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Burst mains and climate factors project

Soil and climatic causes of water mains infrastructure bursts

A report for Anglian Water plc.

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Report cover. A segment of ductile iron water mains pipe with corrosion due to soil conditions.

Soil and climatic causes of water mains infrastructure bursts

Burst mains and climate factors project.

Farewell, T.S., Hallett, S.H., and Truckell, I.G.

Contents

Tables

Figures

Glossary

AMP – Asset Management Plan
AT – Accumulated Temperature
AW – Anglian Water
LandIS – Land Information System
MORECS - Meteorological Office Rainfall and Evapotranspirational Calculating System
NSRI – National Soil Resources Institute
PSMD – Potential Soil Moisture Deficit
SMD –Soil Moisture Deficit

Introduction

Anglian Water plc. have recorded a recent rise in the number of bursts to water mains, impacting on the reportable serviceability of the network to the regulator. Cranfield University National Soil Resources Institute were asked to investigate and advise on potential environmental causes for this. This report 'Soil and Climatic causes of water mains infrastructure bursts' forms a part of the contractual obligations entered into by Cranfield University with Anglian Water plc. and is provided for Anglian Water plc., submitted as a deliverable for Cranfield University project 'WU33701V ' as part of the wider Anglian Water plc. 'Burst mains and climate factors project'.

Details of the Task Descriptions as set out in the Contract are included at Appendix A. The Deliverables from this work are summarised in Table 1. The work undertaken comprised data analysis and interpretation of the results in the context of know soil mechanical models and the methods and results are presented in this report.

Table 1 Key project Deliverables and Activities

Deliverables	Key Activities
Deliverable 1	Assessment of burst records against soils criteria
Deliverable 2	Assessment of burst records against meteorological criteria
Deliverable 3	Literature review of academic publications

This report is structured into five parts which, together with the Appendices, fulfil the requirements of the contract.

Part 1 provides a summary literature review of key documents discovered pertaining to soil and climate-related causes of water infrastructure bursts.

Part 2 provides contextual information on the datasets, materials and methods employed in the analyses undertaken.

Part 3 investigates chronic pipe degradation by non-seasonal effects, such as corrosion

Part 4 investigates the effect of cold winters on burst rates

Part 5 investigates the effect of hot and dry summers, and the subsequent re-wetting in autumn, on burst rates

Part 6 considers a spring baseline status of burst level

Part 7 provides conclusions to the report and Part 8 makes suggestions for further research.

Literature Review

1 Literature Review

This section provides a review of the potential environmental causes of water mains failures from the academic literature. Further to this an overview is provided of the types of failure mechanisms pipe assets are subject to.

A review of the academic literature addressing the causes of mains water failures relating to soil, meteorology, or other environmental phenomena is presented below. This helps to identify themes and combinations of causal factors that have not been fully explored to date, as well as to guide and set the context for the factor analysis undertaken by Cranfield.

1.1 Types of pipe failure mechanism

Pipes fail for a variety of reasons, physical and bio-chemical. Physical mechanisms result in loading forces being brought to bear on the pipe wall materials (*Pers. Comm.*, 2012, Dr M.Hann, CEng. EnvEng. FIAgEng. MICE), including (Table 2):

Table 2 Principle types of pipe failure mechanisms

Principle types of pipe failure mechanism
Shear force
Compression force (pushing)
Tensile force (pulling)
Bending (combing compression and tensile forces)
Collapse (compression force)
'Hoop' force (a commonly used engineering term)
Corrosion
Embrittlement
Leverage from plant root encroachment

Such loading forces can play on the mains water pipes in a number of ways:

1.1.1 Internal forces

Internal forces occur due to the pressure of the pumped water playing upon the internal wall of the pipe itself, producing:

1. Tensile failures – usually manifesting as joint pulling (where the ferrule joint 'pops') so leading to circumferential failure. Sudden variations in water pressure can also lead to a 'hammer' effect that can exacerbate such failures.

2. Hoop failure – forming longitudinal splits in pipe walls forming at localised imperfections in pipe wall material due to the outward forces of pressurised water, the unequal response of the pipe wall leading to this preferential failure.

1.1.2 External forces

External forces occur due to external factors playing on the laid pipe material:

1. Building weight load

Shearing – due to differential loading from adjacent built structures etc.

Compression – due to crushing loads (having a direct bearing loading on the pipe).

Bending (combines compressing and tensile) – produces bending and torsion of the pipe in the trench, produces tensile (lower side) and compressive (upper side) forces. Both compression and more particularly tensile forces will produce both longitudinal and/or circumferential failures.

Collapse (compressible) – where the weight of a building load collapses trench materials which then come to bear on the pipe wall.

2. Traffic load

Shear – due to differential loading from vehicles passing on roads above etc.

Compression – due to crushing loads of traffic (direct loading on pipe), for example, bursts may be more likely to occur under bus stops than on open roads.

Bending (combines compressing and tensile) – produces bending and torsion of the pipe in the trench. This produces tensile (lower side) and compressive (upper side) forces. Both compression and more particularly tensile forces will produce both longitudinal and/or circumferential failures.

Collapse (compressible) – where the weight of passing traffic collapses trench materials which then come to bear on the pipe wall.

3. Soil trench load

Differential trench loads can form where weight of the backfill in trench, plus the bedding and packing around pipe can come to bear on the pipe. The likelihood of failure here will depend upon the pipe instatement.

Shear forces in the trench may also result from ‘bridging’ (which is a span of unsupported pipe, resulting from failure in the ‘trench bedding’ beneath). This produces tensile (lower side) and compressive (upper side) forces. Both compression and more particularly tensile forces will produce both longitudinal and/or circumferential failures.

1.2 Ground conditions

The ground in which utility service pipelines are buried inevitably controls, to a large degree, the structural performance and progressive deterioration of the pipelines themselves (Royal *et al*., 2011), highlighting impacts from ground features such as voids, ground wettening and softening due to leakage, as well as ground weakening due to progressive subsurface erosion. Consideration of impacts on community services such as pipes and conduits carrying fresh water, storm water, sewage, gas and electric cables requires knowledge of soil conditions to a depth of 1.5 to 3m or more (Brink *et al.,*1982). Ground condition geohazards can cause a range of issues to manifest in buried assets such as water mains. Conditions that affect such services adversely include high water tables, soft soils, soils of low shear strength and compressible soils subject to differential movements on changes in moisture content (*op cit.*, 1982). Reported impacts to buried infrastructure from other sectors can also be relevant where materials concerned are the same. Leigh et al (2010) and Oliveira (2009) identify how linear works, such as highways, power lines, gas and oil pipelines can all be threatened by a range of geohazards, including landslides, floods and erosion. Also highlighted are the importance of appropriate installation methods in the project design phase and the utility of a 'pipeline integrity management plan', as commonly used in Brazil, Italy and Canada (Leigh *et al.*, 2010).

Once in digital GIS format, definitive soils information for England and Wales can be used effectively to underpin a range of modelling applications such as geohazard assessments for buried assets and structures (Keay *et al*., 2009; Hallett *et al*., 1996).

From the literature, the following environmental themes have emerged (Table 3).

Table 3 Summary of the soil-related causal themes relating to main failures

Causal themes relating to main failures identified in the literature
Clay-related subsidence
Effects of vegetation
Sand washout and cavitation
Compressible soft soils
Silt soils and freeze effects
Wetness and drainage
Soil temperature flux
Changing climatic conditions
Soil corrosivity
Solution pits and cavitation
Soil liquefaction and solifluction
Electromagnetic induction effects

1.3 Clay-related subsidence

Soil-related subsidence originates from a number of causes, the most significant of which is shrinking and swelling clays as they impact on buried assets (Jones *et al*., 1995; Hallett *et al*., 1994; Reeve and Hall, 1978). Many geohazard impacts arise from siting structures in expansive clays (Doorkamp, 1994). Such clays impact on building foundations (Boden and Driscoll, 1987), as well as affecting buried linear assets such as water supply pipelines. The effects of clay shrinkage beneath the ground are hidden, however surface effects from clay movement can be striking. Figure 1 highlights the impact of lateral ground movements.

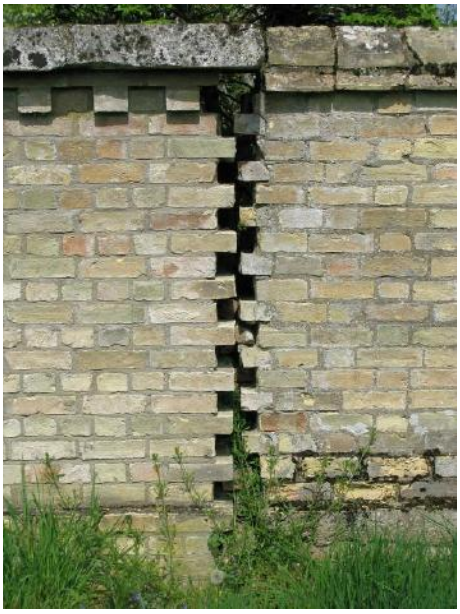

Figure 1 The effects of severe clay-related movement on brickwork.(Wimpole, Cambs. *S. Hallett*)

The degree of shrinkage and swelling of silicate clays is related to their mineralogy, and it is important to note that not all clays exhibit the same swelling characteristics. Clays are comprised of arrangements of silicate (tetrahedral) and aluminium, magnesium and iron (octahedral) sheets contained in crystal units or layers, each being only some 0.1 to 1.0 µm in size (Brink *et al.*1982). There are two such main clay groups: 1:1 silicate clays, having one tetrahedral and one octahedral sheet, and 2:1 silicate clays, having one tetrahedral layer sandwiched between two octahedral sheets (Brady and Weil, 2002). The 1:1 silicate clays include kaolinite, halloysite, nacrite and dickite. These clays are not prone to great shrinkage and swelling. Conversely, 2:1 silicate clays (also known as '2:1 lattice clays') include smectites and vermiculites which are capable of significant expansion. Other 2:1 clay minerals such as illite (mica) and chrlorite do not expand, changing little in volume when wetting and drying. Smectitic soils, previously termed 'montmorillonites', are common across the Anglian Water region. Smectitic clays expand when water molecules enter the inter-layer spaces, forcing the layers apart. Due to the plate-like layers comprising these clays, there is a surprisingly large surface area onto which water can bond – smectites have some 550-650m^2/g internal surface area (*op cit.*, 1982).

Soils that possess vertic properties, being high in swelling type clays, develop wedge-like structures in subsoil horizons (Brady and Weil, 2002). This occurs when, during the dry season, deep cracks (or gilgaï) appear in the soil to more than 1m in depth (Figure 2). Some surface soil crumbs fall into these cracks (causing partial soil mixing, or churning). During subsequent wet seasons, rainwater pours down the cracks, wetting the soil near the bottom of the cracks first, extending subsequently to the whole soil column, or profile. As smectitic clays absorb water they expand, entrapping the collected granular soil. The increased soil volume causes first lateral, then upwards soil movement after the cracks close. If the heave continues the soil mass shears, due to the strain, and features termed 'slickensides' appear (being sliding plates in the clay), see Figure 3. These features are characteristic of the heaving in the soil that can damage lain infrastructure such as pipes. This movement can affect not only inflexible pipe materials such as cast and ductile iron (Clayton et al, 2010), but the soil movement also affects more contemporary materials such as polyethylene or PVC pipes (Gallage et al, 2012). Experimental research has identified causes of such leakage to be the net result of a range of factors, including leakage flow, water pressure, freeze/thaw events, pressure surges as well as poor installation and maintenance (Noack and Ulanicki, 2007).

Water-logged soils that contain a high proportion of swelling clays are prone to swell and subsequently shrink more than do drier (e.g. better-drained) soils in the same type of clay material. A characteristic of soils that are subject to fluctuating water table levels is ‘mottling’. This is where ferrous iron in the soil is oxidized to a characteristic brown or ochre colour, contrasting with the ‘anaerobic’ grey and olive coloured clay (Figure 4) (FitzPatrick, 1974). Waterlogging of such soils leads to the reduction, mobilization and removal and redeposition of any iron compounds present. 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).

Figure 2 Exposed vertic (swelling clay) soils exhibiting surface cracking. (*S. Hallett*)

Figure 3 Slickensides, or clay shear plates. (*S. Hallett*)

Figure 4 Characteristic mottling in seasonally-waterlogged gley soils. (Northamptonshire. *S. Hallett*)

The presence of expansive and shrinking clay soils requires special construction techniques (Godfrey, 1978) due to the impact this can exert on the buried structures (Jahangir et al, 2012; Li, 2008; Kitchen, 1994).

1.4 Vegetation Effects

Vegetation can significantly exacerbate soil-related geohazards under certain conditions. Most ‘soil moisture deficit’ modeling is based upon a ‘short grass sward’ (mown or closely cropped grass). This is the case with datasets such as MORECS (Thompson *et al.*, 1981; Gardner, 1983). However, larger plants, such as trees and shrubs, are capable of transpiring more water than short green grass because of deeper rooting and their larger leaf indices. This in turn can exhibit considerable effects on the soil (White, 1975). Corrections can also be applied to accommodate differing aspects of the growth cycle where, for example, transpiration may cease from bare soil. Jones and Thomasson (1985) describe corrections applied for various agricultural crop types to provide crop-adjusted soil moisture deficits.

By contrast, Biddle (1998a-c) identifies the impact of a range of tree species and other large vegetation across a range of soil types on underground structures. Roots of trees and large shrubs can cause damage to drains where root growth seeks moisture and can gain entry to pipework (NHBC, 1985).

1.5 Sand Washout

In sandy soils there is a greater danger posed by excess water moving through the subsoil, resulting in ‘running sand’ conditions (Brink *et al.,*1982), where a cavity can develop under a structure, for example a leaking pipe, resulting in collapse of the pipe structure due to ‘bridging’.

Modelling tools can be employed to investigate the variation in pipe leakage characteristics from such phenomena to mitigate their effects (Noack and Ulanicki, 2007), but such impacts still present a real threat to infrastructure serviceability.

1.6 Compressible Soils

Subsidence may also occur in soft compressible soils. If pipes are laid in compressible soils that are affected by nearby foundations there may be differential movements leading to structural damage (Brink *et al.,*1982).

1.7 Silt Freeze

Moisture fluxes in soil, combined with freezing conditions can cause soil-related problems in soft silty soils. On freezing, ice expands by some 9% of the volume of water (ISPWS, 2012). Where water has permeated through loosely-consolidated soil and freezes, such ‘ice lens’ expansion can lead to significant damage to buried assets.

Studies report frost-related damage to sanitary engineering plants and water-pipe networks (Bittner and Heine, 1998; Hotloś, 2009; Royal et al, 2011). Instatement procedures and condition assessment are suggested as being crucial measures in protecting infrastructure exposed to sustained cold temperatures.

1.8 Wetness and Drainage

Large seasonal fluxes in soil water content represent key causal factors in pipe damage and affect engineering parameters (Richards, 1968). The more contrasting the soil water regime is in the surrounding soil mass, the greater the amount of pipe damage is likely to be caused from factors such as soil water corrosivity (Karpachevskii *et al.*, 2011).

For inter-seasonal modeling, the regional MORECS system (Thompson *et al.*, 1981) can be used usefully to investigate effects of climate on foundations of low-rise structures (OCA, 2007). MORECS is a system that provides estimates of evaporation, soil moisture deficit and effective precipitation under British climatic conditions (Hough and Jones, 1997). MORECS provides a 40km x 40km gridded interpolated dataset providing regional climatic summaries based on linked meteorological station data. Temperature values reported by MORECS are extracted from station data and reduced to mean sea level, using a lapse rate of -0.6^{o}C/100m, before being interpolated to the gridded surface. The water balance (soil moisture deficit, SMD) is calculated daily, where the difference between actual evaporation and rainfall, when added to the previous day’s SMD, gives the current timeperiod SMD. The soil available water data used in MORECS calculations are extracted from Cranfield University’s Land Information System (Keay *et al.*, 2009).

1.9 Soil Temperature Flux

In general, soil is a poor conductor of heat and so soil temperatures at depth tend to exhibit a lagged, buffered pattern, as compared to surface air temperatures (Hall, 1945). Soil heat conductivity (denoted ‘K’) is a calculated number, derived from data on the soil’s effective heat capacity (denoted ‘c’), this being the rate of change of the temperature gradient and the change in temperature over a given period of time. Soil temperature ‘diffusity’ (being ‘K/c’), denotes the temperature change that takes place in any portion of the soil as heat flows into it from an adjacent layer (Baver, 1956). The important factors affecting soil heat conductance are soil composition, moisture and porosity. In a seminal experiment, Von Schwarz (1879) showed the heat conductivity of different soils followed the order of *sand (quartz) > loam > clay > peat*, with water content increasing conductivity. Later investigations by Smith and Byers (1938) confirm these findings, but also highlight the significance of soil porosity (being the degree of packing, or bulk density, of soil particles) on heat conductivity. The rate of increase in thermal conductivity and density is approximately the same at any moisture content for a given soil.

The magnitude of temperature variations decreases with depth; temperature effects on soil being more pronounced in the topsoil region. Smith (1932) showed that at about 3.5m soil temperature variation remained fairly constant annually. After November, heat was shown to continue to move upwards from depth through the soil column; after March the direction of heat transfer was reversed downwards. Snow layers act as an efficient insulator of soil against rapid and extensive temperature changes, unless air temperatures sink very low for prolonged periods (Baver, 1956).

Alternate winter freezing and thawing cause a granulating, or disintegrating, action on soil clods. This process is usually more effective (pronounced) than drying and wetting processes and leads to ‘aggregated’ soil structures in spring (Baver, 1956). Certain soil conditions seem to be essential for realising the maximum effects of freezing. Thus, where soils dry during the winter there is little subsequent soil disintegration; where soils are wet and thawing is accompanied by rain, any aggregated materials can become dispersed.

1.10 Long-term Climate Change

Blenkinsop et al (2010) chose a London study area to identify how the probabilistic UKCP09 weather generator can be employed to derive predictions of future climatic scenarios and how this data could then be used to model temperature and evapotranspiration data, applied in turn to clay soil datasets to identify potential geohazard impacts. If future climate conditions lead to a greater frequency of extreme weather events, then lessons should be learned from environments today where buried pipe networks are maintained in, or subject to, extreme weather conditions such as prolonged cold (Bittner and Heine, 1998; He and Jin, 2010).

1.11 Soil Corrosivity

Soil water can be strongly corrosive to buried assets, particularly those constructed from ferrous iron. The presence of soluble salts or aggressive, acidic groundwater can lead to corrosion problems in laid pipes (Brink *et al.*,1982). Other factors such as presence of sulfate ion content, chloride ion content, soil resistivity, water content, temperature, and soil oxidation-reduction (redox) potential are contributory causes (Jiang *et al.*, 2011; Kleiner *et al.*, 2012; Md.Noor *et al.*, 2012). Pipe corrosion leads to characteristic pitting of the pipe and ultimately localized failure (Figure 5).

Both cast iron and ductile iron pipes can be particularly susceptible to soil-related corrosion (Gummow, 1984), although certain practices such as cathodic protection can be useful in mitigating such conditions. Mild steel is also susceptible to corrosive attack (Ismail and El-Shamy, 2009). This is important because as well as the cost of reinstatement and repair, water supplies can also become contaminated as a result of corrosion to metallic pipes – an additional cost to a water utility (Hussain *et al.*, 2010). Predictions can be undertaken to identify the levels of spatial vulnerability to such corrosion based upon localized soils and climatic information (Corcoran *et al.*, 1977; Smith, 1968).

Figure 5 Characteristic pitting in water mains pipe due to soil-water corrosion. (*S. Hallett*)

Such approaches can be extended to permit water companies and other utilities to choose the tools required to plan for mains replacement with less vulnerable materials (Jarvis and Hodges, 1994). Predictions of the causes of corrosion from analysis of corrosion pits compared with surrounding soil conditions have been undertaken (Kleiner *et al.*, 2012) and multi-sensor locational devices used to map pipe condition with surrounding environmental conditions (Royal *et al.*, 2011).

1.12 Solution Pits and Cavitation

In karstic environments, acidic rainwaters, charged with CO_2, are able to etch out cavities in underlying strata (for example chalk and limestone). This can lead to ‘solution pits’ and ultimately sinkholes (Brink *et al.*, 1982). Over a period of many years, these sinkholes can reach great size. Figure 6 shows an advanced sinkhole, or ‘doline’. However, even at a small size, such cavitation can lead to structural instability in the ground, potentially affecting buried pipes.

Figure 6 An exposed karstic sinkhole on open ground – an extreme case of solution (*S. Hallett*)

1.13 Soil Liquefaction and Solifluction

Soil properties behave very differently from what can be considered normal in conditions of earthquakes. A number of studies (Li et al, 2004; Hwang et al, 1998; Koseki et al, 1998; Huat *et al.*, 2012) document the process of soil liquefaction in earthquake and mudslide/landslide conditions as well as measures for protecting against such seismic conditions. Such conditions are not anticipated in the Anglian Water region.

Conversely, although major mudslides are not common in the UK, mass soil creep conditions, or ‘Solifluction’ is observable. Here over a period of time a mass of soil moves under gravity downslope, with conditions often hastened by climatic conditions and soil wetting (Figure 7).

Figure 7 Solifluction in the Undercliff area of the Isle of Wight (*S. Hallett*)

1.14 Electromagnetic Induction

Although not a common cause of bursts in water mains, lightning has been recorded as affecting buried assets. Eberle et al (1995) document how tracer wires can increase the incidence of lightning impacts on buried gas lines, recording the associated damage to polyethylene pipe material. Another study identifies how buried electric supply cable can affect the thermal characteristics of different soil types, also affecting soil moisture conditions (De Lieto Vollaro, 2011). Water pipes are also often used to earth domestic and commercial electricity supplies.

1.15 Cross-Sectoral experience

The issues of soil and weather-related impacts on critical infrastructure extend well beyond the water industry. For example, the Transport and Road Research Laboratory identify geotechnical measures needed to ensure stability of transport infrastructure against adverse ground conditions (TRRL, 1973).

The finance and insurance sector are also affected greatly by soil-related geohazards, particularly clay-related subsidence, which can pose a significant issue to domestic insured residences (Figure 8). The insurer ‘Direct Line’ note that there are several factors contributing to subsidence (Direct Line, 2012), thus:

1. *Soil type* – clay soil is particularly susceptible when it shrinks and swells according to its moisture content and this can be troublesome in periods of exceptionally dry weather. (Around 75% of subsidence claims are for properties built on clay soil).

2. *Vegetation* – trees and shrubs can extract moisture from deep within the soil, causing shrinkage, especially during long periods of dry weather, as roots extend in search of water, but removal of mature trees can cause previously dry soil to swell up and ‘heave’, resulting in damage to building foundations.

3. *Leaking drains* – can also contribute towards subsidence damage. Around one in five subsidence claims are a direct result of drains leaking into sandy soil material causing subsurface soil erosion beneath a building’s foundations.

Figure 8 House underpinning necessitated by soil-related subsidence. (*S. Hallett*)

Buried natural gas pipelines are also subject to the types of corrosive attack outlined for water pipes. Soil-water regimes in the soil body adjacent to the pipe installation trench have been observed to lead to the proliferation of sulphate-reducing bacteria – a principle cause of pipe destruction (Karpachevskii *et al*., 2011). Leakage from gas mains, where soil factors are involved, can also lead to fatal consequences (Ogle *et al.*, 2011). Leakage of water pipes in sandy soils has also been reported as affecting adversely adjacent gas lines due to the formation of acidic sand/water slurries (Majid and Mohsin, 2012).

Soil movement and shrinkage may also become an issue on engineered slopes and embankments (Anderson *et al.*, 1982; Bertrand and Papanicolaou, 2009; Alex Baylot *et al.*, 2012) as well as in 'naturalised' soil bodies.

As with any civil engineering project, methodologies employed at the time of instatement of pipework are important to the future serviceable lifespan. Contractors must take into account known information about site conditions as well as identifying what is not known and what needs to be known (ICE, 1991). Such measures can aid the appraisal of impacts of potential environmental changes at a location and reduce the potential consequences of problems that might occur.

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Materials and Methods

2 Materials and Methods

This section outlines the datasets and techniques used in this research.

These data include

Anglian Water datasets of pipe networks and burst records

Met Office MORECS meterological data

NSRI Soil and environmental vulnerability datasets

Techniques include GIS manipulation, normalisation and analyses.

This research examined datasets from Anglian Water, the Meteorological ('Met') Office and the National Soil Resources Institute ('NSRI') of Cranfield University. Analysis was undertaken by visual inspection, burst frequency by day, week, month and season examining the relationship between potential causal factors and water mains bursts.

2.1 Anglian Water Datasets

2.1.1 Pipe Network and management areas

Data for the pipe network and management areas was provided by Anglian Water. Each record was simplified in terms of pipe diameter (Figure 12) and material types (Figure 13), which are mapped. The simplified classes are provided in Table 5 and Table 6.

2.1.2 Bursts database

A bursts database, containing approximately **34,000** recorded burst events was provided, as shown in Figure 9, which identifies their locations as recorded in the region, overlain on an altitude map. The data used ranges from 2005 to 2012 It is noted that there are a number of geographical placement anomalies, inevitable in a dataset of this magnitude.

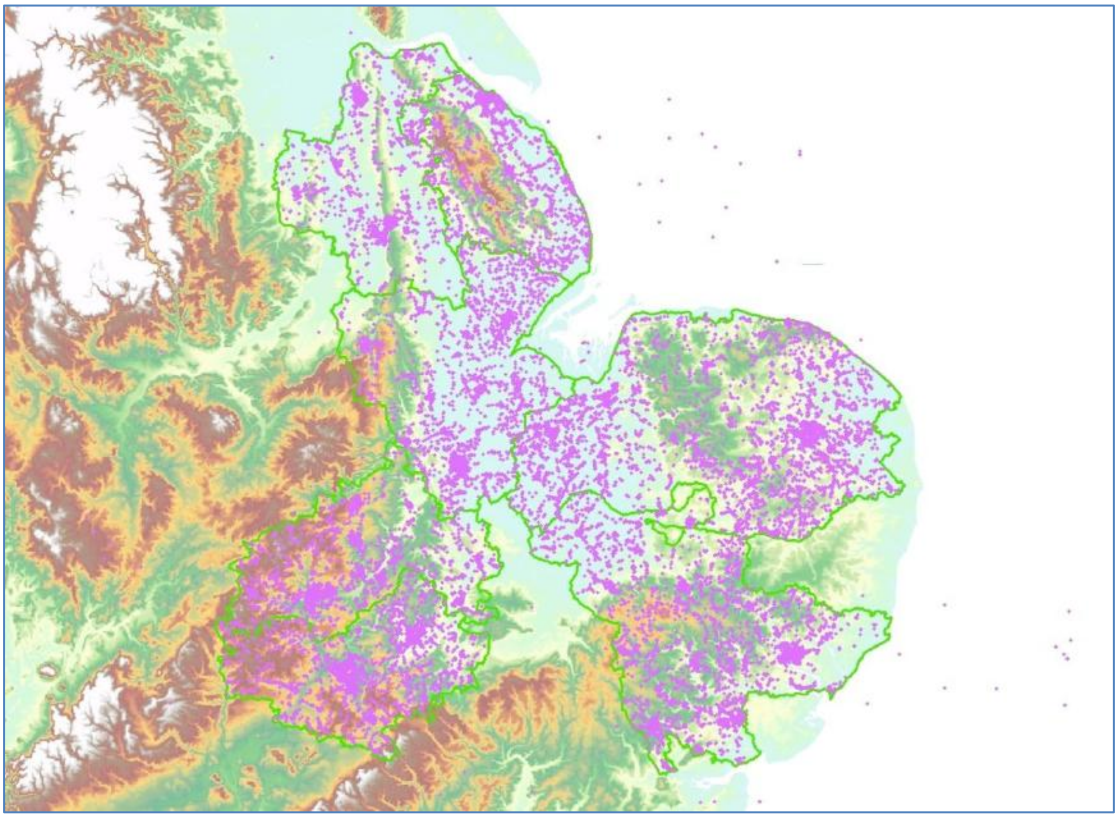
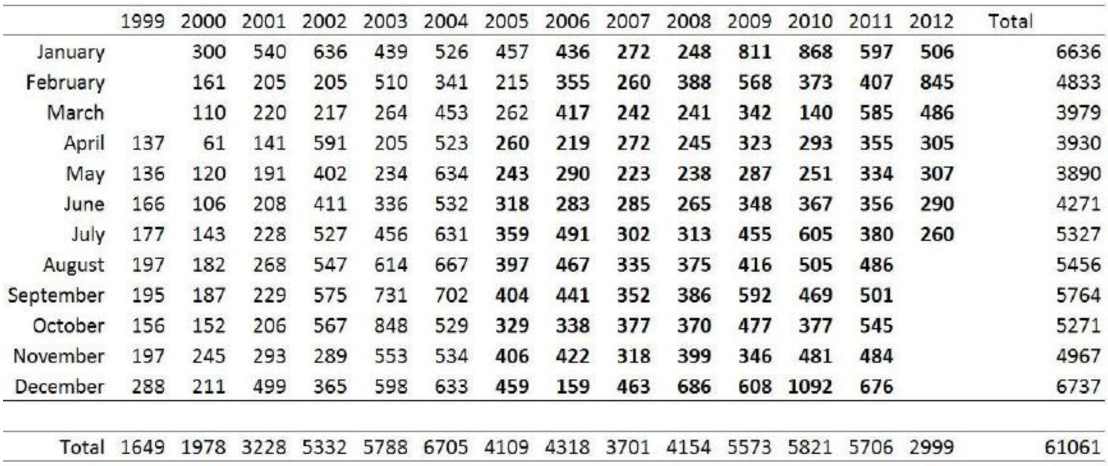


Figure 9 The water mains burst location. Bursts outside the Anglian Water region have been excluded.

Bursts are recorded with date and Table 4 identifies the bursts, as recorded, broken down by month and year.

Table 4 Total bursts by year and month. Total Bursts by year, by closed date.



	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Total
January		300	540	636	439	526	457	436	272	248	811	868	597	506	6636
February		161	205	205	510	341	215	355	260	388	568	373	407	845	4833
March		110	220	217	264	453	262	417	242	241	342	140	585	486	3979
April	137	61	141	591	205	523	260	219	272	245	323	293	355	305	3930
May	136	120	191	402	234	634	243	290	223	238	287	251	334	307	3890
June	166	106	208	411	336	532	318	283	285	265	348	367	356	290	4271
July	177	143	228	527	456	631	359	491	302	313	455	605	380	260	5327
August	197	182	268	547	614	667	397	467	335	375	416	505	486		5456
September	195	187	229	575	731	702	404	441	352	386	592	469	501		5764
October	156	152	206	567	848	529	329	338	377	370	477	377	545		5271
November	197	245	293	289	553	534	406	422	318	399	346	481	484		4967
December	288	211	499	365	598	633	459	159	463	686	608	1092	676		6737
Total	1649	1978	3228	5332	5788	6705	4109	4318	3701	4154	5573	5821	5706	2999	61061

Data was extracted from Anglian Water's SAP system. Additional data was provided from older databases at Anglian Water. We were informed by Anglian Water's Tim Acland that the older database was less reliable and did not report the same number of bursts as were reported to OFWAT for the relevant return periods. Attention was therefore focused on the data extending from April 2005.

2.1.2.1 Errors of burst location

In the course of this project, numerous errors have been identified with the burst data. Many of these have been corrected.

The bursts were initially intersected within a buffered distance of the pipe network to ensure bursts were within a reasonable distance of the pipe network. This excluded a large number of bursts and Anglian Water requested that all bursts within the Anglian Water area have been included in the analyses, irrespective of their distance to the nearest pipe. Bursts which lie outside the Anglian Water area have been removed (Figure 9).

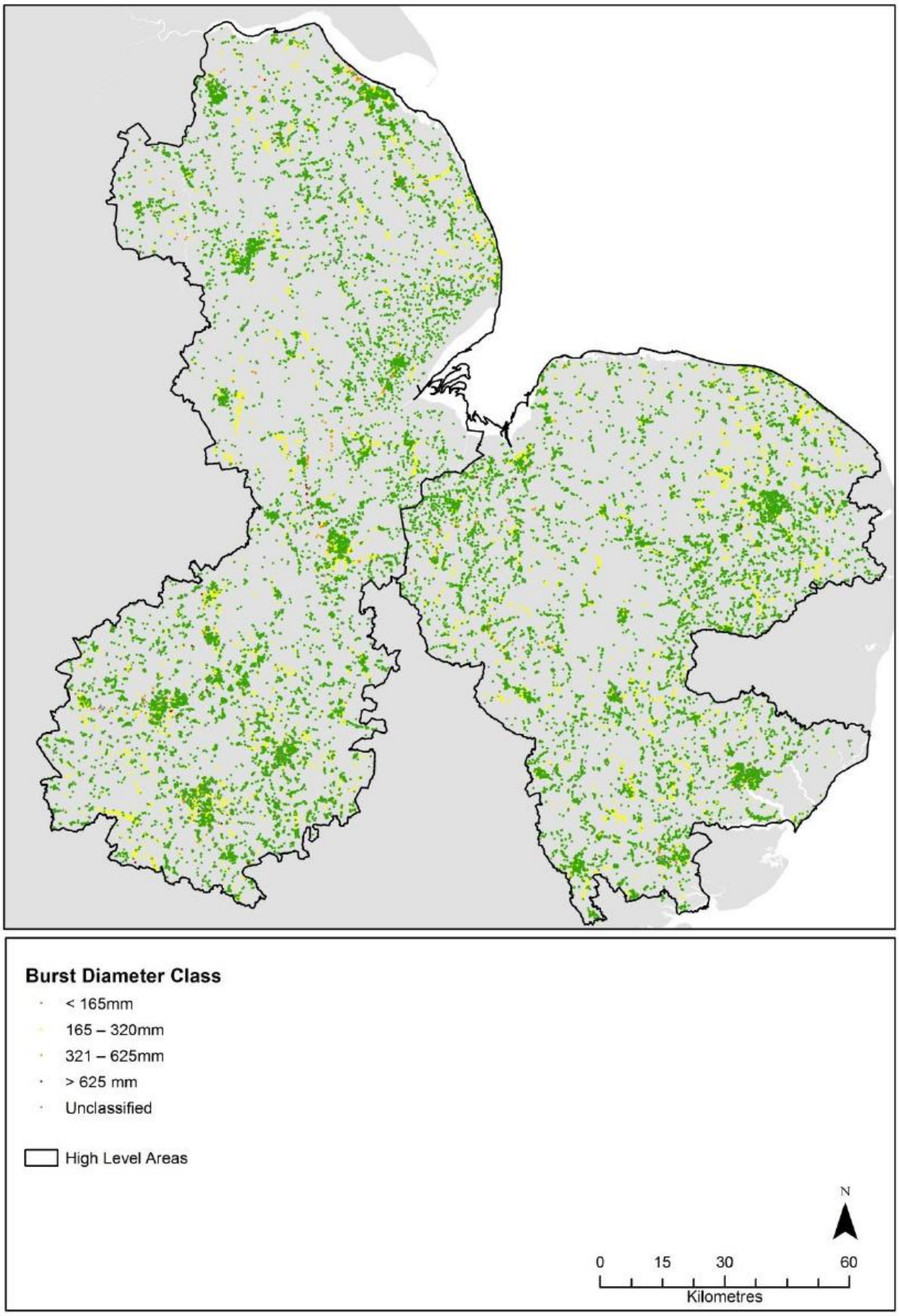


Figure 10 Burst diameter class

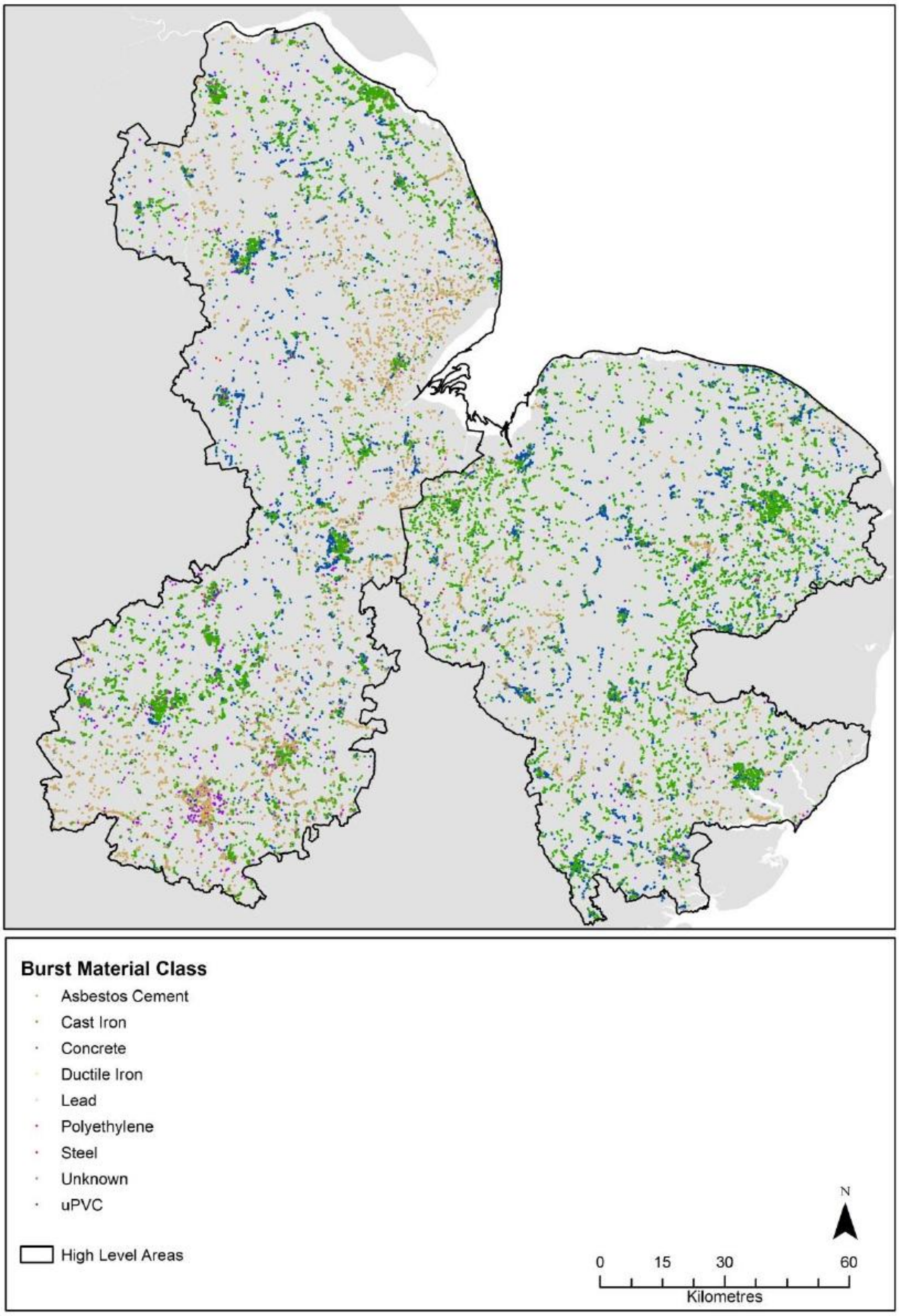


Figure 11 Burst material class

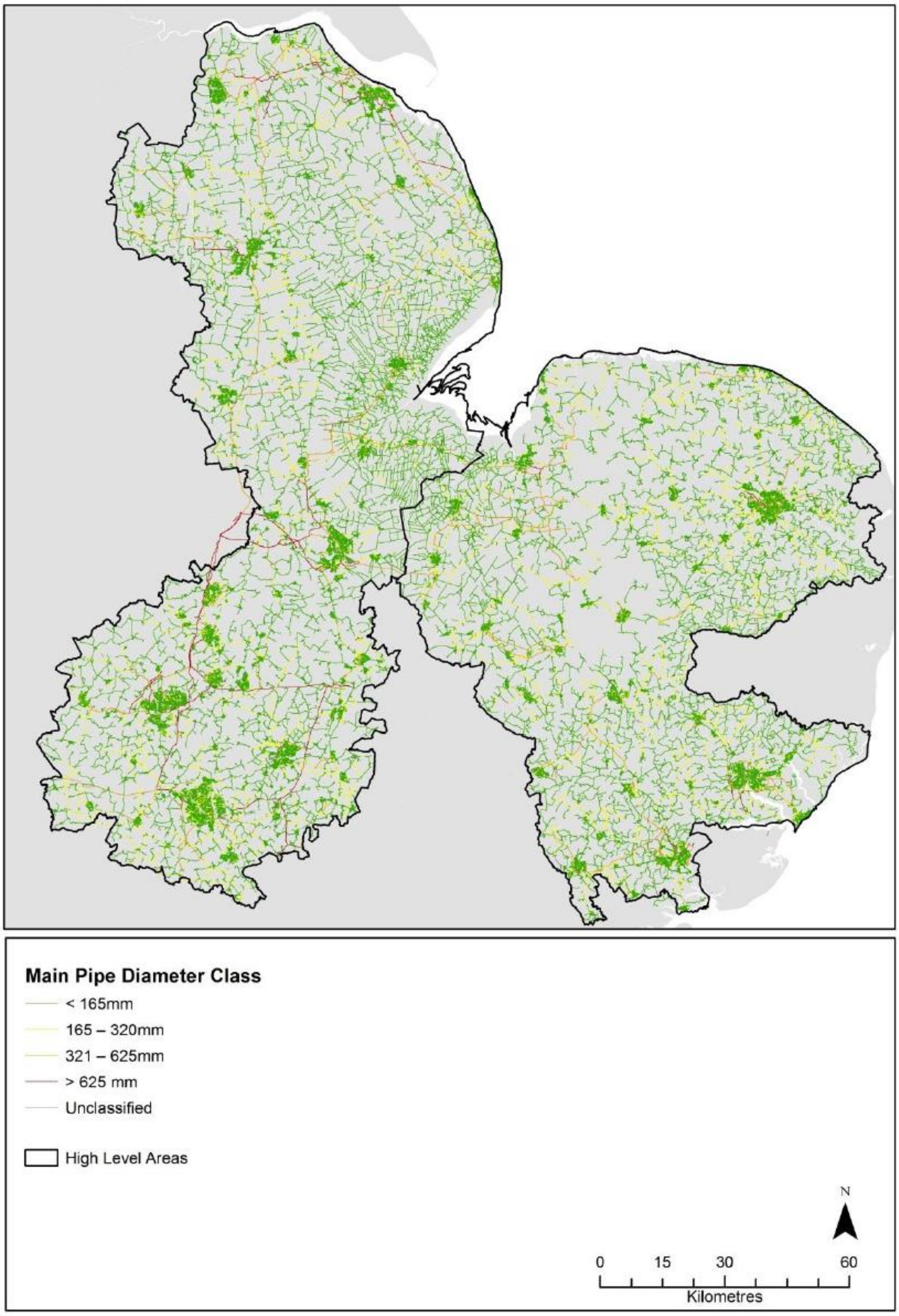


Figure 12 Pipe diameter class

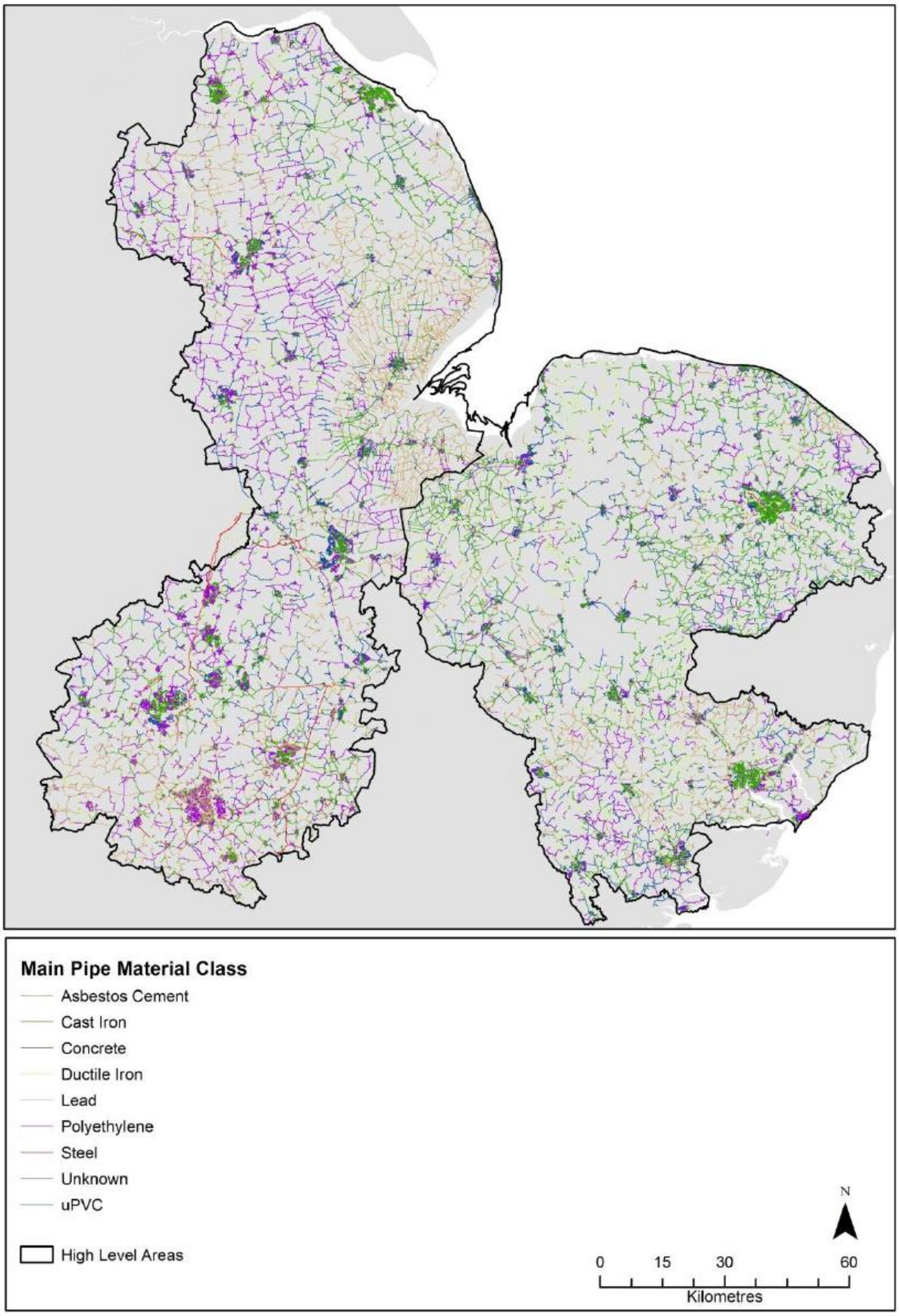


Figure 13 Pipe material class

2.2 Met Office Datasets

It is apparent that there is a strong seasonal bias to the bursts occurrence. It is considered that winter temperature extremes can play a formative part in causing bursts. Statistical analyses were therefore conducted to try to establish any evidential relationship between burst date, burst location and patterns of climatological data.

Met Office Rainfall and Evaporation Calculation System (MORECS) data have been provided for the Anglian Water region. In its operational form MORECS uses daily meteorological data to produce weekly estimates of evapotranspiration, soil moisture deficit (SMD) and hydrologically effective rainfall for each square of a 40 x 40 km grid superimposed upon Great Britain (Gardner, 1983). Grid square estimates of meteorological data are found using interpolation methods. A modified version of the Penman-Monteith equation is used to calculate evapotranspiration; a ‘two-reservoir’ model is used to simulate the extraction of water in the SMD calculations.

2.2.1 *MORECS* (The Met Office Rainfall and Evaporation Calculation System)

Anglian Water provided Cranfield with MORECS data for the Anglian Water region. This data presents temperature, rainfall, evapotranspiration and soil moisture deficit data.

The MORECS data provided for this analysis holds values from the year 2000 (4/1/2000) to 2012 (3/7/2012) and for 33 grids used in the analysis (grids 80 and 102 were excluded from the analysis). Figure 14 shows the locations of the numbered MORECS grids, overlain on the AW management areas.

2.3 Summary temperature analysis

The MORECS datasets were used to conduct a summary analysis. First a summer period of July to September was selected and used to filter the bursts. These were then plotted again against a range of soil characteristics and also plotted bursts across the whole year.

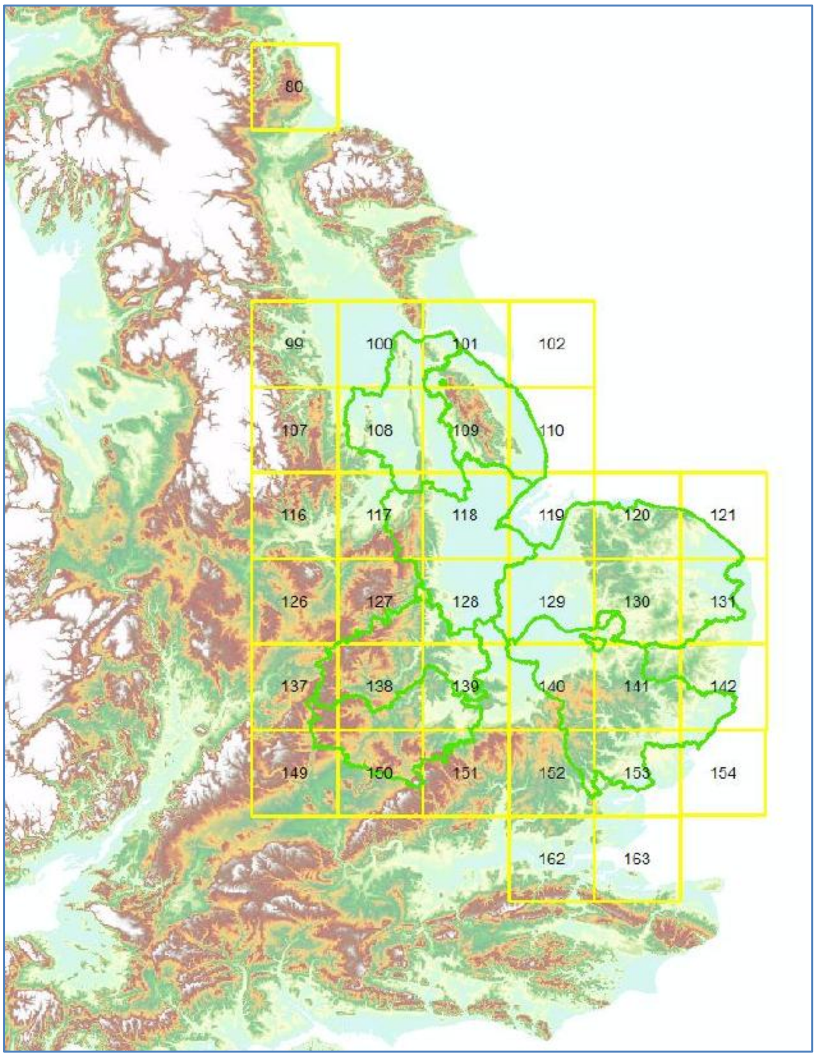


Figure 14 Location of the MORECS 40km x 40km gridcells

Grids ‘110’ and ‘80’ were excluded from the analysis

2.3.1 Meteorological Station Data

Data for meteorological stations was also provided (Figure 15). This data is more sparsely and inconsistently populated than MORECS, but it has daily recording. MORECS data provides weekly levels. Because of the sparse and inconsistent nature, most of our meteorological analyses have focused on the MORECS data.

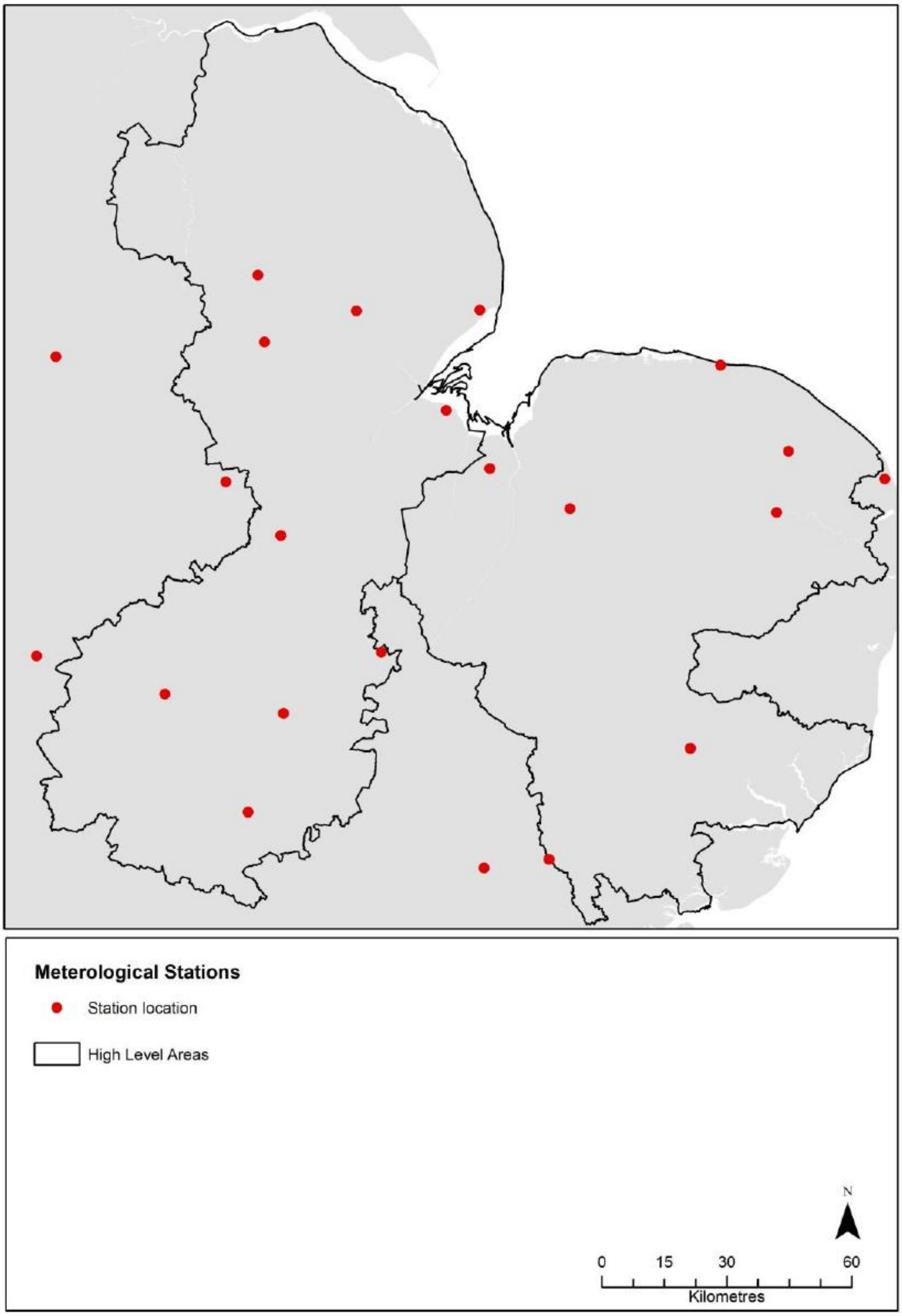


Figure 15 - locations of available met station data

Due to time constraints and the disparate nature of these locations, we have focussed our meteorological analyses on the MORECS data. We have not conducted detailed analyses with these meteorological station data.

2.4 Cranfield University Soil Datasets

Cranfield University's 'National Soil Resources Institute' (NSRI), , is the primary UK centre for research, development, and consultancy concerning soils and their interaction with the atmosphere, land, and water resources of the earth. NSRI is officially recognised as the source of soils information for England and Wales.

NSRI and its forebears have had a national responsibility for researching and documenting the soils of England and Wales over the last 60 years, incorporating exhaustive soils information which has been gathered systematically, starting in the early 1930s, and transformed into computer-compatible format and is today collated into the 'Land Information System 'LandIS' (**www.landis.org.uk**), one of the largest natural land information systems of its kind in Europe (Keay et al 2010; Hallett et al. 1996).

LandIS holds information predominantly concerning soil, but includes also associated climatic, topographic and land use data. Analytical tools and techniques are also embedded within LandIS, alongside the geospatial data, and these have been utilised to aid the analysis of burst records on behalf of Anglian Water plc.

Key data holdings in LandIS include the national soil map and associated legend. This geospatial data is held along with a substantial body of soil property datasets used to characterise and determine soil behaviours.

2.4.1 Soil types and mapping units

There are 720 individual soil types called, soil series, present in England and Wales. Groups of soil series are represented as map units on the National Soil Map. Soil, and its properties are variable within even a small distance. Within each map unit there are multiple soil series and so a range of properties may apply to one demarked area of soil. Thus the classifications used in this report are the predicted dominant property of the soil.

2.4.2 Soil properties

Numerous soil properties have been assessed in the course of this research. These have included, amongst others, pH, ground movement potential, corrosivity to iron, drainage properties and textural characteristics. The effect of soils on different pipe materials has been investigated.

2.5 Techniques

A variety of technical methodologies were employed to undertake the analyses provided, notable using the software tools ArcGIS from ESRI, Microsoft Excel and the open source statistical package 'R' (http://www.r-project.org/).

2.1 Use of Google ‘Street View’ to aid analysis

The literature review has determined a number of potential environmental causes of water mains bursts. One of these is the potential exacerbation of clay subsidence effects from large vegetation such as trees. It is important to have a perspective as to where the burst locations are and what, if any, local conditions might be seen to prevail at the point of the burst.

Burst locations were supplied in a spatially-referenced GIS file format. This permitted the conversion of the data to the OGC implementation standard ‘Keyhole Markup Language’ (KML) data format (http://www.opengeospatial.org/standards/kml/), which in turn enables the interaction of the locations with the Google ‘Street View’ product, embedded in Google Earth (http://www.google.com/earth/).

The KML file as attached as a digital Appendix to the report for a selection of the MORECS 40km x 40km squares that seemed to be subject to a high burst rate (MORECS grids ‘151’ and ‘138’). These squares also captured a spread of urban, peri-urban and rural environments.

2.2 Results

A summary review was taken to identify locations of bursts, noting potential relevant local conditions.

Figure 16 Example burst location proximal to a tree and subject to potential vehicle loading. (Clay soil location in Wellingborough, Google Street View)

Figure 17a & b Example burst locations proximal to a road junction and subject to potential vehicle loading from waiting traffic.(Northampton, Google Street View)

Figure 18 Example burst location proximal to road speed bumps, subject to potential vehicle loading from passing traffic.(Northampton, Google Street View)

This exercise has highlighted that in addition to rather blunt statistical analysis of the whole dataset, it is important to be able to capture localized conditions as part of understanding the potential causes of burst events.

Chronic pipe degradation

3 Chronic pipe degradation

This section outlines some of the chronic, ongoing processes and soil effects which can degrade pipe networks. Seasonal effects such as winter temperature and summer / autumn shrinkage and swelling of soils are dealt with in later chapters.

Issues identified as effecting pipe longevity include pipe material and diameter, soil corrosivity, depth to fluctuating water table.

There is noted a dominant effect of peat on pipe degradation. However, pipes in peat soils only make up 0.6% of the pipe network of Anglian Water.

3.1 Pipe materials and diameter

The pipes in the Anglian Water region fall predominantly in the diameter range of 56mm to 320mm (Table 5). Cast Iron makes up approximately 1/3rd of the pipes in the Anglian Water region (Table 6) yet accounts for 45% of the bursts. Polyethylene makes up 25% of the pipes, yet has a much lower fracture rate per 1000 km than Cast Iron (Figure 20) and only accounts for 2% of the bursts. Steel pipes are relatively inextensive (1%) yet fracture frequently.

There are seasonal trends in the burst rates of these pipes and materials (Figure 21), which will be dealt with in subsequent sections.

Table 5 - Breakdown of diameter of pipes in Anglian Water Region

Note: Diameter classes 11, 12,13,14 are subdivisions of class 1 (1-165 mm).

Diam_Class_v2	Diameter (mm)	Length pipe(km)	%	bursts / 1000 km
0	0	375.81	0.99	
11 (1)	0-55	1449.83	3.83	168.63
12 (1)	56-85	10514.69	27.81	46.6
13 (1)	86-130	10123.83	26.78	46.31
14 (1)	131-165	6641.84	17.57	65.46
2	166-320	5953.17	15.75	83.66
3	321-625	2043.61	5.41	185.8
4	>625	706.44	1.87	1198.49

Total	37809.23	100	

Table 6 – Breakdown of pipe material in the Anglian Water Region

Matt_Class	Material	Length pipe(km)	%
CI	Cast Iron	10941.05	29.03
PE	Polyethylene	9744.15	25.85
AC	Asbestos Cement	7168.37	19.02
uPVC	uPVC	6027.41	15.99
DI	Ductile Iron	2833.56	7.52
ST	Steel	462.00	1.23
UNK	Unknown	388.06	1.03
PRC	Polyester re-inforced concrete	110.24	0.29
CO	Concrete	11.21	0.03
GRP	Glass re-inforced plastic	2.43	0.01
PB	Lead	2.13	0.01
	Total	37690.60	100.00

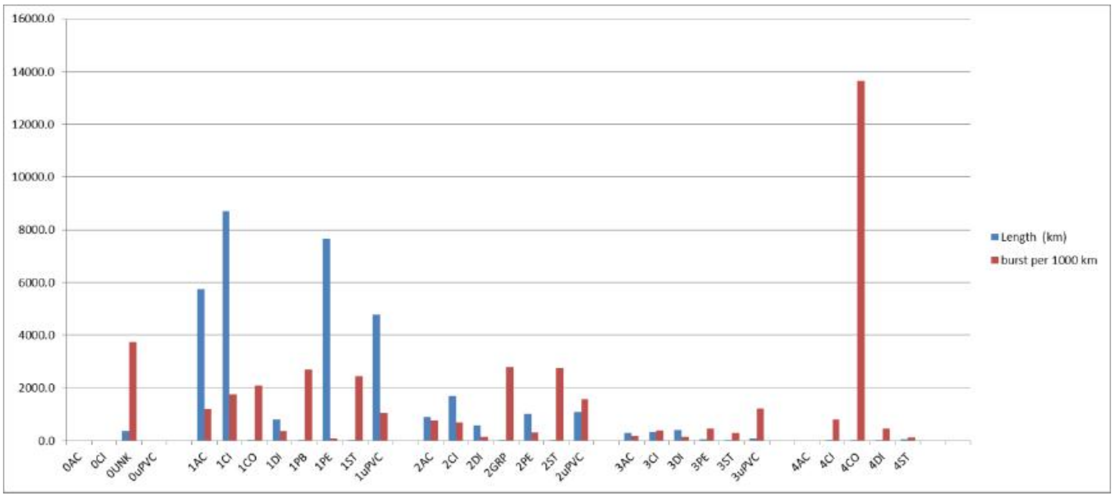


Figure 19 - length of pipes and bursts per 1000 km by material and diameter class.

Note: For description of the classes, please refer to Table 5 and Table 6. e.g. 2AC = diameter class 166-320mm, Material: Asbestos Cement.

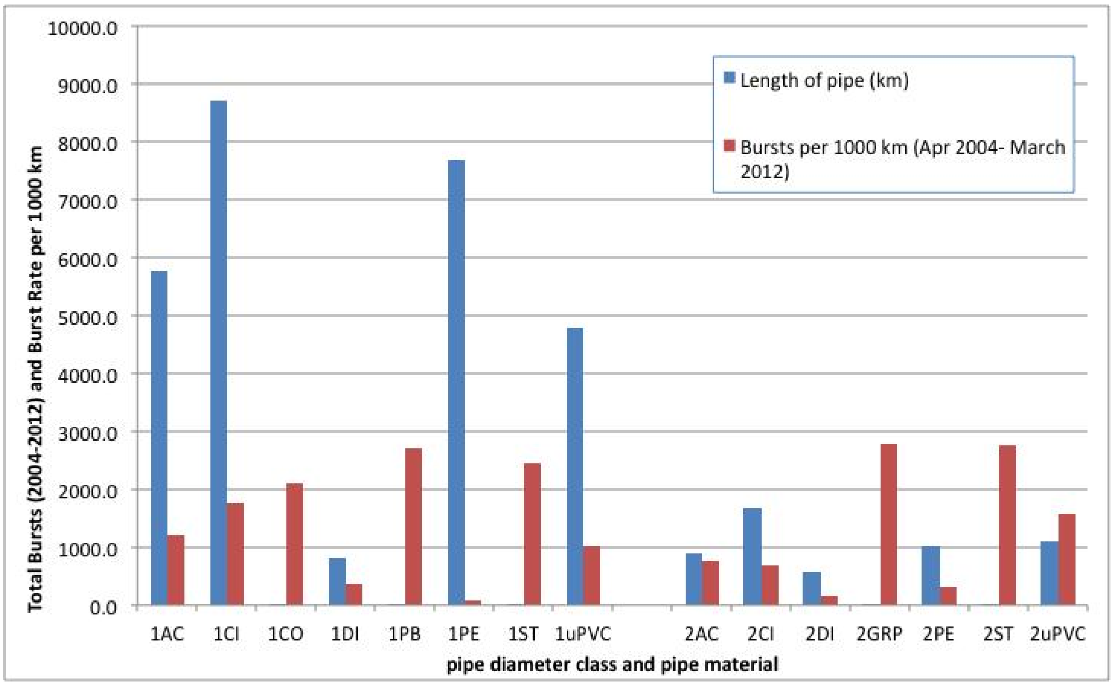


Figure 20 - length of pipes and bursts per 1000 km by material and diameter class. (reduced)

Note: For description of the classes, please refer to Table 5 and Table 6. e.g. 2AC = diameter class 166-320mm, Material: Asbestos Cement.

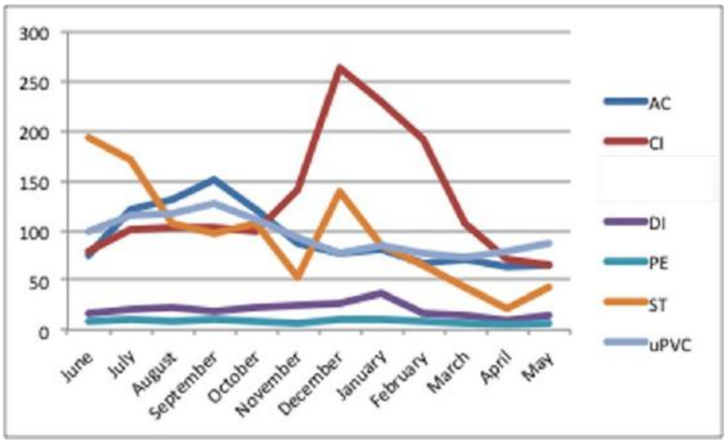


Figure 21 - average monthly bursts per 1000 km (2004-2012) by pipe material

Note: Cast Iron tend to burst more in the winter months. UPVC and Asbestos Cement tend to burst more often in summer and Autumn months.

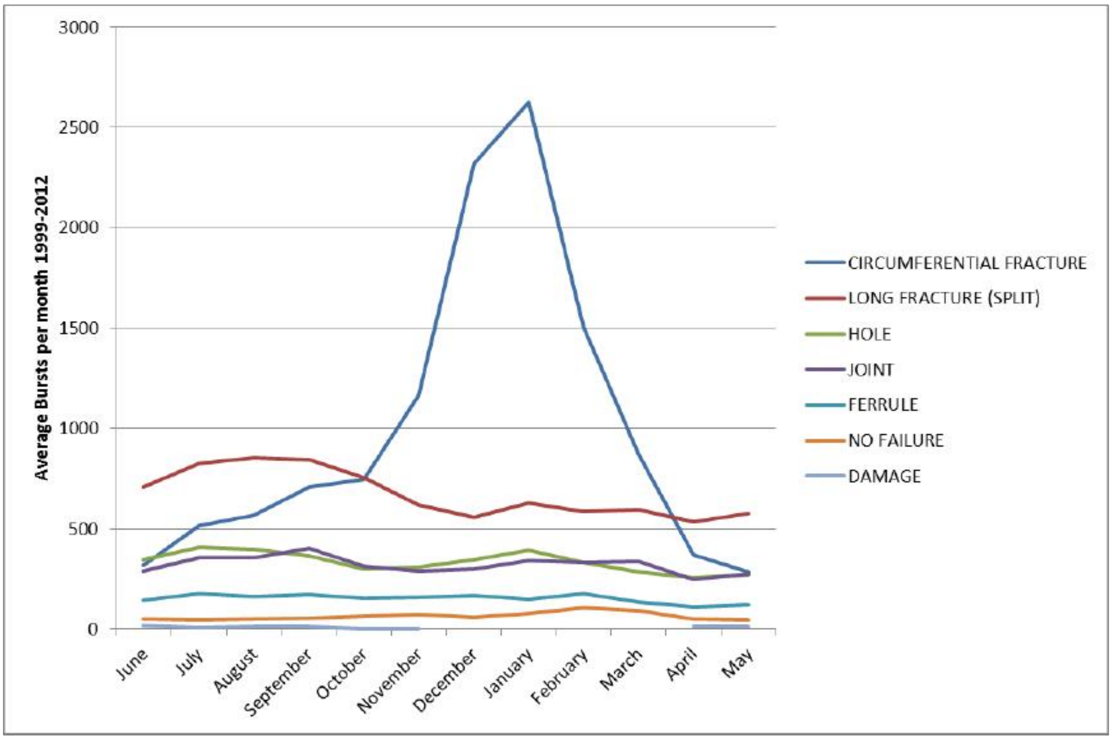


Figure 22 Burst type by month. Circumferential fractures are typical failure mode for Cast Iron pipes

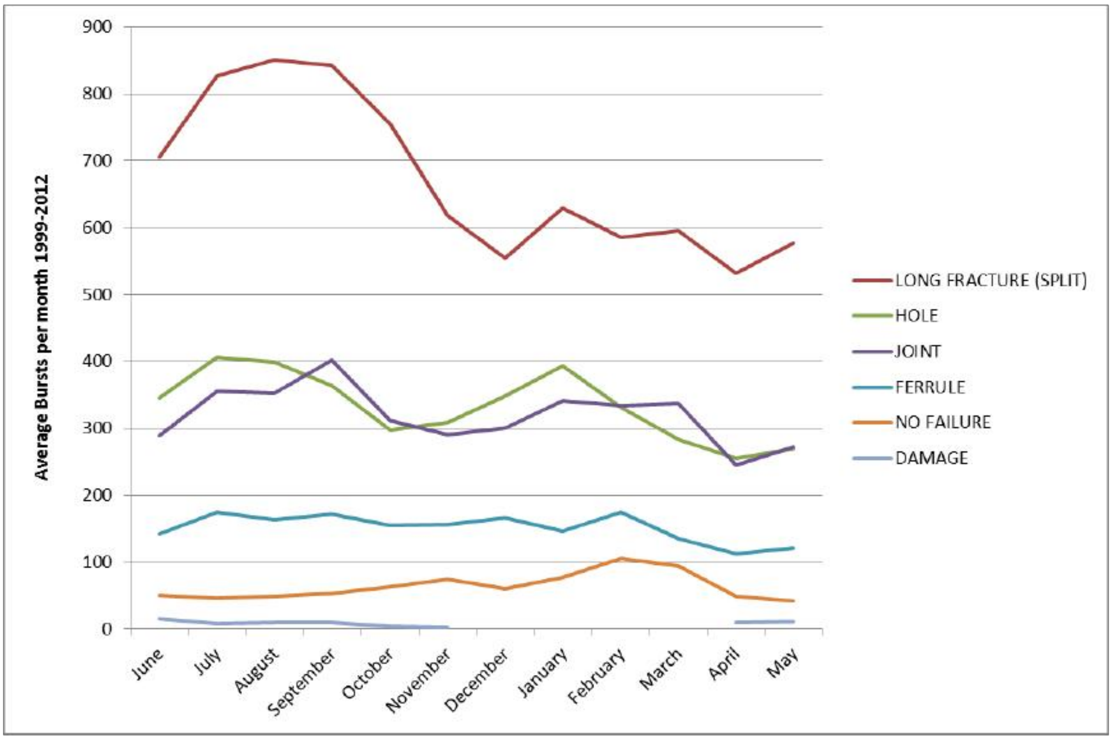


Figure 23 Burst type by month. Circumferential fractures removed. Long fractures are typical of uPVC and Asbestos Cement pipes.

3.2 Soil corrosivity and pH

3.2.1 The NSRI Soil Corrosivity Model

The classification system used by NSRI is believed to be the most appropriate system currently available for this country in the absence of more extensive results from direct measurements. This system linked to the *soil series* concept allows a rapid appraisal of any locality or extensive area in England and Wales, such as the Anglian Water region, where NSRI soil maps exist. It also ensures that there is a consistent national approach to the assessment of soil aggressivity classes.

The corrosion of metal in soil is a complex electrochemical process and it is difficult to identify all the contributing factors. There is no national standard for assessing the corrosivity of soil, although there are standards for some individual tests, and standards produced by interested organisations. However, the following soil properties are considered to be the most important in having a significant effect on the corrosion of buried metal pipes (Figure 28).

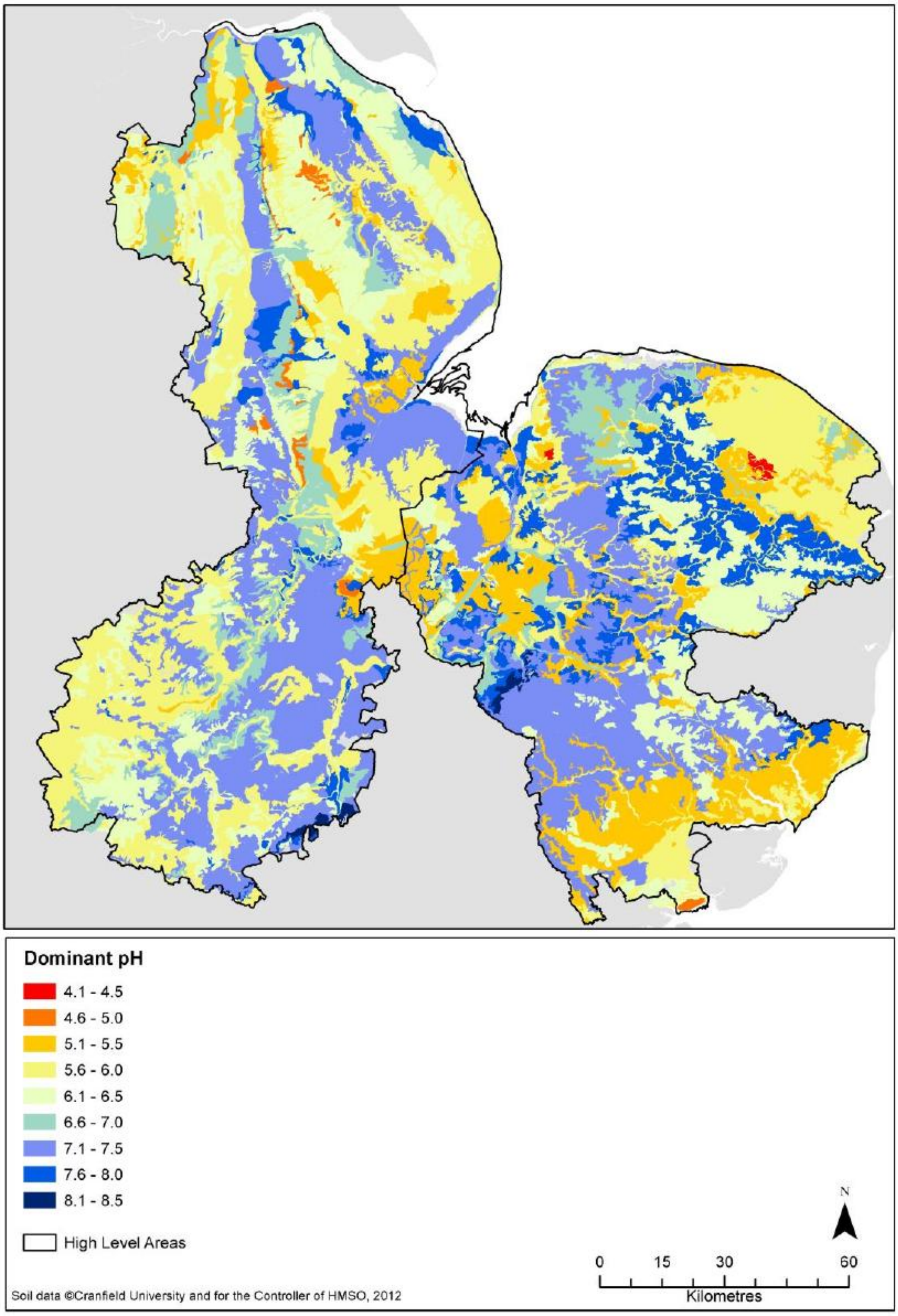
3.2.2 Soil Acidity

Metal pipes can suffer chemical attack. Metals usually dissolve more rapidly in acidic conditions, particularly where the soil is strongly acid with a pH less than 4.5.

With leaching, soils gradually become more acid with time. This is especially so where there was little or no free lime in the original soil parent material. Agricultural land is usually limed to a pH of 6.5 for arable use and 6.0 for grassland, and with time some of the applied lime reaches the subsoil in non-calcareous materials to raise the pH to between 5.0 and 7.0; moderately acid to neutral. Old woodlands and heaths are likely to remain strongly acid in the subsoil. However, with rainfall exceeding evaporation, leading to an excess of water in most years in Britain, the general tendency is for acidification through leaching of bases in the soil.

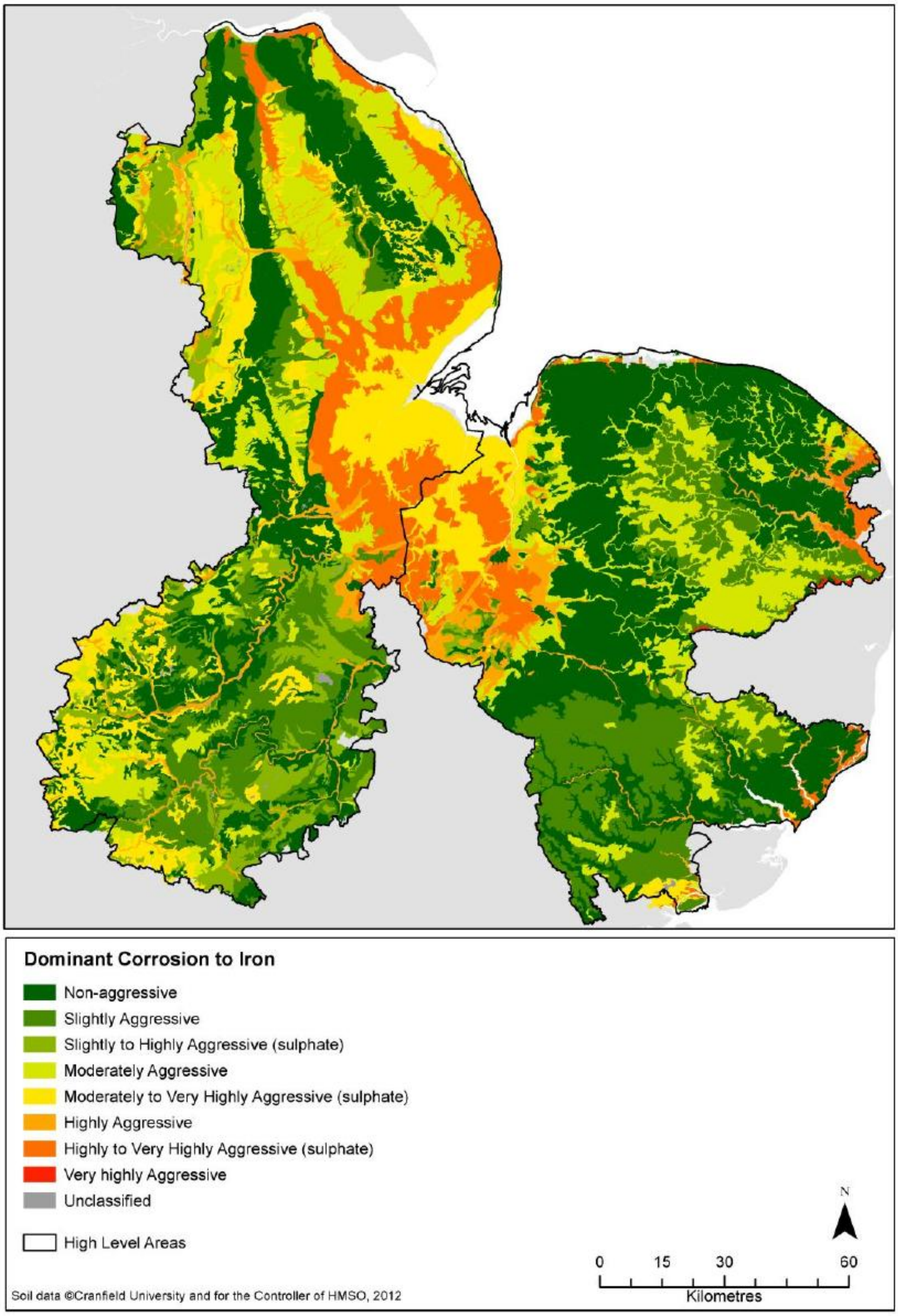
Figure 24 - length of pipe in soils of different pH

Dominant pH	Length pipe (km)	%
NULL	18.88	0.05
4	283.17	0.75
5	14785.24	39.23
6	9036.63	23.98
7	13290.22	35.26
8	276.45	0.73
Total	37690.60	100.00



Soil data ©Cranfield University and for the Controller of HMSO, 2012

Figure 25 - Dominant pH mapping across the Anglian Water Region



Soil data ©Cranfield University and for the Controller of HMSO, 2012

Figure 26 - NSRI's Soil Corrosivity Model

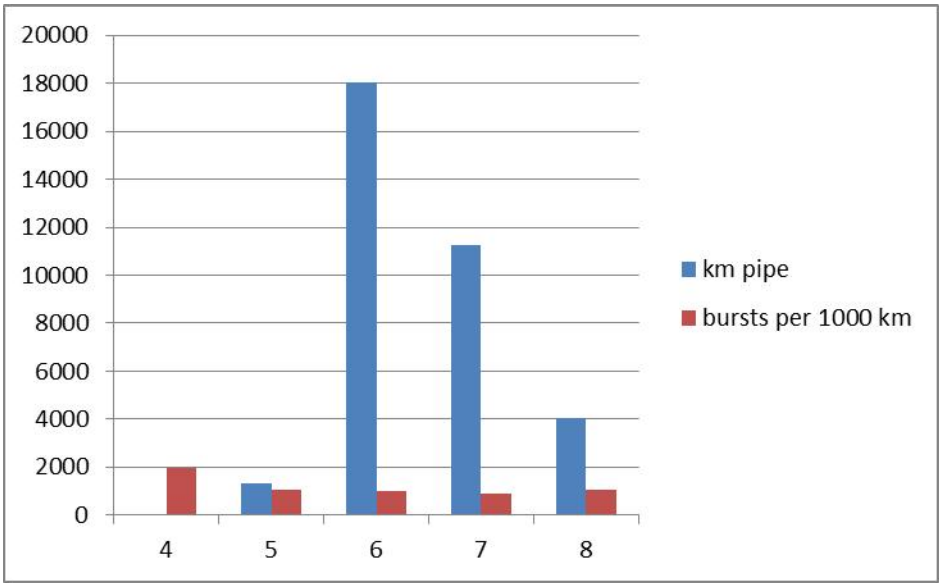


Figure 27 - pH and burst rate (2004- 2012)

3.2.3 Soil Moisture Content

Water is essential for the corrosion process to take place and moisture contents above 20% (on a weight basis) can be particularly corrosive. Where a water-table is present in the subsoil, its level in relation to pipe depth will affect soil water content. In the absence of a water-table, soil water contents at pipe depth are fairly constant throughout the year and will only vary between sites according to clay content and permeability. Thus the principal soil factors are water-table levels, expressed as Soil Wetness Class, and the clay content.

Variations in the colour of soil (mottling) are to a large extent determined by the degree and duration of waterlogging, in the soil's natural state. Field drains reduce the wetness of the subsoil where installed on agricultural land, so that the colours may represent a relict wetness feature. In this study the natural wetness state is used to determine the corrosion class as this state may have prevailed in the past when pipes were first installed, prior to modern drainage measures. Furthermore, it is unlikely that all land has been drained to the same standard and the corrosion class thus represents a worst-case scenario as far as wetness is concerned.

3.2.4 Soil Corrosivity Class

The Soil Corrosivity model, results in a classification system that can be used to identify risk. Various properties have been incorporated into a potential soil corrosivity model which defines a number of corrosivity 'risk' classes. These categories are presented in Table 7 with an assessment of the % water mains in each class in the Anglian Water region.

Table 7 Soil Corrosivity Classes

COR_FE	Soil Corrosivity Class	Length pipe(km)	%
1	non-aggressive	14182.73	37.63
2	slightly aggressive	7344.58	19.49
3	moderately aggressive	5980.40	15.87
4	highly aggressive	947.56	2.51
5	very highly aggressive	13.78	0.04
3*	moderately aggressive (sulphates)	2384.12	6.33
4*	highly aggressive (sulphates)	4400.22	11.67
5*	very highly aggressive (sulphates)	2418.34	6.42
(blank)		18.88	0.05
	Total	37690.60	100.00

Figure 28 shows a summary of the various soil and soil-related factors incorporated in the NSRI soil corrosivity model.

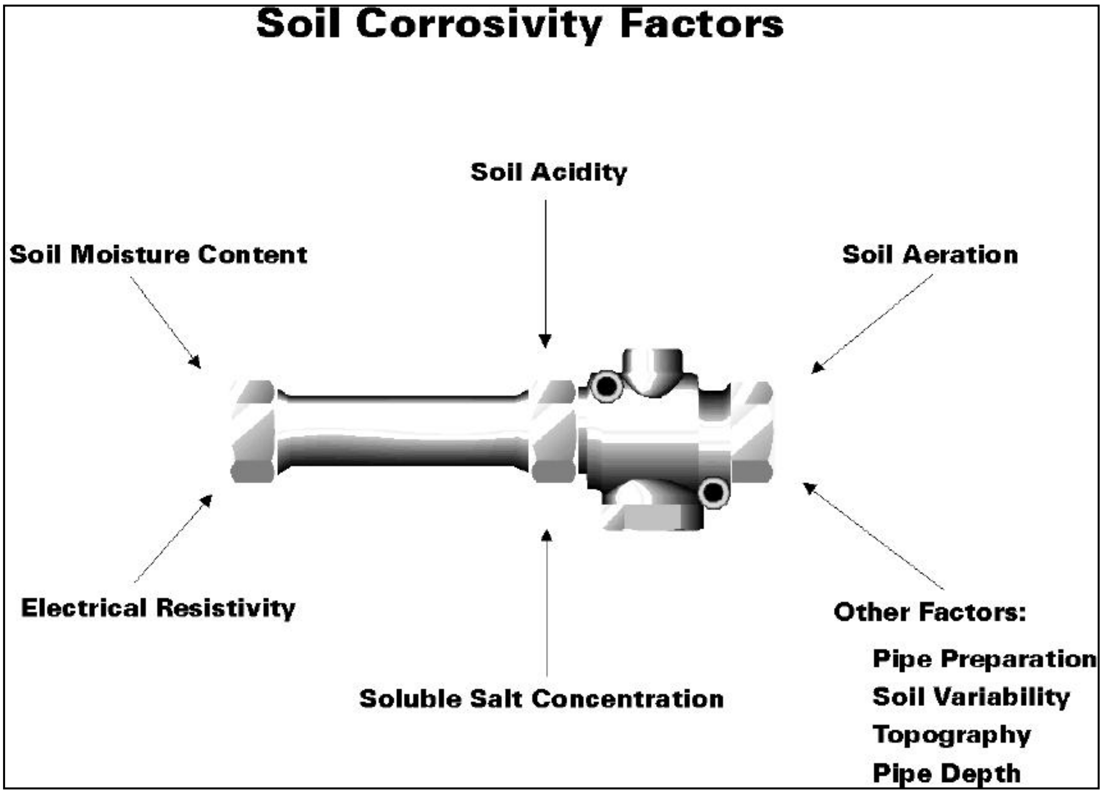


Figure 28 Corrosivity Factors Modelled

3.2.5 Soil Aeration

In a well aerated soil there can be an initial phase of corrosion when the pipe is laid but the dense corrosion product does tend to quickly form a protective coat. Poorly aerated (anaerobic) soils promote corrosion. The corrosion under anaerobic conditions proceeds at a slow but steady rate and does not form a protective coating around the pipe so leading to early failure. Anaerobic environments in soils are usually associated with dense clay-rich layers that are slowly permeable to water, *e.g.* in most clayey soil parent materials.

3.2.6 Soluble Salt Concentration

Soils containing chlorides or sulphates, the latter commonly as gypsum, are potentially highly aggressive to buried ferrous iron pipes. The risk can be estimated by measurement of the sulphate and chloride ion concentration. Bacteria thrive in some of these environments and create conditions conducive to corrosion, for example, by reducing sulphate to sulphide in anaerobic conditions, or in assisting in the oxidation of sulphides to form sulphuric acid.

3.2.7 Electrical Resistivity

The resistivity of the soil gives a measure of the concentration of soil electrolyte, essential in the corrosion process. Soils with low resistivity will encourage corrosion, whereas soils with high resistivity are likely to inhibit corrosion. Some researchers suggest that soils with resistivities less than 2,000 ohm cm should be regarded as aggressive, with fairly severe conditions indicated by values less than 1,000 ohm cm. Electrical conductivity (the reciprocal of resistivity) is commonly used to measure salt concentrations in the soil solution, and thus the aggressiveness of the soil to buried metals.

3.2.8 Other Influencing Factors

A number of other factors may impact on pipe corrosion; these include:

- Pipe depth and preparation
- Topographical influences
- Localised soil variability

3.2.8.1 Pipe Depth and Preparation

For consistency, this study has taken a soil depth of 1 metre throughout the area as a basis for the interpretation. Where pipes are buried at shallow depths, the risk of corrosion is likely to be slightly reduced, and conversely slightly increased where pipes are buried deeper than 1 metre. Different preparations of the pipe trench and the nature of the refill material can, if different from the surrounding soil, affect corrosivity.

3.2.8.2 Topographical Influences

Local variability in corrosion risk may be influenced by topographical features, such as dips and valleys, where salt applied to roads is concentrated as run-off. This salt is especially effective in corroding metal pipes where the run-off has rapid access to the lower subsoil by a ditch along the grass verge. Such localised influences can not be taken into account in this generalised study.

3.2.8.3 Localised Soil Variability

In some map units the soil in its natural state can vary sufficiently in texture, wetness and pH over a matter of a few metres to affect the corrosion classification. In such cases, a median corrosion class is given for the range of soils.

Soils with a marked change in texture in the subsoil offer a higher corrosion risk than uniformly textured soil. Subsurface-water flow, for example, is concentrated at the base of loamy soil material overlying slowly permeable clay, promoting increased corrosion of any ferrous pipe laid there.

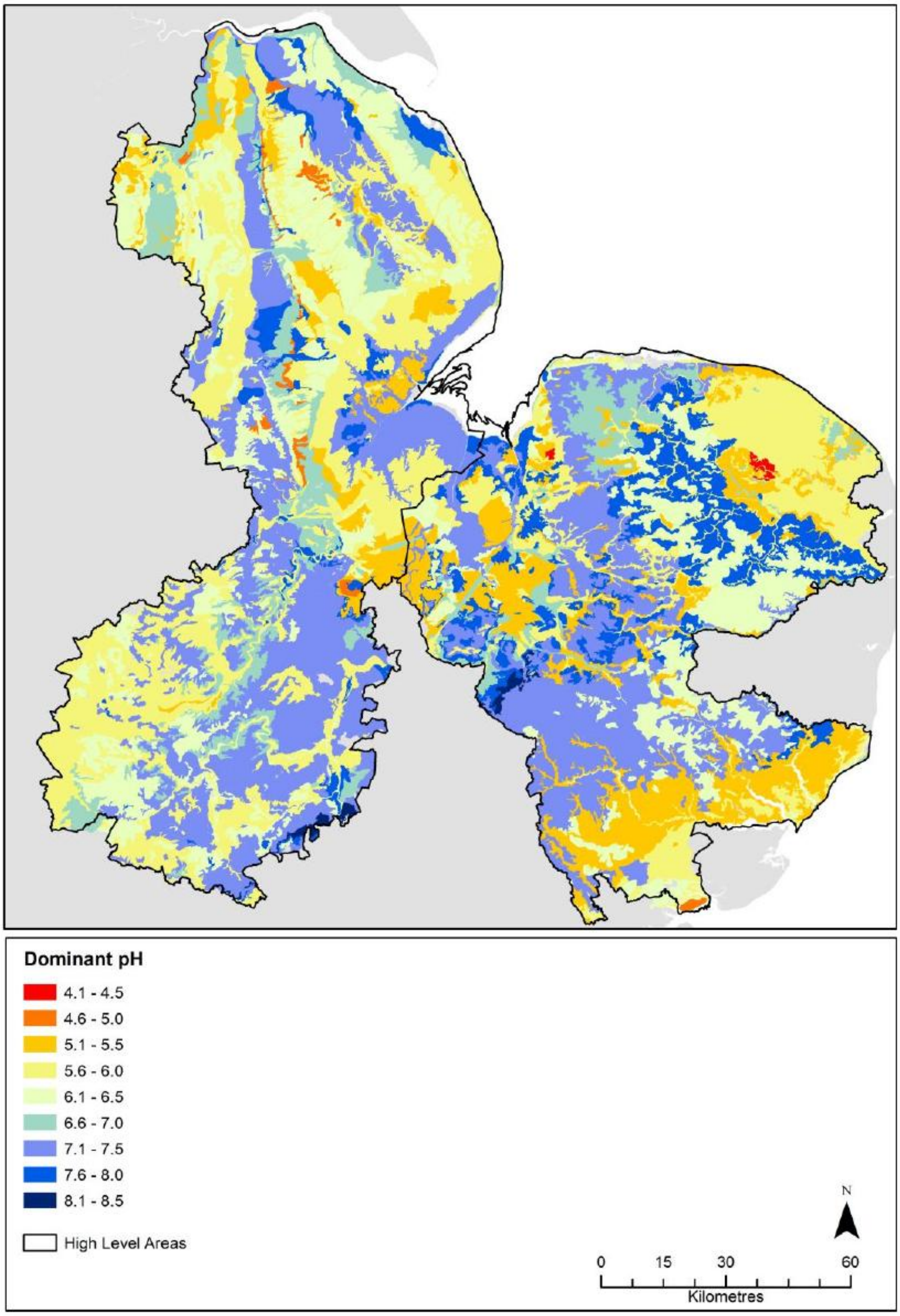


Figure 29 - Dominant pH in soils across the Anglian Water Region

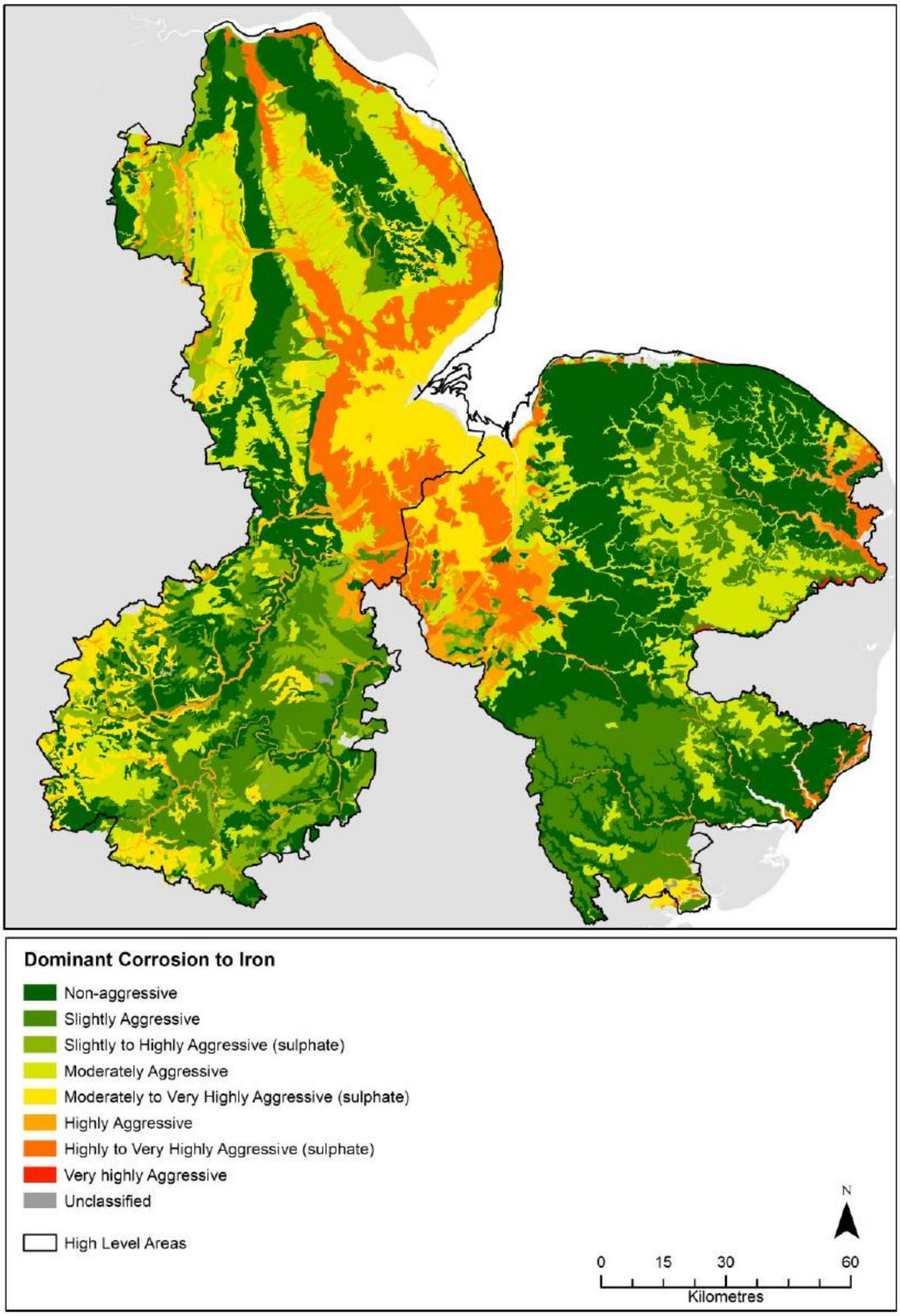


Figure 30 - Dominant corrosivity to Iron

3.3 Soil depth to rock

The majority of pipes in the Anglian Water area are found within deep soils, with a depth of greater than 80 cm.

Table 8 Soil depth to Rock

Depth to Rock	Length pipe(km)	%
Deep (>80cm)	31945.41	84.76
Medium (40-80cm)	5623.49	14.92
Shallow (<40cm)	121.70	0.32
Total	37690.60	100.00

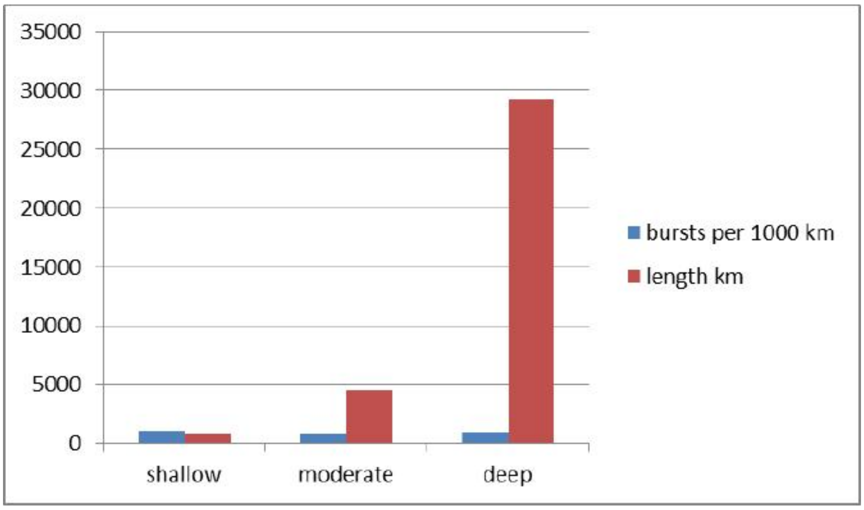


Figure 31 - Comparison of burst rates in soils of different depths.

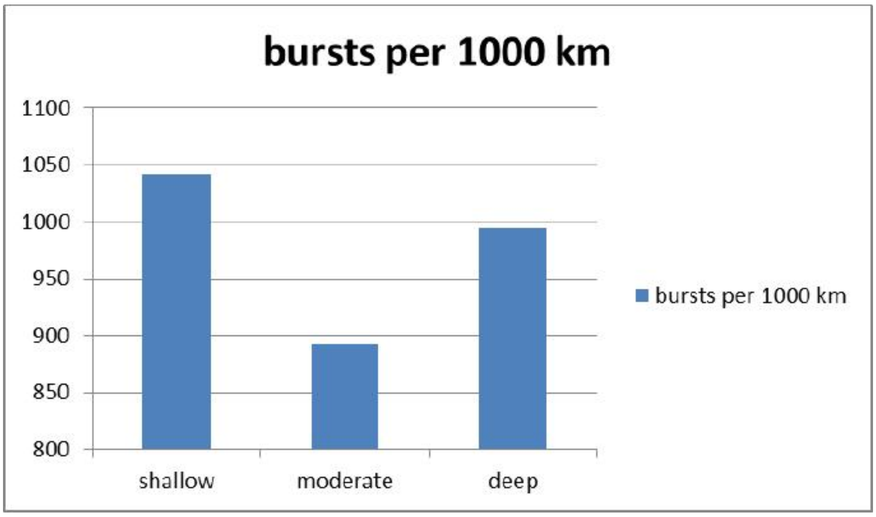


Figure 32 - Burst rate by soil depth

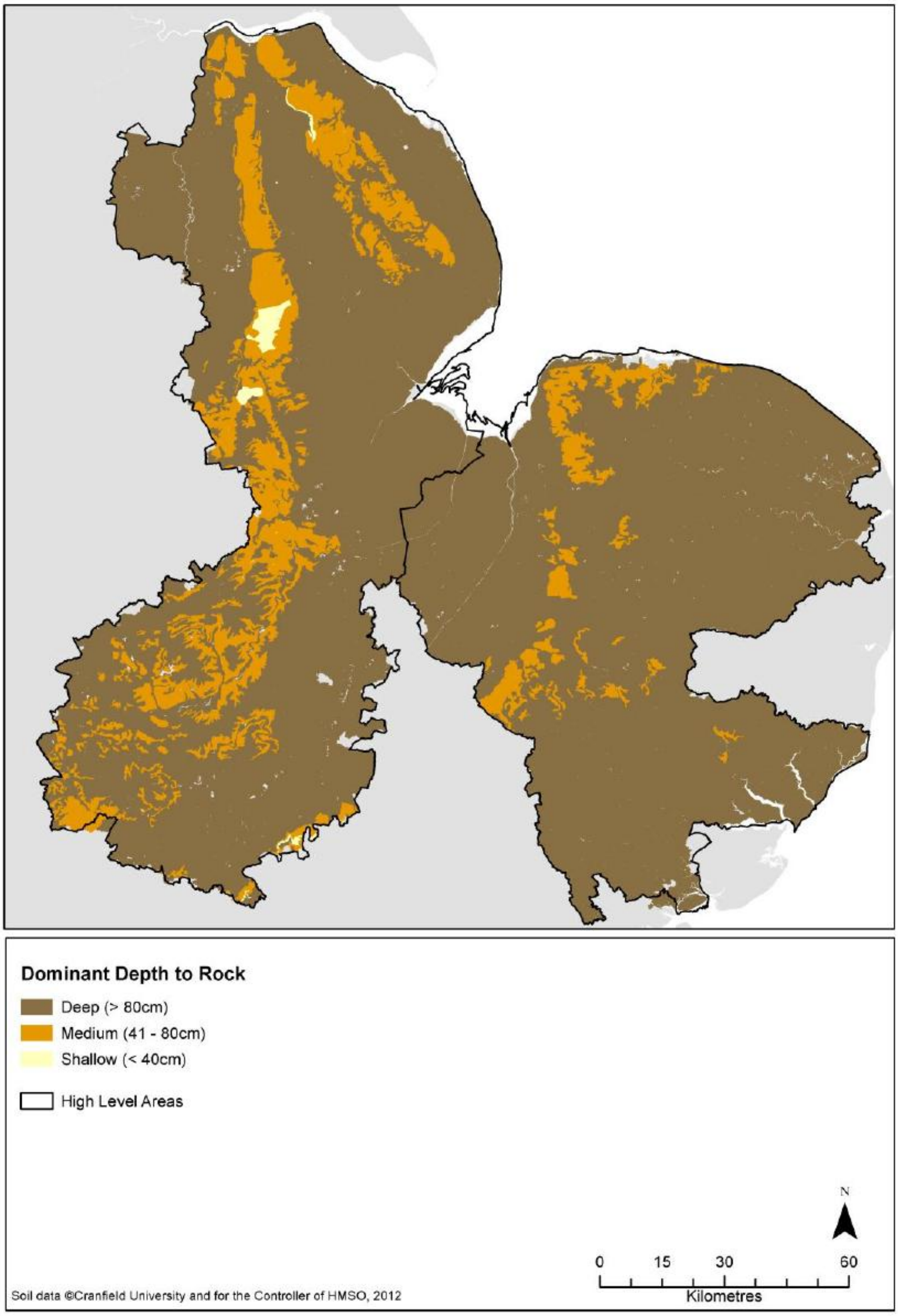


Figure 33 - Dominant depth to rock

3.4 Soil depth to fluctuating water tables

Soil moisture levels and the transition from reducing and oxidising conditions develop aggressive conditions for metal pipes.

Over 60% of the Anglian Water area has signs of gleying near the surface. These surface gley soils have more bursts per 1000km than the deeper soils (Table 9).

Table 9 Soil depth to gley layer - indicative of fluctuating water table

Depth to Gley	Length pipe(km)	%	Bursts/1000km
Shallow < 40 cm	13739.60	36.45	983
Medium 40-80 cm	9767.79	25.92	900
Deep >80 cm	14164.34	37.58	827
0	10.13	0.03	
No Data	8.75	0.02	
Total	37690.60	100.00	

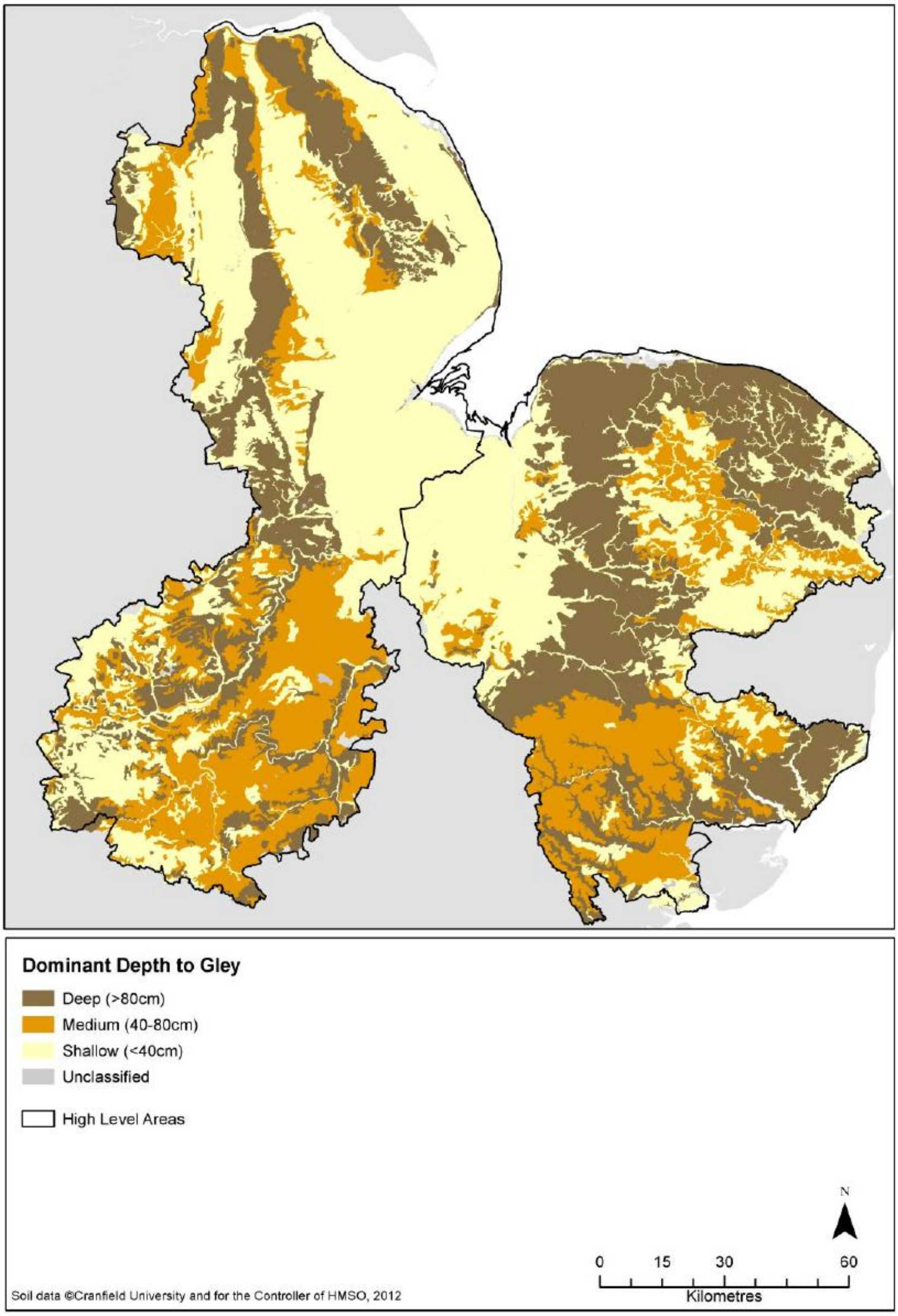


Figure 34 - Map of Depth to Gley layer (indicative of fluctuating water table)

3.5 Peat soils

While many soils in the Anglian Water region are rich in organic carbon, true peat soils only make up a small fraction of the Anglian Water region, and only 226 km (0.6%) of Anglian Water's pipes are laid in peat soils. Nevertheless, where these soils occur, the pipe network is heavily affected by such soils, with the highest burst rates approaching 200 bursts per 1000 km at many months of the year (Figure 35).

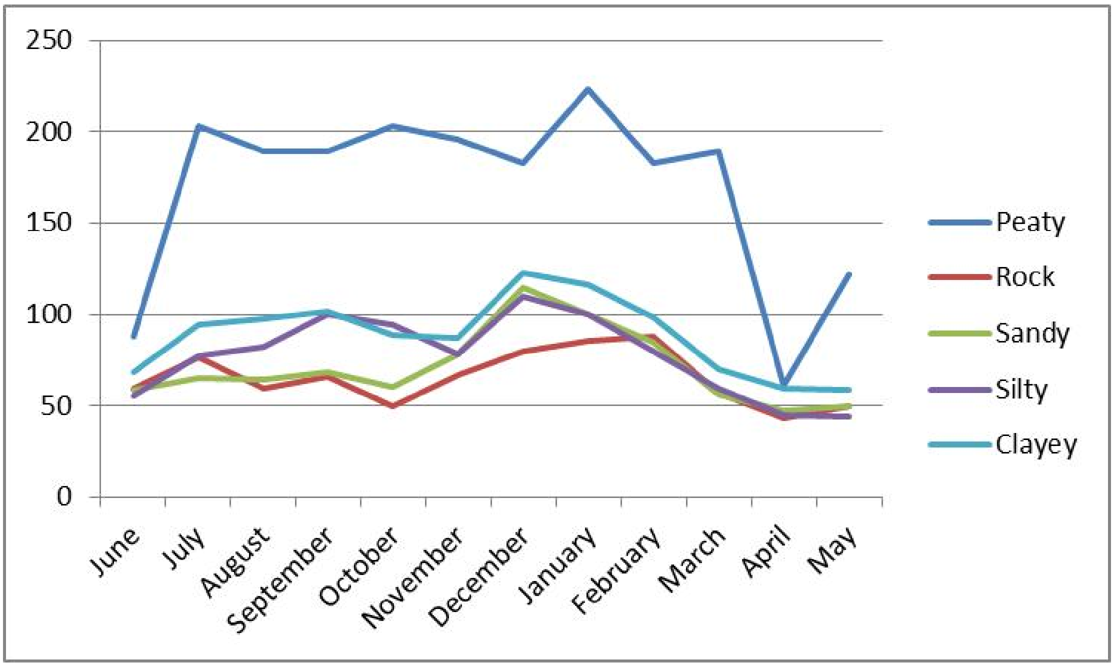
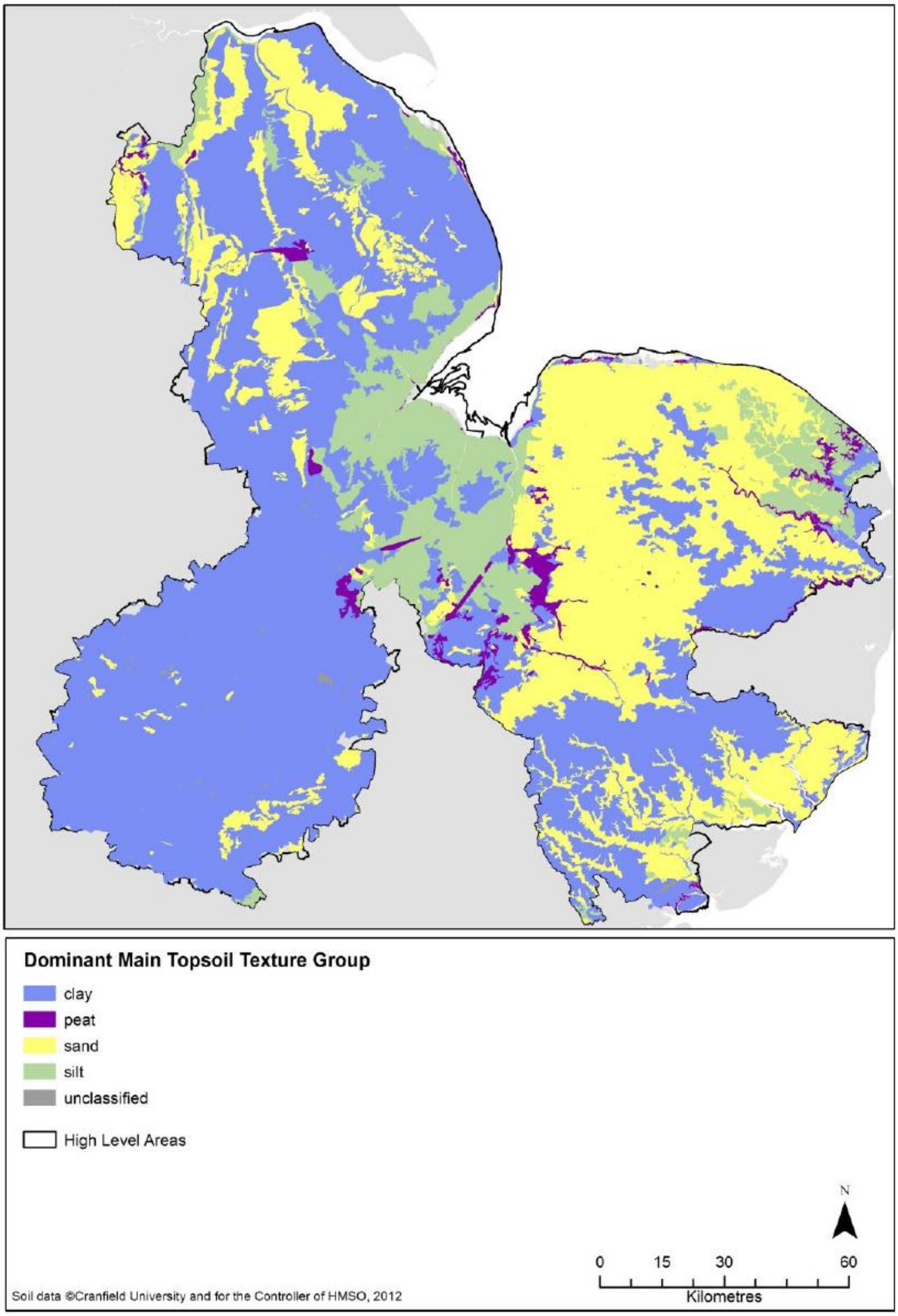


Figure 35 average monthly burst rate (2004-2012) by simple subsoil texture class.

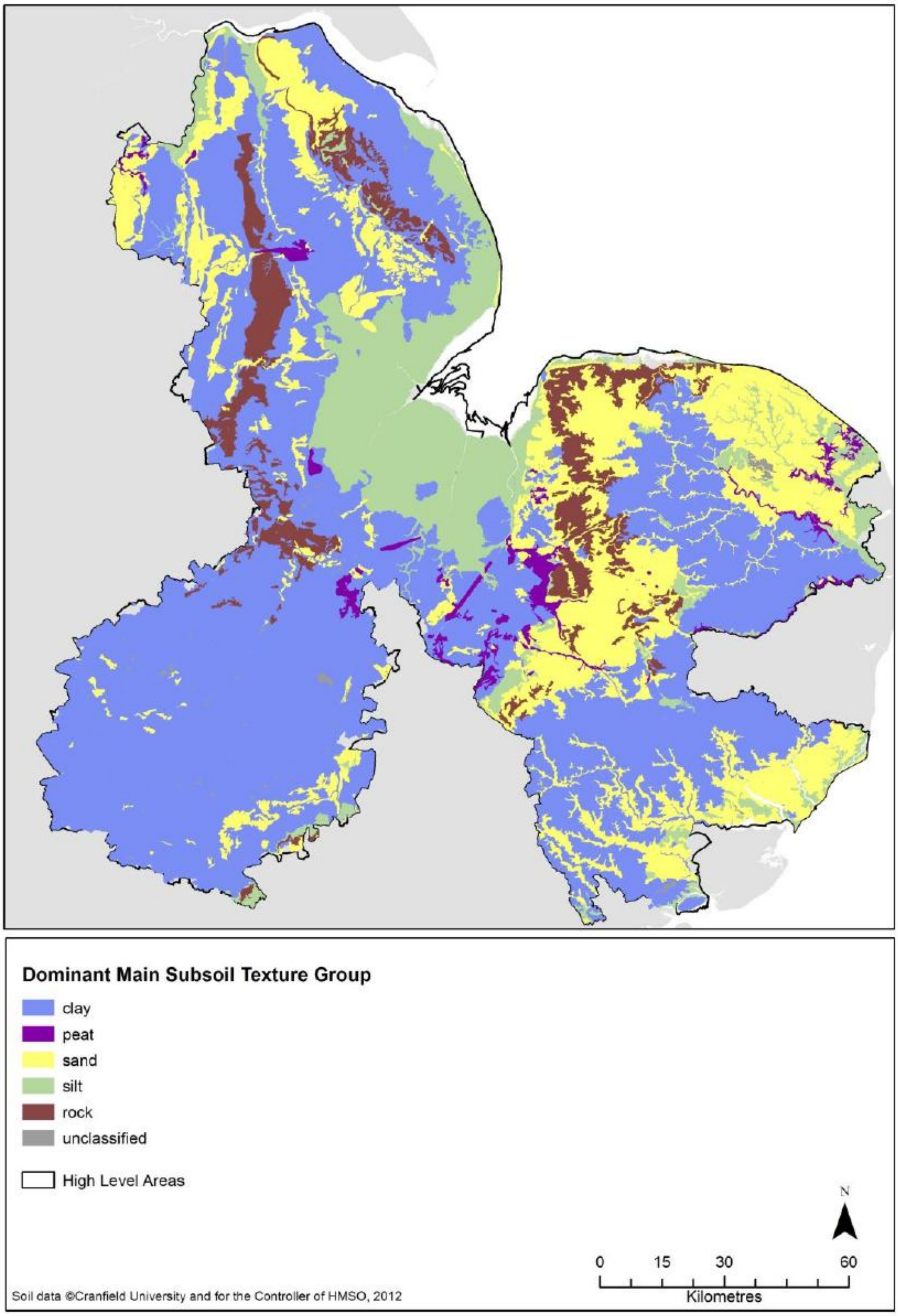
Table 10 Topsoil texture (simple) and length of pipe

Topsoil texture group	Length pipe(km)	%
clay	21268.69	56.43
sand	11404.75	30.26
silt	4771.92	12.66
peat	226.36	0.60
#N/A	18.88	0.05
Total	37690.60	100.00



Soil data ©Cranfield University and for the Controller of HMSO, 2012

Figure 36 - Dominant Topsoil Texture Class (Simple)



Soil data ©Cranfield University and for the Controller of HMSO, 2012

Figure 37 - Dominant Subsoil Texture Class (Simple)

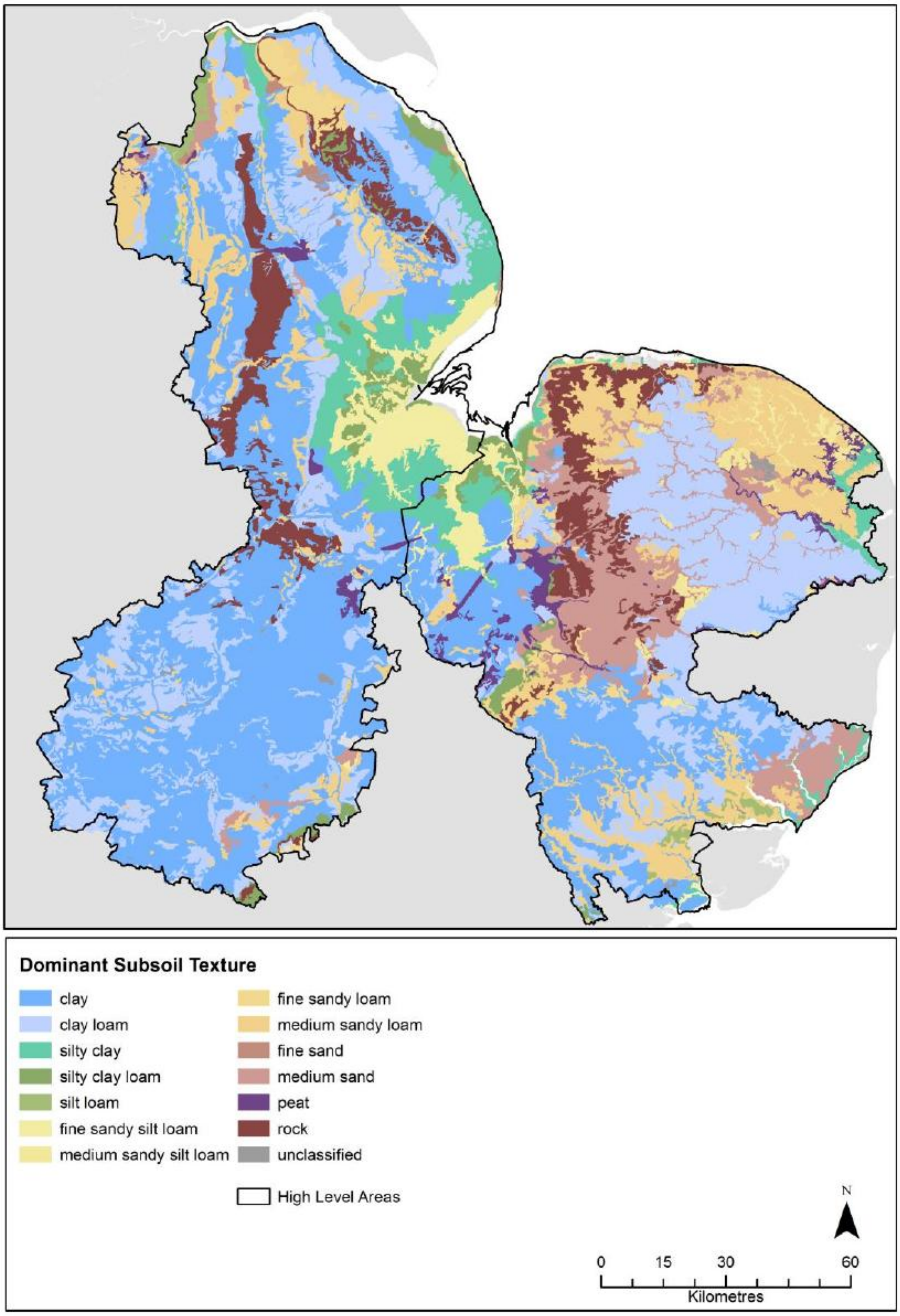


Figure 38 - Dominant Subsoil Texture

Table 11 Subsoil texture (simple) and length of pipe

Subsoil texture group	Length pipe(km)	%
clay	20886.16	55.41
sand	9731.49	25.82
silt	4924.82	13.07
rock	1764.86	4.68
peat	223.48	0.59
#N/A	159.79	0.42
Total	37690.60	100.00

3.6 Sand washout

While sand washout has been identified as a causal factor in fractures and subsidence, there have not been any unique trends identified with such soils in the Anglian Water region in this research.

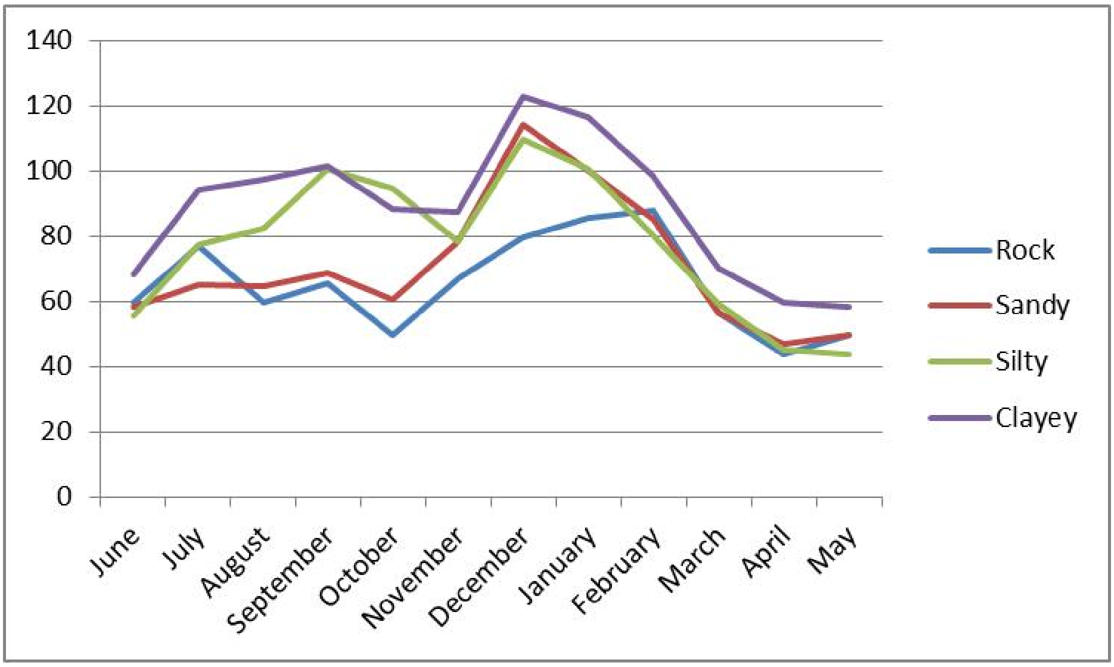


Figure 39 - average monthly burst rate (2004-2012) by simple subsoil texture class (peat removed).

Winter Bursts

4 Winter Bursts

This section outlines the effects of successive cold winters on the Anglian Water pipe network.

It is shown that the last four winters have had more sustained colder periods than the previous eight years. These last four years have also had more bursts during the winter time. These bursts have occurred across all soil types.

4.1 Background

A plot of the number of bursts by month through from 2005 to 2012 shows clear visual patterns of burst peaks in the cold winters of 2008-9, 2009-10, 20010-11 and 2011-12 (Figure 40).

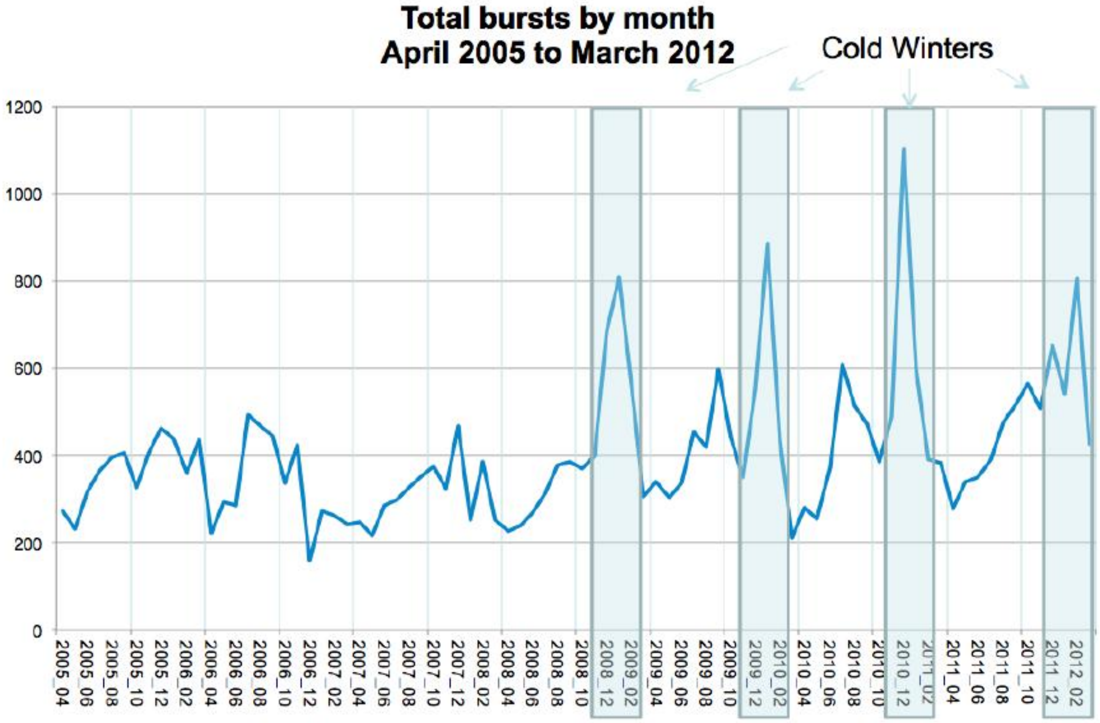


Figure 40 - Cold winters and the increase in winter bursts

Looking at the number of bursts through the year expressed side-by-side also highlights this pattern visually (Figure 41).

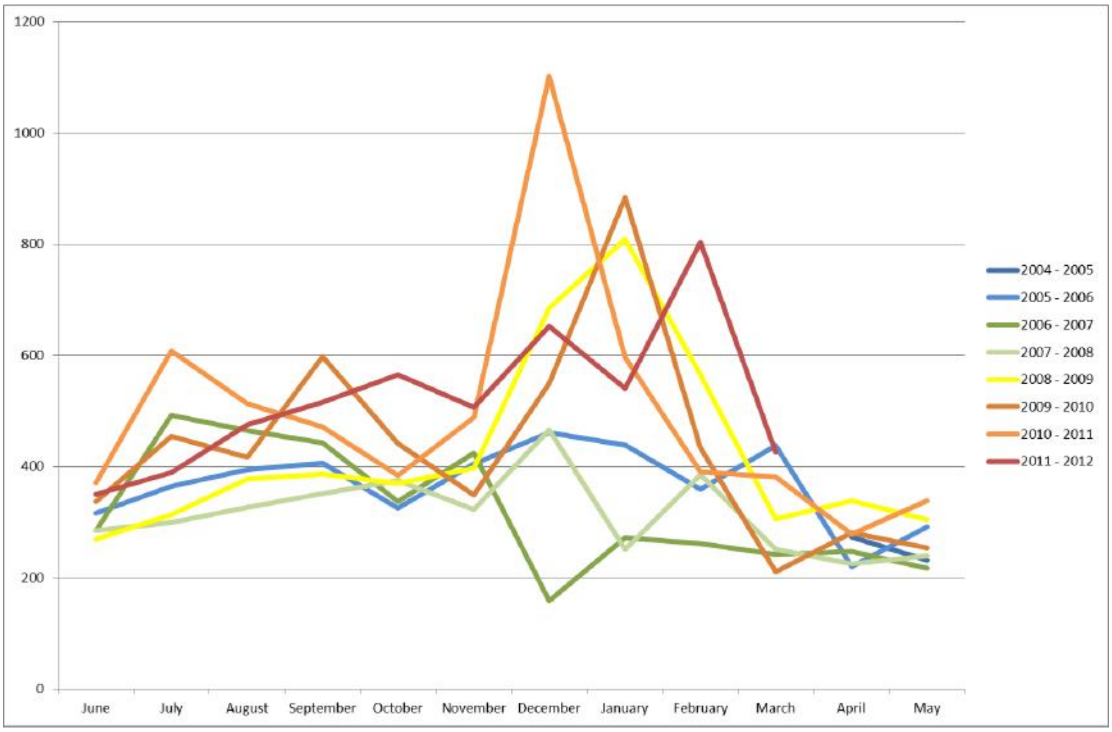


Figure 41 - Monthly burst rates by year.

Soil subsoil texture was considered for the period before these four cold years (Figure 42) and during the cold years (Figure 43). This shows an increase in bursts (average/1,000km pipe) across all subsoil texture types, with perhaps a slight lag on clayey soils into the Spring period – but overall a consistent response by soil type.

4.2 Accumulated Temperature analysis

If soil types are not highlighting strong differentiation, other measures can be employed to investigating climatic effects. For investigating temperature extremes, a useful and commonly used index is *Accumulated Temperature* (AT) (Shellard, 1959).

Accumulated Temperature (AT) has been defined as the "integrated excess or deficiency of temperature with reference to a fixed datum, usually called the basal temperature, over an extended period of time" (Shellard, 1959). AT is derived as a scalar integration of day-degrees below (and above where required) a chosen threshold (or ‘basal’) temperature, this being selected relative to the investigation’s purpose. The parameter AT is obtained from temperature data. This can be used subsequently in a variety of climatic modeling applications (Hallett, 1993). AT has been used widely as an index in models of crop growth and also in models of thermal efficiency in construction.

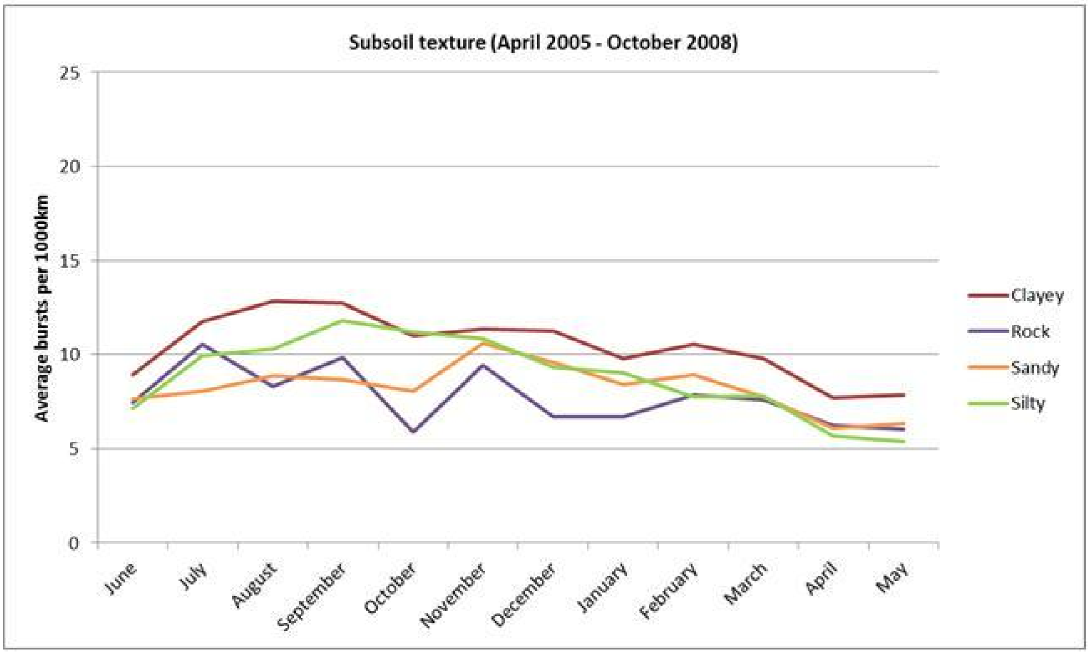


Figure 42 – Average monthly burst rate by subsoil texture in clay sandy and silty soils April 2006-October 2008)

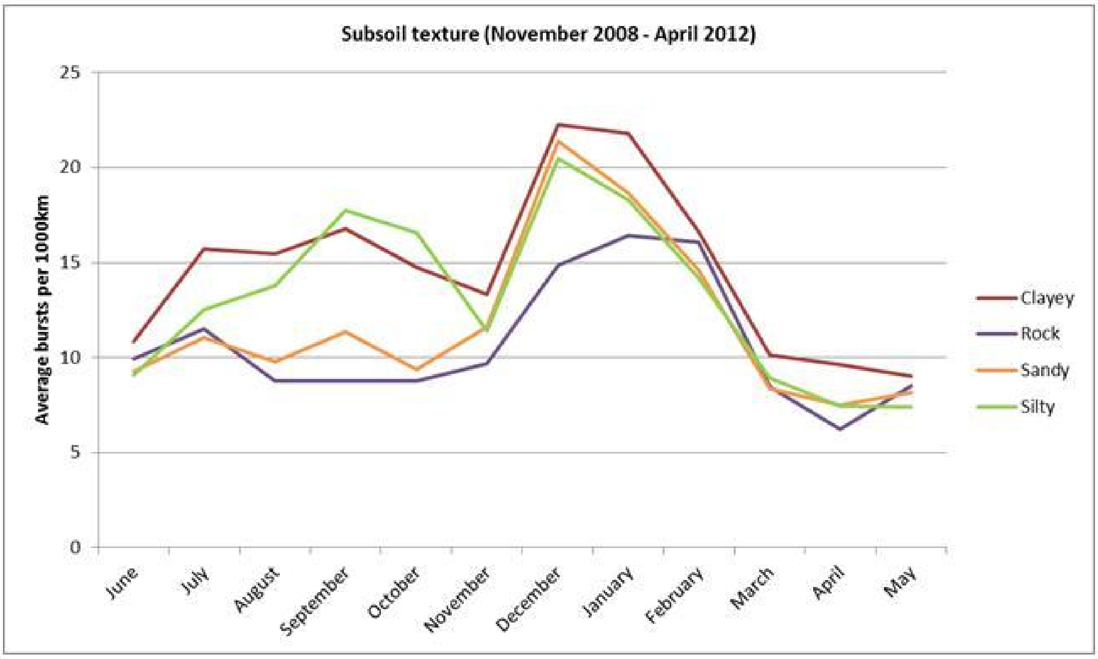
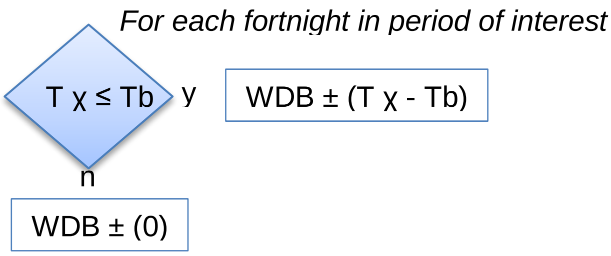


Figure 43 – Average monthly burst rate by subsoil texture in clay sandy and silty soils (November 2008 – April 2012)

In this study, AT values are utilized to provide a single index value concerning the impact of temperature on buried pipe assets and thus an index of winter burst likelihood. In this context, AT provides a single 'index of severity' whereby the AT values used represent the sum of ‘week degrees’ below a given threshold selected to reflect potential pipe damage in the Anglian Water region.

Accumulated temperature for the MORECS data is calculated according to the formula approach below.



4.3

Where:
T χ = Mean fortnightly MORECS temperature
Tb = Basal threshold (Centigrade)
WDB = Week Degrees Below Basal Threshold

A computer programme ‘CreATe.pl’ was written in the programming language PERL (Appendix B – Computer Software) to process the MORECS data provided. This allows the operator to select an in-year period of interest, as well as a Basal Threshold, which is used in the calculation. Values are output for Day Degrees below the threshold for each MORECS grid at Ordnance Datum. It was necessary to determine an ‘altitude-normalised’ dataset to allow post-correction of the burst location altitude values. Therefore, additionally the geometric centre-point of each MORECS grid was also determined allowing the Adiabatic Lapse Rate of 0.0064 (or 6.4 ^{o}C per 1000 metres) to be applied, permitting the normalisation of the result to Mean Sea Level (MSL).

The MORECS weekly data was manipulated such that each run of AT was conducted from the month of June to May, thereby ensuring that the pre-Christmas and post-Christmas months were considered together and the years were not split at January. This was considered a pragmatic approach and supported advice from Anglian Water that burst episodes would typically build up over this period.

The determination of the basal threshold was made by analysing a frequency distribution of burst temperature (Figure 50). A threshold of 1^{o}C was then selected for the analysis of AT.

Due to its crystal lattice, freezing water expands by some 9% in volume compared with water and this can cause considerable shear stress on buried infrastructure (ISPWS, 2012). The volume expansion of ice is calculated thus (Figure 44):

Density = Mass / Volume (g/ml^{-1})

	Water	*Ice*
Density	$1g/ml^{-1}$	$0.92g/ml^{-1}$

Thus, 100g water x 1ml / 0.92g = 108.7 ml ice (8.7% increase in volume)

Figure 44 Calculating volume increase from water to ice.

4.4 Accumulated Temperature Results

The Accumulated Temperature calculations were undertaken using the MORECS weekly mean temperature values for each of the 40km x 40km grid squares across the Anglian Water region.

$$\text{WDB} \mathrel{+}= \text{Absolute value of } (\text{Tb} - (\text{T}\,\chi + (\text{Altitude} \times 6.4/1000)))$$

The accumulated week degrees below the threshold were graphed for each MORECS square. The differences are presented cartographically (Figure 45) and graphically (Figure 47) showing a striking pattern becoming apparent. The winter periods of 2008-2009, 2009-2010 and 2010-2011 highlight considerable divergence from the adjacent earlier years – especially in 2010-2011. This corresponds well with the recorded incidences of burst events.

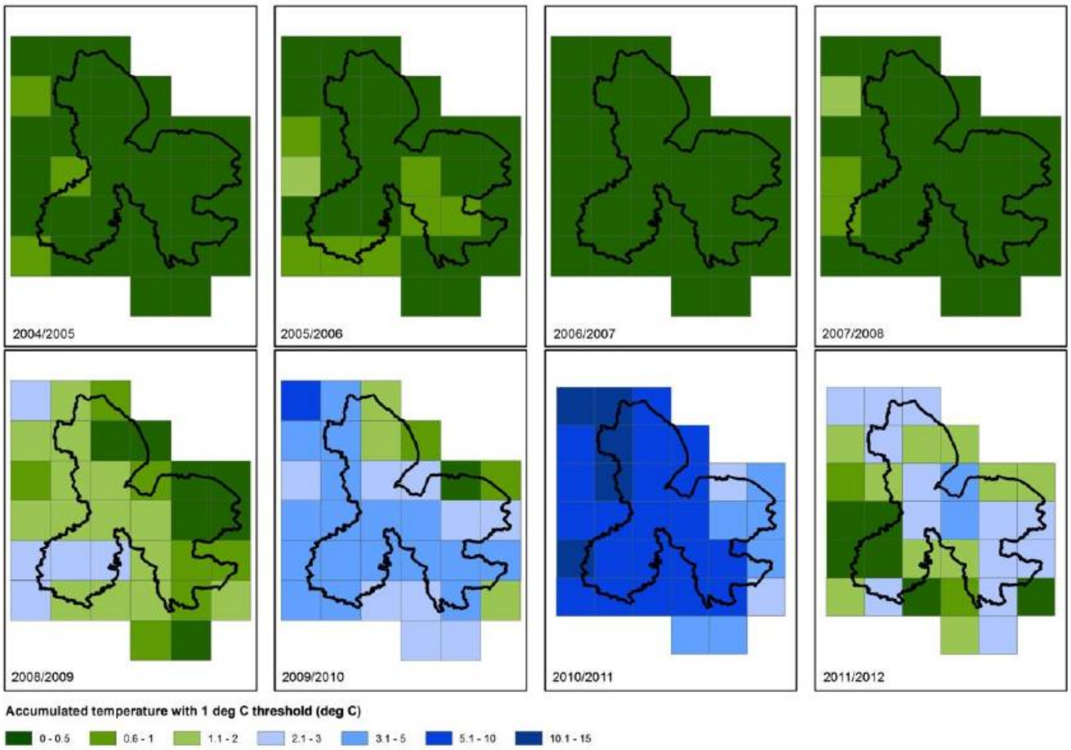


Figure 45 - Maps of accumulated temperature for the period 2004- 2012

The two spans of years before and during the cold spell are integrated and also shown cartographically for the two periods (Figure 46).

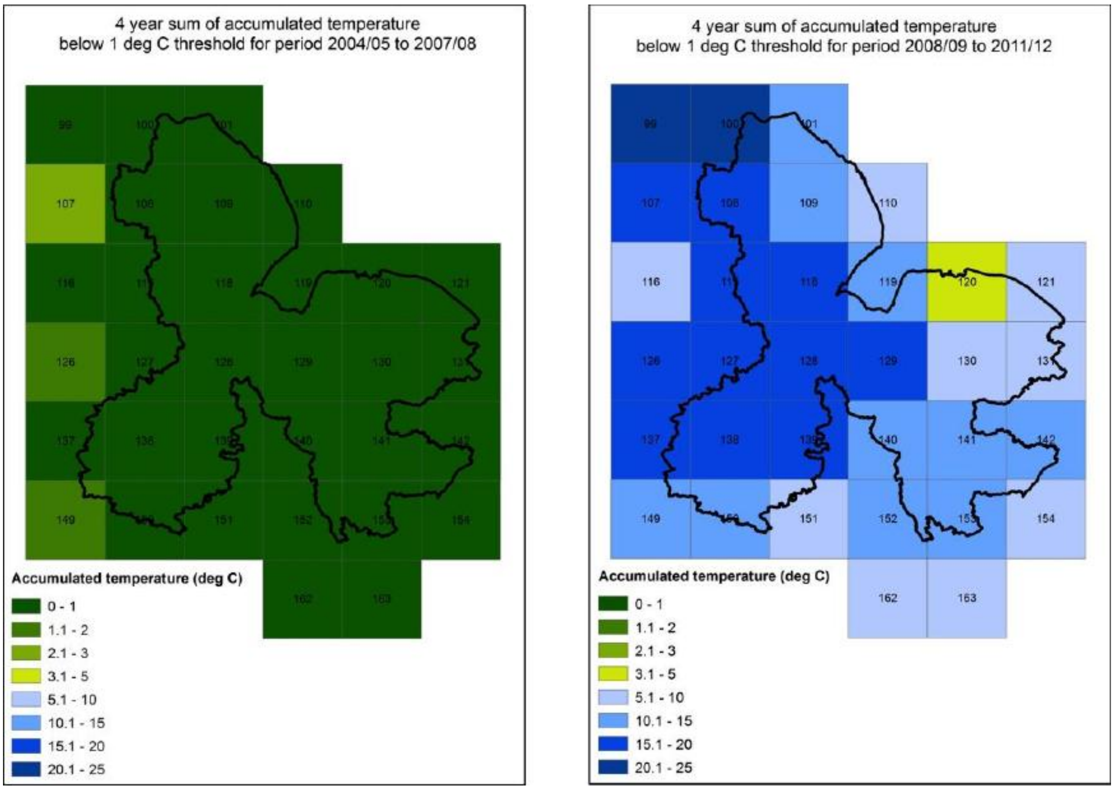


Figure 46 - Four year summary of accumulated temperature - pre and post November 2008

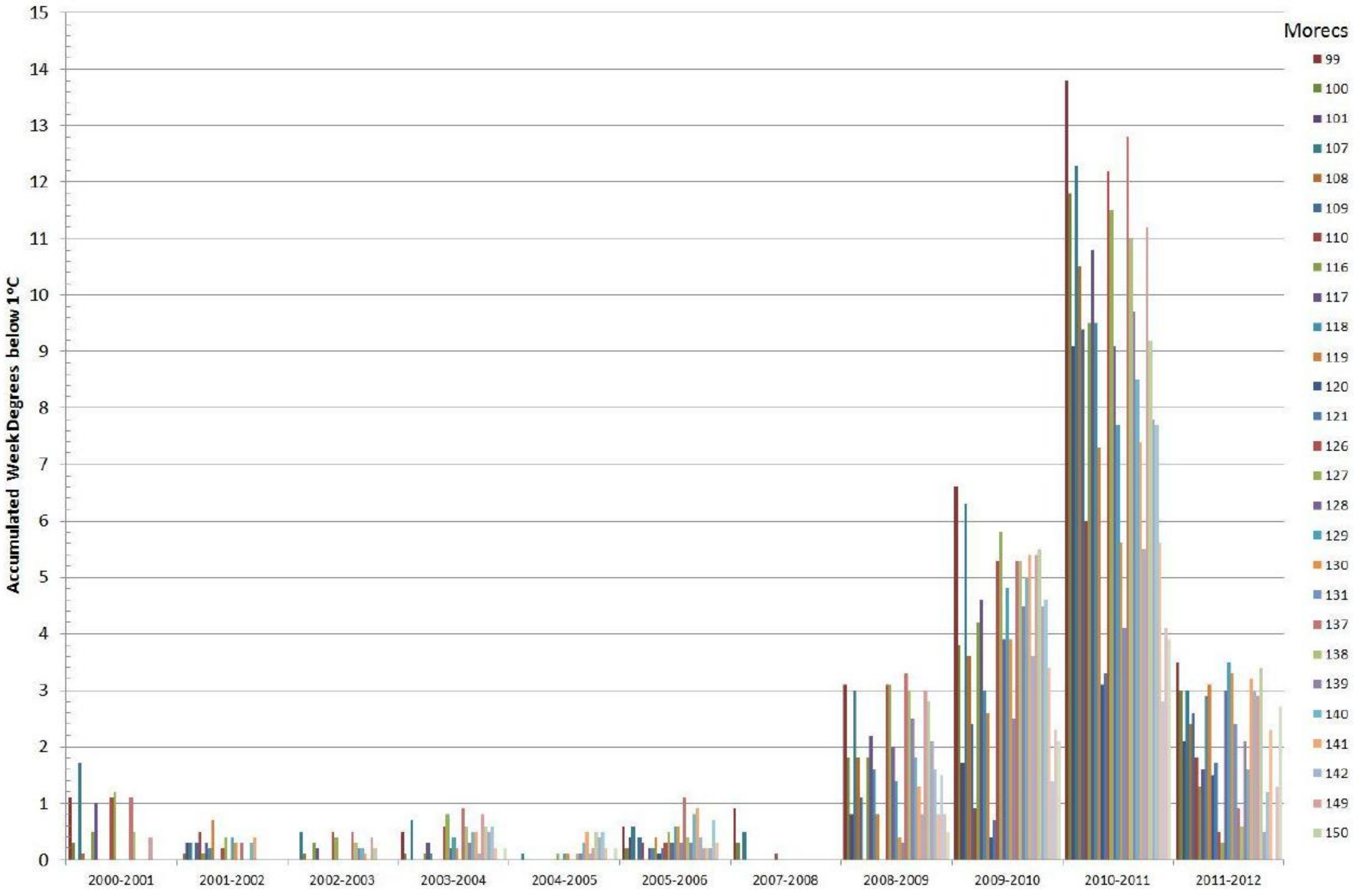


Figure 47 - Accumulated Week Degrees below 1°C by winter period, 2000 - 2012

4.5 Analysis of cold temperatures preceding bursts

In addition to the AT analysis, further analysis was conducted on the bursts to establish, for each burst event, the coldest temperatures over the three week period preceding the date of the burst. The programme ‘MorecsValues.pl’ (Appendix B – Computer Software) was used to derive this. To undertake this, temperatures were taken from the corresponding MORECS square that each burst fell in. These temperatures were then corrected to Mean Sea Level (using the MORECS square centrepoint altitude and the Adiabatic Lapse Rate of 0.0064, or 6.4 degrees every 1,000m) and then re-corrected back to the Ordnance Datum altitude for the Digital Terrain Model 50m pixel in which the burst was located. The same Adiabatic Lapse Rate of 0.0064 was used for these latter corrections. This analysis allows the plotting of burst date (throughout the year) against the minimum, as well as maximum, temperature in the three weeks leading to the burst event (Figure 48). The graph also presents the difference between maximum and minimum temperatures. The following graph, Figure 49, presents the same maximum and minimum data, but in a ‘stacked graph’ format, such that the corresponding data series values for maximum and minimum are shown stacked as a percentage of the total sum of their values. Thus, instead of comparing total temperatures, it is possible to observe what percentage that value in each data series contributed.

In interpreting these graphs, it is important to note how the maximum and minimum stacked temperatures show coincidence in the winters of 2009, 2010 and 2011 respectively, whereas in the winters of 2006, 2007 and 2008, there is quite a marked gap between the maximum and minimum stacked temperatures, e.g. the ‘. This suggests the winters of 2009, 2010 and 2011 suffered prolonged bouts of cold as opposed to swings from cold to hot. This pattern is borne out in the bursts data where the latter three years experienced higher burst rates than in previous periods.

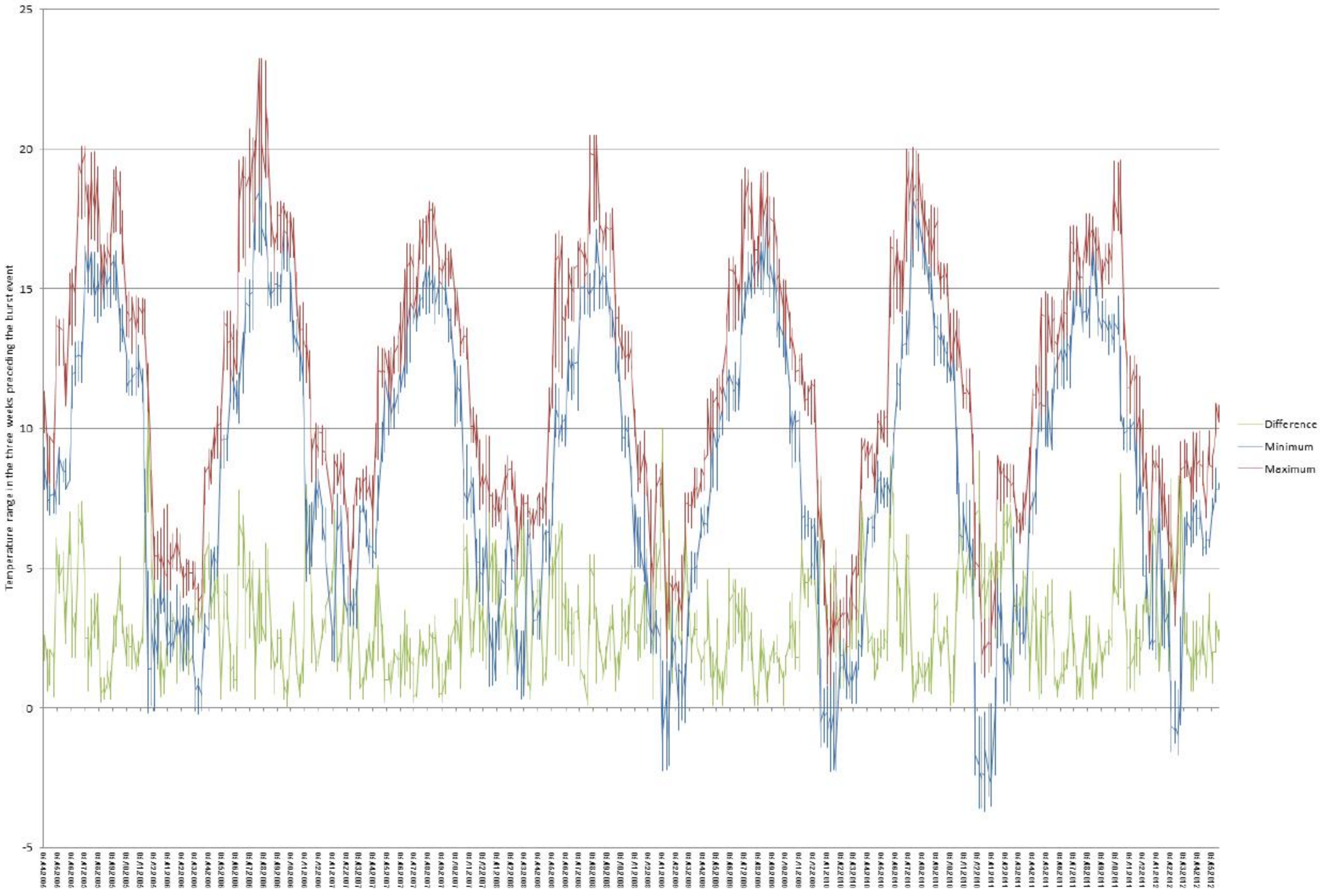


Figure 48 - Temperature range in the three weeks preceding a burst, for each burst expressed throughout the year

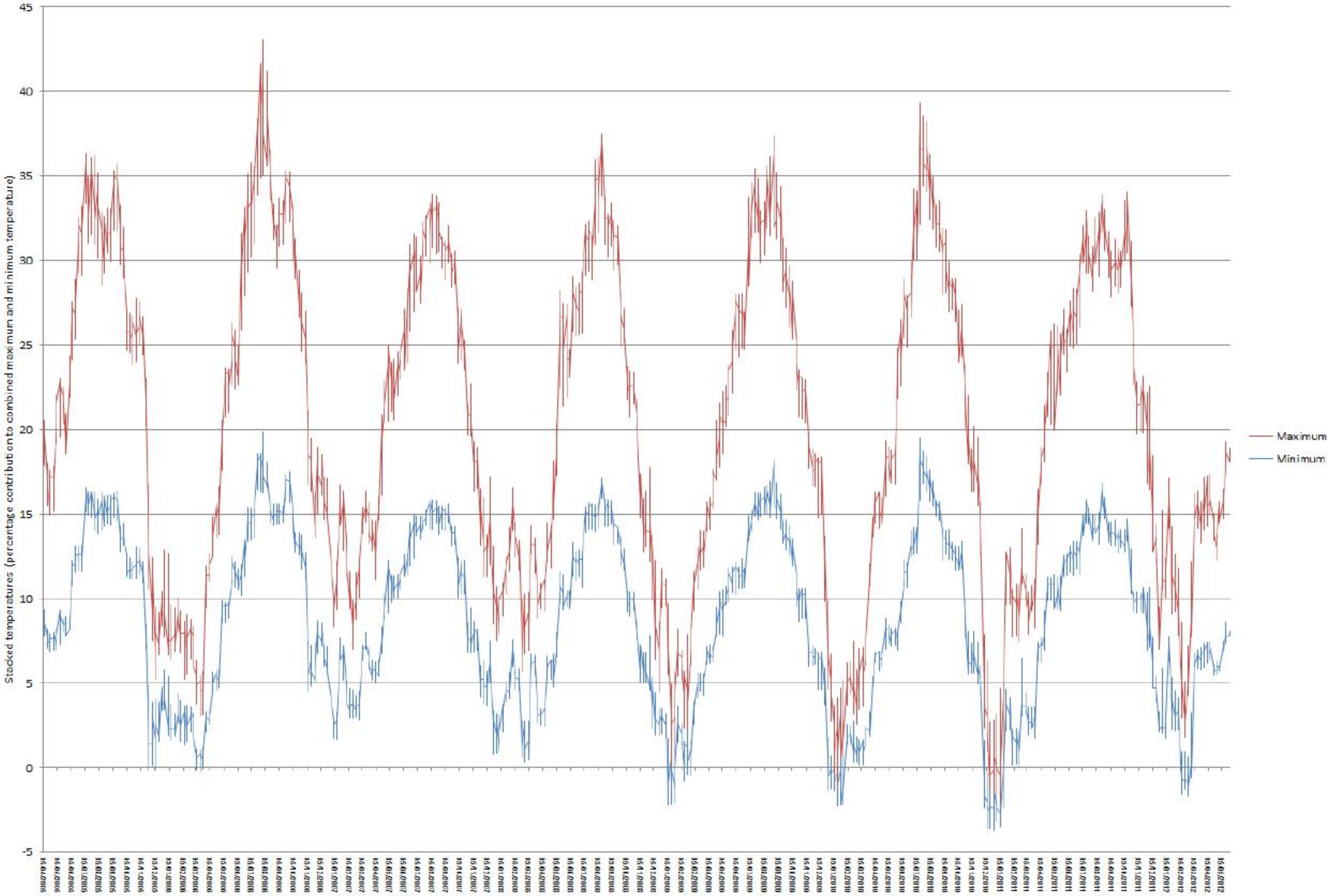


Figure 49 - Stacked temperature range in the three weeks preceding a burst, for each burst expressed throughout the year

4.5.1 Burst temperature frequency analysis

The data used to create the graphs Figure 49 and Figure 50 was further analysed and a frequency table extracted of number of bursts by the temperature in the week of the burst at the location of the burst, across all years and across the whole Anglian Water Region. The resulting frequency distribution graph (Figure 50) identifies two peaks associated with bursts (the colder centered on c. 1°C), as well as a warmer peak (c. 15°C). For the analysis of cold weather bursts, this provides a justification for adopting 1°C for the basal threshold of the Accumulated temperature modeling above.

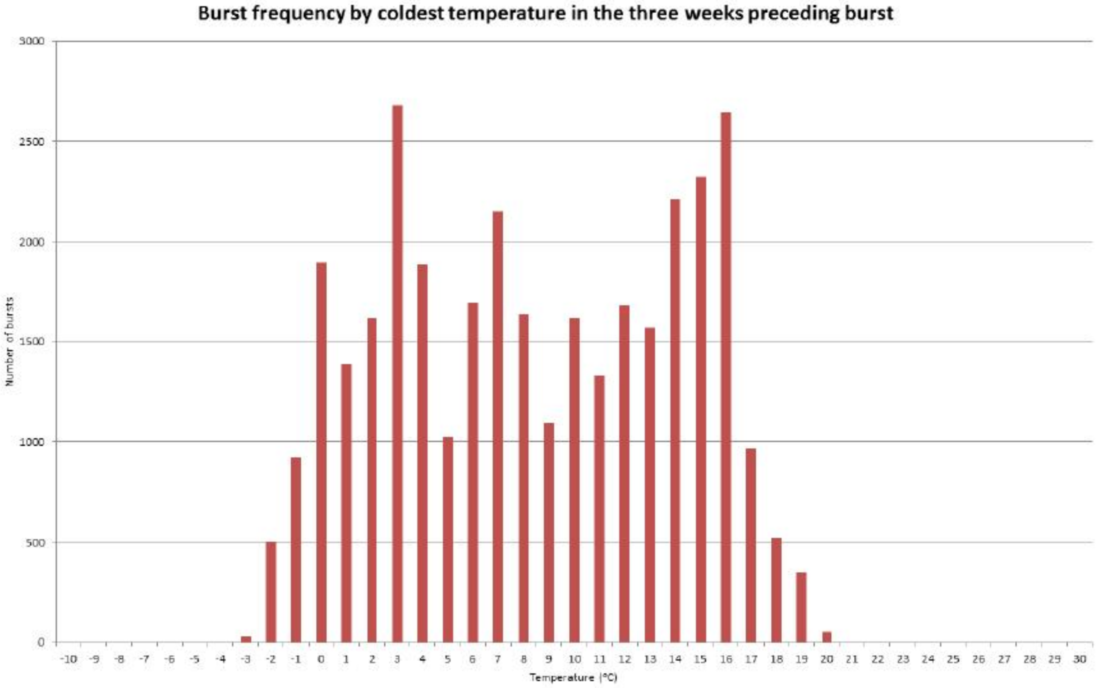


Figure 50 - Burst frequency by temperature for all years across Anglian Water region

Lastly a graph was produced showing a summary correlation of the minimum MORECS weekly temperature against the total number of bursts. The resultant value confirms the relationship between cold temperatures and the winter burst episodes recorded over the period of interest (2005 to 2012).

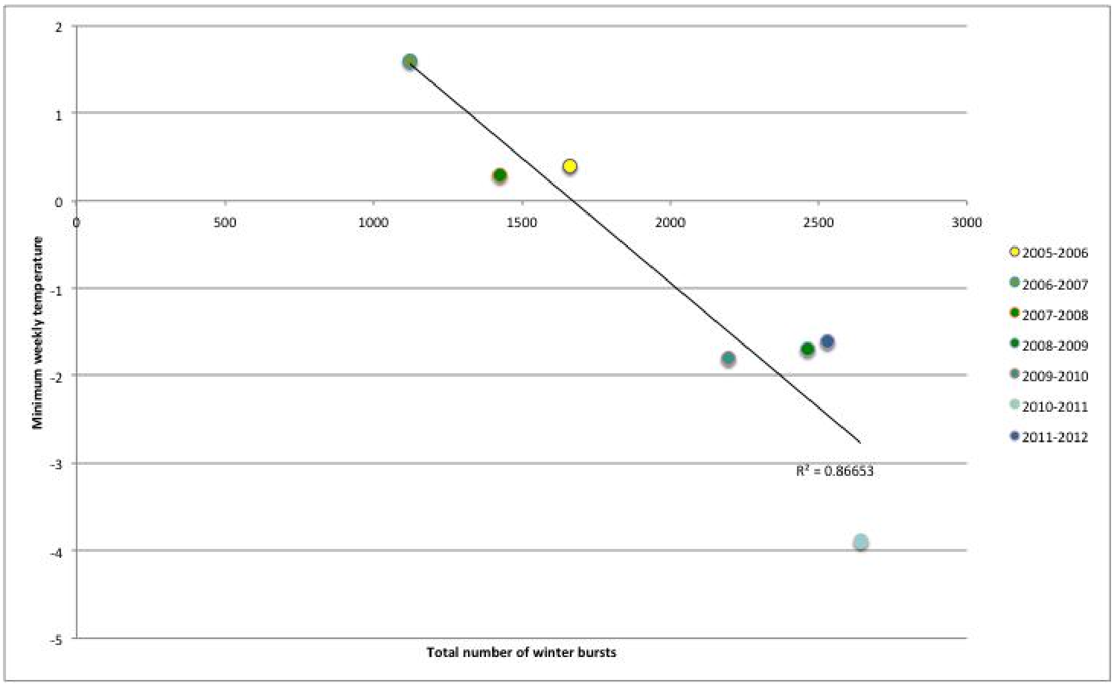


Figure 51 - Winter bursts compared to minimum temperature

4.6 Conclusions

The Anglian Water was manifestly struck by a series of severe weather conditions in the winters 2008-2009, 2009-2010 and 2010-2011 which exhibited a considerable divergence from temperatures in the earlier adjacent years – especially the cold winter of 2010-2011. This study has not sought to determine the conditions in adjacent water company regions over this period, however, extreme conditions at this time were well reported in the news affecting other parts of the country (e.g. Heathrow). There is a discernible relationship that can be expressed between the temperature and the number of bursts. Accumulated temperature is a powerful mechanism to represent the integration of temperatures falling at or below a chosen threshold. The 1°C threshold selected reflected the patterns of bursts/temperature observed in the data provided.

Further work would usefully highlight and explore intra-regional temperature comparisons through the time periods in question.

Summer and Autumn Bursts

5 Summer and Autumn Bursts

This section outlines the effects of summer and autumn shrinkage and swelling on the soils proximal to the Anglian Water pipe network.

It is shown that there is a relationship between soil moisture deficit and bursts in shrinkable soils, and that those soils that are highly shrinkable are more susceptible to bursts in the late summer and winter months.

5.1 Background

Soils rich in shrinkable clays change volume with fluctuating moisture levels. In the summer the soil progressively dries out and deep cracks can form as the soil volume shrinks. In autumn, rapid swelling of these soils accompanies re-wetting with precipitation (Figure 61). This soil movement can cause buried assets, such as water mains, to fail as the forces build up on them. In order for these processes to occur, two environmental factors are required. Firstly, shrinkable soils need to be present (about 30% of Anglian Water’s pipes are in shrinkable soils) and secondly, the summers need to be hot and dry enough to desiccate the soil down to or near to pipe depth. Our analyses consider these aspects of the process.

5.2 Fracture potential (ground movement) class

Among the inorganic particles that constitute the solid component of any soil, clay particles are the smallest, generally defined as being <0.002 mm in size. Clay particles occur in most kinds of soil but they only begin to exert a strong influence on the behaviour of the whole soil where there is in excess of 35% clay-sized material present. Since clay particles are very small and commonly platy in shape, there is an immense surface area to which water can be attracted relative to the total volume of the soil material. For example, a gramme of smectitic clay soil, common in the Anglian Water region, can have some 650m^2 surface area (Brady and Weil, 2002).

In their natural undisturbed condition, the moisture content of clays does not change greatly, and consequently there are no changes in volume leading to soil fracture. However, the situation is very different when clays are exposed at or near the ground surface, especially if vegetation is rooting in them. This is due to the fact that the roots of plants extract moisture from the soil to support their growth and transfer necessary nutrients into their structures.

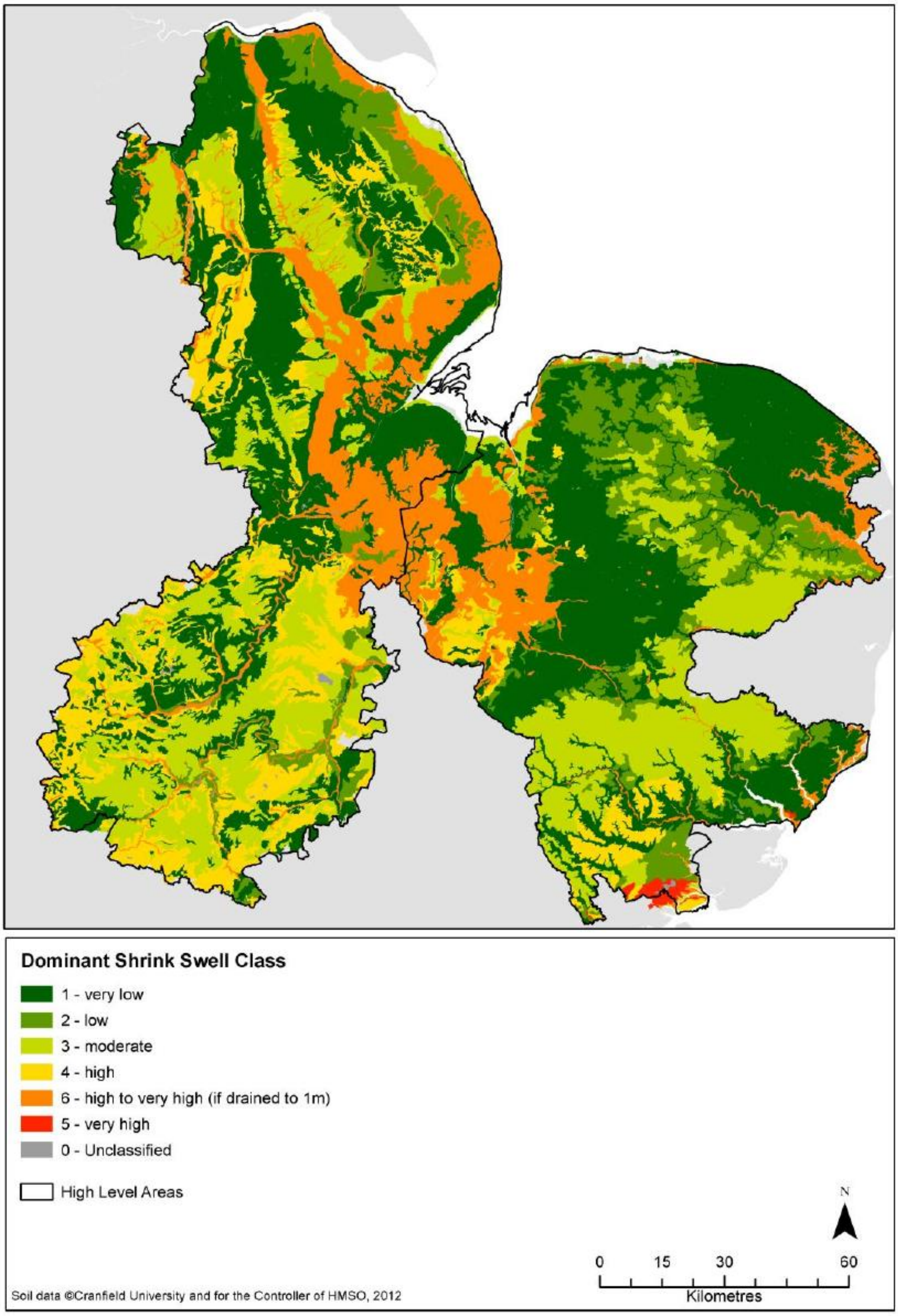
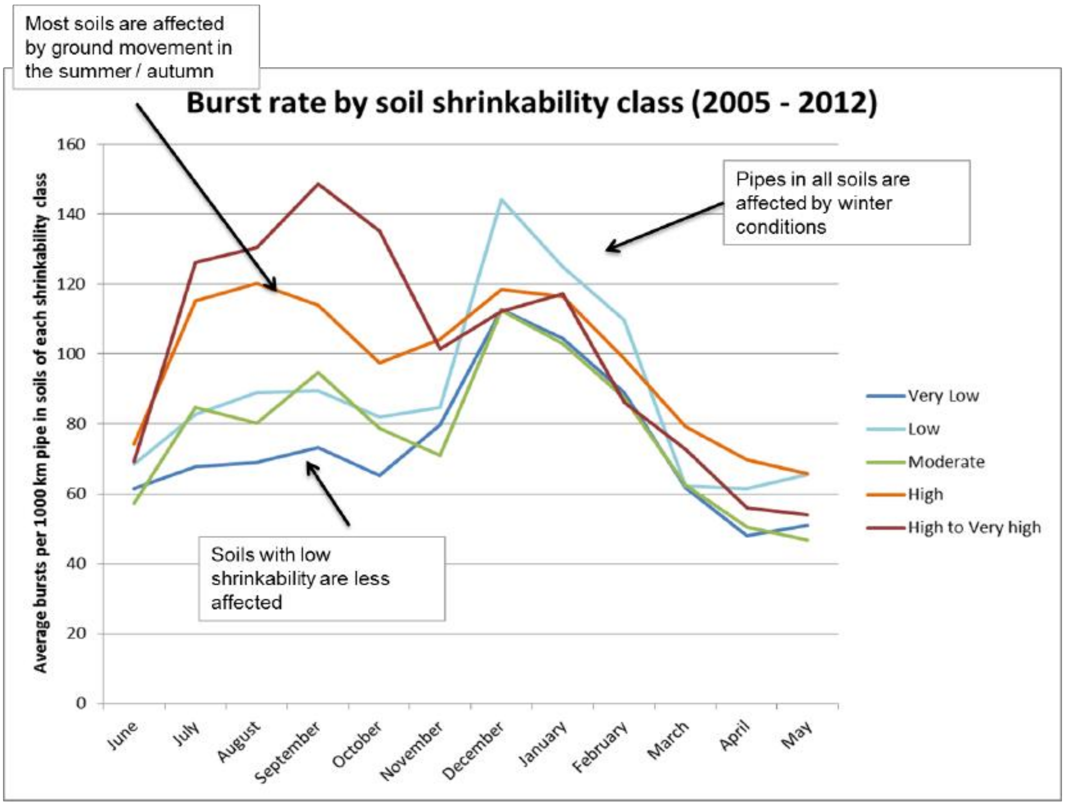


Figure 52 - NSRI Shrink swell (fracture potential) classes

Whilst soil moisture is continuously being replenished by rainfall, the soil itself will be unaffected by this removal of moisture, but in many parts of Britain, particularly in the south and east, summer rainfall is small and is exceeded by evapotranspiration. At this time of year water reserves are not replenished by rainfall so soil moisture deficits occur. Water being removed from the soil by the plants leads to a reduction in soil volume and the consequent shrinkage causes stress in the soil materials leading in turn to stress on structures that are resting in the soil. These structures may move, thus causing damage.

NSRI have categorized the soils of England and Wales into their propensity to Shrink and Swell (Figure 52). Soils are classified from ‘Very Low’ to ‘Very High’. Plotting the soils proximal to the burst locations, classified in this manner reveals a bi-annual pattern of shrinking and swelling (Figure 53).



Most soils are affected by ground movement in the summer / autumn

Pipes in all soils are affected by winter conditions

Soils with low shrinkability are less affected

Figure 53 – Average monthly burst rate by shrinkability class (2005- 2012)

This data may also be tabulated (Table 12).

Table 12 Percentage of pipes in soils of different shrinkability

SSWELL	Shrink-swell Class	Length pipe(km)	%
1	Very Low	16935.17	44.93
2	Low	5264.89	13.97
3	Moderate	7532.40	19.98
4	High	4355.37	11.56
5	Very High	80.20	0.21
6	High*	3503.69	9.30
0	No Data	18.88	0.05
	Total	37690.60	99.95

The effects of natural shrinkage on the soils of the Anglian Water region can be quite pronounced (Figure 54).

Figure 54 - Soil cracking in shrinkable soil in Cheddington (in the Anglian Water Region) Photo: I Truckell

5.3 Soil Moisture Deficit Modelling

Analysis of temporal patterns of bursts indicate clear summer and winter episodes (Figure 53). Therefore, following an analysis of the meteorological data to establish potential linkages between cold weather and bursts, further analysis was required to investigate the relationship between hotter drier conditions, soil types and bursts.

Cranfield operate the Natural Perils Directory (NPD) dataset, a ground geohazard assessment model. This incorporates locations of soils prone to shrinkage and swelling, together with historical patterns of ‘potential soil moisture deficit’ (PSMD). Soil moisture deficit represents the difference between precipitation at a point and the seasonal integrated levels of both evaporation and plant transpiration (together termed ‘evapotranspiration’), thus **PSMD = SUM(R - PT)** where R=Rain (mm) and PT=Evapotranspiration (mm) (Jones and Thommasson, 1985). PSMD and the MORECS SMD values are dissimilar in scale (PSMD attaining typically a higher value), but exhibit similar relative patterns. As Anglian Water have provided SMD values, these have been used widely throughout this research.

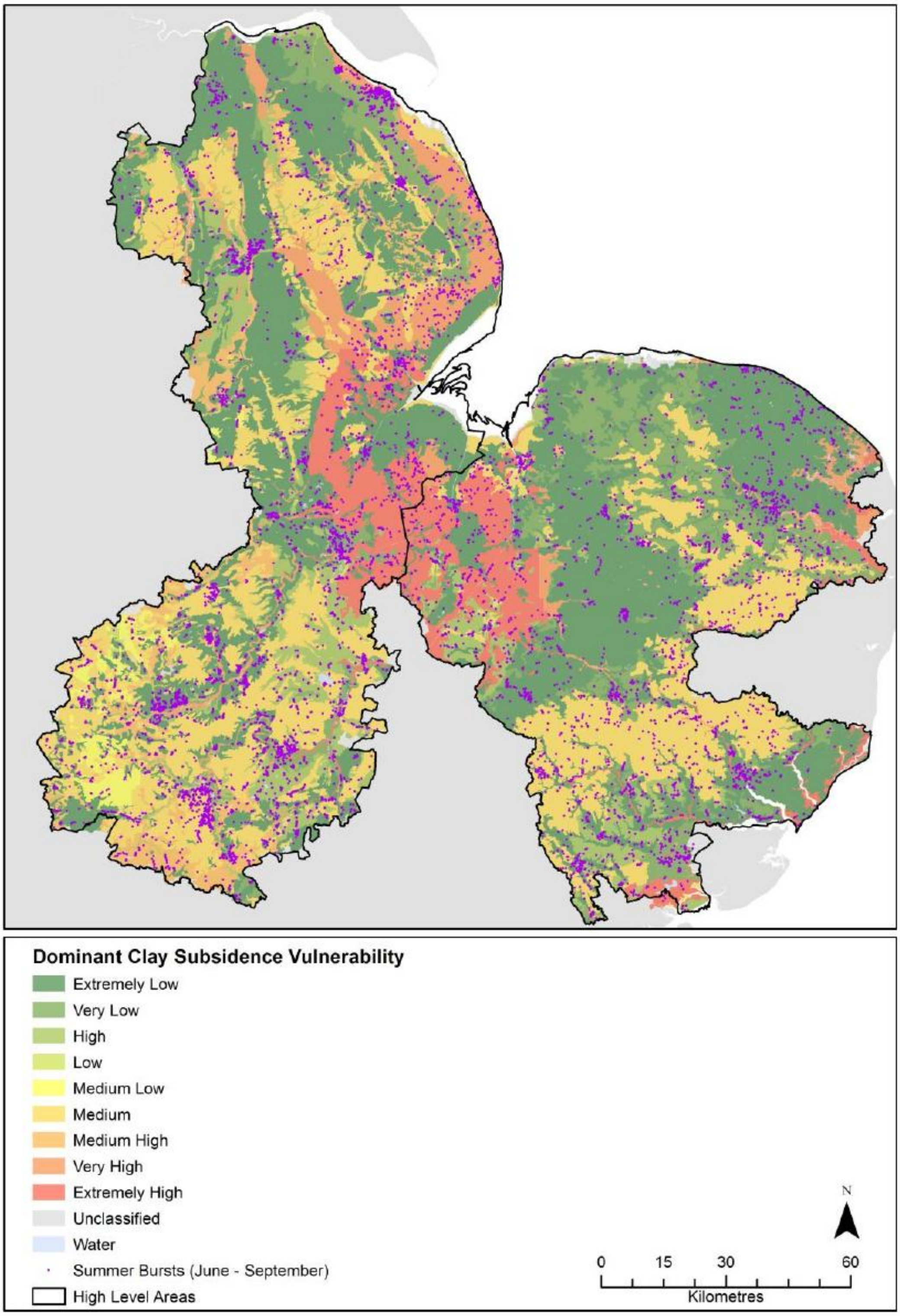


Figure 55 - Natural Perils Directory Climate Adjusted Clay shrink-swell model with Summer and Autumn Bursts

The subject of evapotranspiration (PT) was introduced by Penman (1948) who defined it as the water transpired by a short green crop such as a grass sward, completely covering the ground and which is amply supplied with water around the roots. Given these conditions, PT varies with meteorological conditions. PT is computed from the Penman Monteith equation, of which there are a number of forms. Used as a component here in modelling soil moisture deficit (SMD) is seen as an important component in seeking to explain summer water main bursts in the Anglian Water region.

SMD data are provided by the MORECS 40km x 40km square datasets from the Meteorological Office. The calculations of the SMD data here use a slightly different form of the Penman Monteith equation to that used in the existing NPD datasets from NSRI. However, the spatial relativities of the data hold the same. An adaptation of the NPD models was therefore selected that utilised the MORECS SMD data in place of Cranfield's historic PSMD data.

The MORECS data extended over a considerable time period, however the most reliable bursts data commenced in 2005. Therefore pre-2005 MORECS SMD data was discarded for the analysis, leaving some 392 weeks' worth of data across the Anglian Water region, from 04/1/2005 to 3/7/2012. Furthermore, only data pertaining to the MORECS squares containing bursts records were retained. Further rows of data were discarded to commence SMD accumulation analysis on February 1st, which in agro-climatological modelling represents the traditional start of the SMD year.

Soil Moisture Deficits build up throughout the year as the soil dries out. A deficit usually develops in April or May, reaching a maximum in July, August or September Figure 63. Thereafter the SMD declines during Autumn as the soil wets up. The situation is cyclical and indeed reversible; in May 2012, after a dry winter, the rains of spring 2012 removed much of the soil moisture deficit which had by then accrued.

Mechanically in the soil, at first swelling clays expand with the rains to fill the cracks and voids left after the earlier drier conditions (Figure 61). Once these are filled, further expansion can lead to vertical shearing and the phenomena of 'slickensides' – very characteristic in heavy clay, where the vertical shear surfaces appear. In some drier districts deficits can persist into January or even February.

Figure 62 presents a graph of the values of accumulated SMD from the MORECS data ranging from 2005 to 2012. One can see the typical patterns outlined above are exhibited in this data. Figure 63 shows the mean aggregated temperature and SMD values for all MORECS squares across the Anglian Region together with total burst count.

The existing Cranfield NPD data (e.g. Figure 55) utilises historical soil moisture deficit data representing the mean average annual deficit over the period 1961 to 91. From this data are drawn the standard deviations for each meteorological station – allowing for data trends to be superimposed. Using the MORECS data however requires a different approach, partly as it represents already an interpolated data surface, but also as one seeks to identify the seasonal concurrence of bursts with the build up of SMD.

Under ‘average’ summer conditions, soil can be said to lose some 6mm of water to evaporation per day. The drying effect on soil is therefore a gradual one through periods of sustained high temperature and reduced precipitation. Conversely, local rainfall events can easily average some 20mm in a day. It can therefore be seen that soil wetting can occur more quickly than drying, with a correspondingly higher soil stress from the wetting rather than the drying phase on soils that are susceptible to ground movement. In the Anglian Water region, about 30% of the soils have moderate to highly shrinkable soils (Table 12). In the case of buried water mains, this could then be supposed to lead to a greater incidence of bursts in the wetting phase than the corresponding drying phase.

There is a variation in the SMD expressed spatially, cartographically across the Anglian Water region and also through time. In some years the soils dry more deeply than other years (Figure 56). A simple correlation, by year, between the maximum recorded SMD across the Anglian water region and the total number of bursts for the summer show a an r^2 of 0.76 (Figure 57). This increases to $r^2 = 0.79$ if the pipes/ bursts in soils having a volumetric shrinkage of less than 5% (Very Low) are removed (Figure 58).

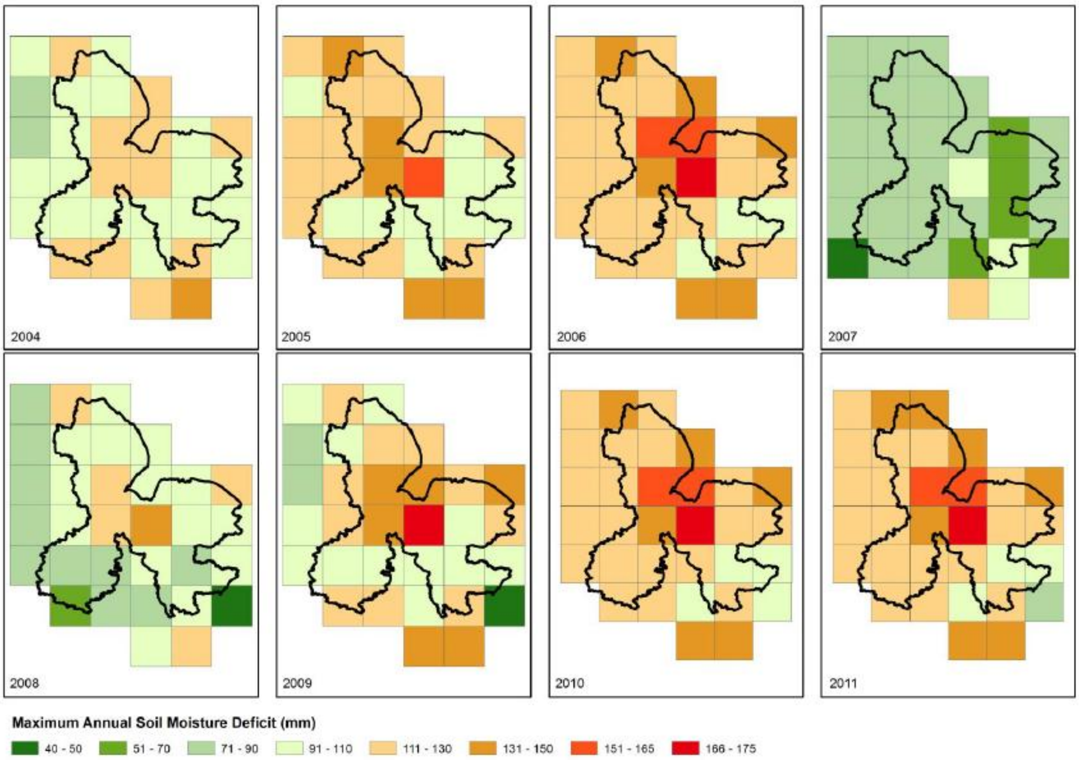


Figure 56 - Maximum SMD across the Anglian Water region, by MORECS square 2004- 2012

A comparison of the years 2006, 2009, 2010, 2011which all have SMD in one square above 165 (Figure 56), with total bursts (Figure 57) show a clear pattern of hotter summers, more burst.

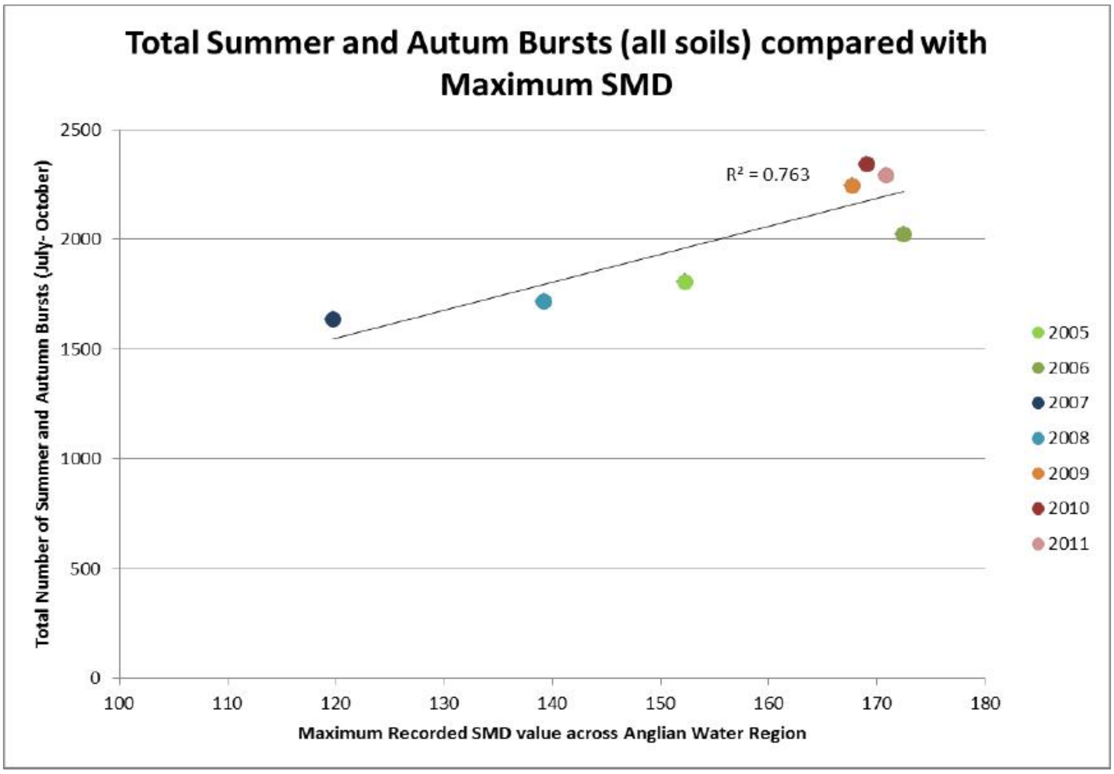


Figure 57 - Correlation between maximum SMD recorded across the Anglian Water Region and total summer bursts in all soils.

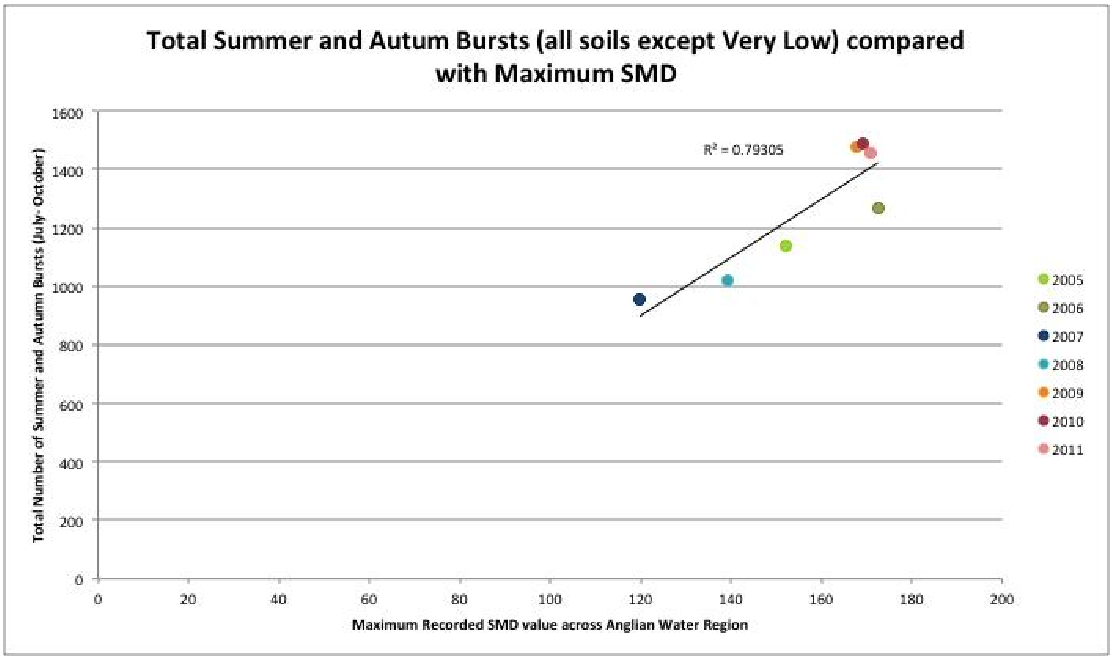


Figure 58 - Correlation between maximum SMD recorded across the Anglian Water Region and total summer bursts in all soils, except those with Very Low (Class 1) shrinkability.

Charting the conditions of the subsoil texture of soils adjacent to burst locations in the period 2005-2008 (Figure 59), and then from 2008-2012 (Figure 60) reveals an elevated summer and autumn burst rate in the latter period. Also in the latter period, the early summer (drying) phase burst rate presents more gradually than the autumn (wetting) phase – matching the mechanical expectations of soil behaviour as noted.

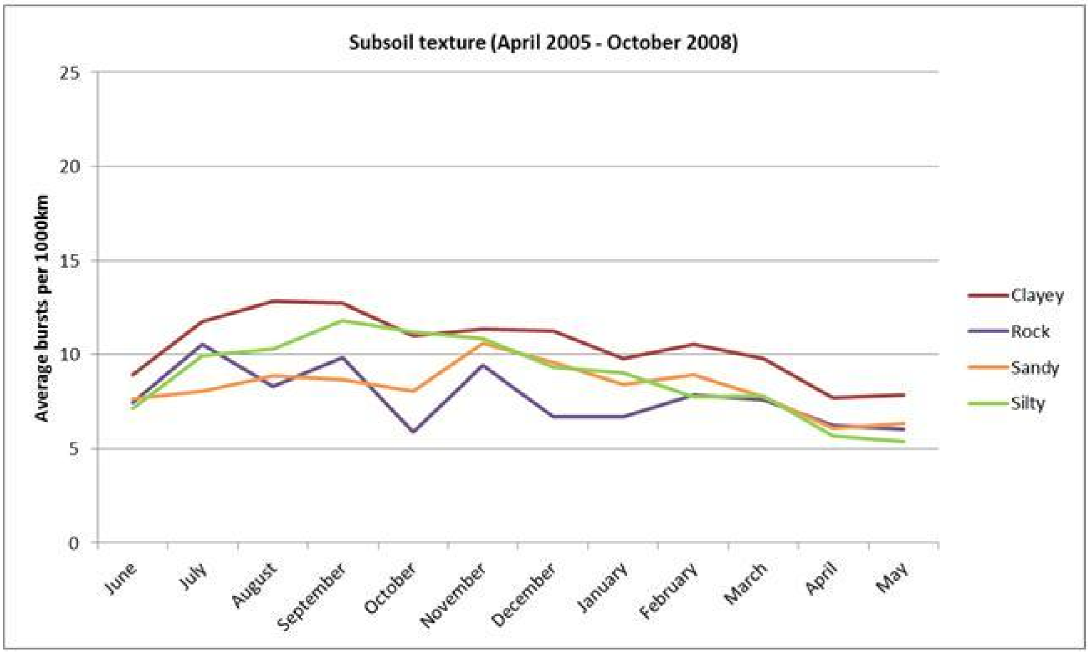


Figure 59 – Average monthly burst rate by subsoil texture in clay sandy and silty soils April 2006-October 2008)

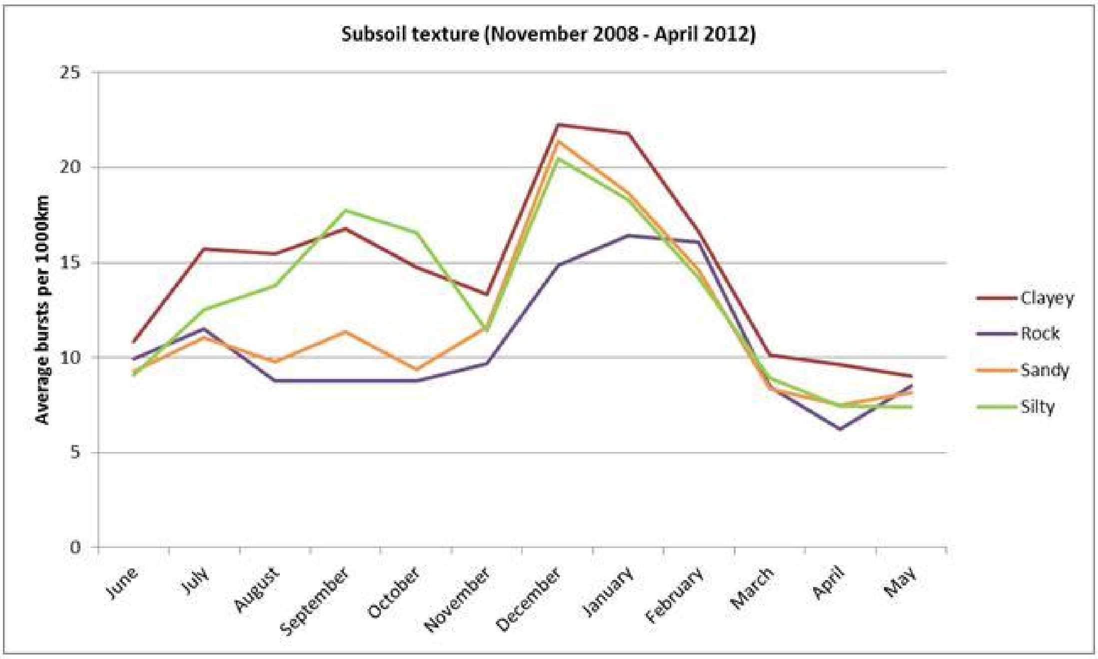


Figure 60 – Average monthly burst rate by subsoil texture in clay sandy and silty soils (November 2008 – April 2012)

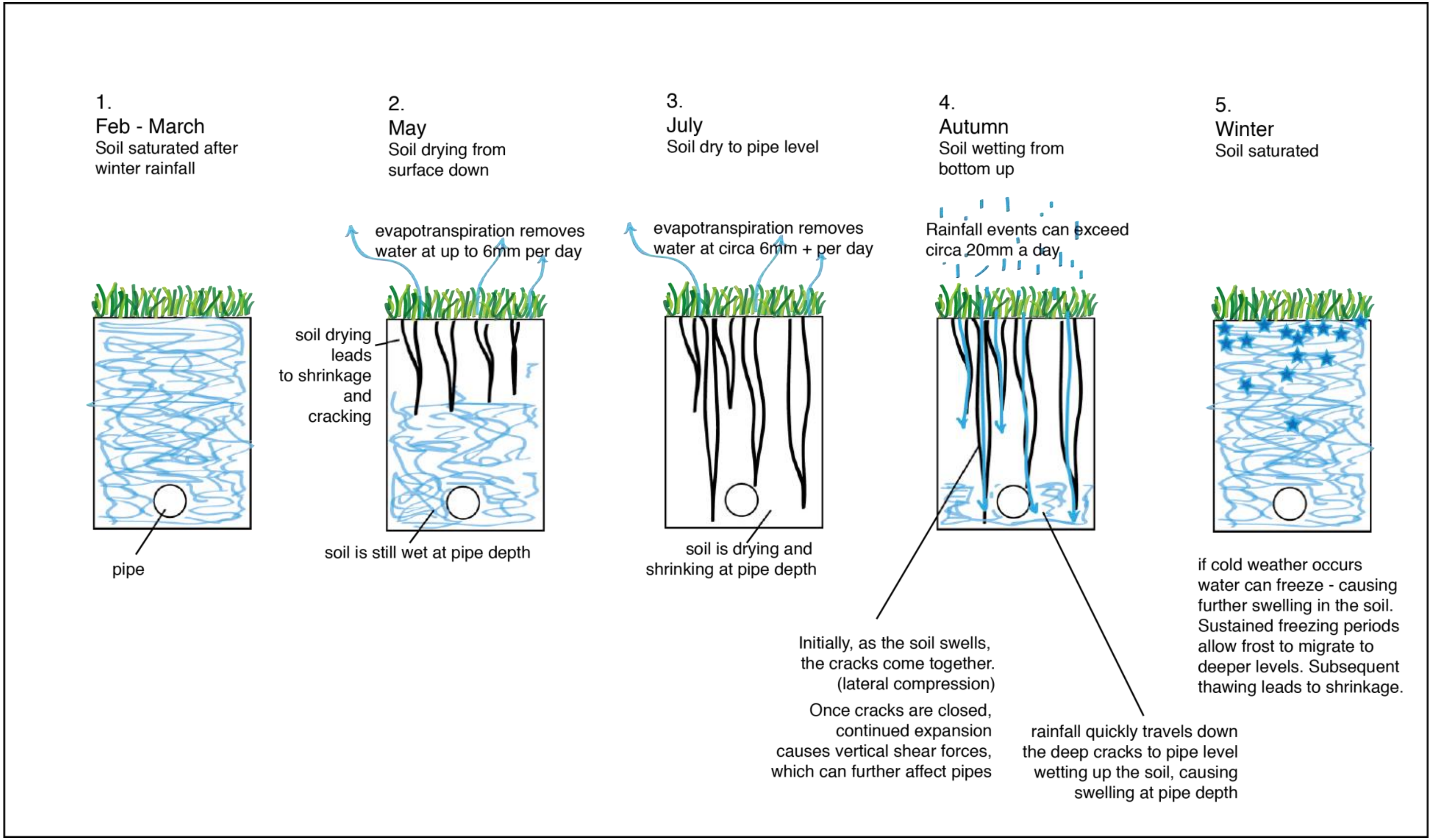


Figure 61 - The seasonal processes effecting soil movement and pipe failure

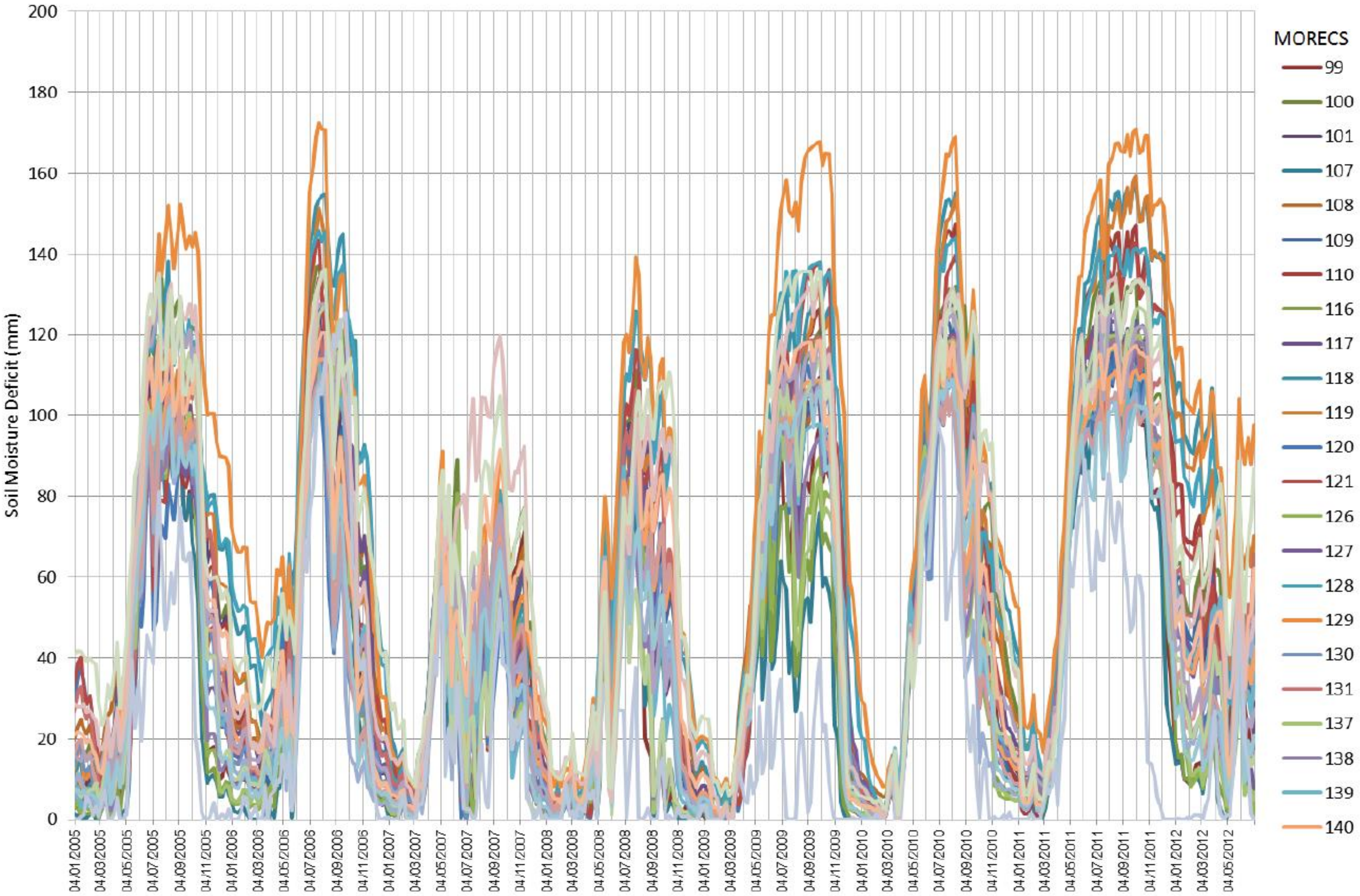


Figure 62 Soil Moisture Deficit values from 2005-2012

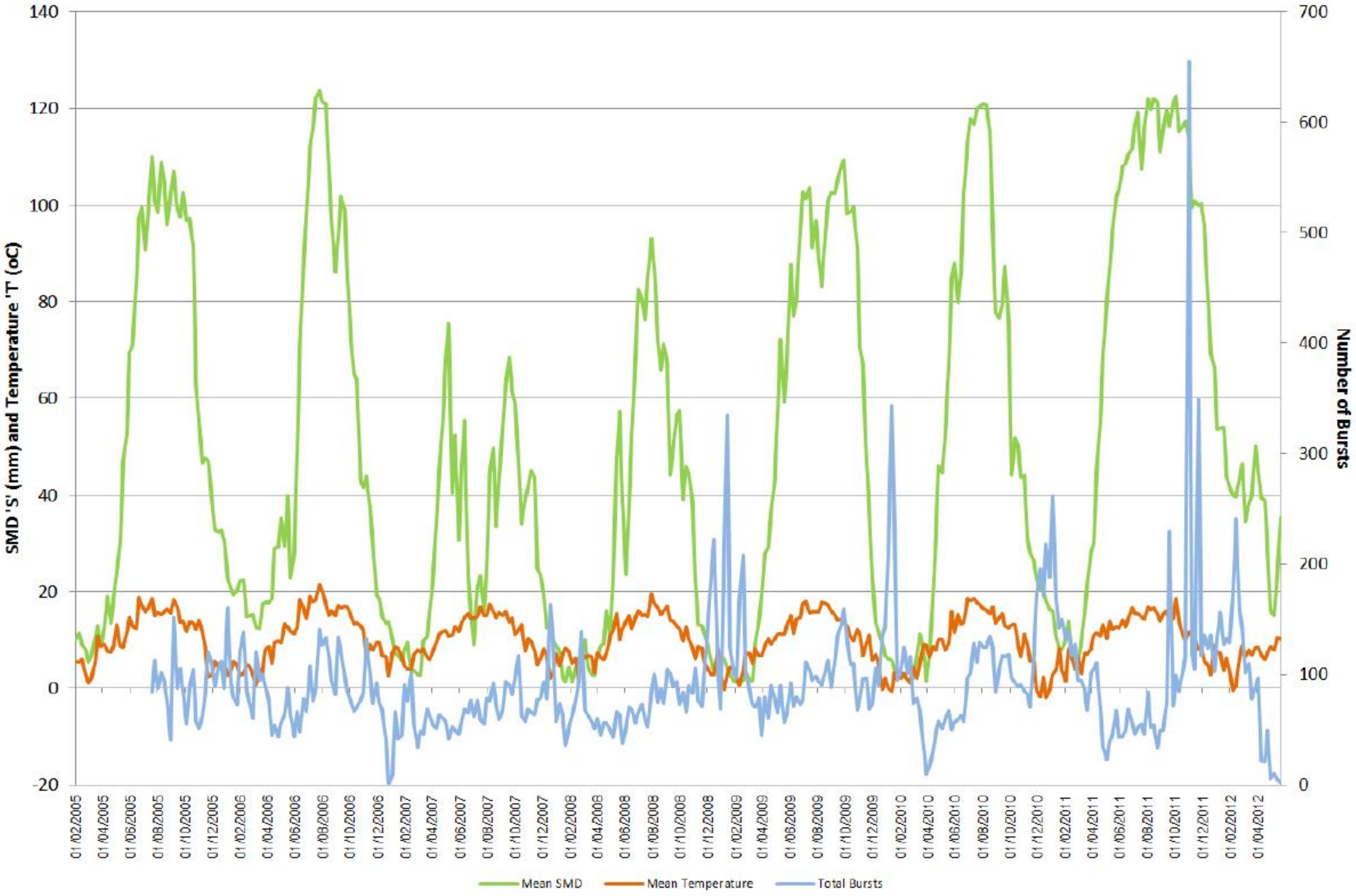


Figure 63 Aggregated mean SMD and Temperature values with bursts, weekly from 2005-2012

5.4 Conclusion

Anglian Water has approximately 30% of its pipes founded in soils which are at least moderately shrinking and swelling (Table 12). An additional 13% of its pipes are in soils which may swell by up to 4%. Even these soils show a seasonal relationship with summer / autumn fractures, but to a lesser degree than those in more swelling soils (Figure 53).

The summers in 2006, 2009, 2010, and 2011 were warmer and dryer than those in 2004, 2005, 2007, 2008. Summer bursts have increased, accordingly in the summer period in 2009-2012 compared to summers of 2005-2008 (Compare Figure 59 and Figure 60). This relationship is also borne out in a general comparison of total bursts *vs* the highest SMD recorded for the year, with correlations greater than 0.75.

An overall conclusion is that there is a relationship between the number of bursts and hotter, drier summers shrinking certain soils, and the subsequent re-wetting and swelling of the soil in the autumn.

Spring Baseline

6 Spring Baseline

The effect on burst rate of water mains of winter, summer and autumn seasonal patterns has been shown. During spring, soils are typically wet, so less prone to shrinkage and swelling, and the temperature is less extreme, so less susceptible to temperature related failures. Spring provides an ideal season to assess the baseline status of Anglian Water's pipe network.

It is shown that variation in spring burst rate is low, compared with summer, autumn and winter months.

6.1 Spring as a baseline index

The effect on burst rate of water mains of winter, summer and autumn seasonal patterns has been shown and discussed in previous sections. During spring (April, May, June), soils are typically wet, so less prone to shrinkage and swelling (Figure 61), and the temperature is less extreme, so less susceptible to temperature related failures. Figure 64 highlights the variation in burst rates across the year in time.

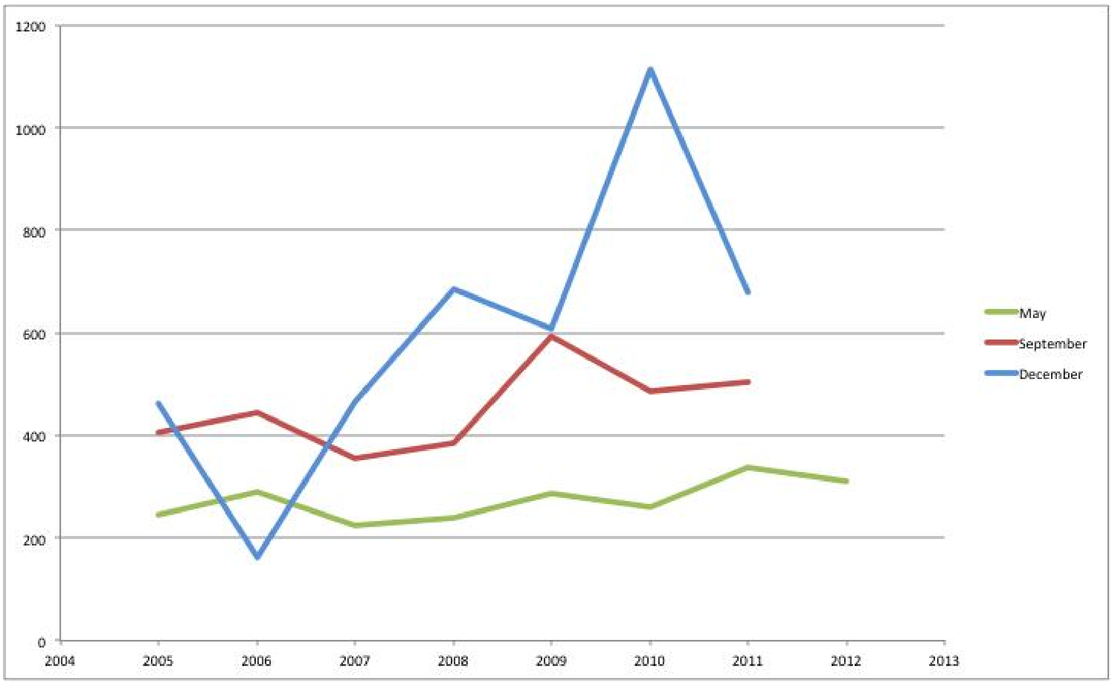
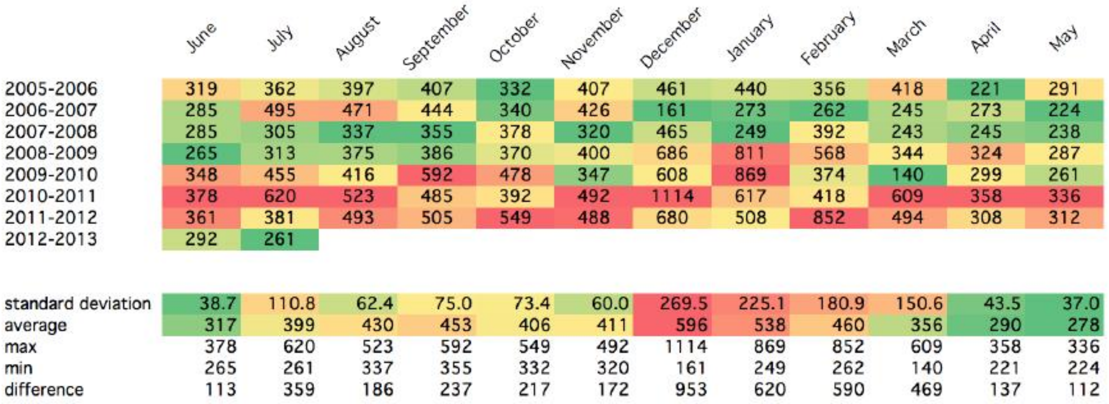


Figure 64 - The variation in burst rates in May, in comparison with September and December

6.2 Spring’s low number of bursts, low variation in bursts numbers

Table 13 shows that the variation in spring burst rate is low (Standard Deviations 37 to 43), compared with summer, autumn and winter months (Standard Deviations up to 296) (Figure 64). As can been seen, December bursts are variable, dependent on the temperature (e.g. 2006 was a warm winter with very few bursts (Figure 45).

Table 13 – Variation in bursts by calendar months.



	June	July	August	September	October	November	December	January	February	March	April	May
2005-2006	319	362	397	407	332	407	461	440	356	418	221	291
2006-2007	285	495	471	444	340	426	161	273	262	245	273	224
2007-2008	285	305	337	355	378	320	465	249	392	243	245	238
2008-2009	265	313	375	386	370	400	686	811	568	344	324	287
2009-2010	348	455	416	592	478	347	608	869	374	140	299	261
2010-2011	378	620	523	485	392	492	1114	617	418	609	358	336
2011-2012	361	381	493	505	549	488	680	508	852	494	308	312
2012-2013	292	261										
standard deviation	38.7	110.8	62.4	75.0	73.4	60.0	269.5	225.1	180.9	150.6	43.5	37.0
average	317	399	430	453	406	411	596	538	460	356	290	278
max	378	620	523	592	549	492	1114	869	852	609	358	336
min	265	261	337	355	332	320	161	249	262	140	221	224
difference	113	359	186	237	217	172	953	620	590	469	137	112

While the month of May is typically a low-burst rate month, 2012 and 2011 saw higher than normal bursts (An increase of approximately 60 over the average of 2005-2010). While there may be an issue of increased reporting of bursts due to Anglian Water’s proactive reporting scheme, we have not investigated this.

We focused our investigation on the relationship of soil moisture deficit (SMD) and spring bursts. This showed that, normally, SMD in May was rising as the soil was drying. 2012, however, was an unusual winter and spring, with the drought conditions witnessed across the Anglian Water regions meaning that SMD was high and falling (soils were dry, but wetting up) coming into the spring (Figure 65). There was a subsequent fall in SMD in May. With this largely different pattern in SMD it is logical that the burst rate for this May is not typical.

2011 also saw SMD reaching a peak shortly after May, indicating deep drying of the soils. June 2012 was a relatively benign month, with only 292 bursts – down from an average of over 360 from the previous 3 years. More research is required into the variation in weather in spring and the effect of this on buried assets.

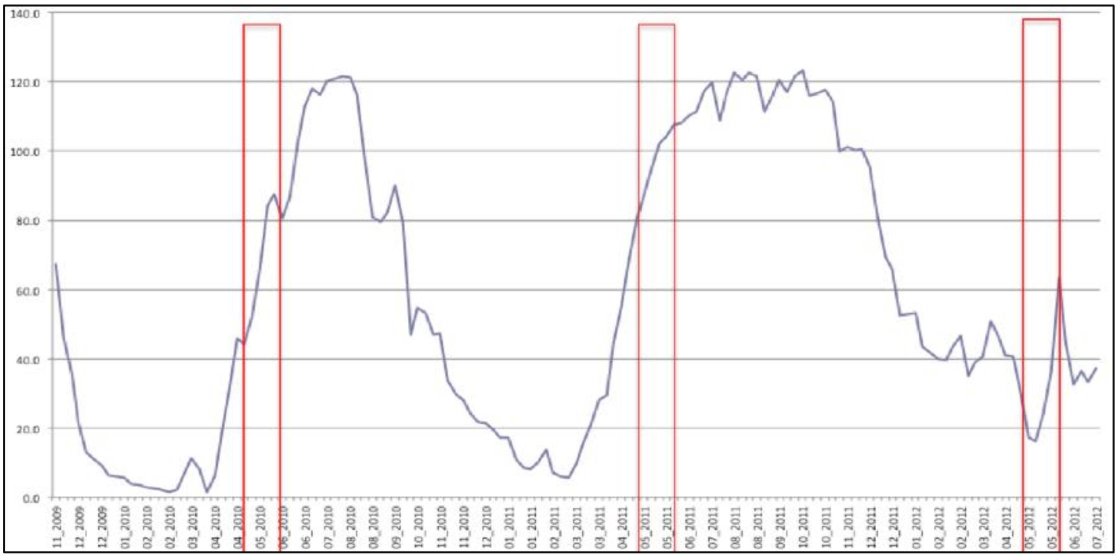


Figure 65 - Soil moisture deficit and the position of May.

6.3 Conclusions

Burst rates are at their lowest in spring months, and show the least variation in burst rate compared to winter, summer and autumn. The springs 2010-2012 have shown higher levels of bursts than in previous springs. Whether this is due to procedural changes at Anglian Water or the more variable, unseasonal climate requires further research.

Compared to the weather-related large increases in burst rates in the summer, autumn and winter, burst rates in the spring have been relatively stable.

Conclusions

7 Conclusions

Despite falling leakage rates, there has been an increase in the number of bursts which Anglian Water have reported over the period 2008-2012, potentially affecting the serviceability rates as reported to the regulator. This one-month research project undertaken by Cranfield University has examined the environmental effects of weather and soils upon the water main network of Anglian Water. Company policy effects and localised factors have not been considered. The most reliable and detailed burst data analysed was for the period April 2005 to July 2012. Bursts were compared against a range of soil and environmental vulnerability dataset, as well as values from or derived from the MORECS climatic data from the Met Office.

7.1 Chronic Pipe Degradation

Pipes in acidic, peaty soils were more to be susceptible to failure than pipes in other soil. A relationship was also observed between corrosive soils, those with shallow gley layers, and increased pipe burst rates.

These chronic effects do not change considerably before and after November 2008 and so are not considered to be a cause of the observed increased burst rates.

7.2 Winter

The greatest increase in bursts relates to the colder winters of 2008-2012 when compared to the previous eight years. A correlation of greater than 0.85 is found when comparing total winter bursts with the minimum recorded temperature for the winter.

Accumulated temperature was shown to be a useful metric to identify prolonged and sustained harsh winters. A basal threshold of week degrees below 1 was identified for the analysis. The study did not consider inter-regional comparisons with the territories of other water companies, but focused solely on the Anglian Water Region.

The colder, harsher winters of 2008-2012 have led to an increase in winter bursts, across all soil types, relative to the 2005-2007 baseline.

7.3 Summer and Autumn

It has been shown that late summer soil shrinkage and early autumn swelling of certain soils also has an effect on burst rates. This effect is more pronounced in highly shrinkable soils in the wetting phase than the earlier equivalent drying phase. There is a correlation of greater than 0.75 between the maximum recorded soil moisture deficit (SMD) and the total number of summer and autumn bursts.

The hotter and drier summers of 2009-2012 have led to an increase in bursts in these periods relative to the 2005-2008 baseline.

7.4 Spring

During spring the soils are wet, so ground movement due to shrinkage and swelling is typically not an issue. Temperatures are less extreme in spring, so this is an ideal season to assess the baseline status of a pipe network. Some increase in burst has been seen in May 2012 and 2011 over the baseline 2005-2010.This small increase of approximately 60 bursts per month may be due to unseasonally dry winters and uncharacteristic soil moisture deficits that have been recorded. Additionally, proactive burst reporting by Anglian Water.

Overall, compared with winter, summer and autumn fluctuations, spring bursts were found to have remained relatively stable over the period 2005 -2012.

Recommendations

8 Recommendations

A series of recommendations follow from this study.

8.1 Recommendations for future research

This report has identified some clear environmental relationships with water mains bursts and environmental conditions pertaining to the locations of the Anglian Water water mains. These conditions vary in time, and it is suggested that a more thorough investigation be conducted as to the build up of the contributory conditions affecting this critical infrastructure. This rapid research project has identified some likely causes of the increased burst rate in the Anglian Water region. It is noted that there remain many questions deserving a more detailed and thorough analysis. Following discussion with Anglian Water staff, a number of research topics are suggested as being of merit. In brief, these potential development suggestions could include specific developments by Cranfield on behalf of Anglian Water plc. as follows:

Reporting

1. An annual assessment and environmental audit of the previous annual burst records and the effect of soils and climate, commenting on changes and variations to baseline conditions. It is suggested this be conducted in the springtime. This approach can help Anglian Water prepare in a timely manner for future serviceability reporting to the regulator.

Further Scientific Investigations

2. An investigation in to the installation age of PVC pipes and AC pipes – Longevity of these pipes may depend strongly on the quality of the installation. We would seek to identify pipes most likely to fail in the summer / autumn months to enable targeted replacement.
3. Investigation of THRUST potential (forces) for the variety of soils in the Anglian Water region and how these are affected by climatic controls.
4. A more substantive investigation of the causes of the winter bursts. Possible causes include: soil movement, water temperature flux, transmission of cold through soil water. This to be backed with experimental data for the range of soil types in the Anglian Water region.

5. An investigation of the fluctuation of soil determinants such as pH throughout the year and across longer periods of time – as well as an assessment as to how this may affect pipe degradation.

6. The development of a series of robust computational decision support tools for Anglian Water, comprising: water mains bursts; sewer failure; and sludge to land.

Data refresh and upgrade

7. Digital Soil Mapping / upgrade datasets

   To achieve the greatest accuracy of soil-related causes of bursts, interpretation is more successful using soil data at a scale of 1:50,000 or larger (Jarvis and Hodges 1994). At these scales individual soil series can be identified opposed to 1:250,000 scales used in this present study, where each soil map unit may comprise of a number of soil series which are found associated together in a particular type of landscape.

   We would model the soils of the Anglian Water region at a more detailed scale of 1:50,000 enabling more accurate assessments of the soil hazards to pipes.

8. Enhanced visualisation techniques to enable better decision making – including DMA focused reporting and integration with web-visualisation tools.

Failure and Criticality modelling

9. Combining likelihood / criticality of failure to create models identifying the failure footprint of different assets. This would enable the visualisation of threats at the DMA level. DMAs and pipes within them could be ranked to enable informed decision making in the area of asset management.

10. Development of a near-real time summer / autumn model of movement potential and likely bursts incorporating higher resolution soils and meteorological data.

11. Development of a winter model of burst rates based on recorded meteorological conditions.

Training and Communication

12. Seasonal replacement - How to prioritise replacement schemes by season and soil conditions, to dig safely and effectively at different times of the year to minimise personal injury and mitigate collateral damage to other buried assets.

13. Soil / ground condition training for field staff, including soil identification and the development of good practices in reinstatement of trench excavation, maintaining ordering, even packing density and porosity.

14. Enhance Anglian Water's soil maps by improving communication with field staff to educate and engage them in taking better, more accurate notes on the soil condition / pipe failure mechanism etc. Field guidance notes for maintenance operators on soil management issues relating to future asset performance.

8.2 Working with Cranfield

Cranfield University work with Anglian Water in many ways. Our research staff can undertake research and consultancy project, such as in this case. Alternatively Cranfield often embeds research students in utility companies to focus on specific research questions.

An effective means for Anglian Water to address many of these research questions would be to have Cranfield undertake a PhD (3 years) or an MSc by research (1 year) whereby aspects of the analysis and contributory data would be assembled and exposed to discriminatory statistical techniques to allow levels of confidence to be placed on the findings.

8.3 Facilities - soil physics and field laboratories

The National Soil Resources Institute (NSRI) operate a range of world-class facilities used to underpin and support the research programmes underway at the University. We can make these large scale facilities available to Anglian Water for specific research projects, for example, examining the effect of climate or swelling on soil volume or pipe networks.

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9 References

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Appendix A – Project Task Descriptions

The following appendix lists the task descriptions comprising this work programme and constituting the contractual obligations of Cranfield University, NSRI to Anglian Water plc.

Project: WU33701V

Key Task descriptions

Deliverable 1
Assessment of burst records against soils criteria

Deliverable 2
Assessment of burst records against meteorological criteria

Deliverable 3
Literature review of academic publications.

10 Appendix B – Computer Software

This appendix presents a range of computer software written in the computer programming language PERL which were created to help with the analysis. Each programme is documented and listed below.

10.1 CreATe.pl

CreATe.pl is a perl script that takes MORECS data held in a CSV file and calculates, for each MORECS grid, the accumulated day degrees below a set threshold over the year (running July to June to ensure the full winter period is accumulated together.

```perl
# CreATe.pl [PERL] v2
# Purpose: Create Accumulated Degree Days below basal threshold for MORECS grid data
# AT is the integrated excess or deficiency of temperature around a threshold
# S Hallett, NSRI 14/8/12
# Run on cmd line as: perl CreATe.pl
#!/usr/bin/perl

###############################
# EDIT VALUES BELOW           #
my $basalThreshold  = 1;      # threshold in degrees centigrade
###############################

#initialise
my $lapseRate = 0.0064;
my $counter = 1;
my $periodIndex=-1;
open(INFILE,"MORECSSquaresData_JULY12_SHH_Summer_Split.csv")    ||    die    "Could    not    open
'MORECSSquaresData_JULY12_SHH_Summer_Split.csv' file";
open(OUTFILE,">MORECS_DD.txt") || die "Could not create 'MORECS_DD.txt' file";
print "Starting ...\n";

# Process file
while (<INFILE>) {
  chop;
  @_ = split /,/;
  if ($counter == 1) { @Header = @_;}
  if ($counter == 2) { @East = @_;} #don't need
  if ($counter == 3) { @North = @_;} #don't need
  if ($counter == 4) { @Altitude = @_;}
  if ($counter >= 5) { # morecs data
    $currentPeriod = @_[1];
    for  ($index=2;  $index<=@_-1;  $index++)  {  #  process  Morecs  squares,  skipping  date  and
processing period col
      if (@_[$index] <= $basalThreshold) { # acumulate deficit
        if  (!grep(  /^$currentPeriod$/,  @period_labels))  {push(@period_index,  ++$periodIndex);
push(@period_labels, $currentPeriod);} # store each processing period
#print OUTFILE $periodIndex;
            $tmpOD = abs($basalThreshold - (@_[$index]+0));
            $tmpMSL = abs($basalThreshold - (@_[$index]+($lapseRate*@Altitude[$index])));
            $Years_OD[$periodIndex][$index] += $tmpOD;
            $Years_MSL[$periodIndex][$index] += $tmpMSL;
            @Total_OD[$index] += $tmpOD;
            @Total_MSL[$index] += $tmpMSL;
          }
    }
  }
  $counter++;
}

# Output results
#header
print OUTFILE "Morecs_Id,Total_ATOD_$basalThreshold,Total_ATMSL_$basalThreshold";
for( $period = 0; $period<= @period_labels-1; $period++) { # each separate period
  printf(OUTFILE   ",%s_ATOD_$basalThreshold,%s_ATMSL_$basalThreshold",   @period_labels[$period],
@period_labels[$period]);
}
print(OUTFILE "\n");
```

```
#data
for($i=2; $i<=@Header-1; $i++) { # skipping first element
  printf(OUTFILE "%s,%.02f,%.02f", @Header[$i], @Total_OD[$i], @Total_MSL[$i]);
  for($period=0; $period<=@period_index-1; $period++) { # each separate period
    printf(OUTFILE              ",%.02f,%.02f",             $Years_OD[@period_index[$period]][$i],
$Years_MSL[@period_index[$period]][$i]);
  }
  print(OUTFILE "\n");
}

# Close files
close(INFILE);
close(OUTFILE);
print "... Finished\n";
####################

# eof: CreATe.pl
```

10.2 MorecsValues.pl

MorecsValues.pl is a perl script that identifies, for each recorded burst, the meteorological values for the week of the burst as well as the two preceding weeks, for the MORECS gridsquare that the burst is located in. Additionally the programme identified the coldest temperature in that period as well as the burst date.

```
# MorecsValues.pl [PERL] v2
# Purpose: Extract the Morecs values for various meteorological data for the week of the
# burst and the two preceding weeks, plus the minimum of those temperatures and the burst date.
# S Hallett, NSRI 15/8/12
# Run on cmd line as: perl MorecsValues.pl
#!/usr/bin/perl

#initialise
use List::Util qw[min max];
my $missingData = -999;
my $lapseRate = 0.0064;
my $week = 0;
my $weekEnd = 0;
my $weekEndMinus1 = 0;
my $weekEndMinus2 = 0;
my @weekResult = 0;
my @timeTemporary = 0;
my $burstWorkOrder = 0;
my $burstMorecsId = 0;
my $burstAlt = 0;
my $burstWeek = 0;
my $burstWeek_MinusOne = 0;
my $burstWeek_MinusTwo = 0;
my $morecsWeekTempMSL = 0;
my $morecsWeekTempMSL_MinusOne = 0;
my $morecsWeekTempMSL_MinusTwo = 0;
my $burstTempOD = 0;
my $burstTempOD_MinusOne = 0;
my $burstTempOD_MinusTwo = 0;

open(INFILE_BURSTS,"bursts_v6_in_DMA_Morecs_Date_DTM_Only.csv")    ||    die    "Could    not    open
'bursts_v6_in_DMA_Morecs_Date_DTM_Only.csv' file";
open(OUTFILE,">BURSTS_Meteo.txt") || die "Could not create 'BURSTS_Meteo.txt' file";
print "Starting ...\n";

#header
print OUTFILE "WorkOrder,Week_end_date,Temp_OD,Temp-1_OD,Temp-2_OD,MinTemp_OD\n";

# Process file
while (defined($eachBurstLine = <INFILE_BURSTS>)) {
  next unless ($. > 1); # skip header lines
  chop;
  @eachBurst = split (/,/, $eachBurstLine);
  $burstWorkOrder = @eachBurst[3];
  $burstMorecsId = @eachBurst[11];
  $burstAlt = @eachBurst[12];
  #
  @timeTemporary = split(' ', @eachBurst[5]); #week of burst
  $burstWeek = @timeTemporary[0];
```

```
  $morecsWeekTempMSL = getMorecsValues($burstMorecsId, $burstWeek);
  $burstTempOD = ($morecsWeekTempMSL != $missingData) ? ($morecsWeekTempMSL - ($lapseRate *
$burstAlt)) : ($morecsWeekTempMSL); # trap missing data
  #
  @timeTemporary = split(' ', @eachBurst[6]); # week before burst
  $burstWeek_MinusOne = @timeTemporary[0];
  $morecsWeekTempMSL_MinusOne = getMorecsValues($burstMorecsId, $burstWeek_MinusOne);
  $burstTempOD_MinusOne = ($morecsWeekTempMSL_MinusOne != $missingData) ?
($morecsWeekTempMSL_MinusOne - ($lapseRate * $burstAlt)) : ($morecsWeekTempMSL_MinusOne); # trap
missing data
  #
  @timeTemporary = split(' ', @eachBurst[7]); # two weeks before burst
  $burstWeek_MinusTwo = @timeTemporary[0];
  $morecsWeekTempMSL_MinusTwo = getMorecsValues($burstMorecsId, $burstWeek_MinusTwo);
  $burstTempOD_MinusTwo = ($morecsWeekTempMSL_MinusTwo != $missingData) ?
($morecsWeekTempMSL_MinusTwo - ($lapseRate * $burstAlt)) : ($morecsWeekTempMSL_MinusTwo); # trap
missing data
  printf(OUTFILE "%s,%s,%.02f,%.02f,%.02f,%.02f\n", $burstWorkOrder, $burstWeek, $burstTempOD,
$burstTempOD_MinusOne, $burstTempOD_MinusTwo, min($burstTempOD, $burstTempOD_MinusOne,
$burstTempOD_MinusTwo));
}

# Close files
close(INFILE_BURSTS);
close(OUTFILE);
print "... Finished\n";
###################

###################
sub getMorecsValues {
  # Passed: morecs id and week number
  # Returns: Temperature and Morecs grid centre Altitude
  ($_morecsId, $_week) = @_; # name parameters
  my $_lapseRate = 0.0064;
  my $_morecsCounter = 1;
  open(INFILE_MORECS,"MORECSSquaresData_JULY12_SHH_Summer_Split.csv") || die "Could not open
'MORECSSquaresData_JULY12_SHH_Summer_Split.csv' file";
  while (defined($eachMorecsLine = <INFILE_MORECS>)) {
    chop;
    @eachMorecs = split (/,/, $eachMorecsLine);
    if ($_morecsCounter == 1) { @Header = @eachMorecs;}
    if ($_morecsCounter == 4) { @Altitude = @eachMorecs;}
    if ($_morecsCounter >= 5) { # morecs data
      if(@eachMorecs[0] eq $_week) { # match on date
        for( $i = 2; $i <= @Header-1; $i++) { # skipping first two elements
          if(@Header[$i] == $_morecsId) { # match on Morecs square
                          close (INFILE_MORECS);
                          return @eachMorecs[$i] + ($_lapseRate * $Altitude[$i]) # return MSL
corrected temperature
                   }
                 }
      }
    }
        $_morecsCounter++;
  }
  close (INFILE_MORECS);
  return -999;
}
###################

# eof: MorecsValues
```