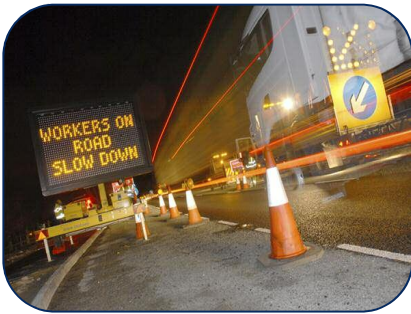




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The costs and benefits of increasing the resilience of rail geotechnical assets to climate change

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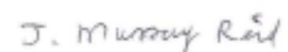
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Executive summary

The stability of rail earthworks is influenced by meteorological conditions, so is likely to be affected by the changing climate. In this project, carried out under TRL's 2012/13 reinvestment research programme, a methodology was developed to investigate the economic implications of this, and compare the costs associated with engineering solutions. This methodology was applied to three case studies, seeking to determine if, in the long-term, the most cost effective option would be to carry out work to stabilise vulnerable earthworks, or if remedial work whenever required is the more economic option.

The study was carried out in conjunction with Network Rail, who provided data and technical advice for the project. Initial discussions with Network Rail directed the focus of the project towards earthwork instability associated with desiccation. During the drought conditions in 2010/11, earthwork failures as a result of low soil moisture were experienced on London Clay and Peat geologies, particularly on the Anglia Route. Therefore, three sites on the Anglia Route were selected as case studies; one peat (Ely Station) and two London Clay sites (West Horndon to Dunton and Harold Wood to Brentwood).

Maintenance data, in relation to soil moisture deficit (SMD) was analysed. This showed a correlation between SMD and the amount of online track maintenance for the peat case study site. For the clay sites, a correlation between the rate of increase in SMD and maintenance data was found. There was also a correlation between SMD and the number of earthwork incidents causing delay. The timing for the peat and clay sites was different; incidents and maintenance occurred throughout the year, but a majority in autumn for the peat site, and most incidents and maintenance occurred in spring for the clay sites.

Data was obtained from the UK Climate Projections (UKCP09) Weather Generator on the typical weather patterns likely in the 2020s and 2050s, and from this it was possible to calculate estimates of future SMD. The annual average and summer maximum SMD at all three sites increased over time. The SMD in spring and autumn changed the most, and the SMD increased earlier in the year and decreased later in the year. However, the rate of change in weekly SMD showed no change.

The relationships established using historic data were applied to the future SMD values to estimate the amount of delay and maintenance likely in the future. This information, together with the costs of delay and tamping, was used to develop a cost model, allowing the costs of carrying out work to stabilise the earthworks to be compared to the costs generated from delay and maintenance.

The cost model calculates the Net Present Value (NPV) for both carrying out stabilisation actions and not carrying out work, the Incremental Economic Indicator (IEI) (a measure of the cost-effectiveness of action), and the payback time for the remedial works. The model was run for the three sites, and the sensitivity of these calculations to climate uncertainties, traffic levels and remediation lifespan was assessed.

The IEI for each of the three sites was found to be negative, meaning that the high cost of stabilisation was not recovered within the analysis period, although for the Harold Wood site this was marginal. The Ely site experienced the largest change in the level of maintenance over time; however, the additional cost associated with this was far below

the cost of the adaptation work. The clay sites showed no change in maintenance over time, as the rate of change in weekly SMD did not appear to change significantly over time. This warrants further investigation to discover if it is an artefact of the analysis methodology or a genuine finding.

This scoping study successfully developed a methodology for studying the costs and benefits of adapting rail geotechnical assets to climate change using climate projection and asset data. Although one failure mechanism and type of asset was focussed on, the methodology could be adapted for use with other failure mechanism and asset types.

The study also provided an initial indication of the costs and benefits involved in adapting geotechnical assets to climate change, for three case study sites on the Anglia Route. For the three sites studied and the deterioration mechanism of desiccation and shrinkage, the costs of remedial works to stabilise the earthworks are greater than the costs of delay and routine maintenance to cope with the problems when they occur under projections for climate change over 60 years. Further work in this area is required to verify the relationships identified, validate the model and ascertain if this methodology could be applied to other types of soil and locations.

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1 Introduction

This is the final report for a reinvestment project funded by TRL under the 2012/2013 research programme. The project aim was to study the costs and benefits associated with adapting rail geotechnical assets to climate change. Geotechnical stability is greatly affected by weather conditions (amongst other factors), particularly changes in precipitation and temperature which affect soil moisture. Climate change projections for the UK suggest that more frequent intense rainfall events, and more frequent and prolonged periods of drought will occur in the future. Both these types of extremes and the combination of these conditions have a negative effect on soil stability, and consequently rail infrastructure. The challenge that faces Network Rail is to manage this increase in risk appropriately and cost effectively. This involves considering if taking action to reduce the risk of adverse effects is a more cost effective solution than repeatedly dealing with increasing damage and disruption.

The project was carried out with the support of Network Rail (NR), which provided advice and data for the model development. Discussions with NR geotechnical experts steered the project focus towards the impacts of drought on clay and peat soils in the Anglia region. The NR Anglia Route is located in the driest part of the UK, which climate projections show is likely to experience more severe and prolonged droughts in the future. The soil moisture during periods of low rainfall, especially when combined with high temperatures, decreases sufficiently that susceptible soils such as peat and clay shrink significantly. This movement destabilises the infrastructure above, necessitating repair work and speed restrictions to maintain safety and performance standards. This is becoming an increasing problem in this region and NR would like to know more about the problem and potential solutions. The project also aligns with other NR adaptation and risk assessment work such as the TRaCCA programme (Tomorrow's Railway and Climate Change Adaptation) and the adaptation report for DEFRA (Department for the Environment, Food and Rural Affairs) submitted in response to the Climate Change Act 2008 (Network Rail, 2011). The impact of climate change on soil moisture leading to increased landslips was highlighted as a potential issue in this report, but with no clear evidence to establish a relationship. The desiccation of earthworks was categorised as likely to experience a "high negative impact" due to climate change; however to-date most work in this area has been focussed on the implications of more intense rainfall on earthworks with less emphasis on desiccation.

1.1 Project objectives

The reinvestment project aimed to help NR better understand the relationship between soil moisture deficit (SMD) and earthwork failure, and whether it is more cost-effective to carry out major work to stabilise vulnerable earthworks or to continue to realign track by tamping and ballast renewal when incidents occur. The project calculated the Incremental Economic Indicator (ratio of whole-life cost savings to increased initial outlay) using the baseline climate (1961 to 1990) over the study period and the projected future climate, to determine if climate change will impact on this ratio.

The specific project objectives were to:

- Select suitable study sites and collect data on these;
- Estimate the likelihood of delay and maintenance as a result of earthwork failure and how this could change with climate change;

- Calculate the costs incurred to NR as a result of failure;
- Identify suitable adaptation techniques to reduce the risk of failure;
- Estimate the cost associated with carrying out the adaptation techniques;
- Calculate the Incremental Economic Indicator for adaptation compared to dealing with repeated failure for the three case study sites.

The project developed a methodology for calculating the cost-benefit of adapting rail geotechnical assets to climate change and produced three case studies illustrating this. The results of the case studies provide an indication on whether it is more cost-effective (within the analysis period) to adapt to climate change or if the current policy of repairs and speed restrictions when incidents occur is more appropriate.

1.2 Project scope

This project is a small scoping study, which aimed to provide an indication of the cost-benefit ratio for adapting rail geotechnical assets to climate change. It therefore had a tightly focused scope and made a number of assumptions (see Section 8.2). Key restrictions of the scope were:

- Desiccation was the only earthwork failure mechanism investigated; the impact of high rainfall or other non-weather factors were not considered;
- Only direct costs to Network Rail were used in the cost-benefit study; costs to train operating companies, customers, indirect costs such as loss of reputation and non-monetary costs such as environmental impact were not included;
- The methodology was developed using data for the Anglia Route, and for three specific case study sites. Therefore, although the methodology is generic, it is not known if the results and correlations established are applicable to other routes or sites; and
- The analysis period used was from 2010 to 2070.

1.3 Project tasks

The main tasks in carrying out this project were:

1. The selection of suitable case study sites and obtaining data relating to these.
2. Analysis of the data to establish correlations which could be used in the model.
3. The development of a cost model in Excel.
4. Calculation of Incremental Economic Indicator and payback time for the case study sites, using baseline and future climate data.
5. Compilation of a project report, summarising the methodology developed and results obtained.

1.4 Report structure

The sections of the report are arranged as follows:

- Chapter 2 provides background information on how geotechnical assets are affected by soil moisture, climate change impacts on soil moisture and earthwork failures.
- Chapter 3 gives an overview of the methodology, including case study selection and acquisition of data.
- Chapters 4 to 7 describes the analysis and data used as inputs to the different model elements:
 - o Chapter 4 describes the climate information acquired and how it was used to calculate estimates of future soil moisture deficit (SMD).
 - o Chapter 5 summarises the analysis of historic failure data and how it relates to SMD and site characteristics.
 - o Chapter 6 focuses on the calculation of the consequences of the failures both in terms of infrastructure damage and delay costs.
 - o Chapter 7 identifies the options for reducing the risk of failure and their cost.
- Chapter 8 summarises the development of the cost model and the assumptions made.
- Chapter 9 gives the results of the calculations for the case studies and the sensitivity to traffic level and remediation life.
- Chapter 10 discusses the project findings and further areas of development for the model.

2 Background information

2.1 Soil moisture and earthworks

2.1.1 Defining soil moisture deficit

The moisture content of soil at a particular time depends on both precipitation and temperature, as temperature affects the rate of evaporation. It also depends on the characteristics of the soil, as pore size affects drainage, type of vegetation and topography. Moisture is removed via evaporation, either directly from the soil or through the transpiration of vegetation. In the UK evaporation follows a seasonal pattern, with evaporation normally at its highest in June/July and only 10% of annual evaporation occurring from October to March. This makes soil wetter in the winter and drier in the summer, even if rainfall amounts are similar.

Soil moisture conditions are normally defined in terms of soil moisture deficit (SMD). SMD is a measure of the volume of water required to provide the soil with as much water as it can hold against gravity. A negative SMD indicates the soil is wet, with surplus water and a positive SMD that it is dry. SMD can be calculated as follows (Met Éireann, 2012):

$$\text{SMD}_t = \text{SMD}_{t-1} - \text{Rain} + \text{ET}_a + \text{Drain} \quad \text{Equation 1}$$

Where SMD_t and SMD_{t-1} are the SMDs on day t and day $t-1$ respectively (mm),

Rain is the daily precipitation (mm per day),

ET_a the daily actual evapotranspiration (mm per day),

Drain is the amount of water drained daily by percolation and/or overland flow (mm per day)

Potential evapotranspiration (PE) is the maximum amount of water lost through evaporation and plant transpiration with a plentiful supply of moisture, and is dependent on temperature, wind speed, solar radiation, land use etc. Actual evapotranspiration is often less than this value as it is limited by the amount of soil moisture present.

SMD varies between soil types, regions and years, but generally follows the seasonal cycle shown in Figure 1 - rising in spring as potential evaporation exceeds rainfall and recovering during the autumn months. Maximum SMD occurs in late summer, after the PE maximum.

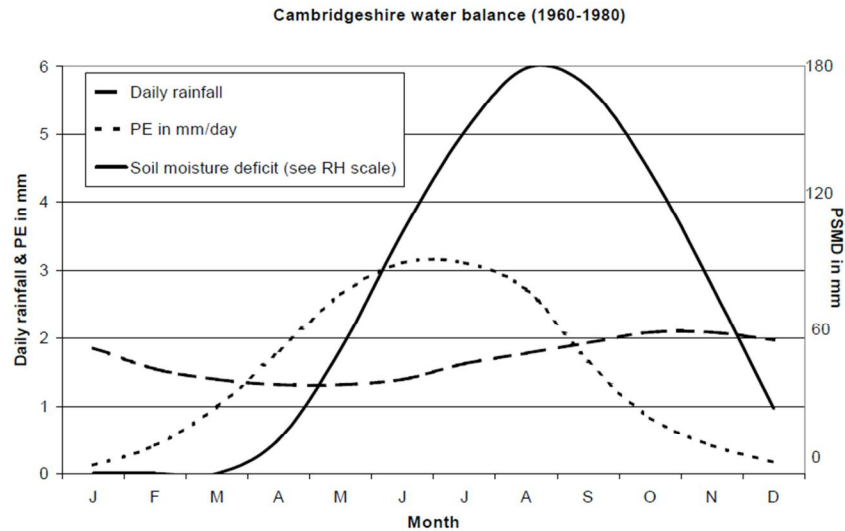


Figure 1. Seasonal cycle of SMD (Mullins, 2004)

2.1.2 *Expansive soils*

Some types of soil (referred to as expansive soils) undergo significant changes in volume in response to moisture content. Soils containing certain types of minerals (clays) attract and store a large number of water molecules between the soil particles increasing the soil volume when wet. When the soil dries the volume decreases, producing a “swell-shrink” effect. As shown in Figure 2, the UK’s most strongly expansive soils (clays such as the London Clay, Gault Clay and Oxford Clay) are primarily located in the south east of England.

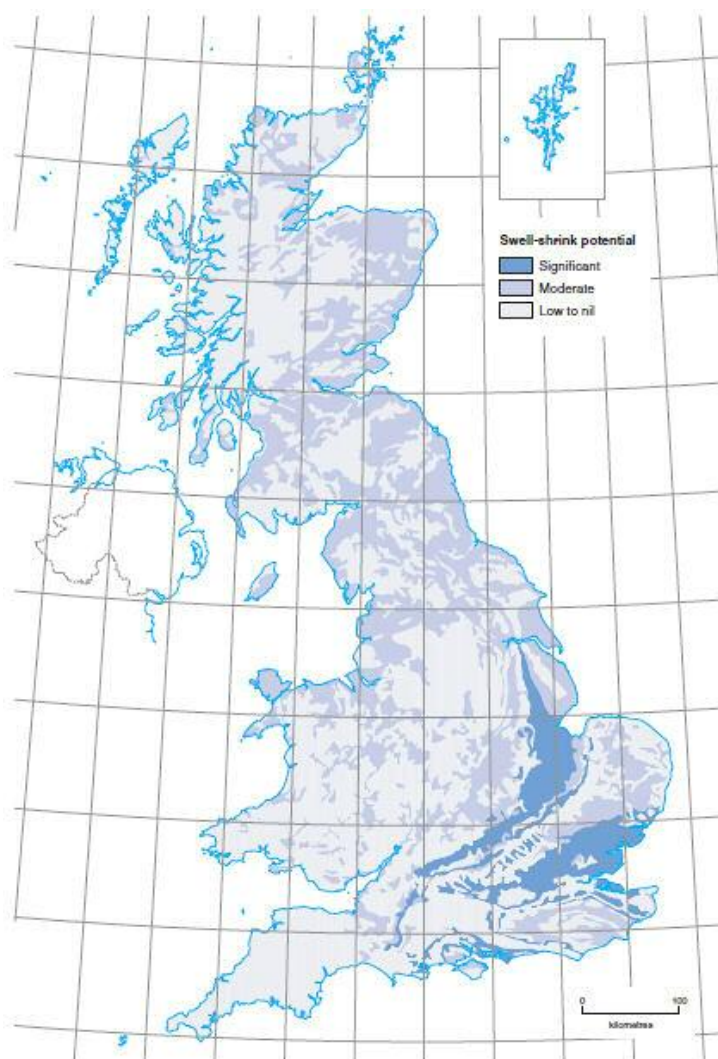


Figure 2. Location of soils susceptible to shrink-swell (BGS, 2012)

The most expansive soils can undergo large changes of volume, creating significant ground movement which can affect infrastructure constructed above them. An increase in soil volume due to heavy rainfall can cause heave; and a decrease in volume due to drought can cause subsidence. Both can de-stabilise slopes, creating landslips or causing damage and misalignment in infrastructure unable to cope with the change in ground level, especially if the change in volume is uneven. The shrink-swell effect is not always reversible. The cracks caused by shrinkage may not always close up completely when soil moisture increases, providing access for water during later rainfall. Most shrinkage occurs within the first metre of ground level, but in extreme drought drying can extend up to three metres into the ground. Research (Harrison, 2012) has shown that the preceding two years of rainfall is important for the manifestation of shrink-swell behaviour. Temperature also has an influence, as it affects the amount of evapotranspiration.

2.1.3 The impact of soil moisture on rail earthworks

The majority of British rail earthworks were constructed around 1830 to 1900, using local material (which was not always suitable) and without any engineering of the foundation material or appropriate drainage. This makes them much more vulnerable to changes in soil moisture than, for example, modern engineered motorway earthworks.

The growth of vegetation exacerbates the problem by decreasing moisture content during summer. Trials on clay embankments found that ground movements were ten times greater when trees are present compared to grass (Railway Engineer, 2012). Cracking as a result of desiccation also allows the infiltration of rainfall into the earthworks increasing their vulnerability during heavy rainfall.

2.1.4 SMD as an indicator of infrastructure risk

SMD is a measure used in agriculture to help plan irrigation for crops (Lawson, 2012); however changes in SMD can also be used as an indicator of when expansive soils are expanding or shrinking, and therefore when infrastructure may be vulnerable to subsidence and heave. It would be impractical and expensive to measure the SMD of the entire network. However, there are various models used to estimate SMD taking into account geology, land use and meteorological variables, such as precipitation, temperature and wind speed. Network Rail uses the Met Office Rainfall and Evaporation Calculation System (MORECS) which produces SMD values for 40km² grids across the UK (Figure 3). MORECS has seven types of land use; grass, rough grazing, deciduous trees, orchards and evergreen trees, bare soil, open water and rock/urban land. An additional type "real land use" which consists of appropriate fractions of the separate components is also used. NR uses the deciduous trees value as an indicator of the risk to their earthworks. Models do not exactly reflect the real soil moisture; for example MORECS data often over-estimates SMD (Limbrick et al., 2000). The model is designed for agricultural purposes, not earthworks, and does not take into account factors such as increased evaporation on south facing slopes. However, it does provide a good indication of SMD trends.

NR have identified through experience high (200mm) and low (50mm) SMD thresholds, above and below which earthworks are likely to be vulnerable to shrinkage and swelling respectively and engineers should be vigilant. They obtain average SMD values every week for the MORECS grid squares, so that engineers are aware if there are likely to be issues related to soil moisture.



Figure 3. MORECS grid squares (Lawson, 2012)

2.1.5 Climate change impacts on soil moisture

Future changes in precipitation patterns and evaporation (due to differences in temperature, wind speed and radiation) projected by climate models are likely to affect soil moisture. The latest UK Climate Projections (UKCP09) do not provide direct information on soil moisture, but the previous climate scenarios (UKCIP02) indicated a decrease of up to 20 to 50% in soil moisture (and hence an increase in SMD) by the 2080s in south east England could be expected. UKCP09 does project higher temperatures and lower summer rainfall for the south east, conditions which are likely to increase SMD. In addition, the longer growing season expected increases the amount of evapotranspiration that occurs and a shorter winter recharge period limits recovery during the winter. Periods of drought are expected to become more frequent and severe in the future, and extend further into the autumn and even winter. Work carried out by the University of Southampton (2008) suggests SMD in the 2080s will be 40mm higher in the London Heathrow area by the end of the summer, compared to historic climate. They state that a 1 in 33 year dry summer in London today is likely to become the average summer in the 2080s. Research by BGS and the University of Birmingham (Harrison, 2012) based on the UKCIP02 projections showed the areas of the south east which are likely to be more susceptible to subsidence in 2080, under the high emissions scenario. These are shown on Figure 4.

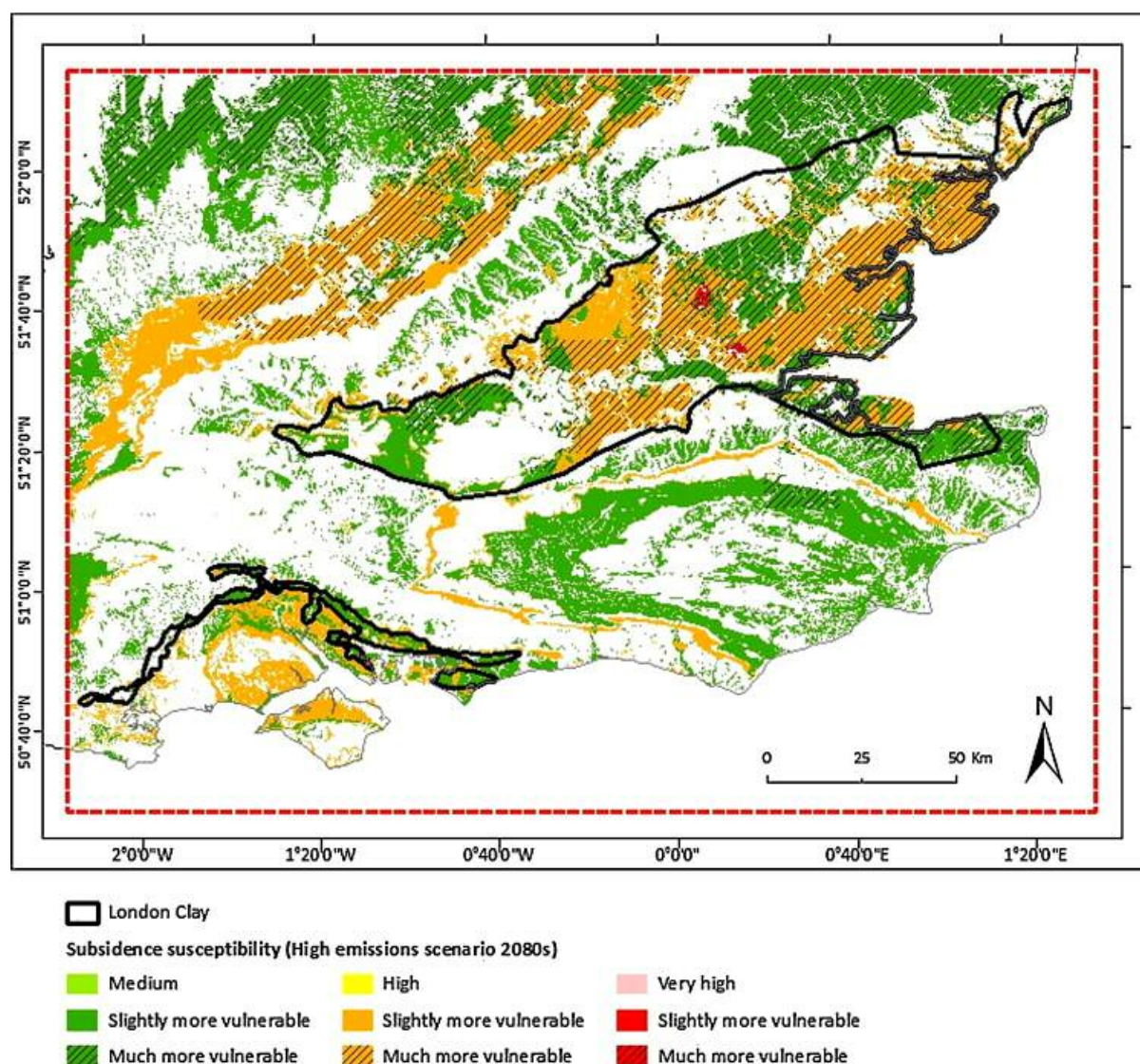


Figure 4. Subsidence susceptibility classification for the south-east of England using the UKCIP02 scenarios (high emissions 2080s). Contains public sector information licensed under the Open Government Licence v1.0. UKCIP 2011. Coastline courtesy of The Digital Chart of the World (DCW); from: Harrison et al., 2012.

Climate change may also affect soil characteristics, for example through waterlogging or cracking, that could change the soil's ability to store water. Some studies (Boix-Fayos et al., 1998), suggest that infiltration and water-holding capacity of soils on limestone are greater with increased frost activity, therefore warmer winters may reduce water-storing capacity. Vegetation may also die off due to drought, or the type of vegetation present change, which can impact on soil moisture.

The implications of these changes are that there is likely to be a greater degree of expansive soil shrinkage in summer and this will last for longer periods of time. This will have consequences for rail earthworks.

2.2 Rail earthwork failures

Earthwork failures include landslides and changes in track geometry that occur as a result of ground movement and affect safety or performance levels. They can occur on embankments, cuttings or at grade. The number of earthwork failures on the Network Rail network is given in Table 1 for the past six years. The number of earthworks failures has fallen due to improved risk management process.

Table 1. Earthwork failures (Network Rail, 2011b)

	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12
Earthworks failures (No.)	90	107	61	57	42	28

Earthwork failure can affect safety and service levels on the network. Impacts include:

- **Safety** - From 1997 to 2002, there were 10 occasions when earthwork failure resulted in derailment, producing minor injuries for 19 people. However, there has been no fatality attributed, either directly or indirectly, to an earthworks failure since 1995. The RSSB Rail Safety Model uses a risk contribution of 0.393 fatalities per year for derailment due to landslip and subsidence/landslip under the track.
- **Service** – Geotechnical problems can cause delays and disruption due to closure of a line necessitating diversions or replacement buses, or the implementation of unplanned speed restrictions. Thirty eight unplanned and thirty two planned temporary speed restrictions were put in place due to earthwork problems in 2011/12. There are cost implications of these delays for Network Rail, the train operators and for the country in terms of loss of productivity. In 2010/11 there were 61,894 delay minutes attributed to civil engineering structures, earthworks and building failures (Network Rail, 2011b).
- **Maintenance** – Increased maintenance may need to be carried out to rectify poor track geometry, clear landslip debris from the line and stabilise slopes. This has cost implications, safety implications for staff and can cause delay while the work is being carried out. In 2007/2008 Network Rail spent approximately £80 million on earthworks; the majority of this was on planned preventative measures (RAIB, 2008)).
- **Environment** – Soil erosion, damage to vegetation and habitat and increase of sedimentation in water courses can be caused by earthwork failure.
- **Reputation and meeting of ORR targets** – The delay and disruption associated with earthwork failure can damage the reputation of NR. It can also contribute to difficulties in meeting ORR performance targets, with potential financial penalties.

2.2.1 Earthwork risk management

Network Rail has a team of geotechnical experts who manage the risk of earthwork failure and carry out regular inspections on the 10,000 miles of earthworks in the network. Earthworks greater than 3m and earthworks with a history of instability or

located close to a bridge or tunnel are included in the inspection process. Information is collected for each 5 chain earthwork section on characteristics such as height, slope, animal activity, vegetation present, earthwork drainage and signs of any failure. From these, a Soil Slope Hazard Index is calculated to indicate the condition of the earthwork and its likelihood of failure. The inspection frequency depends on condition rating; serviceable earthworks are examined every 10 years, marginal every 5 years and poor every year according to the standard NR/L3/CIV/065 (Network Rail, 2008). A geotechnical hazard map is being compiled to highlight vulnerable sections of earthwork, and other assessment techniques such as LIDAR and topographical and drainage surveys are being increasingly used to assess earthwork risk. The management system looks at five key variables:

- Asset type (cutting, at grade, embankment)
- Geology (granular/rock, cohesive/clays)
- Condition (serviceable, marginal, poor)
- Moisture content (SMD) (saturated, normal, desiccated)
- Vegetation type (trees, grass).

2.2.2 *Implications of climate change*

Network Rail's previous work on climate change impacts for the TRaCCA programme (RSSB, 2010) and its Adaptation Report for DEFRA (Network Rail, 2011a) identified the potential for increased risk of earthwork failure due to climate change. This will affect the management of earthwork risk and has potential cost implications. Several research projects such as BIONICS (Biological and engineering impacts of climate on slopes), CLIFFS (Climate Change Impact Forecasting For Slopes) etc. have been studying different aspects relating to future earthwork risk, mainly related to landslip triggered by heavy rainfall events.

Costing climate change impacts can be challenging, due to the large amounts of uncertainty involved in aspects such as the change in future climate variables, the potential impact of these changes on infrastructure and the effectiveness of adaptation options to reduce impacts. Some estimates of the costs of climate change to UK rail have been given by Dobney (2010), who used climate projections to estimate the change in frequency of exceeding a climate threshold over which track buckling could occur, and calculated the cost implications of this in terms of delay. TRaCCA also looked at the delay implications for different specific events such as sag of overhead lines and flooding of the track.

3 Methodology overview

3.1 Modelling approach

The approach taken in this study was to estimate the likelihood of delay and maintenance shifts due to geotechnical failure by analysing the historic relationship between SMD and failure, and using the UKCP09 Weather Generator to look at the potential change in number of failures under the projected future climate. The costs associated with failure were then calculated based on past figures and appropriate discount and inflation rates. The frequency and cost of failure are compared to the costs of carrying out adaptation work to reduce/eliminate the risk of failure. This process is shown in the diagram in Figure 5.

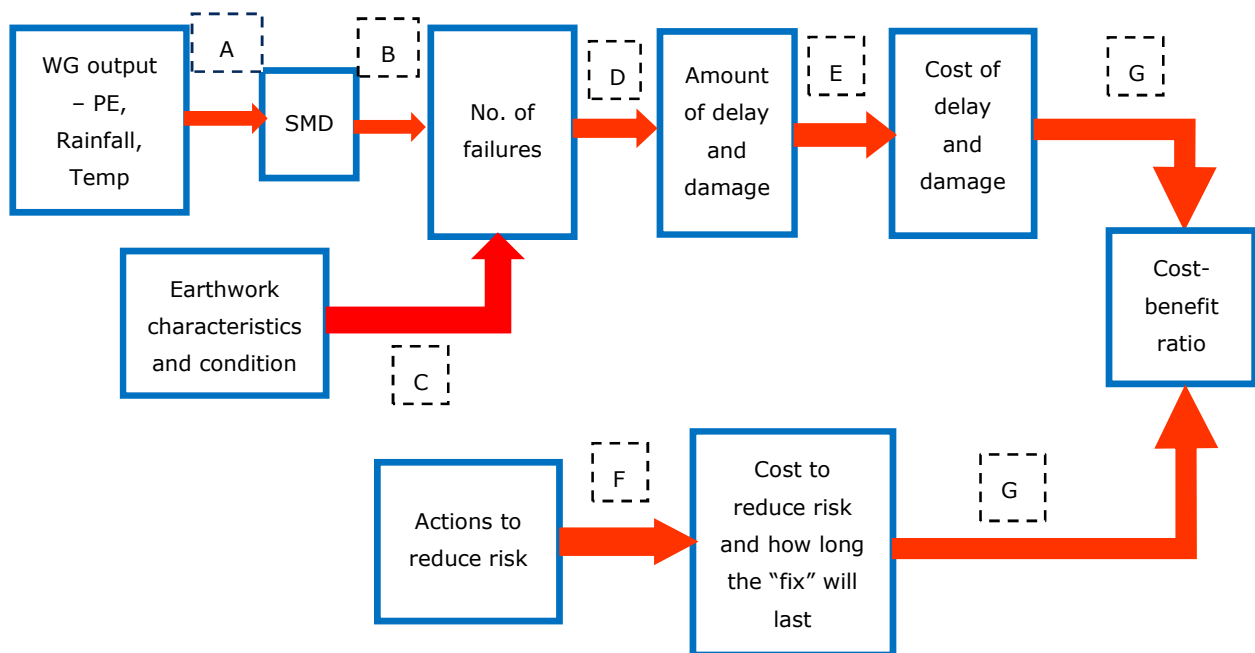


Figure 5. Model process diagram

A = Link between UKCP09 Weather Generator (WG) output and SMD

B = Link between SMD and failure frequency

C = Link between earthwork characteristics and failure

D = Link between failure and delay plus damage

E = Link between delay plus damage and cost

F = Cost of actions to reduce risk

G = Feeds into cost-benefit calculation

The most important aspect of this process is identifying the links between the different model elements. A description of the links A to G and the information that was required to establish the different relationships is given in Table 2.

Table 2. Relationship between different model elements

Link	Link description	Requirements to establish link
A	Calculation of SMD based on UKCP09 WG outputs, such as PE, temp and rainfall.	• A methodology to obtain SMD from WG outputs • WG outputs for the case study sites
B	Establishment of a relationship between SMD and failure based on past events.	• Past SMD data • Past incident data
C	Identification of the earthwork characteristics associated with failure.	• Details of past failures • The characteristics of the earthworks in failure locations
D	The average amount of delay minutes and maintenance shifts associated with failure.	• Delays associated with past failure • Maintenance associated with past failure
E	Costs of carrying out remedial work and delay cost per minute due to speed restrictions before maintenance can be carried out.	• Costs of past maintenance work • Average delay costs per incident
F	Actions to reduce the risk of earthwork failure and the cost of implementing them.	• Identification of adaptation actions • Cost of adaptation actions
G	Cost analysis with appropriate discount rate.	• Development of a cost model • Select appropriate discount rate

Once the methodology was developed the cost model was run several times:

- For the baseline climate in order to identify how climate change is affecting the Incremental Economic Indicator (IEI).
- For the future climate scenario in order to identify how climate change will affect the Incremental Economic Indicator.
- For all three case studies areas.
- With different levels of traffic, life times of the adaptation action and climate variations to carry out sensitivity analysis.

3.2 Selection of case studies

3.2.1 Case study locations

East Anglia is the driest region of the UK and also has a large amount of expansive soil, which changes in volume in response to moisture levels. During the prolonged dry period experienced from 2010 to early 2012, problems associated with subsidence were experienced on a numbers of sections of the Anglia Route. It was therefore decided to focus the study on the Anglia Route.

Two types of geology widely found in the region, which shrink in response to low moisture levels, are peat and London Clay. It was decided to investigate sections of track located on both these types of soil where earthwork problems had occurred during the recent drought.

Network Rail identified three areas where issues relating to soil desiccation had been reported as suitable case study sites:

- Site A: Ely Station
- Site B: West Horndon to Dunton
- Site C: Harold Wood to Brentwood

Site A has peat soil, and sites B and C have London Clay. London Clay is well-known to shrink and swell in response to seasonal meteorological changes and peat has a high degree of settlement in response to loading and drainage. Details of the three study sites are given in Table 3 and a schematic of the three sections are given in

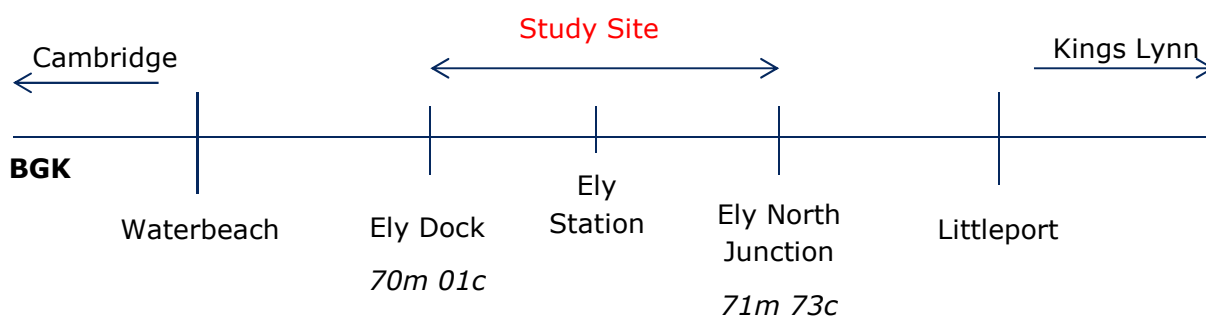
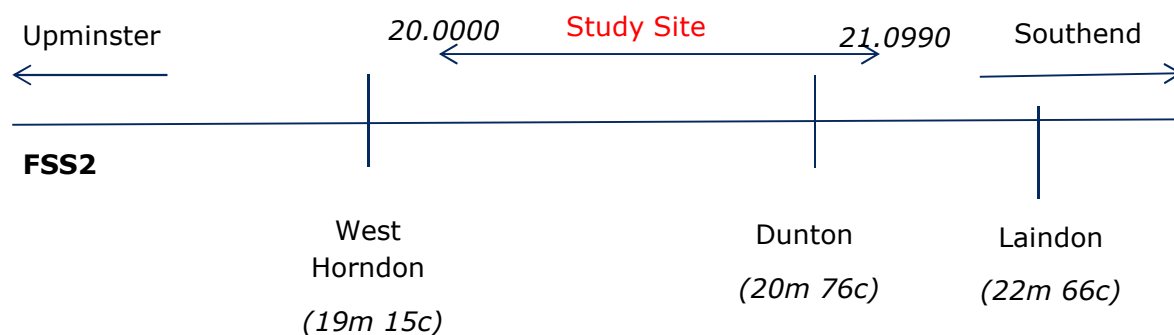
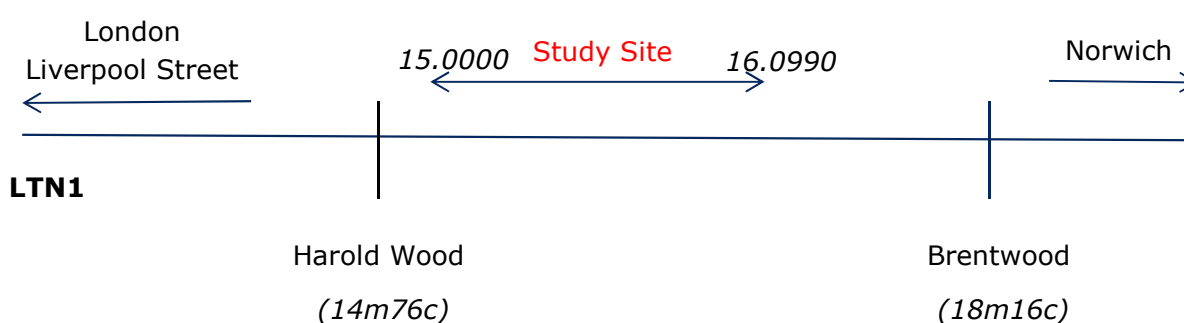
Figure 6 (c = chain, there are 22 yards in a chain and 1760 yards in a mile).

Table 3. Case study site details

	Site A	Site B	Site C
Description	Ely Station (Ely Dock to Ely North)	West Horndon to Dunton	Harold Wood to Brentwood
ELR¹ and mileage (miles.yards)	BGK 70.0022 to 71.1606 (up and down lines)	FSS2 20.0000 to 21.0990 (up and down lines)	LTN1 15.0000 to 16.0990 (up and down lines)
Route Length (km)	3.06	2.52	2.52
Maintenance area	IMDM ² Tottenham	IMDM Romford	IMDM Romford
Geology	Peat overlying Kimmeridge Clay	London Clay formation	London Clay formation
Earthwork description	At grade (<3m)	Slope height 4.5m, angle 25°	Slope height 6m, angle 45°
Vegetation	Urban around station, hedges and occasional mature trees either side	Occasional mature trees, bare ground and sparse grass/bramble cover	Occasional mature trees, sparse and dense grass/bramble cover
Condition	No inspection as at grade	Serviceable up and poor down line	Marginal up and down line
Geographic orientation	Southwest – north east	East-west	Southwest – north east

¹ Engineers Line Reference

² Infrastructure Maintenance Delivery Managers

Figure 6. Study Site Schematics**Site A****Site B****Site C****3.2.2 Analysis period**

The UK government guidelines mandate a 60-year cost analysis period for transportation infrastructure procurement (DfT, 2006), therefore a study period of 2010 to 2070 was used. This timescale is sufficiently far into the future to observe climate change impacts compared to the present day and represents NR control period 4 (2009 to 2014) onwards.

3.3 Data collection

The cost model requires several relationships to be established, in particular the link between SMD and failure. For this a number of different types of data were required; these are summarised in Table 4.

Table 4. List of data acquired

Description of data	Source	Temporal details	Spatial details
Historic SMD and rainfall data	NR, obtained from the Met Office MORECS model	From 06/01/09 to 07/08/12, by week on Tuesdays	For the 190 40km grid squares covering GB
SMD, rainfall data and failure data	NR, obtained from the Met Office MORECS model	From January 2000 to March 2012, monthly	Anglia, Kent, Sussex, Wessex and KSW (Kent, Sussex and Wessex combined)
Future climate projections	UKCP09 User Interface and WG (accessed by TRL online)	For the baseline climate (1961–1990), the 2020s and 2050s	For the 25km (UI) and 5km (WG) grid squares covering the study sites
Digital Geological Map of Great Britain	BGS website (downloaded by TRL)	Current	GB, 1:625 000
Bedrock geology and superficial deposits overlaid with the Anglia Route	NR, geological information originally from BGS	Current	Anglia Route
Earthwork examination records	NR, obtained from sub-contractors who carry out the examinations	Last examination records, date varies from 2008 to 2012.	For Site B and C, up and down lines. (Site A is at grade, so not inspected)
Incidents which caused delays, can filter for those assigned to code 105IV	NR, TRUST ³ database	From April 2010 to May 2012	Anglia Route, possible to filter by ELR ¹ and maintenance area.
Online Track Maintenance (OTM)	NR, OTM Plan	From April 2010 to	Anglia Route, possible to filter by

³ Train Running Systems TOPS – Record of delays, the codes they are attributed to and the costs to NR.

records		January 2013	ELR and maintenance area.
Delay and delay cost per incident	NR, TRUST database	From April 2010 to May 2012	Anglia Route, possible to filter by ELR and maintenance area.
Cost of tamping per shift	Estimate from NR contacts.	Current costs (November 2012)	Anglia Route
Rate of tamping per hour	Estimate from NR contacts.	Current (November 2012)	Anglia Route
Site access details	NR, Standard Possession Opportunities	Current (November 2012)	For the three study sites.
Cost of adaptation solutions	Estimate from NR contacts.	Current (November 2012)	For the three study sites.
Discount rate for WLC	The Treasury's Green Book (HM Treasury, 2003)	Used rate relevant for study period.	All public sector.

The following sections describe how the data was used to produce the model links identified in Section 3.1.

4 Link A: Climate and SMD

The first link required for the model is between climate variables such as temperature and precipitation, and soil moisture deficit. To do this it was necessary to look at the relationship between current climate and SMD in East Anglia, and identify a method of obtaining future SMD.

4.1 Current climate for the study sites

The most important climate variable to determine the risk of desiccation is summer rainfall. Summer temperature is also relevant as it affects evapotranspiration.

4.1.1 Summer precipitation and temperature

The Anglia Route is in the driest part of the UK (Figure 7), with an average summer precipitation of between 100mm and 180mm depending on local topography.

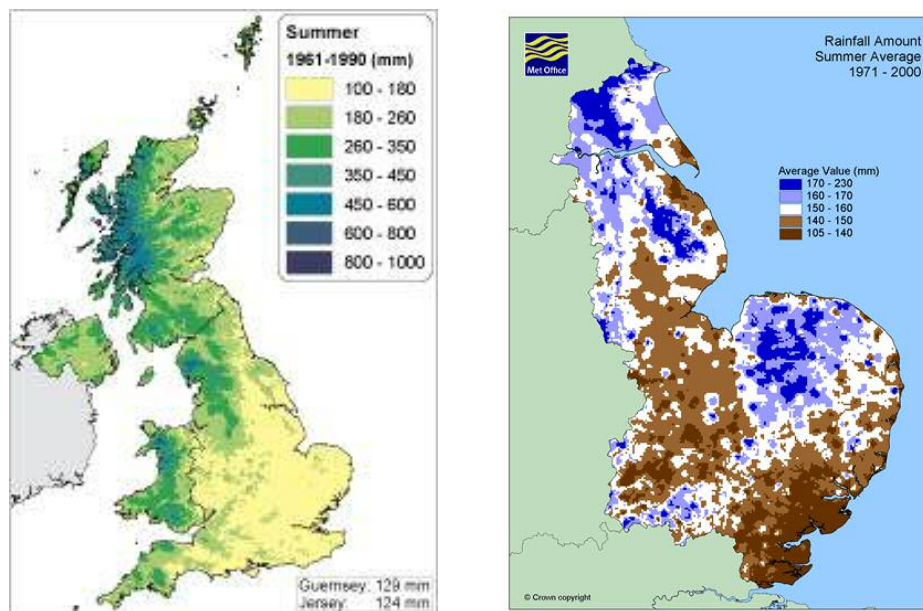


Figure 7. (a) UK summer precipitation (UKCP09 observed trends report (Jenkins et al, 2008) and (b) Average summer rainfall in east England (Met Office, 2012)

With an average summer temperature of 13°C to 18°C it is also one of the warmest regions of the UK (Figure 8).

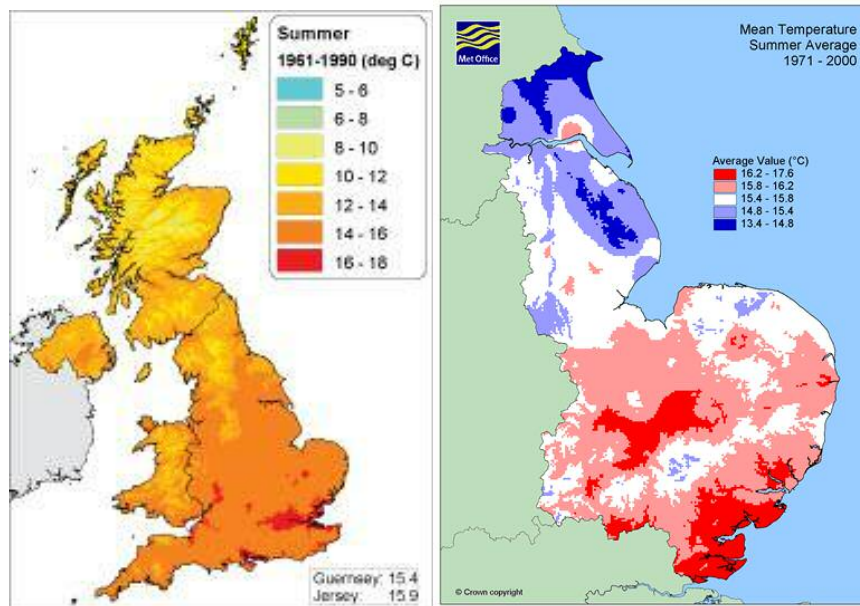


Figure 8. (a) UK summer temperature (UKCP09 observed trends report, (Jenkins et al, 2008) and (b) summer temperature in east England (Met Office, 2012)

4.1.2 Incidents of drought

The combination of low summer rainfall and warm temperatures, mean south east England is the region of the UK most prone to drought. There are a number of types of drought indexes to identify the occurrence of drought. One of the most commonly used is Palmer Drought Severity Index (PDSI), which indicates the soil moisture conditions (-10 (dry) to +10 (wet)). A map of Europe showing the number of exceedences of a PSDI less than or equal to -4.0 from 1901 to 1999 (Figure 9) indicates the regions of the UK where the most incidents of drought are experienced.

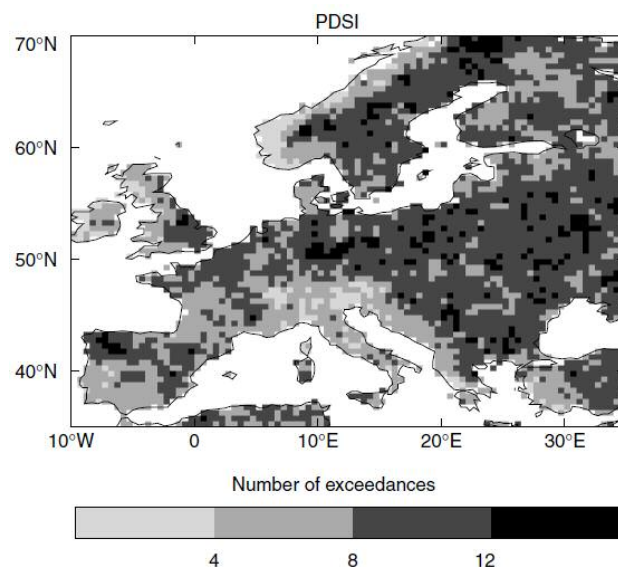


Figure 9. Incidents of drought events in Europe (Lloyd-Hughes and Saunders, 2002)

4.1.3 Soil moisture deficit

As discussed in Section 2.1.1, soil moisture deficit (SMD) depends on a number of factors including precipitation and temperature. As the south east is drier and warmer than other regions, it also tends to have a higher SMD in summer. Figure 10 shows the average seasonal trend for the Anglian region, indicating the historic probability of obtaining different values of SMD. Figure 10 was taken from the Environment Agency's monthly reports on SMD (Environment Agency, 2012), and shows the SMD for real land use rather than the deciduous tree SMD used by NR. The real land-use SMD is less than deciduous tree SMD, but shows a similar trend. Also plotted is the SMD in 2010-11 and 2011-12, showing the impact on SMD of the drought in 2010/11 and early 2012 and then the rapid change due to large amounts of rainfall from April 2012. SMD ranges from exceptionally high compared to the historic average, to exceptionally low.

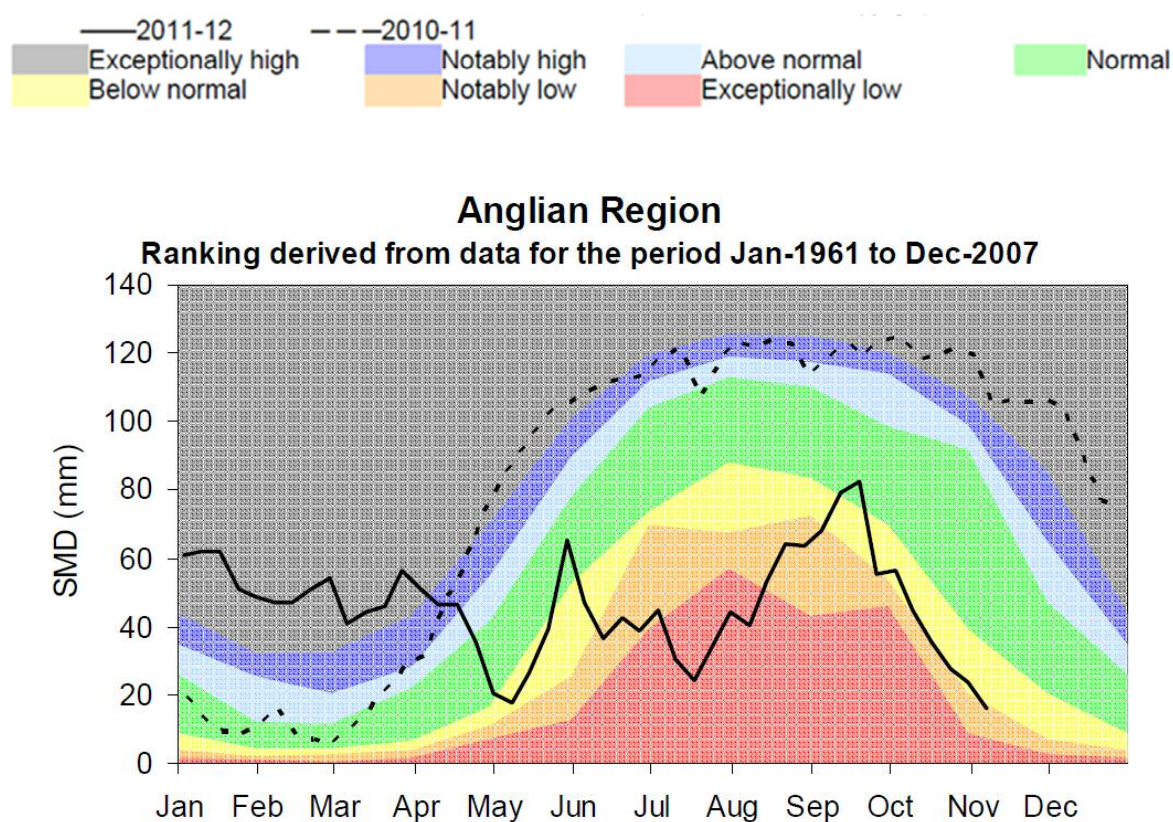


Figure 10. SMD in the Anglia Region (Environment Agency, 2012)

Category	Definition
Exceptionally high	Value likely to fall within this band 5% of the time
Notably high	Value likely to fall within this band 8% of the time
Above normal	Value likely to fall within this band 15% of the time
Normal	Value likely to fall within this band 44% of the time
Below normal	Value likely to fall within this band 15% of the time

Notably low	Value likely to fall within this band 8% of the time
Exceptionally low	Value likely to fall within this band 5% of the time

The SMD data provided by NR for the study sites is given in Figure 11 and Figure 12. The trend of the 2010/11 and 2011/12 information is similar to that given in Figure 10 for the Anglian Region, but the values for deciduous tree SMD is higher than real-use SMD. Site A is located in square 129 and sites B and C in square 161. Square 129 tends to have a higher SMD than 161.

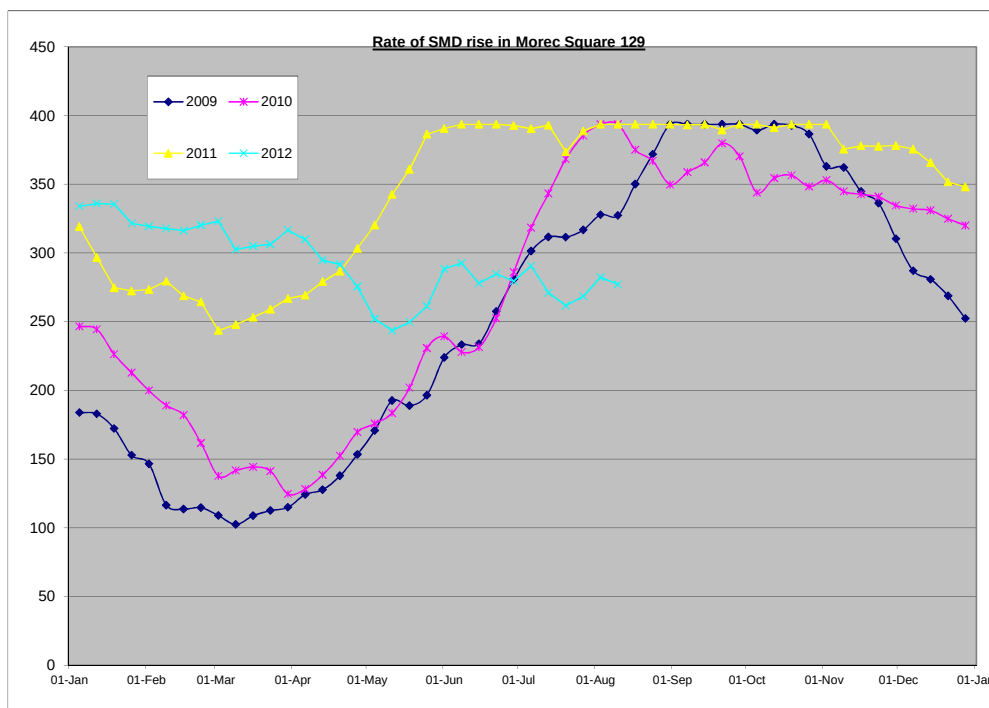


Figure 11. SMD for Study Site A (produced by the Met Office and provided by Network Rail)

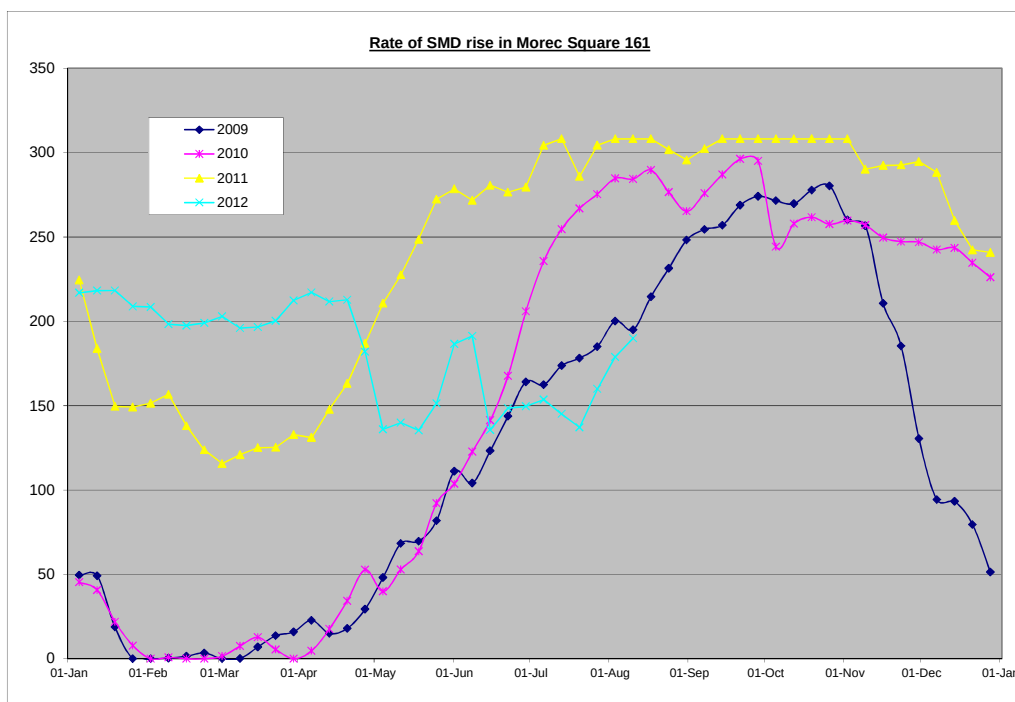
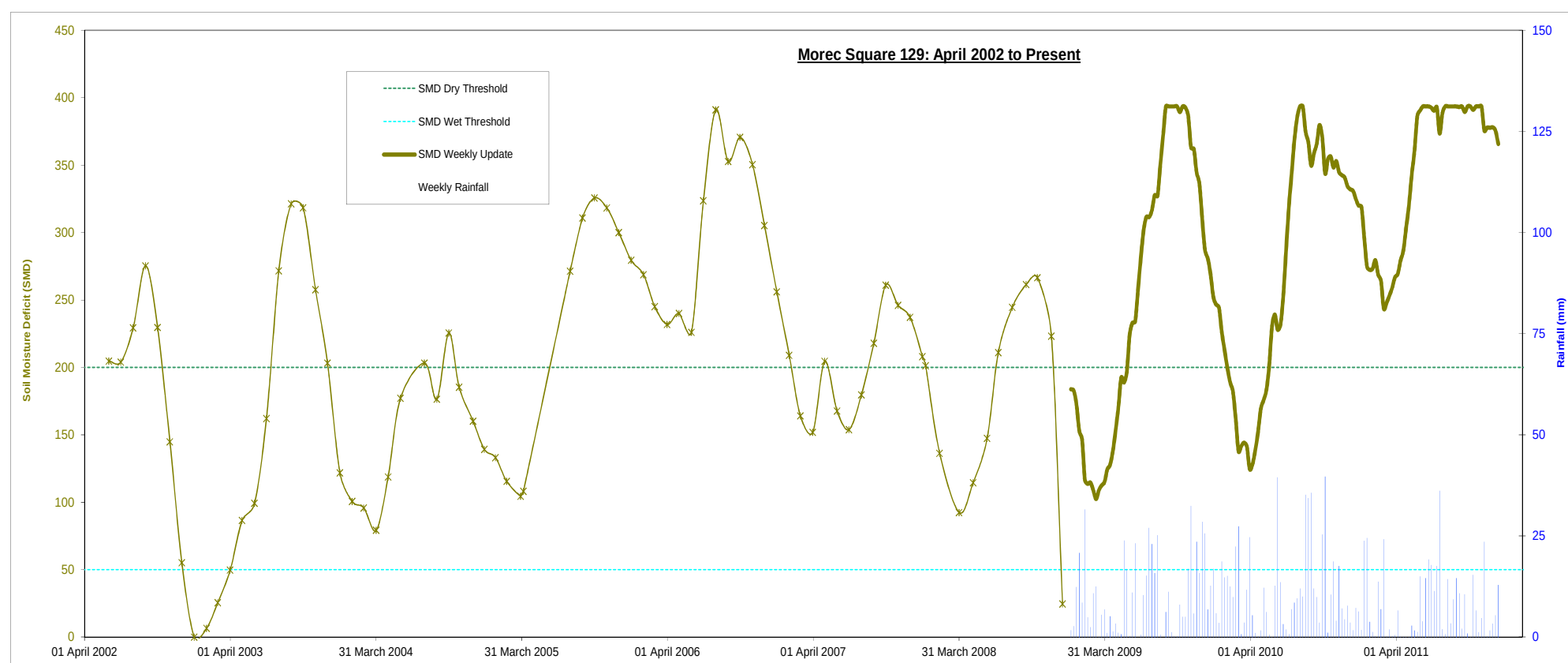


Figure 12. Past SMD for study sites B and C (produced by the Met Office and provided by Network Rail)

Data tracking SMD and rainfall in relation to the NR thresholds (200mm – dry and 50mm – wet) is shown in Figure 13 for the two squares. For both squares the SMD is over the 200mm threshold for a large proportion of the time since 2003, but the proportion is greater for square 129.

(a)



(b)

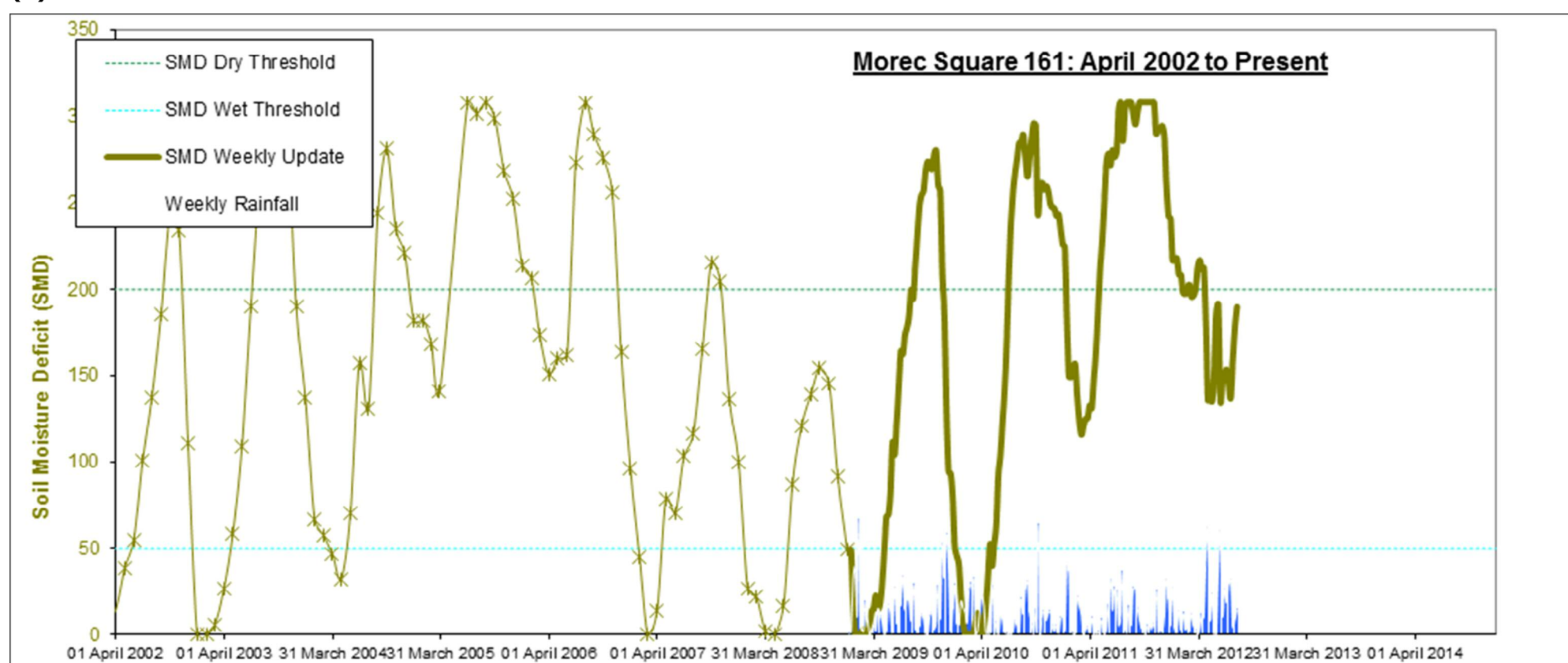


Figure 13. SMD variation over time for (a) study site A and (b) study sites B and C

4.2 Climate changes

The Met Office records (Jenkins et al, 2008) show that the UK's average temperature is increasing, with greater warming in the summer than winter. Annual precipitation trends are less certain, but show a slight increase. The greater changes in precipitation are in the seasonal average and type of rainfall experienced. The summers are becoming drier and the winters wetter, with more rainfall falling as intense rainfall events and more consecutive dry days. Analysis of precipitation patterns from 1961–2000 has shown a 2–4% increase in the frequency of heavy rainfall events, and the proportion of precipitation that falls as intense rainfall events is expected to increase more rapidly than the change in average precipitation (Hulme, 2002). A study by the Met Office found that the number of extreme droughts experienced in the UK is likely to be 10 times as much as the current number by 2100 (Burke et al, 2010). This change in precipitation patterns and temperature is likely to increase the seasonal variation in SMD, and result in more frequent and longer lasting periods of high SMD, with less recovery during winter.

4.2.1 *The future climate for the study sites*

The UK Climate Projections (UKCP09) are the most comprehensive and up-to-date information available on the UK's future climate (Murphy et al., 2009). UKCP09 provides probabilistic projections of different climate variables, for different time frames and emission scenarios. The projections are provided for 25 km grid squares across the UK and include information on the percentage change in average precipitation and the change in mean temperature in °C (annual, seasonal or monthly). Information on the 25km grid squares for the study sites was retrieved and is shown in Figure 14, Figure 15 Figure 16 and Figure 17. It suggests that by the 2050s the study sites will experience around a 20% decrease in summer rainfall compared to the historic average and an increase in summer mean temperature of around 2.5°C. There is a slightly larger decrease in precipitation and rise in temperature in the grid square for Study Sites B and C compared to Study Site A.

**Plot Details:**

Data Source: Probabilistic Land
 Future Climate Change: True
 Variables: precip_dmean_tmean_perc
 Emissions Scenario: Low, Medium, High
 Time Period: 2040-2069

Temporal Average: JJA
 Spatial Average: Grid Box 25Km
 Location: Grid Box No. 1513
 Probability Data Type: pdf

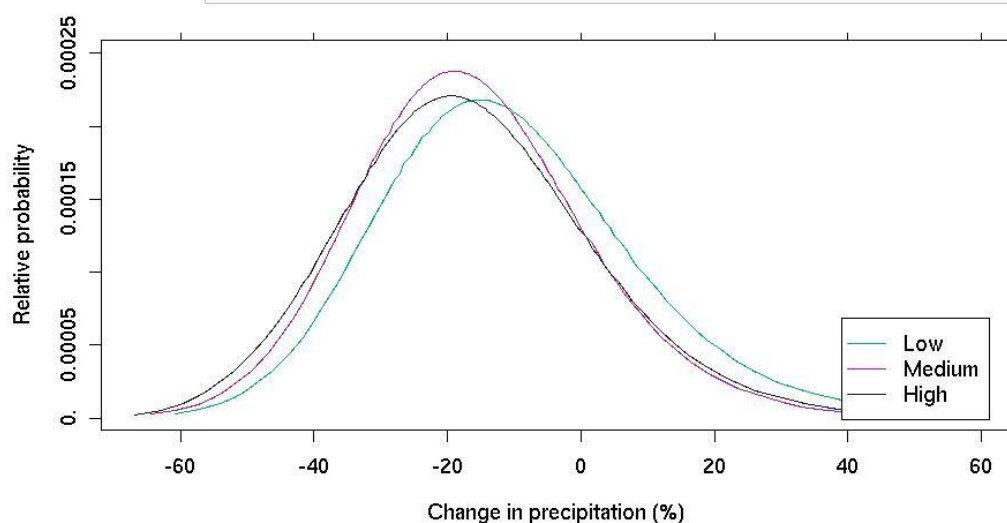


Figure 14. Change in summer precipitation in the 2050s for Study Site A
 (© UK Climate Projections, 2009)

**Plot Details:**

Data Source: Probabilistic Land
 Future Climate Change: True
 Variables: precip_dmean_tmean_perc
 Emissions Scenario: Low, Medium, High
 Time Period: 2040-2069

Temporal Average: JJA
 Spatial Average: Grid Box 25Km
 Location: Grid Box No. 1629
 Probability Data Type: pdf

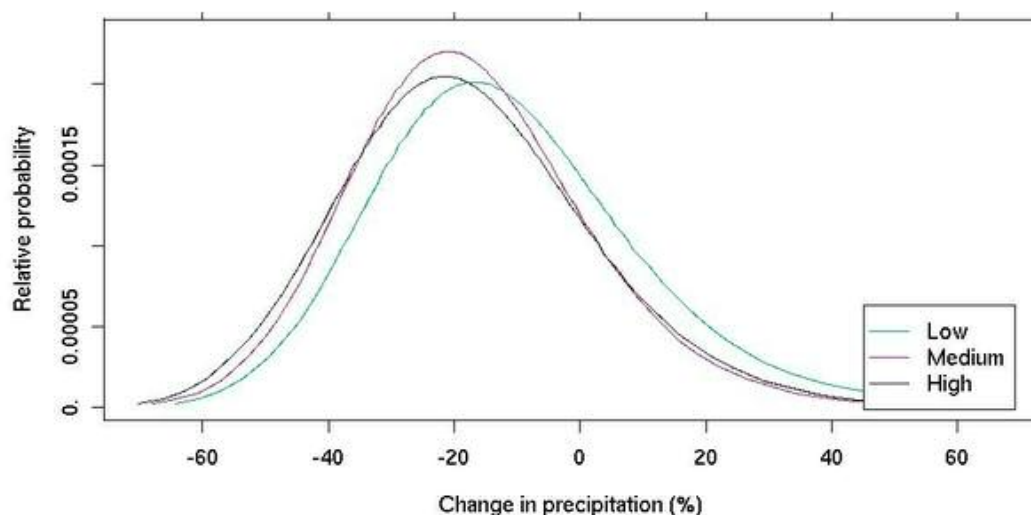
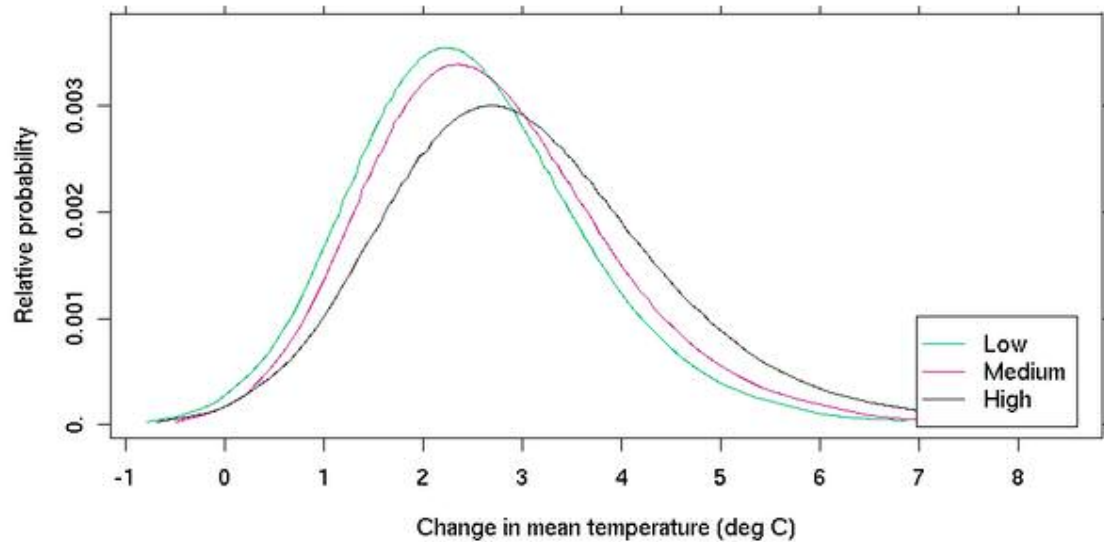


Figure 15. Change in summer precipitation in the 2050s for Study Sites B and C,
 (© UK Climate Projections, 2009)

**Plot Details:**

Data Source: Probabilistic Land
 Future Climate Change: True
 Variables: temp_dmean_tmean_abs
 Emissions Scenario: Low, Medium, High
 Time Period: 2040-2069

Temporal Average: JJA
 Spatial Average: Grid Box 25Km
 Location: Grid Box No. 1513
 Probability Data Type: pdf

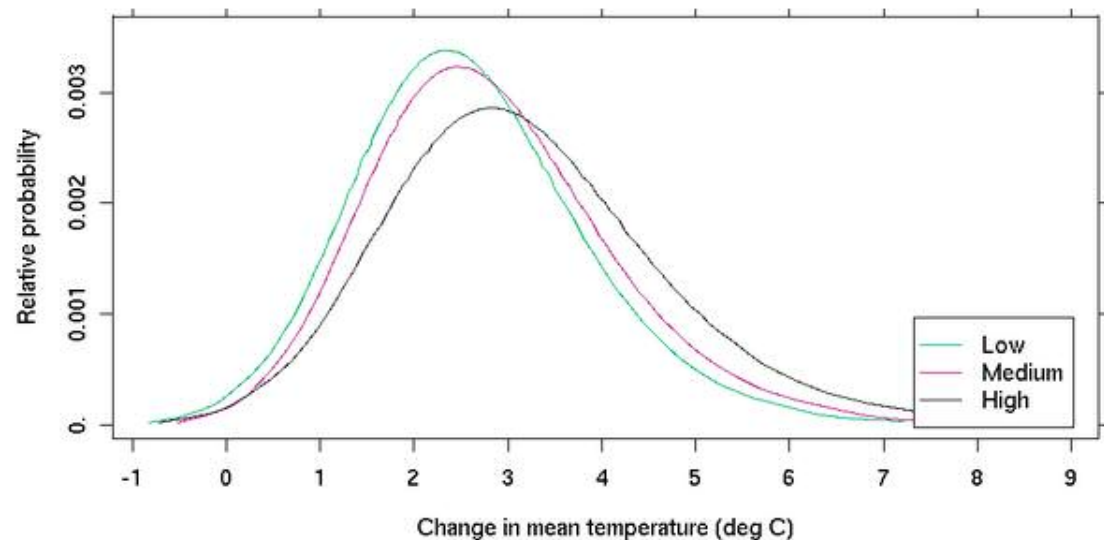


**Figure 16. Change in mean summer temperature in 2050s for Site A,
 (© UK Climate Projections, 2009)**

**Plot Details:**

Data Source: Probabilistic Land
 Future Climate Change: True
 Variables: temp_dmean_tmean_abs
 Emissions Scenario: Low, Medium, High
 Time Period: 2040-2069

Temporal Average: JJA
 Spatial Average: Grid Box 25Km
 Location: Grid Box No. 1629
 Probability Data Type: pdf



**Figure 17. Change in mean summer temperature in 2050s for Sites B and C,
 (© UK Climate Projections, 2009)**

The UKCP09 Weather Generator is a downscaling tool that allows the future weather patterns to be studied in more detail at a local level. The future climate projections are overlaid over the typical weather conditions currently experienced, as recorded by local

weather stations from 1961 to 1990. This allows local topographic effects to be taken into account to better understand climate changes at a local level. Data is produced for typical values of weather variables such as temperature, precipitation etc. for 5 km grid squares at an hourly or daily scale. Daily data from the Weather Generator was obtained for the relevant 5km grids for the study sites and used to produce SMD values for the 2020s and 2050s.

Current global emissions are closest to following the high emissions pathway (IPCC SRES scenario A1F1) (Raupach et al, 2007), so this is the emissions scenario used for this study.

4.2.2 Future soil moisture deficit

Estimates of typical future soil moisture deficit patterns can be generated using the outputs of the Weather Generator. For this analysis the methodology HR Wallingford developed for the EPSRC funded project FUTURENET (www.arcc-futurenet.org), in which TRL is a partner was used (HW Wallingford, 2013). SMD is calculated as a daily time-step using a simple approach, where the values for daily precipitation (P) and evapotranspiration (EP) produced by the WG are used in the equations based on Thornthwaite-Mather (1957) as described in Mansell (2003):

$$\text{SMD} = \text{SiMax} - \text{Si} \quad \text{Equation 2}$$

Where, SiMax is the maximum water holding capacity of the soil (a user defined value) and Si is the amount of water held in the soil, which is calculated from:

When $P > ET$

$$\text{Si} = \text{Min} (P - ET + \text{Si}_{i-1}, \text{SiMax}) \quad \text{Equation 3}$$

When $P < ET$

$$\text{Si} = \text{Si}_{i-1} \times \text{Exp} (-1 \times (ET - P) / \text{SiMax}) \quad \text{Equation 4}$$

When $i = 1$

$$\text{Si}_{i-1} = \text{SiMax} \quad \text{Equation 5}$$

Where P is the rainfall in mm and ET the evapotranspiration in mm.

For the peat site, SiMax was set as 393.6 mm and for the clay sites as 312.8 mm as these were the values used in MORECS for these soil types.

The WG was used to produce 100 randomly sampled runs of 30 years for the baseline climate (1961–1990), 2020s and 2050s with high emissions for all three sites. The same seed value was used for generating each of the data sets, so that the climates at the

three sites were comparable. A macro was compiled to extract P and ET from the WG datasheets and apply the SMD equations to produce daily SMD for each year and run.

Figure 18 shows a summary of the results obtained for Site A, Figure 19 shows Site B and Figure 20 Site C. The points on the graph are the 50th percentile values and the bars indicate the 10th and 90th percentile, i.e. the range within which it is expected the SMD will fall for the majority of years. It can be seen that the maximum SMD in summer and the duration for which SMD is high (above 200mm) is projected to increase with time. Site A is drier than the other two sites, and likely to continue to be so in the future. The SMD for sites B and C is very similar, although Site C is slightly less dry than Site B. The greatest variation in SMD occurs in the spring and autumn when the SMD is changing rapidly.

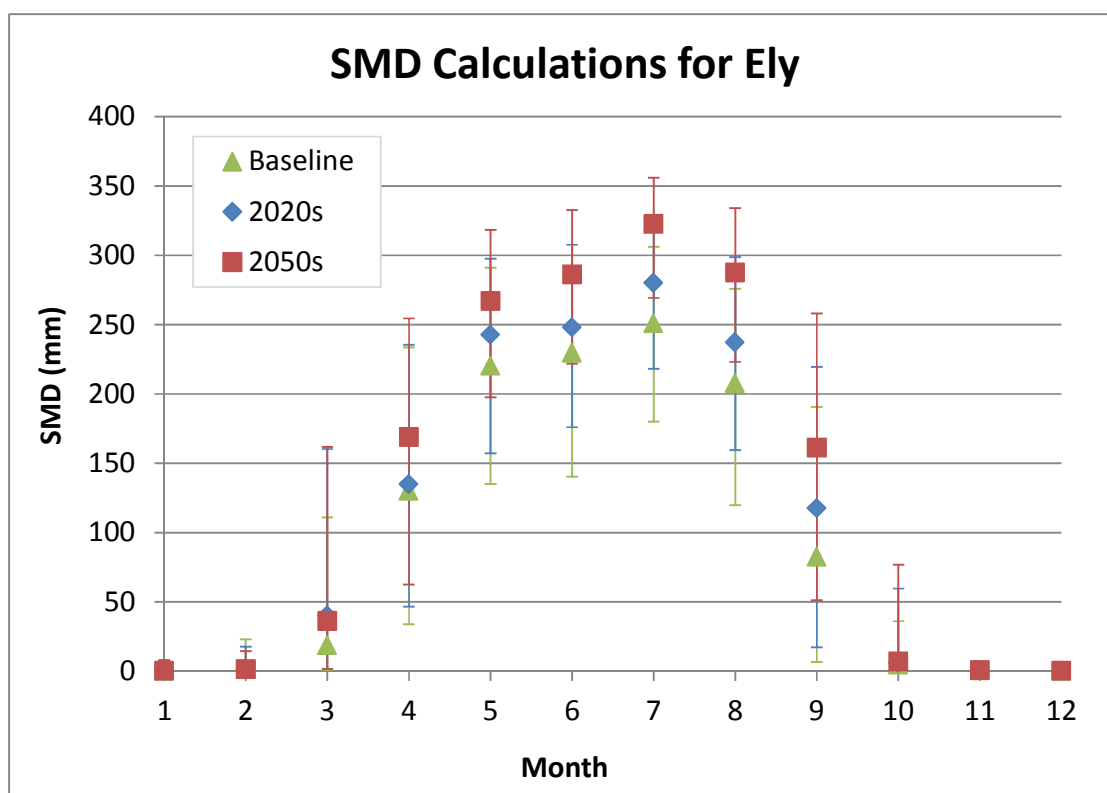


Figure 18. SMD calculations for Ely (Site A)

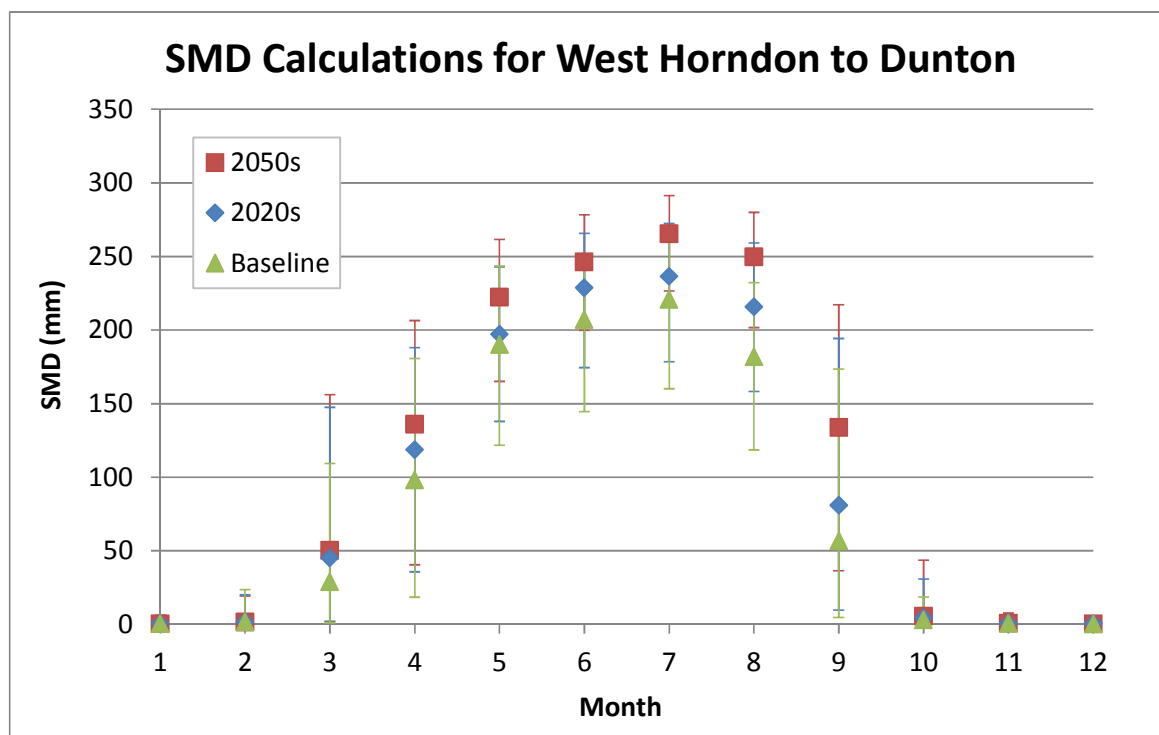


Figure 19. SMD Calculations for West Horndon to Dunton (Site B)

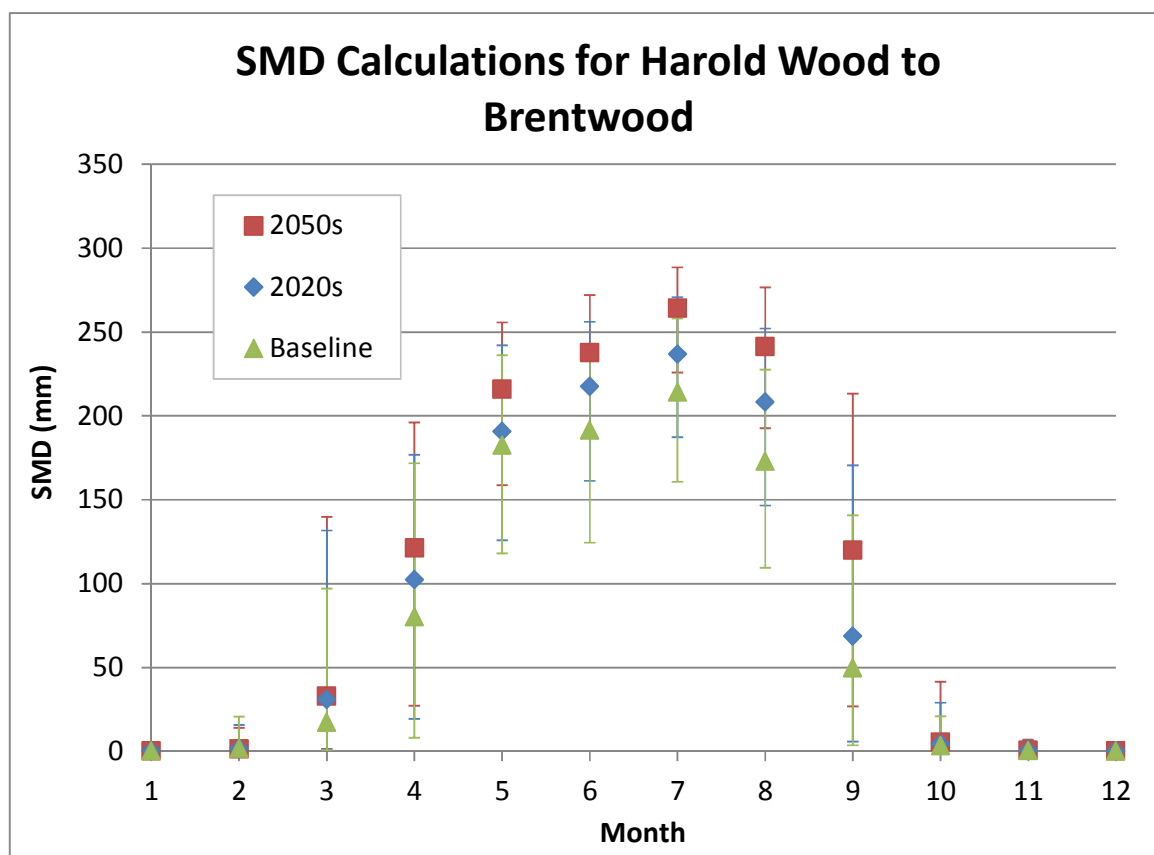


Figure 20. SMD Calculations for Harold Wood to Brentwood (Site C)

Figure 21 shows the percentage change in average monthly SMD (P50) from baseline to 2050s climate for all three sites. It can be seen that the largest changes in SMD are in spring and autumn.

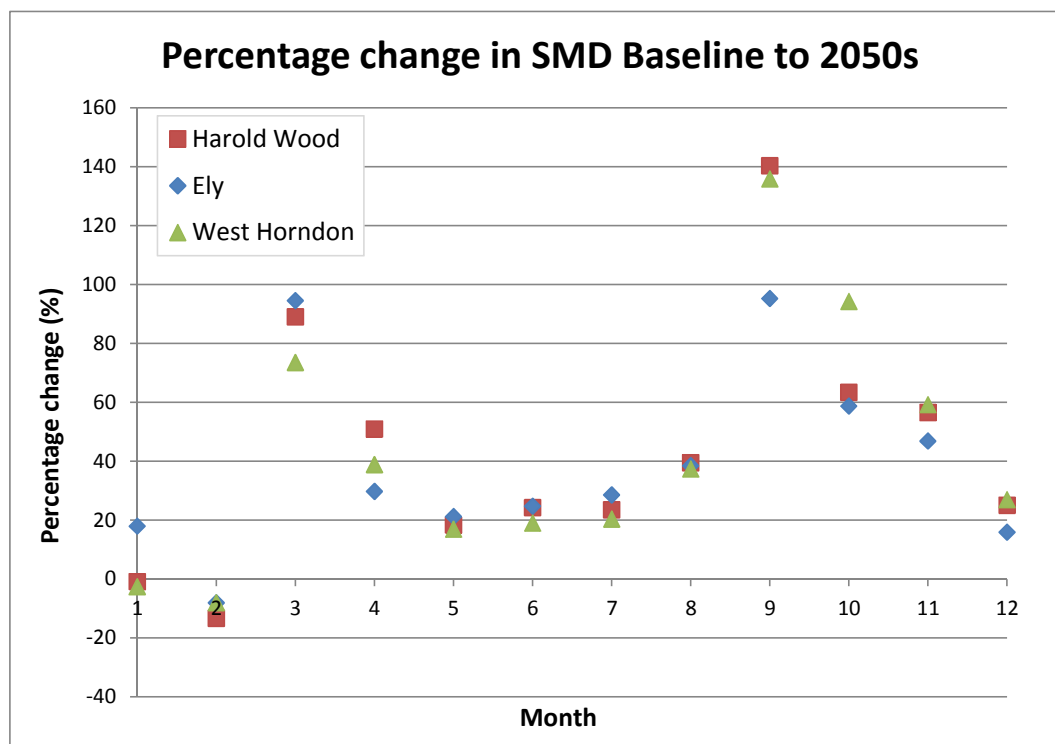


Figure 21. Percentage change in monthly SMD from baseline to 2050s climate

Figure 22 shows the difference in monthly average SMD in mm (P50) for the 2050s and 2020s compared to the baseline climate. Over time SMD becomes increasingly higher in spring and this change occurs earlier in the year. In the autumn SMD recovers, but slightly later in the year.

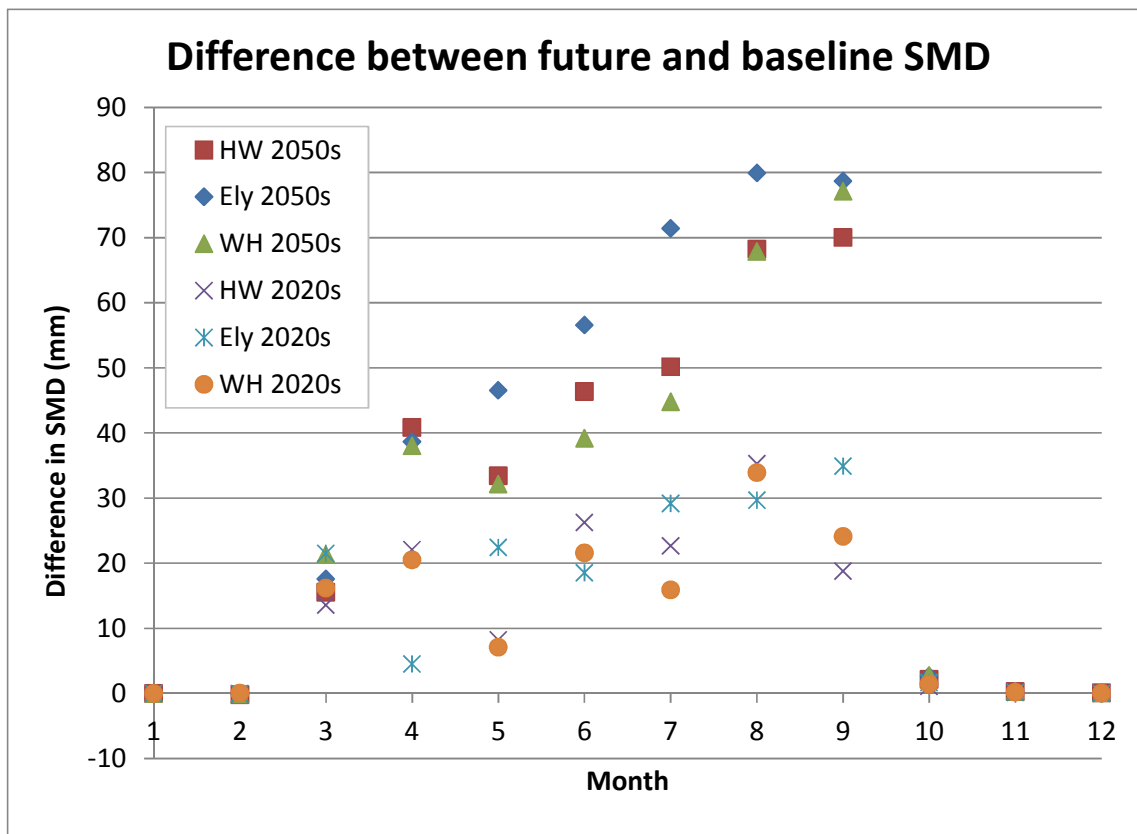


Figure 22. Change in monthly SMD

5 Links B and C: Earthwork failure, SMD and site characteristics

In order to estimate the potential future change in failure rate as a result of changes in SMD, an understanding of the correlation between SMD and earthwork failure and other influencing factors is required. Therefore analysis was carried out on past SMD and failure data in order to identify a relationship which could be incorporated into the cost model.

5.1 Earthwork failure data

All delays which can be attributed to infrastructure failure are recorded in NR's TRUST database, so that compensation can be paid to the Train Operating Companies (TOCs) and Freight Operating Companies (FOCs). Each delay is assigned a code to categorise the reason behind the delay. Rock falls, soil slips, slides or flows in a cutting, natural slope, or embankment on running lines, are given the cost code 105IV. Failures causing a passenger or freight train derailment are recorded separately and were not included in the analysis.

5.1.1 Analysis of failure and SMD on the Anglia Route

Analysis of the recorded earthwork incidents on the Anglia Route and the SMD at the incident location was carried out to identify any correlation. Earthwork failure for the purposes of this analysis is defined as an incident causing greater than three minutes delay which is assigned as the 105IV cost code. The failure data was for the Anglia Route from April 2010 to May 2012.

An initial review of the data found that there were no recorded incidents within the three case study sections, in fact there were only 23 incidents assigned to the 105IV cost code on the Anglia Route during this time period. In order to have sufficient data to identify any correlation, it was decided to use the data for the whole Anglia Route for the analysis. Failure data from a previous comparison of monthly SMD and failure for the Anglia Route supplied by NR was combined with the more recent data to extend the analysis period from January 2000 to May 2012. The geology relating to the location of the incidents was identified from a geological map with the Anglia Route overlaid.

Analysis was carried out looking at the timing of failure and high SMD events (defined as above NR's 200mm threshold), the length of high SMD events and the correlation between SMD and failure. The results were:

- Most landslide incidents occurred on a form of geology that included clay, 3 were on peat and 1 on diamicton (glacial till, probably derived from then underlying clay).
- Most landslide incidents occurred in spring as SMD started to rise. Failures associated with low SMD (< 50mm) were less common. The three failures on peat soil were in autumn, the majority of the others (80%) were in spring.
- If the SMD is above 200mm, there is a 49% probability of failure compared to 32% if it is between 50 and 200mm or 18% if less than 50mm.
- The frequency of failure by SMD band (100 to 150mm etc.) was calculated, and these figures normalised by dividing by the number of months with SMD in this band and the route length in the Anglia Region (795 route miles (Wilson, 2013))

to obtain failure by month per route km. A plot (Figure 23) of the normalised failure frequency against SMD band shows that the likelihood of failure increases with SMD. A polynomial fit of this plot has a R^2 of 0.72. This plot also supports NR's 200mm threshold, as around this value the probability of failure increases substantially.

- Based on the last 12 years, periods where the SMD is less than 50mm occur for an average of 1.8 months per year, whereas there is an average of 3.75 months per year where SMD is greater than 200mm. The average SMD for the whole period is 150mm. Both 2006 and 2011 had an average SMD above 200mm. There is an overall trend of increasing SMD, although it is very variable and the limited data is not sufficient to determine if this is a long term trend.
- Over the past 12 years, there were 10 high SMD events where the SMD went above 200mm; on average these events lasted 4.7 months, but the most prolonged event in 2011 lasted for 12 months. During the events there was an average of 2.4 incidents, with the likelihood of an incident occurring increasing with the maximum SMD reached, duration that SMD is above 200mm, and the average SMD of the incident. There were 7 low SMD events where SMD went below 50mm; only during one of these did any incidents occur.

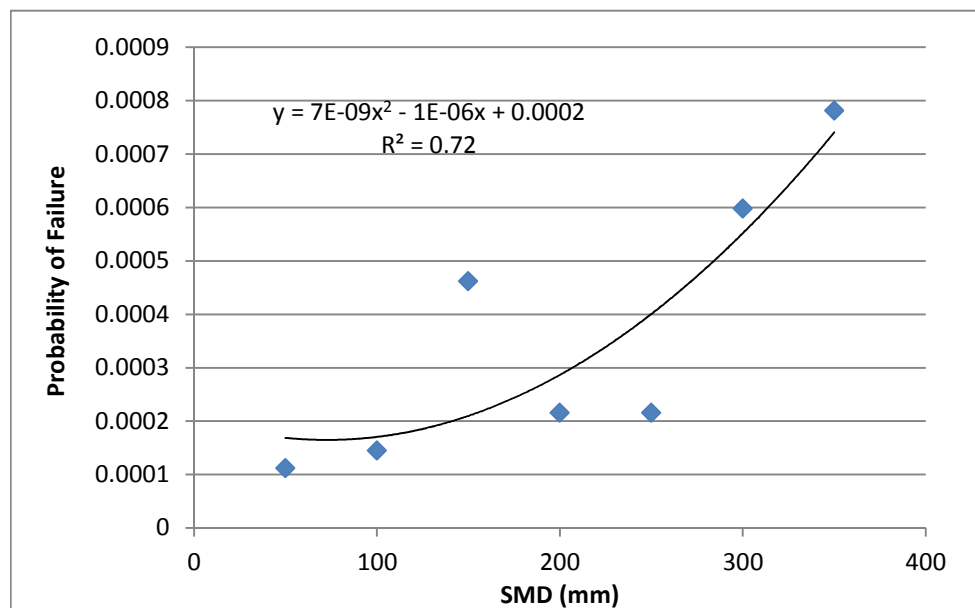


Figure 23. Correlation between SMD and probability of failure

The polynomial correlation found between SMD and probability of failure (multiplied by the length of site) will be used in the cost model to estimate future failure for all three sites.

5.2 Link between maintenance and SMD

In addition to failure, the relationship between the amount of track maintenance carried out and SMD was investigated. Tamping and ballast renewal is the most common method of rectifying the impact of high SMD on the track. The maintenance carried out is logged, with the location, date, plant used etc. in the on-track maintenance (OTM) plan. The OTM data for the Anglia Route from April 2010 to April 2012 was used to investigate

any correlation between SMD and frequency of maintenance. Other maintenance activities taken in response to earthwork failure such as installing a retaining wall are not recorded in this plan and were not included.

There was a greater amount of data available for this analysis, so the maintenance relationships were analysed by study site as far as possible.

5.2.1 Study Site A – Ely Station

There was insufficient maintenance carried out on the actual study site, so this was widened to include all the BGK line in the Ely TME (Track Maintenance Engineer) area. Most of this line is on peat soil.

As shown in Figure 24, the greatest amount of track maintenance was carried out in the autumn for both 2010/11 and 2011/12, and more maintenance was carried out in 2011/12 which had a higher average SMD than 2010/11. Autumn was also when the incidents relating to peat soil occurred, which appears to corroborate that the largest impact of high SMD on peat sites is observed in autumn. This probably reflects that the water table is at its lowest at the time of maximum SMD, and this is when most shrinkage of the peat above the water table takes place. However, significant amounts of maintenance were undertaken in spring in both years, and in summer and winter in 2011/12. There was much less variation between seasons in 2011/12 than 2010/11.

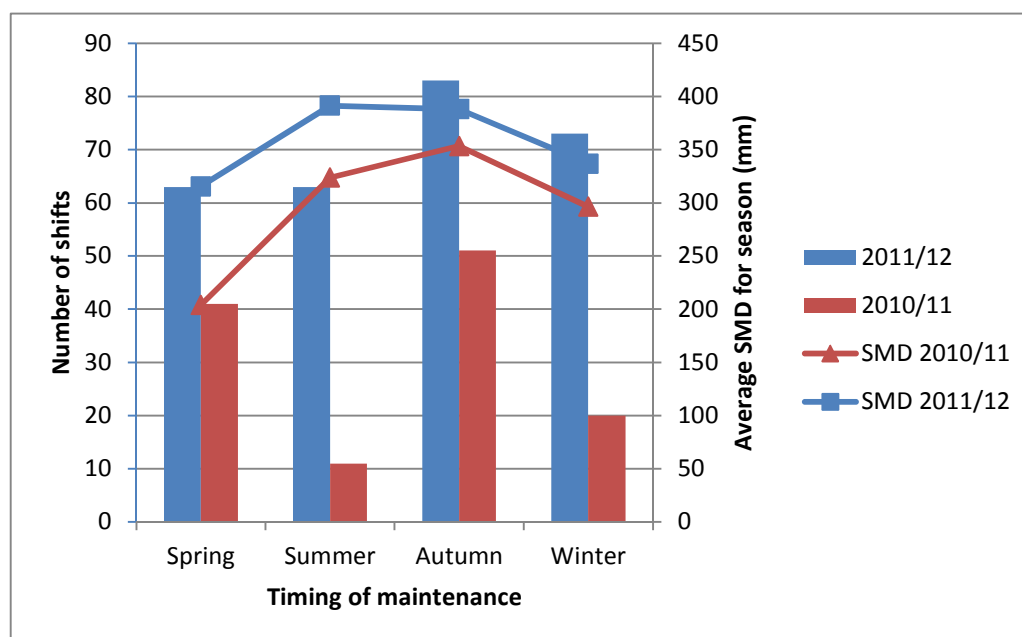


Figure 24. Maintenance timing, BGK Ely TME area

A plot of maintenance against SMD for the combined two years of data (divided by the length of BGK line in the ELY TME and multiplied by the length of the study area) shows a high degree of correlation between the amount of maintenance and SMD (Figure 25).

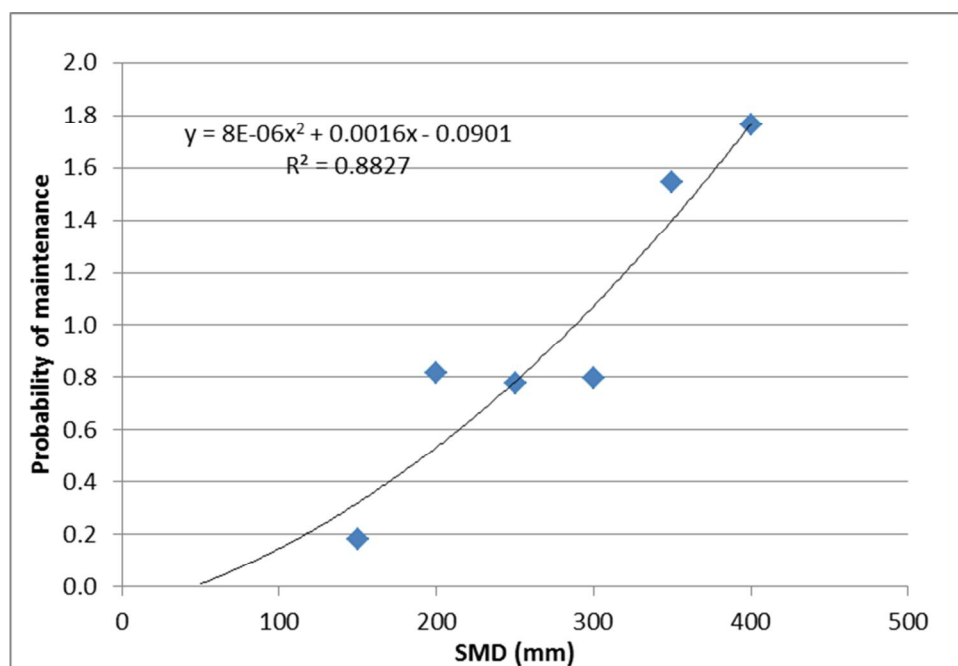


Figure 25. Maintenance in the Ely area

This relationship was used in the model to calculate the amount of maintenance likely to be carried out in the future at the Ely site, based on the future SMD values produced as described in Section 4.2.2. The fit shows a negative probability of maintenance at low SMD, which is not possible. It is more likely that the trend flattens out at a low positive value.

5.2.2 Study Site B - West Horndon to Dunton

More maintenance was carried out on this study site, so it was possible to focus solely on data relating to the study site. From Figure 26 it can be seen that the timing of the maintenance is different from Site A. Here most of the maintenance is carried out in the spring as SMD starts to rise, rather than the autumn. This corresponds with the incident reports, which also suggest that track on clay soil is most affected by drought in the spring.

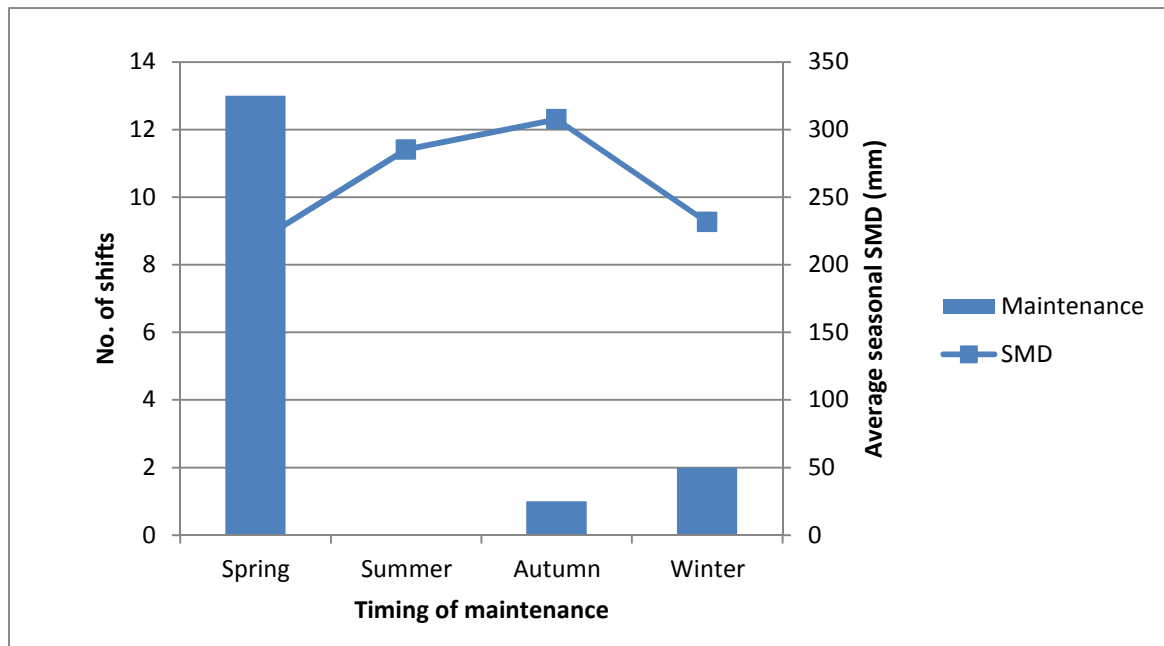


Figure 26. Maintenance timing, West Horndon to Dunton

There is no correspondence between SMD and the amount of maintenance carried out for site B. However, there is a small correlation with the rate of change in SMD as shown in Figure 27. The number of failures corresponding to bands of the difference between the SMD value and previous week's SMD value was calculated. This was normalised by dividing the values by the number of values in each band. It can be seen that a large positive difference (i.e. a large rapid rise in SMD) is more likely to correlate with greater number of failures, although the correlation is very poor ($R^2 = 0.164$).

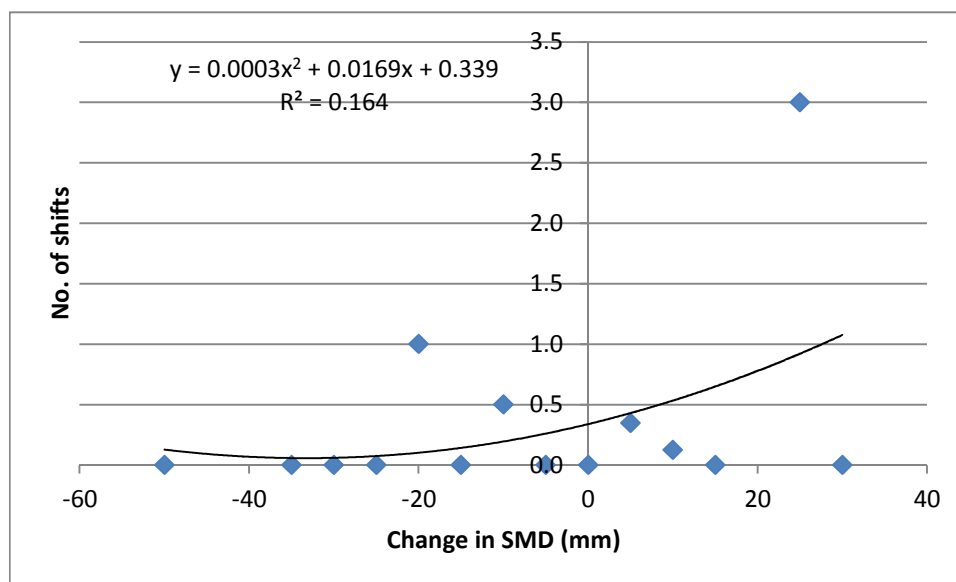


Figure 27. Maintenance and SMD, Site B (West Horndon to Dunton)

5.2.3 Study Site C - Harold Wood to Brentwood

Site C, the second clay site shows a similar trend to site B, with the most maintenance being carried out in spring (Figure 28).

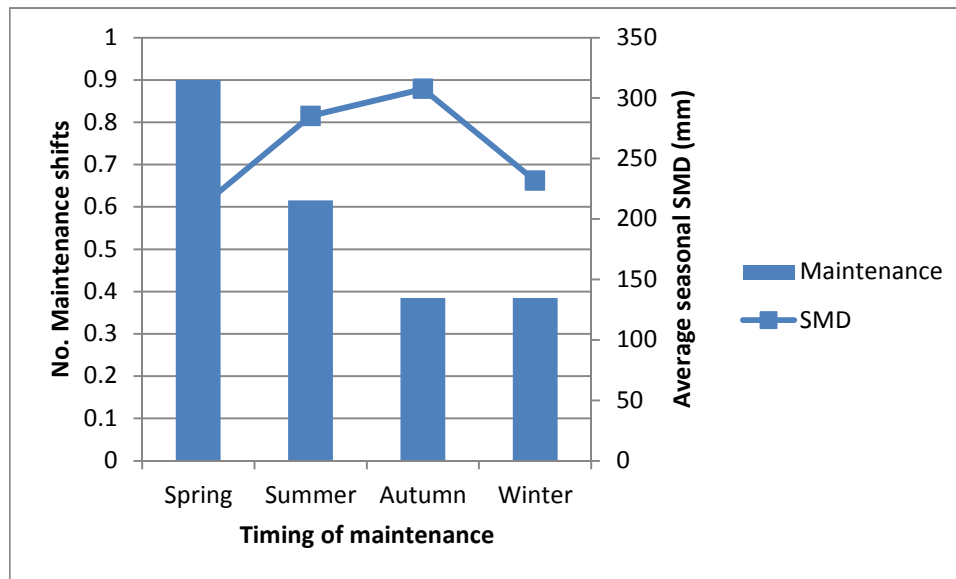


Figure 28. Maintenance timing, Harold Wood to Brentwood

Figure 29 shows a better correlation with change in SMD than site B, with a R^2 value of 0.5599 with a polynomial fit.

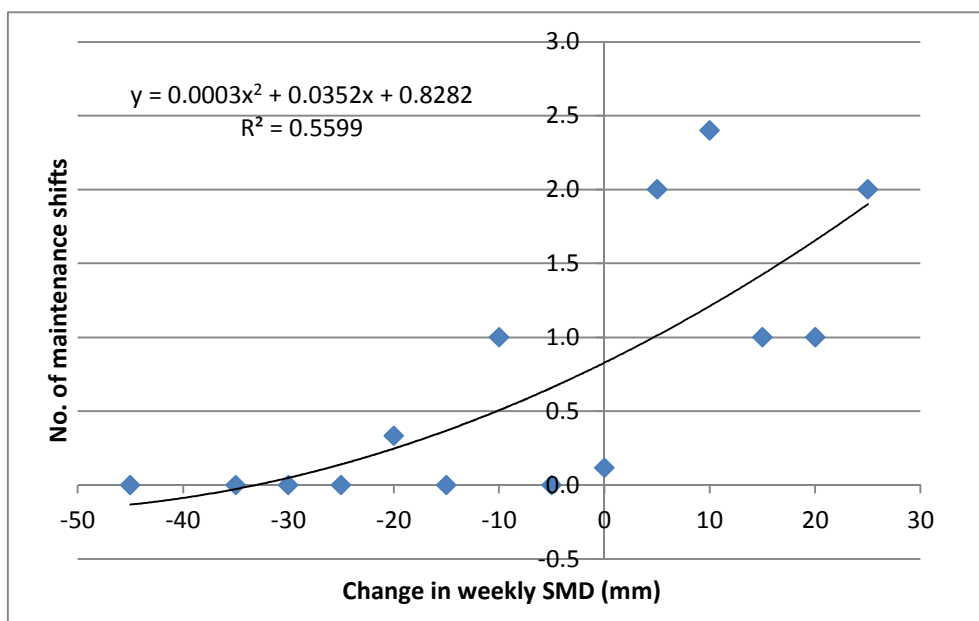


Figure 29. Maintenance and SMD, Harold Wood to Brentwood

This suggests that Site C is more affected by high SMD than site B, despite having similar geology. The reasons for the difference are unclear, but it appears characteristics other than geology type may be influencing the site's vulnerability to changing soil moisture. It could be that south-facing earthworks mean that the SMD is higher than the average for the grid square, or it could be that the track orientation relative to the geological structure or greater slope height and angle make it more vulnerable.

These relationships were used to obtain the level of future maintenance for the different sites, based on future SMD values. The fit shows a negative value of maintenance shifts at high negative changes in SMD, this is not physically possible and it is more likely that the trend plateaus at a small positive value.

6 Links D and E: Consequences of earthwork failures

Links D and E relate to the consequences of earthwork failures, Link D being the relationship between a failure and the amount of delay and maintenance required and Link E the average cost for delay and maintenance.

6.1 Delay due to earthwork failure

If an unplanned speed restriction is put in place due to safety concerns over misaligned track, the delay costs are assigned to Network Rail. Analysis of the delay data for the landslip incidents (Code 105IV) in Anglia, gives an average amount of delay per incident of 315 minutes with an average cost of £9,433 (£29.97 per minute). This value varies enormously, from the minimum amount of time recorded (3 minutes), up to 1,674 minutes and the cost of time varies from £8.35 to £76.84 per minute. It was noted that some entries seem to be for the same incident or same site with repeated problems over several months, which maintenance did not always seem to rectify.

No delay cost is associated with the work carried out as it assumed that this is planned maintenance rather than unplanned emergency work.

This average delay cost of £9,433 per incident (£786 per event per tph) was used for all three sites in the cost model. However, it should be noted that the level and type of rolling stock using each line in the future will affect this value.

6.2 Maintenance to rectify poor track geometry

If subsidence causes track misalignment, realignment is normally achieved by tamping and ballast renewal. Tamping costs around £9000 a shift, which includes plant hire, crew and ballast renewal every third time of tamping. Approximately 100 metres of track can be tamped in an hour, but the length of track that can be maintained in a shift depends on the access restrictions of the particular site. A cost of £9000 a shift was used in the model.

7 Link F and G: Adaptation options and cost

Link F is the identification of appropriate adaptation options for each site and Link G is the costing of these. The options and costs were obtained from experts within Network Rail, based on their experience and past similar work.

7.1 Actions for Study Site A – Ely station

Ely station is located on peat. The typical maintenance work carried out to stabilise peat is piling.

7.2 Actions for study Site B – West Horndon to Dunton

Site B is on London Clay. A potential solution to stabilise track at this location, is:

- Remove the vegetation on the top two thirds of the embankment, with crest anchored soldier pile wall;
- Install drainage gripes to drain sub-ballast trough; and
- Construct anchored sheet pile wall from 21.0400 to 21.1050.

Soil mixing with lime cannot be used to stabilise the clay fill as this requires total line closure and removal of the track, ballast, power and signalling for a period of weeks or months. The cost of this would be so large that it would always be cheaper to maintain the track by tamping and ballast replacement.

7.3 Study Site C - Harold Wood to Brentwood

Site C is on London Clay. A potential solution to stabilise track at this location is:

- Toe sheet pile wall, with slope re-grade.

7.4 Costing adaptation actions

Based on the past maintenance costs for similar work, the costs of applying these solutions to the three study sites are given in Table 5.

Table 5. Adaptation actions and costs

Site	Adaptation action	Cost
Site A: Ely station (Ely Dock to Ely North)	Piling	£6.5M (£5.5k/m/side) to £17M (£14.2k/m/side)
Site B: West Horndon to Dunton	De-veg top 2/3 of emb, with crest anchored soldier pile wall. Drainage girders to drain sub-ballast trough. Anchored toe sheet pile wall from 21.0400 to 21.1050	£30M (£5-6k/m/side increasing to £10k/m on one side through section with toe sheet pile wall)
Site C: Harold Wood to Brentwood	Toe sheet pile wall, with slope re-grade.	£17.5M (£7k/m)

These costs will be used as inputs into the model.

8 Developing the cost model

A model was developed in Excel to calculate the cost-benefit of adapting geotechnical assets to climate change, based on the various relationships and information described above.

8.1 Economic appraisal methodology

The economic appraisal compares two cases:

1. **Baseline:** no remediation is carried out, maintenance and delay costs will be incurred throughout the analysis period depending on the SMD; and
2. **Remediation:** a remediation activity is carried out in the base year, no delay or other maintenance costs are incurred during the analysis period.

It is assumed that any maintenance that is not due to high SMD will be identical for both cases and can therefore be ignored.

8.1.1 Cost base year

The base year for the analyses, to which all costs are discounted, was 2010.

8.1.2 Analysis period

The economic model uses a fixed analysis period, with one-year time steps. UK government guidelines mandate a 60-year analysis period for transportation infrastructure procurement (DfT, 2006), which was adopted for this model.

Two sets of climate projections were used for each scenario, one covering the 2020s (2010 to 2039) and one covering the 2050s (2040 to 2069); the former was assumed to be representative of the climate from years 0 to 30 of the analysis period, the latter from years 31 to 60 of the analysis period. Additionally, the baseline (1961 to 1990) case was applied to the whole analysis period to provide an indication of how climate change is affecting earthwork desiccation.

8.1.3 Discounting

The economic appraisal methodology adopted for this project uses a declining long-term discount rate. This rate represents the time preference for spending (i.e. expenditure at the start of the analysis period is worth more now than the same expenditure at the end of the analysis period). The annual rates used, set by the UK government (HM Treasury, 2003), are 3.5% up to year 30 and 3% thereafter.

8.1.4 Residual value

The adoption of a fixed analysis period for the analysis can introduce “edge effects” to the calculations; for example, an analysis in which the remedial maintenance has to be replaced or repeated in the last year may give a very different result to an analysis where the replacement comes in the first year outside the analysis period.

To correct for this, a calculation of residual value, effectively crediting asset value back to the analysis based on the remaining life of the asset, is carried out. The residual value appears as a negative cost in the final year of the analysis period, and is discounted accordingly.

The model calculates residual value linearly; the value of the asset declines linearly from installation to the predicted time of replacement, with a fixed amount of value lost in each year.

The predicted life of the asset was assumed to be 60 years (i.e. that its residual value would be zero at the end of the analysis period); this was also varied to 40 and 80 years to test the sensitivity of the analysis results.

8.1.5 Traffic

On the Anglia Route passenger numbers have increased 300 per cent in the past four years and this growth is projected to continue (Network Rail, 2013). Therefore it is likely that there will be increased traffic on the three study sites within the study period. On the assumption that the cost of delay-causing events will increase through the analysis period as railway traffic increases, a simple linear traffic growth model has been incorporated into the model. Based on an initial and final level of traffic, measured in tph (trains per hour), the growth model calculates an integer tph value (in both directions) for each year in the analysis period. Two cases were analysed for the case studies: zero growth; and a 50% increase in traffic.

8.1.6 Implementation

A prototype model was constructed, in an Excel spreadsheet, to carry out the case study analyses. The user input parameters, along with default values where applicable, are summarised in Table 6.

As described in Section 5, two different costs were included: the cost of delays and the cost of maintenance. The probability of a delay causing an earthwork incident was calculated by applying the relationship established in Section 5.1.1 to estimates of future monthly SMD. This was then aggregated over a year to give the annual number of incidents, before taking the 10th, 50th and 90th percentile values for each case study.

Similarly the probability of a maintenance shift being carried out was estimated by applying the relationships established for each site in Section 5.2 and applying this to the future weekly SMD or change in weekly SMD. The 10th, 50th and 90th percentile values for the annual number of maintenance shifts at each case study site were produced.

Table 6. Model configuration parameters

Parameter	Unit	Default value
Analysis period	years	60
Initial traffic	tph	12
Final traffic	tph	12 (0% growth)/18 (50% growth)
Remediation cost	£	See Table 5
Remediation life	years	60
Maintenance shifts	-	According to calculated correlation
Cost of maintenance	£ per shift	9,000
Probability of delays	%	According to calculated correlation
Cost of delays	£ per event per tph	786
Residual value method	-	Linear

The economic analysis model produced the following outputs:

1. **Net Present Value:** (i.e. sum of all discounted costs within the analysis period) for both the baseline and remediation cases;
2. **Cost profiles:** discounted and undiscounted cumulative costs;
3. **Incremental Economic Indicator (IEI):** a measure of the cost-effectiveness of the remediation, calculated as the ratio of whole-life cost savings to increased initial outlay; and
4. **Payback period:** how far through the analysis period the remediation case reaches break-even (if the remediation is not cost-effective within the analysis period, no payback period is calculated).

8.2 Assumptions

Various assumptions were made in the model:

- The model only includes the cost to NR, not TOCs/FOCs or customers, or other social or indirect costs such as damage to NR's reputation, inability to meet ORR targets and financial penalties associated with this etc.
- Planned maintenance (i.e. for carrying out the adaptation actions) has no delay cost associated with it.
- Tamping is carried out during planned maintenance windows, so no delay costs are incurred.
- The infrastructure and rolling stock are the same as today throughout the analysis period, with no modifications or upgrades.
- The case study sites and associated lines have the capacity to cope with a 50% growth in traffic.
- All failures have a delay greater than 3 minutes associated with them and are therefore logged in TRUST.

9 Cost-benefit ratio calculations

The cost model was run based on the parameters given in Table 6 for the following:

- The three study sites
- Baseline (1961 -1990), 2020s and 2050s climate (high emissions)
- Current and 50% growth traffic
- Delay and maintenance costs generated from 10th, 50th and 90th percentile climate variables
- For 40 and 80 year remediation life (50th percentile only)

9.1 Results for the case study areas

The results obtained are given in Table 7, Table 8 and Table 9 for the three sites.

Table 7. Cost-model results for Site A

Scenario	Traffic growth (%)	Maintenance shifts		Probability of delays (%)		NPV (£)		IEI	Payback period (years)
		Years 0-30	Years 31-60	Years 0-30	Years 31-60	Baseline	Remediation		
Baseline	0	12.10	12.10	4.54	4.54	4,000,083	17,000,000	-0.79	NA
Baseline	50	12.10	12.10	4.54	4.54	4,153,493	17,000,000	-0.78	NA
10 th	0	13.28	18.50	5.04	7.02	4,864,779	17,000,000	-0.74	NA
10 th	50	13.28	18.50	5.04	7.02	5,077,466	17,000,000	-0.73	NA
50 th	0	15.17	20.29	5.65	7.72	5,464,572	17,000,000	-0.71	NA
50 th	50	15.17	20.29	5.65	7.72	5,699,886	17,000,000	-0.70	NA
90 th	0	16.99	21.59	6.35	8.15	6,020,882	17,000,000	-0.68	NA
90 th	50	16.99	21.59	6.35	8.15	6,274,104	17,000,000	-0.66	NA

Scenario	Remediation life	Traffic growth (%)	Maintenance shifts		Probability of delays (%)		NPV (£)		IEI	Payback period (years)
			Years 0-30	Years 31-60	Years 0-30	Years 31-60	Baseline	Remediation		
50 th	40	0	15.17	20.29	5.65	7.72	5,464,572	20,259,131	-0.91	NA
50 th	40	50	15.17	20.29	5.65	7.72	5,699,886	20,259,131	-0.90	NA
50 th	80	0	15.17	20.29	5.65	7.72	5,464,572	16,376,177	-0.67	NA
50 th	80	50	15.17	20.29	5.65	7.72	5,699,886	16,376,177	-0.66	NA

Table 8. Cost-model results for Site B

Scenario	Traffic growth (%)	Maintenance shifts		Probability of delays (%)		NPV (£)		IEI	Payback period (years)
		Years 0-30	Years 31-60	Years 0-30	Years 31-60	Baseline	Remediation		
Baseline	0	35.47	35.47	2.89	2.89	9,140,131	30,000,000	-0.73	NA
Baseline	50	35.47	35.47	2.89	2.89	9,237,882	30,000,000	-0.73	NA
10 th	0	30.27	30.81	3.18	4.17	8,076,210	30,000,000	-0.76	NA
10 th	50	30.27	30.81	3.18	4.17	8,204,781	30,000,000	-0.76	NA
50 th	0	35.72	35.67	3.45	4.44	9,399,179	30,000,000	-0.72	NA
50 th	50	35.72	35.67	3.45	4.44	9,537,035	30,000,000	-0.72	NA
90 th	0	43.07	41.41	3.80	4.79	11,130,309	30,000,000	-0.67	NA
90 th	50	43.07	41.41	3.80	4.79	11,279,888	30,000,000	-0.66	NA

Scenario	Remediation life	Traffic growth (%)	Maintenance shifts		Probability of delays (%)		NPV (£)		IEI	Payback period (years)
			Years 0-30	Years 31-60	Years 0-30	Years 31-60	Baseline	Remediation		
50 th	40	0	35.72	35.67	3.45	4.44	9,399,179	35,751,408	-0.92	NA
50 th	40	50	35.72	35.67	3.45	4.44	9,537,035	35,751,408	-0.92	NA
50 th	80	0	35.72	35.67	3.45	4.44	9,399,179	28,899,135	-0.68	NA
50 th	80	50	35.72	35.67	3.45	4.44	9,537,035	28,899,135	-0.68	NA

Table 9. Cost-model results for Site C

Scenario	Traffic growth (%)	Maintenance shifts		Probability of delays (%)		NPV (£)		IEI	Payback period (years)
		Years 0-30	Years 31-60	Years 0-30	Years 31-60	Baseline	Remediation		
Baseline	0	59.11	59.11	2.48	2.48	16,920,261	17,500,000	-0.04	NA
Baseline	50	59.11	59.11	2.48	2.48	14,732,796	17,500,000	-0.18	NA
10 th	0	56.52	55.49	2.92	3.85	14,140,980	17,500,000	-0.22	NA
10 th	50	56.52	55.49	2.92	3.85	14,259,653	17,500,000	-0.21	NA
50 th	0	60.72	60.00	3.15	4.17	15,219,557	17,500,000	-0.15	NA
50 th	50	60.72	60.00	3.15	4.17	15,347,780	17,500,000	-0.14	NA
90 th	0	67.15	65.88	3.44	4.44	16,782,526	17,500,000	-0.05	NA
90 th	50	67.15	65.88	3.44	4.44	16,777,722	17,500,000	-0.05	NA

Scenario	Remediation life	Traffic growth (%)	Maintenance shifts		Probability of delays (%)		NPV (£)		IEI	Payback period (years)
			Years 0-30	Years 31-60	Years 0-30	Years 31-60	Baseline	Remediation		
50 th	40	0	60.72	60.00	3.15	4.17	15,219,557	20,854,988	-0.37	NA
50 th	40	50	60.72	60.00	3.15	4.17	15,347,780	20,854,988	-0.36	NA
50 th	80	0	60.72	60.00	3.15	4.17	15,219,557	16,857,829	-0.11	NA
50 th	80	50	60.72	60.00	3.15	4.17	15,347,780	16,857,829	-0.10	NA

The results from the model suggest that carrying out work to stabilise earthworks would not be the most cost-effective solution any of the three sites; although Site C (Harold Wood) is marginal. Site A, where there is a strong link between SMD and failure shows the largest increase in maintenance requirements over time (potentially up to 10% compared to the baseline). Although, the increase in maintenance is insufficient to make stabilisation cost effective, it does mean that over the 60 year analysis period the cost from maintenance and delays increases by 37% compared to the baseline (P50) (22% and 51%, for P10 and P90 respectively).

Site B has higher maintenance levels even at a baseline climate, and although SMD appears to have less of an impact and maintenance levels change very little over time the IEI is closer to zero than for Site A. The increase in maintenance and delay cost with climate change compared to the baseline climate is only 3% (P50) (-12% and 22%, P10 and P90).

Site C has the highest maintenance levels, and is the site where adaptation action is closest to being the most cost-effective action (IEI is only slightly negative). However, the maintenance and delay costs with climate change compared to the baseline climate actually seems to decrease by -10% (P50) (-16% to -1% for P10, P90).

The results for the two clay sites suggest there will be no change in future maintenance levels as a result of the drier climate, which is counter-intuitive. The future SMD estimates (Figure 19 and Figure 20) show an increase in SMD over time and the failure data analysis shows, in the case of Site C at least, a reasonable correlation between SMD and failure. However, examining the SMD data in more detail, it can be seen that although future summer SMD is projected to be higher than current levels and recover to the current level over autumn, so it could be expected that the increase in SMD during spring would be more rapid, this is not reflected in the average weekly change in SMD. The rate of change in weekly SMD, as calculated from the WG data, is very variable from year to year (Figure 30) and there is no discernible change over time (Figure 31). It is unknown if this is a real feature or if as the weather generator is based on current weather patterns with the UKCP09 projections overlaid, changes in the rate of change of SMD is something which the WG is not able to currently simulate. This requires further investigation to understand it more clearly, which unfortunately was not possible within this project.

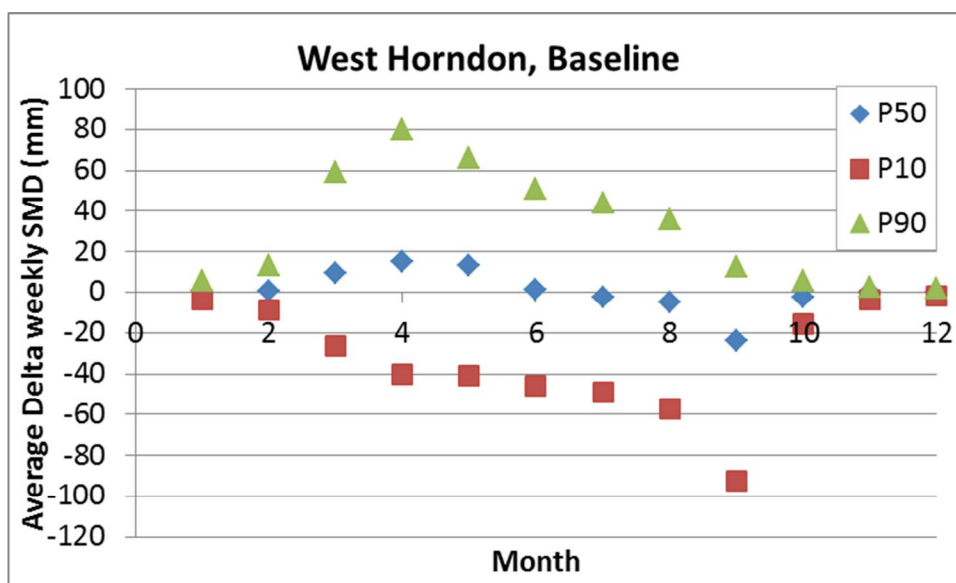


Figure 30. Variation in rate of SMD change, West Horndon baseline climate

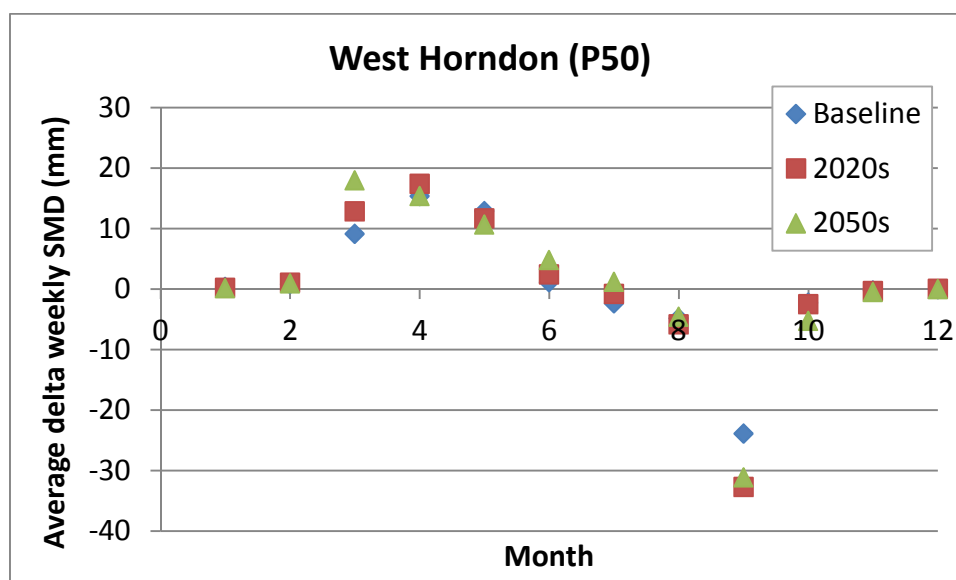


Figure 31. Variation in delta weekly SMD over time

9.2 Sensitivity analysis

9.2.1 Climate

The future climate variables provided by the WG are subject to both natural variability and uncertainties in climate models. By running the model for 30 years, some of the natural variability is captured, but this does not necessarily include some very extreme low probability events. The variation as a result of uncertainties in the climate models is given by running the model 100 times with slightly different initial conditions for each run.

The impact of the variation in climate was explored by comparing the P10 and P90 with the P50. Figure 32 shows the difference this can make to the delay and maintenance

cost with site A, which had a strong link between SMD and failure (9-11% in delay and maintenance costs). Sites B and C showed similar variations of 7% to 16%.

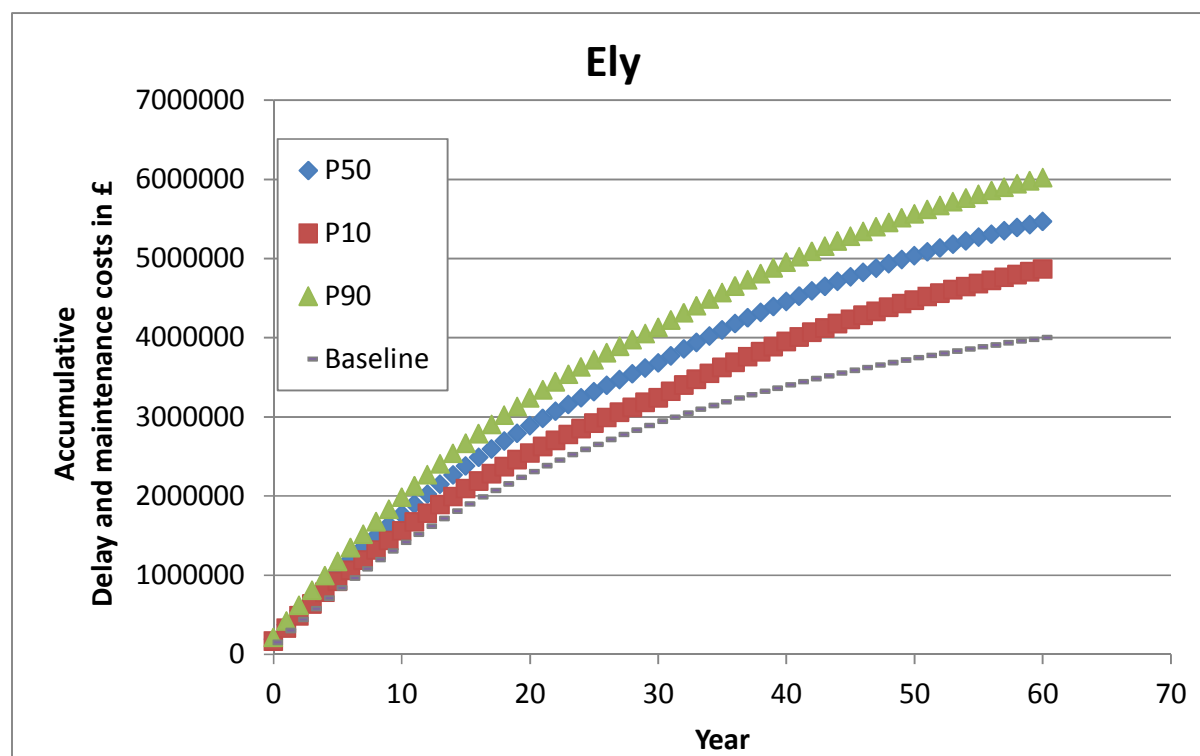


Figure 32. Site A cost sensitivity to climate variation

9.2.2 Traffic levels

The consequences of increasing the number of trains per hour were assessed, by comparing the impact of increasing tph by 50%. It was found that this slightly increased the IEI, and increased the delay cost over the 60 years by around 4% for Ely, 2% for West Horndon and 1% for Harold Wood. Figure 33 shows the sensitivity of delay and maintenance costs to traffic growth for Ely.

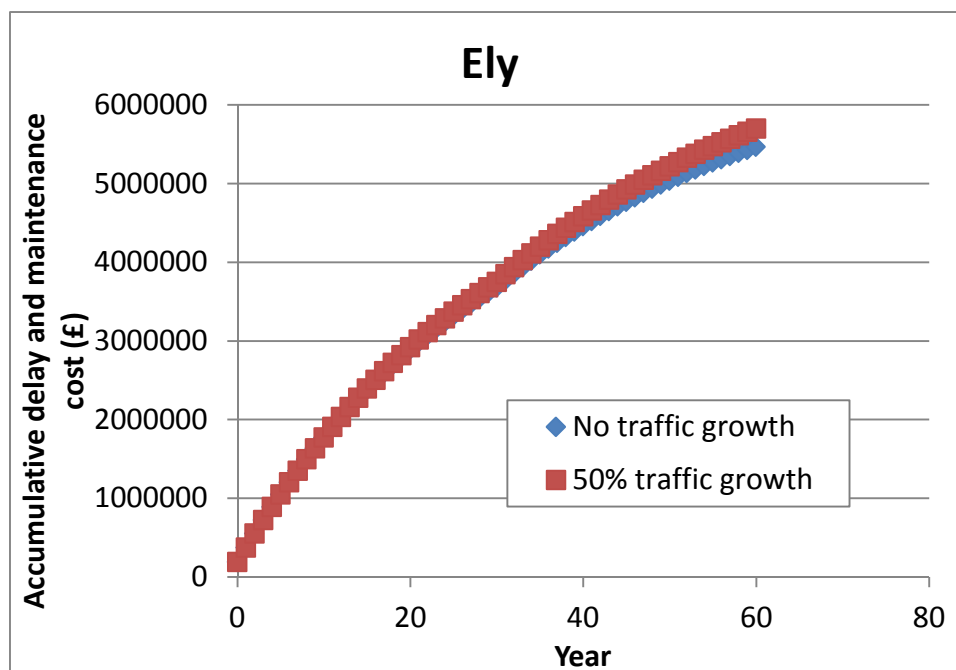


Figure 33. Site A cost sensitivity to traffic growth

9.2.3 Asset life

The result of using a 40 or 80 year life compared to the chosen 60 year life was investigated. It was found that this made more of a difference to IEI than a 50% increase in traffic or climate variations. Figure 34 shows the impact asset life makes to the costs for Site C, where the IEI was closest to a positive value. A 40 year asset life changed the IEI by 0.22, compared to 0.01 and 0.10 for traffic and climate variations).



Figure 34. Site C sensitivity to asset life

The sensitivity analysis showed the importance of asset life in cost calculation. Variation in climate from one year to the next also has a significant impact. However, a small amount of traffic does not greatly affect the delay cost. This does not take any account of any physical impact of additional load on the earthworks.

10 Discussion and conclusions

10.1 Discussion

A number of assumptions were made in order to develop this methodology. These were due to limitations in the current state of knowledge in this area, lack of availability of data and as a result of the small scale of this scoping project. These are discussed below.

10.1.1 *Climate uncertainties*

Weather is naturally variable, with wet years and dry years and it is impossible to predict the exact weather a place will experience for a particular year in the future. However this variability centres around the average climate of the area, and is manifested within a particular range. Therefore, it is possible to estimate the probability of a particular temperature or precipitation occurring within a certain timeframe. This average climate and range of variability is changing, therefore when studying any weather related failure and projecting into the future it is essential to take this into account. The UK has a set of national climate projections based on global climate models (UKCP09) which enables people to do this, and these were used in this model.

There are a number of uncertainties related to these projections. The future global climate is dependent on the amount of greenhouse gases emitted by the international community which is unknown. However, it is related to population, technological development and carbon reduction strategies and several scenarios have been created by the IPCC to explore the plausible range of future emissions. UKCP09 includes low, medium and high emissions scenarios. Ideally all three would have been used in the model, but the limited nature of this scoping study allowed the consideration of only one. The high emissions scenario was used as is considered this is the scenario the current pathway most closely matches. Due to the inertia in the climate system, there is around a forty year delay in the reaction of the climate to GHG emissions, therefore the climate associated with the different scenarios only start to deviate at around the 2040s and the choice of scenario makes little difference up to this point. The further into the future the projection the greater difference the emissions scenario selection makes.

In addition to the uncertainty over the amount future emissions, there is uncertainty associated with modelling a complex system such as the global climate. UKCP09 uses the results of an ensemble of global climate models from across the world to incorporate this uncertainty into the projections. Each model represents the physical processes which influence the climate slightly differently and the parameters in each can be varied, providing a spread of results with those produced by the majority considered most likely.

There are some things which are unable to be included in the models, such as future volcanic eruptions, and there may be unknown uncertainties or failures common to all models. Therefore there remains some uncertainty unaccounted for.

Actions which may have increased the accuracy of the climate data, but increased the amount of data processing are using additional model runs (100, the minimum recommended was used), this may have increase the spread of variability. Also, using climate data for each relevant time slice (2020s, 2030s, 2040s, 2050s, 2060s, 2070s) and the UKCP09 trend report for 2010 to 2020, instead of only the 2020s and 2050s

data would be more accurate as the 30 year periods are climate stationary, i.e. do not contain any incremental changes in climate within the timeframe.

10.1.2 SMD calculations

The future SMD values used in this model were calculated using a simple water balance approach, whereas more complex models such as MORECS take into account geology, vegetation type etc. The difference using a more complex SMD model would make to the cost model results is unknown, and it also has to be noted that even complex models are not totally accurate in all situations. A comparison of MORECS with field measurements found the model showed soil drying out too quickly in spring, wetting up too quickly in autumn and in very dry summers didn't dry out enough (Hough, 2003).

In addition, both the simple approach used and MORECS calculate the average SMD of a particular grid square. Local characteristics such as whether the earthworks are south-facing can affect the soil moisture for that particular site, making it more or less vulnerable than the average SMD suggests.

10.1.3 SMD and failure relationships

Although soil moisture has been established as a trigger of earthwork failure, there are many other factors which influence failure such as geology, orientation relative to the geological structure, slope characteristics, earthwork condition and antecedent weather conditions. In this study a simple correlation between SMD and failure was investigated. However, it is clear from even this simple analysis that there are other factors involved. A key factor is geology, and differences were seen between the London Clay and peat sites. However, there were also differences between the two London Clay sites, and the reasons for this are less clear. It could be that there were particular characteristics of Site C, which made it more vulnerable to SMD changes or it could be the data was insufficient to establish a clear relationship. The small number of sites and geologies studied, the limited historic failure and maintenance data, the lack of information on the specific sites and the difficulties relating delay and maintenance data to ground movement, mean that the correlations identified need more work to be fully established and the influence of other factors understood.

10.1.4 Change in SMD

For the clay sites a correlation was found with the rate of change in SMD, rather than the absolute SMD value. This fits with the timing of the greatest amount of delay and maintenance on these sites – spring, which has the greatest positive change in SMD. However, although it was expected that the rate of change in SMD would increase over time in addition to the value of SMD, this was not found when the weekly SMD values were analysed. The reason for this is unclear, it could be that the change in weekly SMD will not differ significantly in the future (especially given it is so variable) or it could be that the methodology used was not able to simulate this change either because of the way the WG works or because the timeframe (weekly) was not sufficiently long. This is something which needs further investigation.

10.1.5 Cost figures

Estimates, based on average figures were used for the costs of delay, tamping and adaptation actions. Further investigation and a fuller cost assessment based on the specific details of the site may increase the accuracy of these figures.

10.1.6 Cost modelling

The delay costs only include the delays that are recorded in TRUST, not cancellations or planned restrictions. Also, the cost of the delays to passengers and freight, replacement buses, cost of fines relating to missed performance targets and non-monetary impacts such as damage to reputation are not included.

The only maintenance cost included was for tamping, other kinds of maintenance e.g. to stabilise embankments or cuttings were not included. It was not possible to say which maintenance shifts were as a result of poor track geometry due to ground movement and which were due to general wear and tear or other factors. The analysis looked in general at the amount of tamping shifts and its correlation with SMD. It was not possible establish a link between a specific delay incident occurring and additional tamping taking place.

The Government guidelines on discounting contained in the Green Book were used in this economic analysis, but there has been some debate on the appropriateness of discounting when considering climate change impacts (Conceição, 2007). Government supplementary guidance (HM Treasury, 2008) suggests that when considering long term investments (greater than 50 years) a lower discount rate may be used. Future work could include comparing the results obtained with this discount rate.

It was assumed that the adaptation action removed the need for any tamping for the whole of the study period. It is possible that it would reduce the level of tamping, but not remove the need for it altogether or that the action may stabilise the earthworks for more or less than the 60 years assumed. The impact of a 40 or 80 year lifetime was explored in the sensitivity analysis (Section 9.2.3) and asset lifetime was found to be an important factor in the IEI results.

10.2 Conclusions

A methodology was developed to calculate the cost effectiveness of stabilising rail earthworks vulnerable to desiccation. There were a number of assumptions made in carrying out this calculation with regard to future climate, the relationship between SMD and failure, the delays and maintenance that could be assigned to ground movement and the costs involved in tamping, delays and stabilising the earthworks. The methodology was piloted on three sites on the Anglia Route, one on Peat and two on London Clay. A number of results were found:

- Peat failures occur throughout the year but are more likely to occur in autumn when SMD is at its highest and especially when it had been high for a long period of time.
- Clay failures are likely to be in the spring, especially when SMD increases rapidly.
- On the Anglia Route there is a correlation between SMD and the number of incidents causing delay, related to earthworks.

- On peat soil, there is a correlation between SMD and the amount of online track maintenance carried out.
- On London Clay soil, there is a correlation between the rate of increase of SMD and the amount of online track maintenance.
- The correlation at the West Horndon to Dunton site is less than at the Harold Wood to Brentwood site despite the similar geology, so other factors are likely to be contributing to earthwork vulnerability.
- SMD estimates show that SMD is likely to increase in the future at all three sites, and at similar rates.
- No future increase in the average change in weekly SMD was found.
- There is likely to be an increase in the maximum SMD which given the correlation found for Site A, is likely to increase the failure of earthworks on peat.
- The rate of change in weekly SMD was not found to increase in the future, which, based on the correlation found for Sites B and C, suggests no increase in maintenance on London Clay sites. (However, this needs further investigation).
- It is not cost-effective to carry out work to stabilise any of the sites even at the 90 percentile value for maintenance and delay. (However this study did not include all costs associated with failure.)
- If the traffic increases by 50% over the next 60 years, this would slightly increase the cost of delays, but this is not sufficient to make action at any of the sites cost-effective.
- Changing the lifespan of the adaptation action by 20 years has a larger effect on the IEI than traffic or climate variability.

10.3 Potential improvements

Additional work is required to build on this scoping study; to reduce or clarify the assumptions and extend the model, so it is applicable to more sites:

- The variation of rate of change in weekly SMD due to climate change needs further investigation both to establish if it does change, and if this is the most appropriate indication of failure for London Clay.
- In order to establish if all types of clay behave similarly with respect to SMD and if there is a clear difference between shrinkable and non-shrinkable soils, the study needs to be extended to other sites with different types of geology. Both those geologies susceptible to soil moisture e.g. Gault clay, Weald clay, but also non-susceptible geologies need to be studied as a comparison. This would help to establish a baseline level of tamping, for normal wear and tear where SMD is not a factor.
- In order to identify other factors which affect failure it is necessary to compare sites of similar geologies but with other characteristics. It would be useful to build up a range of relationships, so that when certain characteristics are present, different equations are used. In this way the methodology could be used on other areas of the network without repeating the data analysis.

- Establish a better link between SMD and maintenance/delay, it would be useful to carry out field trials to measure SMD and the maintenance/delay that can be associated with it, rather than relying on modelled SMD averaged by 40km square and TRUST categories and maintenance logs. It would allow the actual local SMD to be used which includes factors such as orientation to the geological structure, vegetation etc. and the delays and maintenance carried out that are actually a result of ground movement rather than assuming all tamping and earthwork related delays are relevant. This would help to validate or modify the assumptions made in the model.
- Establish the costs of capital works to prevent shrinkage and desiccation more accurately.
- Extending the model to include other emissions scenarios and to use climate data for each decade, might improve its accuracy and give a better understanding of uncertainties. Comparing the WG baseline data for the grid square with observed data obtained close to the site being studied would help to validate the WG data and using a more complex soil moisture model such as MORECS to calculate SMD from the WG output may make it more accurate.
- Producing a user-friendly version of the model with guidance that others could use would extend its usefulness.
- The methodology could be extend to other NR Routes and used to look at correlations between low SMD (wet soil) and failure by landslipping.

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