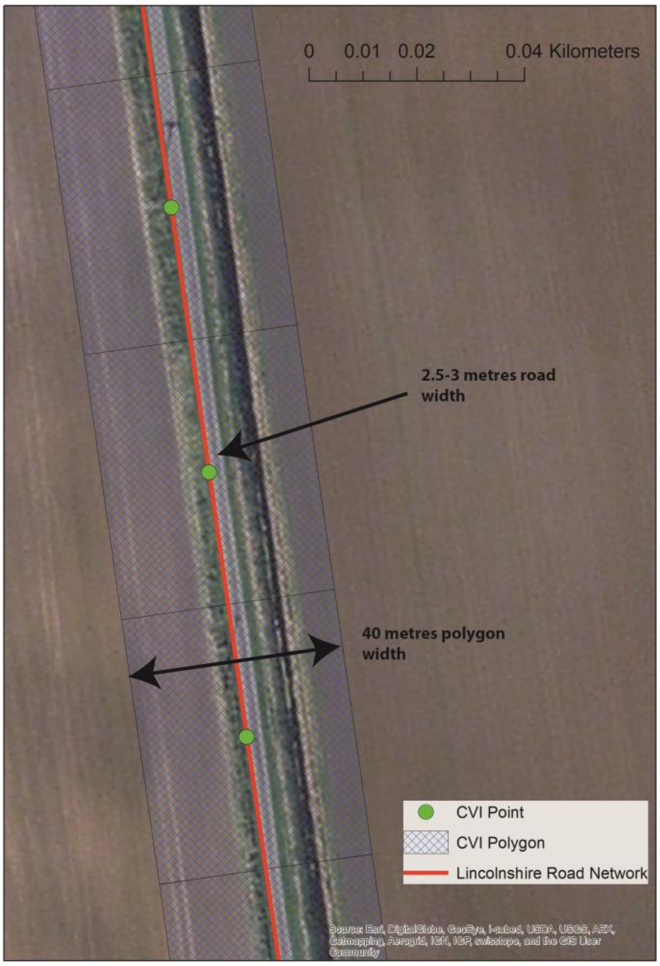


Figure 5-6: Visual representation of CVI polygon and processed point data with associated spatial inaccuracies.

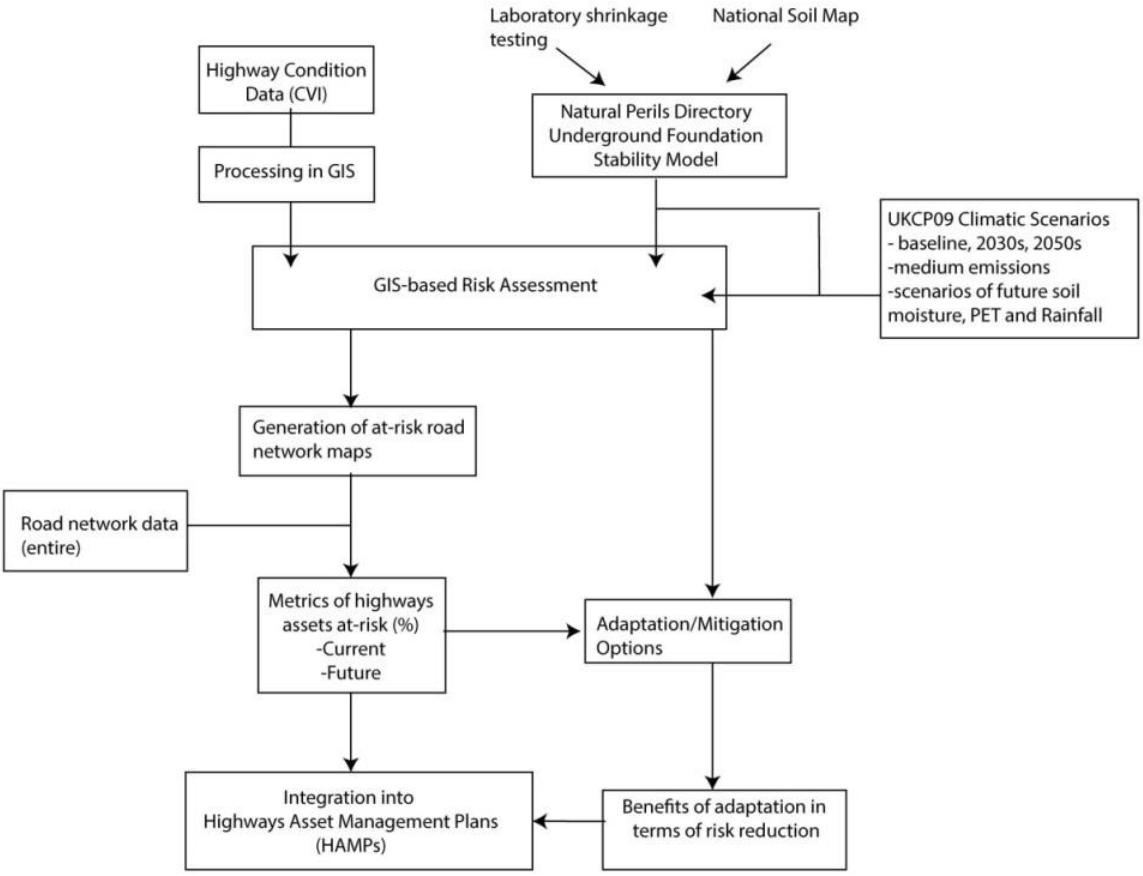


Figure 5-7: Conceptual risk assessment framework for spatial clay subsidence risk impacts upon Lincolnshire road network

Table 5-4: CVI points assessed for each survey period per subsidence risk class

	Extremely High	Very High	High	Medium High	Medium	Medium Low	Low	Very Low	Extremely Low
2007-11	3,065	4,976	1,348	1,544	4,615	9	0	1,249	11,794
2011-12	3,311	5,237	1,359	1,577	4,779	10	0	1,340	12,373
2012-13	3,340	5,483	1,398	1,588	4,904	10	0	1,360	12,181
2013-14	3,418	5,367	1,336	1,541	4,775	10	0	1,323	11,801

5.6 Results

5.6.1 Current risk

Results suggest that a spatial and statistical relationship exists between clay-related subsidence risk and CVI (structural index) value. The boxplots in Figure 5-8 present the relationship between CVI over the survey periods of 2007-11, 2011-12, 2012-13 and 2013-14. Due to the extensive unclassified road network in Lincolnshire, a 4 year rolling CVI assessment program is used by the Local Authority. Therefore, each survey year often represents different road sections to those assessed in the previous year.

Ideally analysis would have considered many years/decades of CVI data. However, the use of GIS in Lincolnshire’s highways asset management remains a relatively emergent technology. Prior to GIS techniques, CVI data recording was predominantly paper-based and is therefore difficult to investigate alongside other environmental data.

Overall, the CVI structural index for Lincolnshire's unclassified network shows significant deterioration between the years 2007 and 2014. This is especially so on soils with an *Extremely High* to *High* risk of clay-related subsidence, where consistently high CVI values (i.e. >60) are observed; representing a significant deterioration of the structural road condition on these higher-risk soils: roads identified at current risk (50th percentile) are provided in Figure 5-9; roads at risk for the 10th and 90th percentile are presented in Appendix J. Moreover, by 2012-13 the CVI value on these soils has reached a critical point, whereby the roads are deemed to have failed structurally (i.e. CVI >80), resulting in the enforcement of speed restrictions as a result.

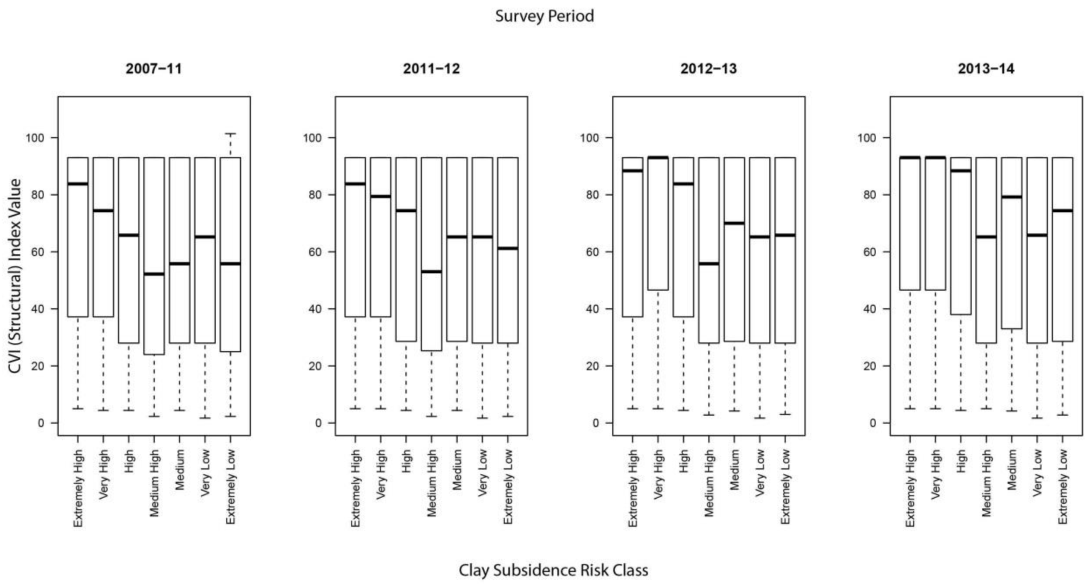


Figure 5-8: Clay subsidencerisk (Baseline, 50th percentile) against structural CVI (coarse visual inspection)

CVI for roads on soils at a *Medium Low* risk for all survey periods showed a consistently high level of subsidence risk. However, this is only representative of a relatively low number of CVI points for each survey period (9, 10, 10 and 10, respectively). These values were therefore excluded from the analysis.

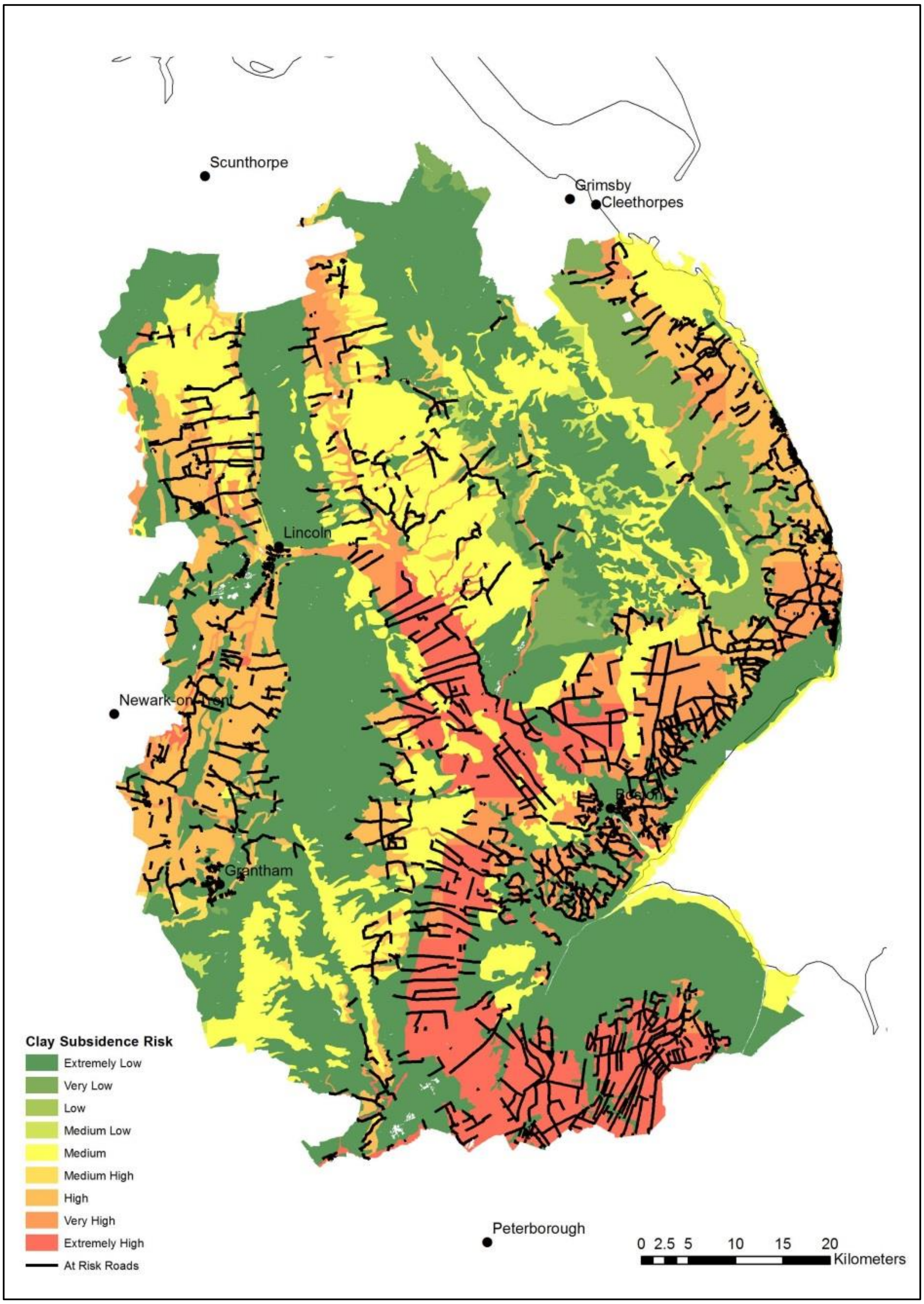
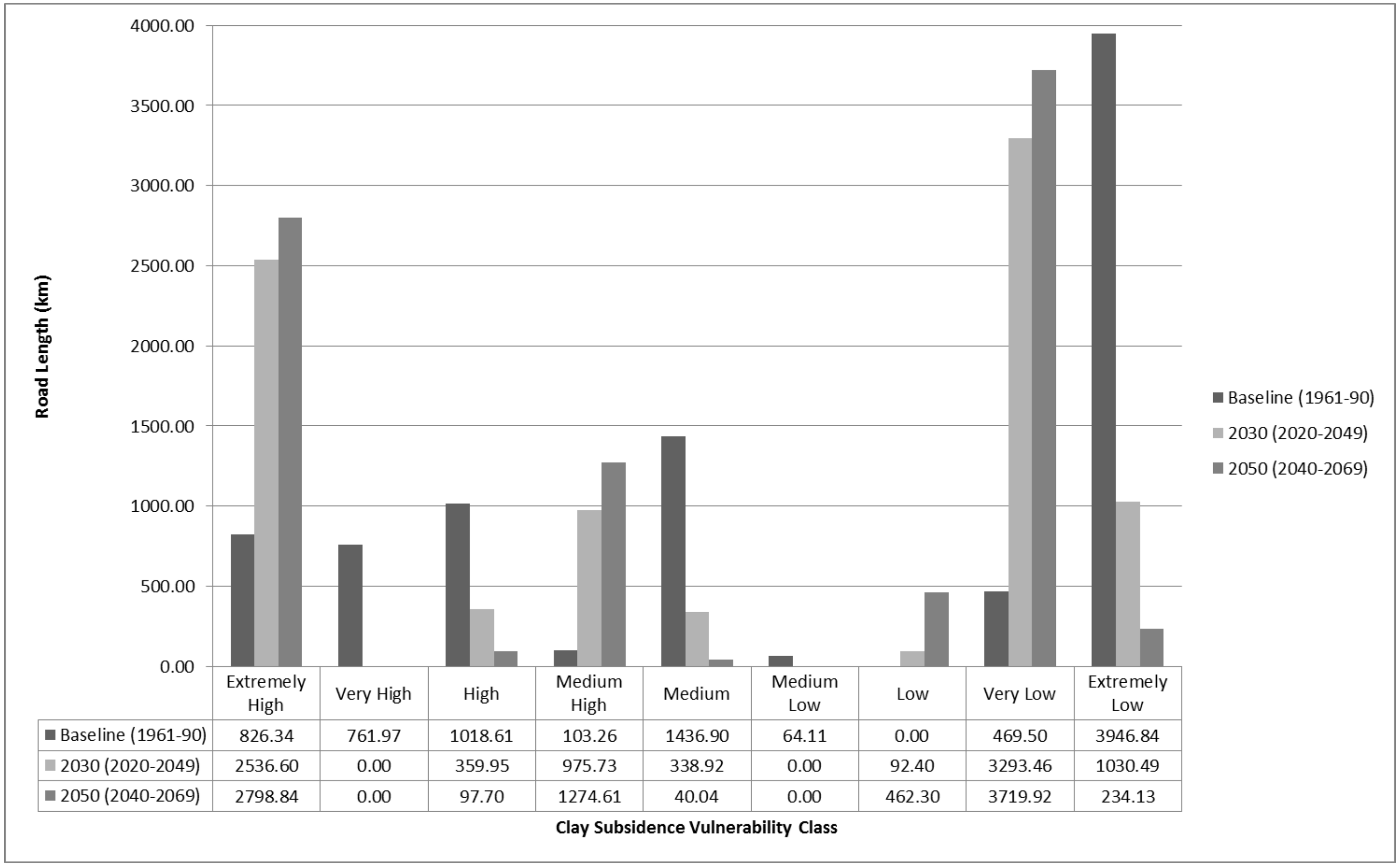


Figure 5-9: Road sections identified "at risk" of clay-related subsidence at present (Baseline: 50th percentile) (Soils data (England and Wales) © Cranfield University and for the Controller of HMSO, 2015)

5.6.2 Future risk

The entire unclassified road network for Lincolnshire was intersected with future projections of clay subsidence hazard for 2030 and 2050 (Figure 5-5), using the 50th percentile or *central estimate*. From this, metrics were produced that identify lengths (kilometres) of road sections falling into each particular clay-related subsidence hazard class. Figure 5-10 shows clear shifts of road sections into higher vulnerability classes from the baseline (1961-90) through to 2050 (2040-2069); this is representative of the 50th percentile PSMD (data for the 10th and 90th percentiles is presented in Appendix J). This is especially so for the *Extremely High* class where between the baseline (1961-1990) and 2050, there is a ~>300% increase in the amount of road length on these soils. There is also a ~1200% shift from roads being at a *Medium* risk to those becoming at *Medium High* risk between baseline and 2030 and 2050 scenarios. However, *Medium High* risk soils do not appear to exert such structurally damaging effects on road condition as compared with the higher classes (Figure 5-8).



	Extremely High	Very High	High	Medium High	Medium	Medium Low	Low	Very Low	Extremely Low
Baseline (1961-90)	826.34	761.97	1018.61	103.26	1436.90	64.11	0.00	469.50	3946.84
2030 (2020-2049)	2536.60	0.00	359.95	975.73	338.92	0.00	92.40	3293.46	1030.49
2050 (2040-2069)	2798.84	0.00	97.70	1274.61	40.04	0.00	462.30	3719.92	234.13

Figure 5-10: Road length kilometres per clay subsidence vulnerability class for Baseline, 2030 and 2050 scenarios (50th percentile)

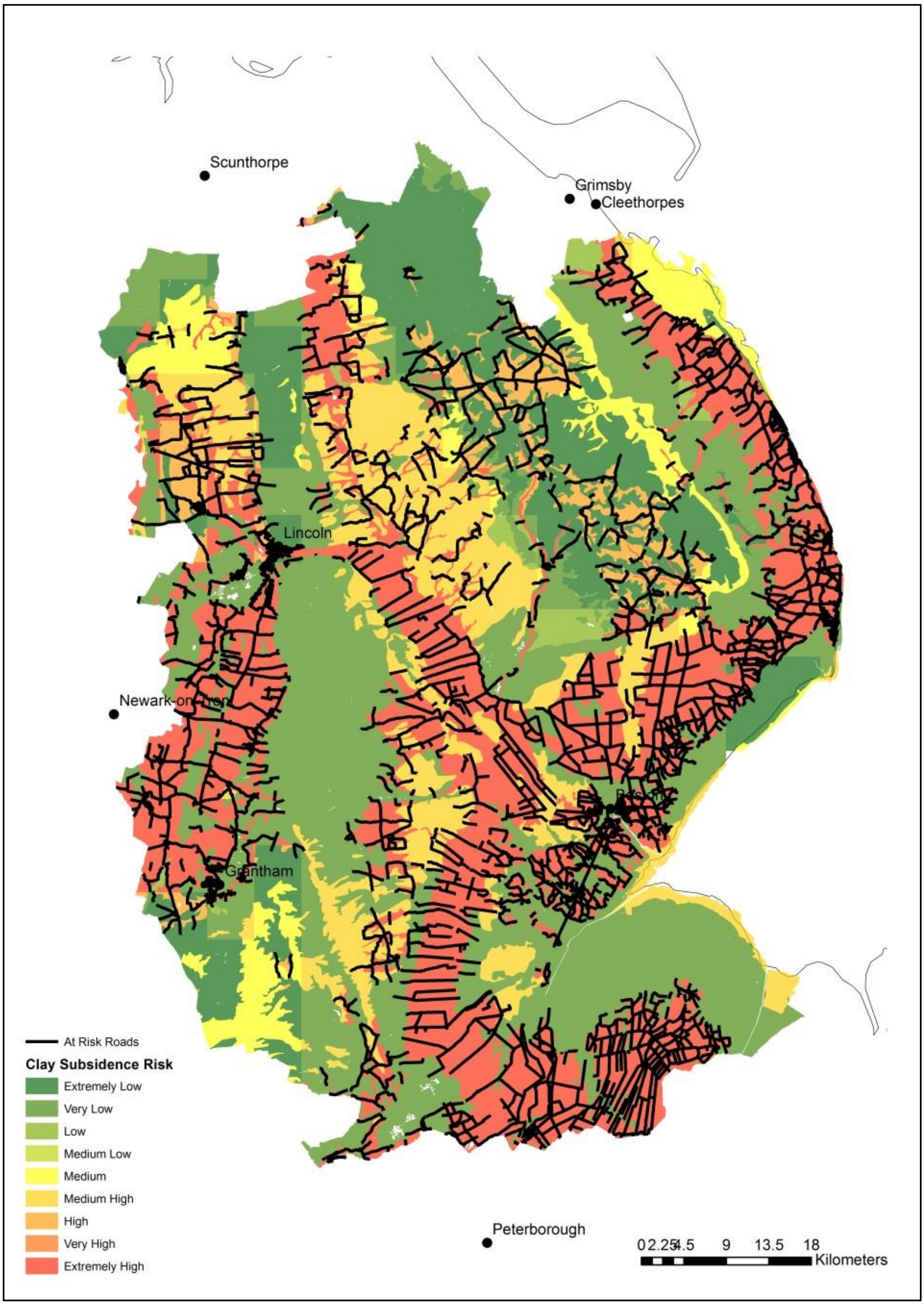


Figure 5-11: Road sections identified "at risk" of clay-related subsidence for 2030 (2020-2049) scenario, 50th percentile PSMD (Soils data (England and Wales) © Cranfield University and for the Controller of HMSO, 2015)

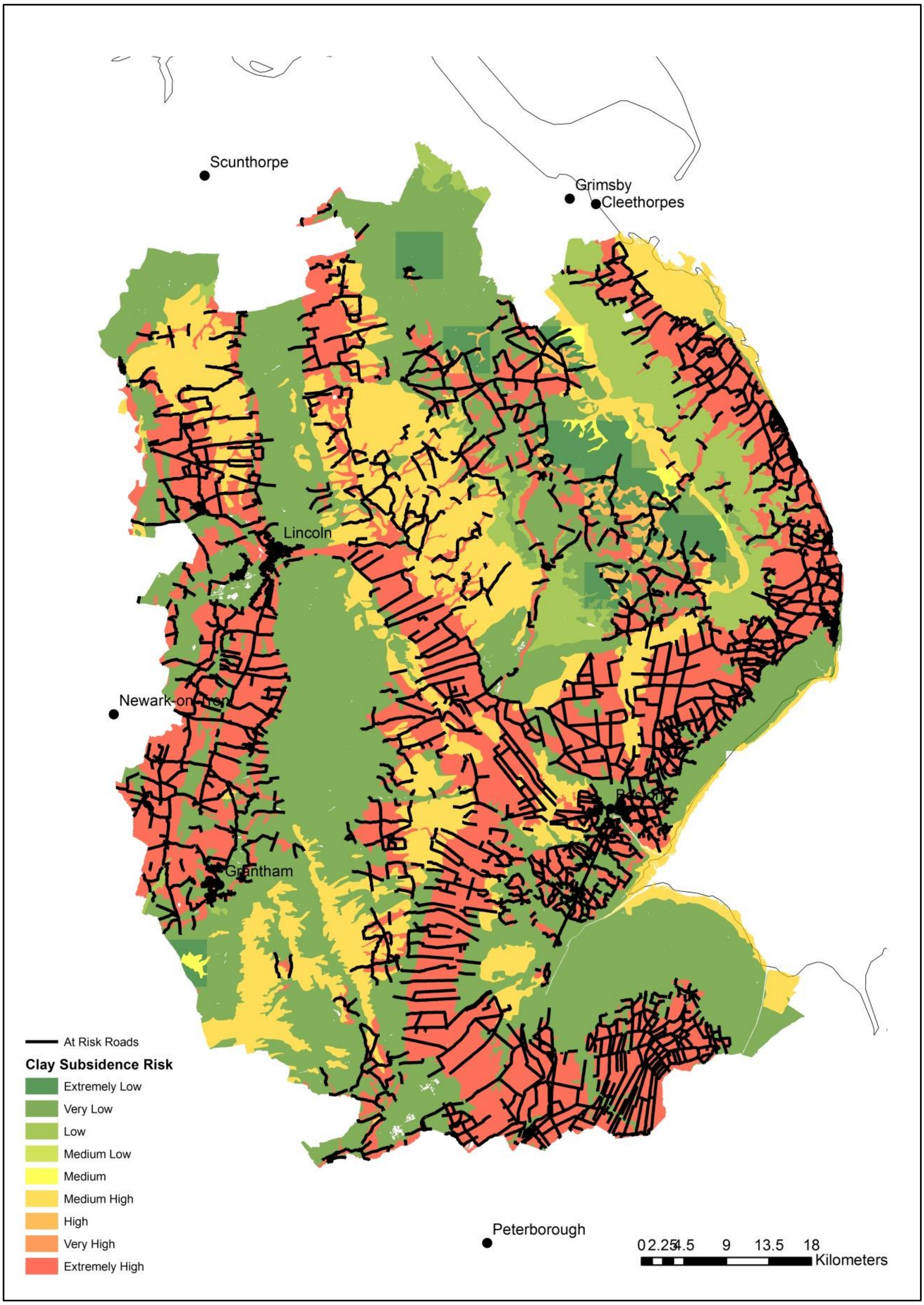


Figure 5-12: Road sections identified "at risk" of clay-related subsidence for 2050 (2040-2069) scenario, 50th percentile PSMD (Soils data (England and Wales) © Cranfield University and for the Controller of HMSO, 2015)

5.7 Discussion

The low traffic volumes on local road networks mean that the large capital investments required to adequately engineer all unclassified roads on highly shrinkable soils are an unaffordable solution in mitigating the impact of soil-related subsidence. Road deterioration is affected by a number of factors however, this chapter has shown quantitatively that clay-subsidence prone soils exert a profound structural impact upon road condition in the Lincolnshire study area. Analysis of the entirety of GB presented in Section 5.2 showed that south-east England will be particularly affected by clay-related subsidence between now and 2030 particularly (Figure 5-1). This is due to the shrink-swell susceptible clay soils (see Figure 4-2 for SSWELL distribution) of the south-east of England combined with higher PSMDs (Figure 4-7) which leads to greater subsidence risk. PSMD distribution analysis showed that areas in the south-east of England are likely to witness the largest changes between the baseline and 2030 (Figure 4-11). Risk will continue to increase from 2030 to 2050, but will not be of the same magnitude as between the prior scenarios.

To date, the impact of clay-related subsidence has manifested in subsequent economic impacts, with calls made by both the county of Lincolnshire and neighbouring local authority areas for emergency funding from the DfT to clear the maintenance backlog. ADEPT (2009) argue that climatic change may lead to wide-scale failure of the UK minor highways network. As this work shows, UKCP09 scenarios indicating hotter, drier summers and warmer, wetter winters through to 2080 (Jenkins et al. 2009) are likely to exacerbate clay-related subsidence risk (Harrison et al. 2012b; Blenkinsop et al. 2010). Moreover, what we consider as an 'extreme' event now (i.e. 90th percentile) will likely become the norm by 2030 and worsen through to 2050 (Figure 5-1). However, the impact will not be equally felt across GB, with many northern counties of England, Scotland and Wales remaining largely unaffected compared to the current baseline climate (Figure 5-1).

Williams *et al.* (2012) argue that decisions around risk made by local authorities are predominantly a consequence of regulatory obligations. As a result, many studies have discussed the acute problem of flooding impact on highways, which causes widespread and economically significant damages (e.g. Bollinger et al. 2014). However, little attention has been brought to the impact of more chronic, systemic and less visible geohazards such as clay-related subsidence to highway infrastructure. An analysis of the impacts of current and future geohazards to road infrastructures nationally will lead to a greater awareness amongst local authorities and policy-makers. It will also lead to a better understanding of the viable adaptation and mitigation options which can be implemented to tackle the issue at hand (Williams et al. 2012) as well as informing the debate on infrastructure investment planning.

The construction of entirely new roads in the UK is rare. More commonly, existing networks are upgraded (Brown, 2013). Rawlins et al*.* (2013) state that with new developments, an awareness of the potential hazards and the influence of climate change should be incorporated into design principles. As a result, the findings of this research can aid planning of new highways.

The All Party Parliamentary Group on Highway Maintenance recently called for the incorporation of highway asset management plans (HAMP) within local authorities highways departments to become mandatory (APPGHM, 2013). Moreover, recommendations exist to make funding streams from the Department for Transport accessible only if HAMP's are in place. Therefore, specific risk information, in this case relating to the spatial distribution of hazardous soils, is vital in supporting these asset management plans. Within LCC, integration of clay-related subsidence assessment within the planning of highway maintenance has provided the basis for a decision-support tool for establishing which specific treatments highways engineers can use to improve drought-damaged road sections. Whereas previously a blanket approach to resurfacing would have been applied to all affected sections, it is now recognised that unclassified road sections on drought susceptible soils are predominantly prone to failure. Therefore, with large capital investment not being an option, other value-for-money options are being sought. Such approaches as shown in this chapter will be widely applicable across south-eastern England.

LCC have made attempts to reinforce their road network, for example, with the use of steel reinforcing grids (e.g. at A1073, Crowland) which act to reinforce the road structure on clay-subsidence susceptible soils (Figure 5-13). Although this technique has proven successful, it is both expensive and proves problematic when resurfacing works or a utility trench has to be emplaced below the road surface, so it is not a wholly viable option. Moreover, Wanyan et al. (2014) state that thicker and stronger road surface layers do not necessarily provide better performance in respect to expansive clay soils, but rather just delay inevitable cracking of the road surface. Instead, they posit that more attention should be focused on improving the stiffness and strength of the roads foundation (or subgrade).

Figure 5-13: Installation of steel reinforcing grid on Lincolnshire highway (Photo: Lincolnshire County Council)

More recently, LCC have been trialling an *in-situ* road recycling process known as *retread*, for specific drought affected sections of their network. This process involves the re-incorporation of *in-situ* road planings into the foundation of the road. Retread offers an *in-situ* treatment, using cold-laying techniques, therefore heat and more energy is not required (Heaton, 2014). Being *in-situ* this also reduces the high disposal costs of potentially hazardous (bitumen-containing) waste to landfill. Moreover, road planings acquired from other sites across the network have been imported in some areas to further deepen road foundations to try and minimise the impacts of clay-related subsidence.

A sum of £1 million, within the Lincolnshire road maintenance budget, has been sourced from a bid to central government, and assigned to the retread project over the period 2013-2015. This process, although having been implemented in other counties for a number of years, is a new initiative by LCC. Due to this approach being novel in Lincolnshire, it is not currently known what the long-term reliability of this method will be on Lincolnshire's subsidence-prone soils, however, current results appear positive (Heaton, 2014).

Although not explored within this thesis, the shrinkage of clay soils is a known precursor to shallow and deep seated slope movements (Page, 1998). In this situation, shrinkage cracks allow water ingress to reach clay shear surfaces (Loveridge et al. 2010). This results in increased pore-water pressures, especially during intense storms. High pore water pressure with additional weight from large agricultural vehicles or articulated delivery vehicles, can result in shear slippage, slope movement and subsequent highway failure (Hawkins, 2013; Loveridge et al. 2010). As a result of agricultural and drainage practices, much of the highway network in Lincolnshire is flanked by steep-sided drainage dikes, or has been left raised above the surrounding land due to peat shrinkage. Therefore, these steep sided embankments and the presence of shrink-swell soils can lead to specific localised slope failure (e.g. Figure 5-14).

This chapter has assessed the use of soil-related geohazard mapping in the asset management of minor highway networks within Lincolnshire. The risk-assessment framework (Figure 5-7) presented has enabled LCC to prioritise its limited road maintenance capital on road sections at risk from drought-related clay subsidence. It has also acted as the basis for a decision-support tool, making highways engineers more conscious as to where hazardous soils present themselves spatially, highlighting the damaging effect that these can have upon the unclassified road network during drought conditions, as well as guidance as to which treatments prove economically and structurally viable.

The study also highlights the structurally damaging effects that are likely to occur on England's unclassified road network under the UKCP09 climate projections, and on soils prone to clay-related subsidence, especially in the south-east of England. The incorporation of probabilistic subsidence projections provides a novel approach to evaluate the future risk of soils to highway networks. The standardised CVI method of road condition survey within the UK means that rapid soil-geohazard assessment could be readily applied to other administrative areas affected. Further research is required to consider the potential impacts of other infrastructure failures and maintenance activities (e.g. water mains failures and construction of utility trenches) on the soil structure and to what extent this results in degradation road foundations and ultimately of road surface quality.

Figure 5-14: Road embankment instability, B1165 Ravens Bank, Lincolnshire

5.8 Conclusion

This research has considered the impact of clay-related subsidence on highways from a UK perspective. Analysis has shown that the south-east of England is at highest risk of clay-related subsidence, both now and increasingly so for future scenarios, which is directly comparable to the conclusions presented in Chapter 4. This has been verified through analysis of road condition data for the administrative county of Lincolnshire and is further supported by the attributed costs in Table 5-2.

The issue of expansive soils impacting on road surface condition however is a recognised problem for a number of countries. The soil-informed maintenance strategy proposed here could be extended and applied successfully in an international context, highlighting the inherent value in a greater cooperation between highways engineers and engineering geologists, geomorphologists and soil scientists; highways engineers often having little earth-science backgrounds. This strategy also enables the incorporation of modelled climate change impacts, which with global scenarios indicate an increased vulnerability of global infrastructure networks as a result. Therefore, any improvement of climate adaptation measures is highly beneficial for the continuous and economical running of highway networks globally.

The availability of appropriate soils data (e.g. national soil survey maps) and empirically derived shrink/swell assessment, will often dictate the potential of the methodology presented here. However, the the launch of SMOS (Soil Moisture and Ocean Salinity) and SMAP (Soil Moisture Active Passive) satellite platforms in 2009 have provided tools to obtain almost real-time data, in areas where meteorological data is sparse, to predict soil moisture levels and where expansive soil distribution is known, to predict potential damaging impacts on highways infrastructure. However, this data may be unsuitable in urban environments where soil sealing will prevent measurement of soil moisture. Differential SAR Interferometry, which is able to detect ground movements at the millimetre scale (Calò et al. 2014) could however be a source of estimating where expansive soils are distributed, importantly providing a more economical means to undertake regional, national scale and even cross-border assessments of shrink-swell impacts on road infrastructure.

6 Making UK infrastructure resilient to chronic geohazards under climate change: A framework for governance

Chapter synopsis

This chapter draws together the previous chapters to provide a framework methodology for the climate adaptation of local UK infrastructure networks. It uses the modelling results, incorporating UKCP09-derived projections of soil moisture deficit into a geohazard model to understand the future spatial distribution of such hazards. It expands on the highways case-study, highlighting and exemplifying how such an approach can be used to assess the risk to infrastructure systems. It also draws upon wider research in the ITRC project to provide a systems-of-systems analysis of climate impacts on UK infrastructure networks.

6.1 Preface

Chapters 4 and 5 of this thesis have considered the impact of climate change on a single geohazard (clay-related subsidence). Furthermore, the likely impact of this particular geohazard under different climatic scenarios was asessed for the minor road network of GB supported quantitatively by a case-study drawn from the UK administrative county of Lincolnshire.

Results show that clay-related subsidence has had a profound affect on local highway networks, particularly in the south-east of Great Britain. Climate change projections presented in this thesis suggest that this trend is likely to be exacerbated moving forward. However, the biggest magnitude of change will likely occur between the baseline and 2030.

The literature review undertaken in Chapter 2 established that a number of other soil-related geohazards (e.g. soil corrosivity and sand washout), which are predominantly driven by soil moisture, have also affected infrastructure founded within the uppermost soil layer (i.e. 1.5m below ground level). Results show that soil moisture (i.e. PSMD) is likely to be subject to significant changes between now and 2050. However, this will not be a uniform response across GB (e.g. Figure 4-11) and as such individual infrastructure operators and local authorities will need to undertake their own assessments to understand how climate change and soil-related geohazards may particularly affect them and their regions.

Chapter 2 also argued that there is currently a lack of awareness surrounding the impact of soil-related geohazards upon Great Britain's infrastructure networks, more so when incorporating the impacts of climate change. As such, Section 2.10 in Chapter 2 argued for the creation of a national framework methodology for mitigating the impact of soil-related geohazards on infrastructure in a changing climate. Using the knowledge presented collectively in the previous chapters, and summarised above, this chapter presents a multi-hazard and multi-infrastructure framework assessment. It is aimed at both infrastructure operators and owners, but also regulators, local authorities, national Government and academia who collectively need to work together to help deliver a climate resilient UK infrastructure.

6.2 Introduction

UK infrastructure is threatened by climate change and a range of environmental hazards (Royse, 2010; Defra, 2011; Defra, 2013; Pritchard et al. 2014;

Hawkins, 2013; Forster & Culshaw, 2004). This is exacerbated by a nexus of ageing infrastructure components (some in excess of 100 years), variable construction materials and technologies, increasing interdependencies, and an ever increasing customer demand. This has led the Institution of Civil Engineers in their recent State of The Nation report to identify rising populations and climate change as the main threats to the UK's infrastructure networks (ICE, 2014). Population projections for the UK indicate that, especially in urban areas, increased demand will further stress already 'fragile' infrastructure assets, making them more susceptible to failure (Hickford et al. 2015; ONS, 2010). As a result, infrastructure assets are likely to become increasingly susceptible to deterioration and failure as a result of what are presently considered minor, or chronic environmental hazards (Bollinger et al. 2014; Walsh et al. 2015). It is argued that degradation and failures, from that of individual assets up to the network-level, have the potential to occur if climate change adaptation measures are not adopted (Bollinger et al. 2014).

Local infrastructure is essential for the UK's economic, social and physical wellbeing (Defra, 2013). In this chapter *local* infrastructure follows the definition of Rogers et al. (2012), incorporating the seemingly ubiquitous network of buried utility services including, pipes (gas, water and wastewater), cables (electricity and telecommunications) as well as local authority owned ‘local’ roads. Major arterial roads, such as Highways England-owned A-class roads and Motorways have not been included, due to these structures being founded in deeper geological deposits and therefore not subject to shallower soil-related processes. Also included as local infrastructure are shallow-founded structures (i.e. <1.5 m below ground level) including water pumping stations, distribution network operator level electricity substations and telephone exchanges. Infrastructure is often regarded as a socio-technical system (Figure 6-1), and therefore any failure(s) has the potential to impact not only on the built environment itself, but also on society (Chappin & van der Lei 2014). A particular aim for Defra (2013) is that the UK works towards 'an infrastructure network that is [both] resilient to today's natural hazards and prepared for the future changing climate'. This is set in the context that UK local infrastructure is becoming more and more interdependent, and particular infrastructure networks cannot be considered as isolated technical components but rather as a system-of-systems (Bollinger et al. 2014; Eusgeld et al. 2011; Hall et al. 2013). This increasing system interconnectivity and interdependence can mean that even potentially small-scale, single asset failures can result in high-profile cascading asset failure events (e.g. Kirshen et al. 2007).

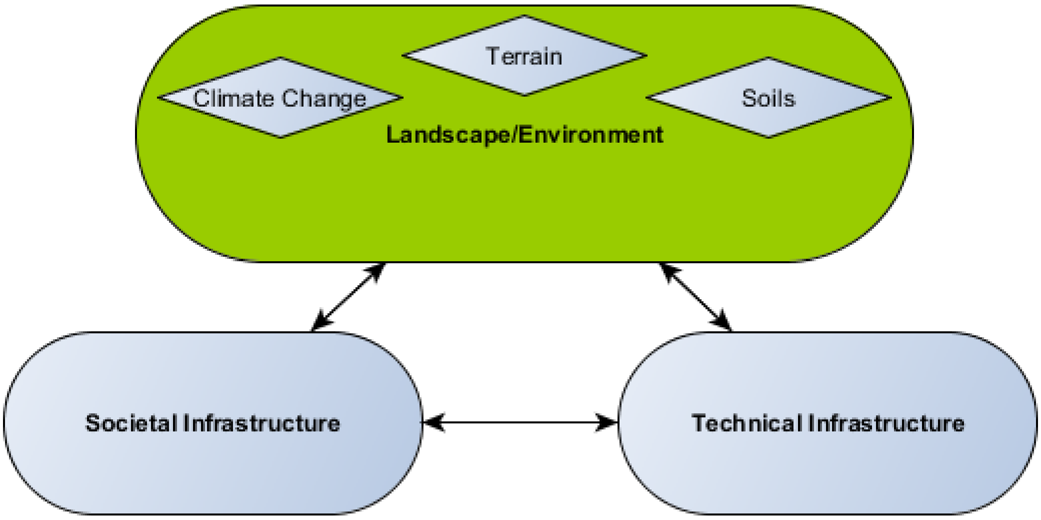


Figure 6-1: Socio-technical landscape of infrastructure systems (adapted from Chappin & van der Lei, 2012)

A range of environmental hazards, termed here as ‘geohazards’, can impact upon infrastructure. These include flooding, high winds, clay-related subsidence heatwaves, and snow. Here a geohazard is defined as an environmental phenomenon capable of causing harm to both life and the built environment. The majority of UK research and policy debate to date has predominantly focused upon flood impacts, due to their high and immediate economic damage, with attendant media interest. There is a clear apparent direct relationship between climate and flood events (Fedeski & Gwilliam 2007). However, the impacts of soil-related geohazards, which sometimes represent chronic, prolonged events, have received less attention, with knowledge in this area being regarded as weak to moderate by HM Government (HM Government, 2013)(Table 6-1). Much of the UK's local infrastructure is buried or founded within the uppermost soil layers (i.e. <1.5 m below ground level). Therefore, soil properties and related physical processes exert a profound impact on buried infrastructure assets (Pritchard et al. 2014a). Physical processes can manifest in a wide range of soil-related geohazards. For example, clay-related subsidence is the UK's most damaging soil-related geohazard and is regarded as an important geohazard but often overlooked (Mills, 2003); it also results in average annual insurance costs of between £100-600 million. However, the costs of clay-related subsidence reported above directly relate to domestic and commercial property insurance claims with the true cost of soil-related geohazards to UK infrastructure remaining unquantified, despite a number of articles stating the impact of such hazards on infrastructure (e.g. Hawkins, 2013; Pritchard et al. 2014a; Pritchard et al. 2015b; Rogers et al.

2012; Kleiner et al. 2012). It is likely that reluctance by UK policymakers to place more recognition on soil-related geohazards is a result of the complexity of external factors acting upon infrastructure networks that make the individual causes of failure difficult to determine. Also, unlike flooding which has the Environment Agency dedicated to managing and controlling flood risk, soil-related geohazards do not have a similar body to ensure further resilience to this widespread hazard. A recent Committee on Climate Change report to UK Parliament revealed that shrink/swell subsidence was one of many systemic risks not currently being considered by UK policy on climate change risks, with no inclusion in the National Adaptation report (Committee on Climate Change, 2015). Furthermore, the modelling of soil-related geohazards is more problematic, ‘chronic’, and has more ambiguity than flood risk modelling. Clay-related subsidence and other forms of land instability (e.g. landslides) are also not included on the National Risk Register (Cabinet Office, 2015).

This chapter presents a climate change adaptation framework for local infrastructure networks which potentially face a number of risks from varied soil-related geohazards. This research has been developed as part of the Infrastructure Transitions Research Consortium (ITRC) which has sought to assess the risks of infrastructure failure and identify how the development of robust models and methodologies can help make UK infrastructure more resilient to climate change (Hall 2011). The research presented further builds upon the earlier CREW (Community Resilience to Extreme Weather) project (Blenkinsop et al. 2010; Hallett 2013) as well as providing a future outlook for soil moisture and its impact on the frequency and magnitude of soil-related geohazards (Chapter 4) (Pritchard et al. 2015a).

Table 6-1: Sector specific information on needs for information on climate change impacts (Adapted from: PwC, 2010)

	Infrastructure Operators		***Investors***	
Issue	**General awareness of climate change as an issue**	**Understanding of specific climate change impacts**	**General awareness of climate change as an issue**	**Understanding of specific climate change impacts**
High Impact Events e.g. Flood	Strong for most sectors	Strong for most sectors	Limited to niche investors	Limited to niche investors
Incremental changes in averages e.g. soil moisture	Moderate	Weak, growing in some sectors such as energy, rail and roads	Weak, growing for some niche investors	Weak
Interdependency with other sectors	Weak, although most obvious links such as cooling water for energy or role of ICT where identified	Weak	Weak, but growing for investors with portfolio of interlinked assets	Weak

It is hoped that the framework presented in this chapter will help decision-makers to consider the possible scale and direction of soil-related geohazard impacts under climate change projections, at the medium emissions scenario, from the current time through to 2050. This chapter has considered two temporal 30-year time periods of 2030 (2020-2049) and 2050 (2040-2069), coinciding with the modelling undertaken in Chapter 4. A series of case studies, detailing soil-related geohazard impacts, are drawn from the gas distribution, drinking water and roads infrastructure sectors. We provide insights into the inherent interconnectivity between the networks identified, highlighting examples of cascading failure events. It is important to note that the future scenarios presented in this thesis are modelled, synthetic yet plausible realisations of potential reality which can be utilised to help better inform the planning, design and asset management responses of infrastructure networks (Walker et al. 2003).

6.3 Climate change and geohazards

Climate change is a recognised threat to infrastructure, both for the UK (Rogers et al. 2012; Defra, 2011; Defra, 2013) and globally (e.g. Nelson and Freas, 2012; Lisø, 2006; Larsen et al. 2008; Chinowsky et al. 2015). The Stern Review argued that climate change could potentially cost the world's economy 5% of global gross domestic product (Stern, 2006). A study of the impact of climate change on the cost of Alaskan infrastructure identified that up to 2080, infrastructure maintenance costs could increase by 10-12% (Larsen et al. 2008). A recent African study posited that potential cumulative costs for reactive maintenance of roads to climate change impacts could exceed $923 US million (Chinowsky et al. 2015). For soil-related geohazard impacts on infrastructure, costs are often not known, as understanding of failure mechanisms is limited, or failure data availability and quality has to date obscured potential investigations into the causes of failure.

In this section the impact of climate change on a range of soil-related geohazard processes is explored. Soil-related geohazards magnitude and frequency is controlled to a large extent by the soil moisture regime which in turn is a factor of the balance between precipitation and potential evapotranspiration that is itself climate driven. Alongside soil moisture, for example, soil texture and mineralogy also dictate the potential for a geohazard to develop. This section aims to provide the reader with an understanding that the paradigm of climate stationarity, which refers to climatic averages remaining constant through time, is now known not to be the case; this will be discussed further in section 6.2.1. Soil-related geohazard processes and their impacts on infrastructure networks discussed in Chapter 2 are also briefly redefined for the benefit of the reader.

6.3.1 The death of climate stationarity

To date, building design codes, standards and operations, and infrastructure asset management have predominantly been based on historic weather data and trends (Lisø, 2006). However, with increasing recognition that climate 'stationarity' is dead (Milly et al. 2008), we should no longer assume that past climate scenarios provide a representative view of what infrastructure assets are likely to encounter for future climate scenarios. Previously, technical adaptation decisions in making infrastructure resilient to climate-related risks were based upon knowledge of past events and particular climate thresholds, and then extrapolated forwards (Giordano 2012). Kwakkel and van der Pas

(2011) argue that this approach almost results in the wrong outcome, since the future is almost always different from that forecasted. It is therefore imperative that changes to these existing knowledge paradigms and to the strategic planning of infrastructure are brought about to encapsulate climate change projections and this apparent non-stationarity of climate (Godden & Kung 2011).

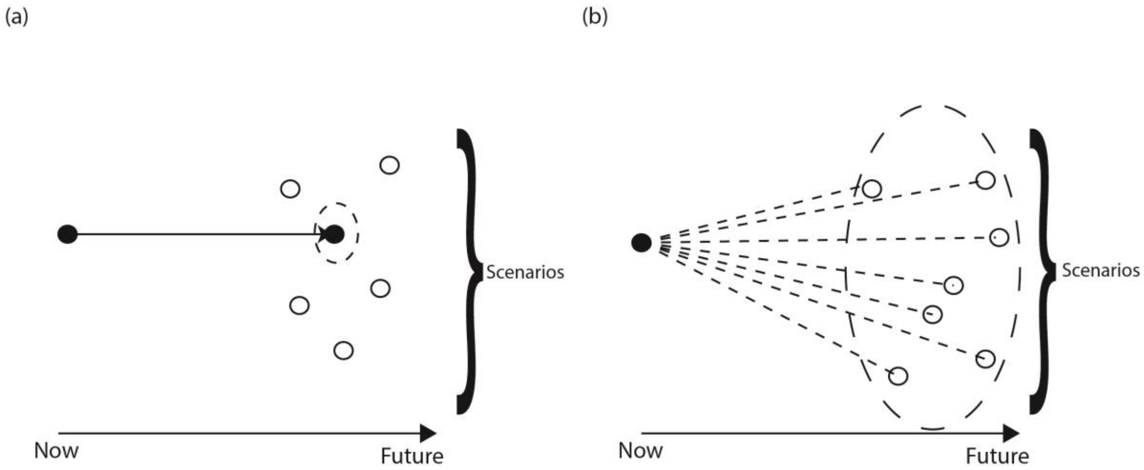


Figure 6-2: (a) one-dimensional approach and (b) multi-dimensional approach to climate change scenario options for infrastructure adaptation (adapted from Kang and Lansey, 2014)

Climate adaptation studies have also seen users of climate projections moving away from one-dimensional scenario solutions to that of multi-dimensional scenario option planning (Figure 6-2) (Kang & Lansey, 2014), which enables an optimum solution to be identified; this is explored in further detail in section 6.4.1. Scenarios in this thesis have used the 'medium emissions' (equivalent to the IPCC's A1B scenario), within which is attained a probabilistic, or 'ensemble' based approach handling inherent uncertainty.

6.3.2 Geohazard impacts on infrastructure

In Chapter 2, it was argued that clay-related subsidence, sand-washout (a form of soil erosion) and soil corrosivity are the most prevalent soil-related geohazard processes resulting in failure of UK infrastructure assets (Pritchard et al. 2014a). For the reader's benefit definitions of these geohazards are provided in Section 1.5 alongside maps depicting their spatial distribution in Great Britain (

Figure 6-3).

With soils providing the foundation medium for the majority of local infrastructure assets, the soil environment plays an important role in determining infrastructure asset performance (Allan, 2011). The volumetric shrinkage and swelling of clay soils is a factor of both mineralogy and climatic regime. Due to its drier climate, the south east of England is particularly susceptible to the damaging effects of clay-related subsidence. With this geohazard representing the highest impact on infrastructure networks (Pritchard et al. 2014a) a strong physical impact will be exerted on the infrastructure buried or founded within.

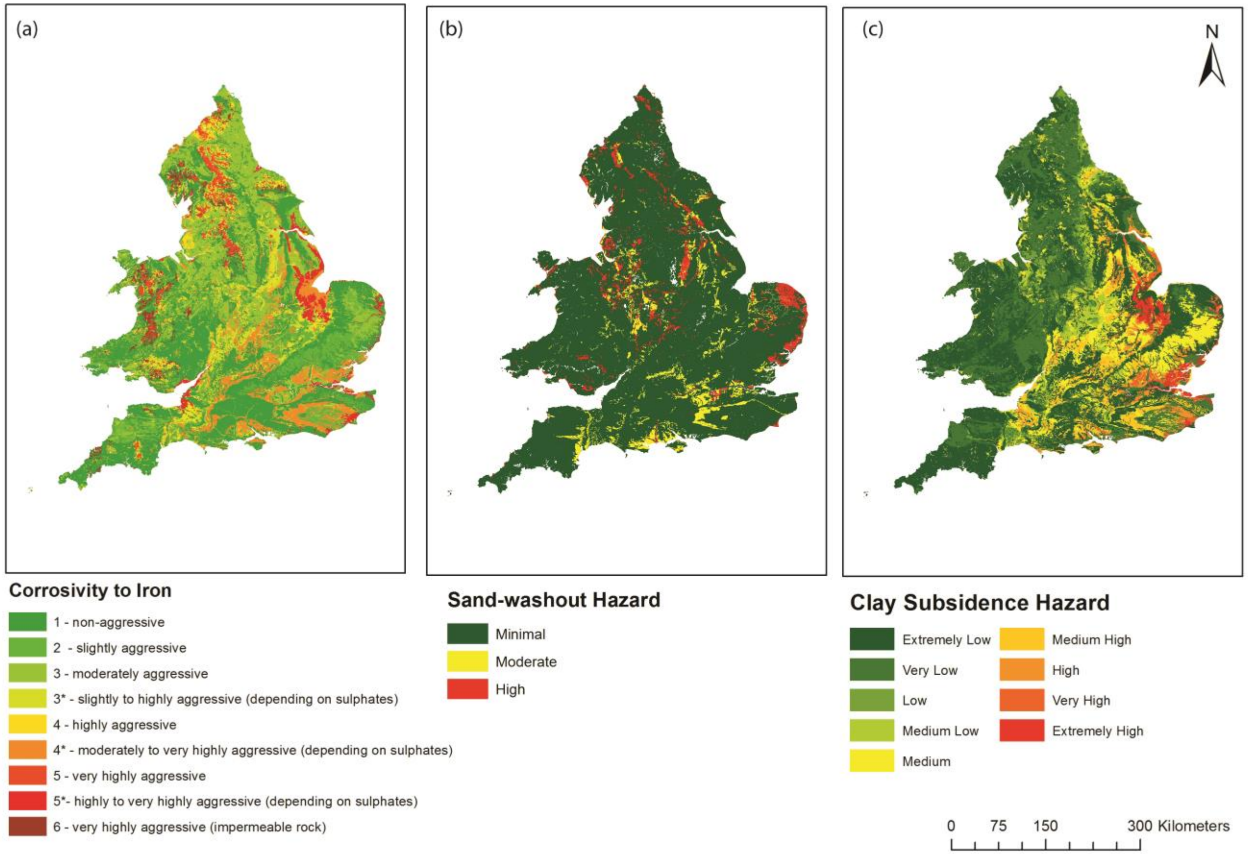


Figure 6-3: The current spatial distribution of the geohazards considered for England and Wales. (a) Corrosivity to Iron; (b) Sand washout; (c) Clay subsidence (Soils Data (England and Wales) © Cranfield University and for the controller of HMSO 2015)

The erosion of sandy soils, which often leads to cavitation (e.g. Figure 6-4), has been well documented by the media (Farewell et al. *In preparation*). This phenomenon can result from pluvial, fluvial and groundwater flooding, but can also commonly be a result of infrastructure failure (i.e. a burst water main). Cases of sand-washout have impacted on a number of close proximity infrastructure networks, sometimes resulting in high-impact cascading failure events (e.g. Worcester News, 2012; getSurrey 2013; BBC, 2015).

Figure 6-4: Cavitation causing extensive damage to the Mancunian Way, Manchester as a result of a burst water main (source: BBC, 2015)

The corrosion of buried metallic iron, resulting from the chemical interaction of specific soil properties, is also proven to be a particular risk to buried assets (Hembara & Andreikiv, 2012). Corrosion of gas pipelines has led the Health and Safety Executive (HSE) to implement a statutory replacement of cast-iron gas mains to reduce pipe failure and leakage which can ultimately lead to an explosion, posing a significant risk to life as well as the built and natural environment (HSE, 2001; HSE, 2010).

Climate change projections indicate changing patterns in rainfall and potential evapotranspiration through to the end of the 21st Century (e.g. Figure 6-5). This is likely to exacerbate the frequency and magnitude of a number of soil-related geohazards, but will predominantly affect clay-related subsidence (Pritchard et al. 2015a). HM Government posit that soil-related geohazards will lead to increased risks to the UK's built environment. However, despite the large costs associated with clay-related subsidence, little quantitative research has been published that links geohazards and climate change (notable exceptions being: Blenkinsop et al., 2010; Harrison et al., 2012; Pritchard et al., 2015a).

Brook and Marker (2008) argue that the geoscience community could do more to 'press for the recognition of [geo]hazards, including subsidence' in infrastructure planning policy. An overarching theme for the papers discussing geohazards and planning is how to most appropriately transfer complex knowledge to non-specialists, that has perhaps impeded the greater inclusion of geohazard data into the planning process to date. Lee and Griffiths (1987) argue that improvements in the presentation of technical environmental information are of great importance when disseminating information to planners who predominantly have economic and social-science backgrounds. Lindley et al. (2007) argue that highly visual outputs help better communicate the spatial distribution of geohazard risk. However, despite these advancements, the incorporation and adoption of soil-related geohazard information by the planning sector has become somewhat stagnated.

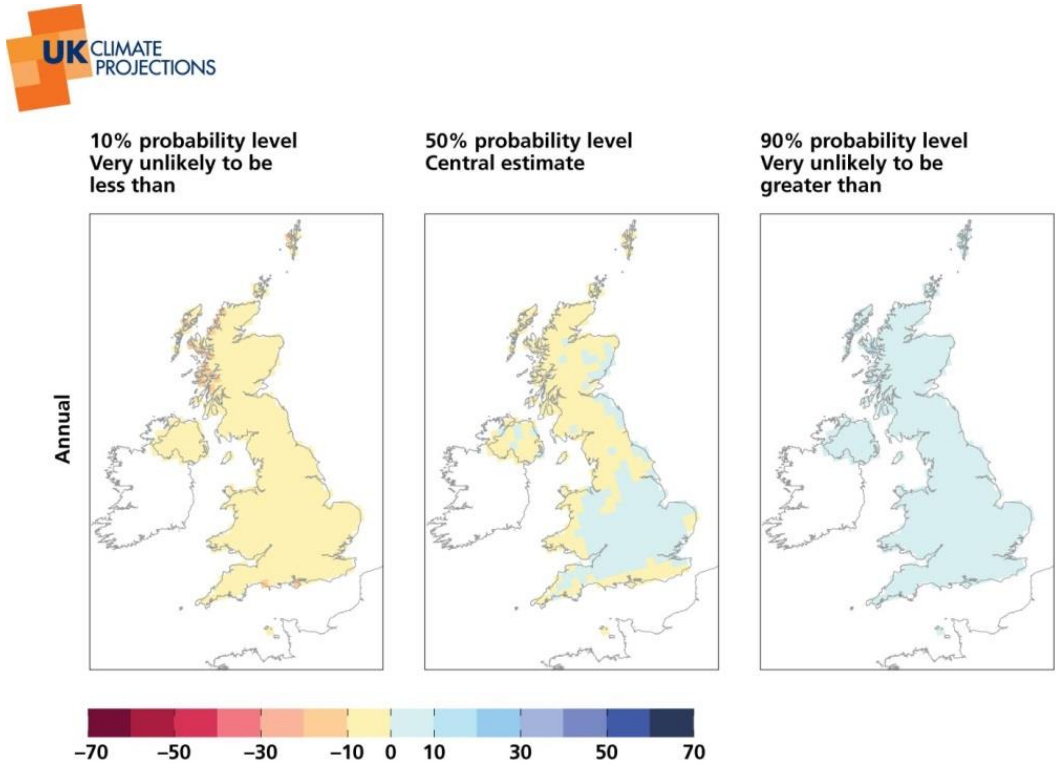


Figure 6-5: Change in annual mean precipitation (%) for the 2050s, Medium Emissions Scenario (Source: UK Climate Projections)

6.4 Adaptation Roles

A number of stakeholders have a role to play in the climate change adaptation of UK infrastructure networks (Figure 6-6). These include: utilities, utility regulators, local authorities and central government, and academia. Each body holds specific responsibilities, for instance utilities are responsible for upgrading asset materials (e.g. cast-iron to plastic water pipes), thereby increasing their immediate resilience to specific climatically driven soil-related geohazards. Conversely, central and local governments are responsible for spatial planning measures in both the construction of new infrastructure and the resilience of existing assets. This section aims to provide the reader with a background into the adaptation roles of each stakeholder. Below, utilities and their regulators are combined into one section, due to the fact that regulators are a key driving force for utilities implementing adaptation measures across their respective networks.

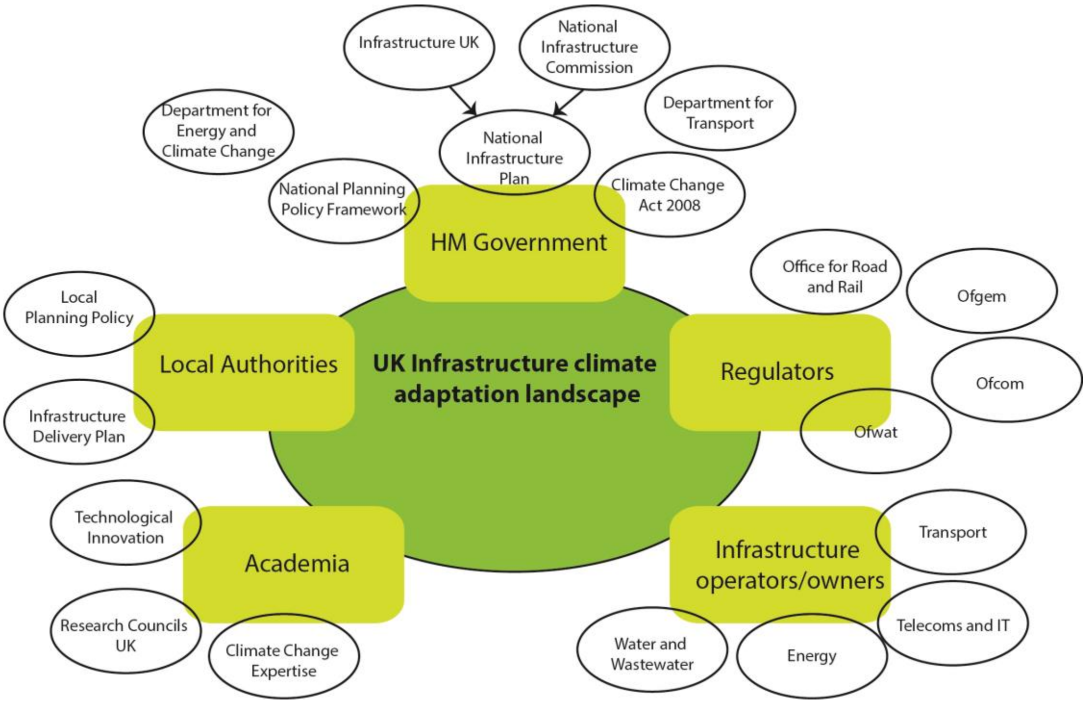


Figure 6-6: The UK Infrastructure high-level climate adaptation landscape

Cooperation is needed amongst all stakeholders to help ensure climate resilient infrastructure (Bollinger et al. 2014). However, stakeholder's engagement with climate change adaptation ultimately depends upon their knowledge and expertise of climate change impacts (Williams et al. 2012). Hertin et al. (2003) found in a series of interviews, that climate impacts require consideration from both the sub-organisational level to the organisational (or executive board) level, as individual's perceptions and expertise will inherently differ.

6.4.1 Utilities and their regulators

Previous studies have argued that utility companies should lead on climate change adaptation measures (Nierop, 2014). This is a result of their inherent and extensive knowledge of the networks which they manage. A key question utilities must address is the amount of spend the business commits in preparing for climate change compared to other, and perhaps more immediate and pressing needs. Helm (2009) argues that short-term budget constraints have resulted in capital expenditure (CAPEX) and maintenance often being sacrificed for current consumption (Operational Expenditure – OPEX). However, no-regret measures, such as reducing water reduction (e.g. through pipe leakage) are highlighted by Huntjens et al. (2012) as actions that yield benefits even if climate didn't change and so could potentially act as a 'veiled' climate adaptation measure.

Regulators exist to ensure networks are kept running at costs deemed acceptable to customers. Therefore, they also play a key role in the management of climate change adaptation measures by ensuring that the right strategies are being implemented so as not to burden users economically. Asset management strategies have greatly improved as a result and have become widely accepted during the last two decades. Furthermore, Aikman (2014) stresses that the introduction of regulatory bodies in the water sector has greatly improved the practice of good asset management. Problematically, asset management frameworks to date rarely extend beyond the 5-year cycle of forward-looking planning measures, which are linked to both funding cycles and political changes (Shah et al. 2014). To account for the potential of climate change however, a medium to long-term approach is now required. Some utility owners are now taking a step in the right direction with the National Adaptation Programme (Defra, 2013) reporting that several water utility companies are using tools embedded within the UK Climate Projections (UKCP09) (i.e. the weather generator) to assess the future potential climate risks to their respective businesses.

6.4.2 Central Government

The UK Climate Change Act (2008) provides the constitutional legal framework by which the impacts of climate change are addressed. One of its key provisions is the requirement (every 5 years) to list the key risks of climate change to the UK and to set about how these issues should be addressed (Webb, 2011). Incidentally, the UK was the first country to make action on climate change legally binding (Lorenz et al. 2015). Moreover, in the UK, HM Government are responsible for the national-scale planning of infrastructure. UK Planning policy exists to regulate the development of land for the public interest. Giordano (2012) argues that planning is the 'crucial first step' in ensuring a long-lived, climate resilient infrastructure. Current planning policy includes the mitigation of risk as a result of potentially hazardous ground conditions. The National Planning Policy Framework (2012) states that the planning system should contribute to the natural and local environment by 'preventing both new and existing development…being put at unacceptable risk, or being diversely affected by unacceptable levels of…land instability'. Furthermore, the document points towards 'new development(s) [that] should be planned to avoid increased vulnerability to the range of impacts arising from climate change'. However, land instability is not mentioned explicitly, but rather the following themes are: flood risk, coastal change, water supply and changes to biodiversity and landscape. The recognition and appropriateness of geohazard information within planning policy has been discussed and is incorporated into HM Government planning guidance (e.g. DTLR, 2002). However, flooding remains the highest risk in HM Governments National Risk Register (NRR), due its significant and acute economic impact, and as a result remains the principal natural hazard considered by Government (Cabinet Office, 2015).

Planning Policy Guidance (PPG) 14, Annex 2 provides local planning authorities and developers with a framework for mitigating the impacts of potentially hazardous ground conditions arising from subsidence and landslip. It advises that 'local planning authorities should identify areas where consideration may be needed of the potential impacts of subsidence on development'. However, it currently lacks foresight regarding the impacts of climate change on potential geohazard processes, particularly as it is now precedes the UKCP09 outputs. Brook and Marker (2008) also stress that the recent introduction of Planning Policy Statements (PPSs) will lead planners to leave PPG 14 at the wayside with the new PPS documents having further diluted planning advice for potentially unstable ground conditions.

In Chapter 4, the range of National Policy Statements (NPS) currently applicable to the design and planning of UK infrastructure were considered (Pritchard et al. 2015a). It was found that they appear very fragmented in their consideration of geohazard and soil impacts upon infrastructure networks. Moreover, the water sector does not currently have an NPS, and there is no intention to implement one in the short term. Most government and subsequently policy attention was drawn to high impacting events (i.e. flooding), and furthermore consideration of potential climate change was not addressed in the sector specific NPSs. Contrastingly, the national networks' NPS, states that applicants *must* apply climate change projections, and suggests that transport infrastructure with safety-critical elements should apply the UKCP09 high emissions scenario against the 2080 projections at the 50% probability level.

The Health and Safety Executive (HSE) mandates that infrastructure operators and providers are required to protect citizens from the impacts of their systems and operations. They also provide guidance and statutory policies in respect to mitigating the impacts of soil-related geohazards. This is particularly so with respect to buried cast-iron gas mains, which are now part of a statutory replacement scheme. This resulted from a number of corroded cast-iron pipes leading to build-up of gases in properties and soil and consequently several explosions which posed a significant risk to life (e.g. HSE, 2010).

The establishment of Infrastructure UK (IUK) in 2009 aims to redress the historic, '*siloed*' nature of the respective infrastructure sectors, by encouraging a long-term vision for UK infrastructure planning and adaptation. The consequences of this have been the publication of several National Infrastructure Plans (NIP) (HM Treasury, 2010, 2011, 2013;, 2014). The latest NIP (HM Treasury, 2014) addresses the 'longer-term challenges' of infrastructure planning and, in particular, that of population and climate change.

6.4.3 Local authorities

In the UK, local authorities represent a key stakeholder in ensuring climate-resilient infrastructure (Table 6-2). This is principally due to their enforcing role regarding planning policy and building regulations as well as being responsible for their respective road networks not under Highways England control. For instance, by enforcing minimum foundation depths in susceptible soils building regulations have helped to mitigate the impacts of foundation damage to commercial and domestic properties caused by clay-related subsidence. Williams et al. (2012) have argued, however, that regulatory obligations around risk, which often solely address immediate climate change problems (e.g. flooding), remain the focus of resources. Therefore, local authorities spending on more chronic, non-immediate issues (e.g. clay subsidence) often become postponed. In the UK, utilities and local authorities are also responsible for planning for and addressing emergency situations, potentially arising from infrastructure failure, under the legislation of the Civil Contingencies Act (2004).

Table 6-2: 'Climate-sensitive' local authority functions important for adaptation, and relevant National Adaptation Plan (NAP) actions (Adapted from: Committee on Climate Change, 2015)

Theme	Local authority functions	Relevant National Adaptation Plan Actions
Built Environment	Land-use planning	• Implement National Planning Policy Framework
Infrastructure	Highways and local transport	• Build capacity and knowledge of local transport climate resilience

6.4.3.1 Worcestershire: towards climate risk adaptation

An example of spatial planning for climate change adaptation is the focus of a recent report by Worcestershire County Council, in collaboration with Sustainability West Midlands (Sustainability West Midlands 2012). Here, a number of key climate-related hazards that may affect, or indeed which have affected, infrastructure networks were identified. It is fairly simple in its methodological approach, leading to the added benefit that it can easily be adopted by other local authorities. Flooding, outdoor fire risk and subsidence were each assessed at a range of spatial scales, with their potential impacts considered for a number of infrastructure networks. Although UKCP09 projections are considered, their use is only qualitative in relation to the potential climatic effects on the hazards. An assessment of the interconnections between infrastructure networks was not attempted. This is likely due to both the complexity of the issue and the fact that data sharing amongst utility providers continues to prove problematic, with many infrastructure owners unwilling for commercial reasons to make data available, even under licence or non-disclosure agreements.

The expertise required in using Geographical Information Systems (GIS), with which the methodology above was implemented, was highlighted as a potential barrier for other local authorities wishing to implement a similar approach. A Cabinet Office 2004 survey however, showed that 79% of public organisations do currently use GIS systems (Cabinet Office, 2004). Interestingly, this survey revealed that, of 207 responses, 61 had used 'geology' and only 36 had used 'soil' datasets in their projects, identifying that there is currently further scope for improving the use of both geological and soils data within the UK. A later survey found that the main obstacle facing GIS-based services was a ‘lack of resources’, meaning both staff and equipment (LGA, 2009). However, with the onset of powerful open-source GIS software (e.g. QGIS) alongside open-source statistical software (e.g. the R Statistics package), there is increased opportunity for stakeholders to improve use of digital data and climate change assessment.

6.4.4 Academia

Academia is ultimately responsible for ensuring the scientific basis and rigour for implementing climate adaptation measures. The modelling and simulation of infrastructure networks and environmental processes provide stakeholders with a better understanding of the inherent complexities that exist between climate change and associated impacts on infrastructure networks, often which are beyond stakeholders institutional expertise (Bollinger et al. 2014). Climate change projections such as UKCP09 are borne from many years of scientific research and modelling. Climate change projections bring uncertainties, which academia must communicate appropriately to non-experts (e.g. policy-makers and infrastructure operators). To date, planners have seemingly ignored climate change uncertainties and its subsequent inclusion into the planning process (Giordano, 2012). Importantly however, Hulme & Turnpenny (2004) argue that complex issues such as climate change will never be fully understood before action is required to address them. Hulme & Turnpenny (2004) go further to say that joint learning and research with those undertaking and implementing climate adaptation is required to move research on in context of a practical world. This brings us back to the beginning of this section, which encourages cooperation amongst all in climate adaptation roles.

6.5 Geohazard risk management framework

The previous section identified the relevant stakeholders and their varied roles in the climate adaptation of infrastructure networks. The UK Government is responsible for infrastructure planning and for setting climate change objectives which sets the overarching objectives of CAPEX (Capital Expenditure) programmes (Helm, 2009). It is these CAPEX programmes which are causal in utility owners incorporating widespread climate adaptation measures. However, Nierop (2014) argues that it is important to differentiate what utilities are able to do themselves and what requires government approval in terms of adaptation options. Shah et al. (2014) also comment that medium to long term views of asset management and planning frameworks often do not extend beyond the current 5 year political and financial cycles. The planning system is therefore key for infrastructure adaptation to climate change and potential soil-related geohazards (Wilson, 2006). Considering this, the methodological framework presented in Figure 6-7 is aimed at the range of stakeholders in Section 6.3. The framework presented uses a risk-based approach to understand the potential effects of soil-related geohazards on infrastructure assets and networks and incorporates previous geohazard modelling research undertaken (Pritchard et al. 2015a). A decision-making flowchart has also been created for infrastructure asset owners and operators to help analyse and subsequently mitigate against the risk of soil-related geohazards; this is presented, along with accompanying notes in Appendix H. The following section describes the separate elements of the framework.

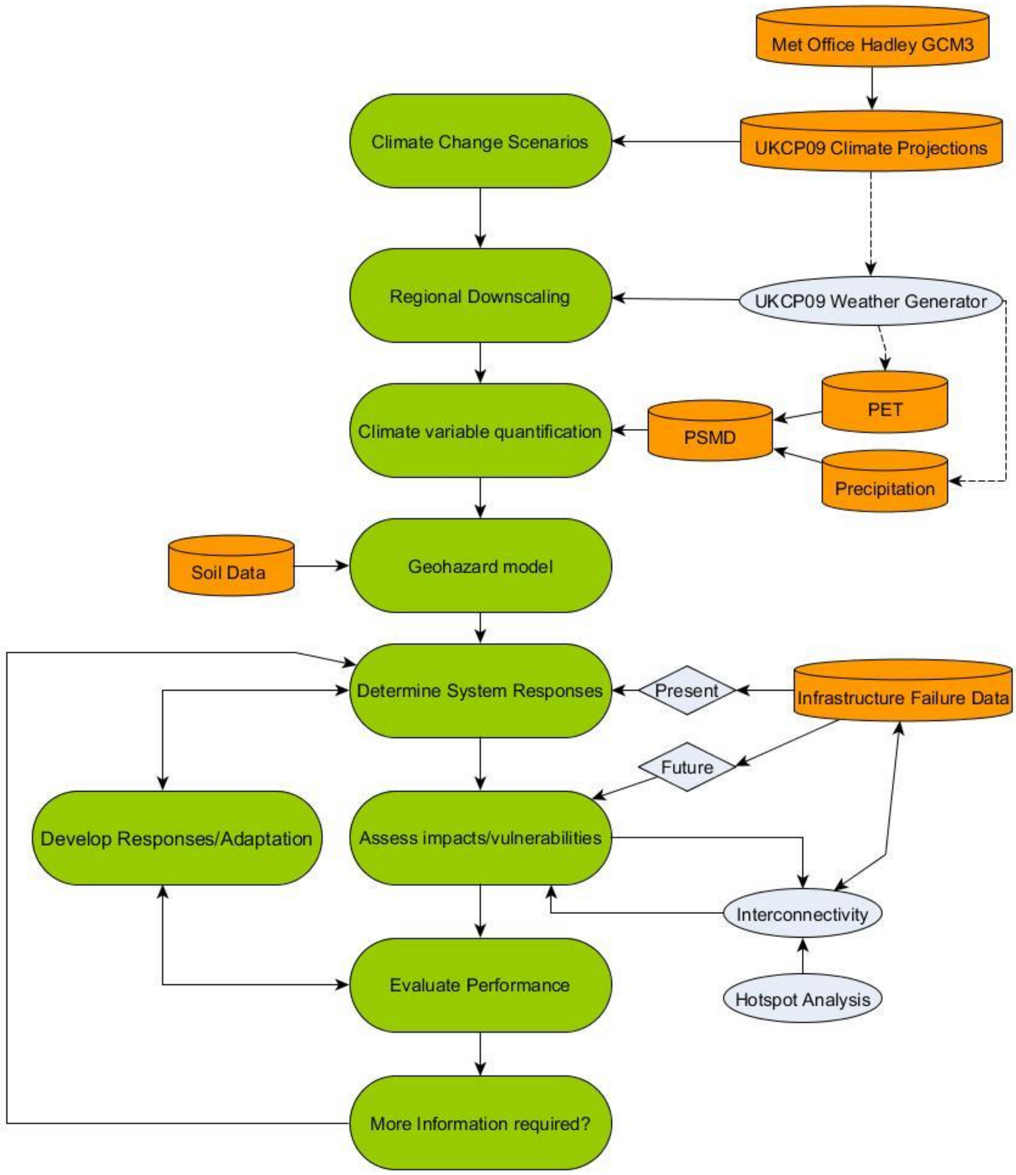


Figure 6-7: Framework for climate change adaptation of infrastructure networks to impacts of soil-related geohazards

Notes: Green boxes indicate key framework steps; orange boxes indicate datasets; light blue boxes indicate intermediate steps

6.5.1 Climate change scenarios

Historically, there has been a tendency to rely on empirical climate data to inform evidence-based UK policy making. The IPCC (Intergovernmental Panel on Climate Change) have produced a range of socio-economic scenarios upon which a series of climate change projections are based (IPCC 2000). It is these scenarios which have formed the basis of climate adaptation policy-making internationally. Kunreuther et al. (2013) argue that we are still not completely aware of climate forcing mechanisms (e.g. carbon cycle feedbacks) which will likely play a key role in future climate scenarios. As a result, frameworks which can easily incorporate new climate modelling and scientific knowledge as it evolves will prove more useful for long-term infrastructure adaptation to climate change.

Climate projections have their uncertainties, which stakeholders need to be acutely aware of when making adaptation decisions. Orrell and McSharry (2009) suggest that models should be used to provide further understanding of a system's behaviour, and subsequently what adaptation measures are likely to improve its health, rather than trying to predict what will happen in the future (Enserink et al. 2013). Berkhout et al. (2002) argued that engaging stakeholders within the scenario planning process is critical. However, stakeholders can sometimes be cautious of estimating what could potentially occur 10-20 years into the future, which can lead to failure in making an adaptation decision. Moreover, validation of such models is difficult, if not impossible. What modern climate projections offer is a range (or 'ensemble') of uncertainties which can be used to plan for a range of eventualities, the adoption of which ultimately depend upon the risk appetite of the decision-maker.

6.5.2 Regional Downscaling

Global Circulation Models are not appropriate for understanding regional and local impacts of climate change, due to their large spatial resolutions (>250 km). Downscaled climate models are therefore used to provide decision-makers with tools that provide projections at appropriate localised, regional and national scales, assessing potential impacts for their respective areas. The UK Climate Projections, 2009 (UKCP09) is an example of this downscaling and is specific to the UK, with projections being derived from the IPCC global AR4 assessment (IPCC 2007). UKCP09 represents the UK's first probabilistic assessment of climate for the 21st century, subsampling from a series of 30 year time slices, each with 10,000 realisations of daily, monthly and annual climate. These downscaled outputs are derived from the Met Office's Hadley Global Circulation Model, HAD GCM3, and both 25 km and 5 km resolutions are made available to users. The latter 5 km outputs are climate change projections based upon a stochastic weather generator (WG) (Kilsby et al. 2007), which has been further refined to provide spatially-coherent projections (Burton et al. 2013).

UKCP09 projections suggest that certain parts of the UK will become exposed to hotter, drier summers, and warmer, wetter winters (Jenkins et al. 2009). In Chapter 4, a modified spatially-correlated version of the UKCP09 WG (Burton et al. 2013; Kilsby et al. 2007) was used to ascertain potential soil moisture deficit for the entirety of Great Britain (England, Scotland and Wales) (Pritchard et al. 2015a). It should be noted that many downscaled models exist internationally, which project a range of scenarios. UKCP09 has become widely accepted within the climate change community for modelling climate change impacts in the UK. Users of downscaled climate projections must also be aware that, although they appear to represent finer time and space scales, they are still dependent on current knowledge and understanding of climate systems which is currently far from comprehensive (Wilby & Dessai 2010).

6.5.3 Climate variable quantification

The climate variables that contribute to the realisation of soil-related geohazard processes are of importance. Soil moisture change exerts significant effects upon the frequency and magnitude of the soil-related geohazards which are the focus of this chapter (Section 6.3.2). Precipitation and potential evapotranspiration are regarded as the key indicators of soil moisture change (Blenkinsop et al. 2010; Pritchard et al. 2015a). In this section links are established between the soil-related geohazards highlighted in Section 6.3.2 and that of the UKCP09 climate variables modelled using the weather generator (Table 4-2).

For clay-related subsidence, UKCP09 projections of soil moisture reveal (Chapter 4) that in particular the south-east of England will likely witness increased clay-related subsidence and heave events, which could affect significantly shallow-founded infrastructure assets. Additionally, subsequent drying and wetting of soils, resulting in fluctuating groundwater levels can lead to particularly aggressive corrosive soils. Cracking clay soils can also allow water to enter the soil and be transported directly to pipe level, especially when cracks can propagate to several metres below ground level (Hawkins 2013)

(Figure 2-2). This could lead to increased moisture contents at pipe depth, accelerating pipe corrosion rates (Jarvis and Hedges, 1994) and the rate of swelling in the autumn. Finally, the erosion of sandy soils leading to cavitation could potentially occur as a result of higher groundwater levels or intense rainfall events in areas susceptible to sand-washout (Figure 2-5). Temperature could also have a significant effect on infrastructure asset degradation, as argued by Wols and van Thienen (2014) in their assessment of the climatic influence on water-pipe failures. However, this has not been investigated explicitly in this framework assessment.

6.5.4 Determine System Responses

The incorporation of spatially-referenced infrastructure failure events as a means of understanding what environmental and asset conditions led to the ultimate failure of a particular asset are highlighted in the framework (Figure 6-7). It is well documented that infrastructure failure may often be a result of multiple external factors, and thus it is important to consider further the potential impacts (e.g. Saul et al. (2007); Rajani & Kleiner (2001)). This data not only provides a means for establishing past causes resulting from environmental phenomena, especially during particularly damaging weather-related events, but it can also serve as a proxy for what could potentially occur in future climate scenarios. From this assessment, it is possible, through incorporation and interrogation of downscaled climate projections, to assess potential future impacts of particular climates upon a range of infrastructure networks. Users must be aware however, that downscaled models of environmental systems serve as approximations of reality, and as such can lead to uncertain predictions if not applied correctly (Rinderknecht et al. 2012). Users should also consider Figure 6-2 which highlights the importance of adopting a multi-dimensional view of climate change projections in light of potential adaptation responses.

Spatially-defined failure data, if available for a range of infrastructure sectors, can feed in to analyses of secondary impacts and interconnectivities. These approaches can prove problematic however if the temporal recording of infrastructure asset condition is such that it would not account for intermediate asset third party damage and repair; for example, the annual assessment of road condition will make it difficult to understand the true relationship with the impact of water pipe failures as often the road is immediately repaired without notification to the acting highway authority (M. Coates, *Pers. Comm.*). Development of methods drawing on such approaches are considered and discussed further in Section 6.4.5.4.

6.5.5 Assess impacts/vulnerabilities

In this section the soil-related geohazard impacts to drinking water, gas distribution and road distribution, local infrastructure networks of the UK are considered. Assessment is made regarding how the proposed framework can help adapt these infrastructure networks to climate change. These specific sectors have been selected as they are regarded as being at the highest risk from soil-related geohazards (ICE 2014; Pritchard et al. 2015a). Also assessed are the risks posed by soil-related geohazards in terms of interconnected, systems-of-systems infrastructure networks.

6.5.5.1 Drinking water infrastructure

The provision of water is regarded as a 'lifeline' infrastructure, therefore any potential failure can be of critical importance (McDaniels et al. 2008). However, D'Agata (2003) argues that predicting the life-span of water infrastructure is like predicting that of a human being, which is extremely difficult. The failure of water mains and consequential reactive maintenance results in high costs and impacts, notably: water waste, contamination, and localised flooding (Cooper et al. 2000; Shi *et al*. 2013). Water distribution networks are regarded as the single most expensive component of the overall water-supply system (Kleiner & Rajani 2001). A recent example of a high impact case was reported in the Severn Trent Water Plc. Region. Here, a broken water pipe, thought to be disconnected, allowed cattle slurry to enter the water supply leading to traces of both E. Coli and Cryptosporidium being present in drinking water (BBC, 2014). As a result, pipe burst events can prove commercially and importantly politically damaging to water companies, furthermore reporting events can result in significant financial penalties from the regulator.

Rajani and Kleiner (2001) suggest that the principal causes of pipe failure to external environmental and operational stresses are corrosion, degradation, inadequate installation and manufacturing structural integrity defects. Gould et al. (2011) identify that summer and winter peaks in bursts have been noted in a number of studies. However, summer peaks in burst rates often receive little attention. My own previous studies have shown distinct relationships between burst rates and the propensity of a soil to shrink and swell (e.g. Figure 6-8), suggesting that drying and wetting of soils, leading respectively to shrinkage and swelling, results in differential ground movement events in susceptible soils that can cause pipes to fracture. Moreover, if soils are also corrosive, then the likelihood of failure is increased (Fahmy & Moselhi 2009; Jarvis & Hedges 1994). Indeed, a report by United Utilities (United Utilities, 2011) where the impacts of climate change on water drinking infrastructure were assessed using UKCP09 climate projections, identified that changes in moisture content can lead to greater soil movement and thus increased burst rates. The recognition of asset management, alongside the onset of water regulation in the UK within the last three decades have prompted companies to acquire more detailed asset knowledge, including location and material characteristics (Aikman 2014). However, due to the UK’s aging water infrastructure, where the majority of assets are in excess of 50 years in age (Boot et al. 1996), with some even being in excess of 100 years in age (Greater London Authority, 2005), water companies have historically, often not recorded the cause(s) of pipe failure (Kleiner and Rajani, 2001). Consequently, knowledge of buried assets and their relationship with long-term environmental impacts are poorly understood. St. Clair and Sinha (2012) argue that a lack of understanding regarding environmental impacts on buried pipes has resulted in limitations to the modelling and prediction of infrastructure failure. It has been argued however that buried water pipes, subject to previous failures, are more likely to fail in future (Jafar et al. 2010).

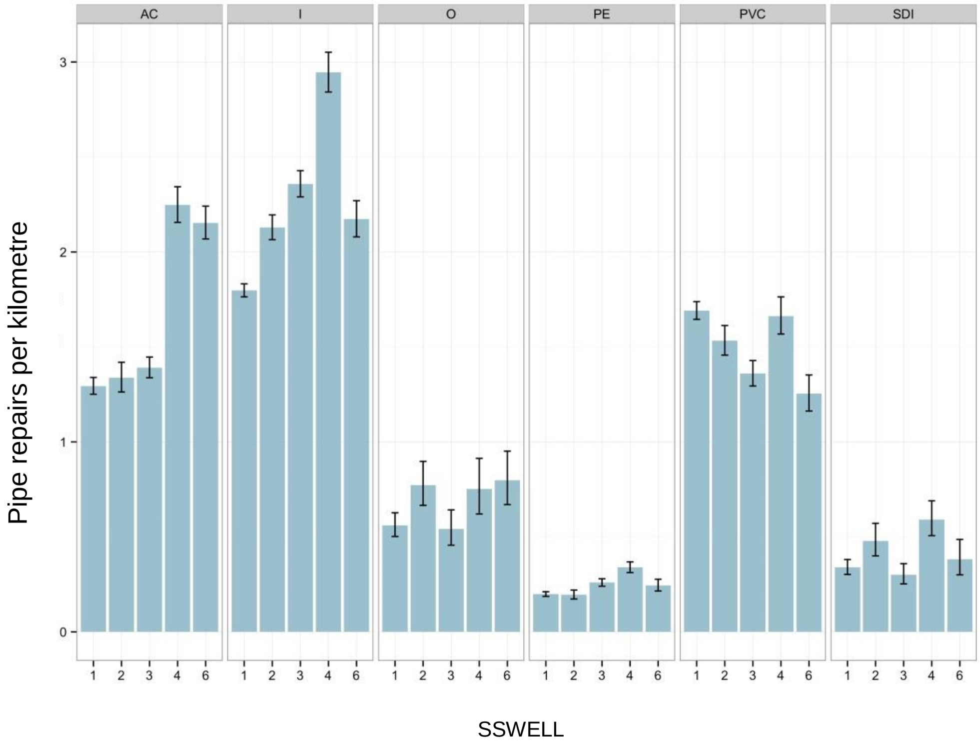


Figure 6-8: Pipe repairs per kilometre rate by clay shrink/swell (SSWELL) class. Material types: AC – Asbestos Cement; I – Iron; O – Other (minor materials); PE – Polyethylene; PVC – Poly Vinyl Chloride; SDI – Steel and Ductile Iron. (Data: Anglian Water Plc.). SSWELL: 1 – Very Low; 2 – Low; 3 – Moderate; 4 – High; 6 – High* (See Table 4-1 for more details).

Boxall et al. (2007) argue that a large number of variables control burst rates, factors that are often unknown and unquantifiable, thus making it a complex issue. Importantly, St. Clair and Sinha (2012) raise the issue that a majority of the models reported in the literature are often too complex and as such are unlikely to be adopted by water utility companies, especially if scientific skills are not available to hand in-house. There is also perhaps ignorance with regards to the causal factors of asset failure, with more emphasis being placed upon the statistical relationships alone, especially for network-level analysis.

6.5.5.2 Road infrastructure

UK local roads are currently ranked at 24th best in the world based on their condition (Schwab et al. 2012). Road infrastructure faces particular risks from soil-related geohazards. This mainly arises from soil being the primary engineering material for local road construction (Biggs & Mahony, 2004). Changing moisture conditions in particular can affect the mechanical properties of such road foundations (Brown, 2012). Clay-related subsidence is argued to pose the most damaging soil-related geohazard to road surfaces (Pritchard et al. 2015b). Erosion and subsequent cavitation of road foundations, particularly in sandy textured soils, caused by the rapid escape of water (e.g. a burst water main) and subsequent sand-washout events can cause significant damage to road surfaces (Farewell et al. *In Preparation*).

It is posited that climate change will increase the risk of clay-related subsidence, particularly to the ‘evolved’ roads of the UK (ADEPT 2009); Evolved roads are less engineered than main trunk roads and motorways of the UK. However, this ‘local’ evolved road network represents as much as 60% of the overall network (DfT, 2012) and is vital to local economy and society (HM Treasury, 2014).

In Chapter 5, analysis into the effect of clay-related subsidence on road infrastructure for the UK county of Lincolnshire was undertaken (Pritchard et al. 2015b). Here it was demonstrated that drought events had led to significant shrink-swell events of susceptible clay soils, which subsequently impacted on the county's local road network, resulting in damage costs equating to millions of pounds sterling (Pritchard et al. 2015b). To date, many road sections have had speed restrictions enforced due to the road condition; some UK counties have even had to resort to road closures due to dangerous road conditions combined with limited maintenance budgets (BBC News, 2014). Lincolnshire's highway authority has since reassessed road resurfacing techniques in areas vulnerable to clay-related subsidence. They assume that these specific roads are 'doomed to fail' and therefore require resurfacing techniques which not only provide a more economical offering, but also which help to reduce CO2 emissions by carrying out in-situ remediation of the road surface, thus avoiding the need for material to go to landfill (Heaton, 2014). Moreover, an assessment of sand-washout events from burst water mains has caused the biggest secondary impact on the road network from a UK perspective (Farewell et al. *In Preparation*).

6.5.5.3 Gas distribution infrastructure

Gas infrastructure failure presents the highest risk to human life in contrast to other infrastructure asset failures. Approximately 23,000 fractures, leading to 600 ‘gas in building’ events, resulting in the fatalities of 1-2 people annually, had occurred up to 2001 in the UK. In such cases, most of the iron pipes involved were 40-100 years in age. Moreover, a number of explosions have also been reported by the Health and Saftey Executive, and are often a result of the fracturing of cast-iron gas distribution mains, due to corrosion. Fracture rates have increased from 13 per 100 km in 1977 to 14.5 per 100 km in 1999 (HSE, 2001). Soils which are aggressive to iron pipes, coupled sometimes with their propensity to shrink and swell can prove particularly hazardous to buried gas infrastructure. The corrosion and fracturing of buried iron gas distribution pipes has led the HSE to enforce a statutory replacement of all cast-iron gas mains throughout the UK (HSE, 2001). The HSE has identified almost 91,000 km of remaining cast and ductile iron gas mains within 30m of a building which would need replacing so as to not pose a risk if pipe fracture occurred (HSE, 2001).

As well as posing a risk to life, more commonly, failures in the gas distribution network can result in extremely high remediation costs on the part of the utility asset owner. Furthermore, if water or soil enters a broken pipe, perhaps from a nearby burst water main or high groundwater levels and surface flooding, then this requires purging from the system which can be both expensive and time consuming.

Due to the enforced statutory replacement of gas mains, this sector is adapting to potentially hazardous future climate scenarios. However, soil-related geohazard mapping can provide the basis for a soil-informed asset management strategy for the replacement of mains helping to identify those locations being potentially at a higher risk to soil-related geohazards, thus aiding the prevention of possible dangerous gas leakage.

6.5.5.4 Systems-of-systems infrastructure

As well as considering the climate impacts posed to the networks of individual infrastructure sectors, attention should also be made to how these impacts will affect adjunct, co-located and wider interdependent infrastructure networks within a systems-of systems (Cagno et al., 2011). Infrastructure networks no longer act in isolation, as they are dependent upon each other (Hall et al. 2013). The resultant interdependencies can be technological, geographical (e.g. Figure 6-9) or cyber and can manifest whereby even minor disruptions in one infrastructure sector can lead to significant disruption in one of more other infrastructures. Interdependent effects occur when an infrastructure disruption spreads beyond itself to cause appreciable impact upon other infrastructures (Little, 2002).

With infrastructure considered as a socio-technical system (Figure 6-1), the potential exists for any failure to affect both local society and economy. An assessment of streetworks activities, whereby utility openings are made to access failed or to replace infrastructure assets, reveals that local convenience stores suffer losses in sales ranging between 10-24% during streetworks activities (LGA, 2012). Additionally, local authorities reported 13% of maintenance budgets are spent on premature road maintenance due to utility streetworks activities, with many highway engineers arguing that utility openings reduce road life by some 30% (ALARM, 2015). The New Roads and Street Works Act (NRWSA) (applicable to England only) aims to ensure that the 'duty of street authorities to coordinate all works in the highway (section 59 of the NRSWA)' is adhered to (DfT, 2009). However, utility openings in England are on an apparent increase (Figure 6-10), which could be the result of an increase in emergency repairs, further expressing the need to adapt infrastructure to potential weather and soil-related impacts.

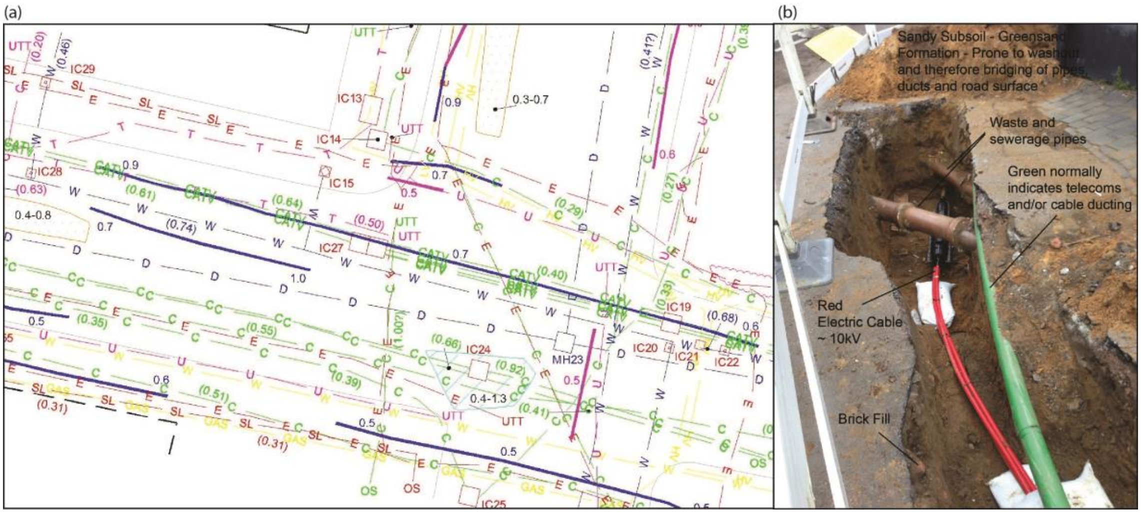


Figure 6-9: Example of typical urban street showing geographical co-location of infrastructure at street-level scale. (a) Underground service map; (b) uncovered buried infrastructure in Ampthill, Bedfordshire (Map: Phase Site Investigations; Photo: S. Hallett)

More research is required to fully understand the interconnectivities of infrastructure networks. To date, most infrastructure sectors have often operated as silos, but the establishment of Infrastructure UK and increased academic and industrial research on interconnectivity (e.g. Infrastructure Transitions Research Consortium) has led to a fundamental shift and increased awareness of systems-of systems infrastructure (Defra, 2013). Problematically however, Taylor et al. (2014) found that risk perceptions are linked to past experiences, which in low frequency events (e.g. sand-washout) may have led to limited consideration of both the impact and its possible multi-infrastructure impacts. Future climatic trends indicate more extreme and severe weather events as well as changing soil moisture levels (as shown in Chapter 4), which could lead to previously low frequency geohazard events becoming increasingly common. An increase in interconnectivities, combined with aging infrastructure and increased demand will therefore result in higher vulnerability of networks to environmental hazards.

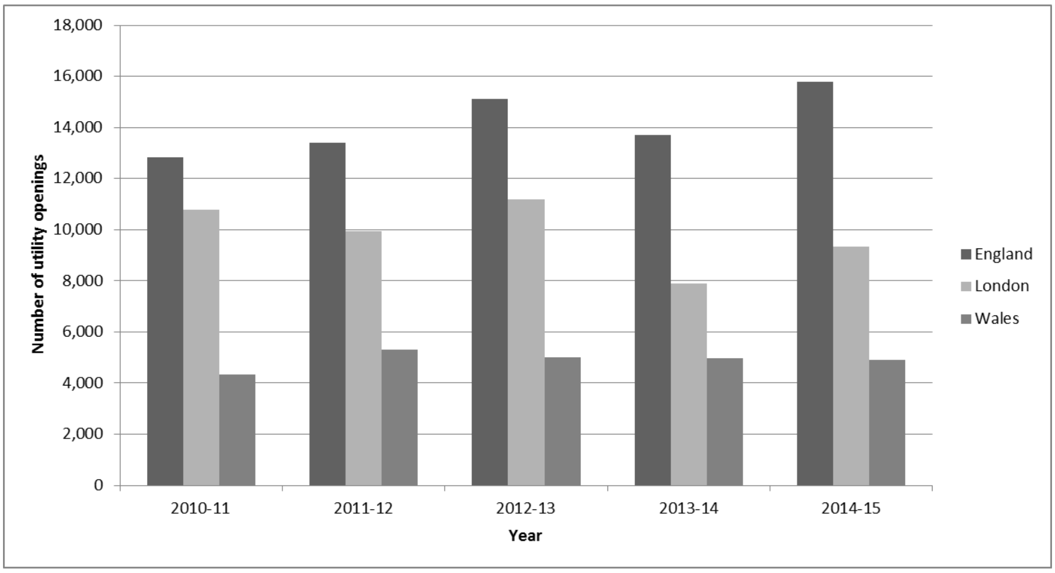


Figure 6-10: Number of utility openings for England, London and Wales between 2010-15 (Source: ALARM survey, 2015)

6.5.5.4.1 Hotspot analysis

Recent research by the Infrastructure Transitions Research Consortium (ITRC) has focused on establishing hotspots of infrastructure interconnectivity for the critical national infrastructure (CNI) of England and Wales (ITRC, 2015) (Figure 6-11). The Cabinet Office (2010) defining CNI as "those infrastructure assets that are vital to the continued delivery and integrity of the essential services upon which the UK relies, the loss or compromise of which would lead to severe economic or social consequences or to loss of life". This analysis is converse to the aim of this chapter which is to consider the impact of soil-related geohazards on local infrastructure networks defined by Rogers et al. (2012). Major infrastructures (e.g. motorways and large diameter pipes) are unlikely to be significantly affected by shallow geohazards and therefore such hotspot assessments could be considered unsuitable for understanding interdependencies between local-scale infrastructure distribution networks.

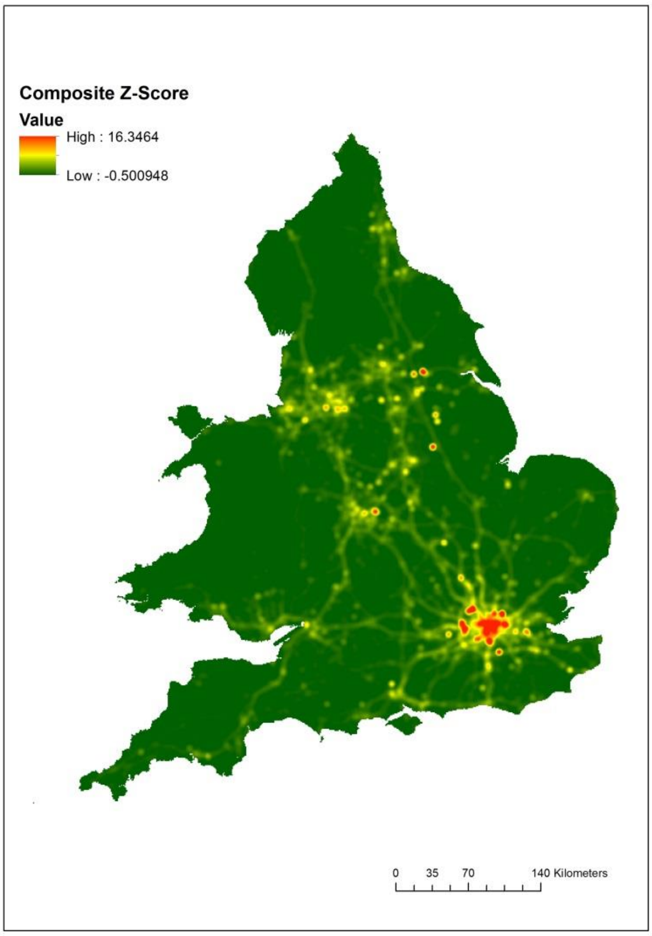


Figure 6-11: ITRC Hotspot analysis showing infrastructure interconnectivities based on derived composite Z score representing spatial co-location in England and Wales (Source: ITRC, 2015)

Interrogation of local infrastructure datasets reveals that the GB local road network (i.e. B, C and U road classes (DfT, 2012)) can act as a suitable proxy for the co-location of infrastructure services (Figure 6-12); Figure 6-9 depicts the co-location of many infrastructure networks in a typical urban street setting. Using the minor road network of the UK, derived from a database layer contained within the ITRC geospatial infrastructure database, suitable tools in

ArcGIS (v. 10.2) have been used to calculate line kernal density estimation (KDE) of the road network at 1 x 1 km grid resolution for the entirety of GB (Figure 6-13).

The south-east of England, especially around London, exhibits the highest density of interconnected infrastructures (Figure 6-12 and Figure 6-13). However, whereas the hotspot analysis in Figure 6-11 shows interconnectivities of key critical infrastructure (e.g. Strategic Road Network, Railway, Electricty and Gas Transmission lines), Figure 6-13 shows the local infrastructure interconnectivities. As a result, the latter map is more appropriate for the research presented here in that it identifies areas of local infrastructure vulnerable to possible cascading failure. This is made more important for the case of south-east England as this geographic area also coincides with higher clay subsidence hazards for both the present and future scenarios (Figure 4-12).

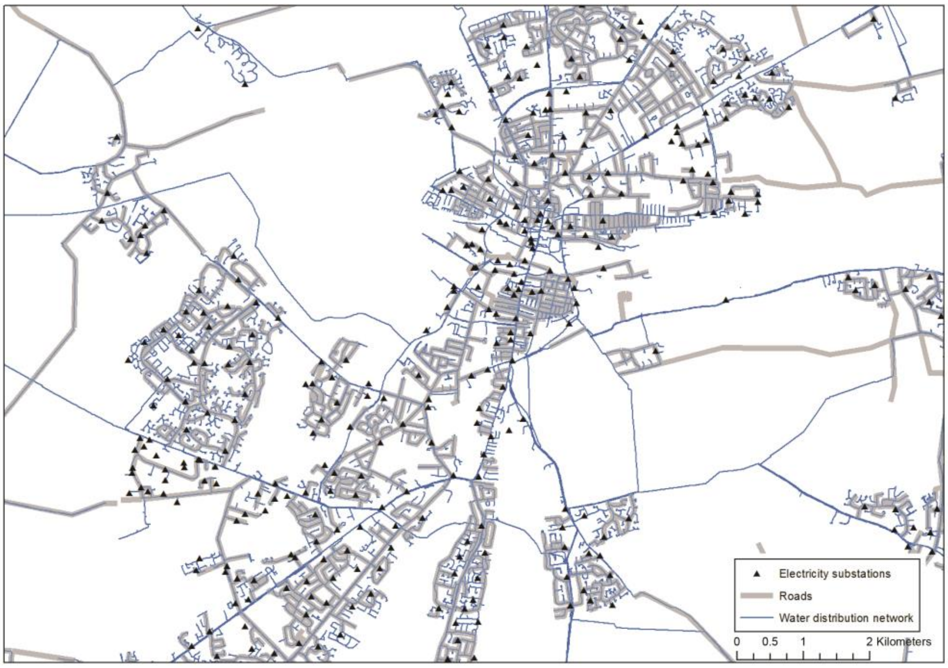


Figure 6-12: Example of co-location of infrastructure assets with road network in a UK city

The increasing use of GIS systems and improved data capturing technologies amongst asset managers is leading to an increased potential and application for geospatial analysis, consideration of infrastructure interconnectivities, and the depiction of impacts arising from cascading failure events. However, further research is needed to harmonise data capture for consistency across all infrastructure networks. This may prove difficult in sectors or organisations where GIS knowledge and understanding is limited.

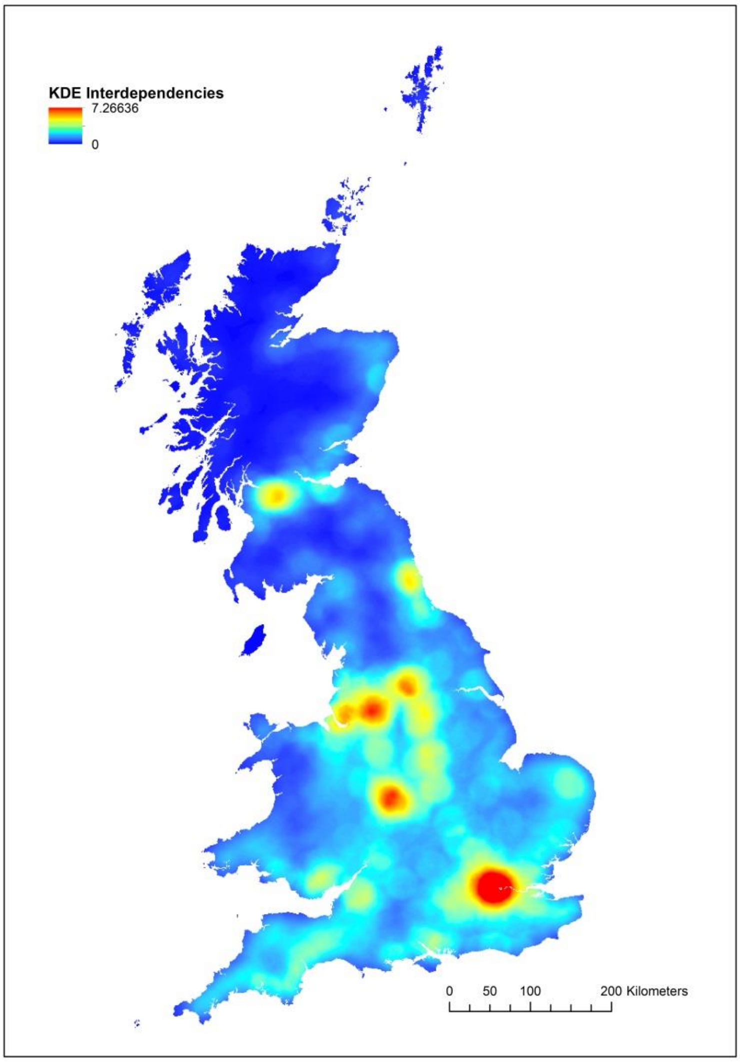


Figure 6-13: Local infrastructure interconnectivity hotspot map derived from kernel density analysis (KDE) of GB local roads

6.5.5.4.2 Example of cascading failure – Northern Gas Networks

An example of a minor failure resulting in widespread disruption in another infrastructure sector was described by Northern Gas Networks in a recent NERC (Natural Environment Research Council) funded workshop (26th February, Cranfield University), that considered the impacts of sand washout events on infrastructure networks. They described how a water main ruptured, which when escaping water mixed with the sandy soil formed an abrasive slurry that was subsequently able to bore a hole through a closely co-located gas pipe (Figure 6-14).

Figure 6-14: Polyethylene gas main damaged by high pressure erosional (sand & water) slurry (Photo: Northern Gas Networks)

A similar event has been detailed by Majid et al. (2010). The sand-washout event here also led to damage of the road surface due to the formation of a cavity. However, more problematic was the water and silt which entered the damaged gas main, which led to loss of gas supply for ~250 customers for 2-7 days as cleaning and repressurisation was undertaken. In a similar event in Sevenoaks in March 2012, some 800 premises were left without gas for several days after a burst water main located in sandy soils bored a huge hole in a proximal co-located gas pipe. Thousands of litres of water had to be pumped from the gas mains. Due to the length of time that the gas supply was interrupted, vulnerable people were supplied with electric heaters and an emergency centre was established at a nearby village hall.

In the cases highlighted here, no climate adaptation measures were apparent in accounting for any such eventuality. Therefore, the framework methodology proposed here could potentially be of significant benefit to a number of infrastructure owners and operators.

6.5.6 Develop Responses/adaptations

It is imperative that society adapts to a changing climate, because even if measures are in place to reduce human-induced climate change, a certain degree is still 'locked in' (Godden & Kung 2011). Long-lived infrastructures, which are the predominant focus of this thesis, are at highest risk of climate change impacts (Giordano 2012). Learning from prior weather and soil-related geohazard impacts on infrastructure, policy-makers as well as utility owners and operators will be provided with knowledge as to how climate change projections will likely affect infrastructure assets in future. Climate projections currently point towards a higher magnitude and frequency of soil-related geohazards in certain areas of the UK (Figure 4-12). This will inevitably lead to increased numbers of asset failures. By evaluating current asset performance, and by implementing probabilistic climate projection-based geohazard models, adaptation measures can be engineered and built in to the respective infrastructure networks in order to try to ensure the climatic-impacted resilience of infrastructure. This would result in subsequent potential impacts arising from cascading infrastructure failures to be reduced. However, more data is required, both on infrastructure assets, including their present condition, material attributes, as well as on previous failures, so as to provide a better picture for informing climate adaptation schemes. As a result, it is likely that further reconsideration of system responses to climate change will be required as this information is made available and is collected. Organisational expertise in the realm of climate risks and adaptation may be lacking however and in such instances specialist expertise might still have to be sought external to the affected stakeholder organisations. It has been argued that many technologies exist for serving infrastructure climate adaptation, one example being the use of flexible pipe material in the sustainable management of water systems. However, it is often socio-institutional barriers which have hindered climate adaptation schemes to date (Godden & Kung 2011; Brown & Farrelly 2009).

Importantly, having prior knowledge of future climate change can allow stakeholders to plan and be informed as to the timing and magnitude of investments (Gersonius et al. 2012). Much as in the case of flood protection, adaptation measures for given specific climatic scenarios may not function well under other circumstances; therefore the appreciation of climate uncertainties and related scenarios becomes important for testing decision-making and policy interventions. Bollinger et al. (2014) argue that adaptation measures should be able to respond to a diverse range of events.

Referring back to Rogers et al's. (2012) concept of local infrastructure, it is argued that adopting a national approach to infrastructure climate adaptation will prove challenging, in comparison to approaching adaptation measures at a local-level and subsequently exploring their expansion to a national context. Throughout this research, it is witnessed that infrastructure owners/operators possess a detailed knowledge of their systems, yet may not have faced issues which other operators have regularly faced or indeed have faced in the past. Corti et al. (2009) identified this as an issue in France, where an extensive drought caused subsidence damage to buildings in areas that had not previously experienced this phenomenon and which therefore inevitably led to damage costs rising above those of flooding for that particular year. Therefore, the challenge is to ensure that knowledge is shared and brokered between a range of stakeholders when considering UKCP09 climate change projections which suggest spatial changes in soil-related geohazards for future scenarios, possibly resulting in previously unexperienced threats to certain areas of the UK, as considered in Chapter 4. This is where local authorities, national government and academia have a greater part to play. Local resilience forums, whereby category 1 responders (i.e. emergency services, National Health Service, Environment Agency and local authorities) alongside utility providers (category 2 responders) share knowledge and best practice on how to deal with possible risks and resulting emergency situations (Cabinet Office, 2013); this inevitably incorporates assessment of potential cascading infrastructure failure scenarios.

6.6 Discussion

In terms of climate adaptation, the ubiquity of the UK's local infrastructure distribution network, particularly in the water sector, means that extensive wholescale renewal of assets and networks is both financially and physically impossible under present funding mechanisms. Moreover, the exhumation of buried infrastructure, referred to as streetworks, can add significant additional impacts on local businesses and economies (ALARM, 2015; LGA, 2012). Utility companies have sought to reduce their impact and disruption on local communities by undertaking no-dig methods for pipe asset replacement and by using existing infrastructure as a conduit for replacement pipes (e.g. using cast-iron gas mains as conduits for polyethylene replacement pipes) (HSE, 2015). What the framework presented offers is a methodology for stakeholders to understand the potential risks arising from soil-related geohazards, both now and within a range of future climate scenarios. These assessments will help prioritisation and targeting of replacement schemes, pending regulatory approval, as well as informing land-use and planning policies.

In the interim, infrastructure asset failures resulting from the impact of soil-related geohazards will continue to occur, with the magnitude and frequency of events increasing in some areas of the UK under the future soil-related geohazard scenarios presented in Chapter 4 (Pritchard et al. 2015a). Alongside these challenges, UK infrastructure faces additionally a range of external pressures, including: aging assets, population/demographic changes, and increases in user demand. In combination, these factors will inevitably increase the fragility of UK local infrastructure, making it more susceptible to even minor, chronic soil-related geohazard events, but which can ultimately lead to network-wide degradation and failure. This is exacerbated by the increasing interconnectivity or systems-of-systems ontology of infrastructure networks, meaning that even minor asset failures (e.g. a burst water main) can lead to significant and high-impact cascading failures (Farewell et al. *In Preparation*). Both the ITRC critical infrastructure hotspot analysis (Figure 6-11), as well as the hotspot analysis of local infrastructure presented here (Figure 6-13) reveals a number of potential interconnectivities in both geographical and technological space which are potentially susceptible to cascading failures resulting from a number of soil-related geohazard processes.

Considering interconnectivity hotspots and the spatial distribution of soil-related geohazards, the south-east of England is likely to become increasingly vulnerable to impacts in future scenarios (Pritchard et al. 2015a). The Office of National Statistics also indicate that this area is projected to have the greatest population increase up to 2022 (Figure 6-15). Clay-related subsidence in this area is particularly prevalent (Blenkinsop et al. 2010; Harrison et al. 2012a; Pritchard et al. 2015a), the result of higher potential soil moisture deficits as depicted by UKCP09 projections combined with a high density of shrink/swell susceptible soils (Pritchard et al. 2015a).

The risk of sand-washout events will also be problematic for a number of areas, especially as buried infrastructure further deteriorates. This chapter has shown that sand-washout events can have significant impacts on secondary infrastructure networks, exacerbated by the often extremely close co-location of multiple infrastructures (Figure 6-9). However, other areas of the UK not having been previously exposed to specific geohazards may become more so in future climate scenarios (see changing clay subsidence risk in Figure 4-12) (Pritchard et al. 2015a). It is therefore imperative that further stakeholder cooperation and discussion is undertaken to share both knowledge and best practices as to how to ensure appropriate climate adaptation. For example, the introduction of standard treatments for road maintenance or water mains pipe renewal could be tested and established in practice in areas particularly affected by climate-related soil geohazard risks.

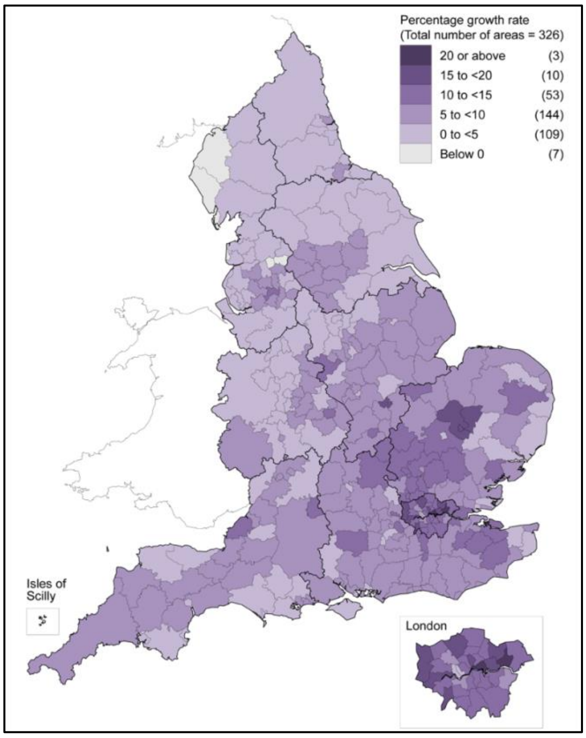


Figure 6-15: Projected population growth rate by local authority, England, mid-2012 to mid-2022 (Source: Office for National Statistics. Contains National Statistics data © Crown copyright and database right 2014. Contains Ordnance Survey data © Crown copyright and database right 2014)

Soil-related geohazards have and will continue to impact on a range of UK local infrastructure networks. For specific areas of the UK, this is likely to become more prevalent, considering the climate projections of UKCP09. Some argue about the validity and use of climate projections, ever striving for better, more detailed outputs. However, Katzav and Parker (2015) make an important point, suggesting that pursuing more accurate predictions will likely mean efforts are delayed towards the reduction of vulnerability of infrastructure in the near term.

There is an increasing recognition that current decisions need to account for climate change projections, and that we cannot afford to wait to make climate-related decisions (Hallegatte 2009; Katzav & Parker 2015). UKCP09 climate projections suggest that the UK's climate will likely lead to the increased frequency and magnitude of soil-related geohazards in certain areas. Climate change projections also suggest a shift in the spatial distribution of some soil-related geohazards. As a result, it is imperative that regions having previously experienced these geohazards are able to share guidance and best practice with those areas becoming affected as conditions change. This could apply both to the UK and internationally. However, in developing countries, the issue of short-term necessity can often outweigh the visions of long-term planning (Chinowsky et al. 2015), but perhaps current asset management strategies in developed countries will show how prudent such visions can be.

One potential approach that could bear promise would be the creation of smart asset management information systems and similar expert system approaches, whereby encapsulating the local-scale expertise of stakeholders in advising the effectiveness of alternative climate adaptation schemes for areas facing similar issues in other regions of the UK. Osman & El-Diraby (2011) developed a knowledge enabled system to aid in the routing of buried urban infrastructure, where soil was considered a significant constraint on constructability and maintainability of the infrastructure asset, such an approach is a likely end-use of the information derived from this research as a whole. This will ultimately help ensure the greatest resilience for the UK network as a whole.

6.7 Conclusion

This chapter has presented a framework (Figure 6-7) providing stakeholders with a robust and tested methodology to assess the impact of a range of soil-related geohazards under the UKCP09 medium emission climate scenarios of 2030 and 2050. It is thought that this framework can subsequently provide a valuable input in the development of asset management strategies, forming a soil-informed climate adaptation strategy, helping to future-proof UK local infrastructure networks to the impact of climate change and soil-related geohazards.

It is argued that to date, chronic, soil-related geohazards have been less considered than those acute hazards such as flooding. Stakeholders and policy makers appear to have lost sight of the long-term impact of processes such as clay-related subsidence, sand-washout and corrosion. This is likely a result of the complex interaction of these processes with prevailing weather and longer-term climate patterns, as compared to the direct and immediate relationship between flooding and rainfall. However, it has been shown through a series of case studies, supported by the author's papers (Pritchard et al. 2014a; Pritchard et al. 2015a) that these soil-related geohazards continue to result in significant disruptions and cascading failure events in UK local infrastructure networks and therefore require more considered attention. There is still some way to go before a complete view regarding the impacts of soil-related geohazards on infrastructure is established, further complicated by the lack of understanding as to the rate at which assets are likely to degrade under future climate scenarios, especially as new technologies emerge. In large part, this is due to most assets being ubiquitous and buried, and therefore out of sight and perhaps also out of mind, until a failure occurs. To investigate the effects of climate change and soil-related geohazards on UK infrastructure in more detail requires further interrogation of infrastructure failure and condition databases (see Appendix G). Furthermore, research is required in assessing the often-complex interactions between infrastructure networks themselves. However, this has often proved problematic due to the quality and availability of failure data resulting from the fact that organisational protocols have led to the incorrect spatial and temporal collection of both asset locations and failure data. Moreover, the adoption of asset management for many sectors is relatively recent, prior to which this data was perhaps simply not collected or was predominantly paper-based and therefore is difficult for internal staff, academia and consultants to quickly assess impacts over long temporal scales.

Despite these challenges, the view expressed in this chapter is that the inherent value of both high-resolution climate projection data and soil-related geohazard assessments will enable these factors to become further embedded within infrastructure network asset management strategies. Furthermore, as scientists understanding of climate increases, the release of improved regional climate projections will become fully apparent. The framework structure presented is such that new climate projections can be readily incorporated. Moreover, the increasing capability of remote-sensing applications, which can provide almost real-time monitoring of geohazard processes and key determinants, such as volumetric assessment of soil moisture levels, is one that is relatively unexplored on a day-to-day operational basis; this may be particularly beneficial for use in developing countries where data is often sparse or lacking.. This could potentially be applied to give utility operators a better idea of where potential failure(s) may occur and therefore undertake proactive maintenance. This could be further refined by assessing asset criticality in terms of triggering cascading failure events.

6.7.1 Recommendations

This section describes the recommendations to decision-makers (i.e. utilities, regulators, local and central government actors), and researchers in industry and academia regarding the adaptation of infrastructure networks to the impacts of soil-related geohazards under climate change scenarios. The framework presented requires implementation and testing across a range of infrastructure sectors.

6.7.1.1 Decision-makers

The recommendations suggested below have been sent out for review by asset managers within the utility companies: Anglian Water Plc., Lincolnshire County Council Highways and Northern Gas Networks. Comments gratefully received have been incorporated into the recommendations herein.

1. **Increase organisational understanding of soil-related geohazard impacts on infrastructure**

A number of studies demonstrate that soil-related geohazards have impacted on infrastructure networks, leading to the failure of particular assets. Importantly, soils are the medium in which most infrastructures are founded and supported. However, organisational knowledge of these geohazards and associated available thematic geohazard maps is highly variable across both infrastructure organisations and sectors. The introduction of knowledge exchange and climate adaptation workshops supported by representatives from both industry and academia may help to level the playing field in this respect. Knowledge of soil-related geohazard impacts as well as their spatial distribution in relation to infrastructure networks can help decision-makers target available investment towards areas at higher risk of infrastructure failure, ensuring more effective investment, as well as more resilient infrastructure.

2. **Increase organisational understanding of climate change projections and their uncertainties**

Downscaled (higher resolution) future climate projections, such as UKCP09 (expected to be updated in 2016), represent a valuable resource for assessing potential climate change impacts to infrastructure assets. Projections arising from a range of scenarios can help inform asset management strategies and climate adaptation options. Such projections can also act as a component of investigatory measures in assessing how engineering decisions are likely to be affected by future patterns and extremes in weather and climate. Decision-makers should be acutely aware that UK climate projections carry inherent uncertainties, which suggest a number of potential eventualities of future climate scenarios are likely. Therefore, when implementing adaptation options, the entire spectrum of scenarios/uncertainties should have been considered in asset management strategies.

3. **The quality of infrastructure asset and failure data is of great importance**

Business procedures and processes within organisations may lead to incorrect spatial and temporal reporting of infrastructure assets and their linkages to recorded failures. This then makes it difficult for employees, consultants and academia to assess properly the impacts of weather and soil-related geohazards on infrastructure networks. Collecting and maintaining appropriate and accurate data is therefore of significant importance. Ultimately, this will ensure that appropriate and proportionate adaptation is undertaken in the light of projected climate change scenarios. Failure data possessing and/or accompanied by accurate spatial and temporal attributes will help enable assessments of the antecedent soil and weather conditions which led to asset failure. Subsequently, this will provide improved assessments of potential future climate change impacts. Furthermore, accurate failure data across the range of infrastructure sectors can also aid the establishment of cascading failure footprints and interconnectivities.

Several respondents also noted that asset standards could play a key role in their susceptibility to climate change and soil-related geohazards. For example, the shallow laying of pipes for cost-saving measures will make them more susceptible to weather-related events and shallow geohazard processes identified in this chapter. Anglian Water provided an example where sustained freezing in Lincolnshire for 2 weeks during 2009/10 at < -10^{o}C was in excess of the -5^{o}C design parameter of the pipe material, leading to a number of issues for customers and service provision (T. Acland, *Pers. Comm.*).

4. Engagement with academia

Active and direct engagement with academia, through research programs, funded research and secondments will lead to greater knowledge exchange diffusing between academia and stakeholders. The benefit of broadening an organisation's knowledgebase will help build in-house recognition of potential climate and soil-related impacts on respective infrastructure networks. Making academic engagement an integral part of the planning process will also lead to issues important to specific stakeholders being recognised and addressed, rather than academia assuming what questions the stakeholder is looking to answer. Organisations will also become exposed to new climate change scenarios, climate impact research and scientific expertise as they develop and emerge over time. Climate adaptation strategies developed through such partnerships will therefore more easily be able to integrate emerging climate models.

5. Sharing best climate adaptation practice

Local knowledge is an important asset in climate change adaptation. However, the UK is becoming more devolved, and to ensure that this knowledge is not kept in isolation, as well as engaging with academia, stakeholders should also engage with each other both within region, and across the UK. Local Resilience Forums, which have developed from the Civil Contingencies Act (2004), offer a suitable medium for discussing best climate adaptation practice, whereby multiple infrastructure operators, local authorities and emergency services can understand specific weather and the climate-related risks that they may face.

Furthermore, climate change projections suggest a shift in the spatial distribution of some soil-related geohazards. As a result, it is imperative that regions that have previously experienced geohazards impacts are enabled to share guidance and best practice with those areas becoming affected as conditions change. One potential approach that could bear promise would be the creation of smart asset management information systems and similar expert system approaches, thereby encapsulating expertise of stakeholders to advise on the effectiveness of alternative climate adaptation schemes for different regions of the UK. This will ultimately help ensure the greatest resilience for the UK network as a whole.

6.7.1.2 Research

The recommendations detailed below are directed at academics and researchers focusing on the climate change adaptation of infrastructures likely to be impacted by soil-related geohazards.

1. **Engagement with decision makers**

   Similar to the recommendation for decision-makers, there is an important need for ensuring that the academic and research community actively engages with decision-makers and stakeholders. This will help ensure their needs and requirements are understood, bringing direct impacts to industry and policy-making; as achieved in the case study presented in Chapter 5.

2. **Promote further research into climate-soil impacts on infrastructure networks**

Further research of links between geohazard processes, climatic change and infrastructure failures is currently lacking. This is predominantly due to data accessibility and accuracy issues with regards to infrastructure asset condition and failures. The relatively recent adoption of GIS in most infrastructure industries has also possibly hampered data collection in the last few decades from which to gain a temporal understanding between weather, soil and their impacts on infrastructure assets. Moreover, policy to date has often neglected these hazards in place of higher-impact, more acute risks (e.g. flooding). However, chronic hazards which are often difficult to quantify and model have had and will continue to have the potential to place significant pressures on the UK's infrastructure networks if not appropriately understood.

3. **Make research accessible**

Outputs of researchers investigating climate adaptation issues should be made accessible for a wide variety of stakeholders who are likely to come from a range of academic and policy backgrounds. A recent study showed that the IPCC Summary for Policymaker reports may have stifled accessibility to a wider audience through low readability (Barkemeyer et al. 2015). Improved readability and understanding will encourage wider uptake of soil-related geohazard information in both asset management planning and policy-making. For example, the research presented in Chapter 5 allowed Lincolnshire County

Council to clearly understand the risks posed to their road network as a result of potential climate change and soil-related geohazards.

7. Synthesis and conclusions

Chapter synopsis

This chapter revisits the aims and objectives of the thesis, and provides a synthesis of how these have been met in order to draw conclusions. The contribution to knowledge of the research undertaken, alongside further avenues of potential research are also identified.

This research was undertaken based upon the realisation that existing soil-related geohazard assessments have to date focused on historic, empirical climate data. Climate change projections however indicate a change to the temporal climatic baseline for the United Kingdom, which supports the theory that climate should no longer be perceived as stationary. The creation of geohazard models, which incorporate climate change projections will therefore contribute to a better understanding of the future spatial soil-related geohazard risks that potentially face UK infrastructure networks for future climate scenarios.

This thesis aimed to address these uncertainties and gaps in knowledge by consideration of the following aim:

To establish the role of soil-related geohazard assessments in maintaining climate-resilient infrastructure

For the remainder of this section, the aim, objectives and hypothese of the thesis are revisited. A summary of whether these objectives and hypotheses have been respectively met and accepted is then provided for the reader.

In order to reach an answer to the aim, a number of objectives were set:

1. *To undertake a critical review of soil geohazard processes which impact upon UK infrastructure.*
2. *To incorporate UKCP09 climate projection data into soil geohazard models.*
3. *To investigate the current failure and degradation of infrastructure networks as a result soil-related geohazards through a series of case studies.*
4. *To conduct case-study based probabilistic failure analysis for infrastructure assets resulting from future modelled geohazard scenarios.*
5. *To establish the impact of soils on national infrastructure fragility.*
6. *To develop a national framework methodology to mitigate the impacts of soil-related geohazards on UK infrastructure.*

6.8 Research objectives compared with research achievements

This section presents the realisation of the research aim and the conclusions drawn from the research objectives examined.

6.8.1 Objective 1

'To undertake a critical review of soil geohazard processes which impact upon UK infrastructure'

A critical review of the available literature was undertaken in Chapter 2 to investigate the impact of soil-related geohazards on UK infrastructure networks. Furthermore, Chapter 3 investigated the applications of geohazard assessments to date, understanding further the origins of soil survey information and its use in creating thematic geohazard maps.

The following conclusions were made during the undertaking of this objective:

- There is limited literature on the impact of climate change on soil-related geohazard processes and subsequently infrastructure networks.
- To date, there has been no national-scale quantitative assessment of the impact of climate change projections on soil-related geohazard processes.
- Awareness of soil-related geohazard impacts to infrastructure operators and policy makers is fragmented.
- The emergence of geographical information systems (GIS) and geoinformatics has enabled combination of complex soil data with other environmental data to produce easily understandable thematic geohazard mapping products.
- Current asset management inspection regimes have an apparent inability to detect deterioration not yet visible; this is more prolific with chronic soil-related geohazards.
- A methodological framework which provides practitioners and policy-makers with best practice guidance regarding the risk management of soil-related geohazards is currently lacking for the UK.

6.8.2 Objective 2

'To incorporate UKCP09 climate projection data into soil geohazard models to assess future spatial hazard distribution'

Chapter 4, based upon a publication in *Climatic Change* (Pritchard et al. 2015a), describes the methodology and results of producing high-resolution, UKCP09-derived projections of rainfall and evapotranspiration in order to calculate potential soil moisture deficit. This was subsequently incorporated into a soil-related geohazard model.

The following conclusions were drawn from the novel, soil moisture modelling and subsequent clay-related subsidence mapping:

- Calculated soil moisture deficits, derived from UK climate projections suggest a shift away from the current empirically-derived climatic baseline (1961-1990) (Figure 4-4).
- Modelled weather variables indicate that soil moisture levels are likely to decrease, particularly in summer months, for large areas of Great Britain.
- In contrast, upland areas of Wales, England and Scotland are likely to exhibit similar PSMD patterns to the present day.
- Areas of south-east England, due to higher PSMDs and abundance of susceptible clay soils are likely to see increases in clay-related subsidence risk through to 2050.
- Users should be aware that climate and geohazard spatial projections have a range of uncertainties, and these should be considered when making adaptation decisions.

- There is potential benefit from these projections of both soil moisture deficits and soil-related geohazards to many sectors including: finance, central and local government, residential property markets, utilities and infrastructure operators.

6.8.3 Objective 3

'To investigate the current failure and degradation of infrastructure networks, as well as future failure probability as a result of soil-related geohazards through a case study analysis'

This objective has been approached in Chapter 5, which specifically considers the impact of soil-related geohazards on a local authority road network. From this assessment the following conclusions were drawn:

- Climate change projections indicate that UK's local roads are likely to suffer further deterioration from a range of soil-related geohazards in future scenarios.
- Development of a soil-informed maintenance strategy for the asset management of UK local roads.
- Greater cooperation is required between highways engineers and engineering geologists, geomorphologists and soil scientists to understand the environmental and climate impacts on road surfaces.
- Road condition data is currently collected at a temporal resolution unsuitable for understanding the specific inter-annual implications of soil moisture loss and clay-related subsidence and infrastructure.

- Road condition data which can be used by third parties, such as academia and consultants, is often problematic to analyse alongside climatic data due to long temporal gaps between subsequent surveys as well as the relatively recent adoption of GIS in local authorities. Recommendations are to increase the temporal nature of surveys, and to ensure consistency between operators so that interdependent impacts can be investigated.

6.8.4 Objective 4

'To establish the impact of soils on national infrastructure fragility'

From review of the literature in Chapter 2 and 3, alongside the case study provided in Chapter 5 the following conclusions are drawn:

- Soil-related geohazards have and continue to have an impact on infrastructure networks and assets
- A number of soil-related geohazard processes cause deterioration, increasing asset fragility and ultimately causing failure of particular assets.
- Due to increasing infrastructure fragility, even minor, soil-related geohazard events can result in multi-infrastructure cascading failures.
- Aging UK infrastructure, as well as increasing population growth will put mounting pressure and add to the fragility of infrastructure assets. This will in turn increase the susceptibility of infrastructure assets to soil-related geohazards.

- However, more research is required to understand and quantify the true scale of impact of soil-related geohazards under UKCP09 projections.

6.8.5 Objective 5

'To develop a national framework methodology to mitigate the impacts of soil-related geohazards on UK infrastructure'

Chapter 6 presented a framework that supports Defra's aim of achieving a climate resilient UK infrastructure network. It incorporated the modelling of soil-related geohazards from Chapter 4 and built upon the findings of the case-study discussed in Chapter 5. The following conclusions have been made during the undertaking of this objective:

- UK planning policy currently appears fragmented in the way it approaches climate change and geohazards impacts and adaptation in respect of infrastructure.
- Policy attention has to date been drawn to acute, high impact events (e.g. flooding). However, chronic events such as soil-related geohazards can have significant, cascading impacts on UK infrastructure assets and networks.
- A certain amount of climate change is inevitable and 'locked-in', therefore, adaptation requires immediate implementation.
- A framework has been presented which will aid stakeholders and decision-makers in adapting infrastructure networks to the potential impacts of soil-related geohazards under a changing climate.

- It is more appropriate to consider climate change adaptation at the local/regional scale and then scale up to national level; often expertise of climate change issues lies in locally derived expertise.
- Further research is required regarding the understanding of the secondary effects of soil-related geohazard on infrastructure interconnectivities and cascading failures.
- Recommendations for stakeholders and academia have been presented, facilitating potential future research streams (see Section 7.3).

6.9 Hypotheses testing

Two hypotheses were proposed at the beginning of this thesis (Section 1.3.2). In this section, these hypotheses are revisited and the thesis findings are used to decide whether to accept or reject the hypothesis.

6.9.1 Hypothesis 1

'UK infrastructure networks are currently susceptible to the perils of soil-related geohazards'

A literature review (Chapter 2) argued that soil-related geohazards have had an impact on UK infrastructure networks to date. A number of studies were shown to have undertaken assessment of the impacts of soil-related geohazards on predominantly buried infrastructure networks, especially pipelines. Several case studies were also presented in Chapter 6, which further argue that UK infrastructure networks are at present susceptible to soil-related geohazards.The ubiquitous network of distribution infrastructure including, buried pipes, local roads and shallow founded structures (e.g. electricity substations, telephone exchanges and pumping stations) appear to be at highest risk of the hazards as identified in Table 2-1.

This thesis undertook a detailed case study (Chapter 5) of the impacts of clay-related subsidence on Great Britain's local road infrastructure, both at the national-scale (Figure 5-1) and as a regional case study comprising the county of Lincolnshire. This analysis showed that particularly in the south-east of England, there are significant parts of the minor road network which are at ‘High’ to ‘Extremely High’ risk of clay-related subsidence at the current baseline climate (i.e. 1961-1990). Analysis of Lincolnshire road condition data supported this by demonstrating that a relationship between poor road condition and the spatial occurrence of the highest three classes of clay subsidence risk exists.

Overall, the thesis findings argue that this hypothesis can be accepted. However, more research is required into the long-term deterioration effects that soil-related geohazards have on specific networks and materials. Moreover, due to the temporal recording of road condition, it is currently not possible to understand particular seasonal effects of soil on road condition. Therefore, higher spatial and temporal resolution asset data is required for more informed analysis. Experience also indicates that this is the case for a number of other infrastructure sectors (Farewell et al. In Preparation).

6.9.2 Hypothesis 2

'Climate change will likely increase the impact of these soil-related geohazards on UK infrastructure'

The spatial distribution of soil-related geohazards is driven by both soil properties and climate, as discussed in Chapters 2 and 3. Soil geohazard models have historically incorporated potential soil moisture deficit, derived from historic baselines (Figure 3-3) as a means to assess the potential likelihood for clay-related subsidence to occur. Previous laboratory testing on particular soils physical shrinkage and swelling responses to changing soil moisture have validated these empirical models.

The PSMD modelling presented in Chapter 4 incorporated projections of precipitation and potential evapotranspiration, derived from a version of the

UKCP09 weather generator, for timeslices of 2030 (2020-2049) and 2050 (2030-2069). This analysis showed that an increase in the average annual PSMD for certain areas of the UK, particularly the south-east of England, is likely going forward. However, further analysis (Figure 4-11) demonstrated that the climate change response will not be equal across GB. Moreover, it appears that the biggest magnitude of change will occur between the baseline and 2030, with the mean and extremes of PSMD, and consequently clay-related subsidence risk, increasing significantly for some areas (Figure 4-11). Changes between 2030 and 2050 in terms of climate are not as stark, and in some areas PSMD reaches a limit by 2030 which means that an increase in clay subsidence risk will not be apparent (Figure 4-16 and Figure 4-17).

Ultimately, this means that these changes are occurring now, and that infrastructure owners and operators should already be establishing the risks of soil-related geohazards to their networks, if not doing so already. As such, the framework presented in Chapter 6 would help towards preparation of such a risk assessment (Figure 6-7).

The hypothesis presented can therefore be accepted, but the reader should be aware of this non-uniform response in terms of how soils throughout the UK will react to potential climate change. There will therefore, be certain 'hotspot' areas of increased likelihood of soil-related geohazards (Figure 4-12), which may also be of a higher magnitude than that witnessed previously. This will undoubtedly result in further infrastructure failures, considering a static maintenance programme, and combined with an increasingly aging UK infrastructure.

6.10 Contribution to knowledge

A summary of the principal novel aspects of this thesis are stated in the following points:

- From undertaking a literature review, this thesis found that forward-looking approaches as a means to assess UK infrastructures vulnerability to soil-related geohazards are currently lacking. Furthermore, a suitable methodology for both policy and practice is required.
- Creation of a novel assessment of clay-related subsidence hazard which incorporates high-resolution UKCP09 climate projections for the entirety of Great Britain.
- The creation of a risk assessment methodology for assessing the impact of geohazards on UK local roads both now and in future climate scenarios. The methodology was tested on the local road network of Lincolnshire, having now been implemented into their asset management plan. This also has applicability for all UK local authorities.
- Development of a framework methodology, for both policy and practice, which outlines areas of potential vulnerability in UK infrastructure networks as a result of soil-related geohazards under a changing climate.

6.11 Concluding remarks

This thesis has analysed a single soil-related geohazard (clay subsidence) and how this may be affected if climate change projections derived from UKCP09 are realised (see Chapter 4). Subsequently, the impacts of clay subsidence on the highways infrastructure of GB has been analysed for the present day and extrapolated into the future (i.e. baseline, 2030 and 2050) (see Chapter 5). Chapter 6 of this thesis then presented a methodology for how such analysis could be applied for multiple soil-related geohazards over a range of infrastructure sectors.

Analysis has demonstrated that the climate change response will not be uniform, in terms of PSMD values, across the UK. Furthermore, the biggest change in PSMD and consequently clay subsidence risk will occur between the UKCP09 baseline (1961-1990) and 2030 (2020-2049) scenarios. Although PSMD is likely to increase between 2030 and 2050, particularly in the south-east of England, this will not be at the same magnitude. As a result, it is imperative that infrastructure operators and owners, as well as policy makers and academia recognise that measures need to be taken now to ensure that infrastructure networks are resilient to the effects of clay subsidence hazard. This thesis has presented a usable framework for infrastructure operators and asset managers to assess the risk of a range of soil-related geohazards to their respective networks. These soil-informed maintenance strategies are however, only one potential mechanism for ensuring the climate resilience of UK infrastructure which can be incorporated into a wider asset management planning policy.

6.12 Future work

Upon completion of this research project into the use of soil-related geohazard assessments for a climate resilient UK infrastructure, several aspects have been identified as avenues for future work.

Exploring the full range of UKCP09 scenarios for geohazard modelling

For this research, only the medium emissions scenario, equivalent to the IPCC's SRES A1B scenario was applied on a national scale in geohazard modelling due to both time constraints and large data sizes. Exploration of the high and low emissions scenarios was undertaken for the county of Worcestershire, which found only subtle changes in clay subsidence hazard across all three scenarios. It would be beneficial to undertake, in particular the high emissions scenario processing of soil moisture deficits for the entirety of GB as this may reveal further areas at potential risk of soil-related geohazards in future.

The effect of probabilistic soil moisture on clay soils

In this thesis, the effect of modelled PSMD on clay subsidence hazard has been considered, which is based on the extrapolation of previously undertaken laboratory data. However, the exact behaviour of clays under PSMD's which are projected to be several orders of magnitudes higher than the present day, have not been physically examined. Moreover, the effect of topography, soil hydrology and land-use in relation to specific shrink-swell soils has not been assessed in the model to date due to its national-scale. Therefore, more regional analyses of these environmental effects on geohazard risk would be beneficial.

The effect of climate and soil moisture deficit at pipe level

The geohazard models presented in this thesis (e.g. Chapter 4) are based on the characteristics of soils at approximately 1-1.5 m below ground level. However, sealed surfaces, large vegetation and the characteristics of the pipe itself could all lend themselves to affect the actual soil moisture deficit at pipe-level or under road foundations for instance. A previous study by Burton (2001) examined the soil structure and moisture levels near to Thames Water distribution mains in North London, which provided more in-depth knowledge regarding the soil-climate interactions with the pipe network; it is proposed that a similar such study be conducted over a range of geographical and climatologically differing areas.

Impact of high water demand vegetation of clay subsidence hazard

It is known that high water demand trees result in the additional loss of soil moisture. However, the impacts of trees have predominantly been recorded on an extremely local scale, more often on a tree-by-tree analysis. The recent release of the National Tree Map™ depicting the spatial location of every tree three metres and above in height over England and Wales will enable an assessment of the impact of trees in exacerbating clay-subsidence hazard. Supported by in-situ measurements and remote sensing (Section 7.3.4) this could provide a valuable assessment of risk posed by trees to buried or shallow-founded infrastructure networks at regional level. Moreover, how trees are likely to impact both directly (i.e. via tree roots) and indirectly (i.e. by removing soil water) on infrastructure assets and networks can be modelled and assessed.

Near real-time monitoring of soil moisture change and geohazard risk

The increasing capability of remote sensing platforms for both the estimation of soil moisture levels and ground displacement can prove a valuable tool in understanding, in almost real-time, soil-related geohazard risks to infrastructure networks. Currently, soil moisture estimates in the UK are provided by the Met Office's MORECS system, which is provided at a 40km grid resolution and therefore is perhaps unsuitable for understanding local-scale risks and events. Remote sensing, alongside empirical testing identified as a research need in Sections 7.3.1 and 7.3.2, could provide a higher resolution approach in the risk assessment of assets susceptible to soil-related geohazards. For example, infrastructure operators could identify areas at particular risk during drought periods, and where specifically to target maintenance/replacement or risk-assess possible asset failure. This could prove particularly beneficial for replacement of the cast-iron gas mains infrastructure network, which poses significant secondary risks to life in the event of failure (e.g. fire and explosion).

The linking of shallow geohazard processes with deeper geological hazards

A recent spate of sinkholes and dissolution features throughout the UK, during the 2014-15 period, prompts an assessment of how shallow geohazard processes, such as those identified in this thesis, could contribute to asset failure which in turn could lead to the triggering of deeper geological processes. For example, the rupture of a water main, caused by corrosion due to the pipe being buried in an aggressive soil could lead to a prolonged leak, or rapid escape of water which could result in dissolution of chalk bedrock, leading to sinkhole formation and collapse of the ground surface.

Local-scale infrastructure interconnectivity analysis

To date, assessment of infrastructure interconnections have predominantly been undertaken at national-scale, and concern only the most critical pieces of infrastructure. In particular, the ITRC hotspot analysis focused upon the main electricity, road, rail and gas networks, as this was the remit of Infrastructure UK. However, more regional infrastructure owners and operators as well as those local authorities dealing with local issues are more interested in the interconnectivity of the local infrastructure networks defined in Chapter 6 of this thesis. Research is needed to further understand these local interconnections, scaling-down the previous ITRC research, and building upon the coarse analysis undertaken in Chapter 6 (e.g. Figure 6-13).

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APPENDICES

Appendix A Data Formats of UKCP09-derived weather generator projections and post-processing

This Appendix provides examples of the various data files provided and created in the modelling activities described in Chapter 4, and using the Perl Scripts in Appendix B and C. Data is currently stored at Cranfield University, with options being sought to make data more accessible to potential users. However, users can seek raw weather generator data from the UKCP09 website (see: http://ukclimateprojections.metoffice.gov.uk/23261).

The sequence of processing the datasets is outlined in Figure A-1. Three key scripts were used, thus:

Perl script: 'ITRC.pl'

This Perl script was used to process the raw text 'txt' files output by the weather generator, creating the 'Comma Separated Value' CSV files for each determinant (e.g. Accumulated SMD).

Thus source file '5200125_cntr.txt' is processed to create files

5200125_cntr_pet_output.csv

5200125_cntr_accsms_output.csv

5200125_cntr_accsmd_output.csv

5200125_cntr_sms_output.csv

5200125_cntr_smd_output.csv

5200125_cntr_rain_output.csv

Perl script: 'ITRC_Statistics.pl'

This Perl script takes these cell by cell outputs and creates a single statistics file

Thus files are created:

5200125_cntr_accsmd_output.csv

5200150_cntr_accsmd_output.csv etc...

Batch file: 'BatchRun_ITRC_Statistics.bat'

This is a MS Windows 'Batch' file that can be used to help automate the process of running the Perl scripts above.

Batch file: 'merge_statistics.bat'

The number of grids are too numerous to run in one go, so a country was split into a series of sub-regional runs. Once all the separate run statistic files are created, then as long as the source data files are in the prescribed folder structure below, the batch file can be used to merge the results into one file suitable for subsequent use in GIS etc.

```
|
 \ Results_Run1  (each results folder contains the set of
grid cells exported
          in form: 'Run6_Export_Output.csv')
     |
     \ Control  (each end folder contains the source txt
files, all processed csv
          file and final statistics file)
     \ 2030  (statistics file name follows form:
'Run6_Statistics_accsmd_2050.csv')
     \ 2050
 \ Results_Run2
     | etc...
```

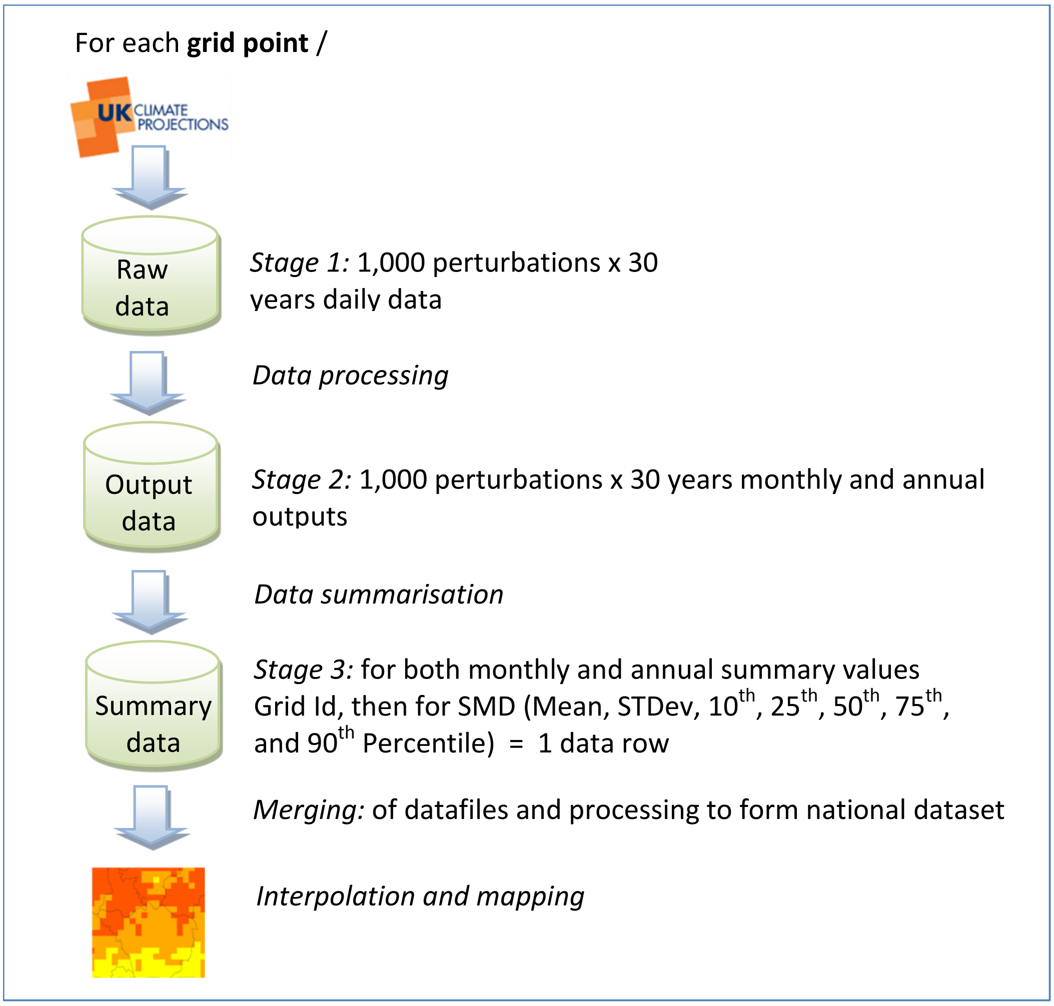


Figure A-1: The data processing workflow used for manipulating the UKCP09 data files

Table A-1 shows the raw data format output by the weather generator. These files were substantial in size. For the 1,000 runs of 30 year data for the climate future scenarios, the files were c. 1.2Gb in size, for the Control files of 100 runs of 30 year data the files were 120Mb in size. Combining output data for each of the 10,398 5km^2 cells representing the land mass of England, Wales and Scotland, the total file size approximated 12.5 Tb.

```
3001  01  01    1   1     0.00     0.43     5.05     6.69     0.90
0.74     4.95     0.52     0.52     0.00
3001  01  02    2   5     0.00     2.00     7.01     8.41     1.00
5.14     0.32     0.46     0.04     0.04
3001  01  03    3   3     4.40     0.81    11.06     7.92     0.85
5.06     0.75     0.49     0.06     0.69
3001  01  04    4   2     3.20     3.84     7.67     9.18     1.00
8.84     0.90     0.51     0.07     0.08
3001  01  05    5   2     1.20     0.44     8.35     8.35     1.00
10.15     0.60     0.49     0.05     0.24
3001  01  06    6   2     5.10     0.85    10.35     9.08     1.00
11.56     2.49     0.57     0.21     0.20
3001  01  07    7   2     5.80     3.78     8.51     8.68     0.92
10.99     0.74     0.51     0.06     0.50
…
```

Table A-1: Raw data table output by the weather generator

Scripts were written in the Perl programming language to process these substantive files for each of the parameters required, calculating monthly sum values as well as an annual value. Processed control files were c.300Kb each, processed scenario files c. 3Mb each, Table A-2.

```
Perturbation, Year, Jan_AccSMD,  Feb_AccSMD,  Mar_AccSMD,  Apr_AccSMD,
May_AccSMD,  Jun_AccSMD,  Jul_AccSMD,  Aug_AccSMD,  Sep_AccSMD,
Oct_AccSMD,  Nov_AccSMD,  Dec_AccSMD, Year_AccSMD
1, 3001, 0.00, 0.00, 0.00, 0.00, 27.22, 87.53, 148.01, 115.58, 59.49,
0.00, 0.00, 0.00, 148.01
1, 3002, 0.00, 0.00, 0.00, 0.00, 47.72, 70.40, 24.60, 0.00, 0.00,
0.00, 0.00, 0.00, 70.40
1, 3003, 0.00, 0.00, 0.00, 0.00, 11.58, 29.43, 0.00, 9.14, 0.00, 0.00,
0.00, 0.00, 29.43
1, 3004, 0.00, 0.00, 0.00, 8.65, 0.00, 0.00, 1.30, 0.00, 0.00, 0.00,
0.00, 0.00, 8.65
```

Table A-2: Processed data

A further script was then written, also in Perl to process these specific determinant files into an aggregate summary file suitable for inclusion in a modelling application. Each processed output file was c.90Kb, Table A-3.

```
Grid, Source, Jan_Mean, Jan_StDev, Jan_P10, Jan_P25, Jan_P50, Jan_P75,
Jan_P90, Feb_Mean, Feb_StDev, Feb_P10, Feb_P25, Feb_P50, Feb_P75,
Feb_P90, Mar_Mean, Mar_StDev, Mar_P10, Mar_P25, Mar_P50, Mar_P75,
Mar_P90, Apr_Mean, Apr_StDev, Apr_P10, Apr_P25, Apr_P50, Apr_P75,
Apr_P90, May_Mean, May_StDev, May_P10, May_P25, May_P50, May_P75,
May_P90, Jun_Mean, Jun_StDev, Jun_P10, Jun_P25, Jun_P50, Jun_P75,
Jun_P90, Jul_Mean, Jul_StDev, Jul_P10, Jul_P25, Jul_P50, Jul_P75,
Jul_P90, Aug_Mean, Aug_StDev, Aug_P10, Aug_P25, Aug_P50, Aug_P75,
Aug_P90, Sep_Mean, Sep_StDev, Sep_P10, Sep_P25, Sep_P50, Sep_P75,
Sep_P90, Oct_Mean, Oct_StDev, Oct_P10, Oct_P25, Oct_P50, Oct_P75,
Oct_P90, Nov_Mean, Nov_StDev, Nov_P10, Nov_P25, Nov_P50, Nov_P75,
Nov_P90, Dec_Mean, Dec_StDev, Dec_P10, Dec_P25, Dec_P50, Dec_P75,
Dec_P90, Annual_Mean, Annual_StDev, Annual_P10, Annual_P25,
Annual_P50, Annual_P75, Annual_P90
2950230, 2950230_50s_scen_rain_output, 210.92, 87.06, 108.40, 150.10,
201.40, 260.40, 324.60, 149.21, 67.25, 69.30, 101.70, 142.10, 188.90,
238.30, 126.58, 56.30, 59.40, 86.20, 120.90, 160.30, 201.20, 100.33,
47.53, 43.40, 66.30, 95.60, 129.20, 163.00, 85.53, 41.00, 37.50,
56.80, 80.80, 109.00, 139.10, 68.95, 42.35, 21.10, 38.80, 62.40,
91.50, 124.00, 64.14, 43.91, 16.80, 32.40, 55.80, 85.90, 120.80,
73.49, 48.70, 21.60, 38.80, 64.00, 97.80, 137.20, 122.00, 64.60,
47.60, 75.50, 114.30, 158.80, 206.40, 166.84, 78.15, 75.00, 111.10,
157.50, 212.30, 271.20, 192.29, 74.13, 105.40, 139.90, 183.90, 235.00,
290.30, 228.73, 94.09, 115.60, 162.20, 219.40, 284.50, 353.70,
1589.01, 227.83, 1304.10, 1431.50, 1580.50, 1735.50, 1886.00
2950235, 2950235_50s_scen_rain_output, 172.42, 71.22, 88.60, 122.40,
164.40, 213.30, 265.40, 124.22, 56.00, 57.60, 84.70, 118.40, 157.20,
198.00, 106.06, 47.11, 49.80, 72.20, 101.30, 134.40, 168.30, 87.21,
41.35, 37.60, 57.70, 83.10, 112.10, 141.60, 71.92, 34.54, 31.60,
47.50, 67.90, 91.90, 116.90, 60.61, 37.24, 18.50, 34.20, 54.90, 80.50,
108.80, 58.34, 39.94, 15.20, 29.50, 50.80, 78.10, 110.10, 64.36,
42.71, 18.80, 33.90, 56.10, 85.80, 119.80, 104.90, 55.56, 41.20,
65.20, 97.90, 136.30, 177.60, 142.61, 66.86, 64.30, 95.00, 134.30,
181.60, 231.90, 164.12, 63.33, 90.10, 119.50, 157.10, 200.40, 247.50,
193.29, 79.34, 98.00, 136.90, 185.50, 240.80, 298.70, 1350.05, 193.54,
1107.80, 1217.40, 1342.10, 1475.30, 1602.20
```

Table A-3: Final data summary file

This file contained percentiles (10, 25, 50, 75, 90) for each month, as well as a mean and Standard Deviation value. The same was also provided as an annual calculation.

Appendix B Perl code for processing UKCP09 weather generator data

The Perl code detailed below is used to process the raw data produced by the UKCP09 generator (ITRC.pl as discussed in Appendix A). It strips out the unwanted climate variables, and retains rainfall and potential evapotranspiration (PET). Daily data provided by the weather generator is summarised to monthly and annual values. Soil moisture deficit (SMD) and soil moisture surplus (SMS) are calculated at the same temporal scale using outputted rainfall and PET variables. Results are outputted as a series of csv files.

```
#!/usr/local/bin/perl

#####
# ITRC
# Dr Stephen Hallett, Cranfield University; Oliver Pritchard, Cranfield
University
# 15/08/14
#
# Call as 'perl itrc.pl *.txt'  (where *.txt, or filelist, are the input
climate files to process)
#
# Processes input Newcastle UKCP09 datasets to produce PSMD output for ITRC
project points
#
###
use warnings;
use strict;
# with ActivePerl these are installed via ppm if not already present
use List::Util qw(min max);
BEGIN {@ARGV=map glob, @ARGV} # expand wildcard file arguments

######################################
#### Don't edit below here
our %months = ("Jan", 1, "Feb", 2, "Mar", 3, "Apr", 4, "May", 5, "Jun", 6,
"Jul", 7, "Aug", 8, "Sep", 9, "Oct", 10, "Nov", 11, "Dec", 12);
our $firsttime;

# Note:
# SMD = Soil Moisture Deficit
# SMS = Soil Moisture Surplus, summed from Oct-Mar. This is excess winter
rainfall, important e.g. for flooding.
our %results = ("Jan_Rain", 0, "Jan_PET", 0, "Jan_Rain-PET", 0, "Jan_SMD", 0,
"Jan_SMS", 0, "Jan_AccSMD", 0, "Jan_AccSMS", 0,
"Feb_Rain", 0, "Feb_PET", 0, "Feb_Rain-PET", 0, "Feb_SMD", 0, "Feb_SMS", 0,
"Feb_AccSMD", 0, "Feb_AccSMS", 0,
"Mar_Rain", 0, "Mar_PET", 0, "Mar_Rain-PET", 0, "Mar_SMD", 0, "Mar_SMS", 0,
"Mar_AccSMD", 0, "Mar_AccSMS", 0,
"Apr_Rain", 0, "Apr_PET", 0, "Apr_Rain-PET", 0, "Apr_SMD", 0, "Apr_SMS", 0,
"Apr_AccSMD", 0, "Apr_AccSMS", 0,
```

```
"May_Rain", 0, "May_PET", 0, "May_Rain-PET", 0, "May_SMD", 0, "May_SMS", 0,
"May_AccSMD", 0, "May_AccSMS", 0,
"Jun_Rain", 0, "Jun_PET", 0, "Jun_Rain-PET", 0, "Jun_SMD", 0, "Jun_SMS", 0,
"Jun_AccSMD", 0, "Jun_AccSMS", 0,
"Jul_Rain", 0, "Jul_PET", 0, "Jul_Rain-PET", 0, "Jul_SMD", 0, "Jul_SMS", 0,
"Jul_AccSMD", 0, "Jul_AccSMS", 0,
"Aug_Rain", 0, "Aug_PET", 0, "Aug_Rain-PET", 0, "Aug_SMD", 0, "Aug_SMS", 0,
"Aug_AccSMD", 0, "Aug_AccSMS", 0,
"Sep_Rain", 0, "Sep_PET", 0, "Sep_Rain-PET", 0, "Sep_SMD", 0, "Sep_SMS", 0,
"Sep_AccSMD", 0, "Sep_AccSMS", 0,
"Oct_Rain", 0, "Oct_PET", 0, "Oct_Rain-PET", 0, "Oct_SMD", 0, "Oct_SMS", 0,
"Oct_AccSMD", 0, "Oct_AccSMS", 0,
"Nov_Rain", 0, "Nov_PET", 0, "Nov_Rain-PET", 0, "Nov_SMD", 0, "Nov_SMS", 0,
"Nov_AccSMD", 0, "Nov_AccSMS", 0,
"Dec_Rain", 0, "Dec_PET", 0, "Dec_Rain-PET", 0, "Dec_SMD", 0, "Dec_SMS", 0,
"Dec_AccSMD", 0, "Dec_AccSMS", 0,
"Year_Rain", 0, "Year_PET", 0, "Year_AccSMD", 0, "Year_AccSMS", 0);

###############################################

print "\nFor the ",$#ARGV + 1," files passed in:\n\n********\n";
foreach (@ARGV) {
    $firsttime = 1; # manages header output to each file
    &main($_); # call main with each successive input datafile in turn
}

# Called Functions ##########################

####################
# Function main
###
sub main {
    my ($basename)=$_;
    $basename =~ s/(.+)\.[^.]+$/$1/; # strip off all after the file extension
    print "File: ",$_, " stripped to: ", $basename,"\n";

    our %data1 = (#"in_file",   $basename . ".txt",
    "in_file",   $_,
    "rain_file", $basename . "_rain_output.csv",
    "pet_file",  $basename . "_pet_output.csv",
    "smd_file",  $basename . "_smd_output.csv",
    "sms_file",  $basename . "_sms_output.csv",
    "accsmd_file",  $basename . "_accsmd_output.csv",
    "accsms_file",  $basename . "_accsms_output.csv");

      # "out_file",  $basename . "_summaryoutput.htm",

    print "... please wait .. initialising\n";
    my ($perturbation, $totalrows, $yearcounter); # Initialise counter for No.
objects
    $perturbation = 1;
    $totalrows = 0;
    $yearcounter = 0;
    my ($Year, $Month, $Day); # Initialise year variables
    $Year = 0;
    $Month = 0;
    $Day = 0;
    local $\ = "\r\n"; # EOL character for Windows file
    print "... preparing for run with input file '", $data1{"in_file"}, "'";

    # Files: open input and output files, name and handle set from %data(n)
    open(INFILE, '<', $data1{"in_file"}) || die sprintf("Oops - Could not open
%s", $data1{"in_file"});
    # open(OUTFILE,sprintf(">%s",$data1{"out_file"})) || die sprintf("Oops -
Could not open %s", $data1{"out_file"});
```

```
    open(OUTFILE_RAIN,sprintf(">%s",$data1{"rain_file"})) || die sprintf("Oops
- Could not open %s", $data1{"rain_file"});
    open(OUTFILE_PET,sprintf(">%s",$data1{"pet_file"})) || die sprintf("Oops -
Could not open %s", $data1{"pet_file"});
    open(OUTFILE_SMD,sprintf(">%s",$data1{"smd_file"})) || die sprintf("Oops -
Could not open %s", $data1{"smd_file"});
    open(OUTFILE_SMS,sprintf(">%s",$data1{"sms_file"})) || die sprintf("Oops -
Could not open %s", $data1{"sms_file"});
    open(OUTFILE_ACCSMD,sprintf(">%s",$data1{"accsmd_file"})) || die
sprintf("Oops - Could not open %s", $data1{"accsmd_file"});
    open(OUTFILE_ACCSMS,sprintf(">%s",$data1{"accsms_file"})) || die
sprintf("Oops - Could not open %s", $data1{"accsms_file"});

    &zeroresults();
    # Analysis
    #&header; # Construct header
    # Main loop
    print "... please wait .. processing";

    while (my $line = <INFILE>) {
        chomp $line;
        my @fields = split " " , $line;
        if ($Year != $fields[0] && $totalrows != 0) { # Starting into a new
year, so now do last year's sums
            &setyearstats();
            &writestats($perturbation, $Year);
            #print "Perturbation: ", $perturbation, ", Year: ", $Year, "
[having ", $yearcounter, " days] : ", $totalrows, " rows so far \n";
            # 365 (year days) x 30 (span of years) x 100 (perturbation
scenarios) = 10,950,00. Note data file has 10,957,00 lines (wc -l) (actually
there is a final blank line too = 10,957,01)
            # Add in 7 leap days over the 30 years: ((365 x 30) + 7) = 10957 x
1000 = 10,957,00
            if ($totalrows % 10957 == 0) { # Starting into each new
perturbation of 365 x 30 days.
                $perturbation++;
                #print "\n";
            }
            &zeroresults();
            $yearcounter=0; # Re-initialise counter
        }

        # Load in raw data
        if ($Month == $months{"Jan"}) {
            $results{"Jan_Rain"} += $fields[5]; #Rain
            $results{"Jan_PET"}  += $fields[14]; #PET
            } elsif ($Month == $months{"Feb"}) { # including leap days
            $results{"Feb_Rain"} += $fields[5]; #Rain
            $results{"Feb_PET"}  += $fields[14]; #PET
            } elsif ($Month == $months{"Mar"}) {
            $results{"Mar_Rain"} += $fields[5]; #Rain
            $results{"Mar_PET"}  += $fields[14]; #PET
            } elsif ($Month == $months{"Apr"}) {
            $results{"Apr_Rain"} += $fields[5]; #Rain
            $results{"Apr_PET"}  += $fields[14]; #PET
            } elsif ($Month == $months{"May"}) {
            $results{"May_Rain"} += $fields[5]; #Rain
            $results{"May_PET"}  += $fields[14]; #PET
            } elsif ($Month == $months{"Jun"}) {
            $results{"Jun_Rain"} += $fields[5]; #Rain
            $results{"Jun_PET"}  += $fields[14]; #PET
            } elsif ($Month == $months{"Jul"}) {
            $results{"Jul_Rain"} += $fields[5]; #Rain
            $results{"Jul_PET"}  += $fields[14]; #PET
            } elsif ($Month == $months{"Aug"}) {
```

```
            $results{"Aug_Rain"} += $fields[5]; #Rain
            $results{"Aug_PET"}  += $fields[14]; #PET
            } elsif ($Month == $months{"Sep"}) {
            $results{"Sep_Rain"} += $fields[5]; #Rain
            $results{"Sep_PET"}  += $fields[14]; #PET
            } elsif ($Month == $months{"Oct"}) {
            $results{"Oct_Rain"} += $fields[5]; #Rain
            $results{"Oct_PET"}  += $fields[14]; #PET
            } elsif ($Month == $months{"Nov"}) {
            $results{"Nov_Rain"} += $fields[5]; #Rain
            $results{"Nov_PET"}  += $fields[14]; #PET
            } elsif ($Month == $months{"Dec"}) {
            $results{"Dec_Rain"} += $fields[5]; #Rain
            $results{"Dec_PET"}  += $fields[14]; #PET
        }

        $Year  = $fields[0];
        $Month = $fields[1];
        $Day   = $fields[2];
        $totalrows++;
        $yearcounter++;

        # Row by row status output  [note, hugely slows down run time - use
for debug only]
        #print "Counters: ", $yearcounter, "/", $totalrows, ", ", $Year, "/",
$Month, "/", $Day, "\n";
    }
    # Compute and output final year's data
    &setyearstats();
    # Annual status output [slows down run time, but acceptably]
    #print "Perturbation: ", $perturbation, ", Year: ", $Year, " [having ",
$yearcounter, " days] : ", $totalrows, " rows so far \n";
    &writestats($perturbation, $Year); # report on final year

    # Finish up
    #&footer($perturbation,$totalrows);
    close(INFILE);
    # close(OUTFILE);
    close(OUTFILE_RAIN);
    close(OUTFILE_PET);
    close(OUTFILE_SMD);
    close(OUTFILE_SMS);
    close(OUTFILE_ACCSMD);
    close(OUTFILE_ACCSMS);

    print "Finished processing '", $data1{"in_file"}, "'\nNumber of rows
processed in total was ", $totalrows, "\nNumber of perturbations was ",
$perturbation, "\n********\n";
}

####################
# Function writestats
###
    sub writestats {
        my ($perturbation, $Year)=@_;
=for comment
        printf(OUTFILE "*********************\nStats:\nPerturbation: %d,
Year: %d\n", $perturbation, $Year);

        printf(OUTFILE "\nJanuary\n");
        #  printf("Jan");
        printf(OUTFILE "Rain [mm]: %.2f\n", $results{"Jan_Rain"});
        printf(OUTFILE "PET  [mm]: %.2f\n", $results{"Jan_PET"});
        printf(OUTFILE "Rain-PET  [mm]: %.2f\n", $results{"Jan_Rain-PET"});
        printf(OUTFILE "SMD  [mm]: %.2f\n", abs($results{"Jan_SMD"}));
```

```
printf(OUTFILE "SMS  [mm]: %.2f\n", $results{"Jan_SMS"});
printf(OUTFILE "AccSMD  [mm]: %.2f\n", abs($results{"Jan_AccSMD"}));
printf(OUTFILE "AccSMS  [mm]: %.2f\n", $results{"Jan_AccSMS"});

printf(OUTFILE "\nFebruary\n");
#  printf(" Feb");
printf(OUTFILE "Rain [mm]: %.2f\n", $results{"Feb_Rain"});
printf(OUTFILE "PET  [mm]: %.2f\n", $results{"Feb_PET"});
printf(OUTFILE "Rain-PET  [mm]: %.2f\n", $results{"Feb_Rain-PET"});
printf(OUTFILE "SMD  [mm]: %.2f\n", abs($results{"Feb_SMD"}));
printf(OUTFILE "SMS  [mm]: %.2f\n", $results{"Feb_SMS"});
printf(OUTFILE "AccSMD  [mm]: %.2f\n", abs($results{"Feb_AccSMD"}));
printf(OUTFILE "AccSMS  [mm]: %.2f\n", $results{"Feb_AccSMS"});

printf(OUTFILE "\nMarch\n");
#  printf(" Mar");
printf(OUTFILE "Rain [mm]: %.2f\n", $results{"Mar_Rain"});
printf(OUTFILE "PET  [mm]: %.2f\n", $results{"Mar_PET"});
printf(OUTFILE "Rain-PET  [mm]: %.2f\n", $results{"Mar_Rain-PET"});
printf(OUTFILE "SMD  [mm]: %.2f\n", abs($results{"Mar_SMD"}));
printf(OUTFILE "SMS  [mm]: %.2f\n", $results{"Mar_SMS"});
printf(OUTFILE "AccSMD  [mm]: %.2f\n", abs($results{"Mar_AccSMD"}));
printf(OUTFILE "AccSMS  [mm]: %.2f\n", $results{"Mar_AccSMS"});

printf(OUTFILE "\nApril\n");
#  printf(" Apr");
printf(OUTFILE "Rain [mm]: %.2f\n", $results{"Apr_Rain"});
printf(OUTFILE "PET  [mm]: %.2f\n", $results{"Apr_PET"});
printf(OUTFILE "Rain-PET  [mm]: %.2f\n", $results{"Apr_Rain-PET"});
printf(OUTFILE "SMD  [mm]: %.2f\n", abs($results{"Apr_SMD"}));
printf(OUTFILE "SMS  [mm]: %.2f\n", $results{"Apr_SMS"});
printf(OUTFILE "AccSMD  [mm]: %.2f\n", abs($results{"Apr_AccSMD"}));
printf(OUTFILE "AccSMS  [mm]: %.2f\n", $results{"Apr_AccSMS"});

printf(OUTFILE "\nMay\n");
#  printf(" May");
printf(OUTFILE "Rain [mm]: %.2f\n", $results{"May_Rain"});
printf(OUTFILE "PET  [mm]: %.2f\n", $results{"May_PET"});
printf(OUTFILE "Rain-PET  [mm]: %.2f\n", $results{"May_Rain-PET"});
printf(OUTFILE "SMD  [mm]: %.2f\n", abs($results{"May_SMD"}));
printf(OUTFILE "SMS  [mm]: %.2f\n", $results{"May_SMS"});
printf(OUTFILE "AccSMD  [mm]: %.2f\n", abs($results{"May_AccSMD"}));
printf(OUTFILE "AccSMS  [mm]: %.2f\n", $results{"May_AccSMS"});

printf(OUTFILE "\nJune\n");
#  printf(" Jun");
printf(OUTFILE "Rain [mm]: %.2f\n", $results{"Jun_Rain"});
printf(OUTFILE "PET  [mm]: %.2f\n", $results{"Jun_PET"});
printf(OUTFILE "Rain-PET  [mm]: %.2f\n", $results{"Jun_Rain-PET"});
printf(OUTFILE "SMD  [mm]: %.2f\n", abs($results{"Jun_SMD"}));
printf(OUTFILE "SMS  [mm]: %.2f\n", $results{"Jun_SMS"});
printf(OUTFILE "AccSMD  [mm]: %.2f\n", abs($results{"Jun_AccSMD"}));
printf(OUTFILE "AccSMS  [mm]: %.2f\n", $results{"Jun_AccSMS"});

printf(OUTFILE "\nJuly\n");
#  printf(" Jul");
printf(OUTFILE "Rain [mm]: %.2f\n", $results{"Jul_Rain"});
printf(OUTFILE "PET  [mm]: %.2f\n", $results{"Jul_PET"});
printf(OUTFILE "Rain-PET  [mm]: %.2f\n", $results{"Jul_Rain-PET"});
printf(OUTFILE "SMD  [mm]: %.2f\n", abs($results{"Jul_SMD"}));
printf(OUTFILE "SMS  [mm]: %.2f\n", $results{"Jul_SMS"});
printf(OUTFILE "AccSMD  [mm]: %.2f\n", abs($results{"Jul_AccSMD"}));
printf(OUTFILE "AccSMS  [mm]: %.2f\n", $results{"Jul_AccSMS"});

printf(OUTFILE "\nAugust\n");
```

```
        #  printf(" Aug");
        printf(OUTFILE "Rain [mm]: %.2f\n", $results{"Aug_Rain"});
        printf(OUTFILE "PET  [mm]: %.2f\n", $results{"Aug_PET"});
        printf(OUTFILE "Rain-PET  [mm]: %.2f\n", $results{"Aug_Rain-PET"});
        printf(OUTFILE "SMD  [mm]: %.2f\n", abs($results{"Aug_SMD"}));
        printf(OUTFILE "SMS  [mm]: %.2f\n", $results{"Aug_SMS"});
        printf(OUTFILE "AccSMD  [mm]: %.2f\n", abs($results{"Aug_AccSMD"}));
        printf(OUTFILE "AccSMS  [mm]: %.2f\n", $results{"Aug_AccSMS"});

        printf(OUTFILE "\nSeptember\n");
        #  printf(" Sep");
        printf(OUTFILE "Rain [mm]: %.2f\n", $results{"Sep_Rain"});
        printf(OUTFILE "PET  [mm]: %.2f\n", $results{"Sep_PET"});
        printf(OUTFILE "Rain-PET  [mm]: %.2f\n", $results{"Sep_Rain-PET"});
        printf(OUTFILE "SMD  [mm]: %.2f\n", abs($results{"Sep_SMD"}));
        printf(OUTFILE "SMS  [mm]: %.2f\n", $results{"Sep_SMS"});
        printf(OUTFILE "AccSMD  [mm]: %.2f\n", abs($results{"Sep_AccSMD"}));
        printf(OUTFILE "AccSMS  [mm]: %.2f\n", $results{"Sep_AccSMS"});

        printf(OUTFILE "\nOctober\n");
        #  printf(" Oct");
        printf(OUTFILE "Rain [mm]: %.2f\n", $results{"Oct_Rain"});
        printf(OUTFILE "PET  [mm]: %.2f\n", $results{"Oct_PET"});
        printf(OUTFILE "Rain-PET  [mm]: %.2f\n", $results{"Oct_Rain-PET"});
        printf(OUTFILE "SMD  [mm]: %.2f\n", abs($results{"Oct_SMD"}));
        printf(OUTFILE "SMS  [mm]: %.2f\n", $results{"Oct_SMS"});
        printf(OUTFILE "AccSMD  [mm]: %.2f\n", abs($results{"Oct_AccSMD"}));
        printf(OUTFILE "AccSMS  [mm]: %.2f\n", $results{"Oct_AccSMS"});

        printf(OUTFILE "\nNovember\n");
        #  printf(" Nov");
        printf(OUTFILE "Rain [mm]: %.2f\n", $results{"Nov_Rain"});
        printf(OUTFILE "PET  [mm]: %.2f\n", $results{"Nov_PET"});
        printf(OUTFILE "Rain-PET  [mm]: %.2f\n", $results{"Nov_Rain-PET"});
        printf(OUTFILE "SMD  [mm]: %.2f\n", abs($results{"Nov_SMD"}));
        printf(OUTFILE "SMS  [mm]: %.2f\n", $results{"Nov_SMS"});
        printf(OUTFILE "AccSMD  [mm]: %.2f\n", abs($results{"Nov_AccSMD"}));
        printf(OUTFILE "AccSMS  [mm]: %.2f\n", $results{"Nov_AccSMS"});

        printf(OUTFILE "\nDecember\n");
        #  printf(" Dec");
        printf(OUTFILE "Rain [mm]: %.2f\n", $results{"Dec_Rain"});
        printf(OUTFILE "PET  [mm]: %.2f\n", $results{"Dec_PET"});
        printf(OUTFILE "Rain-PET  [mm]: %.2f\n", $results{"Dec_Rain-PET"});
        printf(OUTFILE "SMD  [mm]: %.2f\n", abs($results{"Dec_SMD"}));
        printf(OUTFILE "SMS  [mm]: %.2f\n", $results{"Dec_SMS"});
        printf(OUTFILE "AccSMD  [mm]: %.2f\n", abs($results{"Dec_AccSMD"}));
        printf(OUTFILE "AccSMS  [mm]: %.2f\n", $results{"Dec_AccSMS"});

        printf(OUTFILE "\nYearly\n");
        printf(OUTFILE "Rain [mm]: %.2f\n", $results{"Year_Rain"});
        printf(OUTFILE "PET  [mm]: %.2f\n", $results{"Year_PET"});
        printf(OUTFILE "Acc SMD  [mm]: %.2f\n", abs($results{"Year_AccSMD"}));
        printf(OUTFILE "Acc SMS  [mm]: %.2f\n", $results{"Year_AccSMS"});

        printf(OUTFILE "\n= Data Format
==========================================================================\
n");
        printf(OUTFILE "Perturbation, Year, Month, Rain_mm, PET_mm, Rain-
PET_mm, SMD_mm, SMS_mm, AccSMD_mm, AccSMS_mm\n");
        printf(OUTFILE "%d, %d, Jan, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f\n", $perturbation, $Year, $results{"Jan_Rain"}, $results{"Jan_PET"},
$results{"Jan_Rain-PET"}, abs($results{"Jan_SMD"}), $results{"Jan_SMS"},
abs($results{"Jan_AccSMD"}), $results{"Jan_AccSMS"});
```

```
        printf(OUTFILE "%d, %d, Feb, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f\n", $perturbation, $Year, $results{"Feb_Rain"}, $results{"Feb_PET"},
$results{"Feb_Rain-PET"}, abs($results{"Feb_SMD"}), $results{"Feb_SMS"},
abs($results{"Feb_AccSMD"}), $results{"Feb_AccSMS"});
        printf(OUTFILE "%d, %d, Mar, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f\n", $perturbation, $Year, $results{"Mar_Rain"}, $results{"Mar_PET"},
$results{"Mar_Rain-PET"}, abs($results{"Mar_SMD"}), $results{"Mar_SMS"},
abs($results{"Mar_AccSMD"}), $results{"Mar_AccSMS"});
        printf(OUTFILE "%d, %d, Apr, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f\n", $perturbation, $Year, $results{"Apr_Rain"}, $results{"Apr_PET"},
$results{"Apr_Rain-PET"}, abs($results{"Apr_SMD"}), $results{"Apr_SMS"},
abs($results{"Apr_AccSMD"}), $results{"Apr_AccSMS"});
        printf(OUTFILE "%d, %d, May, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f\n", $perturbation, $Year, $results{"May_Rain"}, $results{"May_PET"},
$results{"May_Rain-PET"}, abs($results{"May_SMD"}), $results{"May_SMS"},
abs($results{"May_AccSMD"}), $results{"May_AccSMS"});
        printf(OUTFILE "%d, %d, Jun, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f\n", $perturbation, $Year, $results{"Jun_Rain"}, $results{"Jun_PET"},
$results{"Jun_Rain-PET"}, abs($results{"Jun_SMD"}), $results{"Jun_SMS"},
abs($results{"Jun_AccSMD"}), $results{"Jun_AccSMS"});
        printf(OUTFILE "%d, %d, Jul, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f\n", $perturbation, $Year, $results{"Jul_Rain"}, $results{"Jul_PET"},
$results{"Jul_Rain-PET"}, abs($results{"Jul_SMD"}), $results{"Jul_SMS"},
abs($results{"Jul_AccSMD"}), $results{"Jul_AccSMS"});
        printf(OUTFILE "%d, %d, Aug, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f\n", $perturbation, $Year, $results{"Aug_Rain"}, $results{"Aug_PET"},
$results{"Aug_Rain-PET"}, abs($results{"Aug_SMD"}), $results{"Aug_SMS"},
abs($results{"Aug_AccSMD"}), $results{"Aug_AccSMS"});
        printf(OUTFILE "%d, %d, Sep, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f\n", $perturbation, $Year, $results{"Sep_Rain"}, $results{"Sep_PET"},
$results{"Sep_Rain-PET"}, abs($results{"Sep_SMD"}), $results{"Sep_SMS"},
abs($results{"Sep_AccSMD"}), $results{"Sep_AccSMS"});
        printf(OUTFILE "%d, %d, Oct, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f\n", $perturbation, $Year, $results{"Oct_Rain"}, $results{"Oct_PET"},
$results{"Oct_Rain-PET"}, abs($results{"Oct_SMD"}), $results{"Oct_SMS"},
abs($results{"Oct_AccSMD"}), $results{"Oct_AccSMS"});
        printf(OUTFILE "%d, %d, Nov, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f\n", $perturbation, $Year, $results{"Nov_Rain"}, $results{"Nov_PET"},
$results{"Nov_Rain-PET"}, abs($results{"Nov_SMD"}), $results{"Nov_SMS"},
abs($results{"Nov_AccSMD"}), $results{"Nov_AccSMS"});
        printf(OUTFILE "%d, %d, Dec, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f\n", $perturbation, $Year, $results{"Dec_Rain"}, $results{"Dec_PET"},
$results{"Dec_Rain-PET"}, abs($results{"Dec_SMD"}), $results{"Dec_SMS"},
abs($results{"Dec_AccSMD"}), $results{"Dec_AccSMS"});
        printf(OUTFILE "%d, %d, Year,%.2f, %.2f, %.2f, %.2f\n", $perturbation,
$Year,
$results{"Year_Rain"},$results{"Year_PET"},$results{"Year_AccSMD"},$results{"Y
ear_AccSMS"});
        printf(OUTFILE
"==============================================================================
================\n");
=cut
        # Excel format output - all years, all data (don't need to record rain
- pet)
        if ($firsttime == 1) {
            printf(OUTFILE_RAIN "Perturbation, Year, Jan_Rain, Feb_Rain,
Mar_Rain, Apr_Rain, May_Rain, Jun_Rain, Jul_Rain, Aug_Rain, Sep_Rain,
Oct_Rain, Nov_Rain, Dec_Rain, Year_Rain\n");
            printf(OUTFILE_PET  "Perturbation, Year, Jan_PET,  Feb_PET,
Mar_PET,  Apr_PET,  May_PET,  Jun_PET,  Jul_PET,  Aug_PET,  Sep_PET,  Oct_PET,
Nov_PET,  Dec_PET, Year_PET\n");
            printf(OUTFILE_SMD  "Perturbation, Year, Jan_SMD,  Feb_SMD,
Mar_SMD,  Apr_SMD,  May_SMD,  Jun_SMD,  Jul_SMD,  Aug_SMD,  Sep_SMD,  Oct_SMD,
Nov_SMD,  Dec_SMD\n");
```

```
            printf(OUTFILE_SMS  "Perturbation, Year, Jan_SMS,  Feb_SMS,
Mar_SMS,  Apr_SMS,  May_SMS,  Jun_SMS,  Jul_SMS,  Aug_SMS,  Sep_SMS,  Oct_SMS,
Nov_SMS,  Dec_SMS\n");
            printf(OUTFILE_ACCSMD  "Perturbation, Year, Jan_AccSMD,
Feb_AccSMD,  Mar_AccSMD,  Apr_AccSMD,  May_AccSMD,  Jun_AccSMD,  Jul_AccSMD,
Aug_AccSMD,  Sep_AccSMD,  Oct_AccSMD,  Nov_AccSMD,  Dec_AccSMD,
Year_AccSMD\n");
            printf(OUTFILE_ACCSMS  "Perturbation, Year, Jan_AccSMS,
Feb_AccSMS,  Mar_AccSMS,  Apr_AccSMS,  May_AccSMS,  Jun_AccSMS,  Jul_AccSMS,
Aug_AccSMS,  Sep_AccSMS,  Oct_AccSMS,  Nov_AccSMS,  Dec_AccSMS,
Year_AccSMS\n");
            $firsttime = 0;
        }
        printf(OUTFILE_RAIN "%d, %d, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f, %.2f, %.2f, %.2f, %.2f, %.2f\n", $perturbation, $Year,
$results{"Jan_Rain"}, $results{"Feb_Rain"}, $results{"Mar_Rain"},
$results{"Apr_Rain"}, $results{"May_Rain"}, $results{"Jun_Rain"},
$results{"Jul_Rain"}, $results{"Aug_Rain"}, $results{"Sep_Rain"},
$results{"Oct_Rain"}, $results{"Nov_Rain"}, $results{"Dec_Rain"},
$results{"Year_Rain"}); # Rain
        printf(OUTFILE_PET "%d, %d, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f, %.2f, %.2f, %.2f, %.2f, %.2f\n", $perturbation, $Year,
$results{"Jan_PET"}, $results{"Feb_PET"}, $results{"Mar_PET"},
$results{"Apr_PET"}, $results{"May_PET"}, $results{"Jun_PET"},
$results{"Jul_PET"}, $results{"Aug_PET"}, $results{"Sep_PET"},
$results{"Oct_PET"}, $results{"Nov_PET"}, $results{"Dec_PET"},
$results{"Year_PET"}); # PET
        printf(OUTFILE_SMD "%d, %d, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f, %.2f, %.2f, %.2f, %.2f\n", $perturbation, $Year,
abs($results{"Jan_SMD"}), abs($results{"Feb_SMD"}), abs($results{"Mar_SMD"}),
abs($results{"Apr_SMD"}), abs($results{"May_SMD"}), abs($results{"Jun_SMD"}),
abs($results{"Jul_SMD"}), abs($results{"Aug_SMD"}), abs($results{"Sep_SMD"}),
abs($results{"Oct_SMD"}), abs($results{"Nov_SMD"}), abs($results{"Dec_SMD"}));
# SMD
        printf(OUTFILE_SMS "%d, %d, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f, %.2f, %.2f, %.2f, %.2f\n", $perturbation, $Year, $results{"Jan_SMS"},
$results{"Feb_SMS"}, $results{"Mar_SMS"}, $results{"Apr_SMS"},
$results{"May_SMS"}, $results{"Jun_SMS"}, $results{"Jul_SMS"},
$results{"Aug_SMS"}, $results{"Sep_SMS"}, $results{"Oct_SMS"},
$results{"Nov_SMS"}, $results{"Dec_SMS"}); # SMS
        printf(OUTFILE_ACCSMD "%d, %d, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f\n", $perturbation, $Year,
abs($results{"Jan_AccSMD"}), abs($results{"Feb_AccSMD"}),
abs($results{"Mar_AccSMD"}), abs($results{"Apr_AccSMD"}),
abs($results{"May_AccSMD"}), abs($results{"Jun_AccSMD"}),
abs($results{"Jul_AccSMD"}), abs($results{"Aug_AccSMD"}),
abs($results{"Sep_AccSMD"}), abs($results{"Oct_AccSMD"}),
abs($results{"Nov_AccSMD"}), abs($results{"Dec_AccSMD"}),
abs($results{"Year_AccSMD"})); # ACCSMD
        printf(OUTFILE_ACCSMS "%d, %d, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f\n", $perturbation, $Year,
$results{"Jan_AccSMS"}, $results{"Feb_AccSMS"}, $results{"Mar_AccSMS"},
$results{"Apr_AccSMS"}, $results{"May_AccSMS"}, $results{"Jun_AccSMS"},
$results{"Jul_AccSMS"}, $results{"Aug_AccSMS"}, $results{"Sep_AccSMS"},
$results{"Oct_AccSMS"}, $results{"Nov_AccSMS"}, $results{"Dec_AccSMS"},
$results{"Year_AccSMS"}); # ACCSMS
    }

####################
# Function zeroresults
###
sub zeroresults {
    %results = ("Jan_Rain", 0, "Jan_PET", 0, "Jan_Rain-PET", 0, "Jan_SMD", 0,
"Jan_SMS", 0, "Jan_AccSMD", 0, "Jan_AccSMS", 0,
```

```
    "Feb_Rain", 0, "Feb_PET", 0, "Feb_Rain-PET", 0, "Feb_SMD", 0, "Feb_SMS",
0, "Feb_AccSMD", 0, "Feb_AccSMS", 0,
    "Mar_Rain", 0, "Mar_PET", 0, "Mar_Rain-PET", 0, "Mar_SMD", 0, "Mar_SMS",
0, "Mar_AccSMD", 0, "Mar_AccSMS", 0,
    "Apr_Rain", 0, "Apr_PET", 0, "Apr_Rain-PET", 0, "Apr_SMD", 0, "Apr_SMS",
0, "Apr_AccSMD", 0, "Apr_AccSMS", 0,
    "May_Rain", 0, "May_PET", 0, "May_Rain-PET", 0, "May_SMD", 0, "May_SMS",
0, "May_AccSMD", 0, "May_AccSMS", 0,
    "Jun_Rain", 0, "Jun_PET", 0, "Jun_Rain-PET", 0, "Jun_SMD", 0, "Jun_SMS",
0, "Jun_AccSMD", 0, "Jun_AccSMS", 0,
    "Jul_Rain", 0, "Jul_PET", 0, "Jul_Rain-PET", 0, "Jul_SMD", 0, "Jul_SMS",
0, "Jul_AccSMD", 0, "Jul_AccSMS", 0,
    "Aug_Rain", 0, "Aug_PET", 0, "Aug_Rain-PET", 0, "Aug_SMD", 0, "Aug_SMS",
0, "Aug_AccSMD", 0, "Aug_AccSMS", 0,
    "Sep_Rain", 0, "Sep_PET", 0, "Sep_Rain-PET", 0, "Sep_SMD", 0, "Sep_SMS",
0, "Sep_AccSMD", 0, "Sep_AccSMS", 0,
    "Oct_Rain", 0, "Oct_PET", 0, "Oct_Rain-PET", 0, "Oct_SMD", 0, "Oct_SMS",
0, "Oct_AccSMD", 0, "Oct_AccSMS", 0,
    "Nov_Rain", 0, "Nov_PET", 0, "Nov_Rain-PET", 0, "Nov_SMD", 0, "Nov_SMS",
0, "Nov_AccSMD", 0, "Nov_AccSMS", 0,
    "Dec_Rain", 0, "Dec_PET", 0, "Dec_Rain-PET", 0, "Dec_SMD", 0, "Dec_SMS",
0, "Dec_AccSMD", 0, "Dec_AccSMS", 0,
    "Year_Rain", 0, "Year_PET", 0, "Year_AccSMD", 0, "Year_AccSMS", 0);
}

####################
# Function setyearstats
###
# Note negative deficits are all set to positive numbers in final output, as
per convention, using the abs function
sub setyearstats {

    my ($AccSMS_Store, $AccSMS_Switch); # Initialise store and switch for
accumulated SMS
    $AccSMS_Switch=0; # 0=store not used; 1=store in use; 2=store restored
    $AccSMS_Store=0;

    ##############################################################
    # Jan
    $results{"Jan_Rain-PET"} = ($results{"Jan_Rain"} - $results{"Jan_PET"});
if ($results{"Jan_Rain-PET"} < 0) {
        $results{"Jan_SMD"} = $results{"Jan_Rain-PET"}; # Deficit
        } else {
        $results{"Jan_SMS"} = $results{"Jan_Rain-PET"}; # Surplus
    }
    ############################## SMD
    $results{"Jan_AccSMD"} = $results{"Jan_SMD"};
if ($results{"Jan_SMS"} > 0) {
        $results{"Jan_AccSMD"} += ($results{"Jan_SMS"});
    }
if ($results{"Jan_AccSMD"} > 0) {
        $results{"Jan_AccSMD"} = 0; # clip to zero
    }
    ############################## SMS
    $results{"Jan_AccSMS"} = $results{"Jan_SMS"};
if ($results{"Jan_SMD"} < 0) {
        $results{"Jan_AccSMS"} += ($results{"Jan_SMD"});
    }
if ($results{"Jan_AccSMS"} < 0) {
        $results{"Jan_AccSMS"} = 0; # clip to zero
    }
    ##############################

    ##############################################################
    # Feb
```

```
    $results{"Feb_Rain-PET"} = ($results{"Feb_Rain"} - $results{"Feb_PET"});
if ($results{"Feb_Rain-PET"} < 0) {
        $results{"Feb_SMD"} = $results{"Feb_Rain-PET"}; # Deficit
        } else {
        $results{"Feb_SMS"} = $results{"Feb_Rain-PET"}; # Surplus
    }
    ############################## SMD
    $results{"Feb_AccSMD"} = $results{"Jan_AccSMD"} + $results{"Feb_SMD"};
if ($results{"Feb_SMS"} > 0) {
        $results{"Feb_AccSMD"} += ($results{"Feb_SMS"});
    }
if ($results{"Feb_AccSMD"} > 0) {
        $results{"Feb_AccSMD"} = 0; # clip to zero
    }
    ############################## SMS
    $results{"Feb_AccSMS"} = $results{"Jan_AccSMS"} + $results{"Feb_SMS"};
if ($results{"Feb_SMD"} < 0) {
        $results{"Feb_AccSMS"} += ($results{"Feb_SMD"});
    }
if ($results{"Feb_AccSMS"} < 0) {
        $results{"Feb_AccSMS"} = 0; # clip to zero
    }
if ($results{"Feb_AccSMD"} < 0) {
        if ($AccSMS_Switch == 0) {
            $AccSMS_Store = $results{"Jan_AccSMS"}; # Preserve value
            $AccSMS_Switch = 1; # Switch is now made
        }
        $results{"Feb_AccSMS"} = 0;
    }
if ($results{"Feb_AccSMD"} == 0 && $AccSMS_Switch == 1) {
        $results{"Feb_AccSMS"} = $AccSMS_Store;
        $AccSMS_Switch = 2;
    }
    ##############################

    ##############################################################
    # Mar
    $results{"Mar_Rain-PET"} = ($results{"Mar_Rain"} - $results{"Mar_PET"});
if ($results{"Mar_Rain-PET"} < 0) {
        $results{"Mar_SMD"} = $results{"Mar_Rain-PET"}; # Deficit
        } else {
        $results{"Mar_SMS"} = $results{"Mar_Rain-PET"}; # Surplus
    }
    ############################## SMD
    $results{"Mar_AccSMD"} = $results{"Feb_AccSMD"} + $results{"Mar_SMD"};
if ($results{"Mar_SMS"} > 0) {
        $results{"Mar_AccSMD"} += ($results{"Mar_SMS"});
    }
if ($results{"Mar_AccSMD"} > 0) {
        $results{"Mar_AccSMD"} = 0; # clip to zero
    }
    ############################## SMS
    $results{"Mar_AccSMS"} = $results{"Feb_AccSMS"} + $results{"Mar_SMS"};
if ($results{"Mar_SMD"} < 0) {
        $results{"Mar_AccSMS"} += ($results{"Mar_SMD"});
    }
if ($results{"Mar_AccSMS"} < 0) {
        $results{"Mar_AccSMS"} = 0; # clip to zero
    }
if ($results{"Mar_AccSMD"} < 0) {
        if ($AccSMS_Switch == 0) {
            $AccSMS_Store = $results{"Feb_AccSMS"}; # Preserve value
            $AccSMS_Switch = 1; # Switch is now made
        }
        $results{"Mar_AccSMS"} = 0;
```

```
    }
if ($results{"Mar_AccSMD"} == 0 && $AccSMS_Switch == 1) {
        $results{"Mar_AccSMS"} = $AccSMS_Store;
        $AccSMS_Switch = 2;
    }
    ##############################

    ##############################################################
    # Apr
    $results{"Apr_Rain-PET"} = ($results{"Apr_Rain"} - $results{"Apr_PET"});
if ($results{"Apr_Rain-PET"} < 0) {
        $results{"Apr_SMD"} = $results{"Apr_Rain-PET"}; # Deficit
        } else {
        $results{"Apr_SMS"} = $results{"Apr_Rain-PET"}; # Surplus
    }
    ############################## SMD
    $results{"Apr_AccSMD"} = $results{"Mar_AccSMD"} + $results{"Apr_SMD"};
if ($results{"Apr_SMS"} > 0) {
        $results{"Apr_AccSMD"} += ($results{"Apr_SMS"});
    }
if ($results{"Apr_AccSMD"} > 0) {
        $results{"Apr_AccSMD"} = 0; # clip to zero
    }
    ############################## SMS
    $results{"Apr_AccSMS"} = $results{"Mar_AccSMS"} + $results{"Apr_SMS"};
if ($results{"Apr_SMD"} < 0) {
        $results{"Apr_AccSMS"} += ($results{"Apr_SMD"});
    }
if ($results{"Apr_AccSMS"} < 0) {
        $results{"Apr_AccSMS"} = 0; # clip to zero
    }
if ($results{"Apr_AccSMD"} < 0) {
        if ($AccSMS_Switch == 0) {
            $AccSMS_Store = $results{"Mar_AccSMS"}; # Preserve value
            $AccSMS_Switch = 1; # Switch is now made
        }
        $results{"Apr_AccSMS"} = 0;
    }
if ($results{"Apr_AccSMD"} == 0 && $AccSMS_Switch == 1) {
        $results{"Apr_AccSMS"} = $AccSMS_Store;
        $AccSMS_Switch = 2;
    }
    ##############################

    ##############################################################
    # May
    $results{"May_Rain-PET"} = ($results{"May_Rain"} - $results{"May_PET"});
if ($results{"May_Rain-PET"} < 0) {
        $results{"May_SMD"} = $results{"May_Rain-PET"}; # Deficit
        } else {
        $results{"May_SMS"} = $results{"May_Rain-PET"}; # Surplus
    }
    ############################## SMD
    $results{"May_AccSMD"} = $results{"Apr_AccSMD"} + $results{"May_SMD"};
if ($results{"May_SMS"} > 0) {
        $results{"May_AccSMD"} += ($results{"May_SMS"});
    }
if ($results{"May_AccSMD"} > 0) {
        $results{"May_AccSMD"} = 0; # clip to zero
    }
    ############################## SMS
    $results{"May_AccSMS"} = $results{"Apr_AccSMS"} + $results{"May_SMS"};
if ($results{"May_SMD"} < 0) {
        $results{"May_AccSMS"} += ($results{"May_SMD"});
    }
```

```
if ($results{"May_AccSMS"} < 0) {
        $results{"May_AccSMS"} = 0; # clip to zero
    }
if ($results{"May_AccSMD"} < 0) {
        if ($AccSMS_Switch == 0) {
            $AccSMS_Store = $results{"Apr_AccSMS"}; # Preserve value
            $AccSMS_Switch = 1; # Switch is now made
        }
        $results{"May_AccSMS"} = 0;
    }
if ($results{"May_AccSMD"} == 0 && $AccSMS_Switch == 1) {
        $results{"May_AccSMS"} = $AccSMS_Store;
        $AccSMS_Switch = 2;
    }
    ##############################

    ##############################################################
    # Jun
    $results{"Jun_Rain-PET"} = ($results{"Jun_Rain"} - $results{"Jun_PET"});
if ($results{"Jun_Rain-PET"} < 0) {
        $results{"Jun_SMD"} = $results{"Jun_Rain-PET"}; # Deficit
        } else {
        $results{"Jun_SMS"} = $results{"Jun_Rain-PET"}; # Surplus
    }
    ############################### SMD
    $results{"Jun_AccSMD"} = $results{"May_AccSMD"} + $results{"Jun_SMD"};
if ($results{"Jun_SMS"} > 0) {
        $results{"Jun_AccSMD"} += ($results{"Jun_SMS"});
    }
if ($results{"Jun_AccSMD"} > 0) {
        $results{"Jun_AccSMD"} = 0; # clip to zero
    }
    ############################### SMS
    $results{"Jun_AccSMS"} = $results{"May_AccSMS"} + $results{"Jun_SMS"};
if ($results{"Jun_SMD"} < 0) {
        $results{"Jun_AccSMS"} += ($results{"Jun_SMD"});
    }
if ($results{"Jun_AccSMS"} < 0) {
        $results{"Jun_AccSMS"} = 0; # clip to zero
    }
if ($results{"Jun_AccSMD"} < 0) {
        if ($AccSMS_Switch == 0) {
            $AccSMS_Store = $results{"May_AccSMS"}; # Preserve value
            $AccSMS_Switch = 1; # Switch is now made
        }
        $results{"Jun_AccSMS"} = 0;
    }
if ($results{"Jun_AccSMD"} == 0 && $AccSMS_Switch == 1) {
        $results{"Jun_AccSMS"} = $AccSMS_Store;
        $AccSMS_Switch = 2;
    }
    ##############################

    ##############################################################
    # Jul
    $results{"Jul_Rain-PET"} = ($results{"Jul_Rain"} - $results{"Jul_PET"});
if ($results{"Jul_Rain-PET"} < 0) {
        $results{"Jul_SMD"} = $results{"Jul_Rain-PET"}; # Deficit
        } else {
        $results{"Jul_SMS"} = $results{"Jul_Rain-PET"}; # Surplus
    }
    ############################### SMD
    $results{"Jul_AccSMD"} = $results{"Jun_AccSMD"} + $results{"Jul_SMD"};
if ($results{"Jul_SMS"} > 0) {
        $results{"Jul_AccSMD"} += ($results{"Jul_SMS"});
```

```
    }
if ($results{"Jul_AccSMD"} > 0) {
        $results{"Jul_AccSMD"} = 0; # clip to zero
    }
    ############################## SMS
    $results{"Jul_AccSMS"} = $results{"Jun_AccSMS"} + $results{"Jul_SMS"};
if ($results{"Jul_SMD"} < 0) {
        $results{"Jul_AccSMS"} += ($results{"Jul_SMD"});
    }
if ($results{"Jul_AccSMS"} < 0) {
        $results{"Jul_AccSMS"} = 0; # clip to zero
    }
if ($results{"Jul_AccSMD"} < 0) {
        if ($AccSMS_Switch == 0) {
            $AccSMS_Store = $results{"Jun_AccSMS"}; # Preserve value
            $AccSMS_Switch = 1; # Switch is now made
        }
        $results{"Jul_AccSMS"} = 0;
    }
if ($results{"Jul_AccSMD"} == 0 && $AccSMS_Switch == 1) {
        $results{"Jul_AccSMS"} = $AccSMS_Store;
        $AccSMS_Switch = 2;
    }
    ##############################

    ##############################################################
    # Aug
    $results{"Aug_Rain-PET"} = ($results{"Aug_Rain"} - $results{"Aug_PET"});
if ($results{"Aug_Rain-PET"} < 0) {
        $results{"Aug_SMD"} = $results{"Aug_Rain-PET"}; # Deficit
        } else {
        $results{"Aug_SMS"} = $results{"Aug_Rain-PET"}; # Surplus
    }
    ############################## SMD
    $results{"Aug_AccSMD"} = $results{"Jul_AccSMD"} + $results{"Aug_SMD"};
if ($results{"Aug_SMS"} > 0) {
        $results{"Aug_AccSMD"} += ($results{"Aug_SMS"});
    }
if ($results{"Aug_AccSMD"} > 0) {
        $results{"Aug_AccSMD"} = 0; # clip to zero
    }
    ############################## SMS
    $results{"Aug_AccSMS"} = $results{"Jul_AccSMS"} + $results{"Aug_SMS"};
if ($results{"Aug_SMD"} < 0) {
        $results{"Aug_AccSMS"} += ($results{"Aug_SMD"});
    }
if ($results{"Aug_AccSMS"} < 0) {
        $results{"Aug_AccSMS"} = 0; # clip to zero
    }
if ($results{"Aug_AccSMD"} < 0) {
        if ($AccSMS_Switch == 0) {
            $AccSMS_Store = $results{"Jul_AccSMS"}; # Preserve value
            $AccSMS_Switch = 1; # Switch is now made
        }
        $results{"Aug_AccSMS"} = 0;
    }
if ($results{"Aug_AccSMD"} == 0 && $AccSMS_Switch == 1) {
        $results{"Aug_AccSMS"} = $AccSMS_Store;
        $AccSMS_Switch = 2;
    }
    ##############################

    ##############################################################
    # Sep
    $results{"Sep_Rain-PET"} = ($results{"Sep_Rain"} - $results{"Sep_PET"});
```

```
if ($results{"Sep_Rain-PET"} < 0) {
        $results{"Sep_SMD"} = $results{"Sep_Rain-PET"}; # Deficit
        } else {
        $results{"Sep_SMS"} = $results{"Sep_Rain-PET"}; # Surplus
    }
    ############################## SMD
    $results{"Sep_AccSMD"} = $results{"Aug_AccSMD"} + $results{"Sep_SMD"};
if ($results{"Sep_SMS"} > 0) {
        $results{"Sep_AccSMD"} += ($results{"Sep_SMS"});
    }
if ($results{"Sep_AccSMD"} > 0) {
        $results{"Sep_AccSMD"} = 0; # clip to zero
    }
    ############################## SMS
    $results{"Sep_AccSMS"} = $results{"Aug_AccSMS"} + $results{"Sep_SMS"};
if ($results{"Sep_SMD"} < 0) {
        $results{"Sep_AccSMS"} += ($results{"Sep_SMD"});
    }
if ($results{"Sep_AccSMS"} < 0) {
        $results{"Sep_AccSMS"} = 0; # clip to zero
    }
if ($results{"Sep_AccSMD"} < 0) {
        if ($AccSMS_Switch == 0) {
            $AccSMS_Store = $results{"Aug_AccSMS"}; # Preserve value
            $AccSMS_Switch = 1; # Switch is now made
        }
        $results{"Sep_AccSMS"} = 0;
    }
if ($results{"Sep_AccSMD"} == 0 && $AccSMS_Switch == 1) {
        $results{"Sep_AccSMS"} = $AccSMS_Store;
        $AccSMS_Switch = 2;
    }
    ##############################

    ################################################################
    # Oct
    $results{"Oct_Rain-PET"} = ($results{"Oct_Rain"} - $results{"Oct_PET"});
if ($results{"Oct_Rain-PET"} < 0) {
        $results{"Oct_SMD"} = $results{"Oct_Rain-PET"}; # Deficit
        } else {
        $results{"Oct_SMS"} = $results{"Oct_Rain-PET"}; # Surplus
    }
    ############################## SMD
    $results{"Oct_AccSMD"} = $results{"Sep_AccSMD"} + $results{"Oct_SMD"};
if ($results{"Oct_SMS"} > 0) {
        $results{"Oct_AccSMD"} += ($results{"Oct_SMS"});
    }
if ($results{"Oct_AccSMD"} > 0) {
        $results{"Oct_AccSMD"} = 0; # clip to zero
    }
    ############################## SMS
    $results{"Oct_AccSMS"} = $results{"Sep_AccSMS"} + $results{"Oct_SMS"};
if ($results{"Oct_SMD"} < 0) {
        $results{"Oct_AccSMS"} += ($results{"Oct_SMD"});
    }
if ($results{"Oct_AccSMS"} < 0) {
        $results{"Oct_AccSMS"} = 0; # clip to zero
    }
if ($results{"Oct_AccSMD"} < 0) {
        if ($AccSMS_Switch == 0) {
            $AccSMS_Store = $results{"Sep_AccSMS"}; # Preserve value
            $AccSMS_Switch = 1; # Switch is now made
        }
        $results{"Oct_AccSMS"} = 0;
    }
```

```
if ($results{"Oct_AccSMD"} == 0 && $AccSMS_Switch == 1) {
        $results{"Oct_AccSMS"} = $AccSMS_Store;
        $AccSMS_Switch = 2;
    }
    ##############################

    ##############################################################
    # Nov
    $results{"Nov_Rain-PET"} = ($results{"Nov_Rain"} - $results{"Nov_PET"});
if ($results{"Nov_Rain-PET"} < 0) {
        $results{"Nov_SMD"} = $results{"Nov_Rain-PET"}; # Deficit
        } else {
        $results{"Nov_SMS"} = $results{"Nov_Rain-PET"}; # Surplus
    }
    ############################## SMD
    $results{"Nov_AccSMD"} = $results{"Oct_AccSMD"} + $results{"Nov_SMD"};
if ($results{"Nov_SMS"} > 0) {
        $results{"Nov_AccSMD"} += ($results{"Nov_SMS"});
    }
if ($results{"Nov_AccSMD"} > 0) {
        $results{"Nov_AccSMD"} = 0; # clip to zero
    }
    ############################## SMS
    $results{"Nov_AccSMS"} = $results{"Oct_AccSMS"} + $results{"Nov_SMS"};
if ($results{"Nov_SMD"} < 0) {
        $results{"Nov_AccSMS"} += ($results{"Nov_SMD"});
    }
if ($results{"Nov_AccSMS"} < 0) {
        $results{"Nov_AccSMS"} = 0; # clip to zero
    }
if ($results{"Nov_AccSMD"} < 0) {
        if ($AccSMS_Switch == 0) {
            $AccSMS_Store = $results{"Oct_AccSMS"}; # Preserve value
            $AccSMS_Switch = 1; # Switch is now made
        }
        $results{"Nov_AccSMS"} = 0;
    }
if ($results{"Nov_AccSMD"} == 0 && $AccSMS_Switch == 1) {
        $results{"Nov_AccSMS"} = $AccSMS_Store;
        $AccSMS_Switch = 2;
    }
    ##############################

    ##############################################################
    # Dec
    $results{"Dec_Rain-PET"} = ($results{"Dec_Rain"} - $results{"Dec_PET"});
if ($results{"Dec_Rain-PET"} < 0) {
        $results{"Dec_SMD"} = $results{"Dec_Rain-PET"}; # Deficit
        } else {
        $results{"Dec_SMS"} = $results{"Dec_Rain-PET"}; # Surplus
    }
    ############################## SMD
    $results{"Dec_AccSMD"} = $results{"Nov_AccSMD"} + $results{"Dec_SMD"};
if ($results{"Dec_SMS"} > 0) {
        $results{"Dec_AccSMD"} += ($results{"Dec_SMS"});
    }
if ($results{"Dec_AccSMD"} > 0) {
        $results{"Dec_AccSMD"} = 0; # clip to zero
    }
    ############################## SMS
    $results{"Dec_AccSMS"} = $results{"Nov_AccSMS"} + $results{"Dec_SMS"};
if ($results{"Dec_SMD"} < 0) {
        $results{"Dec_AccSMS"} += ($results{"Dec_SMD"});
    }
if ($results{"Dec_AccSMS"} < 0) {
```

```
        $results{"Dec_AccSMS"} = 0; # clip to zero
    }
if ($results{"Dec_AccSMD"} < 0) {
        if ($AccSMS_Switch == 0) {
            $AccSMS_Store = $results{"Nov_AccSMS"}; # Preserve value
            $AccSMS_Switch = 1; # Switch is now made
        }
        $results{"Dec_AccSMS"} = 0;
    }
if ($results{"Dec_AccSMD"} == 0 && $AccSMS_Switch == 1) {
        $results{"Dec_AccSMS"} = $AccSMS_Store;
        $AccSMS_Switch = 2;
    }
    ##############################

    # Yearly
    $results{"Year_Rain"} =
$results{"Jan_Rain"}+$results{"Feb_Rain"}+$results{"Mar_Rain"}+$results{"Apr_R
ain"}+$results{"May_Rain"}+$results{"Jun_Rain"}+$results{"Jul_Rain"}+$results{
"Aug_Rain"}+$results{"Sep_Rain"}+$results{"Oct_Rain"}+$results{"Nov_Rain"}+$re
sults{"Dec_Rain"}; # Rain
    $results{"Year_PET"} =
$results{"Jan_PET"}+$results{"Feb_PET"}+$results{"Mar_PET"}+$results{"Apr_PET"
}+$results{"May_PET"}+$results{"Jun_PET"}+$results{"Jul_PET"}+$results{"Aug_PE
T"}+$results{"Sep_PET"}+$results{"Oct_PET"}+$results{"Nov_PET"}+$results{"Dec_
PET"}; # PET
    #$min = min @list; # template
    #$max = max @list;
    $results{"Year_AccSMD"} = min ( $results{"Jan_AccSMD"},
$results{"Feb_AccSMD"}, $results{"Mar_AccSMD"}, $results{"Apr_AccSMD"},
$results{"May_AccSMD"}, $results{"Jun_AccSMD"}, $results{"Jul_AccSMD"},
$results{"Aug_AccSMD"}, $results{"Sep_AccSMD"}, $results{"Oct_AccSMD"},
$results{"Nov_AccSMD"}, $results{"Dec_AccSMD"} ); # Deficit
    $results{"Year_AccSMS"} = max ( $results{"Jan_AccSMS"},
$results{"Feb_AccSMS"}, $results{"Mar_AccSMS"}, $results{"Apr_AccSMS"},
$results{"May_AccSMS"}, $results{"Jun_AccSMS"}, $results{"Jul_AccSMS"},
$results{"Aug_AccSMS"}, $results{"Sep_AccSMS"}, $results{"Oct_AccSMS"},
$results{"Nov_AccSMS"}, $results{"Dec_AccSMS"} ); # Surplus
}

####################
# Function header
###
sub header {
    #my $datestring = system("date");
    printf(OUTFILE "<html><body><pre>\n<h3>****\n");
    printf(OUTFILE "** UKCP09 Climate Change Crew Data Summary Results
File</h3>\n");
    printf(OUTFILE "<h4>** Source: crew.pl PERL program\n");
    printf(OUTFILE "** Dr S.Hallett; O.Pritchard, Cranfield University\n");
    #printf(OUTFILE "** %s \/n", $datestring);
    printf(OUTFILE "*******************************************</h4>\n");
}

####################
# Function footer
###
sub footer {
    my ($perturbation, $counter)=@_;
    printf(OUTFILE "\n*******************************************\n");
    printf(OUTFILE "** End of File\n");
    printf(OUTFILE "** File processing complete\n");
    printf(OUTFILE "** The number of perturbations was %d\n",$perturbation);
    printf(OUTFILE "** The number of rows processed in total was
%u\n",$counter);
```

```
    printf(OUTFILE
"*****************************************\n</pre></body></html>\n");
}

#########################
# eof: ITRC.pl          #
#########################
```

Appendix C Perl Code to produce monthly and annual statistics for PSMD, Rainfall and Temperature

The Perl code detailed below provides a range of monthly and annual summary statistics (ITRC_Statistics.pl as discussed in Appendix A), including: Mean, standard deviation and 10,25,50,75 and 90th percentiles. This code can be applied to provide statistics of SMD, SMS, Rainfall and PET, which are used in the representation of climate model uncertainty and in the clay-subsidence modelling.

```
#!/usr/local/bin/perl

#####
# ITRC_Statistics
#  Dr  Stephen  Hallett,  Cranfield  University;  Oliver  Pritchard,  Cranfield
University
# 08/05/14
#
# Call as 'perl itrc_statistics.pl *.txt'  (where *.txt, or filelist, are the
climate files output by ITRC.pl to collate and summarise statistically)
# Workflow: Run itrc.pl FIRST on input files from Newcastle, then summarise
and collate the data using this code
# Assumes: All input files (wildcard) are in same format
#
#  Processes  processed  files  from  the  Newcastle  UKCP09  datasets  for  ITRC
project points
#
###
use warnings;
use strict;
#use diagnostics;
# with ActivePerl these are installed via ppm if not already present
use List::Util qw(sum);
use File::Basename;
BEGIN {@ARGV=map glob, @ARGV} # expand wildcard file arguments

######################################
#### Don't edit below here

open(OUTFILE,">Statistics.csv")  ||  die  sprintf("Oops  -  Could  not  open
'Statistics.csv'");
printf(OUTFILE "Grid, Source, Jan_Mean, Jan_StDev, Jan_P10, Jan_P25, Jan_P50,
Jan_P75,  Jan_P90,  Feb_Mean,  Feb_StDev,  Feb_P10,  Feb_P25,  Feb_P50,  Feb_P75,
Feb_P90,  Mar_Mean,  Mar_StDev,  Mar_P10,  Mar_P25,  Mar_P50,  Mar_P75,  Mar_P90,
Apr_Mean,  Apr_StDev,  Apr_P10,  Apr_P25,  Apr_P50,  Apr_P75,  Apr_P90,  May_Mean,
May_StDev,  May_P10,  May_P25,  May_P50,  May_P75,  May_P90,  Jun_Mean,  Jun_StDev,
Jun_P10,  Jun_P25,  Jun_P50,  Jun_P75,  Jun_P90,  Jul_Mean,  Jul_StDev,  Jul_P10,
Jul_P25,  Jul_P50,  Jul_P75,  Jul_P90,  Aug_Mean,  Aug_StDev,  Aug_P10,  Aug_P25,
Aug_P50,  Aug_P75,  Aug_P90,  Sep_Mean,  Sep_StDev,  Sep_P10,  Sep_P25,  Sep_P50,
Sep_P75,  Sep_P90,  Oct_Mean,  Oct_StDev,  Oct_P10,  Oct_P25,  Oct_P50,  Oct_P75,
Oct_P90,  Nov_Mean,  Nov_StDev,  Nov_P10,  Nov_P25,  Nov_P50,  Nov_P75,  Nov_P90,
Dec_Mean, Dec_StDev, Dec_P10, Dec_P25, Dec_P50, Dec_P75, Dec_P90, Annual_Mean,
Annual_StDev, Annual_P10, Annual_P25, Annual_P50, Annual_P75, Annual_P90\n");

###############################################

print "\nFor the ",$#ARGV + 1," files passed in:\n\n********\n";
foreach my $param(@ARGV) {
    &main($param); # call main with each successive output datafile in turn
}
```

```
close(OUTFILE);

# Called Functions ##########################

####################
# Function main
###
sub main {
    my ($file) = @_;
    my  (@Jan_stat,  @Feb_stat,  @Mar_stat,  @Apr_stat,  @May_stat,  @Jun_stat,
@Jul_stat,    @Aug_stat,    @Sep_stat,    @Oct_stat,    @Nov_stat,    @Dec_stat,
@Annual_stat)=();

    local $\ = "\r\n"; # EOL character for Windows file
    print "Please wait .. processing ", $file;
    my ($totalrows) = 0;

    # Open input file if not urban fraction
    if  ($file  =~  m/urban/)  {print  "...  skipping  'urban  fraction'  file\n";
return;}
    open(INFILE,  '<',  $file)  ||  die  sprintf("Oops  -  Could  not  open  %s",
$file);
    my ($basename) = fileparse($file, '\..*');
    my ($grid) = $basename =~ /(\d+)/; # extract numbers
    while (my $line = <INFILE>) {
        chomp $line;
        if (($totalrows > 0) && ($line ne "")) {
            # Process non blank lines > first, and read in raw data
                    my @fields = split ",", $line;
            push(@Jan_stat,  $fields[2]+0);  #  add  0  to  each  to  ensure  dealt
with as a number
            push(@Feb_stat, $fields[3]+0);
            push(@Mar_stat, $fields[4]+0);
            push(@Apr_stat, $fields[5]+0);
            push(@May_stat, $fields[6]+0);
            push(@Jun_stat, $fields[7]+0);
            push(@Jul_stat, $fields[8]+0);
            push(@Aug_stat, $fields[9]+0);
            push(@Sep_stat, $fields[10]+0);
            push(@Oct_stat, $fields[11]+0);
            push(@Nov_stat, $fields[12]+0);
            push(@Dec_stat, $fields[13]+0);
            push(@Annual_stat, $fields[14]+0);
        }
        $totalrows ++;
        #  Row  by  row  status  output   [note,  hugely  slows  down  run  time  -  use
for debug only]
        #print "Counters: ", $totalrows, "\n";
    }

      # Sort and report lists
      @Jan_stat = sort {$a <=> $b} @Jan_stat; # sort lists
    @Feb_stat = sort {$a <=> $b} @Feb_stat;
    @Mar_stat = sort {$a <=> $b} @Mar_stat;
    @Apr_stat = sort {$a <=> $b} @Apr_stat;
    @May_stat = sort {$a <=> $b} @May_stat;
    @Jun_stat = sort {$a <=> $b} @Jun_stat;
    @Jul_stat = sort {$a <=> $b} @Jul_stat;
    @Aug_stat = sort {$a <=> $b} @Aug_stat;
    @Sep_stat = sort {$a <=> $b} @Sep_stat;
    @Oct_stat = sort {$a <=> $b} @Oct_stat;
    @Nov_stat = sort {$a <=> $b} @Nov_stat;
    @Dec_stat = sort {$a <=> $b} @Dec_stat;
    @Annual_stat = sort {$a <=> $b} @Annual_stat;
      print $#Annual_stat+1, " data rows";
```

```
      printf ("Annual: Mean%.2f StDev%.2f (10th)%.2f (25th)%.2f (50th)%.2f
(75th)%.2f      (90th)%.2f      percentiles\n",      average(\@Annual_stat),
stdev(\@Annual_stat),                            percentile(10,\@Annual_stat),
percentile(25,\@Annual_stat),                    percentile(50,\@Annual_stat),
percentile(75,\@Annual_stat), percentile(90,\@Annual_stat));

    # Write out grid statistics
    printf(OUTFILE "%d, %s, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f, %.2f,
%.2f, %.2f, %.2f, %.2f, %.2f\n",$grid, $basename,
    average(\@Jan_stat),     stdev(\@Jan_stat),     percentile(10,\@Jan_stat),
percentile(25,\@Jan_stat),percentile(50,\@Jan_stat),percentile(75,\@Jan_stat),
percentile(90,\@Jan_stat),
    average(\@Feb_stat),     stdev(\@Feb_stat),     percentile(10,\@Feb_stat),
percentile(25,\@Feb_stat),percentile(50,\@Feb_stat),percentile(75,\@Feb_stat),
percentile(90,\@Feb_stat),
    average(\@Mar_stat),     stdev(\@Mar_stat),     percentile(10,\@Mar_stat),
percentile(25,\@Mar_stat),percentile(50,\@Mar_stat),percentile(75,\@Mar_stat),
percentile(90,\@Mar_stat),
      average(\@Apr_stat),    stdev(\@Apr_stat),    percentile(10,\@Apr_stat),
percentile(25,\@Apr_stat),percentile(50,\@Apr_stat),percentile(75,\@Apr_stat),
percentile(90,\@Apr_stat),
    average(\@May_stat),     stdev(\@May_stat),     percentile(10,\@May_stat),
percentile(25,\@May_stat),percentile(50,\@May_stat),percentile(75,\@May_stat),
percentile(90,\@May_stat),
    average(\@Jun_stat),     stdev(\@Jun_stat),     percentile(10,\@Jun_stat),
percentile(25,\@Jun_stat),percentile(50,\@Jun_stat),percentile(75,\@Jun_stat),
percentile(90,\@Jun_stat),
    average(\@Jul_stat),     stdev(\@Jul_stat),     percentile(10,\@Jul_stat),
percentile(25,\@Jul_stat),percentile(50,\@Jul_stat),percentile(75,\@Jul_stat),
percentile(90,\@Jul_stat),
    average(\@Aug_stat),     stdev(\@Aug_stat),     percentile(10,\@Aug_stat),
percentile(25,\@Aug_stat),percentile(50,\@Aug_stat),percentile(75,\@Aug_stat),
percentile(90,\@Aug_stat),
    average(\@Sep_stat),     stdev(\@Sep_stat),     percentile(10,\@Sep_stat),
percentile(25,\@Sep_stat),percentile(50,\@Sep_stat),percentile(75,\@Sep_stat),
percentile(90,\@Sep_stat),
    average(\@Oct_stat),     stdev(\@Oct_stat),     percentile(10,\@Oct_stat),
percentile(25,\@Oct_stat),percentile(50,\@Oct_stat),percentile(75,\@Oct_stat),
percentile(90,\@Oct_stat),
    average(\@Nov_stat),     stdev(\@Nov_stat),     percentile(10,\@Nov_stat),
percentile(25,\@Nov_stat),percentile(50,\@Nov_stat),percentile(75,\@Nov_stat),
percentile(90,\@Nov_stat),
    average(\@Dec_stat),     stdev(\@Dec_stat),     percentile(10,\@Dec_stat),
percentile(25,\@Dec_stat),percentile(50,\@Dec_stat),percentile(75,\@Dec_stat),
percentile(90,\@Dec_stat),
    average(\@Annual_stat),                                stdev(\@Annual_stat),
percentile(10,\@Annual_stat),
percentile(25,\@Annual_stat),percentile(50,\@Annual_stat),percentile(75,\@Annu
al_stat),percentile(90,\@Annual_stat));

    # Finish up
    close(INFILE);
    undef(@Jan_stat); # clear out the lists
    undef(@Feb_stat);
    undef(@Mar_stat);
    undef(@Apr_stat);
    undef(@May_stat);
    undef(@Jun_stat);
    undef(@Jul_stat);
```

```
    undef(@Aug_stat);
    undef(@Sep_stat);
    undef(@Oct_stat);
    undef(@Nov_stat);
    undef(@Dec_stat);
    undef(@Annual_stat);
    print "Finished processing. Number of rows processed in total was ",
$totalrows, "\n********";
}

# Statistics functions
sub average{
        my($data) = @_;
        if (not @$data) {
                die("Empty array\n");
        }
        my $total = 0;
        foreach (@$data) {
                $total += $_;
        }
        my $average = $total / @$data;
        return $average;
}
sub stdev{
        my($data) = @_;
        if(@$data == 1){
                return 0;
        }
        my $average = &average($data);
        my $sqtotal = 0;
        foreach(@$data) {
                $sqtotal += ($average-$_) ** 2;
        }
        my $std = ($sqtotal / (@$data-1)) ** 0.5;
        return $std;
}
sub percentile {
    my ($p,$aref) = @_;
    my $percentile = int($p * $#{$aref}/100);
    return (@$aref)[$percentile];
}

###########################
# eof: ITRC_Statistics.pl #
###########################
```

Appendix D Great Britain Rainfall and Potential Evapotranspiration Maps

The following appendix presents both the baseline and forward-looking (2030 and 2050) rainfall and potential evapotranspiration (PET) scenario maps. The 10^{th}, 50^{th} and 90^{th} percentiles are shown separately in respect of the climatic scenario at both a monthly and annual accumulated value. These maps have been created in the steps outlined in Chapter 4.

Figure D-2: UKCP09-derived projections of accumulated annual Potential Evapotranspiration for GB baseline (1961-1990) (a) 10th, (b) 50th and (c) 90th percentiles; 2030 (2020-2049) (d) 10th, (e) 50th and (f) 90th percentiles; 2050 (2040-2069) (g) 10th, (h) 50th and (i) 90th percentiles

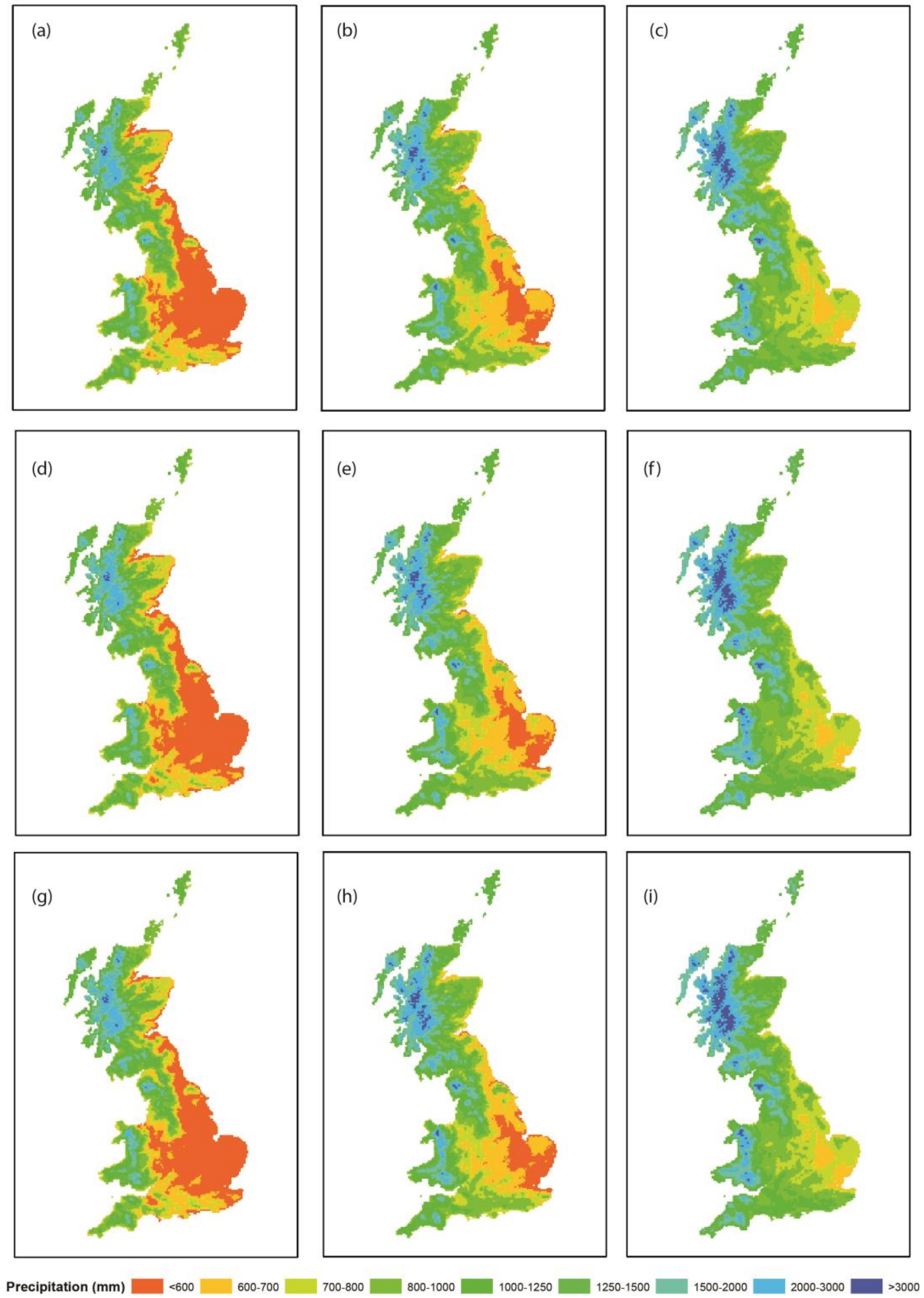


Figure D-3: UKCP09-derived projections of annual Precipitation for GB baseline (1961-1990) (a) 10th, (b) 50th and (c) 90th percentiles; 2030 (2020-2049) (d) 10th, (e) 50th and (f) 90th percentiles; 2050 (2040-2069) (g) 10th, (h) 50th and (i) 90th percentiles

Figure D-4: An 'unlikely to be less than' (10th percentile) monthly UKCP09 baseline (1961-1990) Precipitation

Figure D-5: An 'central estimate' (50th percentile) monthly UKCP09 baseline (1961-1990) Precipitation

Figure D-6: An ‘unlikely to be more than’ (90th percentile) monthly UKCP09 baseline (1961-1990) Precipitation

Figure D-7: An ‘unlikely to be less than’ (10th percentile) monthly UKCP09 2030 (2020-2049) Precipitation

Figure D-8: A 'central estimate' (50th percentile) monthly UKCP09 2030 (2020-2049) Precipitation

Figure D-9: An 'unlikely to be more than' (90th percentile) monthly UKCP09 2030 (2020-2049) Precipitation

Figure D-10: An 'unlikely to be less than' (10th percentile) monthly UKCP09 2050 (2040-2069) Precipitation

Figure D-11: A 'central estimate' (50th percentile) monthly UKCP09 2050 (2040-2069) Precipitation

Figure D-12: An ‘unlikely to be more than’ (90th percentile) monthly UKCP09 2050 (2040-2069) Precipitation

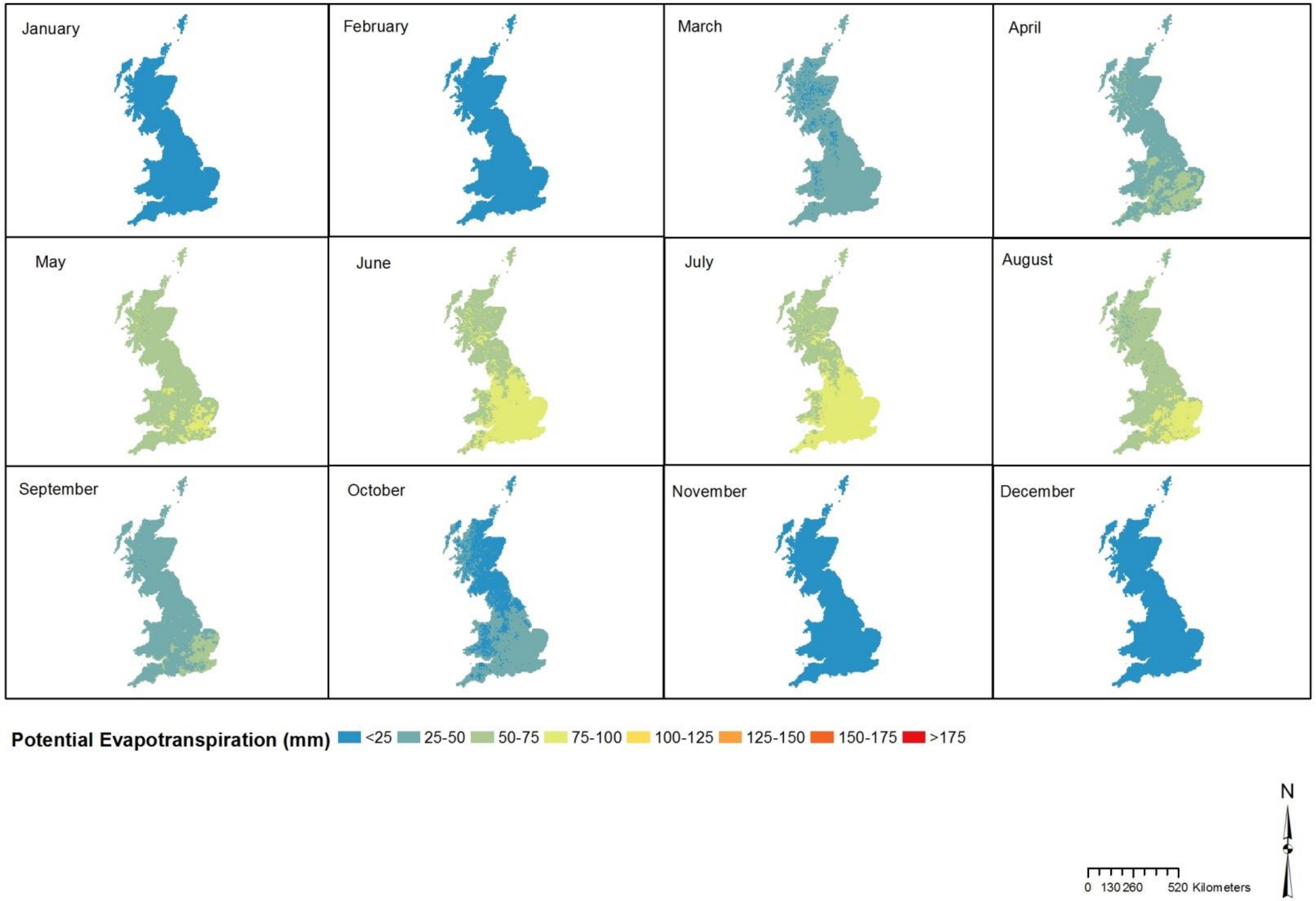


Figure D-13: An 'unlikely to be less than' (10th percentile) monthly UKCP09 baseline (1961-1990) Potential Evapotranspiration

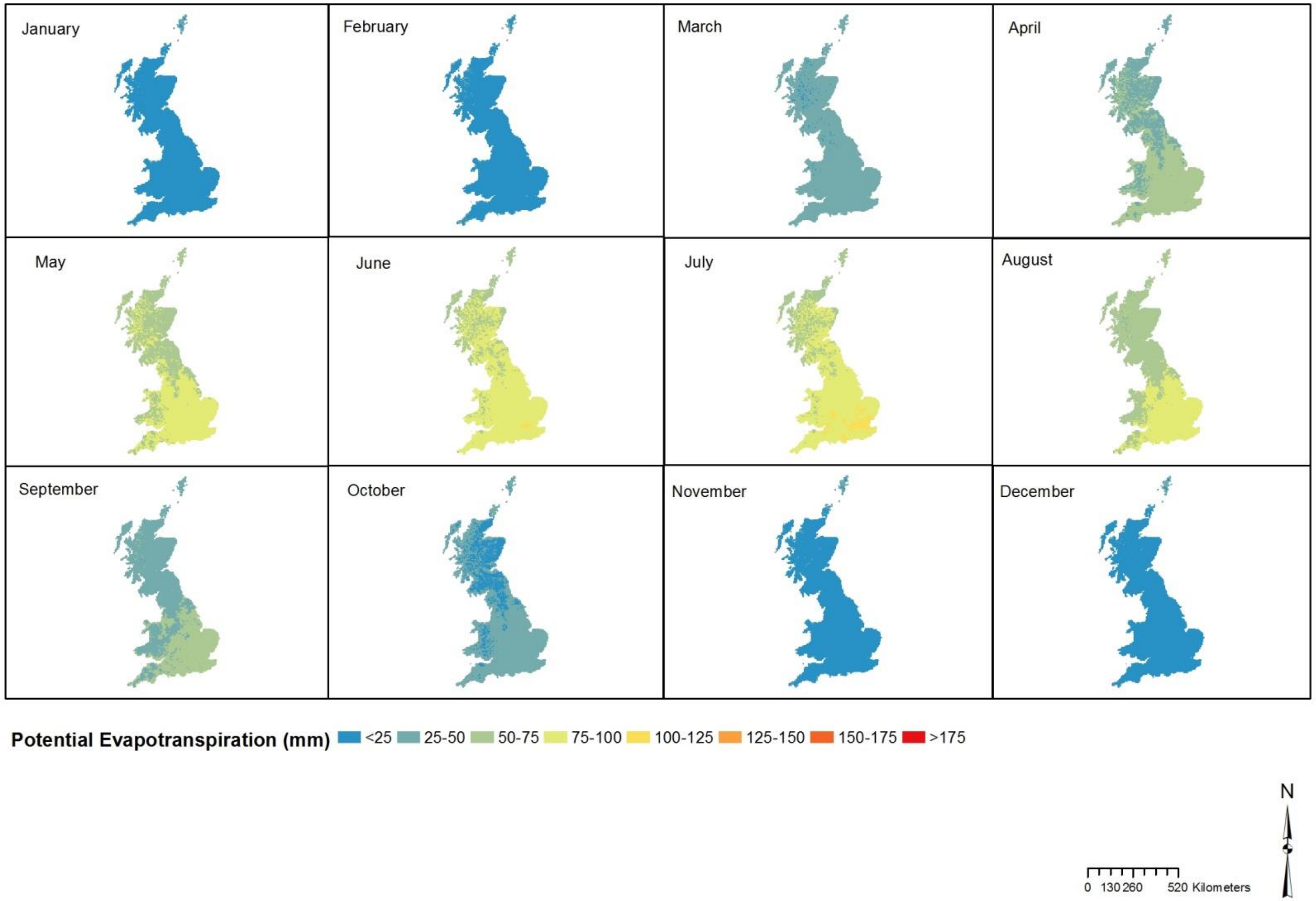


Figure D-14: A ‘central estimate’ (50th percentile) monthly UKCP09 baseline (1961-1990) Potential Evapotranspiration

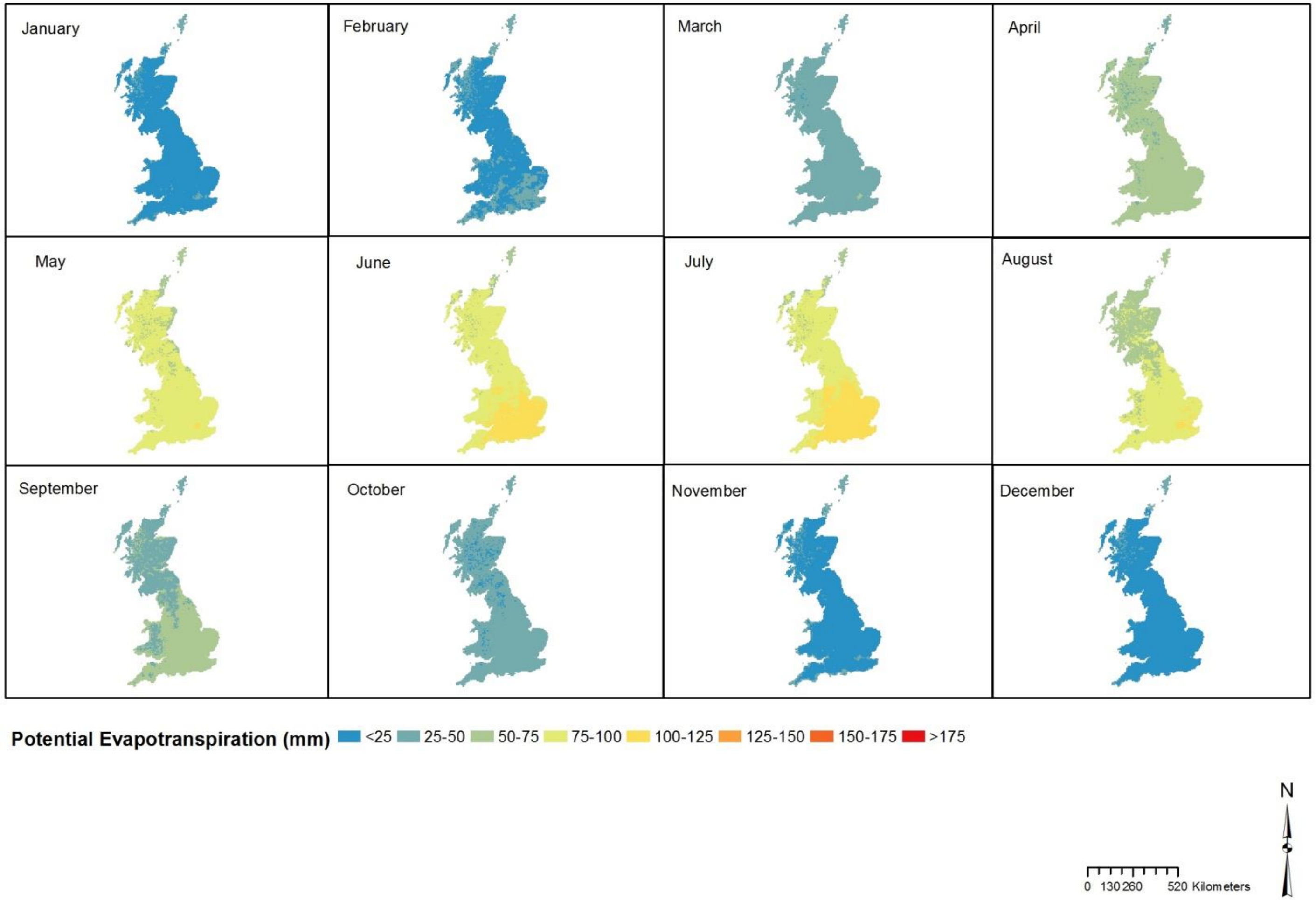


Figure D-15: An ‘unlikely to be more than’ (90th percentile) monthly UKCP09 baseline (1961-1990) Potential Evapotranspiration

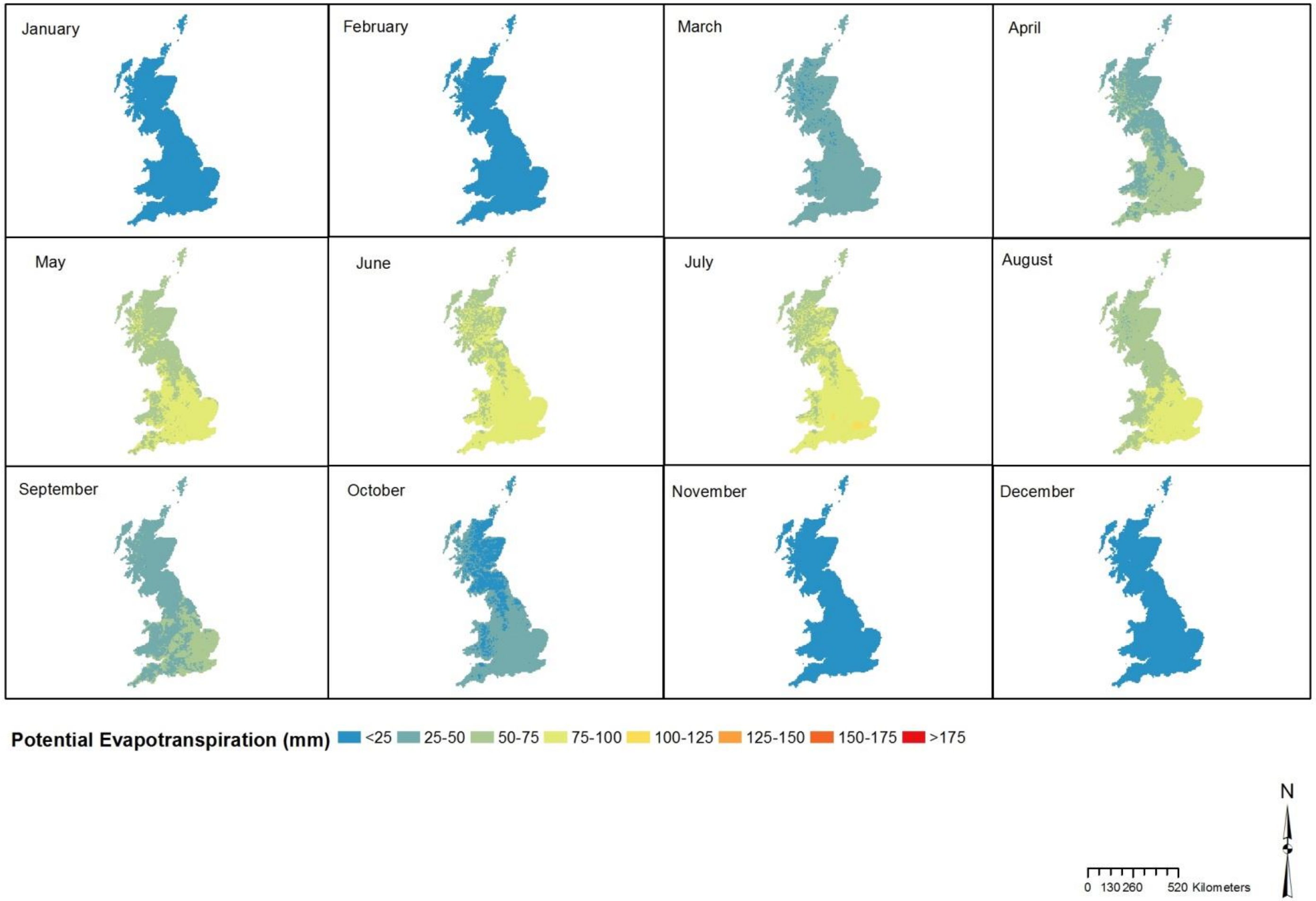


Figure D-16: An 'unlikely to be less than' (10th percentile) monthly UKCP09 2030 (2020-2049) Potential Evapotranspiration

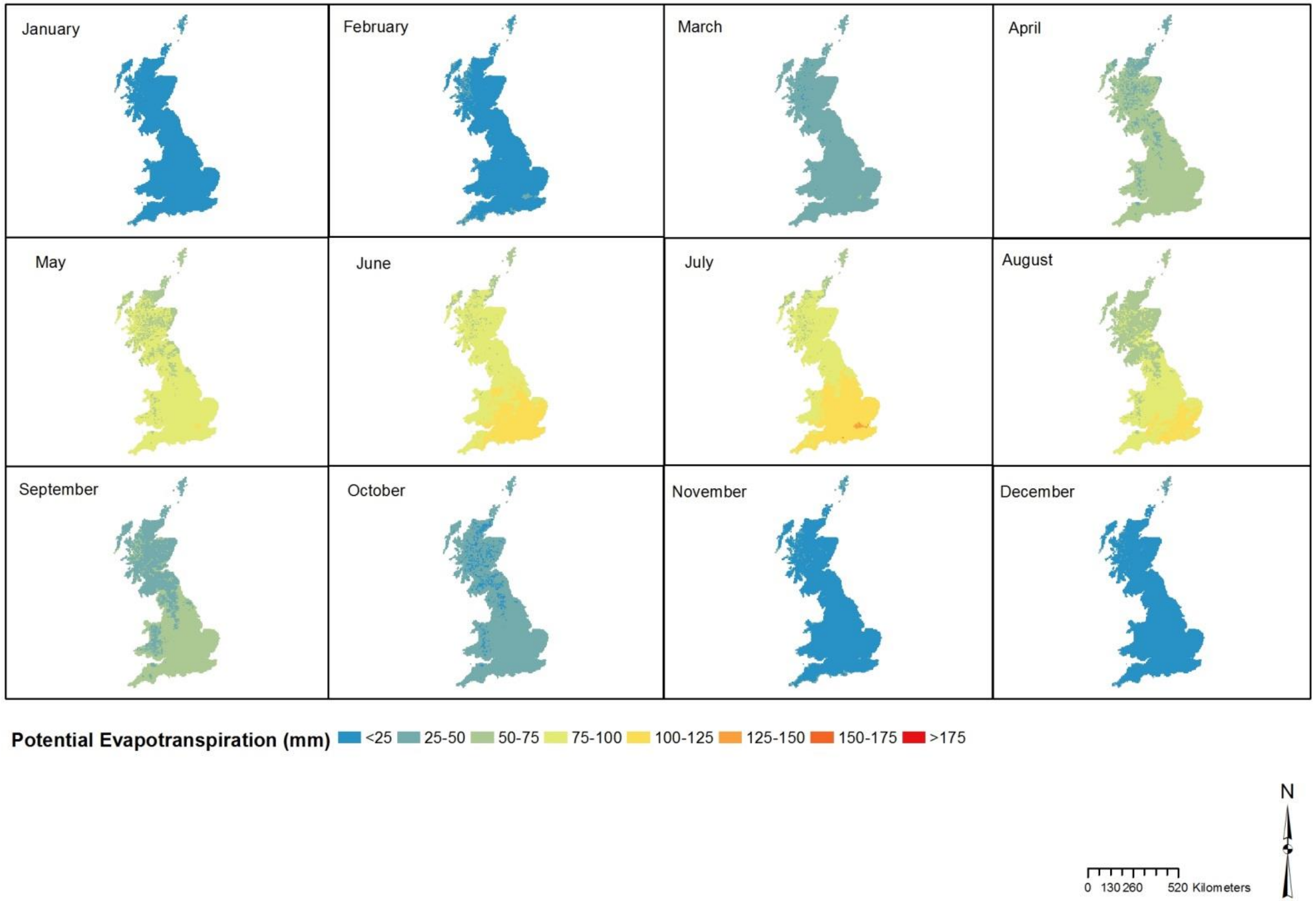


Figure D-17: A 'central estimate' (50th percentile) monthly UKCP09 2030 (2020-2049) Potential Evapotranspiration

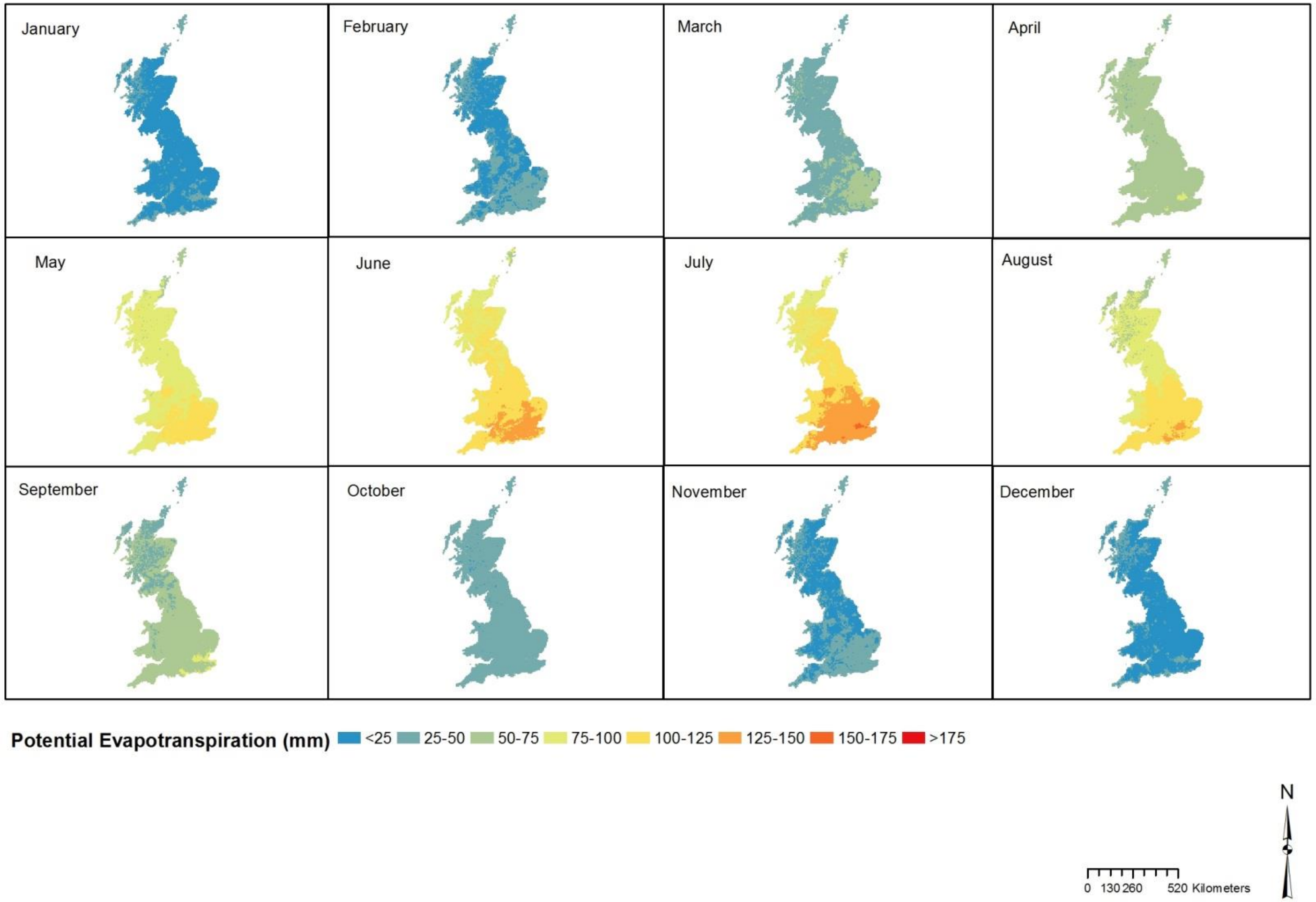


Figure D-18: An ‘unlikely to be more than’ (90th percentile) monthly UKCP09 2030 (2020-2049) Potential Evapotranspiration

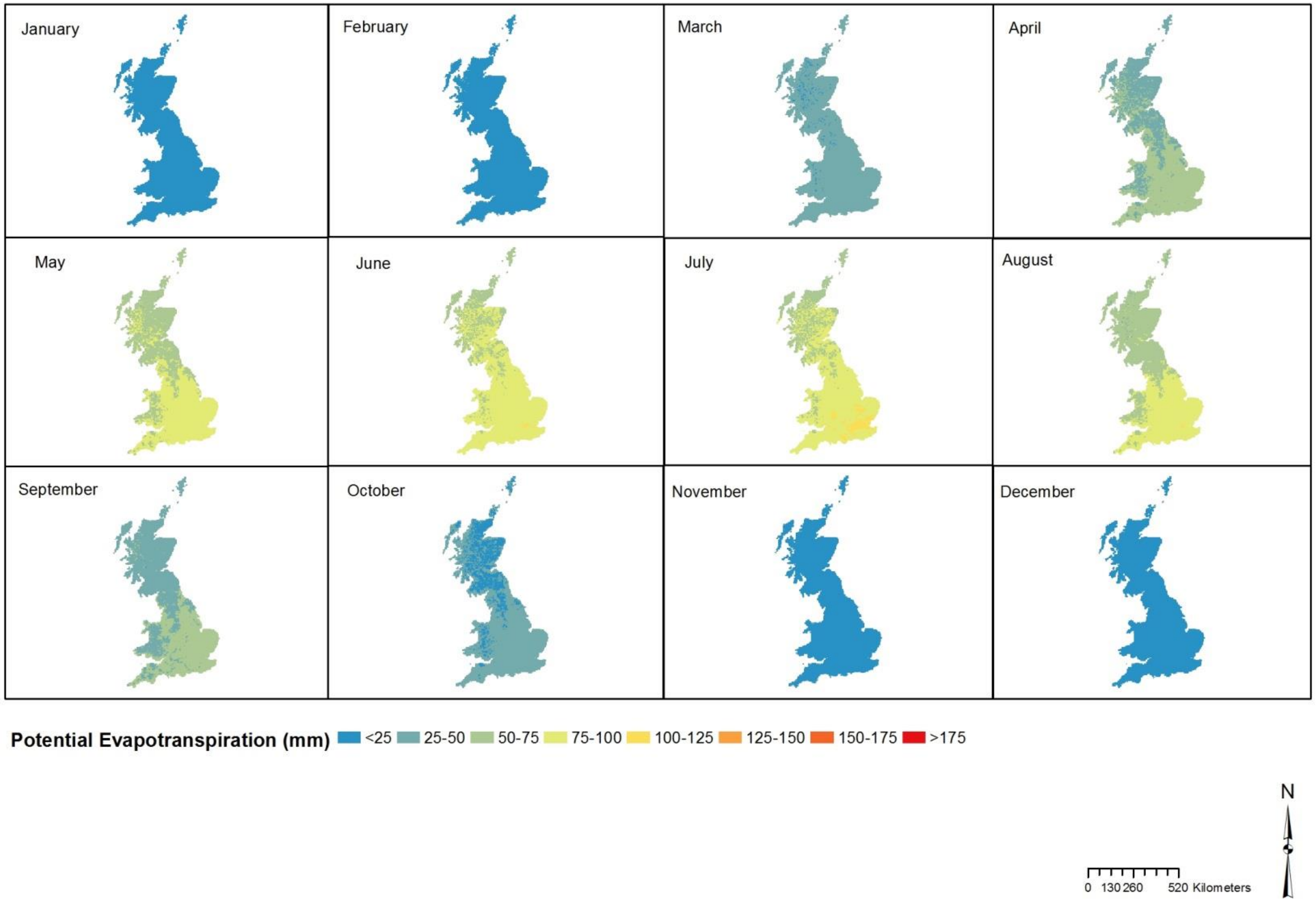


Figure D-19: An 'unlikely to be less than' (10th percentile) monthly UKCP09 2050 (2040-2069) Potential Evapotranspiration

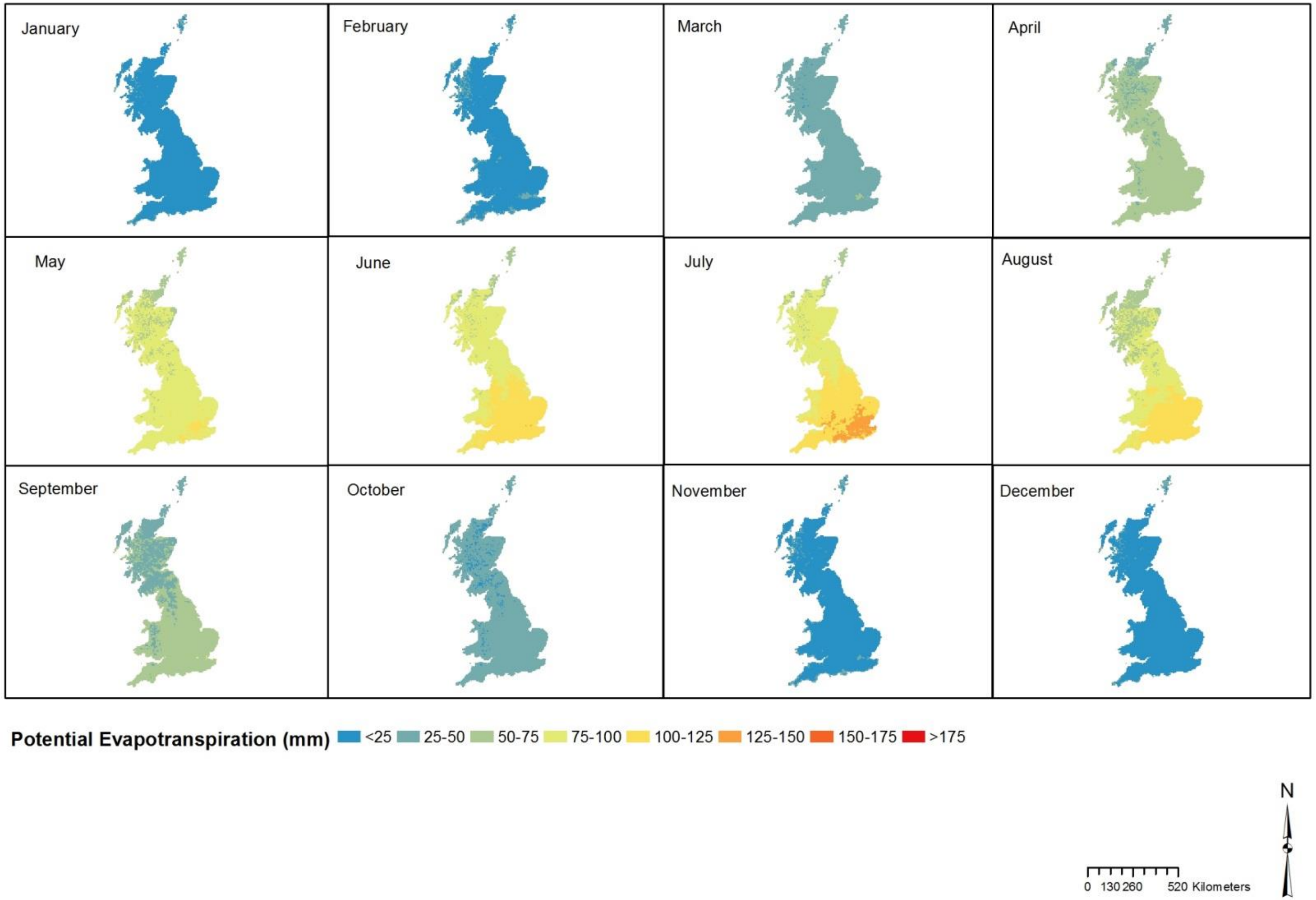


Figure D-20: A 'central estimate' (50th percentile) monthly UKCP09 2050 (2040-2069) Potential Evapotranspiration

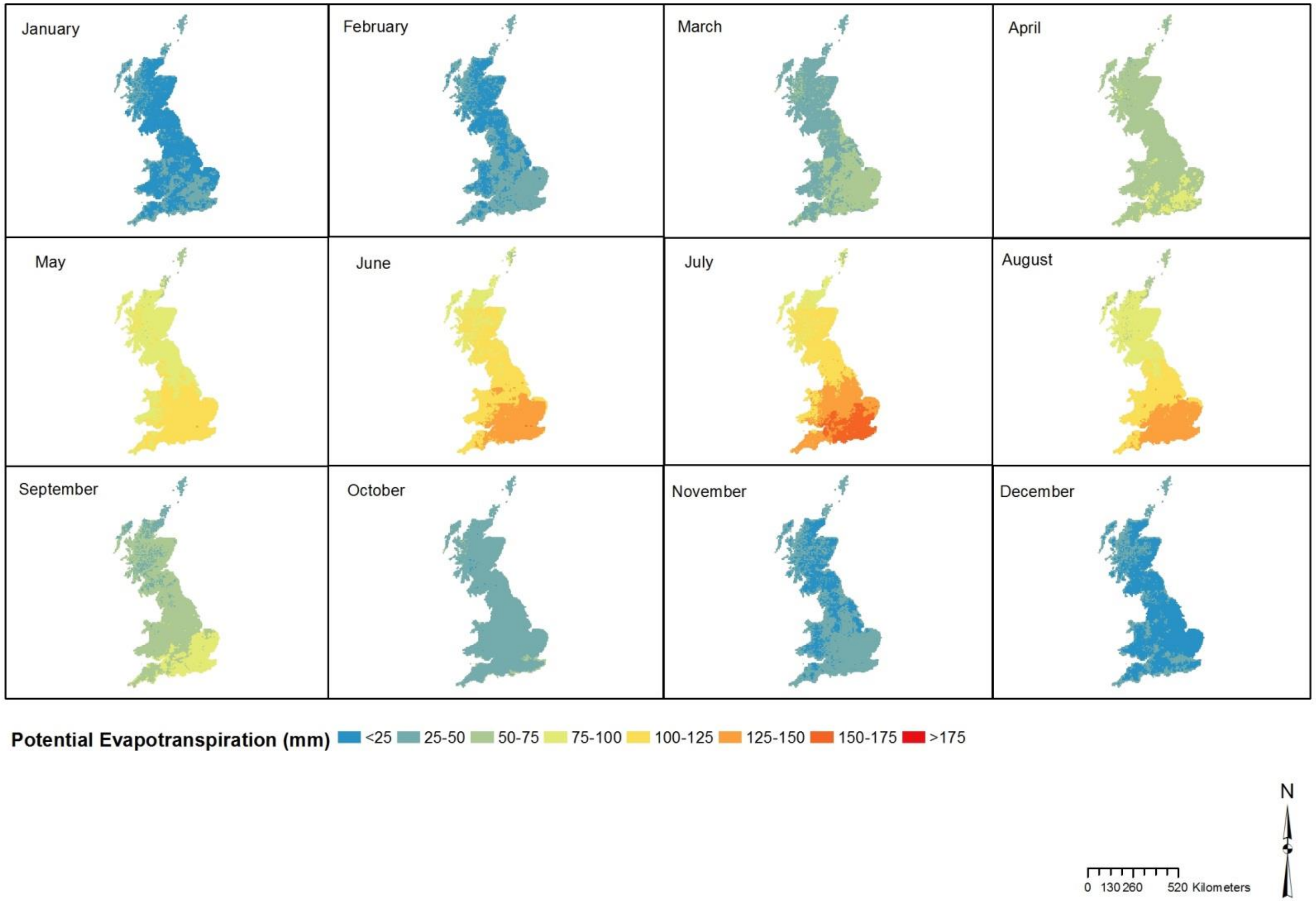


Figure D-21: An 'unlikely to be more than' (90th percentile) monthly UKCP09 2050 (2040-2069) Potential Evapotranspiration

Appendix E Great Britain Potential Soil Moisture Deficit Maps

The following appendix presents both the baseline and forward-looking (2030 and 2050) potential soil moisture deficit (PSMD) scenario maps. The 10th, 50th and 90th percentiles are shown separately in respect of the climatic scenario at both a monthly and annual accumulated value. These maps have been created in the steps outlined in Chapter 4.

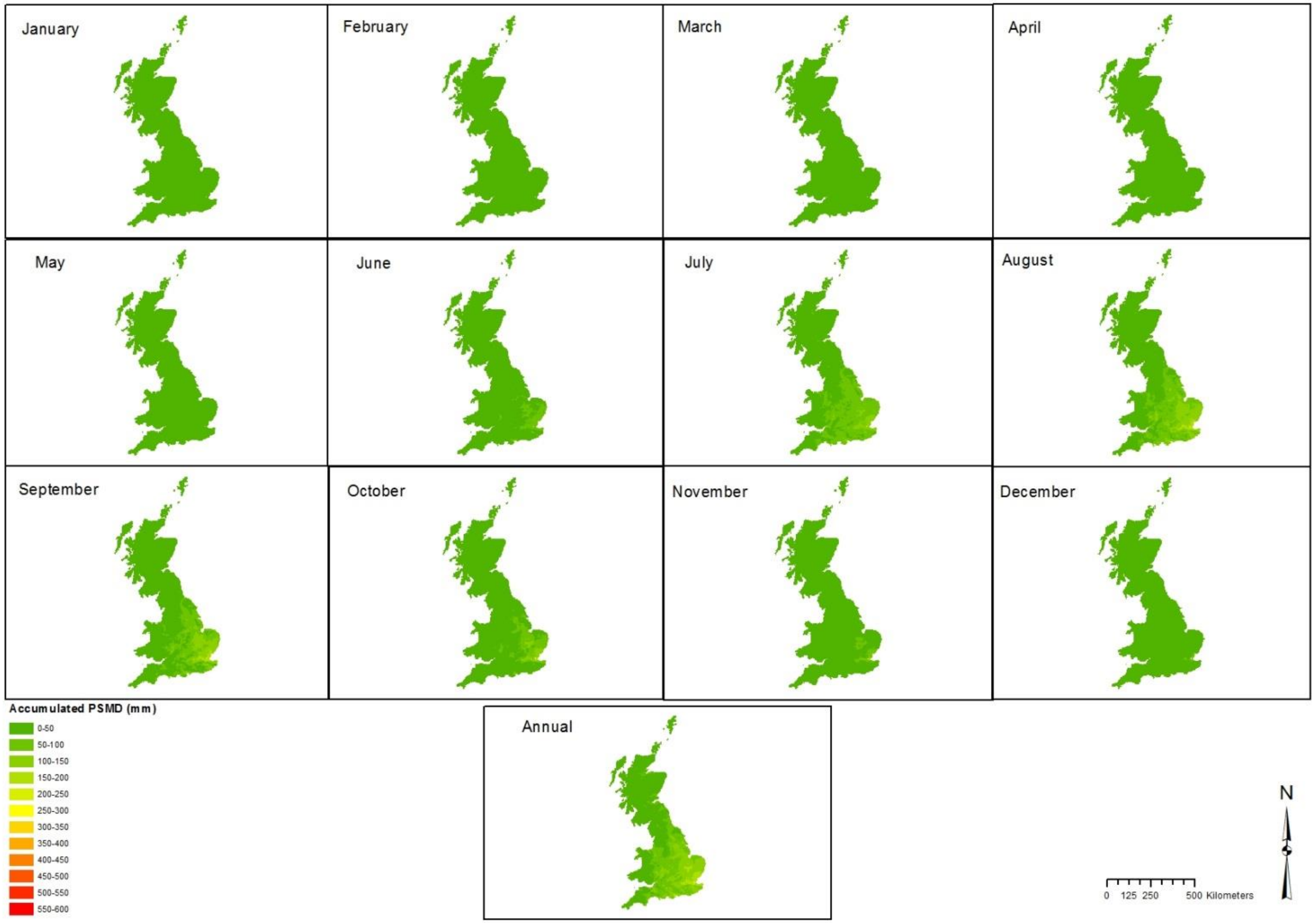


Figure E-22: An ‘unlikely to be less than’ (10th percentile) monthly and annual UKCP09 baseline (1961-1990) Accumulated Potential Soil Moisture Deficit (PSMD)

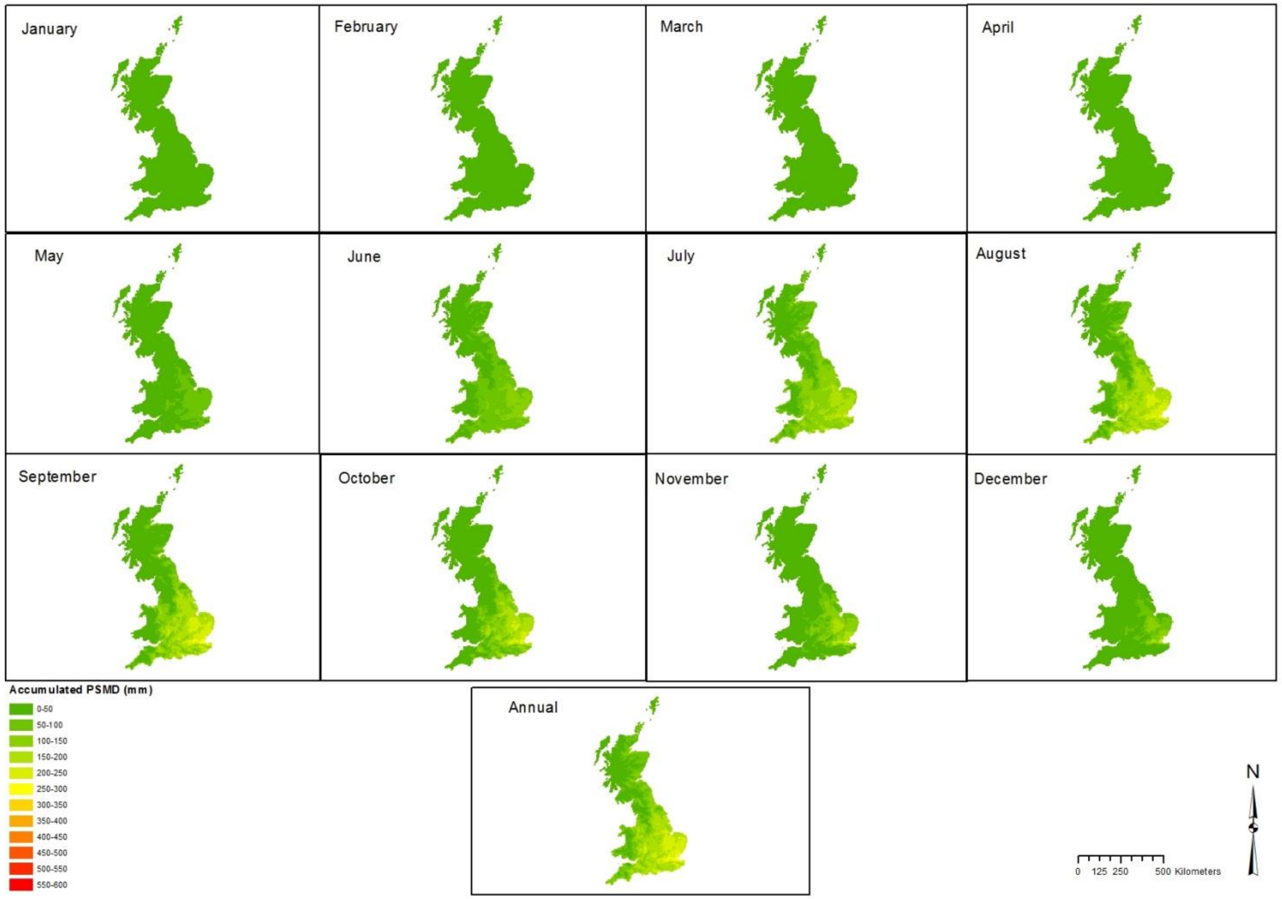


Figure E-23: A 'central estimate' (50th percentile) monthly and annual UKCP09 baseline (1961-1990) Accumulated Potential Soil Moisture Deficit (PSMD)

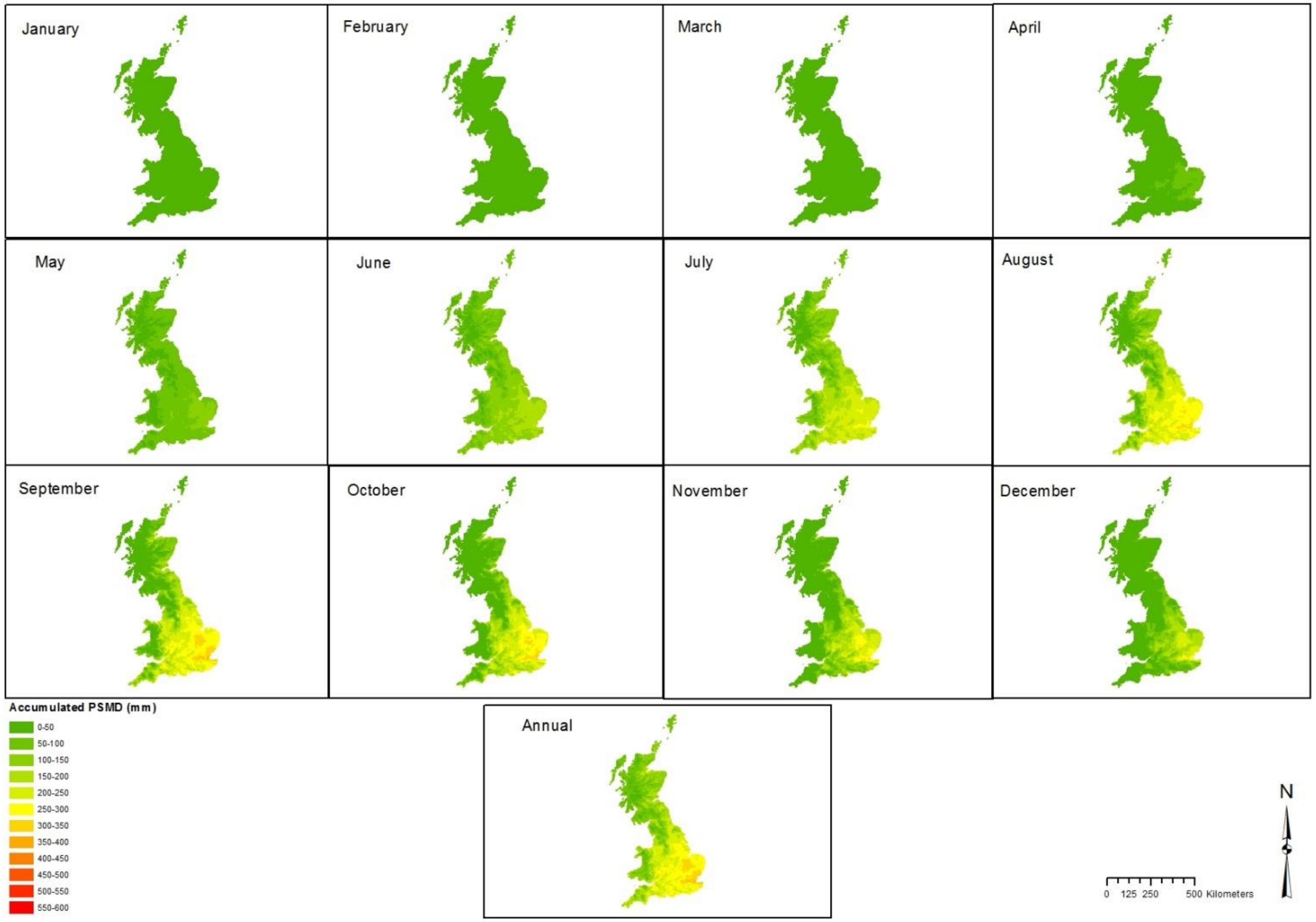


Figure E-24: An 'unlikely to be more than' (90th percentile) monthly and annual UKCP09 baseline (1961-1990) Accumulated Potential Soil Moisture Deficit (PSMD)

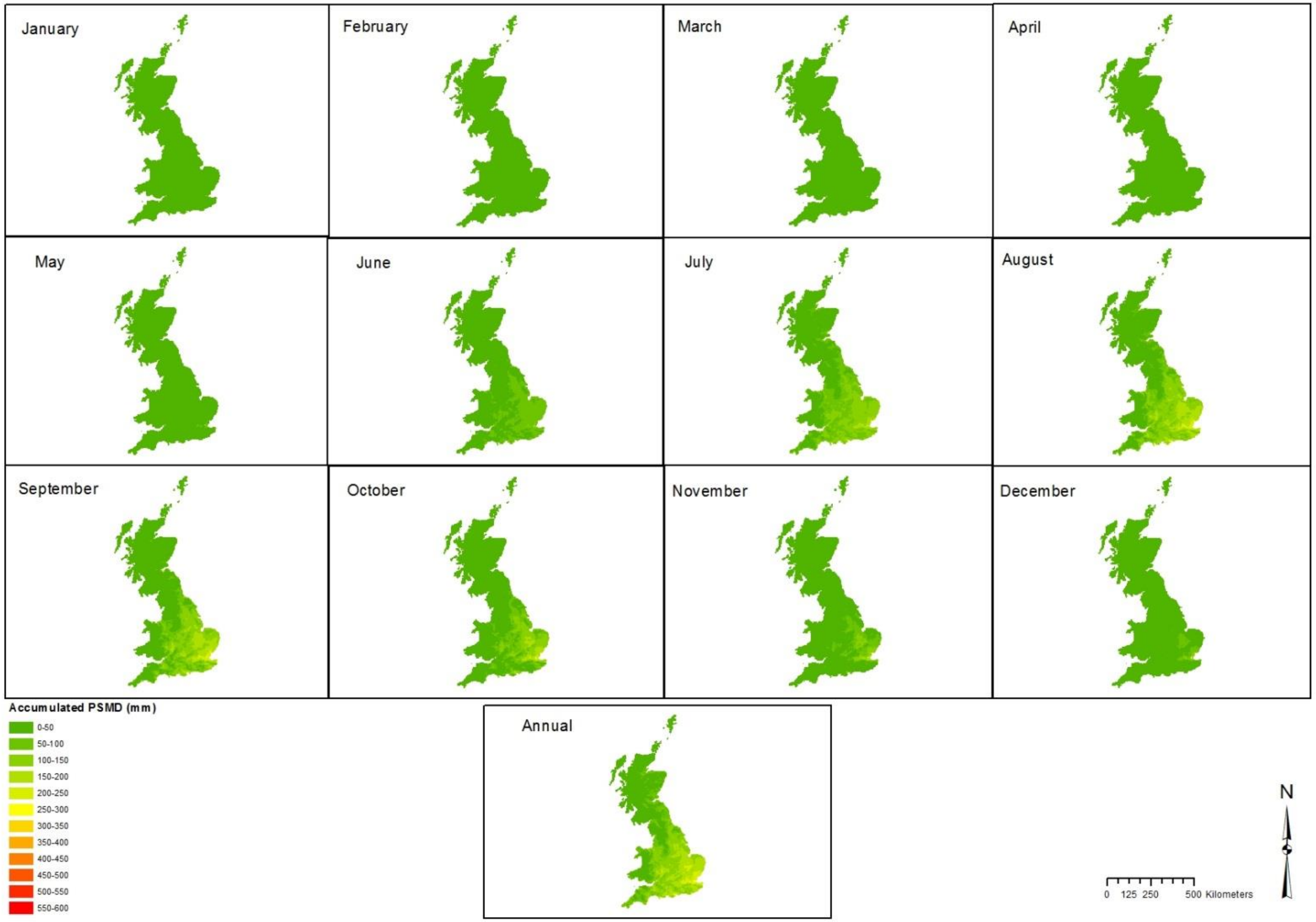


Figure E-25: An 'unlikely to be less than' (10th percentile) monthly and annual UKCP09 2030 (2020-2049) Accumulated Potential Soil Moisture Deficit (PSMD)

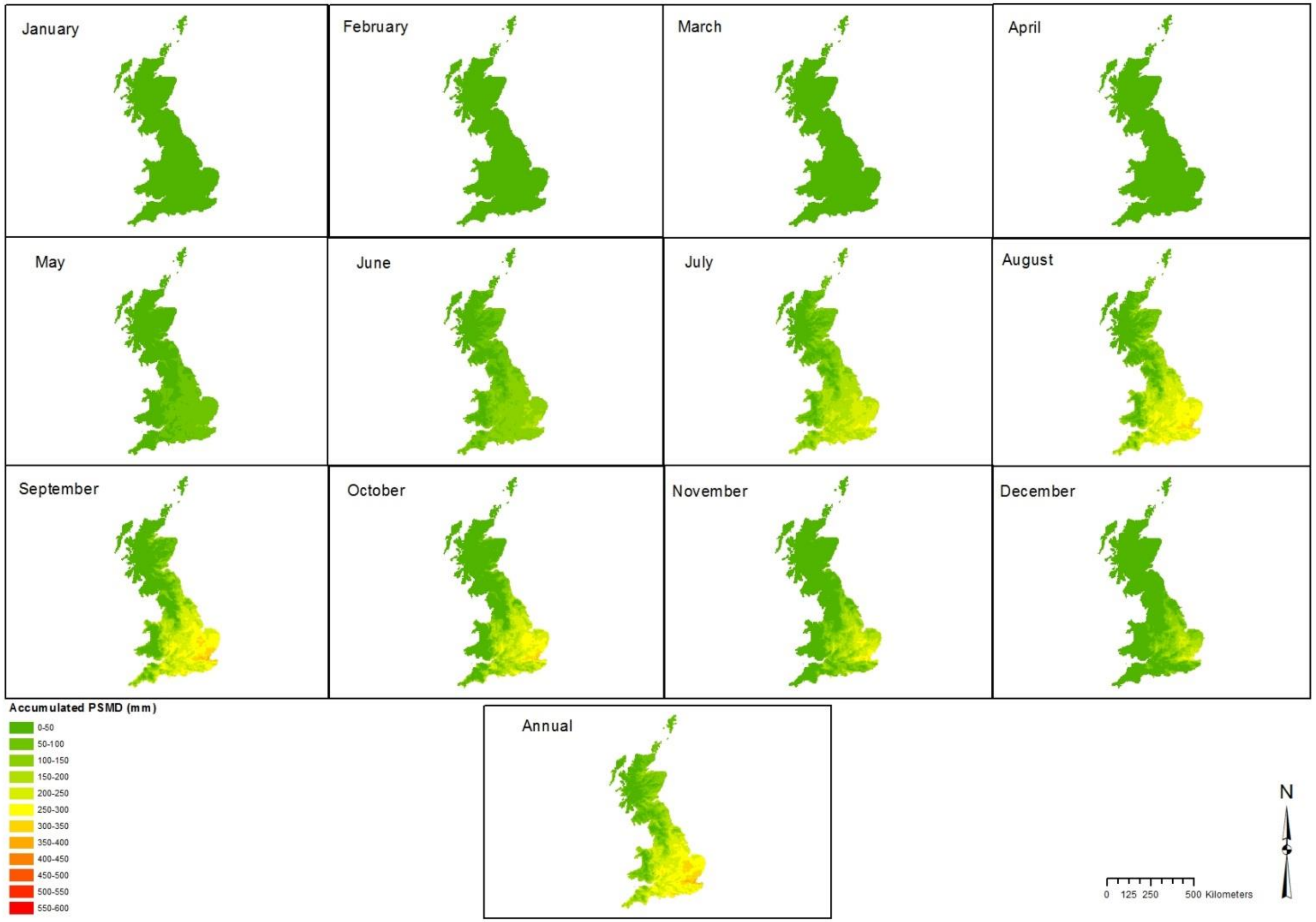


Figure E-26: A 'central estimate' (50th percentile) monthly and annual UKCP09 2030 (2020-2049) Accumulated Potential Soil Moisture Deficit (PSMD)

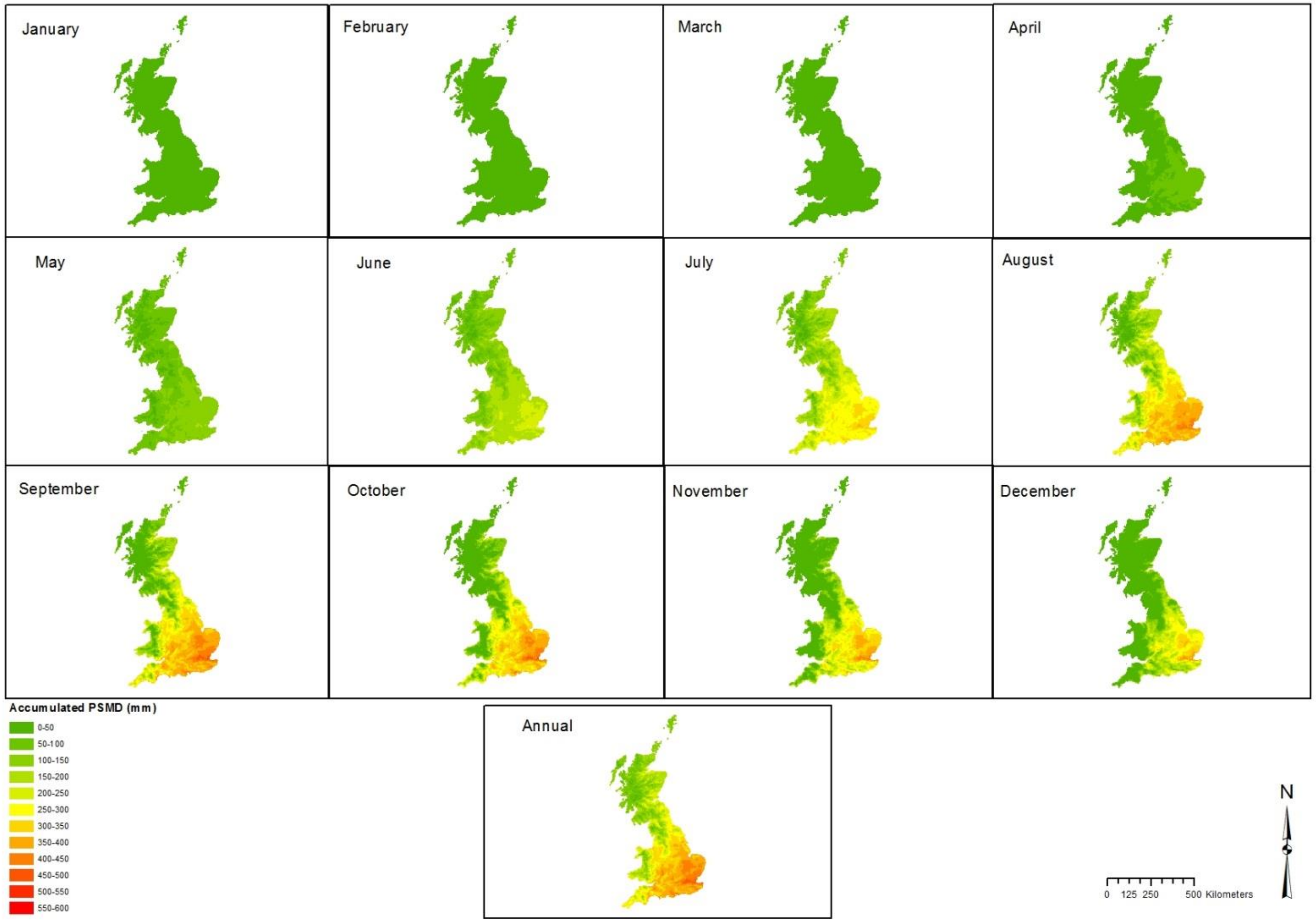


Figure E-27: An 'unlikely to be more than' (90th percentile) monthly and annual UKCP09 2030 (2020-2049) Accumulated Potential Soil Moisture Deficit (PSMD)

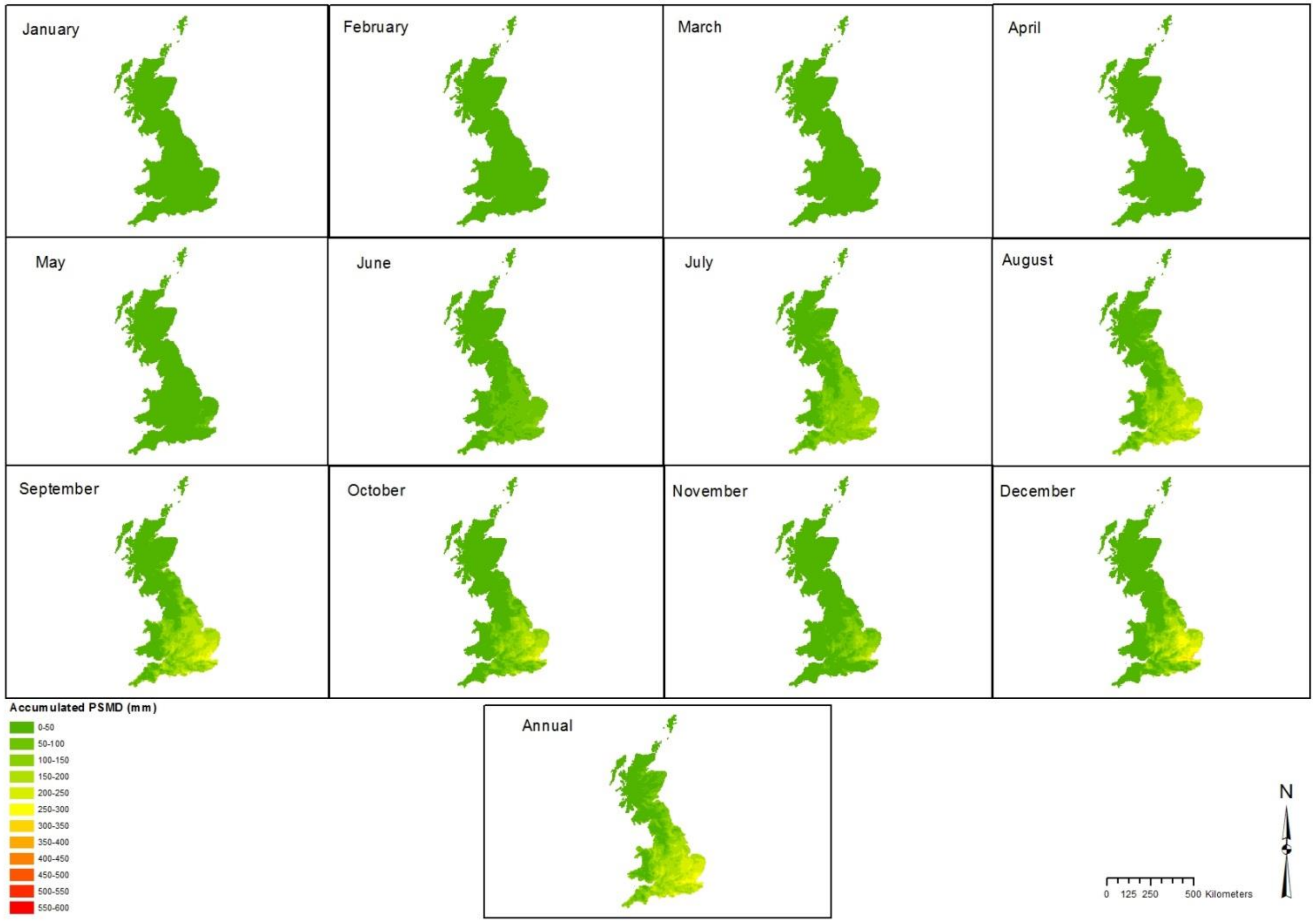


Figure E-28: An 'unlikely to be less than' (10th percentile) monthly and annual UKCP09 2050 (2040-2069) Accumulated Potential Soil Moisture Deficit (PSMD)

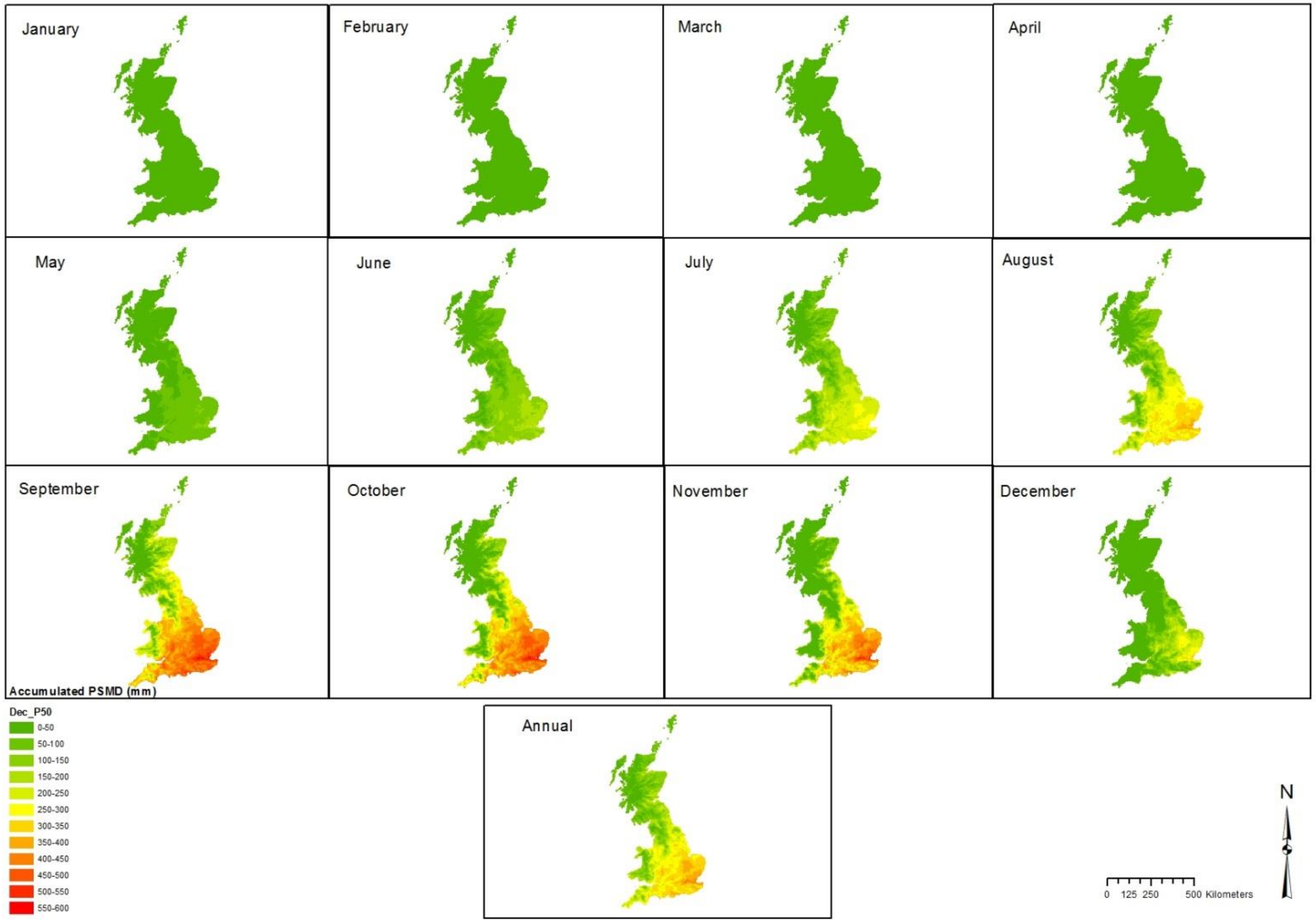


Figure E-29: A 'central estimate' (50th percentile) monthly and annual UKCP09 2050 (2040-2069) Accumulated Potential Soil Moisture Deficit (PSMD)

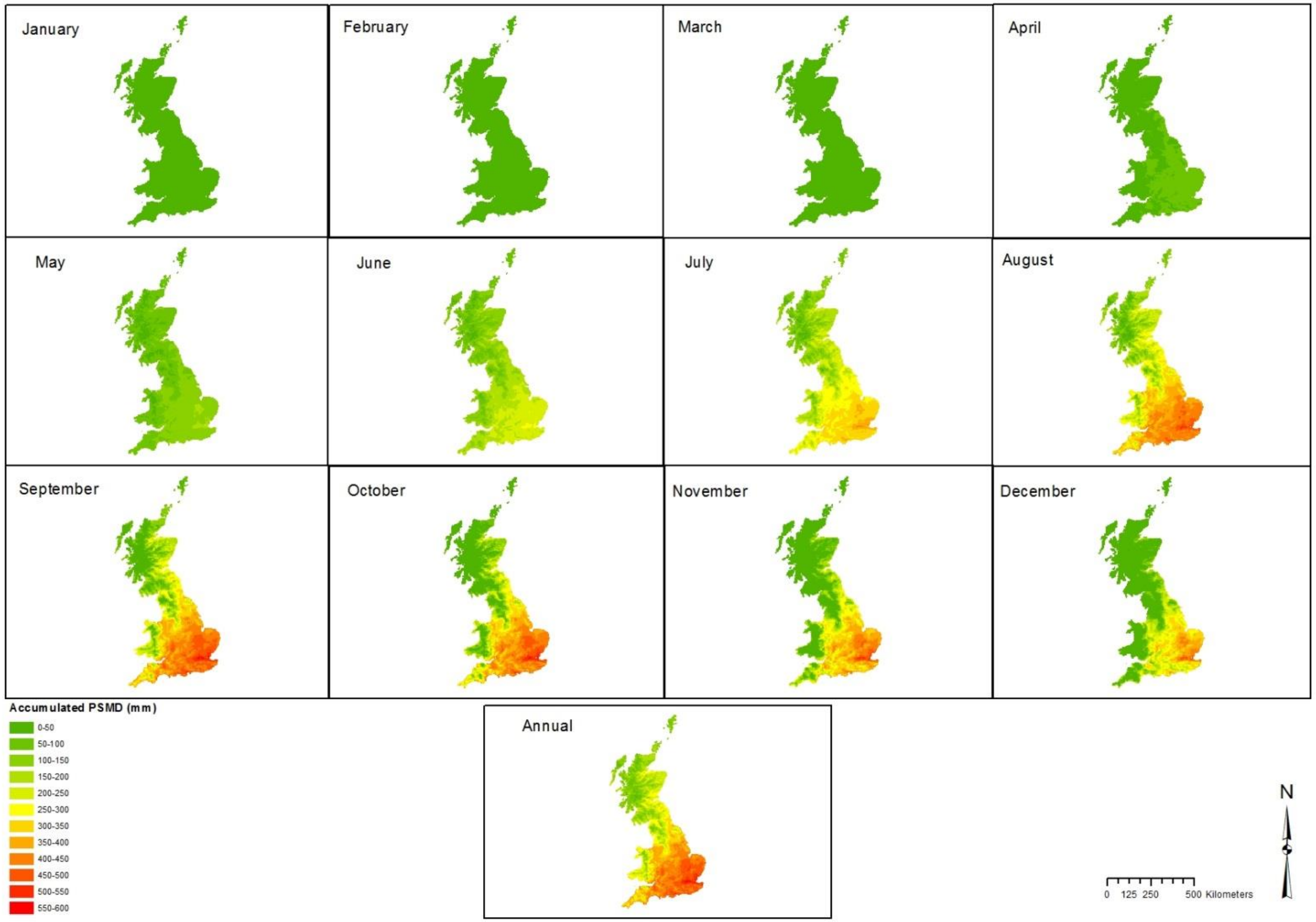


Figure E-30: An 'unlikely to be more than' (90th percentile) monthly and annual UKCP09 2050 (2040-2069) Accumulated Potential Soil Moisture Deficit (PSMD)

Appendix F Python code for NPD Futures model

Clay subsidence risk was calculated in ArcGIS field calculator, using the Python script in the box below. Assessments of clay subsidence risk can be undertaken incorporating the 10, 50, and 90th percentile of modelled PSMD, providing a range of uncertainty maps.

```
#Field calculator (Python):
# Author: Oliver Pritchard, Cranfield University

#To coincide with the likelihoods imposed by UKCP09, the 10th, 50th
and 90th percentiles of probabilistic #PSMD values will be used for
geohazard assessment.
#10th Percentile - Very Unlikely to be less than
#50th Percentile - Central Estimate
#90th Percentile - Very unlikely to be more than

#Subs_p10=
Recode(!DOM_SSWELL!, !Annual_P10!)

#Subs_p50=
Recode(!DOM_SSWELL!, !Annual_P50!)

#Subs_p90=
Recode(!DOM_SSWELL!, !Annual_P90!)

#Pre-Logic Script Code:

def Recode(sswell, psmd):
  if (sswell is None or sswell == 0 or psmd is None or psmd == 0):
    return "Undefined"
  #
  # Risk matrix
  if (psmd < 10):
    return "Extremely Low"

  #
  if (psmd = 1):
    if (sswell == 1):
      return "Extremely Low"
    elif (sswell == 2):
      return "Very Low"
    elif (sswell == 3):
      return "Very Low"
    elif (sswell == 4):
      return "Medium Low"
    elif (sswell == 5):
      return "Medium"
    elif (sswell == 6):
      return "Medium"
  #
  if (psmd = 2):
    if (sswell == 1):
      return "Extremely Low"
    elif (sswell == 2):
```

```
      return "Very Low"
    elif (sswell == 3):
      return "Low"
    elif (sswell == 4):
      return "Medium Low"
    elif (sswell == 5):
      return "Medium"
    elif (sswell == 6):
      return "Medium"

  #
  if (psmd = 3):
    if (sswell == 1):
      return "Extremely Low"
    elif (sswell == 2):
      return "Very Low"
    elif (sswell == 3):
      return "Medium Low"
    elif (sswell == 4):
      return "Medium"
    elif (sswell == 5):
      return "High"
    elif (sswell == 6):
      return "Medium High"
  #
  if (psmd = 4):
    if (sswell == 1):
      return "Extremely Low"
    elif (sswell == 2):
      return "Very Low"
    elif (sswell == 3):
      return "Medium"
    elif (sswell == 4):
      return "Medium High"
    elif (sswell == 5):
      return "Very High"
    elif (sswell == 6):
      return "High"
  #
  if (psmd = 5):
    if (sswell == 1):
      return "Extremely Low"
    elif (sswell == 2):
      return "Very Low"
    elif (sswell == 3):
      return "Medium"
    elif (sswell == 4):
      return "High"
    elif (sswell == 5):
      return "Very High"
    elif (sswell == 6):
      return "Very High"
  #
  if (psmd = 6):
    if (sswell == 1):
      return "Extremely Low"
    elif (sswell == 2):
      return "Very Low"
    elif (sswell == 3):
```

```
      return "Medium"
    elif (sswell == 4):
      return "High"
    elif (sswell == 5):
      return "Extremely High"
    elif (sswell == 6):
      return "Extremely High"
  #
  if (psmd = 7):
    if (sswell == 1):
      return "Very Low"
    elif (sswell == 2):
      return "Low"
    elif (sswell == 3):
      return "Medium High"
    elif (sswell == 4):
      return "Extremely High"
    elif (sswell == 5):
      return "Extremely High"
    elif (sswell == 6):
      return "Extremely High"
  #
  return "Fallen through. sswell: " + str(sswell) + ", psmd: " +
str(psmd)
```

Appendix G Quantile-Quantile plots

The following figures represent quantile-quantile plots for the ten selected grid cells of the analysis presented in Chapter 4. See Figure 4-6 for grid cell locations.

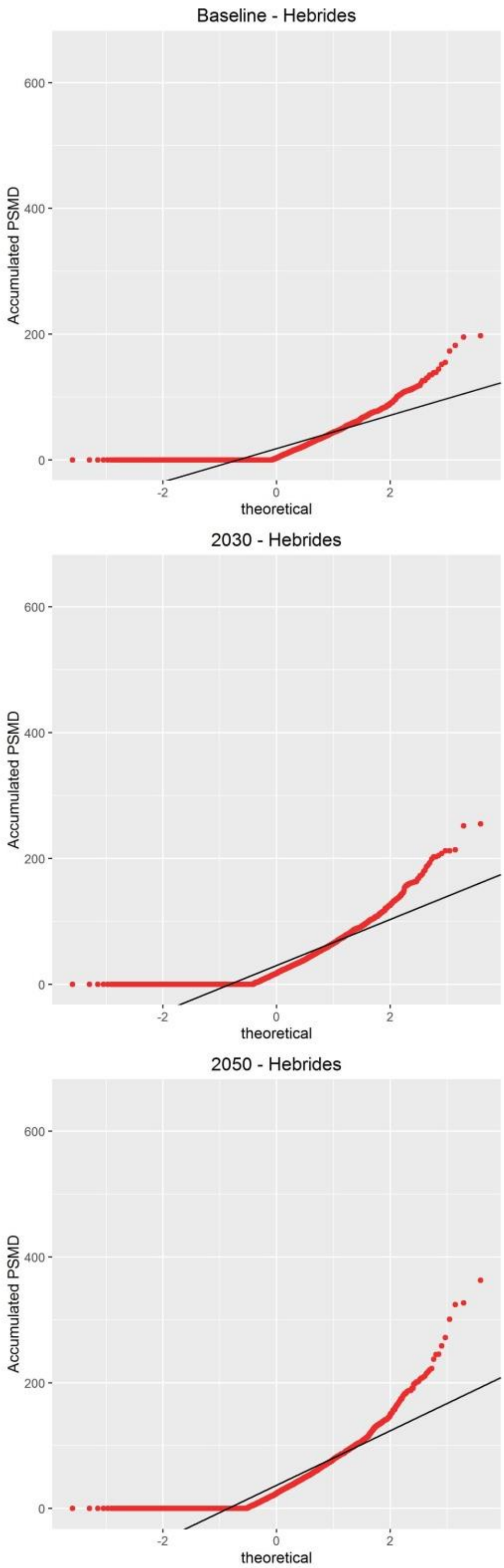


Figure G-31: Quantile-Quantile plot for Hebrides grid cell for baseline, 2030 and 2050 PSMD

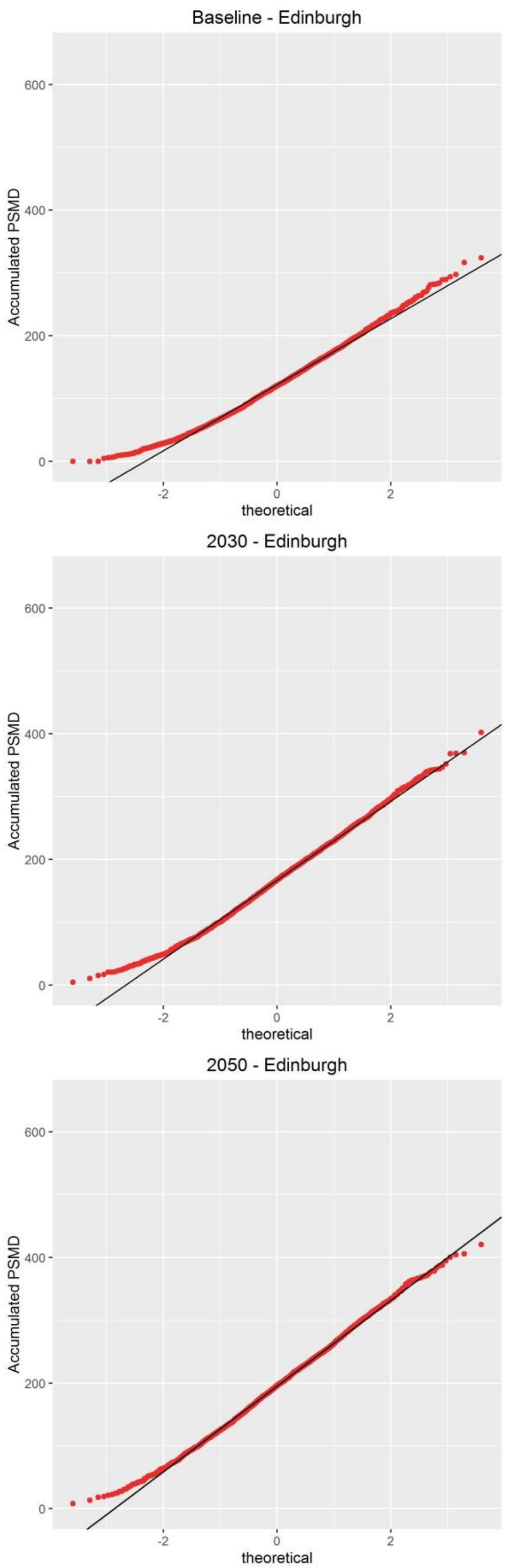


Figure G-32: Quantile-Quantile plot for Edinburgh grid cell for baseline, 2030 and 2050 PSMD

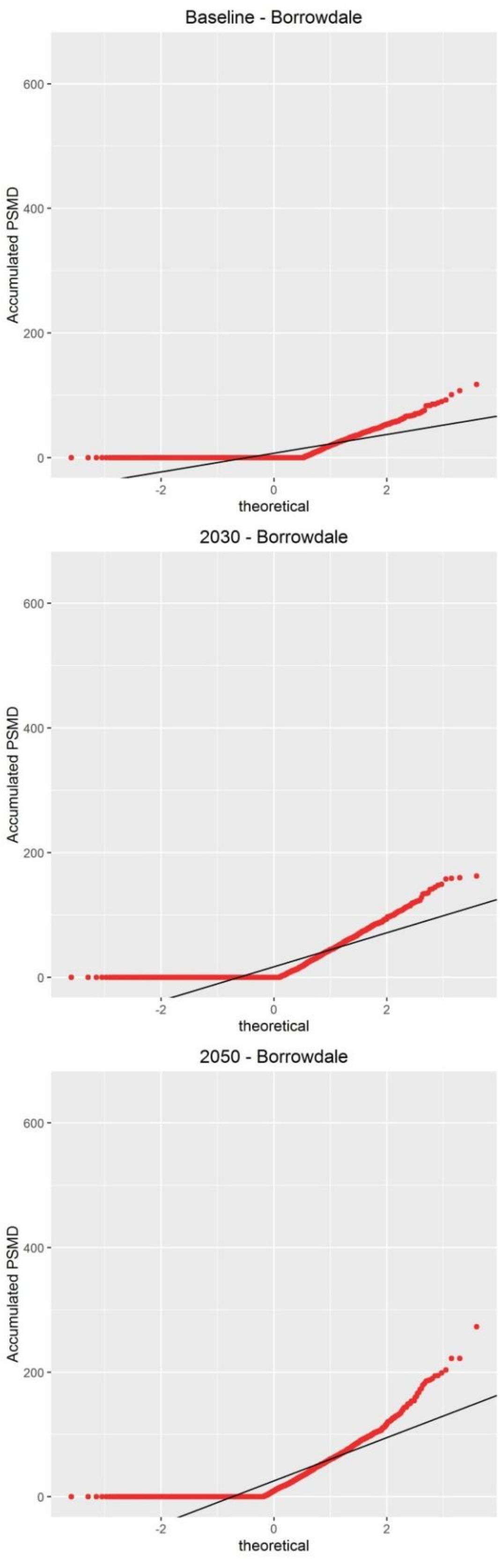


Figure G-33: Quantile-Quantile plot for Borrowdale grid cell for baseline, 2030 and 2050 PSMD

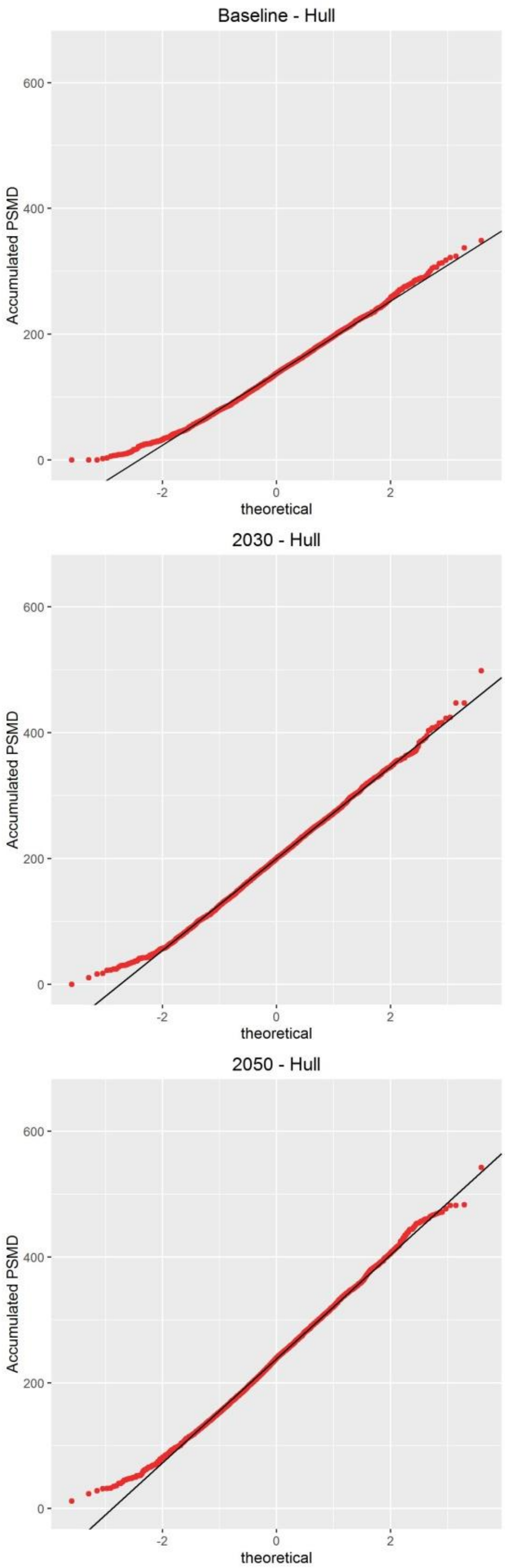


Figure G-34: Quantile-Quantile plot for Hull grid cell for baseline, 2030 and 2050 PSMD

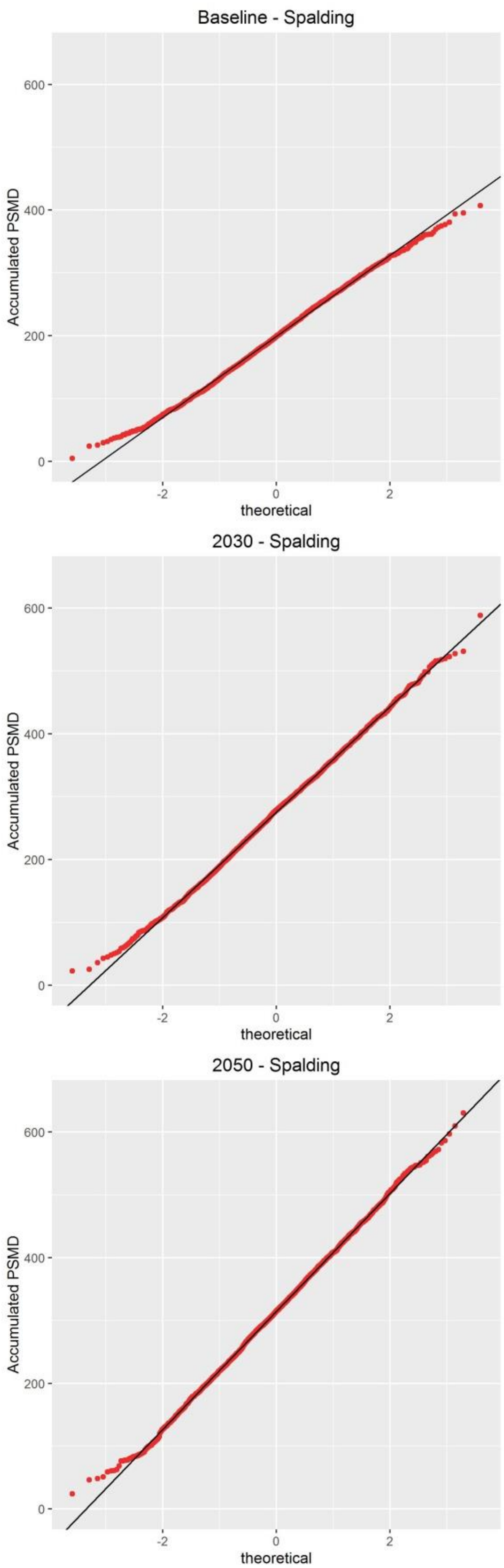


Figure G-35: Quantile-Quantile plot for Spalding grid cell for baseline, 2030 and 2050 PSMD

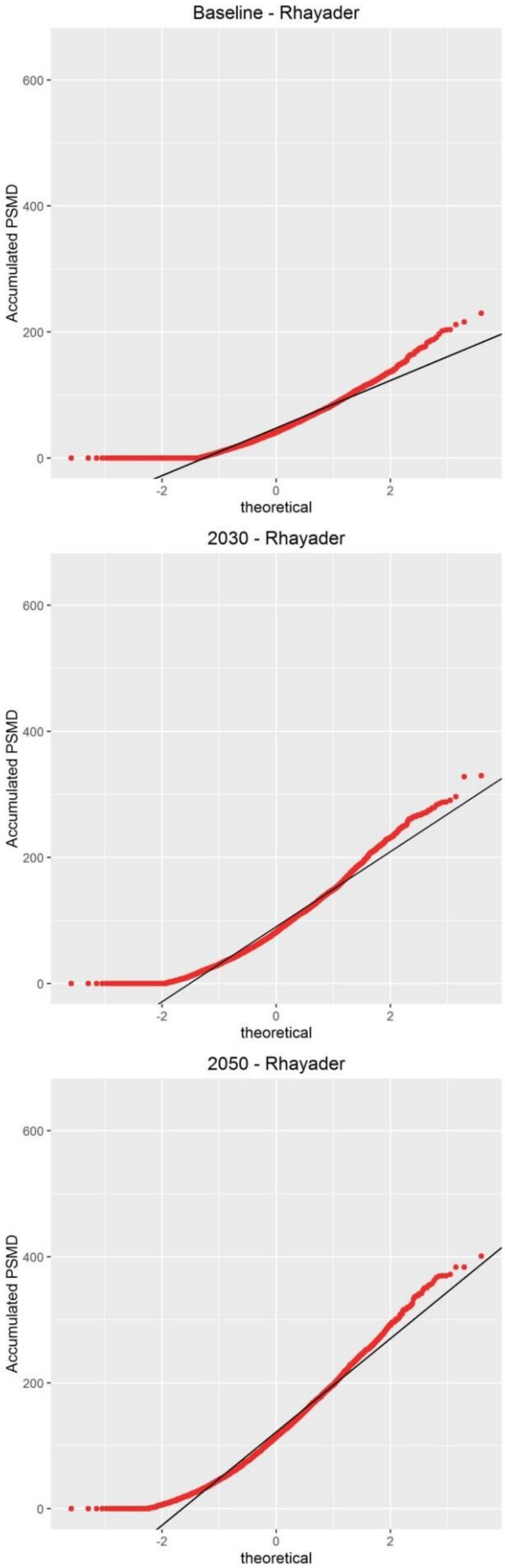


Figure G-36: Quantile-Quantile plot for Rhayader grid cell for baseline, 2030 and 2050 PSMD

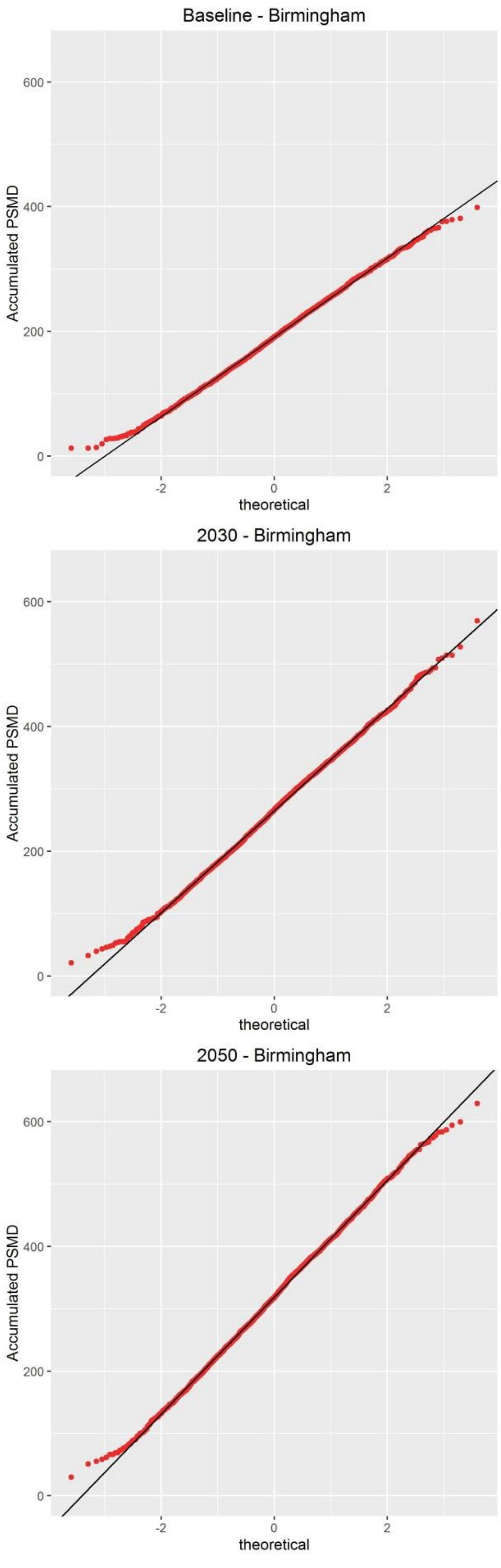


Figure G-37: Quantile-Quantile plot for Birmingham grid cell for baseline, 2030 and 2050 PSMD

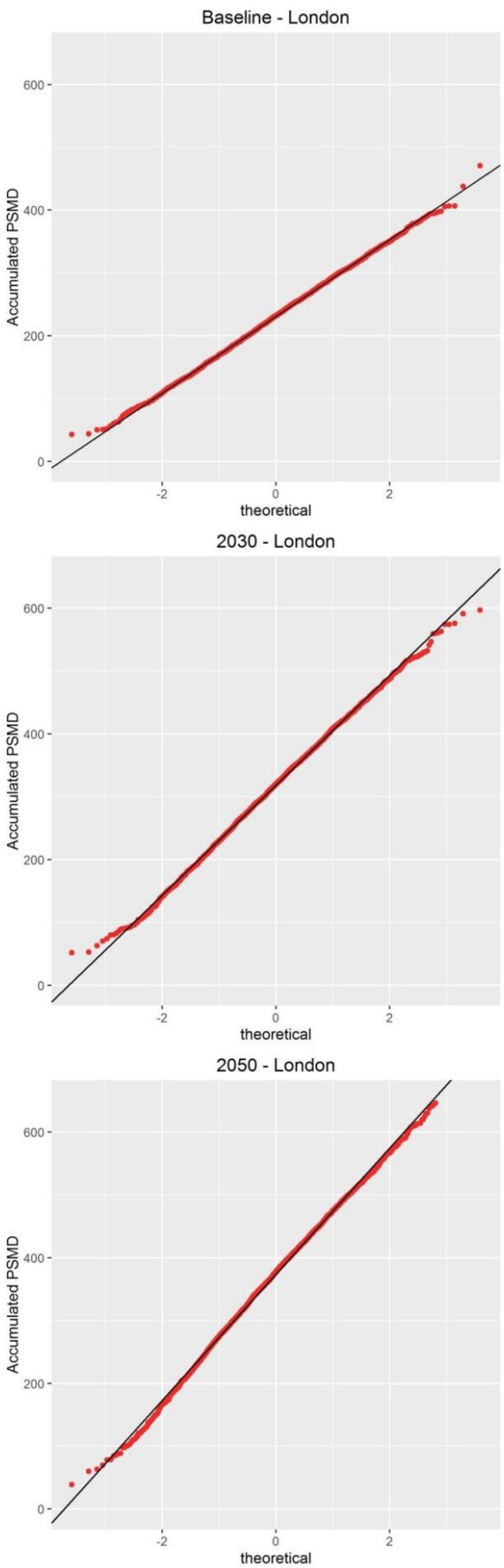


Figure G-38: Quantile-Quantile plot for London grid cell for baseline, 2030 and 2050 PSMD

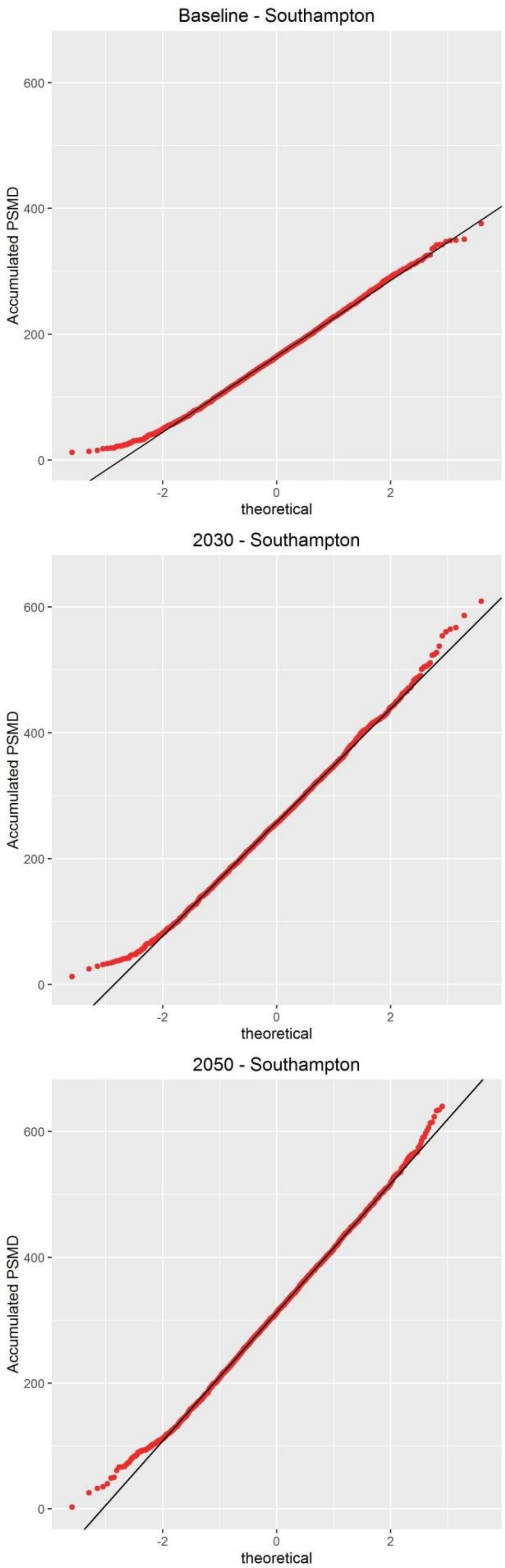


Figure G-39: Quantile-Quantile plot for Southampton grid cell for baseline, 2030 and 2050 PSMD

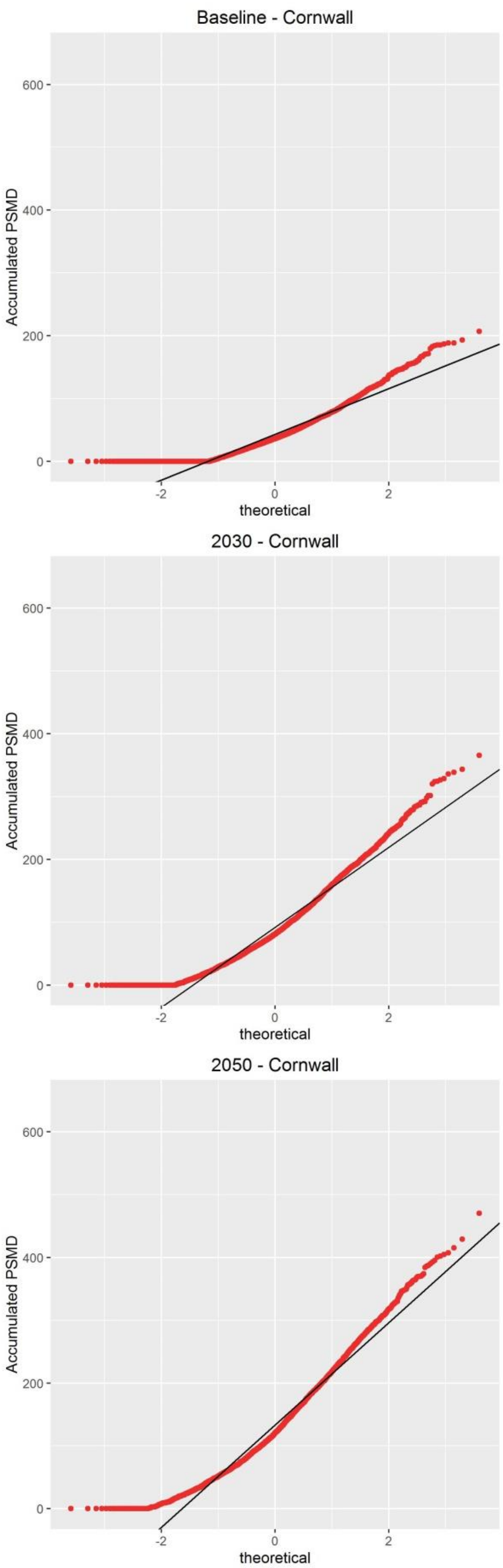


Figure G-40: Quantile-Quantile plot for Cornwall grid cell for baseline, 2030 and 2050 PSMD

Appendix H – Clay subsidence risk by land area

The tables presented below represent the land area of Great Britain, as a percentage of total land area that fall into the respective clay subsidence risk classes. These have been calculated for each climatic scenario (i.e. Baseline, 2030 and 2050) and for the 10th, 50th and 90th percentile PSMD.

Table H-1: Land area percentage (Great Britain) per subsidence risk class for each climatic scenario at the 10th percentile.

	Baseline	2030	2050
Extremely High	0.36	0.93	2.33
Very High	0.34	2.37	5.42
High	1.57	5.45	3.20
Medium High	3.29	5.37	6.50
Medium	3.50	2.83	3.39
Medium Low	5.85	2.91	1.67
Low	8.55	4.63	3.17
Very Low	16.80	18.71	19.38
Extremely Low	58.83	55.91	54.05

Table H-2: Land area percentage (Great Britain) per subsidence risk class for each climatic scenario at the 50th percentile.

	Baseline	2030	2050
Extremely High	2.14	3.73	3.83
Very High	5.17	7.66	7.77
High	3.79	0.23	0.21
Medium High	6.74	9.25	10.04
Medium	4.94	5.28	5.08
Medium Low	1.94	0.67	0.30
Low	2.66	3.87	6.82
Very Low	20.30	23.98	26.42
Extremely Low	51.42	44.44	38.64

Table H-3: Land area percentage (Great Britain) per subsidence risk class for each climatic scenario at the 90th Percentile.

	Baseline	2030	2050
Extremely High	3.84	4.05	4.58
Very High	7.87	8.17	8.38
High	0.24	0.65	1.22
Medium High	10.07	11.42	11.40
Medium	5.06	3.14	1.94
Medium Low	0.49	0.07	0.04
Low	3.89	9.55	12.64
Very Low	24.75	29.01	30.70
Extremely Low	42.89	33.03	28.21

Appendix I - European Region Map

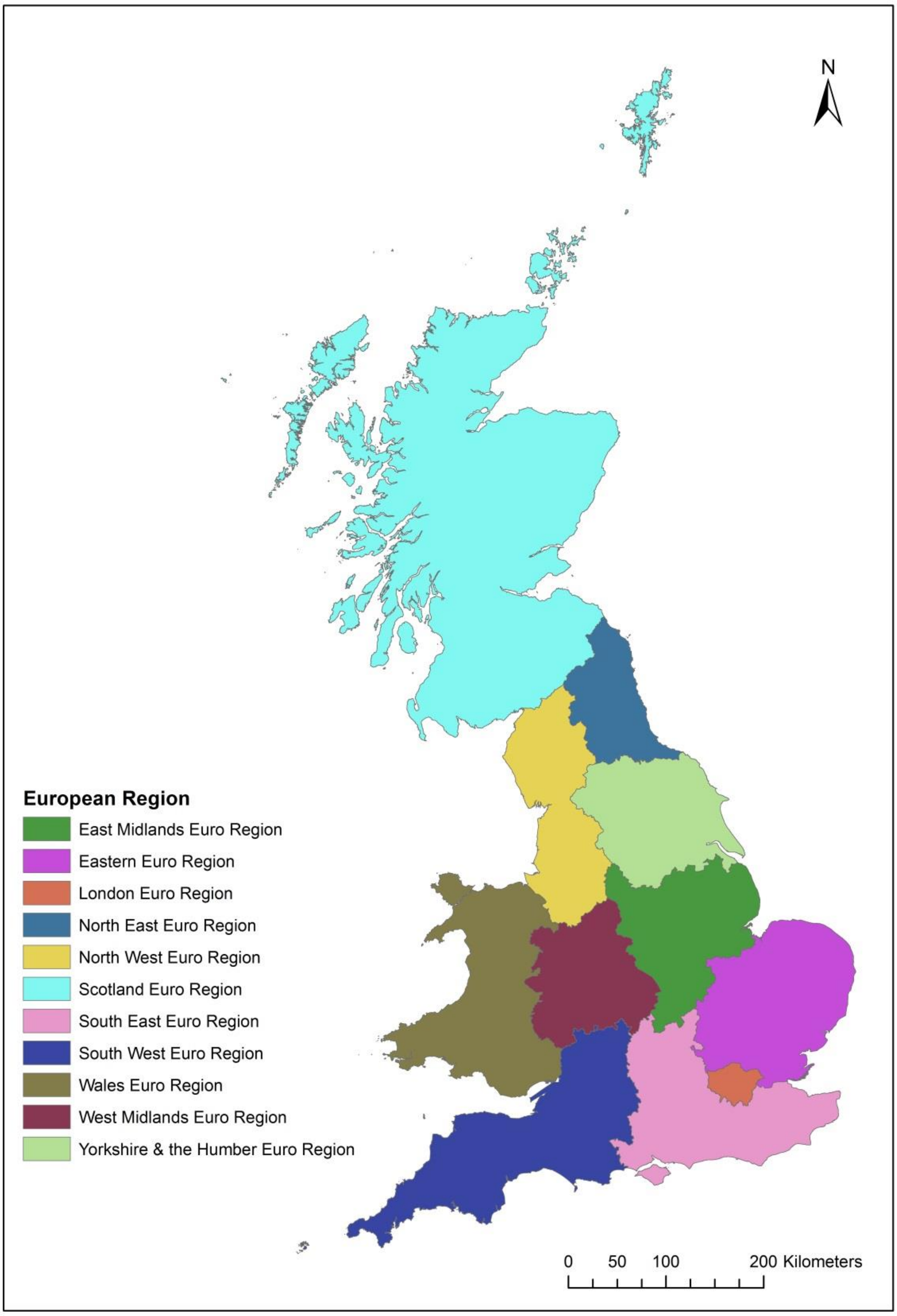


Figure I 41: European electoral regions as used in Chapter 5 analysis (Contains OS data © Crown copyright [and database right] 2016)

Appendix J Lincolnshire road sections identified "at risk" of clay-related subsidence

The maps presented in this appendix show roads identified 'At Risk' of clay-related subsidence in Lincolnshire; roads situated on 'Extremely High', 'Very High' and 'High' vulnerability of clay subsidence are deemed to represent a particular risk to roads and these classes have been used for analysis.

Clay-related subsidence risk at 50th percentile is presented in Chapter 5. The maps shown here represent the 10th and 90th percentiles for the respective time periods of Baseline (1961-1990), 2030 (2020-2049) and 2050 (2040-2069). For the baseline 10th percentile no roads are 'at risk' (i.e. in the top 3 highest risk subsidence classes) and so are not presented.

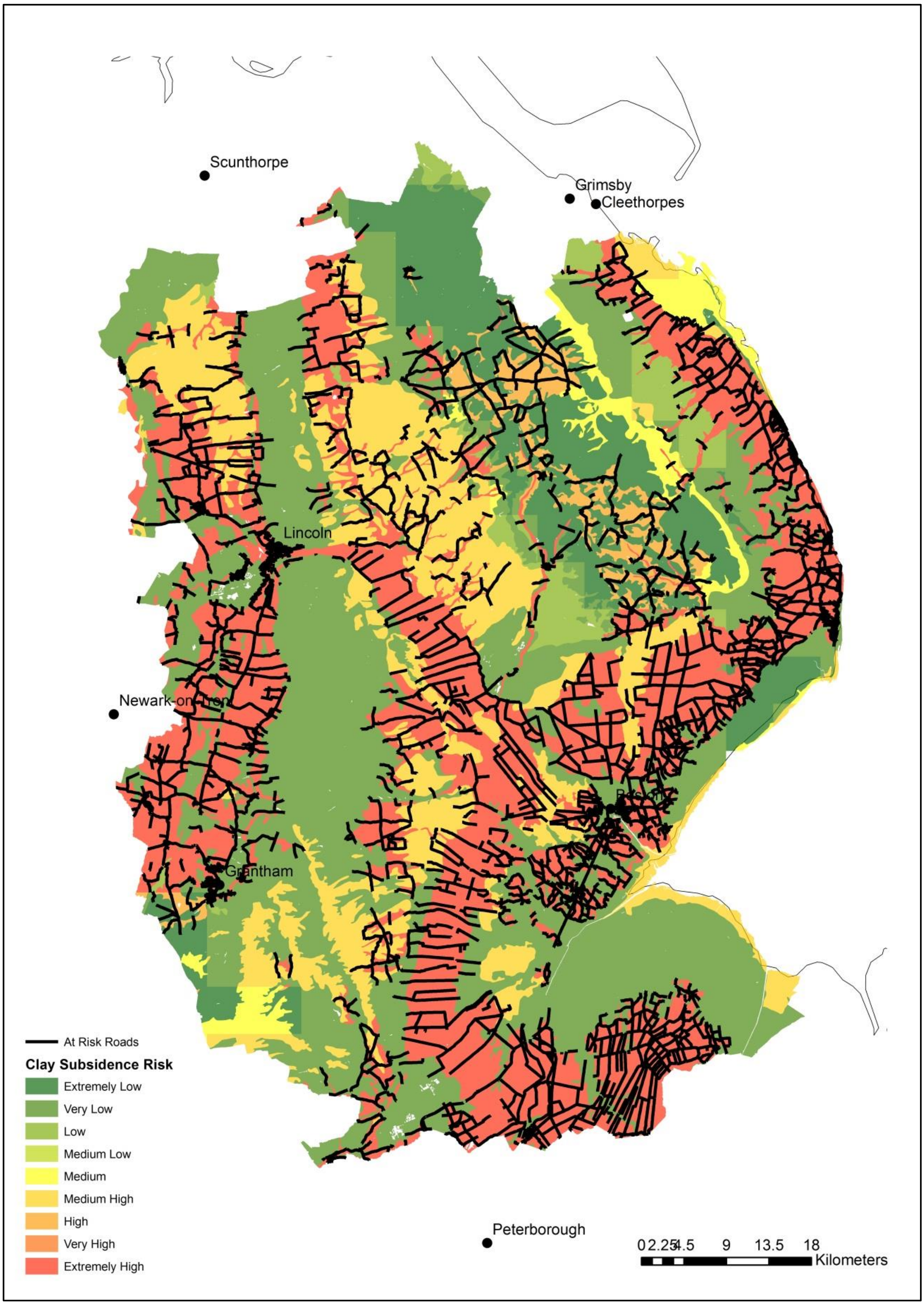


Figure J-42: Road sections identified "at risk" of clay-related subsidence for Baseline (1961-1990), 90th percentile PSMD (Soils data (England and Wales) © Cranfield University and for the Controller of HMSO, 2015)

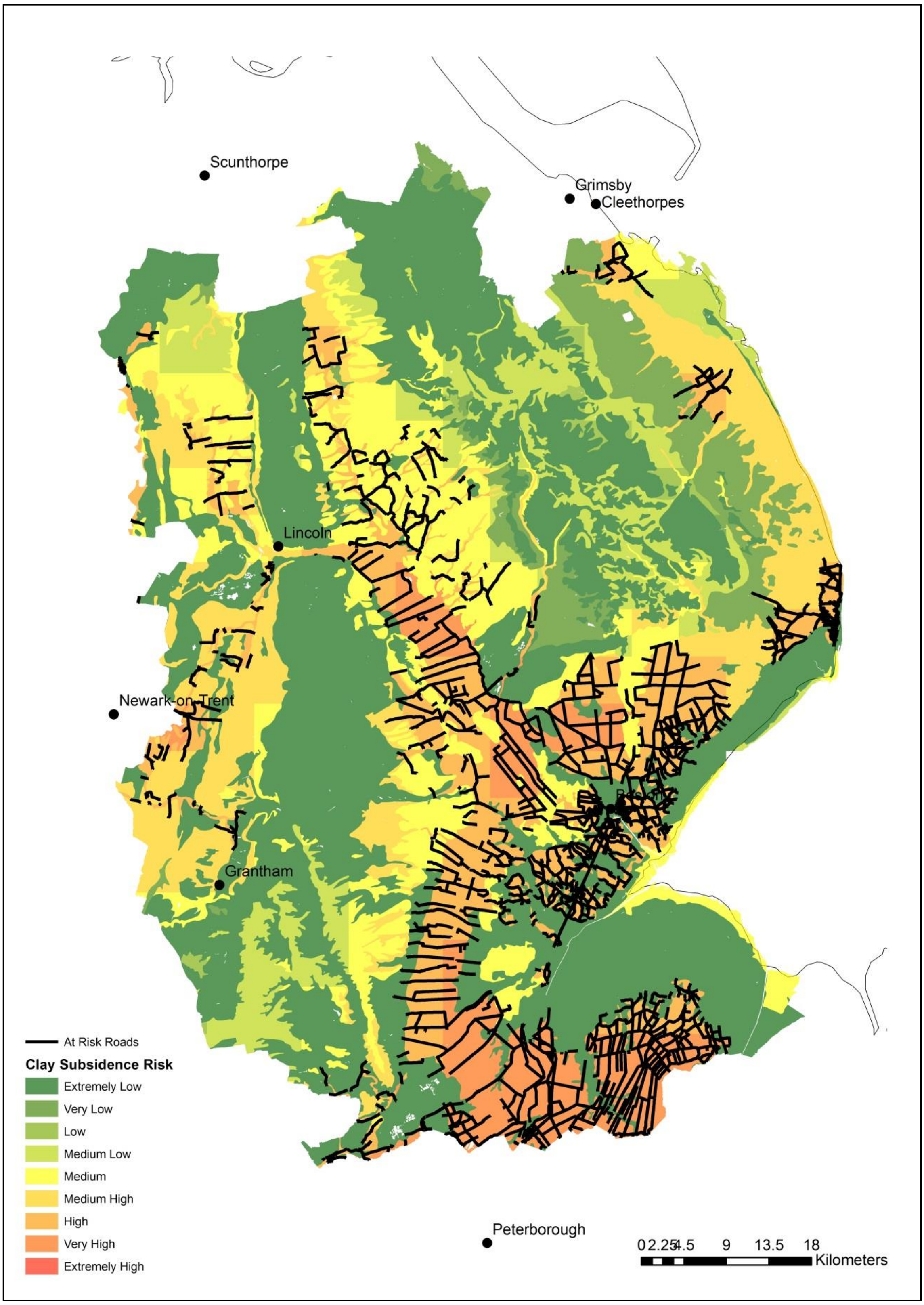


Figure J-43: Road sections identified "at risk" of clay-related subsidence for 2030 (2020-2049) scenario, 10th percentile PSMD (Soils data (England and Wales) © Cranfield University and for the Controller of HMSO, 2015)

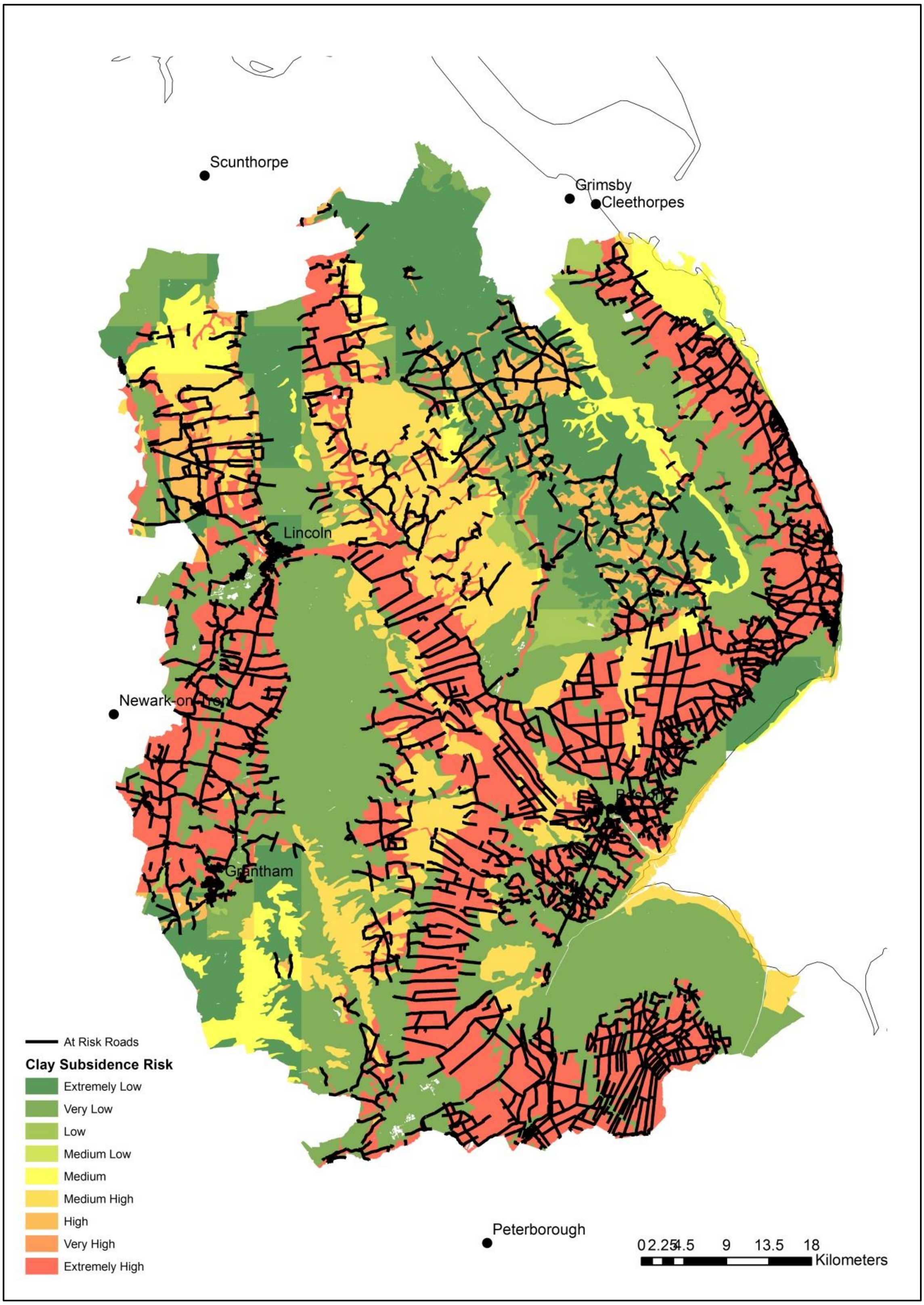


Figure J-44: Road sections identified "at risk" of clay-related subsidence for 2030 (2020-2049) scenario, 50th percentile PSMD (Soils data (England and Wales) © Cranfield University and for the Controller of HMSO, 2015)

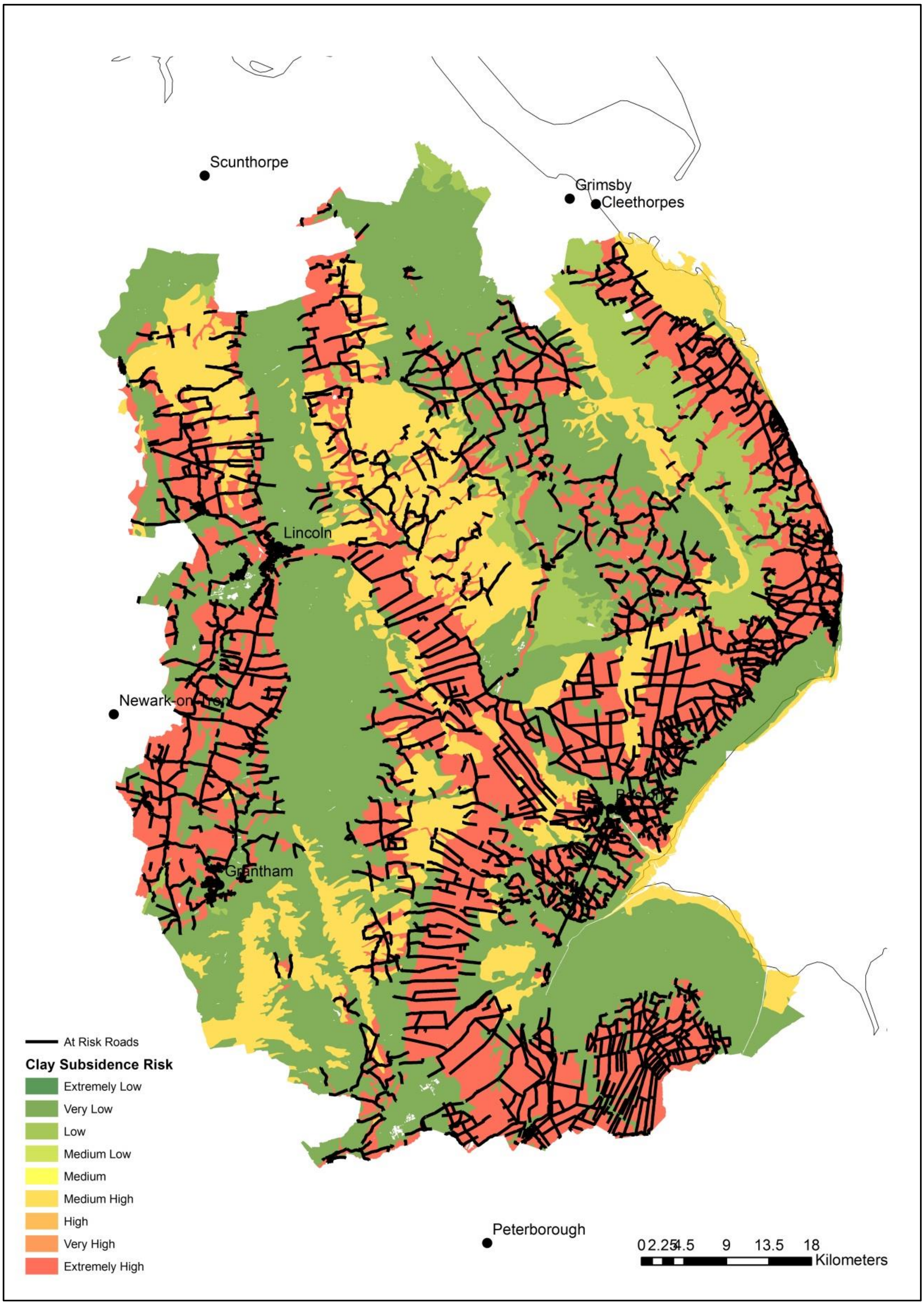


Figure J-45: Road sections identified "at risk" of clay-related subsidence for 2030 (2020-2049) scenario, 90th percentile PSMD (Soils data (England and Wales) © Cranfield University and for the Controller of HMSO, 2015)

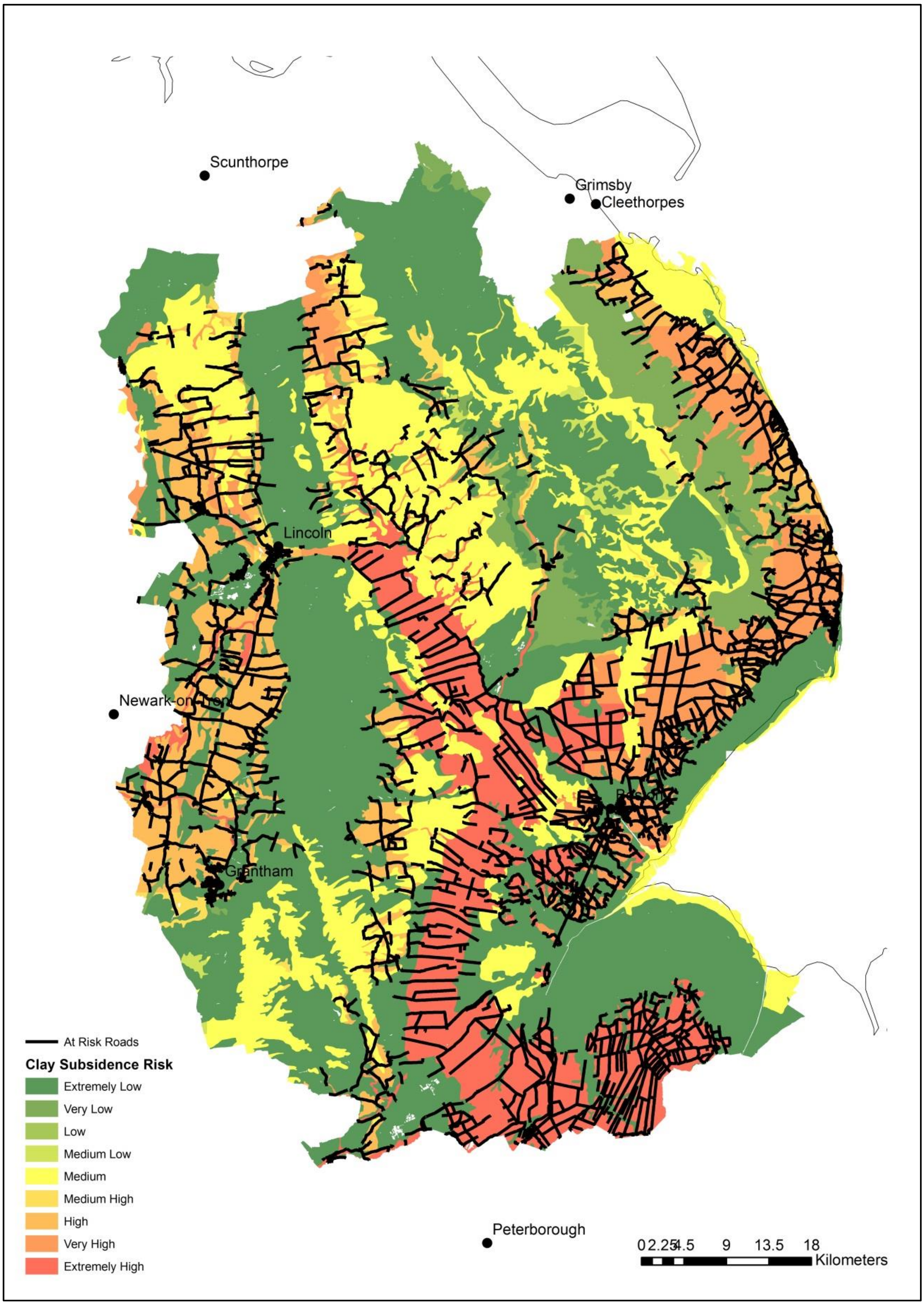


Figure J-46 Road sections identified "at risk" of clay-related subsidence for 2050 (2040-2069) scenario, 10th percentile PSMD (Soils data (England and Wales) © Cranfield University and for the Controller of HMSO, 2015)

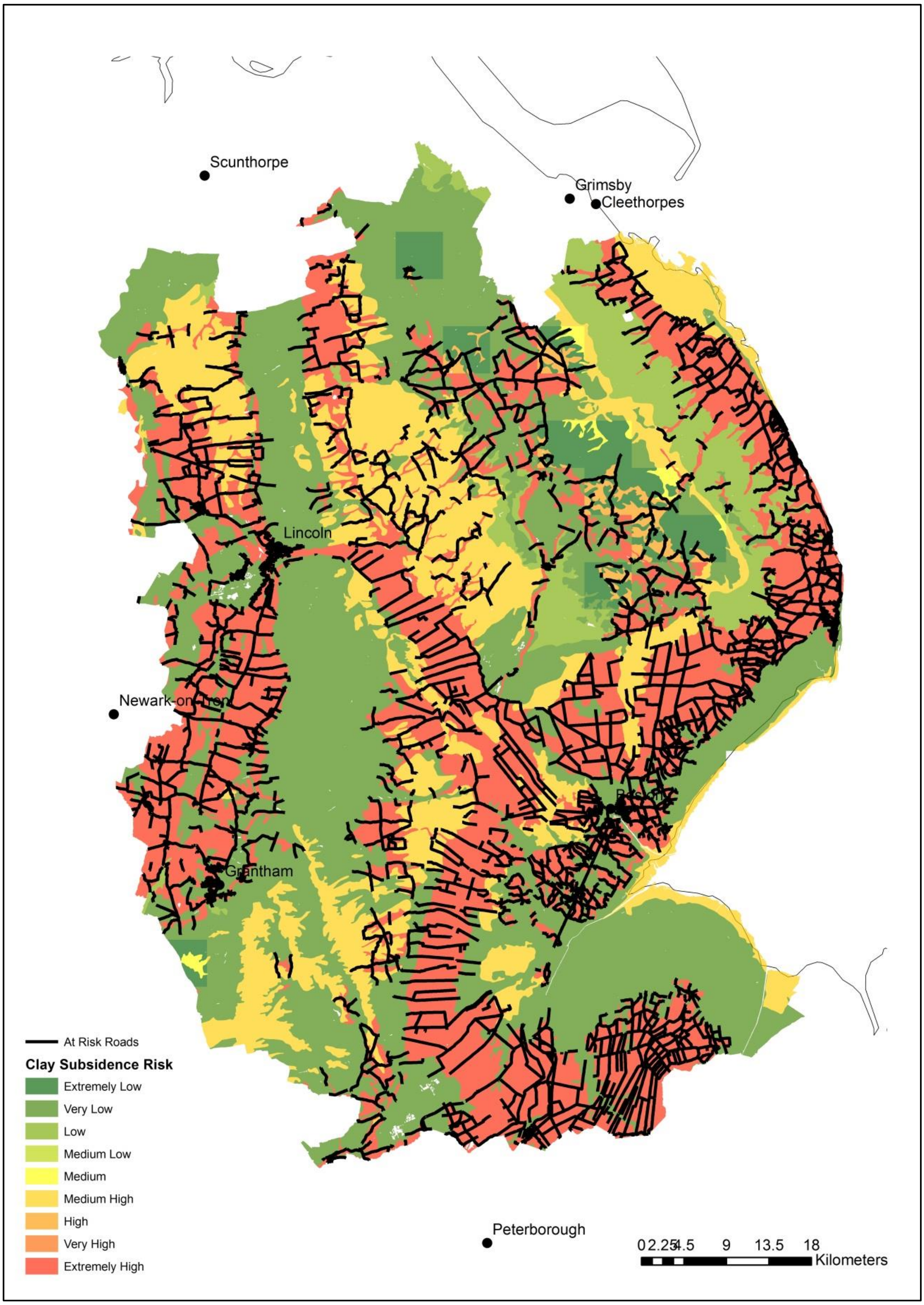


Figure J-47: Road sections identified "at risk" of clay-related subsidence for 2050 (2040-2069) scenario, 50th percentile PSMD (Soils data (England and Wales) © Cranfield University and for the Controller of HMSO, 2015)

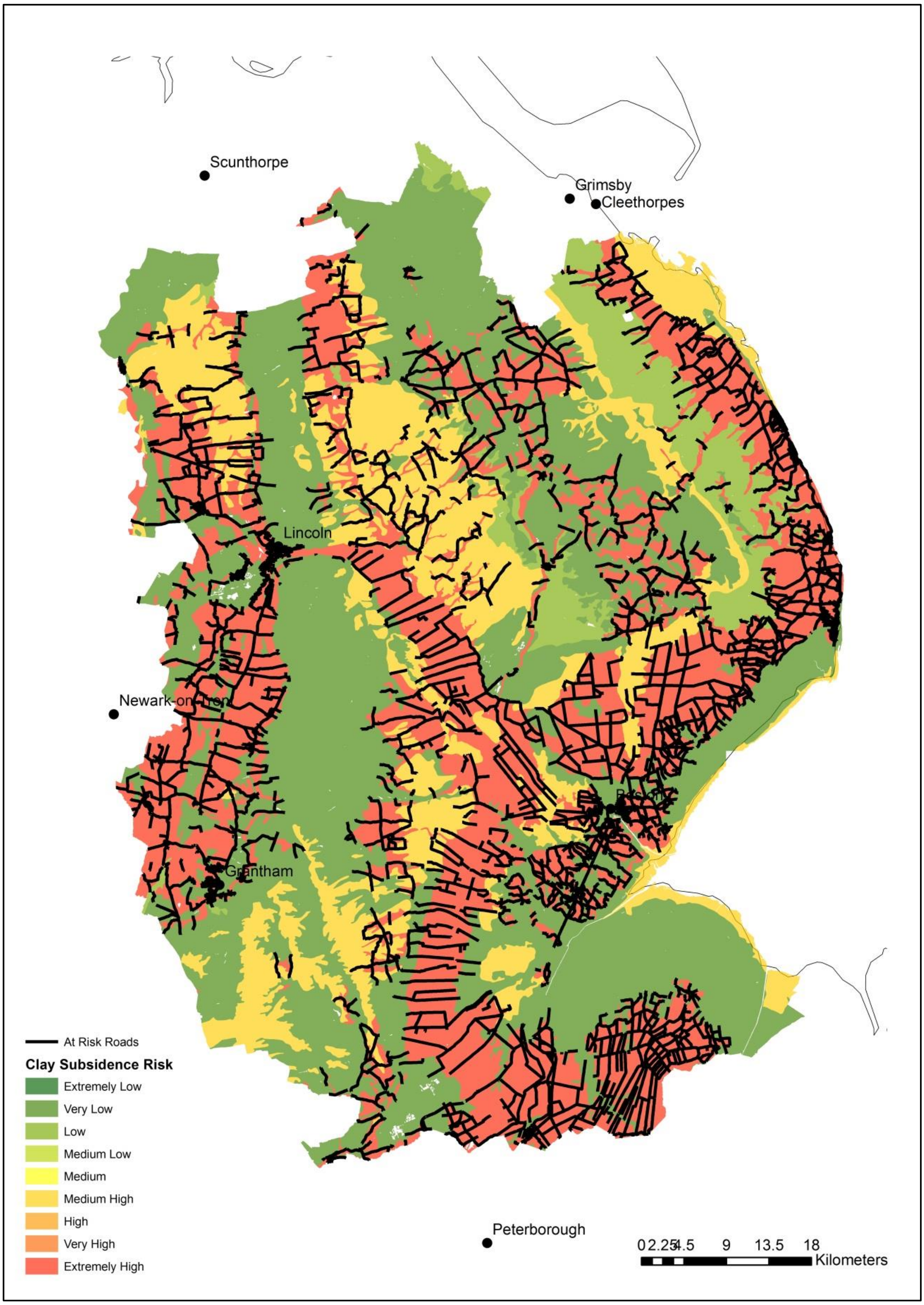
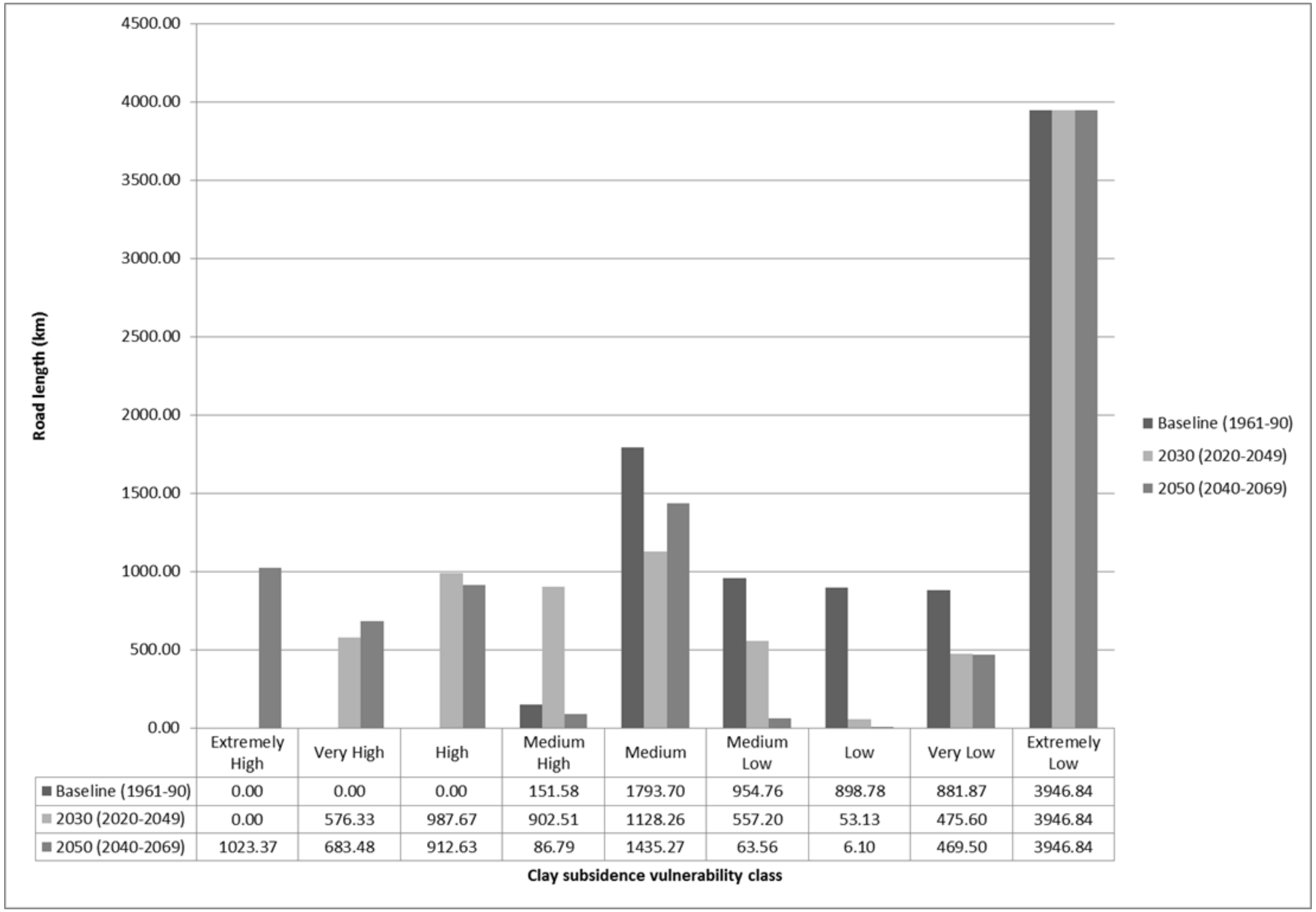
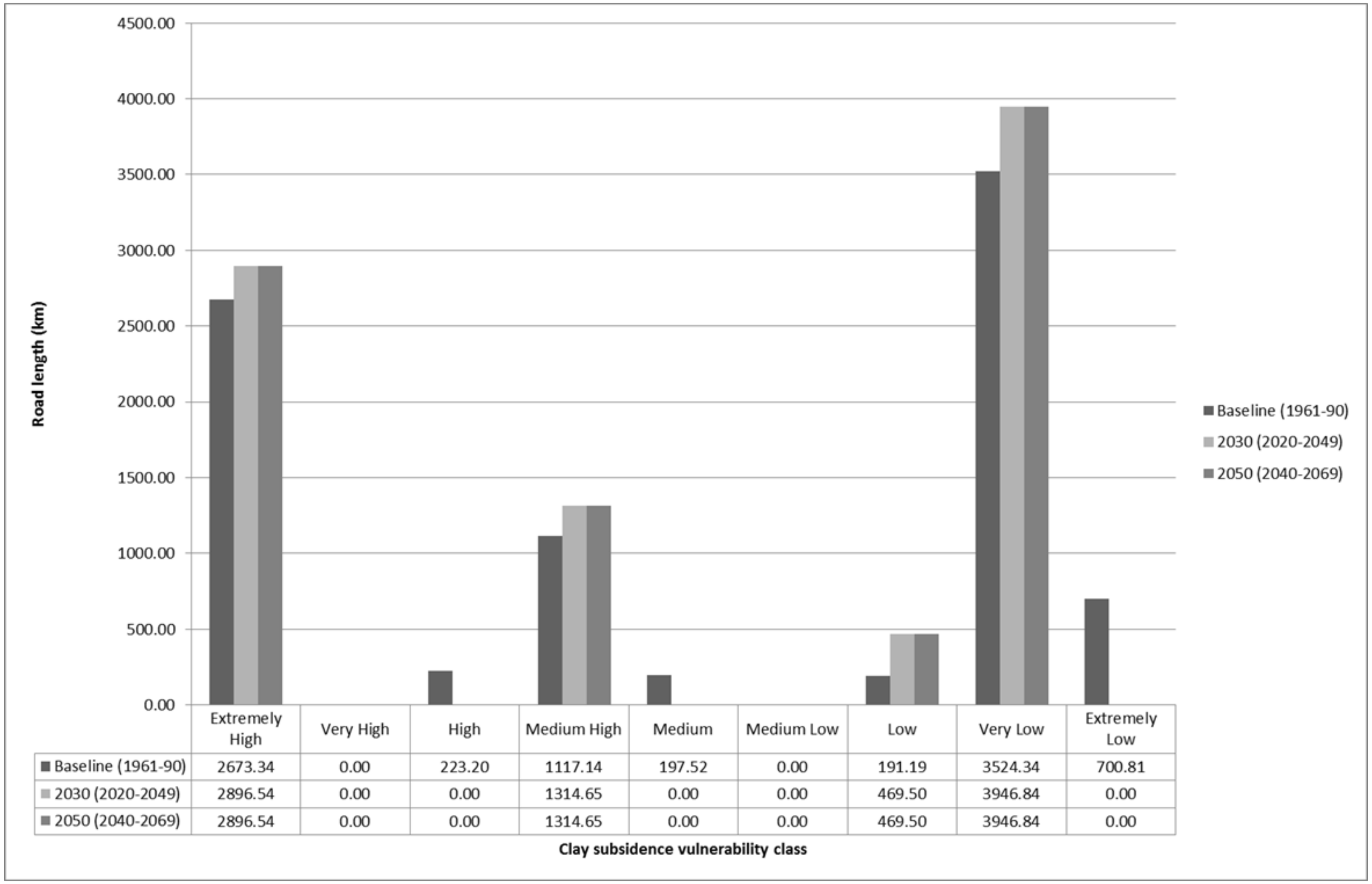


Figure J-48: Road sections identified "at risk" of clay-related subsidence for 2050 (2040-2069) scenario, 90th percentile PSMD (Soils data (England and Wales) © Cranfield University and for the Controller of HMSO, 2015)



	Extremely High	Very High	High	Medium High	Medium	Medium Low	Low	Very Low	Extremely Low
Baseline (1961-90)	0.00	0.00	0.00	151.58	1793.70	954.76	898.78	881.87	3946.84
2030 (2020-2049)	0.00	576.33	987.67	902.51	1128.26	557.20	53.13	475.60	3946.84
2050 (2040-2069)	1023.37	683.48	912.63	86.79	1435.27	63.56	6.10	469.50	3946.84

Figure J-49: Road length kilometres per clay subsidence vulnerability class for Baseline, 2030 and 2050 scenarios (10th percentile)



	Extremely High	Very High	High	Medium High	Medium	Medium Low	Low	Very Low	Extremely Low
Baseline (1961-90)	2673.34	0.00	223.20	1117.14	197.52	0.00	191.19	3524.34	700.81
2030 (2020-2049)	2896.54	0.00	0.00	1314.65	0.00	0.00	469.50	3946.84	0.00
2050 (2040-2069)	2896.54	0.00	0.00	1314.65	0.00	0.00	469.50	3946.84	0.00

Figure J-50: Road length kilometres per clay subsidence vulnerability class for Baseline, 2030 and 2050 scenarios (90th percentile)

Appendix K Practitioners decision-making flowchart to assess impact of soil-related geohazards to infrastructure

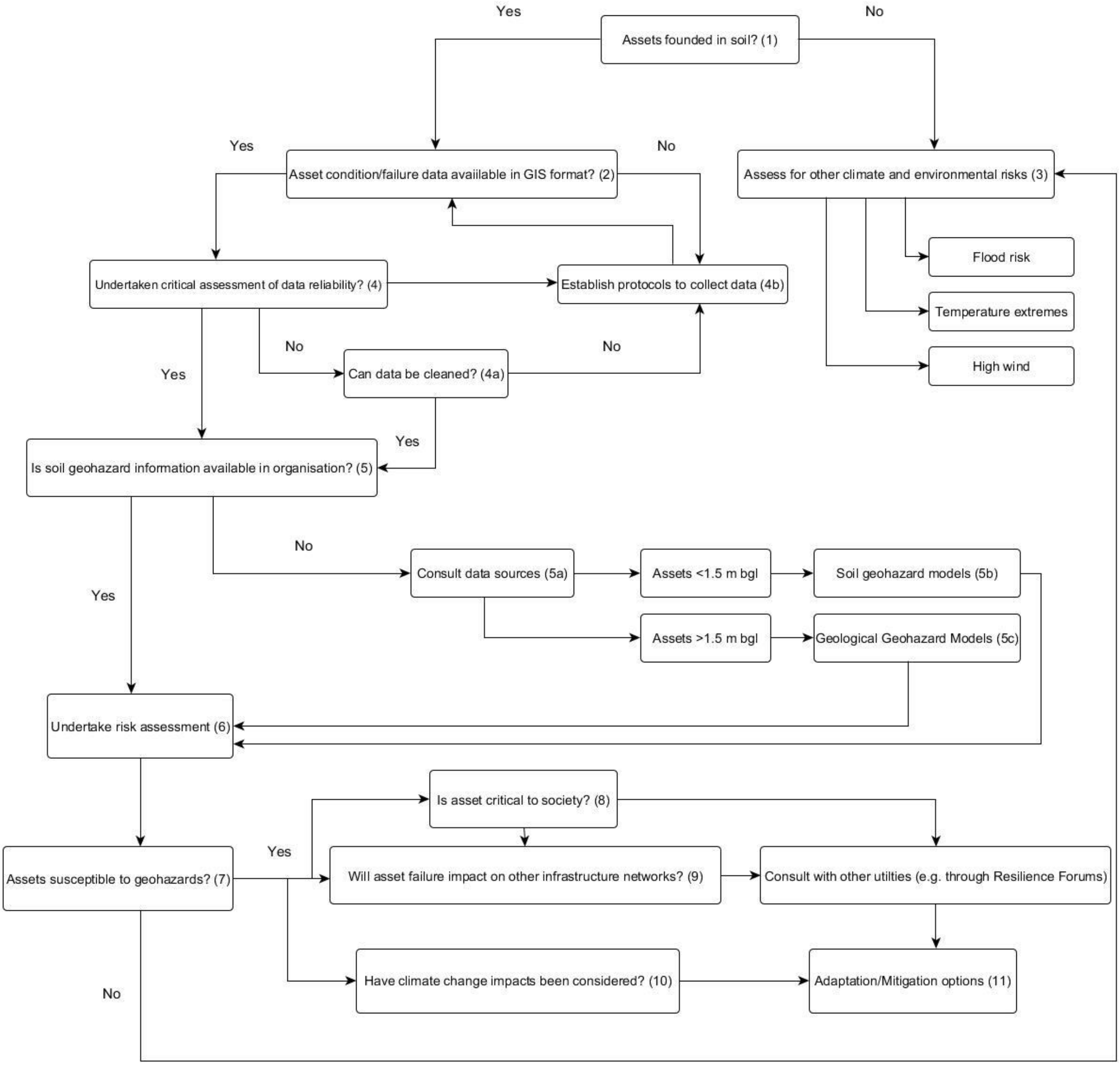


Figure K-51 ***Decision-making flowchart to assess whether soil-related geohazards will likely impact infrastructure assets and networks***

Notes to accompany Figure K-42

(1) – Assets founded in soil?

This refers to infrastructure assets which are founded within the soil substrate. In this context, soil is defined as being approximately 1-1.5 m below ground level. Such infrastructure is likely to incorporate shallow buried pipes and cables, shallow founded structures (e.g. telephone exchanges, pumping stations and electricity distribution substations), and local highway networks (i.e. Department for Transport defined B-U class road network).

(2) – Asset condition/failure data available in GIS format?

Does your organisation have geospatial data providing both asset location as well as asset attributes (e.g. material type, age of installation)? Furthermore, are spatially defined failure records available? The temporal recording of asset installation, failure events and repair dates is also important for risk assessment purposes. If no then the user is directed to (4b).

(3) – Assess for other climate and environmental risks

Assets not founded within the soil may face risks from other climatic/environmental stresses. Several examples are provided in the decision-making flowchart. The user of this framework is advised to consult the latest UK Climate Change Risk Assessment (CCRA) to understand the potential risks facing their assets.

(4) – Undertaken critical assessment of data reliability?

The spatial and temporal accuracy of asset location and condition data is of great importance when understanding geohazard risk to infrastructure networks. Both soil type and climate can differ over relatively small geographical areas, especially important when considering network-scale infrastructure impacts.

(4a) – Can data be cleaned?

By data cleansing, the user is referred to the act of making data ready for analytical purposes. For example, by making sure that data fields are consistent in terminology and units or that the spatial accuracy of the data is correct.

(4b) – Establish protocols to collect asset data

If geospatial information of infrastructure assets is not currently collected then organisations face a significant disadvantage when trying to establish the environmental risks facing their infrastructure networks. It is perhaps advisable to liaise with other infrastructure operators, especially those who champion excellent data-management practices; for example, the Association for Geographic Information (AGI) has a specialist group dedicated to infrastructure asset management (see: http://www.agi.org.uk/join-us/agi-groups/special-interest-groups/asset-management). Furthermore, consultation with academia will enable collection of attributes that are important for risk analysis, reducing later need for data refinements. A suitable temporal period of asset condition assessment also needs to be established, especially considering the seasonality of weather.

(5) – Is soil geohazard information available in organisation?

As discussed in the framework, a number of geohazards can impact on infrastructure networks (e.g. clay-related subsidence, sand-washout and corrosivity to iron). A number of geohazard models are currently available which provide the spatial distribution and probability of such events occurring which can be incorporated into risk management applications. The next stage of the flow chart points the user to define whether the assets are <1.5 m bgl or >1.5 m bgl, pointing then to soil geohazard models (5b) and geological geohazard models (5c), respectively.

Data sources (5a) can vary from both the originators of geohazard models, which for Great Britain consists of Cranfield University for soil geohazard models and the British Geological Survey for geological geohazard models. Moreover, a number of resellers of geohazard information currently operate, where supplementary data such as aerial imagery and Ordnance Survey data can be provided.

(6) – Undertake risk assessment

Once reliable asset data and geohazard information has been acquired, asset managers and decision-makers should undertake a risk assessment. For network level analysis this is best undertaken using a Geographical Information System Software (e.g. Proprietary software such as Esri's ArcGIS. However open-source software such as QGIS are also available to users). In this GIS environment, soil and geohazard attributes can be easily intersected with spatial asset attributes and failure records which can subsequently be statistically assessed and fed into deterioration models to understand if they present a risk to the degradation and failure of infrastructure assets. If the risks posed are not understood, then the user should seek technical help from a qualified expert in industry or academia.

(7) – Assets susceptible to geohazards?

After undertaking step (6), it should have been established whether assets are susceptible to geohazards. This implies that under the most disadvantageous conditions, an asset will likely suffer deterioration (often chronic – many months or years) leading to ultimate or rapid failure leading to the discontinuation of that assets service. Users should be aware that assets are subject to a number of external factors which could cause failure. It is therefore up to engineers to decide on the influence of soil processes on asset failure after exhumation and investigation of the failed asset.

If assets are not susceptible to soil-related geohazards then we refer the user back to the consideration of other climate/environmental hazards (3).

(8) – Is asset critical to society?

If asset failure occurs will this lead to a significant incident, and do a number of vulnerable people rely on the service. For example, the loss of gas supply in winter could mean no heating for the extremely young and elderly leading to possible fatalities. In this instance it is recommended to consult local authorities and emergency services through mediums such as the Local Resilience Forums, established under the Civil Contingencies Act.

(9) – Will asset failure impact on other infrastructure networks?

Some asset failures have the potential to cause degradation and failure to proximal infrastructure networks. For example, the result of a burst water main could be damage to the road surface caused by cavitation of the soil, whilst also leading to the formation of erosive slurry causing damage and fracture to gas pipes and electricity cables. The framework showed that roads act as a proxy for geographical interconnections of infrastructure networks.

(10) – Do climate change projections indicate changes in environmental conditions?

The UK climate Projections (UKCP09) suggest that the UK is likely to be subject to hotter, drier summers and warmer, wetter winters through to the end of the 21st century. The framework and Chapter 4 of this thesis has provided the user with a set of projections of geohazard change under these UKCP09 projections. These should be incorporated into risk assessment practices.

(11) – Mitigation/adaptation options

Following the high-level steps provided here in this flowchart, users should be able to establish the risk of soil-related geohazards to their infrastructure networks and assets. These can be used in wider asset management strategies to consider possible mitigation and adaptation options available to them, perhaps in cooperation or discussion with neighbouring utility owners/operators.