THE IMPACT OF SEA-LEVEL RISE ON THE LONDON-PENZANCE RAILWAY LINE

By

DAVID A. DAWSON

A thesis submitted to the University of Plymouth
in partial fulfilment for the degree of

DOCTOR OF PHILOSOPHY

Department of Geography
School of Geography, Earth & Environmental Sciences

In collaboration with:
Great Western Research, Network Rail, and
Devon and Cornwall County Councils

FEBRUARY 2012

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ABSTRACT

DAVID ANDREW DAWSON

THE IMPACT OF SEA-LEVEL RISE ON THE LONDON-PENZANCE RAILWAY LINE

The coastal section of the London to Penzance railway line (Dawlish-Teignmouth) lies very close to sea level and has been susceptible to frequent closure during high seas and storm events. As the main railway connection for the southwest of England to the rest of Great Britain, it is a vital transport link for the Devon and Cornwall economy. Current understanding of future sea-level rise in the region is compromised by a lack of reliable geological data on which to establish accurate future sea-level projections. Furthermore, the impacts – in engineering and economic terms – of potential sea-level change on the long-term functioning of the main railway are unclear, and future policy making and planning are compromised by a similar gap in scientific knowledge.

The central aim of this thesis is to establish the extent to which future sea-level changes will impact upon the Southwest’s main railway line. This aim carries three objectives: (1) to establish accurate sea-level trends over the last 4000 years (late Holocene) in order to validate geophysical models used in current future sea-level projections in the southwest of England; (2) to establish the likely impacts of future sea-level change on the functioning of the Dawlish-Teignmouth railway line; and (3) to integrate climate and socio-economic futures (scenarios) in an internally consistent manner for future use in regional policy debates.

In addressing these objectives, we estimate that during the last 2000 years the coast of south Devon has subsided at a rate of ~1.1 mm/yr, generating a relative sea-level rise of ~0.9 mm/yr. The geophysical model (used to determine regional sea-level projections) underestimates the geologically estimated coastal subsidence rate by only 17%, which would generate an additional sea-level rise, compared to predicted values, of 0.014 m by 2100. Based on an empirical trend between increases in sea-level changes and rail functioning during the last 40 years, the corrected sea-level projections provide input for establishing future days with line restrictions due to overtopping on the Southwest Mainline. Impacts to both the Southwest economy (e.g., rail users) and the infrastructure owners have been determined, and integrating these forecasts with socio-economic scenarios (SES) has highlighted the important interaction between climate and socio-economic trends and future vulnerability. In a worst case scenario (e.g., high emissions), rail services are predicted to be disrupted (on average) for around 35% of the winter by 2060. By this stage, the cost of these disruptions will have exceeded the capital needed for constructing a new alternative inland route.

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List of Abbreviations

Acronyms used in this thesis are listed here in alphabetical order:

AMS (^{14}C)	Accelerated Mass Spectrometry (Carbon-14)
BBC	British Broadcasting Corporation
BNA	British Newspaper Archive
BP	Before Present
CBI	Centre for Business and Industry
CCC	Cost of Climate Change
CPNI	Centre for the Protection of National Infrastructure
DAL	Dawlish Avoiding Line
DEFRA	Department of Environment, Food and Rural Affairs
DETR	Department of the Environment, Transport and the Region
DfT	Department for Transport
DLR	Days with Line Restrictions
ESR	Emergency Speed Restriction
$EUST_{LH}$	Late Holocene Ice-Equivalent Sea-Level Change
FC	Future Cost
FGW	First Great Western
FMR	Frontage Management Report
FOC	Freight Operating Companies
GDP	Gross Domestic Product
GIA	Glacio-Isostatic Adjustment
GPS	Global Positioning System
GWRUS	Great Western Route Utilisation Strategy
HAT	Highest Astronomical Tide
HEFCE	Higher Education Funding Council for England
HMG	Her Majesty’s Government
HoC	House of Commons

HST	High Speed Train
ICE	Institute of Civil Engineers
ICZM	Integrated Coastal Zone Management
IGCP	International Geological Correlation Programme
IME	Institute of Mechanical Engineers
IPCC	Intergovernmental Panel For Climate Change
ITS	Institute Of Transport Studies
IUGS	International Union of Geological Sciences
LAT	Lowest Astronomical Tide
LCLIP	Local Climate Impact Profile
LENNON	Latest Earnings Networked Nationally Over Night
LGM	Last Glacial Maximum
LOI	Loss on ignition
MLWS	Mean Low Water Springs
MHWS	Mean High Water Springs
MME	Multi Model Ensemble
MOIRA	Model of Inter-Regional Activity
MSFW	Making Space for Water
MSL	Mean Sea Level
MTL	Mean Tidal Level
NAO	North Atlantic Oscillation
NAO	National Audit Office
NOC	National Oceanographic Centre
OD	Ordnance Datum
OECD	Organisation for Economic Co-operation and Development
ORR	Office of Rail Regulation
OVI$_{LH}$	Late Holocene Global Ocean-Volume Increase
POST	Parliament Office of Science and Technology
PSA	Published Sources Archive
PSMSL	Permanent Service For Mean Sea Level
RAE	Research Assessment Exercise
REF	Research Excellence Framework
RLR	Revised Local Reference
RSL	Relative Sea Level
RSSB	Rail Safety Standards Board
SACTRA	Standing Advisory Committee on Trunk Road Assessment
SEC	Socio-Economic Cost
SES	Socio-Economic Scenarios
SL$_{20}$	20th Century Sea-Level Rise
SLIP(s)	Sea-Level Index Point(s)
SRES	Special report on emission scenarios
SSSI	Site of Special Scientific Interest
TAG	Transport Appraisal Guidance
TOC	Train Operating Companies
TOPS	Total Operations Processing System
TRUST	Train Running System TOPS
TSD	TRUST Service Data
UKCIP	United Kingdom Climate Impact Program
UKCP09	United Kingdom Climate Projections
UNESCO	United Nations Educational, Scientific and Cultural Organization
VLMR	Vertical Land-Motion Rate

Acknowledgements

Firstly, I would like to thank my supervisors Roland Gehrels, Jon Shaw and Alistair Hunt. Throughout my PhD they have expertly aided the development of the project but have, above all, helped me push myself to see it finally completed. Equally, I'd like to make special thanks to the external organisations involved in the project: Great Western Research, Network Rail, and Devon and Cornwall County Councils. Thanks also to Ian Bailey and Robert Nicholls for examining my thesis and providing excellent feedback. I'd like to thank all the Geography staff at Plymouth (and those that visited during my time) for their support and encouragement. Particularly, the geography office staff and the cartographers (Tim Absalom and Jamie Quinn) for their excellent work, patience with my spontaneous last minute requests, and their general warm and pleasant greetings - daily!

Carrying out my fieldwork in south Devon had its ups and downs, however, I was luckily enough to have the help and support of some excellent family, friends and colleagues. Out in the marshes: Dan Buscombe, Jon Shaw, Martin & Mike Dawson and Andre Pacheco. Will Marshall for his dating expertise and Rich Hartley for his expert GPS and surveying advice that quite conveniently led us from the field to a pub. Thanks also to the team in Davy, Kev Solman, Katie Head and Debbie Bauckham. Also, this project would not have been possible without significant external support from Peter Kay, Jamie Linley (FGW), Tim Maddocks, Rob Howard, Peter Haigh, John Dora and Ana Chan (Network Rail). Sarah Bradley for providing us with her geophysical model, the Slapton Field Centre, Tom Howard at the Met Office, Mark Garnett at the NERC radiocarbon laboratory and Richard Burningham and Andrew Seedhouse for their insightful chats and 'industry' perspectives.

Finally, some more personal thanks to the friends I have made in Plymouth whom have helped me more than can be explained in writing. Thanks must go to Alex Hugo and Doug Smith for their endless support, Dan Buscombe, Tim Scott and Alex Taylor for all the laughs by the fire at Haystone Place, Chris (and the family) Mintoff for allowing me to vent my frustrations on the River Plym and Matt Sharples for being himself. My excellent friends and drinking buddies at the university: Dr Viet Bachman and Professor Jon Shaw, and not to forget Andy Murphy and the team at Derriford hospital for 'patching me up' at various points during my time in Devon.

Finally, thanks to my Mum and Dad (Martin and Shirley), Brother Mike, Nan, and Jodie. They have shared (whether they liked it or not) all of the adventures, and the blood, sweat, tears, broken bones and 'seaside homes' that have accompanied this, one of my greatest achievements... so far.

Author's Declaration

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award.

This study was financed by Great Western Research, Network Rail, Devon and Cornwall County Councils, and the University of Plymouth.

Word Count: 76,564

Signed..........................D.A.Dawson

Date..............................01/02/2012

Publications:
Gehrels, R., Dawson, D., Shaw, J., Marshall, W. 2011. Using Holocene relative sea-level data to inform future sea-level predictions: an example from southwest England. *Global and Planetary Change,* 78, 116-126.

Conferences:
Presentation given for Cornwall County Councils Annual Rail Forum meeting January 2007.

Dawson, D., Gehrels, R., Hunt, A., Shaw, J. 2007. The impact of future sea-level rise on the Southwest Rail Network. Human Dimensions of Global Environmental Change, Postgraduate workshop, International Human Dimensions Programme, Royal Geographical Society (Climate Change Research Group), University of Leeds, March 29-31.

Dawson, D., Gehrels, R., Hunt, A., Shaw, J. 2007. Impact of sea-level rise on the London to Penzance Railway Line. Young Coastal Scientists and Engineering Conference (YCSEC 07). University of Plymouth, April 19-21.

Dawson, D., Gehrels, R., Hunt, A., Shaw, J. 2007. Impact of future sea-level rise on the London-Penzance railway line. International Geosciences Programme Project 495, UK working group meeting, St. Andrews, Fife, Scotland, July 1-4.

Dawson, D., Gehrels R., Hunt, A., Shaw, J. 2008. Impact of future sea-level rise on coastal transport infrastructure: the case of the London-Penzance railway line. Royal Geographical Society Post Graduate Symposium. University of Liverpool, March 1.

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Dedication

For Mum, Dad, Mike and Nan

Along this particular journey I often became derailed, both mentally and physically. You were always there to pick me up, dust me off, and put me back on track.

Chapter One

Introduction

1.1 Introduction

The central aim of this thesis is to examine the future impacts of sea-level change on the Dawlish to Teignmouth stretch of the London-Penzance railway line (Figure 1.1). The line is vulnerable to sea-level rise, a well-documented consequence of global warming, because as sea levels rise, the probability of overtopping of coastal structures increases. Overtopping damages the rail line in numerous ways that result in impedance and occasional closure. If the number of overtopping events were to increase in frequency and magnitude, the extent to which engineering intervention is needed to maintain a reliable rail service is likely to rise significantly. This is expected to result in a considerable increase in cost both to the railway companies (who repair, operate and use the line) and to the southwest of England's regional economy more widely, as its functioning would be interrupted by the increasing absence of a reliable railway connection. The Southwest region is large with a dispersed population, and the counties of Devon and Cornwall rely on relatively limited motorway and rail access (ICE, 2009b). This problem threatens the region's resilience against infrastructure failure, and understanding future sea-level change and the possible impacts is therefore vital for future decision making and adaptation.

Current understanding of future sea-level rise in the Southwest, however, is compromised by a lack of reliable geological data on which to establish accurate future sea-level projections (Gehrels, 2006, 2010). Furthermore, the impact of potential sea-level change on the long-term functioning of the main railway is unclear, and adaptive strategies for the future are compromised by a similar gap in scientific knowledge.

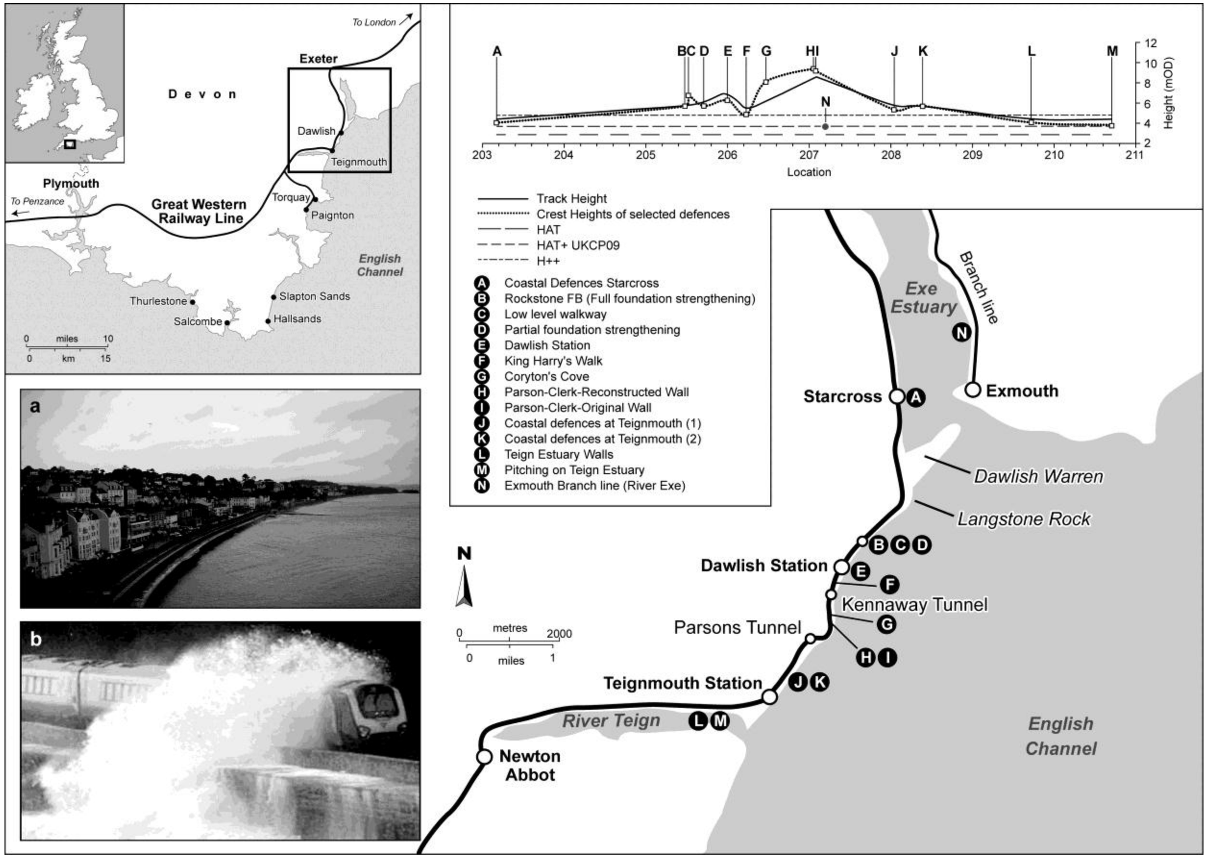

Figure 1.1 Location, and elevation profile, of the Dawlish-Teignmouth section of the London-Penzance railway line. Crest heights have been compared with the current highest astronomical tide (HAT) & UKCP09's sea-level estimates (high & H++) for 2100 (Lowe et al., 2009; see section 1.3.1). (a): view northeast from Kennaway Tunnel. King Harry's Walk (location - F), the lowest section of the frontage, can be seen in the foreground, and Langstone Rock is visible in the distance. This section of the line (B-F) is particularly susceptible to closure during high tides and storm events see insert (b) taken near Rockstone Footbridge (source: BBC News, 2004). The vulnerability of estuary sections (A), (M) and (N) are also identified. Network Rail is responsible for the frontage from Teignmouth to Langstone Rock. Southwest of the frontage the line is managed by Teignmouth District Council, and northeast of the frontage (Dawlish Warren) the line is managed by the Environment Agency.

There has been a recent surge of interest in using scientific information to enhance the legislative and regulatory decisions in the UK by improving evidence-based policy making (HoC, 2007; Lagace et al., 2008). This type of research, directed at tackling real-world problems, is central to the work of applied geographers. However, there relevance in informing policy debates has long been contested within the discipline (Crisholm, 1971; Peck, 1999, 2004; Ward, 2005).

1.2 Applied geography and climate change

Geographers understand complexities in causation and have a deep interest in social and environmental problems, and thus, applied geography is concerned with the application of such knowledge to resolutions of real-world problems (Pacione, 1999). Yet the inability to cross the boundary into the policy arena (or influence it) has been subject to a great deal of criticism within the community, and peaked in the early 1970s with the so called ‘relevance’ debate (Chisholm, 1971; Berry, 1972; Coppock, 1974; Stoddart, 1975, 1987; Pacione, 1999; Peck, 1999; Martin, 2001; Berry, 2002; Ward, 2005). The debate was underlined by basic thesis that, due to the skills of geographers, they should be much more involved in the creation and monitoring of policies, and the education of future generations of policy makers (Chisholm, 1971; Berry, 1972; Clark, 1982; Peck, 1999; Berry, 2002; Johnston and Sidaway, 2004; Martin, 2001; Yeates, 2001; Pelling et al., 2008). The general perceptions of geographers’ role in decision making as just data collectors – and not to be ‘delver, dovetailer and decider’ (Chisholm 1971 p. 67) – divided the geographical community. Much discussion revolved around how the government would actually use the geographical information and developed further into how best to penetrate the policy realm (Chisholm 1971; Eyles 1973; Blowers 1974; Coppock 1974; Harvey 1989; Martin 2001; Massey 2001; Johnston 2004). This increased tension within the geographical academic community as it implied certain research was more useful than others (Pacione, 1999; Martin, 2001).

So-called ‘pure’ and ‘practical’ geographers were defined (Palm and Brazel, 1992), and this separation led some to argue that geography as a whole was at risk of dividing and being swept away into other disciplines (Steel, 1982; Stoddart, 1987; Pacione, 1999; Peck, 1999; Thrift, 2002). The interaction of geography’s social and environmental aspects, and hence its possible application, was seen as one way to promote geography and its applied nature (Massey, 2001; Thrift, 2002; Jones and Macdonald 2007), although combining the two is not a linear interaction by any means (see Jones and Macdonald, 2007). It was argued, however, that the broader differences between government and academic environments challenged the fundamental relationship between applied geography and policy (Chisholm, 1971; Martin 2001; Massey 2001; Lagace et al., 2008). This led to the ‘two cultures’ or ‘communities’ theory, and differences in drivers, timelines, and audiences were recognised as major barriers to applying geography. The outcomes of these discussions commonly described a lack of understanding of each other’s differences and influences, and poor dissemination of research findings (Peck, 1999; Castree, 2002; Ward, 2005). With respect of these discussions, investigating the Southwest’s future transport issues represents a clear area of applied geography that has obvious relevance for policy making in the region. However, in doing so it faces the challenges and barriers of crossing the science to policy gap and it is important to be aware of these potential problems and take steps to address them.

The failure amongst academic geographers to communicate the value of their work effectively or make it visible and accessible to wider audiences has been noted more directly by numerous authors (e.g., Shaw and Matthews, 1998; Castree, 2002; Ward 2005; Jones and MacDonald, 2007). Communicating cutting edge geographical research to non-academics has always been problematic and may require a specialist language (Shaw and Matthews, 1998). Yet, as the debates highlighted, this is as much to do with the cultural environment of academics as with actual research. For instance, the previous university review system, the *Research Assessment Exercise* (RAE), has been criticised as the original purpose of the RAE was to enhance communication of academic work (to wider audiences), yet it does not promote or encourage academics to do so (Shaw and Matthews, 1998; Peck, 1999; Thrift, 2002; Ward, 2005). Past geography RAE panels have struggled with how to evaluate ‘non-standard’ or ‘grey’ research outputs (Peck, 1999; Ward, 2005). As of 2008, the RAE was replaced with the *Research Excellence Framework* (REF). The REF contained an additional criteria, however, to merit the wider impact (or relevance) of research on society and the economy (www.hefce.ac.uk). The Higher Education Funding Council for England (HEFCE, 2010) states that exceptional ‘impact’ research would be able to demonstrate ground-breaking impacts of major value or significance with wide ranging relevance (i.e. to society and the economy). It seems that the implementation of the REF (2010-2014) could bring a bias towards research with policy orientated goals and could benefit both academic and non-academic communities. Projects on climate change and the implications to society (like this study) have significant relevance to society and are a clear example of so called ‘impact’ research.

Despite these developments and discussions, many of the concerns raised over 25 years ago are still relevant today. Some areas of geography have become more successful at addressing them and penetrating the policy realm than others, particularly in physical geography and natural hazards (Ward, 2005; Montz and Tobin, 2011). Geography in its broader definition provides an interface between human and natural worlds, and this relationship has become a key agenda in the twenty-first century amongst issues of climate and society (Daniels et al., 2008). Research on climate and society remains strongly rooted in the natural sciences and problem-solution policy making (Hulme, 2008a). Therefore, it connects more so with the traditional role of geographers as providers of data, but there is a real need to go beyond that. Tol et al., (2008) blames the limited consideration of some of the standard methodologies used in research projects such as the Intergovernmental Panel on Climate Change (IPCC) for the increased physical role in research. It is not sufficient to understand simply the degree to which people at a location are threatened by a particular exposure and dynamic human factors must be addressed (Montz and Tobin, 2011). Research combining both human and physical geography to tackle environmental problems - such as climate change adaptation - is one area that can help disentangle issues of applying geography successfully (Pacione, 1999; Hulme and Turnpenny, 2004; Bailey, 2007, 2008; Daniels et al., 2008).

Climate change and its consequences are problems for the natural environment but also for the socio-economic functioning of society, and the threat of sea-level rise to the Southwest's rail network and the wider economy is of real concern for policy makers. In essence, the job of a climate-policy maker is to help determine the optimal choice among an array of alternative possibilities (Michel, 2009), for example to mitigate or adapt or to do nothing etc. In order to adapt successfully, however, various researchers have noted that climate change demands new forms of research, governance and policy (Olsen et al., 1997; O'Riordan et al., 2006; Tompkins et al., 2008; Gawith et al., 2009). Geographers have been involved in climate change research for many years (Liverman 1999, 2007; Bailey, 2007; Bailey, 2008), and Hulme (2008a, 2008b) and Bailey (2008) have discussed the complexity of governance and policy adaptation amongst changing science and attitudes. Although a global problem, the solutions often lie at lower levels. For instance, internationally the IPCC (2007) and the adaptation of climate scenarios (integrating natural and human impacts) for policy makers are limited by a large spatial scale and scenarios that can be misleading for users (Arnell et al., 2004; Carter et al., 2007; Bailey 2008; Hulme 2008a). However, the distinct skills and insights of geographers could be applied to develop climate research that integrates temporal, spatial and sectoral considerations (Bailey, 2008). Whilst various research efforts have been devoted to evaluate problems – such as coastal vulnerability to climate change – on a national to global level fewer comprehensive and site-specific vulnerability assessments are seen (Torresan et al., 2008). Vulnerability assessments at lower scales are more suitable for planning possible adaptation measures and this study will contribute directly to that recommendation.

At a national level, the United Kingdom Climate Impact Programme (UKCIP) aims to help organisations to adapt to climate change by providing and developing case studies, user tools and communication networks (www.ukcip.gov.org). It was established to facilitate an integrated stakeholder-led assessment of climate impacts in the UK. The Department for Environment, Transport and Regions (DETR) recognised that ‘bottom up’ stakeholder driven research was more likely to provide the information decision makers needed, and thus why it should be stakeholder-led. Individual studies were, at the time, not possible to incorporate into a vulnerability assessment of the whole UK, and UKCIP had to provide an integrating framework so results could be compared and individuals could gain more realistic climate assessments (McKenzie-Hedger et al., 2006). This type of ‘funder driven’ research is often taken up easiest by policy makers but classed as inferior by some scientists (Hunt and Shackley, 1999; Hulme and Turnpenny, 2004) and may deter their future involvement. However, the application of UKCIP work, such as UKCIP02 (Hulme et al., 2002), has been successful particularly as a communication device and in raising the awareness of climate change amongst organisations. Amid minor technical issues (e.g., data formats etc.), more significant problems exist between UKCIP and its consumers, however, and these issues have created substantial weaknesses in their uptake (Gawith et al., 2009).

In light of these discussions, it raises an interesting question regarding the issue being investigated in this project, that is, how will this applied study help inform future management decisions? The originality of this thesis, therefore, lies not only in the fact that it seeks to address a key research aim by improving understanding and knowledge on the subject, but also in the broader context of producing scientific information (or applied geography) that can be used for informing future decision making in the region.

1.3 Aim and objectives

The central aim of this study is to evaluate the impact of sea-level rise on the Dawlish-Teignmouth section of the London-Penzance railway. In pursuit of this aim the project has three objectives, each of which utilises a different methodological approach. The central aim of the thesis connects the multi-disciplinary methodologies in an incremental manner, and the output of each objective is fundamental in the development of the next. The key objectives of the project are as follows:

1.3.1 Objective 1: establishing new late Holocene sea-level data

The first objective is to establish accurate late Holocene sea-level trends in order to validate geophysical models used in current future sea-level projections in southwest England. The late Holocene is important in sea-level studies, because during this period the rate of sea-level rise slowed and vertical land motion became a major component of relative sea-level (RSL) change (Shennan and Horton, 2002; Gehrels, 2006). Vertical land motion in the British Isles results from the process of glacial isostatic adjustment (GIA), and from late Holocene RSL trends the vertical land movement component can be extracted (Gehrels, 2010). Land movement and RSL rates can also be modelled by geophysicists (e.g., Lambeck, 1995; Peltier et al., 2002, Milne et al., 2006, Bradley et al., 2009, 2011), and computer modelled estimates of vertical land motion (e.g., Bradley et al., 2009) are used in the construction of sea-level projections (Lowe et al., 2009, UKCP09). Current estimates in the Southwest are questionable, however, due to a lack of high quality sea level data required to quantify RSL, vertical land motion and to validate the models (Gehrels, 2006; Gehrels, 2010). Collecting new late Holocene sea-level data in south

Devon and Cornwall will enable verification of the computer models and thus allow regional models of future sea-level changes (e.g., Lowe et al., 2009) to be calibrated.

UKCIP have produced climate projections for the UK, including sea-level rise, for the last 10 years (e.g., Hulme and Jenkins, 1998). The most updated projections of regional sea-level change are found in *UKCP09 Science Report: Marine and Coastal Projections* (Lowe et al., 2009). The regional sea-level predictions are based on four published components: global mean sea-level predictions, taken from the IPCC’s Fourth Assessment Report (AR4) (Meehal et al., 2007); storm surge predictions and changes in tidal range, conducted by the National Oceanographic Centre (NOC); and isostatic land movement from the GIA model (Bradley et al., 2009). Interestingly, it seems the call for new geological evidence of sea-level rise from the Southwest (to improve predictions) has been justified as Lowe et al. (2009) clearly acknowledges the original argument of Gehrels (2006), that data for the Southwest are poor, in Annex A1.3 of the report.

In UKCP09, marine projections utilise 11 of the IPCC’s 16 atmospheric-ocean models (known as the multi model ensemble, MME) to estimate absolute mean sea-level rise and are capable of calculating sea-surface height over a 25km^2 regional resolution. UKCP09 have altered the baseline for present day climate change (globally) from 1961-1990 (e.g., Jenkins and Hulme, 1998; Hulme et al., 2002) to 1980-1999 in order to be more consistent with the IPPC’s AR4 (Meehl et al., 2007). This reduces future projections of absolute sea-level by 2.7 cm, and users are recommended to add this figure if wishing to correspond with the original baseline (e.g., UKCIP02, UKCIP98). UKCP09 (Jenkins et al., 2009) has attempted to improve previous methodologies by providing probabilistic projections of climate futures (e.g., temperature, precipitation, etc.). For instance, there is an X % chance mean air temperature in Devon will exceed Y ºC by 2040. However, due to further uncertainty (e.g., deep ocean circulation) and a lack of suitable observational constraints, it is not recommended to assign the same probabilistic method to the marine projections (Lowe et al., 2009).

In order to present the uncertainty, therefore, model frequency distributions of sea-level rise, as in the IPCC AR4 (Meehl et al., 2007), are used. Projections are therefore given for the 5th and 95th percentile, and this should be interpreted as 90% of the modelled results lie between these boundaries (Lowe et al., 2009). As with previous studies, the uncertainty of greenhouses gas emissions (based on future man-made emissions) are included in projections by presenting three scenarios, Low emissions, Medium emissions and High emissions. These correspond with the IPCC scenarios and storylines B1, A1B and A1FI (respectively) outlined in the *Special Report on Emission Scenarios* (SRES) **(**Nakićenović et al., 2000). The limitations of these emission scenarios (e.g. variability, understanding and uncertainty) are detailed in the report and subsequent reports (e.g. IPCC AR4 and UKCP09). All the scenarios, however, assume no political action (i.e. no intervention to reduce emissions in order to mitigate climate change and sea-level rise) and differences between them arise from different assumptions about future socio-economic developments alone (Jenkins et al., 2009).

Lowe et al. (2009) suggest that absolute sea-level change in the UK will be in the region of 0.48-0.76m (emission dependant) over the 21st century; this is assuming that recent accelerations will continue. In order to present relative sea-level changes for the UK regions, however, vertical land movement is included, using Bradley et al.'s (2009) GIA estimates, (Figure 1.2). Although limited by a lack of observational records to constrain the model outputs, the extent to which will be addressed in this study, these projections represent the most accurate estimates of future sea-level rise in the UK.

Sea-level estimates for a 25km grid (grid number: 25727), covering the entire section of railway, are given in Table 1.1 and suggest between 0.05 - 0.07 m of sea-level rise by 2020 (relative to 2010). For a more precautionary approach, the 95th percentile sea-level estimates are used in study. These represent the upper boundary of model outputs and thus show the maximum possible projections. By 2100, however, the estimates suggest up to 0.80 m of sea-level rise.

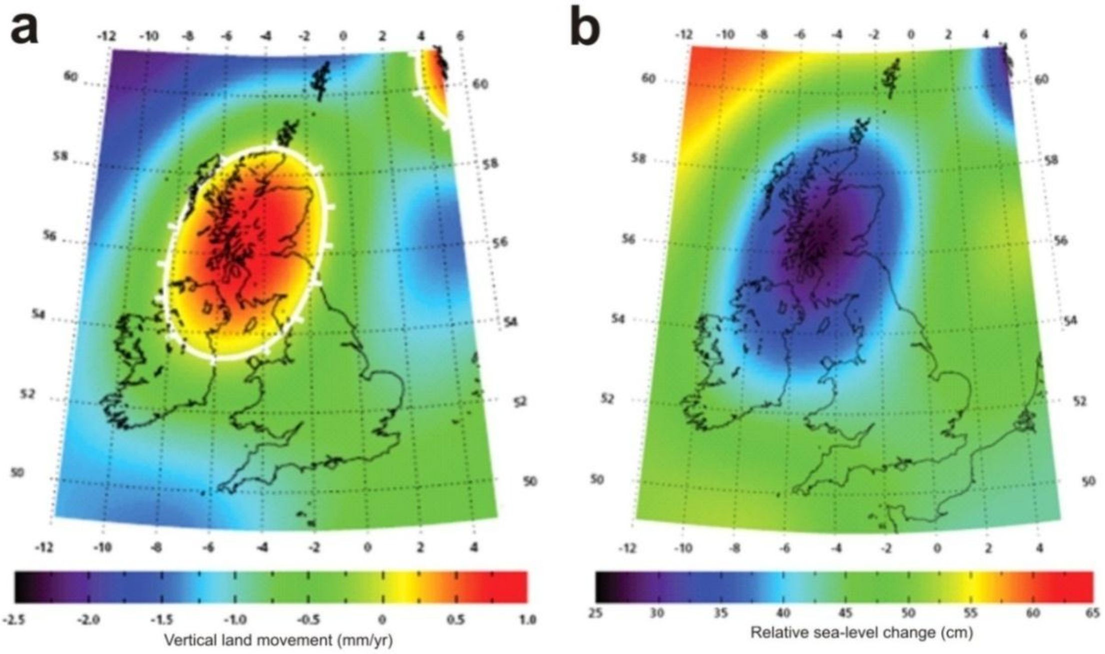

Figure 1.2. Model predictions from UKCP09 (Lowe et al., 2009). (a) Map of the vertical land movement (mm/yr) for the UK, adapted from Bradley *et al*. (2009). (b) Relative sea level change (cm) around the UK over the 21st century. This combines the absolute sea-level change estimates averaged around the UK for the central estimate (50th percentile) for the medium emissions scenario and the vertical land movement as in (a). Values are appropriate to 2095. © UK Climate Projections (2009).

Scenario	**Year**				
	2020	2040	2060	2080	2100
Low	4.5	14.6	26.0	38.9	53.1
Medium	5.5	17.8	31.8	47.5	65.0
High	6.6	21.5	38.5	57.8	79.2
H++	-	-	-	-	93-190

Table 1.1 21st century RSL changes (cm) for Teignmouth, south Devon. Estimates are given from 2010, the 95th percentiles (maximum estimates) are presented as a pre-cautionary measure and are taken from UKCP09's – user interface (**http://ukclimateprojections.defra.gov.uk;** grid: 25757). H++ scenario is a high impact low probability estimate of sea-level rise (relative from 1991) based sea-level rise identified in palaeo proxy records (e.g. Rohling et al., 2008).

UKCP09 also offers an alternative (extreme) future scenario known as the *H++ mean sea-level scenario* that is designed to be used for contingency planning and sensitivity analysis. The H++ scenario presents a range of estimates above the estimated uncertainty range (emissions) and is primarily a result of a rapid global ice melt scenario. It provides low probability, high impact future based on proxy evidence of past interglacial sea-level changes of around 1.6 ± 0.8 m per century (e.g., Rohling et al., 2008) which provides a global upper limit of 2.5 m. In adapting this to regional scales in the UK, Lowe et al. (2009) give an estimated sea-level rise of 0.93 – 1.9 m by the end of the century (Table 1.1). Although unlikely during the 21st century, sea-level rise of this magnitude cannot be ruled out due to palaeo climate observations (from the proxy record) and limitations of the modelling approach (Lowe et al. 2009).

Rising sea levels reduce the return period of extreme water levels and increase the severity of coastal flood events (see Figure 1.3). Given that over 1200 km of the English and Welsh coastline is defended by some level of hard-defence structure, sea-level projections are a vital tool for sustainable coastal management. In the completion of objective one, and the validation of the geophysical model (Bradley et al., 2009) and sea-level projections, the projections of sea-level rise (corrected or uncorrected) will be used as a primary input for completing objective two.

1.3.2 Objective 2: establishing future line impacts

The second objective is to establish the likely impacts of future sea-level change on the functioning of the Dawlish-Teignmouth section of the London-Penzance railway line. The UK's Rail Safety Standards Board (RSSB) states that coastal structures are generally designed to withstand a 1-in-100 year water level (Lane, 2007). In light of the discussion above (e.g., Figure 1.3), the effectiveness of the current railway defences is threatened. As discussed in the previous section, the current unreliability of late Holocene sea-level data has implications for modelled components of the UKCP09 sea-level projections. This subsequently compromises the future planning for the coastal and estuarine defences between Dawlish and Teignmouth. As such this objective carries two research goals:

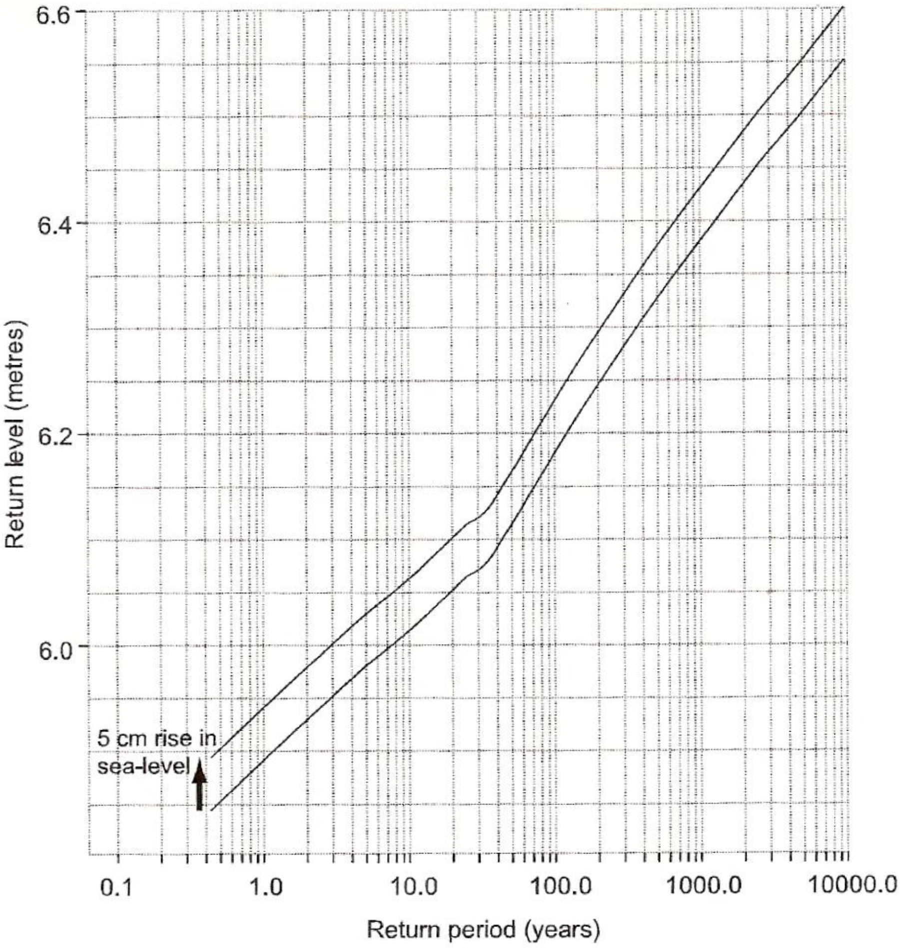

Figure 1.3 Return periods for extreme water levels taken from Newlyn tide-gauge data 1916-1990 (lower line). The upper line shows the increase in return periods with a 5cm rise in mean sea level, assuming no change in storm intensity and frequency. 5cm rise in sea level means a 1 in 100 year event becomes a 1 in 50 year event. Source: Gehrels (2006), modified from Dixon and Tawn (1995). Reproduced with the permission of the Devonshire Association.

- Firstly, collect and construct historical archives of past sea-level change and the nature, frequency and impact of overtopping events on the railway. This will establish a detailed understanding of the railway's past vulnerability to extreme coastal events and determine the extent to which a relationship exists between sea-level change and rail impedance over the past 160 years. Data required include historical accounts of overtopping, maintenance records, structural repair costs along with weather patterns and recent sea-level trends.

- Secondly, establish the likely frequency of future overtopping events based on different sea-level scenarios for the Dawlish-Teignmouth railway line. This will be based on the empirical evidence collected from the historical data collected and the relationship between past sea-level change and rail incidents. This will allow extrapolation of incidents recorded into the future, and the sea-level projections used will have been scrutinised by the new data collected for addressing the first objective.

In completion of the two goals above, projections of rail problems will be used for the third, and final, objective of the study.

1.3.3 Objective 3: integrating climate and socio-economic futures

Essentially, the scenarios to be completed as part of objective two assume that the future is a continuation of the past. Therefore, non-climate factors (such as governance, society and growth) that affect our ability to adapt to climate change are dismissed. The final objective integrates climate and socio-economic futures in an internally consistent manner to construct a plausible range of scenarios for future use in policy debate in the region. Socio-economic changes are an important consideration in any coastal assessment (Hall et al., 2006). In light of this, objective three also carries two subsequent elements:

- Establish the future economic and operational costs resulting from increased rail impedance. Maintaining the line will become increasingly costly in the future as damages and repairs are needed more frequently. Increased rail line closure will also impact the economy, affecting both passenger and freight services and, to a certain extent, wider networks dependent on their reliability.

- Integrate climate futures with socio-economic scenarios to demonstrate that the future could take a number of different socio-economic trajectories, each with varying impacts. The railway exists in a broader policy / socio-economic context, and changes could result in different impacts and planning decisions which, as a result, will affect the resilience of the region to future sea-level rise.

In theory, scenarios are a synthesis of pathways that lead to alternative plausible futures based on expert information. In practice, they often describe particular sets of events or variables (Roubelat, 2000) and can take both qualitative and quantitative forms (Ratcliffe, 2002). The scenario-based approach to impact assessment has already been carried out in various other areas of the UK, with regard to economic development (e.g., Docherty and McKiernan, 2008), and the economic impacts of climate change (UKCIP, 2001). This will provide decision makers with information needed to make informed decisions on the railway's future. By addressing these three objectives, the work undertaken for this project will have established the potential impacts of sea-level rise and socio-economic futures on the Southwest's main railway line. In doing so, it will employ a novel cross-disciplinary approach to make an original contribution to both the sea-level change and climate impact literature. Recent discussions have stated that any decision on the railway's future or plans to seek alternative management strategies will not be made until post 2025 (Hansard, 13th November 2010). This is based on the railway's importance for inter-regional travel and tourism to local coastal communities. Beyond this time frame there remains a high level of uncertainty for the future running of the line, and the information presented in this thesis will provide scientific evidence for discussions on this topic.

1.4 Scope of study

This thesis contains six further chapters. Chapter Two provides the background to the study and reviews key developments and themes of relevance. Chapter Three outlines the methodology needed to address the research objectives presented above. Chapters Four to Six present the results and discussions for each of the objectives (following the same order). Finally, Chapter Seven concludes the thesis with a summary of the main research findings.

At its core, this project represents what is commonly understood as applied geography. Geography has much to offer in understanding the contemporary world and future change, and the visible communication of academic geography could help resolve how and where the work of (geography) academics makes a difference (Shaw and Matthews, 1998).

Chapter 2

Rising sea levels, science and society

2.1. Introduction

In the previous chapter the central aim was introduced along with the key objectives, and the applied nature of this investigation was acknowledged, the broader context of which has clear connections with the concepts of the applied geography debate and the role of geographers' in informing management decisions. In this chapter, the project is put in perspective with reference to the wider literature from the development of sea-level research, globally and locally, to the potential application of the geographical research in addressing current (and future) coastal problems. The central theme in this chapter is the development of science to help inform decisions on future societal issues (such as climate change and sea-level rise). Particular emphasis, however, in made to the UK and the southwest of England. The chapter begins by looking at the advance of palaeo sea-level research and its practical value for coastal management in the UK. Management of sea-level rise, climate change and critical infrastructure (high societal relevance) are then discussed with reference to transport infrastructure in the southwest of England. Finally, a methodological approach to help build information that is useful for decision makers (a theme developed throughout the chapter) is identified in the literature, and this precedes the following methodology chapter (three).

It is clear that one of the major challenges facing policy makers and environmental managers today is change at the coast as a result of rising sea levels (Devoy, 1987; Nicholls and Mimura, 1998; Turner, 2000; Edwards, 2006; O'Riordan, 2006; Turner et al., 2007). The latest consensus projections detailed in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007, Church et al., 2008) suggest a global average rise of 0.10 – 0.79 m by 2100, a range primarily based on various plausible greenhouse gas emission scenarios, thermal expansion of the oceans and the melting of glaciers and ice sheets. These projections are downscaled into national and regional projections (e.g., UKCIP98, UKCIP02, UKCP09) for improved understanding and application in coastal planning. Scientists and researchers, however, use past changes in sea level to improve the models employed to predict future sea-level change in order to understand the likely impacts on future coastlines and the societies and industry that inhabit them. This chapter therefore begins by examining the research and science of palaeo sea-level reconstruction.

2.2 Palaeo sea-level studies

A growing scientific interest in the fluctuations of past sea levels began during the latter part of the 19th century when geological observations in the field (e.g., raised shorelines) were associated with the development of the 'glacial theory' (i.e. the link between sea-level changes and glacier expansion and contraction). Maclaren (1841) was the first to consider the systematic relationship of ocean levels and ice volumes. At times of glacier expansion sea levels would fall as water extracted from the ocean would be locked up in the expanding ice sheets, whereas following the melting of ice (glacial contraction), sea levels would rise as the water was returned to the ocean. This was effectively the first statement of the 'glacio-eustatic theory'. Subsequent work on the coasts of Scandinavia and Scotland concluded that the depression of the Earth's crust – under the weight of additional ice sheets upon it – would eventually result in crustal rebound once the ice was removed. This became known as 'glacio-isostatic theory' (Jamieson, 1865). Since Jamieson's (1865) work, post-glacial (Holocene) *relative* sea-level changes have been recognised to be (primarily) a result of a combination of two processes: eustasy, the global volume of water in the ocean, and isostasy, the crustal movement of land.

The preservation and accessibility of field evidence are the primary components in the study of former sea-level change. It is therefore inevitable that most recent work on sea-level variations has concentrated on the Holocene period (*ca.* 10,000 years before present (BP)), when widespread sequences of coastal sediments were deposited (Sutherland, 1991). Holocene sea-level studies began to 'snowball' in the 1960s as a significant number of researchers sought to map past global sea level, under the belief that there would be a universal pattern of change (Emery et al., 1954; Godwin et al., 1958; Shepard and Suess, 1956; Shepard, 1960). It was subsequently realised that interactions of glacio-isostatic, eustatic, hydro-isostatic and gravitational effects would produce a different sea-level curves for every location on Earth (Clark, et al., 1978; Mörner, 1976). Researchers believed that, so long as allowances for crustal changes were made in unstable areas, a common eustatic curve could be constructed by combining the records with data from (presumed) stable regions (Kidson, 1986).

A new stimulus to sea-level studies emerged in 1974, however, with the implementation of the International Geological Correlation Programme's IGCP Projects. The first, Project 61 *Sea-level change during the last deglacial hemicycle (about 15,000 years)*, ran from 1975-82. The project (and subsequent projects) were set up to present newly emerging sea-level research and to develop a community base where knowledge and expertise could be shared. It was jointly aided by the International Union of Geological Sciences (IUGS) and the United Nations Educational, Scientific and Cultural Organisation (UNESCO). Project 61's primary aim was to develop a single global (eustatic) sea-level curve allowing the comparison and correlation of sea-level records worldwide, and this was to be complemented by a computer based data bank of all the sea-level records available (Shennan, 1989). This goal was eventually abolished as it became commonly accepted that tectonic, isostatic and gravitational factors rule out the possibility of a sea-level curve with a global relevance (Kidson, 1986). Shennan (1989) points out that other unstated aims, such as the prediction of near future changes in sea level, and their application to coastal problems, were to become more evident in later projects. Overall, Project 61 succeeded in establishing a research community that presented new sea-level data along with new hypotheses. Consequently, the continued discussion of unresolved issues helped address some of the key methodological developments (and aims) necessary for the success of future projects and sea-level research.

Many of the problems that existed at the start of Project 61 were passed on to the IGCP's subsequent Project 200 *Late Quaternary sea-level changes: measurement, correlation and future applications* (1983-87). This identified the development of a uniform methodology, with a more interdisciplinary approach, as a key requirement. The universal methodology was supported by an emphasis on three lines of investigation, namely: to identify and quantify the processes that operate to control sea level; to produce local and regional sea-level curves; and to consider the likely effects of future sea-level rise on populated coastlines (Kidson, 1982; Tooley, 1982, 1985). One of the major outputs during the project was van de Plassche's (1986) manual for sea-level research, a publication that remains a key source of reference for many palaeo sea-level researchers. The following IGCP project proved very timely as concerns began to rise regarding increased atmospheric gases and the potential effects of projected global sea-level rise (Shennan et al., 1995). Project 274 *Quaternary coastal evolution: case studies, models, and regional patterns* ran from 1988-93. Many of the papers produced as part of the project provided new high quality sea-level data, but additionally a new methodological approach was presented by a number of authors (e.g., Shennan and Woodworth, 1992; Gehrels, 1994). Their research moved on from a (principally) data collection phase, to incorporate an approach involving the testing and use of modelled parameters (e.g., crustal responses and tidal changes). A further benchmark publication that was presented during the project was Pirazzoli's (1991) *World atlas of Holocene sea-level changes*. The atlas was originally planned to be compiled during Project 200, though inadequate funding and contributions meant it never materialised. Pirazzoli successfully presented the most recent knowledge of regional sea-level changes from all over the world (over 50 regions).

IGCP's final project of the 20th century (Project 374) began in 1994, *Late Quaternary coastal records of rapid change: application to present and future*. The aim of the project was to look at the evidence, and the explanations, of rapid changes in the coastal zone. Quaternary climate records (obtained from ice and deep-sea cores) revealed apparent trends of instability during interglacial climates and the possibility of catastrophic events. The further development of high resolution sea-level records, methodologies and the integration of modelling techniques, however, were essential to the project's aim. The results were to be used to assess the occurrence of global and regional scale sea-level impacts, and to help identify possible future coastal problems regarding catastrophic events. Again, the emphasis of the implications on populated areas and the management of future coastal change continued into the Project 437 (1999-2003), *Coastal Environmental Change during Sea-level Highstands: A global Synthesis with Implications for Management of Future Coastal Changes*. Model simulations again appeared in the publications produced during the project but with the added incorporation, and attempted comparison, of more recent instrumental records (tide gauges) to further test high resolution (late Holocene) sea-level histories (e.g., Gehrels et al., 2005). This approach of comparing more recent records with those from the geological record offers new information of human-induced climate change and the linkages between oceans, sea level and climate. It also provided a further method of calibration between contemporaneous sea-level records.

Overall, in the thirty years of IGCP projects, the global palaeo sea-level community has developed and improved methods of obtaining local, regional and global records of sea-level change. The development of an interdisciplinary approach has allowed the identification of linkages in records between terrestrial, coastal and marine environments and a wealth of publications to be produced. The most recent projects, Project 495 *Quaternary land-ocean interactions: Driving mechanisms coastal responses* (2005-2009) and Project 588 *Preparing for coastal change: detailed process-response frameworks for coastal change at different timescales (2010-2014),* have sought to build on the work established during previous projects, and include work from other disciplines such as geology, archaeology, and marine and fluvial sciences. Improving methodologies to obtain high-resolution records comparable with others (including models and instrumental records) is a major emphasis. An overarching focus for Project 588 (2010-2014), however, is on human influences and reactions to coastal processes and the production of research with immediate stakeholder interest. Comparative research using geological data, models and instrumental measurements can offer information on sea-level changes with real practical value and use (Gehrels and Long, 2008). Extending the link between science and its application to coastal problems seems to be of high priority for research into coastline evolution. Some of the methods used to obtain palaeo sea-level data are now discussed.

2.3 Obtaining relative sea-level (RSL) data

The most basic means of measuring changes in sea level at a particular location is to use data from tide-gauge stations. Measurements at coastal tide-gauge stations contain contributions both from eustatic and isostatic movements, providing continuous records of sea-level changes at an hourly to 100 yr time scale (Woodworth et. al., 1999). The focal point for recording and computing sea-level data from worldwide tide-gauge records is the Permanent Service for Mean Sea Level (PSMSL) based at the National Oceanographic Centre (NOC) in Liverpool, England. To be useful for sea-level studies a tide-gauge record should be temporally dense and long, and retain its internal consistency, but this can be problematic in some records because of repairs and replacements (Douglas, 2001). Yet tide gauges have been used extensively during this century to estimate sea-level changes (Aubrey and Emery, 1991) and such readings are available for a few sites as early as the 19th century (e.g., Brest, France (1807) and Sheerness, England (1832), see Figure 2.5). Due to the nature of the instruments – not least the expense involved in setting up and maintaining them – there is a spatial bias in the number of tide gauges to the Northern Hemisphere, and an even bigger bias in the length of time over which the gauges have been recording. As a result, over 80% of tide gauges have been recording for less than 60 years, and this makes their utility in mapping global sea levels problematic. In addition, the short-term nature of records means that long-term trends in RSL change cannot be constructed. Consequently, longer-term records of past sea-level changes are constructed using geological evidence obtained from locations all over the world.

Organic and minerogenic sediments and landforms whose origin was controlled by palaeo sea levels can offer reliable evidence of the height of past sea level relative to present (Shennan et al., 2006). Where such sediments and morphological features survive they can be used as sea-level index points (SLIPs). SLIPs are obtained by clarifying four attributes: location, age, altitude and tendency. The location of a SLIP simply consists of geographical coordinates of the site from which the sample was collected, and the age attribute is typically measured by radiocarbon dating techniques. The altitude of a SLIP is determined by the ‘indicative meaning’ which defines the relationship of the sample to tidal range. This allows the measurement of ‘relative’ sea-level changes (RSL), defined relative to present (van de Plassche, 1986). Finally, the tendency of a SLIP describes the increase (positive tendency) or the decrease (negative tendency) in marine influence recorded by the index point. A sophisticated understanding of what constitutes a reliable SLIP and actual palaeo sea level has been developed by a number of researchers (e.g., Tooley, 1978; van de Plassche, 1986; Shennan, 1986; Shennan, et al., 1995; Gehrels, 1999; Edwards, 2001). This knowledge, along with recent reconstruction and dating methods, has developed the precision necessary for reconstructing sea-level histories over time scales that can fill spatial gaps in the observational record (Woodworth et al., 2009). Early studies attempted reconstructions without the benefit of these recent advancements in science (e.g., Heyworth and Kidson 1982; Morey, 1983), but their findings remain valuable in constraining results from later research. The general techniques employed in sea-level reconstruction are now described.

2.3.1 Lithology-based approaches

For many years sea-level investigations (and SLIPs) relied heavily on sedimentary or 'lithological' reconstructions. Although research often makes use of the geomorphological evidence of former sea levels (e.g., raised beaches, rock platforms, deltas, spits, stacks and caves), a completed picture of sea-level change can only be obtained by combining geomorphological data with evidence from the stratigraphic record (Lowe and Walker, 1997). The lithostratigraphic method uses the analysis of stratigraphic boundaries between freshwater and marine units. This was developed within the context of the ICGP Projects 61 and 200 (Shennan, 1982, 1986; van de Plassche, 1986). Not only can valuable data be taken from the sediments themselves – in the form of observations taken from depositional environments preserved in the stratigraphic records − but many deposits are also fossiliferous and interpretations based on lithological evidence can often be supported directly by the fossil record (Lowe and Walker, 1997). This increases the reliability of sea-level interpretations and SLIPs.

The quality of SLIPs can vary during sampling however. SLIPs obtained from sediments that have formed directly overlying a hard substrate (e.g., Holocene sands or bedrock) are compaction free, because sediments from which the samples are taken are not likely to have been displaced vertically over time. These are known as 'basal' index points and are of the highest quality possible. Samples taken from deposits found buried within thick sediment sequences are of far lesser quality as they may have been displaced downwards due to the weight of the overlying sediments. These are known as ‘intercalated’ index points and often plot below basal index points, essentially, overestimating sea-level changes. More details of this, including an illustration, are given in Chapter Three. By removing any chance of compaction within the sediments, the reliability of RSL histories is thus significantly improved (Gehrels, 1999; Shennan and Horton, 2002). More recently, quantitative approaches are being employed in sea-level studies – mainly on the basis of the precision they can achieve – although a thorough understanding of the lithostratigraphy should form the framework of any attempted sea-level reconstruction (Szkornik et al., 2007).

2.3.2 Quantitative techniques

Quantitative techniques have increased the accuracy of sea-level science by establishing a better understanding of microfossils (e.g., foraminifera, diatoms, testate amoebae), found in buried intertidal sediments, and their subsequent use as sea-level indicators. These indicators allow direct observations to be made between present sea level and those being reconstructed from the buried sediments. The vertical distribution of microfauna in the intertidal zone is controlled by flooding frequency and salinity and, as a consequence, elevation relative to tidal height (Gehrels, 2000). This ecological consequence, and its relation to tidal height, provides a useful tool for reconstructing former sea levels (Scott and Medioli, 1986; Massey et al., 2006a). Imbrie and Kipp (1971) provided the first quantitative estimate of environmental change, using marine foraminifera found in ocean cores, in order to reconstruct sea-surface temperature and salinity. The further development of quantitative methodologies has become a major theme in sea-level research since the late 1990s (e.g., Gehrels, 1999, 2000; Gehrels and van de Plassche, 1999; Horton, 1999; Horton et al., 1999a, 1999b, 2000; Edwards and Horton, 2000; Edwards, 2001; Horton and Edwards, 2005; Massey et al., 2006a, 2006b). The methodologies pursued in the IGCP’s

Project 495 (2005-09) were designed to develop quantitative, high resolution records of RSL change that can be compared with other local, regional and global records of environmental change. Microfossil-based transfer functions provide one way in which to achieve this, and are useful environmental reconstruction tools that allow an environmental parameter (e.g., acidity, temperature, elevation) to be expressed and quantified as a function of biological data (e.g., pollen, foraminifera and diatoms) (Birks, 1995).

The methodology involved in creating a transfer function involves four stages. Firstly, the modern (present day) biological and environmental data must be collected. This must then be analysed and related to the environmental variable of interest (e.g., salinity, elevation), usually using ordination techniques allowing a wider cluster of data to be explored for possible trends. The relationships identified are then modelled to develop a transfer function, typically using multiple regression analysis. Finally, the data from the transfer function are applied to a fossil core to reconstruct the environmental variables and infer past environmental conditions (Birks, 1995, 1998). The models used to analyse modern data sets, and the subsequent regression analysis used to develop the transfer functions, fall into two main categories: linear-based and unimodal-based techniques (Birks, 1995). Each contains various methods of analysis, and a full discussion of the techniques can be found in Jongman et al., (1995) and Lepŝ and Ŝmilauer (2003). Recent research, however, has shown that multiple indicators offer highly accurate and precise reconstructions of past tidal levels (Gehrels *et al.,* 2001). Diatoms (Shennan et al., 1994; Zong, 1997; Zong and Horton, 1999), testate amoebae (Charman *et al.,* 1998, Gehrels et al., 2006), and plant macrofossils (Belknap et al., 1989) are typical of such proxies found at specific heights within the tidal frame. Since the late 1980s, the emphasis on the development of modelling techniques in sea-level research has also grown, and numerical models have proved useful in allowing the separation of eustatic and isostatic trends from quantitative sea-level reconstructions in different regions (Gehrels and Long, 2008).

2.3.3 Numerical modelling of relative sea-level changes

Following the development of the glacio-isostatic theory by Jamieson (1865), the conceptual theory was taken further by pioneers in the 1930s and 1940s who strived to quantify the geophysical response of the Earth's crust to ice loading (McConnell, 1965). Geophysicists routinely compare quantitative geological studies of sea-level change with predicted sea-level responses produced by their models (e.g., Lambeck, 1995; Peltier, 1998; Milne et al., 2006; Shennan et al., 2006), and likewise sea-level histories old and new can be used as primary data to tune global and regional models (Peltier, 2002). Much of the work carried out by geophysicists regards quantifying eustatic sea levels and isostatic response known as glacial isostatic adjustment (GIA). Despite significant advances over the last decade key debates remain unresolved regarding the quantitative components used in numerical models at both regional and global scales. Components include the palaeotopography and the melt history of ice sheets, which control the ice equivalent sea-level rise and the loading of the Earth's crust, and Earth rheology, which controls crustal response. If these issues are to be resolved, and if models are to improve our understanding of palaeo-environmental change, a large number of geological reconstructions for further testing and comparisons will be needed (Shennan et al., 2002; Gehrels, 2010).

Due to its past glacial history, and the number of geological reconstructions carried out, the United Kingdom remains one of the key regions for developing geophysical models capable of quantifying GIA. Although small in global terms, at the Last Glacial Maximum (LGM) the ice sheet that covered the British Isles was sufficiently large for the GIA processes to produce vastly contrasting RSL at different locations. The United Kingdom's locality near to the ice limits of the LGM, and its influence from both the Scandinavian and British ice sheets, have contributed to the UK being regarded as 'the most exotic [place] on Earth from the perspective of GIA' (Peltier, 1998: p.609) and the ideal testing ground for geophysical modellers (e.g., Lambeck, 1995, 1997; Peltier et al., 2002; Shennan et al., 2006; Milne et al., 2006; Bradley et al., 2009). Not only is the region important for constraining local scale parameters, like the effects of vertical land movements, but it is also significant in constraining reconstructions of ice sheets that have a global relevance to changes in sea level (Shennan et al., 2002; Bradley, et al., 2009). Thus, palaeo sea-level reconstructions in the UK have a fundamental role in geophysical model development and in increasing our understanding of linkages between ocean dynamics, sea level and climate.

2.4 Holocene sea-level changes in the UK

Since Godwin (1940) developed the first Holocene sea-level curve for the UK, knowledge of the methods and techniques used in reconstructing Holocene sea-levels has increased significantly (as discussed), yet the quality and quantity of data available still varies around the UK coastline (Gehrels, 2009). The database of the UK's Holocene SLIPs has been stored at the University of Durham since 1987. The entire geological data set was first reviewed by Shennan (1989) to produce a comprehensive analysis of the disparity of sea and/or land-level changes around the British coastline since the early Holocene. Sea levels around UK coastlines increased rapidly during the start of the Holocene. This can be observed from data taken in northwest Scotland (e.g., Shennan et al., 2000), northeast England (e.g., Plater and Shennan, 1992), mid-Wales (e.g., Heyworth and Kidson, 1982), East Anglia (e.g., Coles and Funnel, 1981) and southwest England (e.g., Healy 1995, 1999). At the beginning of the Holocene (~10,000 yrs BP), sea levels ranged from 10 – 25 m below present in some UK locations (Shennan and Horton, 2002) and, collectively, the records generally identify a marine transgression (rise) that tapered off in the mid Holocene (7000-5000 yrs BP). From this period a distinct spatial pattern of sea-level change can be observed, and this pattern primarily reflects the effect of the GIA processes since the LGM (Figure 2.1).

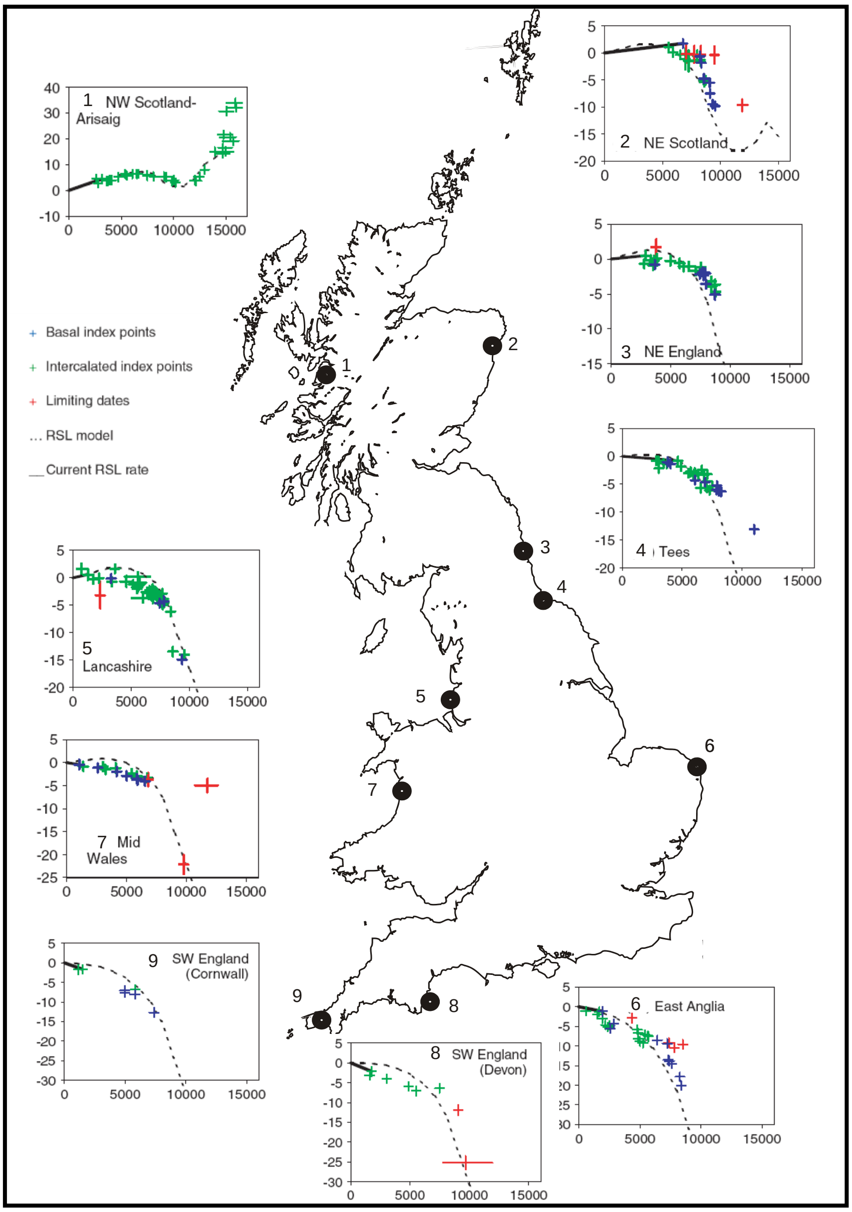

Figure 2.1 United Kingdom relative land- and sea-level changes during the Holocene. Adapted from Shennan and Horton (2002). Some examples of typical sea-level change are shown and the effects of glacio-isostatic adjustment (GIA) can be observed in the difference between Northern and Southern records.

During the mid Holocene period (7000-5000 yrs BP) a relative sea-level high stand was recorded in northern areas of Scotland, but thereafter RSL dropped as crustal uplift in Scotland continued. Similarly observations from southern Scotland, northern England and Wales show the transition from sea levels higher than present to RSL lower than present. Observations from both the east and west coasts show a clear north-south divide in RSL tendencies (i.e. negative to positive) as more marine influences and/or subsidence is observed in southern regions (see Figure 2.1).

On the west coast negative tendencies recorded in Lancashire (e.g., Tooley, 1978, 1985) give way to positive tendencies recorded southward from the Mersey (e.g., Tooley, 1974, 1978). On the east coast this switch is observed further north around the Tees (e.g., Tooley, 1978; Plater et al., 2000). Shennan and Horton (2002) further reviewed Holocene sea-level changes around the coasts of the UK and contrasted geological observations with estimates from geophysical models. This enabled the authors to produce a map of Holocene relative sea- and land-level changes around the UK, summarising the pattern that has emerged from decades of geological research and the apparent subsidence/uplift associated with GIA (Figure 2.2).

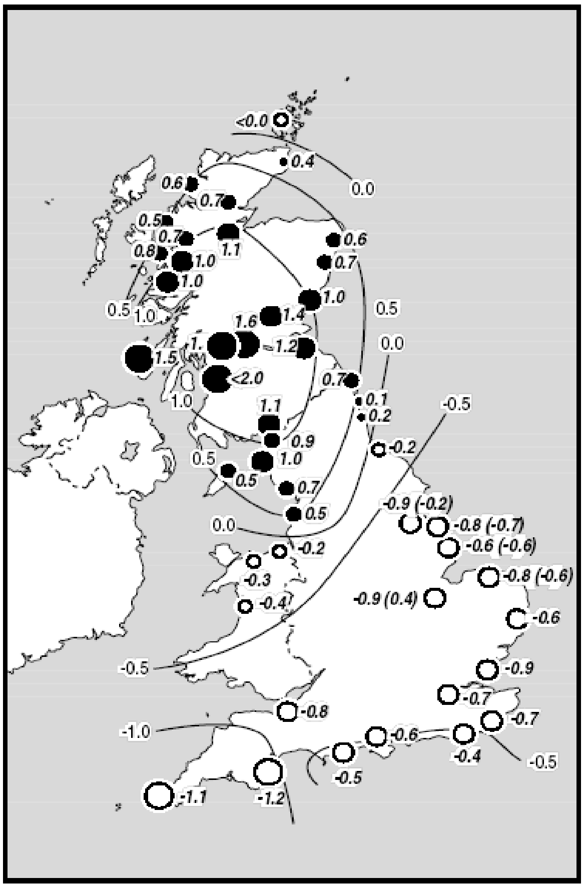

Figure 2.2 Relative land-/ sea-level changes in mm/yr in Britain. Open dots are locations that are undergoing relative land subsidence or sea-level rise. Filled dots are locations that are undergoing relative uplift or sea-level fall. Source: Shennan and Horton (2002).

It was recognised, however, that certain sea-level reconstructions display significant disparities with RSL predictions from GIA models prompting further investigation. The far southwest of England is one area where the quality of sea-level index points has been debated (Gehrels, 2006; Massey et al., 2008; Gehrels, 2010). Shennan and Horton (2002) concluded that the southwest of England has undergone the highest rates of subsidence in the entire UK, estimating up to - 1.2 mm/yr^{-1} of relative land subsidence in the last 4000 years (late Holocene). Current geophysical models also show that the Southwest is affected by post-glacial land subsidence which is the combined effect of the melting of the British/Irish and Scandinavian ice sheets. However, there are still misfits between geological observations and model outputs. The current GIA model reconstructions have produced trends that show vertical ranges as large as two metres during the mid to late Holocene (Figure 2.3).

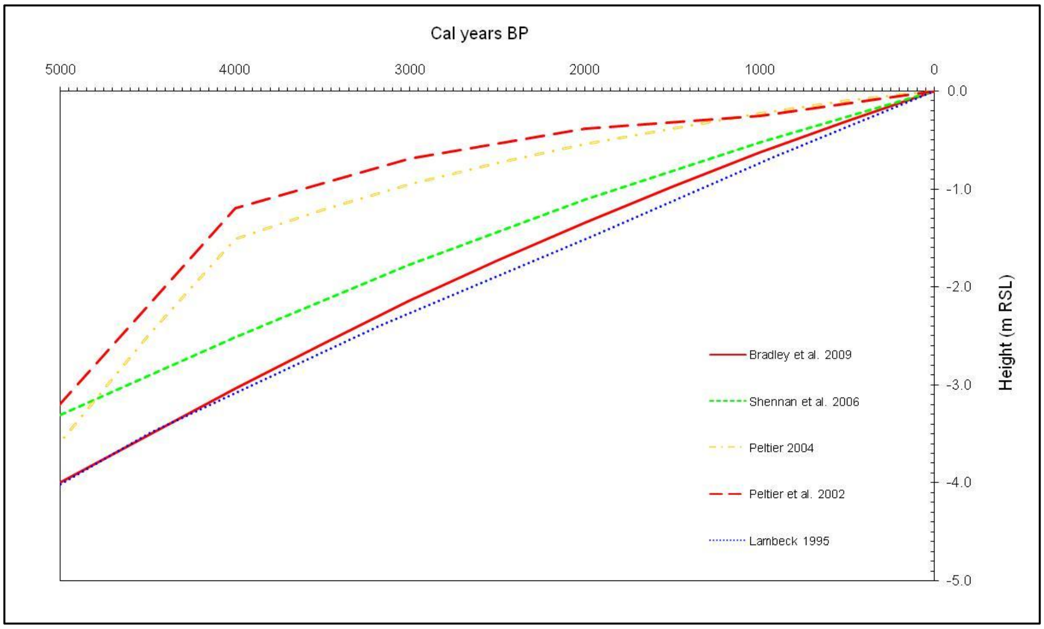

Figure 2.3 Late Holocene sea-level changes estimated by five geophysical models (Lambeck, 1995; Peltier, et al., 2002; Peltier, 2004; Shennan et al., 2006; Bradley et al., 2009).

Additionally, more inconsistencies arise when comparing geological reconstructions with instrumental records from tide-gauge data (e.g., Woodworth et al., 2009) and recent GPS and gravity measurements (e.g., Teferle et al., 2009; Bradley et al., 2009). GPS measurements indicate absolute subsidence rates of 0.0 ± 0.5 mm/yr^{-1}, whilst gravity measurements determine the figure to be 0.9 ± 0.9 mm/yr^{-1} (Teferle et al., 2009). Instrumental measurements, however, are still constrained by a limited length of observations capable of reliably inferring accurate long-term rates of change. The improvement of the technology along with the length of observations is the only way these techniques, and their measurements, can help refine current geophysical models (Gehrels and Long, 2008; Gehrels et al., 2011). The model developed by Bradley et al., (2009) is used in current projections of future sea-level rise in the UK thus its accuracy is of importance to the region. Consequently, long term geological sea-level records are needed to refine these predictions, and the current records of sea level change available in the Southwest are now reviewed.

2.4.1 Sea-level records in the Southwest

Studies of Holocene coastal evolution and RSL change in the southwest of England are limited in comparison with the rest of the UK (Healy, 1995; Waller and Long, 2003; Massey et al., 2008). This is surprising given that Shennan and Horton's (2002) review of post-glacial sea-level changes estimate that the region is subsiding faster than any other shoreline in the UK. The majority of sea-level records available have been obtained from SLIPs from the English and Welsh coastlines along the Bristol Channel, but the lack of SLIPs in the extreme Southwest has been raised by a number of authors (e.g., Heyworth and Kidson, 1982; Haslett et al., 1997; Waller and Long, 2003; Gehrels, 2006; Massey et al., 2008; Gehrels, 2010). Studies along the coasts of Devon and Cornwall have produced only 18 scattered SLIPs, compared with a total of 78 from research in the Bristol Channel area. The region has been subsiding since the LGM (Hawkins, 1971; Emery and Aubrey, 1985; Woodworth, 1987; Allen and Rae, 1988; Shennan, 1989; Allen, 1991; Shennan and Horton, 2002; Shennan et al., 2006; Bradley et al., 2009), although some authors have (mistakenly) argued that there had been little or no subsidence, and recent trends were thought to reflect isostatic and tectonic stability (Churchill 1965; Kidson and Heyworth, 1979; Heyworth and Kidson, 1982).

The constraints on sea level during the early to mid Holocene (around 11500-5000 cal years BP), however, are reasonably well defined. Aided by the improvement of reconstruction techniques, more recent studies have established detailed local changes of RSL (Figure 2.4). Work by Massey et al., (2008) established that between 9000 and 7000 cal years BP the south Devon coastline underwent extensive marine transgression as sea levels were rising ~ 5.4 ± 2.1 m/kyr. The evidence indicates that the pace of the early Holocene marine transgression abated within 2000 years (ca. 9000-7000 cal years BP), and sea levels have risen 21 ± 4 m during the past 9000 years and around 8 ± 1 m during the mid to late Holocene (Massey et al., 2008). This is consistent with data from a number of areas in southwest Britain (Hawkins, 1971, 1979; Kidson, 1973, 1976; Morey, 1976; Heyworth and Kidson, 1982; Healy, 1993, 1995, 1996). The pace of the mid-Holocene sea-level rise in south Devon slowed to ~0.9± 0.4m/kyr around 7000 cal years BP, and this has been confirmed in much of the literature from other locations in the region (e.g., Hails, 1975a, 1975b; Healy, 1995). The RSL history during the early to mid Holocene shows a slight misfit with geophysical model predictions.

It is evident, however, that some geological reconstructions in the Southwest using SLIPs (e.g., Churchill, 1965; Hawkins, 1971, 1979; Kidson and Heyworth, 1973, 1976, 1978; Hails, 1975a, 1975b; Morey, 1976, 1983; Heyworth and Kidson, 1982) have been published without accurate relation to former sea level (Shennan, 1983; Haslett et al., 1997; Gehrels, 2006). Stratigraphic details are frequently lacking and the biostratigraphy used in the analyses are of questionable quality. For instance, the quantification of an indicative meaning is essential to reconstruct reliable palaeo-water levels, and the fact that many authors have not assigned these to their SLIPs means the accurate interpretation of

Holocene sea-level histories cannot be made (Haslett et al., 1998). This is shown clearly in the late Holocene records from Devon and Cornwall (see Figure 2.4).

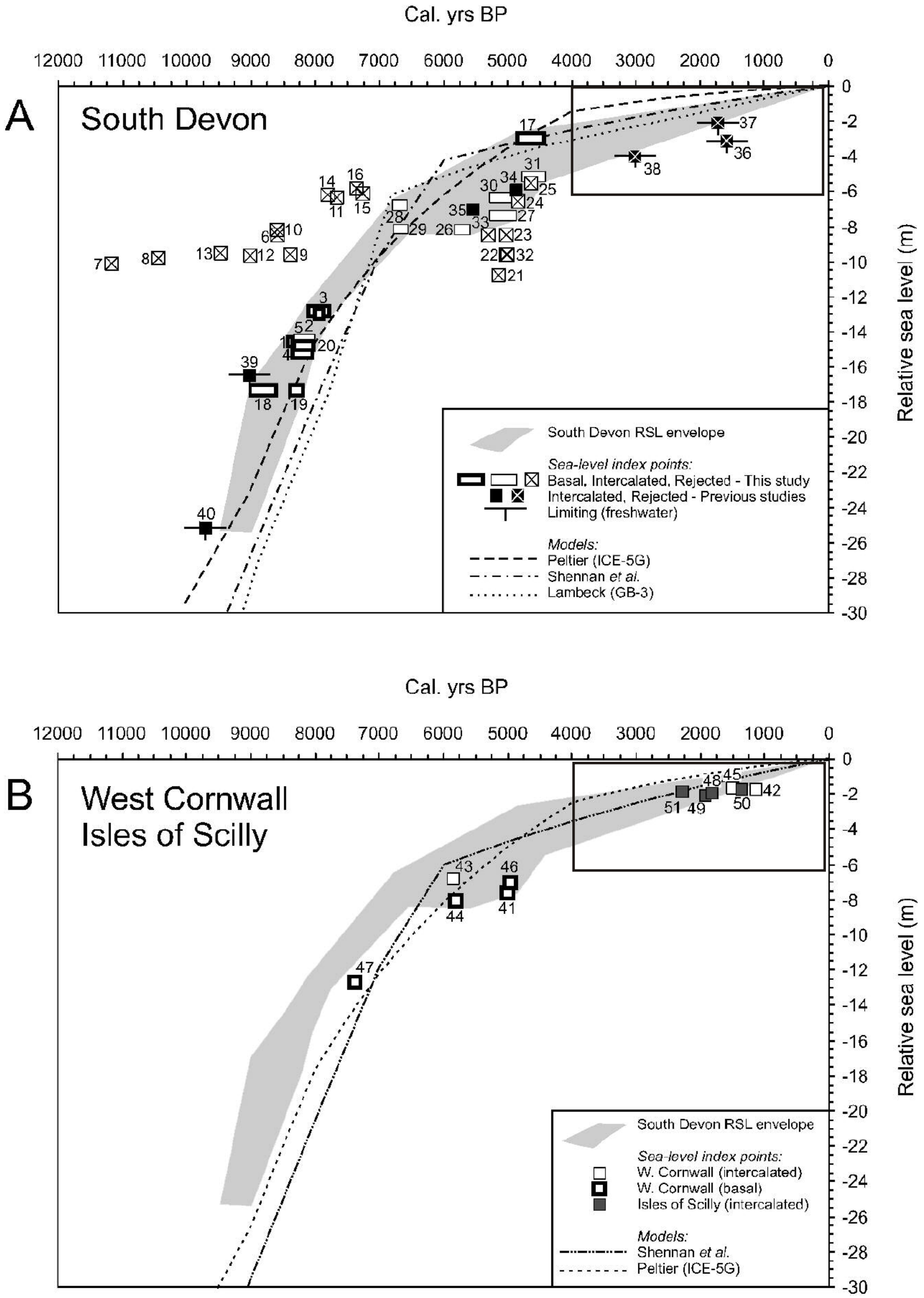

Figure 2.4 (A) Sea-level index points from south Devon compared with three sea-level curves predicted by geophysical models. The envelope of relative sea-level change encompasses the accepted data points. (B) Sea-level index points for western Cornwall (Healy, 1995) and the Isles of Scilly (Ratcliffe and Straker, 1996) compared with south Devon relative sea-level envelope and model predictions. Numbers 1-33 represent new data collected by Massey et al., (2008). The late Holocene period under discussion is highlighted (boxed). Source: Massey et al., (2008).

2.4.2. Late Holocene sea-level records in southwest England

The late Holocene period in southern England is generally characterised by widespread coastal inundation resulting in a return to predominately minerogenic sediments (Waller and Long, 2003), but the evidence available from the Southwest presents a contrasting picture. Morey (1983) and Healy (1995, 1996, 1999) both dated organic horizons that suggested the development of fresh water conditions in coastal back barrier environments during the late Holocene. RSL rise in the region slowed to around 0.8 -1.6 m/ka ca. 3200-1000 cal years BP (Hails, 1975; Heyworth and Kidson, 1982; Morey, 1983; Waller and Long, 2003; Edwards, 2006). These late Holocene SLIPs have been used to estimate the highest rates of isostatic subsidence in the UK of -1.12 mm/yr in western Cornwall and -1.23 mm/yr in south Devon (Shennan and Horton, 2002; Figure 2.2). The SLIPs used by Shennan and Horton (2002) to calculate the rate of relative land movement in west Cornwall and south Devon are based on four intercalated index points (see Table 2.1 and boxed section in Figure 2.4). These data points have been utilised by numerous authors in the last two decades (e.g., Haslett et al., 1997, 1998; Waller and Long, 2003; Gehrels, 2006; Massey et al., 2008).

Site	Laboratory code	Latitude (N)	Longitude (W)	^{14}C Age	±	Calibrated age range (BP)	RSL (m)	Vertical error (m)	Reference
North Hallsands Devon	SRR317	50º14'15''	003º39'28''	1683	40	1517-1706	-3.165	0.65	Morey, 1976
Slapton Ley Devon	SRR492	50º16'58''	003º39'08''	1813	40	1621-1864	-2.155	0.55	Morey, 1976
Marazion Marsh	Q2775	50º07'44''	005º28'54''	1210	40	1014-1263	-1.75	0.70	Healy, 1995
Marazion Marsh	Q2778	50º07'40''	005º29'04''	1610	40	1403-1601	-1.67	0.70	Healy, 1995

Table 2.1 Sea-level index points used by Shennan and Horton (2002) to compute relative subsidence rates for southwest England (see boxed sections) in Figure 2.5 and modified from Massey (2004). Radiocarbon calibrations are according to Reimer et al., (2004). BP – Before Present (Present = AD 1950). Source: Gehrels (2006), reproduced with the permission of the Devonshire Association.

The west Cornwall index points were published by Healy (1995) and were taken from Marazion Marsh where samples from a buried fresh-water peat bed were dated. The peat is overlain by a layer of fine sand two metres below the present surface and is underlain by several metres of coarse sand and shells. Healy (1995) did not discuss this peat layer due to modern artefacts being identified within parts of the sequences thus indicating some level of disturbance by anthropogenic activities. Analysis of the peat found no brackish or marine microfossils and, therefore, attaching a sea-level relationship to this layer is impossible. In a later field guide Healy (1999) produced a pollen and diatom record for an organic-rich sequence found in the upper sections of Marazion Marsh. The stratigraphic evidence shows the replacement of a brackish environment by freshwater conditions, but it is not clear how these relate to the radiocarbon dates. Furthermore, sediment consolidation is likely to be significant as the weight of the overlying clastic layer would have reduced the thickness of the peat bed (Gehrels, 2006). In review of this information, the accuracy of the late Holocene sea-level history of western Cornwall remains highly questionable. Interestingly, similar problems are observed when examining the south Devon index points taken from Hallsands and Slapton Ley.

Morey (1983) dated a tree stump found in an eroding peat bed on the beach at Hallsands, and this was dated at 1643±40 cal yr BP. It is generally considered among researchers in the field that tree stumps are not reliable indicators of sea level as their height cannot be directly related to a former tidal height or zone (Gehrels, 2006). Morey (1983) interpreted the date to represent the death of the tree due a wash over event and thus assumes the tree was growing at, or near, sea level. Further analysis of the peat found no marine or brackish microfossils and the pollen analysis proved to be indicative of a fen marsh environment. It is likely, therefore, that the tree would have been growing well above sea level, and at best the tree stump can only be utilised as a ‘limiting’ date. A second index point was obtained from the top of a fen peat bed buried beneath lake deposits at Slapton Ley, and this was dated at 1813±40 cal yr BP. Pollen found in the section was indicative of a sedge (*Carex*) dominated fen community, and similar to that found today around the Ley. Furthermore, at present the water table of the Ley is well above that of the sea, and is not only dependent on the height of MSL but also the discharge of streams and the precipitation-evaporation balance of the lake. As these are not accounted for it is evident that the indicative meaning of this peat bed is (again) questionable (Gehrels, 2006). Shennan and Horton's (2002) use of late Holocene SLIPs from Devon and Cornwall, consequently, includes considerable vertical uncertainty.

In Shennan's (1989) original interpretation of relative land and sea-level movements it was concluded that the southeast of England was the focal point for isostatic subsidence. In Shennan and Horton's (2002) update the focal point moved over to the extreme southwest as sediment consolidation was claimed to have produced overestimates in the southeastern records. In order to obtain accurate estimates for relative late Holocene land motion for the entire UK, Shennan and Horton (2002) adopted a methodology that would allow for the varying quantity of data available for each site. Where a broad vertical scatter of index points was observed, typically from intercalated SLIPs, the line of best fit relating the SLIPs to present, was (rather simply) placed towards the top of the scatter to minimise the effect of sediment consolidation (see Figure 2.1). An additional requirement was that the line of best fit could not lie above any cluster of limiting dates. This approach, although more accurate than Shennan (1989), creates difficulty in defining the weighted error term given to different data points and additional vertical uncertainty to the calculations made. The error terms for relative subsidence rates of west Cornwall and south Devon are among the highest calculated and are estimated at ±0.21 and ±0.18mm/yr, respectively. With the limited number of late Holocene SLIPs in the Southwest, combined with their questionable quality, calculations are problematic. Firstly Gehrels (2006), and then Haigh et al., (2009), concluded that based on the assumptions in the data, and the methodology used, vertical land movements are not fully understood.

The final (and most recent) late Holocene sea-level records are from instrumental observations. The Newlyn tide-gauge station near Penzance (south Cornwall) has records commencing from 1915 (Figure 2.5), and has recorded an unbroken series of high-quality mean sea level (MSL) data for the last 89 years (Woodworth, 1987). Newlyn has been exceptionally well maintained due to its designation of Ordnance Datum (OD) and, as such, offers the most sensitive recordings of changes in sea level in the Atlantic (Woodworth, 1987). Devonport (Plymouth) also has a tide gauge station that has been recording since the 1960s (Figure 2.5). Due to the length of the Newlyn record, however, it also provides a comparison with those from the tide gauge at Brest (France), across the English Channel, which has a near continuous dataset running from 1807 to present. Trends for the UK south coast are between about 1.2 mm/yr and 2.5 mm/yr, with a weighted average of 1.85 mm/yr (weighted by the SE). Trends along the French Channel coast vary between 1.4 mm/yr and 2.9 mm/yr, with a weighted average of 2.0 mm/yr (Haigh et al., 2009). Both tide gauges show similar sea-level changes and have also indentified that sea levels during 19th century were predominantly more stable in comparison to those of the 20th century (Figure 2.5).

This pattern corresponds with long European instrumental records of temperature change (IPCC, 2007) and geological sea-level data from the western Atlantic (Donnelly et al., 2004, Gehrels et. al., 2005). The data suggest that the onset of accelerating MSL is linked to global temperature rises, and a possible result of human activity (Gehrels, 2006; Gregory et al., 2006). Although the Southwest (Newlyn) has an exceptional record of MSL, the temporal limitations of instrumental records promote the reconstruction of sea-level histories using geological based techniques to lengthen our understanding of sea-level change over longer time scales (e.g., the Holocene epoch). In examining the records of sea-level change in the Southwest a number of uncertainties have been identified. As a result, these uncertainties filter down into the subsequent use of this data which is now examined.

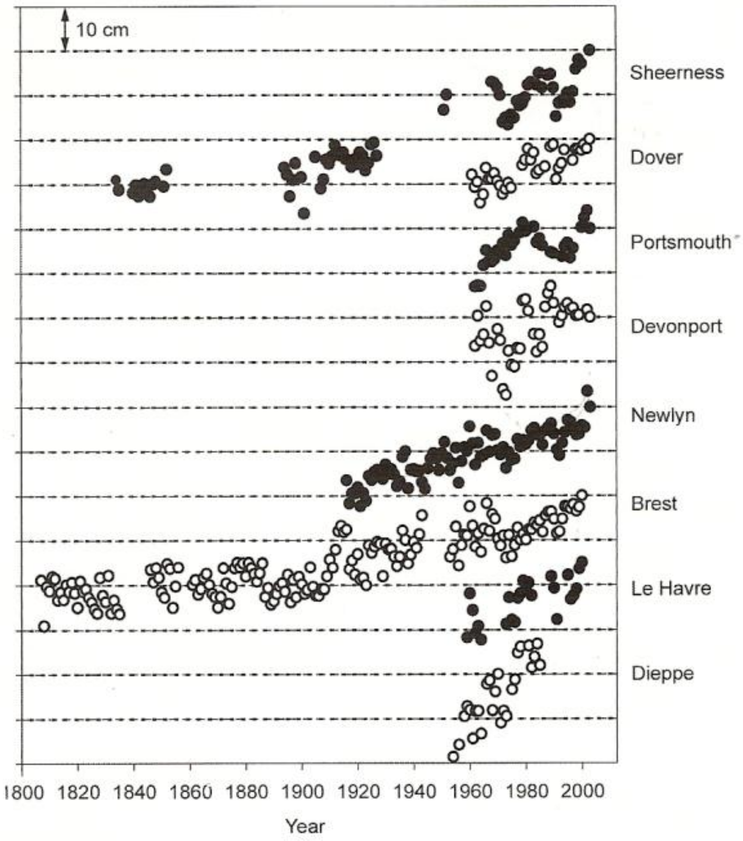

Figure 2.5 Annual tide-gauge observations from both sides of the English Channel for the last two centuries. 20th century sea-level observations show accelerating mean sea levels (MSL), and are a possible consequence of human activities (e.g., carbon emissions). Source: Gehrels (2006), reproduced with the permission of the Devonshire Association.

2.5 Application of sea-level data

It was outlined at the beginning of this review that sea-level studies have developed with the idea of offering data with real practical value. One such example is the geological observations of late Holocene sea-level changes which can be used to extract rates of vertical land movement in the UK (Shennan and Horton, 2002; Gehrels, 2010). Policymakers use the estimates to modify predictions of sea-level rise based on geographical location (e.g., UKCIP, 2005; DEFRA, 2006; Lowe et al., 2009). It is acknowledged, therefore, that late Holocene sea-level studies have considerable societal relevance (Gehrels and Long, 2008; Shennan et al., 2009; Gehrels, 2010). The United Kingdom Climate Impact Programme (UKCIP) is a DEFRA funded organisation (established in 1997) aiming to help public and private organisations adapt to future climate uncertainties (www.ukcip.org.uk). The Shennan and Horton (2002) map (Figure 2.2) was used in UKCIP's regional sea-level projections (Hulme et al., 2002; Lowe et al., 2009) but the use of the map has been questioned by Gehrels (2006), and has subsequently led to the construction of a new map (see Figure 2.6, Gehrels, 2010).

In UKCIP02 (Hulme et al., 2002), however, the original map (Figure 2.2) was misinterpreted to imply figures of absolute land-level movements, when it actually represented relative movements (both land- and sea-level changes). Vertical land movements, and the consequent calculations of sea-level change, were therefore not accurate. UKCIP acknowledged Gehrels' (2006) concerns in August 2006 (UKCIP, 2006), and in October that same year they published an update that lowered the rate of subsidence from -1.2 mm/yr to 0.5 mm/yr (DEFRA, 2006). This correction included a brief footnote to explain that the data had been recalculated with an exponential crustal response as opposed to the original linear one, yet no new geological data had been included in the calculation. The latest update, UKCP09 (Lowe et al., 2009), again includes an evaluation of vertical land movements. However, this time they are provided by independent GIA model estimates (Bradley et al., 2009; Figure 2.6)

GIA models contain three components: an Earth model, an ice model and a sea-level change model. The Earth model used in the GIA simulations by Bradley et al. (2009) was constrained by GPS data (Teferle et al., 2009) to determine optimum parameters for the Earth model, including a lithospheric thickness of 71 km and upper and lower mantle viscosities of 0.5 × 1020 and 3 × 1022 Pa s, respectively (Bradley et al. 2009). To compute vertical land movements the model was combined with the ice model of the British Isles developed by Shennan et al. (2006) and the global ICE-3G deglaciation history (Tushingham and Peltier, 1991) modified by Bassett et al. (2005). The sea-level change model is based on theory developed by Milne and Mitrovica (1998), Mitrovica and Milne

(2003) and Kendall et al. (2005). The algorithm used to calculate present-day crustal motion in response to ice and ocean loading is described by Mitrovica et al. (1994) and Mitrovica et al. (2001).

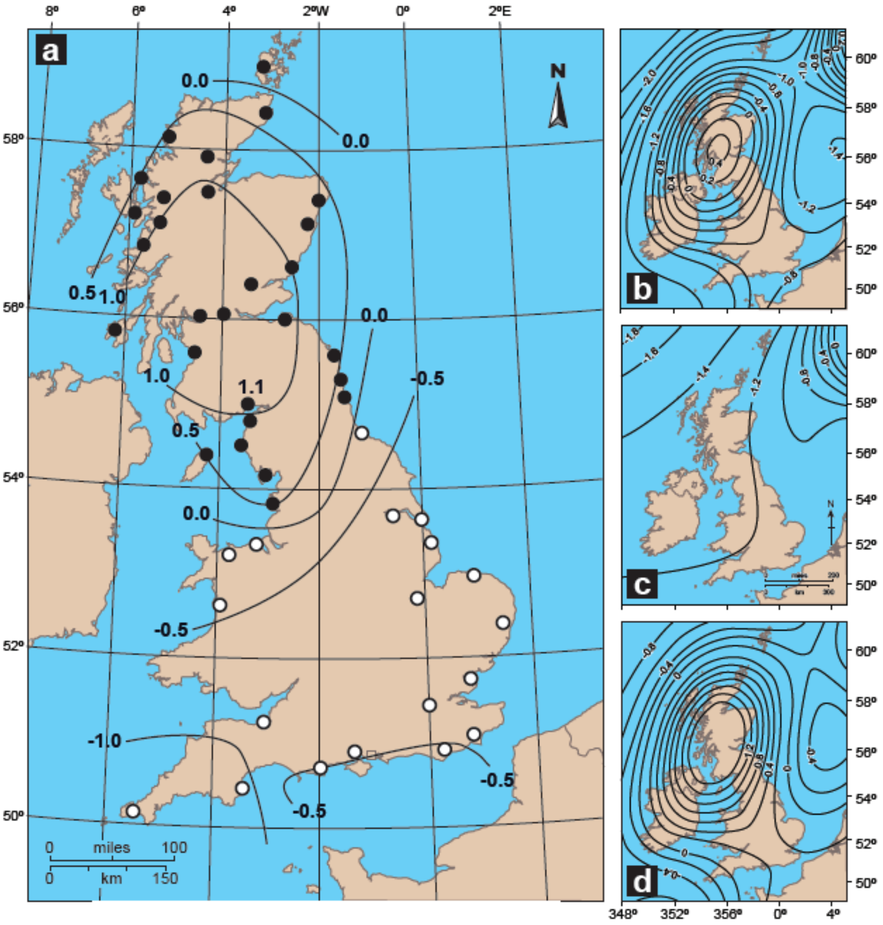

Figure 2.6. Relative vertical crustal movements in mm/yr in Britain according to Shennan and Horton (2002) calculated from late Holocene sea-level index points. Model simulations by Bradley et al. (2009): b. Predicted rates of present-day vertical land movements. c. Vertical land movements due to non-regional effects (i.e. primarily the influence of the deglaciation of Scandinavia). d. Vertical land movements due to regional effects (i.e. demise of the British-Irish Ice Sheet and ocean loading). Adapted from Gehrels (2010 p. 1654).

The GIA model used by Bradley et al. (2009) was tested by Shennan et al. (2006) against the relative sea-level database of Shennan and Horton (2002). From a methodological perspective, the GIA modelling approach to calculate land-motion rates by UKCP09 (Lowe et al. 2009) is an improvement compared to the method adopted by the UKCIP in 2002 (Hulme et al., 2002). Lowe et al. (2009) highlighted the importance of obtaining new relative sea-level data for testing the GIA model in southwest England to verify the postulated rapid rates of land subsidence (Figure 2.2 and Figure 2.6). New data can also improve/validate the geophysical model used for the 21st century sea-level projections (e.g., Bradley et al., 2009, Figure 2.3). More extensively, however, the issue of geological data – and the accuracy of sea-level predictions – has significant implications for coastal flooding in the region.

2.5.1 Implications for coastal flooding

Most coastal flooding occurs when strong storms and low atmospheric pressure combine to produce storm surges and, coupled with high tides, the effects can be devastating. The increased frequency of these extreme events is an important measure of the impacts of future sea-level rise (Nicholls, 2004). The actual relationship between changes in sea level and extreme water levels can be examined by analysing past observations. Newlyn's tide-gauge station has an accurate record of past high water levels for nearly a century. It can be used to estimate the return period of extreme water levels (i.e. the probability that an extreme water level will occur during a given period (Dixon and Tawn, 1995; Gehrels, 2006 (see Figure 1.3)). Taking the record of high water levels from Newlyn tide-gauge station from 1916-1990 and adding a rise in sea level of five centimetres suggests a 1 in 100 year event becomes a 1 in 50 year event. Small changes in sea level can thus have a significant effect on these return periods and the future possibility of coastal flooding. Other factors (e.g., frequency of storm surges and storminess, including wave climate etc.) that cause coastal flooding are still in the research stage (Lowe and Gregory, 2005), and even with no changes in these factors sea-level rise will reduce the return period of extreme water levels (Church et al., 2008). Although extreme weather events cause the most damage to the coast, the limits in the long-term prediction of these water levels mean projections of future sea level offer a more useful tool for strategic coastal planning (Palutikof, 2000; Zong and Tooley, 2003; Lowe and Gregory, 2005; Gehrels, 2006; Hall et al., 2006; Gehrels and Long, 2008; Gehrels, 2009, 2010).

Lowe et al.'s (2009) marine projections (in UKCP09), presented in Chapter One, are intended to help aid coastal planners adapt to climate change and sea-level rise around the UK coastline. Some 1200 km, or one-third, of the English and Welsh coastline has some form of hard engineered shoreline protection, and this is particularly evident in southern England (Environment Agency, 1999; de la Vega-Leinert and Nicholls, 2008). These coastal defences structures are built to a design standard based on the return period of extreme water levels (e.g., 1 in 100 years etc.). Sea-level rise, consequently, poses a significant threat to the life span of current defence structures that protect the low lying regions in the UK. Accurate data on vertical land movements collected near large coastal population centres are crucial to improve the accuracy of future predictions, yet major cities such as Belfast, Bristol, Cardiff, Dublin, Edinburgh and Plymouth are lacking this (Gehrels, 2010). Sea-level rise and extreme water levels are going to be a major threat to society in the next century and predictions and estimates of the impacts will become more crucial in coastal planning. Discrepancies between data (e.g. tide gauge, geological and GPS), however, are likely to be resolved with longer GPS records and the advent of 3D Earth models (Gehrels et al. 2011).The next section of this chapter looks at how the UK is currently geared to manage and adapt to this threat. Particular emphasis is again given to the southwest of England which is predicted to see some of the highest rates of sea-level rise during the 21st century (Lowe et al., 2009).

2.6 Management of UK coasts

The United Kingdom's coastline stretches over 12,000 km (the longest in the EU) and – due to the variety of coastal types and processes – a very diverse range of responses to changes in sea level will occur. Furthermore, in the last two centuries, there has been an increased concentration of socio-economic activity around the coast and the management of the coastline has become important to the British economy (de la Vega-Leinert and Nicholls, 2008; Lowe et al., 2009). It has long been acknowledged that rising sea levels means that managing the coast against potential impacts are a major problem for future policy makers (Devoy, 1987; Nicholls and Mimura, 1998; Turner, 2000; O'Riordan, 2006; Turner et al., 2008). But the diversity of coastline responses, coupled with rising populations, further increases the demand for effective management and long-term planning (Bird, 1993; Nicholls and Mimura, 1998; Edwards, 2007; Nicholls et al., 2008; de la Vega-Leinert and Nicholls, 2008). Figure 2.7 illustrates this by showing the different risk zones of flooding that exist on any low-lying coastline.

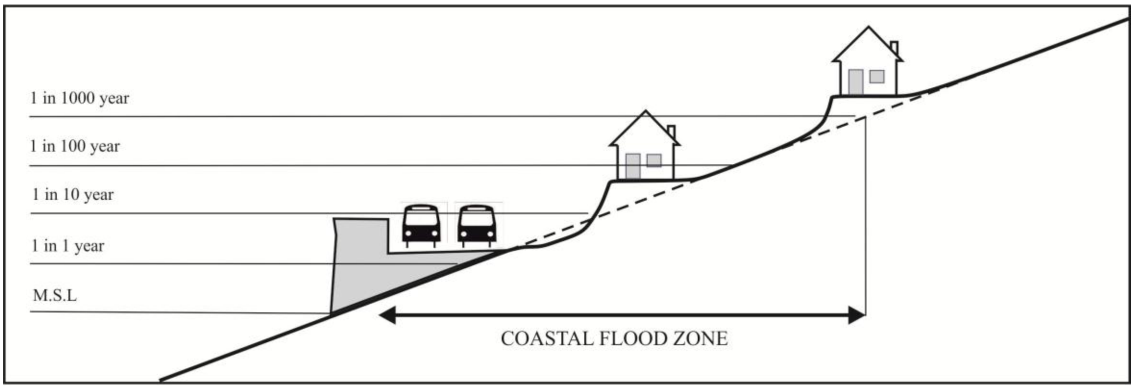

Figure 2.7 An illustration of the coastal flood zone, including different storm surge levels along with corresponding risk zones. Rising mean sea levels (MSL) threaten to raise the flood zones upward and landward increasing the extent of flood risk along our coastlines (adapted from Nicholls et al., 1999 p.72).

Rising sea levels mean these risk zones will migrate upward and landward increasing the area/population susceptible to flooding, and further increasing the vulnerability of the population within the pre-existing flood plain (Nicholls et al., 1999). In terms of costs, it is estimated that with no adaptation or management, the damage of coastal flooding in the UK could range from £1.0 - £13.5 billion annually in the UK. The capital costs required to adapt could be fractional in comparison, and are estimated to be between £12 and £40 billion (Hall et al., 2006). Thus, the assessment of potential impacts of sea-level rise and their adaptation options needs to be more pressing (Parry et al., 2007; Nicholls et al., 2008).

After a recent assessment of the Government's approach to coastal problems - including results from extensive DEFRA/Tyndall technical reports – it was concluded that coastal governance in the UK simply has to change (O'Riordan et al., 2006 p.49). This is despite the Government's increasingly proactive approach to coastal change with, for example, the Foresight *Future Flooding* report commissioned by the Office of Science and Technology (Evan et al., 2004). The report provided an alternative proposal from previous management techniques, namely, stronger stakeholder accountability of coastal planning and protection, whilst reducing the local authority influence (Brown et al., 2005). The report was followed up with the *Making Space for Water* (MSFW) programme (DEFRA, 2005), which was based on the recommendations from the *Future Flooding* report. The report highlighted that UK coastal policy and practice was going through a revolution, as a switch from the traditional 'hard' engineered or 'hold-the-line' approach, is to be phased out to incorporate a more mixed managed approach, with the major emphasis on sustainability and adaptation. Adaptation enables coastal communities to limit their vulnerability by preventing or reducing the potentially negative impacts of sea-level rise whilst benefiting from the potential positive ones (Tol et al., 2008). Managed retreat, for instance, allows the land to be gradually given back to the sea to help maintain natural defences, and this can subsequently allow wildlife habitats to flourish. It is very much a social, political and economic process, however, and it is argued that any assessment requires the involvement of social scientists as much as coastal experts.

Although many researchers have evaluated the technical feasibility of adaptational measures, little consideration is given to the political and economic factors that affect the actual implementation of these measures. Unsurprisingly, there have been increased concerns amongst researchers to integrate natural and socio-economic science into coastal management (Turner, 2000; Nicholls, 2004; Moser, 2005; Nicholls and Tol, 2006; Turner et al., 2007; de la Vega-Leinert and Nicholls, 2008; Nicholls et al., 2008). Olsen et al.

(1997) have long argued that the fundamental challenge of coastal management is one of *governance* (objective, process and structures) rather than *just* technological transfer or scientific knowledge. Furthermore, the transition to a more adaptational approach will not be straight forward, as the politics of coastal management have become increasingly polarised and contested, and are further hindered by a lack of co-ordinated involvement between elected bodies and statutory agencies (Fletcher, 2003; O'Riordan, 2006; Fletcher, 2007; Turner et al., 2007; de la Vega-Leinert and Nicholls, 2008). This evidently adds a further complexity to addressing the current and future coastal problems in the southwest of England.

The most recent Government document for coastal planning, the *Draft Flood and Water Management Bill* (DEFRA, 2008), has been produced for guidance in implementing the objectives set out in the MSFW programme. The aims are to improve Integrated Coastal Zone Management (ICZM) and improve stakeholder involvement through effective dialogue (DEFRA, 2008). Yet concerns still remain about the Government's approach, for instance, how it will cope with (issues of) the physical uncertainties of climate change and the consequent response of coastlines to new management initiatives (POST 2009c). The extent to which increasing the stakeholder engagement addresses the apparent polarised views of the current approach is unknown. This uncertainty, however, if not properly addressed could cause confusion, anxiety, and scepticism in stakeholders, and potentially lead to a loss of trust (O'Riordan, 2006; POSTc, 2009). Timescales are an additional concern for the Government's objectives. The capability to plan on time scales of 50-100 years is difficult when trying to take into account changing electoral constituents and current economic issues. This may become more prominent when further funding is needed to achieve coastal adaptation objectives. Of more concern, however, is the issue that managing the coast does not lie within the remit of a single authority (O'Riordan et al., 2006; POST 2009c), and roles and responsibilities can be confusing, particularly with recent changes in coastal policy:

> '*the arrangements for coastal policy for action and delivery are set in a pattern of governing and financing arrangements that are neither stable nor consistent' (O'Riordan et al., 2006 p.20).*

The current strategies for flooding, outlined in the Government guidelines discussed, do not fit with emerging policy frameworks. The varying arrangements of coastal governance in the UK highlight the need for an improved national framework that can support locally mediated solutions. Underpinning this issue is the fact that existing approaches to coastal zone management (Shoreline Management Plans etc.) in the UK are lacking stakeholder involvement, in order to help make better use of research, even though it has been an aim for some time (Turner, 2000; Fletcher, 2003; Evans et al., 2004; DEFRA, 2005; English Nature, 2005; Fletcher, 2007; Turner et al., 2007; DEFRA, 2008; Tompkins et al., 2008). There is significant empirical research stating that, unsurprisingly, unsupported coastal management decisions are likely to be unsuccessfully implemented (Olsen 1993; Tompkins et al., 2002, 2008). Furthermore, substantial literature can be found discussing the challenges to facilitating and managing stakeholder deliberation in coastal management (see Treby and Clark, 2004; Fletcher, 2007 and Tompkins et al., 2008). It is argued by independent experts, however, that current coastal research does not provide the kind of information useful for policy makers (Tol et al., 2008). This has led to researchers questioning how the Government has the capacity to adapt to climate change (e.g., Yohe and Tol 2002; Pelling et al., 2008).

Adaptive capacity is the ability of a system to adjust to climate change (including climate variability and extremes) and to moderate potential damages (Carter et al., 2001). Building this capacity is a principal component of the Government's institutional role in adapting to climate change, yet UKCIP identifies a lack of policy and academic research on the issue

(West and Gawith, 2005; Pelling et al., 2008). Although recent reviews in the UK suggest positive developments (e.g., Tompkins et al., 2010), there are still disparities in adaptation measures and little real evidence of climate change adaptation trickling down to local levels. MacFadden (2008) suggests that geographical thought has proven useful in improving the integration basis of strategies for managing complex coastal environments. But the extent to which emerging research is actually valued or utilised remains a theme that this project can engage with.

It is clear that the recent calls for more integrated research and increased stakeholder participation in the coastal decision making process (e.g., Fletcher, 2003; O'Riordan, 2006; Fletcher, 2007; Turner et al., 2007; de la Vega-Leinert and Nicholls, 2008) is to ensure that there is ‘buy-in’ and support for adaptive responses to future sea-level change. Long-term decision making on the coast involves both the complexities of climate change uncertainties and levels of socio-economic dynamics (e.g., stakeholders and political involvement), yet little research exists on how to address this (Tompkins et al., 2008). Of the tools available to help decision makers (e.g., maps, GIS, databases etc.), cost-benefit analysis and multi-attribute analysis (of potential options) are most often applied as they help resolve the challenge of resource allocation. Tompkins et al., (2008) note that in the context of the UK, the typical tools applied have involved experts generating a limited set of coastal defence options for stakeholders to select. Fundamental decisions have thus been made by experts rather than stakeholders (Treby and Clark, 2004).

The challenge of engaging stakeholders in making long-term coastal adaption decisions – based on complex environment and socio-economic consequences – and to ensure a continuing level of support will become more pressing. This will be particularly evident where the effects and impacts on society are perceived as high. Areas that are already at risk from rising sea levels (for instance, defence structures or low lying areas that have a particular societal function or service) are relying on effective management. In this respect, the accuracy of sea-level data for future coastal projections becomes increasingly important for the future of the Southwest’s coastal infrastructure. Vulnerable systems like the London-Penzance railway, in the southwest of England, are relying on effective research and future adaptational planning. There is currently a lack of available information on the potential impacts of sea-level rise on the defence infrastructure and, perhaps more importantly, society. This raises important questions regarding future management decisions, and the next section examines the UK’s current management of infrastructure with significant societal roles.

2.7 Critical infrastructure

In recent years, some of the biggest UK news headlines have involved problems with critical infrastructure in some way – the 2005 terrorist attacks on the London transport system, flash flooding across the UK in summer 2007, heavy snow fall in 2009 and 2010 – and all prompt questions concerning the future management of infrastructure in the UK. Infrastructure involves a large spectrum of systems (for instance, energy, telecommunications, water supply, public services, transport etc. Little, (2002)). The UK’s Centre for Protection of National Infrastructure (CPNI) defines these as specific assets which, if destroyed or affected, would cause major disruption to the service being provided and the further functioning of another asset. The consequences of failing critical infrastructure are therefore broad. A small localised power cut, for example, may seem of little significance but if that cut caused the breakdown of a major internet facility then the consequences could be considerable. Among researchers this has become known as interdependency, as a single failure can cascade across the network of critical infrastructure and render otherwise unaffected sectors inoperable (Grubesic and Murray 2006; Grubesic and Matisziw 2008; Murray et al., 2008; Edwards, 2009). There is an increasing societal dependence on critical infrastructure and the importance of ensuring that continuity in the face of potential disruption is a major issue in the 21st century (Little 2002; Church et al., 2004; Miller, 2009). Failure to plan for the future long-term delivery of services has the potential to greatly affect infrastructure networks in the UK. The Government has recently provided new guidance and has taken further steps to improve the resilience of the nation's infrastructure and recent initiatives include:

- Increasing the CPNI's working with asset owners to combat terrorism.
- The newly formed Natural Hazards Team within the Cabinet office civil contingencies secretariat.
- The new flood forecasting centre created by the Met office and the Environment Agency, set up in order that the two bodies work more closely together.

While these are valuable, the initiatives above focus on individual aspects of resilience that operate within different departments. An expert report by The Institute of Civil Engineers (ICE) - *State of the Nation* (2009a) – states there is a lack of scope for sharing information and forward planning within these departments. Furthermore, the current government approach to critical infrastructure in the UK is disjointed and piecemeal. It lacks an overview and co-ordination, and there are issues with funding (Edwards, 2009). Based on this, ICE's (2009a) panel recommends the need for single points of authority to help improve communication and oversee infrastructure resilience threats in the UK. Currently, threats to the nation's critical infrastructure include large scale system failure and terrorism, but the impacts of climate change – and specifically its effect on coastal/inland flooding – have been identified as the biggest threat to the nation (ICE, 2009a; IMechE, 2009).

On this basis, ICE (2009) state that the Government must ensure that the newly created Natural Hazards Team is effective, by investing the team with the power to provide strong leadership for critical asset owners. This will involve collaboration with the Environment

Agency, Met Office and the CPNI to ensure that climate change research and data is correctly interpreted into defensive measures by asset owners. Interestingly, the comparison between ICE's recommendations and calls to improve our coastal management framework parallel each other. ICE's overview primarily recommends an improvement of communication and co-ordination between threat-based resilience agencies, infrastructure sector regulators and all scales of Government authorities (ICE, 2009a). Whether this will help improve the capacity (co-ordination etc.) of organisations and institutions involved to adapt to climate impacts however remains to be seen. In considering the possible impacts of climate induced flooding on critical infrastructure and society, one of the most prominent is the future of the transport network.

All transport is dependent on the weather and climate (Thornes, 2002), and critical transport infrastructure is located at the coast, for instance, all ports/harbours, strategic roads, and rail links (de la Vega-Leinert and Nicholls, 2008). Consequently, climate impacts on the functioning of the transport network will have deeply embedded regional consequences; transport connects people and services and, hence, has a strong social and economic function (Eddington, 2006). The socio-economic functioning of the UK (and Southwest more specifically) could be seriously jeopardised by increased disruption, and poor long-term planning of its transport networks. The future impacts of sea-level rise and closures on the southwest's main railway line are, therefore, a crucial aspect of the long-term development of the region.

2.7.1 Critical transport infrastructure

The Department for Transport's (DfT) UK climate impact report (Wooller, 2006) details the likely impacts of dealing with future climate changes including guidance for road, rail, air and water transport agencies. Some regions and transport modes in the UK are at a higher risk than others however. Railways, for instance, are particularly susceptible to flooding due to the nature of the terrain they travel through (IME, 2009) (i.e. river valleys and coastal flood plains where gradients are minimal). The DfT acknowledges that the railways of Wales and southwest England are already vulnerable to coastal flooding from high wind and tides, and defences may be unable to cope with future sea-level changes (Wooller, 2006). Similarly, ICE’s (2009b) *State of the Nation- Regional Briefing Sheet* acknowledges that in the Southwest, the dispersed population relies on relatively limited motorway and rail access and thus disruption to these routes could be significant to the functioning of the region. Numerous studies have concluded that the main railway network into the Southwest is lacking in resilience as it is susceptible to coastal flooding, sea-level rise and storms (Eddowes et al., 2003; Metcalf, 2003; Rogers and O’Breasail, 2006; O’Breasail et al., 2007; ICE, 2009b). Despite the obvious threat, a climate scoping study produced on behalf of the South West Regional Development Agency stated that much of the Southwest transport sector had not yet adequately responded to climate change (Metcalf et al., 2003) and the issue is still debated today. With the Southwest likely to see some of the highest rates of sea-level rise in the UK the impacts on the railway network in the region are of critical importance.

The United Kingdom’s Rail Safety Standards Board (RSSB) adds further cause for concern as, at present, the national response to sea level and storms on the rail network is via short-term weather forecasting and there is a lack of a long-term strategy (Eddowes et al., 2002). The long-term sustainability of the railway network is therefore questionable and the London-Penzance railway line provides a clear example. Network Rail took ownership of the Southwest mainline, and its sea defences, in 1996 and has experienced the frequent cost of maintaining the line over the short-term. There is currently a dedicated team of engineers to maintain the wall all year round but this does not stop problems. Parts of the line are only metres from the current mean high water level (MHWL). With sea levels increasing it is likely that extreme water levels will become more common, the protective sea walls will be overtopped more frequently, and the cost of maintaining the service may become unsustainable. Recently, Network Rail commissioned two reports on the line (carried out independently by Mouchel). The first, in 2006, titled *Dawlish-Teignmouth Seawall Management Strategy* (Rogers and O'Breasail, 2006) outlining the structural problems along the sea wall, emergency response initiatives and potential long-term line improvements to reduce overtopping along the line (Table 2.2).

However, the costs of a potential re-route were not identified, but a more recent study has calculated estimates based on a new inland route (Philips, 2009: see Appendix A – 1.1). Network Rail's report contains an evaluation of the current defence assets but there is no analysis regarding sea-level rise other than acknowledging the potential threat. Each of Network Rail's line options has the potential to improve the problem but no details for the life span of these additional improvements are discussed. Thus, the long-term sustainability (and life span) of these improvements under future sea-level rise scenarios is questionable.

Potential improvement	Total capital cost (£)	Potential implications
Heighten sea wall	6,036,800	Reduce OT and line closure. However, may lead to the structure becoming unstable and more prone to collapse.
Rock revetment	32,717, 300	Reduce OT and line closure. Conflict with tourism needs and health and safety on amenity beach.
New sea wall	51,636,200	Reduce OT and line closure.
Offshore breakwaters	65,434, 600	Reduce OT and line closure. Possible conflict with recreational, environmental and fisheries issues.
Rail re-route	330,000,000*	Solve the coastal defence problem and enable upgrading of the network system. However, issues relating to socio-economic importance of the line would cause major conflict.

Table 2.2 Potential line improvements (and estimated capital costs) on the Dawlish-Teignmouth railway line. Options may reduce overtopping (OT). Source: Rogers and O'Breasail (2006). *Estimated rail re-route costs based on two additional tunnels and taken from an unpublished post-graduate (MSc) dissertation (Phillips, 2009 – see Appendix A -1.1).

In 2007, the RSSB commissioned a second report on the longer-term (over the 21st century) impacts of climate change on the Dawlish to Teignmouth section of railway line

(O'Breasail et al., 2007). The impact of changes in wave height and sea-level rise on the frequency of overtopping and discharge (e.g., volume of water) were assessed. O'Breasail et al. (2007) used a complex and comprehensive methodology (using numerical models and joint probability), with a limited record of line incident observations (five years). Unfortunately, no clear long-term trend between sea-level change and rail incidents is illustrated. However, they conclude that the impact of sea-level rise has a much stronger impact on the wave overtopping than the predicted increase in wave height. The results for the highest sea-level estimates suggest that a 1 in 100 year return period overtopping at Dawlish could increase by 120% by 2020, and 800% by the 2050s. These estimates are relative to 2006 levels and are for King Harry's Walk (Dawlish) where defences are over 1.5 m lower than other sections (O'Breasail et al., 2007). Addtionally, they highlight the fact that estuary defences on the River Exe (at Starcross) are situated even closer to sea level and look particularly vulnerable to high estimates of sea-level rise.

An important conclusion of the study is that sea-level rise will greatly impact the ongoing operation and structural integrity of the railway line, and they provide some potential options (identical to Rogers and O'Breasail, (2006)). For instance, one recommendation of the report is to increase the design standard of the defence structures from a 1 in 100 year design (as of 2006) to a 1 in 200 year design (O'Breasail et al., 2007) by heightening the sea wall. As noted in the previous study (see Table 2.2), this would reduce the potential overtopping in the future, however, it would also reduce the structural integrity of the defences by increasing the risk of collapse or overturning (Rogers and O'Breasail, 2006). Although the two reports give valuable information on, firstly, the problems on the line and, secondly, the potential future problems, they give little consideration to the wider costs (e.g., socio-economic) of future overtopping and a reduced functioning mainline, thus no meaningful conclusions are drawn. Furthermore, the sea-level rise estimates used in the study have since been superseded by UKCP09's updated, high resolution, marine projections (Lowe at al., 2009). In order improve regional decision making there remains a genuine need for further investigation to illustrate the rising threat of sea-level rise and the extent to which this will impact the Southwest.

It is clear that there is pressing concern from local authorities to understand the long-term physical and socio-economic issues facing the region's mainline in order to be able to adapt to future implications effectively and, more so, sustainably. During the remainder of this century, however, the Southwest mainline will not only face challenges from the natural environment but also, more broadly, issues associated with the governance of UK coastlines and critical infrastructure (as discussed). Network Rail are concerned with keeping the line running and the safety of rail users based on a reactive or short-term proactive management strategy and it will be ultimately an issue of governance (e.g., the DfT) as to whether investment is provided for the long-term future of the line. The issue was recently discussed in Parliament in November 2010 and the DfT's under secretary of state for transport confirmed that no plans to find an alternative route are currently being considered as the coastal communities would be left without rail transport (Hansard, 10th November, 2010). It is important to understand the role of the state in transport problems because territorial governments are heavily involved in the management and ownership of transport activities, strategies and policies (Rodrigue et al., 2006; Shaw et al., 2008).

As the nature of transport involves crossing physical geographical borders, it also means that problems in the transport sector span political and institutional boundaries. Transport policies therefore involve not only different modes of transport but also different spatial scales, which themselves reflect current government institutional hierarchies (Shaw et al., 2008). The UK has a very fragmented system for conceiving and delivering transport policy (Glaister et al., 2006), and the level of state involvement in transport activities is influenced by a number of factors; from direct finance for the current elected Politician to broader political ideologies. A large amount of research has been undertaken to analyse the government's approach to transport policy. This has included work on, for example, sustainable transport policy (Anable and Shaw, 2007; Docherty and Shaw, 2003, 2008) and divergence and convergence of Government in the UK (Shaw et al., 2006; MacKinnon and Vigar, 2008). The use of policy documentation such as Labour's New Deal for Transport (Department of the Environment, Transport and the Regions (DETR), 1998) has been analysed by transport researchers to evaluate the UK government's effectiveness for policy production and implementation (e.g., Docherty and Shaw, 2003, 2008; MacKinnon et al., 2008). A common summation is that transport policy making has remained increasingly complicated, especially in recent years with the development of various 'intermediate' levels of governance between local authorities and central government. This has resulted in deteriorating transport networks, and adapting to future transport problems is an increasing issue (MacKinnon and Vigor, 2008) particularly regarding critical areas with high uncertainty such as climate change (HMG, 2011).

Decision making regarding transport infrastructure and climate change issues – areas that both have numerous levels of government institutions – is an area of high concern to the Southwest region. The extent to which regional climate studies will influence broader decision and policy making in such a complex system carries as much uncertainty as the climate research itself. The DfT (2006) echoes other interdisciplinary institutions, calling for a more permanent focal point to co-ordinate research and raise awareness of climate change and transport issues. Yet little evidence exists on how climate change will impact the transport network (Koetse and Rietveld, 2009) and how to address the current complex government structures. Nicholls and Klein (2004) examined the potential policy implications of rising sea levels on coastal communities across Europe, and they highlighted the importance of geographers in informing and influencing such complexities. Furthermore, transport geography could offer new exciting research if it contributes more directly to the debate of climate change and implications on accessibility and mobility (Keeling 2007; Keeling 2008). But how will new knowledge of climate change and the future of the railway be distilled and put into policy with such a dispersed and fragmented institutional framework?

On a national scale, UKCIP suggest that the least common application of their study (UKCIP02) was to inform policy and decision making, and that there is clearly tension between what stakeholders want and what scientists can give (UKCIP, 2006). Thus, science meets policy in this, the most important challenge of our time: global warming and climate change (Hassol, 2008). Consideration must be given, however, as in the last decade the UK government has increased its interest in evidence (science) based policy making (Cabinet Office, 1999; Morris, 2000; POST, 2003; HMG, 2005; Lagace et al., 2008; POST, 2009), and this project intends to present new evidence on a local/regional scale climate issue for use in future decision and policy making. However, as discussed in Chapter One, applied scientific information is often poorly communicated to wider audiences or fails to acknowledge the potential for policy use. In the context of the railway, this presents the risk that decisions are made with insufficient knowledge (Chisholm, 1971, Johnston and Sidaway, 2004; Jones and Macdonald, 2007). Gawith et al. (2009) state that the key future challenge will be to encourage the use of research in the decision making process.

One option for improving the understanding of complex systems, however, is the use of scenarios (Berkhout and Hertin 2000; Berkhout et al., 2002; Nicholls 2004a; Fletcher, 2007; Hulme and Dessai 2008; Oreszczyn and Carr, 2008; Wright et al., 2008). Furthermore, they have been suggested as a way to integrate disciplines (e.g., engineering, natural and social sciences) to inform climate impact assessments and coastal management decisions (Turner, 1998; Berkhout and Hertin, 2000; Turner, 2000; Berkhout et al., 2002;

Tompkins, 2008; Turner et al., 2007; Torresan et al., 2008). The penultimate section of this chapter discusses the use of scenarios with particular emphasis on climate change and coastal problems.

2.7.2 Scenario approaches to climate impact assessment

Scenario approaches gained prominence in the 1970s as a strategic management tool for research and practice, and for research aimed at modelling causes and consequences of future possibilities (Van der Heijden, 1996; Miller and Waller 2003; Roubelat, 2006). The term scenario describes a fuzzy concept, however, and is used and misused with various depths of meanings; a definitive list is far from complete (Meitzner and Reger, 2005). They are typically considered as alternative stories, but with equally plausible futures, and can be broadly categorised as either *exploratory* (i.e. using past and present trends to build reliable futures) or *normative* (i.e. built up on different visions of the future) (Meitzner and Reger, 2005). Scenarios utilise qualitative perspectives as well as quantitative data (Ratcliffe, 2002), and are developed using methods that systematically gather perceptions about certainties and uncertainties (Selin, 2006). Current approaches are designed to harness interdisciplinary expertise and knowledge in an exploration of future trends so as to inform decision making processes (Oreszczyn and Carr, 2008). This can be linked to a move away from the original mechanistic roots of scenarios that perceive the future as objective and knowable, to futures that are constructed from a number of different perspectives or views. This approach, based on diverse scenarios, rather than a single forecast future, is particularly appropriate for situations involving controversy and scientific uncertainty (Oreszczyn and Carr, 2008).

Scenarios have been around for over 30 years, and as Bradfield et al., (2005) note, there are a multitude of techniques and methodologies that have often been described as a chaotic (see Meitzner and Reger, (2005 p. 228) for an overview). The scenario-type approach can be difficult as it requires facilitation and communication skills that are not necessarily well developed among researchers in the normal course of their work (Locock and Boaz, 2004; Oreszczyn and Carr, 2008). Some methods require high degrees of specialist expertise, such as those needed to utilize the large computer modelling in the global and national climate programmes (Meehl et al., 2007, Jenkins et al., 2008). Others involve more informal and participatory workshops, such as those used by UK government departments to assist policy development (Saunders, 2002), or in human planning (e.g., transport, city planning and socio-economic futures) (Albrechts 2004; Docherty and McKiernan 2008). The broad depth of use, however, has increased the number of research projects that include stakeholder engagement as a fundamental aim, and Docherty and McKiernon (2008) offer an explanation for this.

Firstly, scenarios can influence social and political affairs and develop quality information for public consumption; new ideas can be generated and communicated to a wide audience. Secondly, they can be developed as a strategic support tool for rehearsal of critical decisions against a series of potential outcomes, developing alternative futures for which strategies and policies can be produced. Finally, they can be used for learning and development in organisations which are essential to create, maintain and improve strategic thinking (also see Berkhout et al., 2002). The characteristics described put scenarios in a favourable position as a tool for integrating sciences to produce information that can improve decision making.

Socio-economic scenarios (SES) for climate impact assessment have been constructed using scenario approaches, and are used to integrate sciences to help deal with the complexities of the relationship between climate and society (Berkhout et al., 2002; Hulme and Dessai, 2008). Their wide range of use, however, means that evaluation of their success is difficult (Ratcliffe, 2002; Mietzner and Reger, 2005), although some attempts have been made. For example, Gawith et al.'s (2009) review of UKCIP's scenarios (e.g. UKCIP, 2001; Jenkins et al., 2009) found them primarily used as a communication device for scientific research to inform policy and decision making, and this promotes their potential use in this study.

There are limitations to scenarios, however, and constructing them is a difficult task, particularly when regarding socio-economic futures (UKCIP, 2001). The physical processes involved in climate change are generally understood, but this cannot be stated for factors operating in socio-economic systems (UKCIP, 2001; Berkhout et al., 2002). Some aspects of social change (e.g. demographics) can be modelled over the long term, however, other aspects such as economic growth and inflation are difficult to predict and the extrapolation of trends rarely exceed 15-20 years (UKCIP, 2001). Predicting long term social-system behaviour, therefore, is highly variable despite the use of powerful models and the historical data available, and there is a degree of hesitation about constructing SES among scientists (Berkhout et al., 2002). Furthermore, a reductionist approach to the modelling of socio-economic futures (i.e. reducing the modelled components to core principles) will lower the accuracy of replicating social reality. Yet the importance of considering socio-economic changes in climate impact assessment remains a key stimulus for their use.

Berkhout et al. (2002) outlines some of the risks and assumptions of using SES (also referred to as socio-economic futures) that need to be considered. Firstly, they cannot take into account the dynamic nature of a rapidly changing environment. For example, innovation and surprise are normal features of a developing system, but SES does not account for discontinuality in trends. Similarly, responses to the scenarios constructed (in the future) will be likely, particularly by anticipatory actors (agents) this is known as *reflexivity*. This is a critical issue in constructing socio-economic scenarios. Finally, linking with the previous two points, there will always be wide opinions across society as to what the future may hold and – as the future will affect the material interests of many different groups. The nature of it is therefore highly contested. This has prompted the emergence of debates about what the future *should* be like as much as about what it *will* be like.

Despite these issues, climate impact assessments remain limited in validity and value if they fail to consider socio-economic change (Berkhout et al., 2002). When coupled, socio-economic and climate impact scenarios could provide policy makers with a more complete picture of possible future coastal conditions (Hall et al., 2006; Nicholls et al., 2008). Utilising this approach could be a key aspect of successfully constructing integrated scientific information for illustrating the future of the regions rail network, and further promoting the integration of science into the policy realm. The integration of SES with climate futures is discussed further in the Chapter Three.

2.8 Chapter synopsis

This chapter has shown that scientists have a long history of using past trends of sea-level rise to improve regional projections of change on our coastlines. Palaeo sea-level studies thus have significant societal relevance. Although there are other methods, geological records identify long trends of both land- and sea-level movements with high precision and accuracy. Due to the UK’s proximity to former ice sheets, the region has had significant scientific interest in palaeo sea-level research, and this produced has improved our understanding of ice-sheet behaviour, Earth’s crustal behaviour and Holocene sea-level changes. Not all areas are well understood however. The southwest of England is predicted to receive some of the highest rates of sea-level rise in the UK, yet it is lacking high quality geological data to confirm this accurately. Current geophysical models, which are utilised by coastal policy makers, also suggest that the Southwest will have the highest rates of crustal subsidence in the UK, but there are dissimilarities between models of more than two metres. There is consequently a need for new geological sea-level data in the region to improve, firstly, the accuracy of geophysical model predictions, and secondly, the accuracy of future sea-level forecasts. Improved sea-level predictions will allow more precise estimates of future impacts and coastal flooding to be determined in order to inform better coastal management decisions in the southwest of England.

Coastal management in the UK has a number of problems in terms of the scientific information available to stakeholders and policy makers. More integrated coastal research combining both physical and human aspects is needed to better inform decision makers of future impacts of sea-level rise. Moreover, coastal governance is changing and the previous hard-defence (hold-the-line) approach is being replaced with a more sustainable, and adaptational, approach (mitigation etc.). This will require effective and integrated coastal research and management. However, the current government framework has been criticised for lacking co-ordination and communication with/among key stakeholders, even though it has been an aim for some time. Integrated science and the communication between institutions and stakeholders are therefore major determinants to successful application of management decisions, and a more efficient national framework is required to address this. With an expected increase in people and businesses on our coastlines, communication errors have the potential to become large, and costly, barriers to adaptation, especially when considering issues that involve critical infrastructure networks. According to industry experts one of the biggest threats to the UK’s critical network is climate-driven coastal flooding.

A review of the current Government strategy to tackle impacts on infrastructure also stresses the need for a single-point authority to address the resilience/adaptation of its critical infrastructure. This is on the basis of a lack of clear co-ordination and effective communication between bodies/agencies. An example of where such a problem is likely to be brought to attention is transport infrastructure in the southwest of England. The primary coastal rail route is threatened by increased overtopping under future sea-level rise scenarios. Network Rail has identified the potential frequency of overtopping and has presented options to improve the existing infrastructure (and reduced overtopping). The life span of these defence improvements, however, still remain questionable under future sea-level scenarios, and there is no clear conclusion as to the sustainability of maintaining the existing line in the long term. Furthermore, they give no indication of the impacts to rail users and the regions socio-economy.

This issue requires interdisciplinary research to provide information, for policy makers, for better sustainable transport decisions. But studies and reviews of transport policy in the UK echo wider sector conclusions. Complex government structures and a lack of (strategic) co-ordination can produce barriers to effective delivery of policies, and the communication of research into the process of policy formulation. As mentioned in the first chapter, however, geographers have had a long history of attempting to apply their work, and their role in policy formulation has been debated since the 1970s. Many of the barriers they identified are still relevant today. With increasing public concern and attention on climate change and its impact to society, now is a good time to start to apply their geographical skills more effectively, and in doing so tackle the larger issue of connecting research to policy. Interestingly, both transport and climate researchers have independently concluded that solutions to these problems often lie at lower level (local/regional). The regional issue of increased closure of the London-Penzance railway line presents an ideal opportunity to conduct integrated research for future policy making. Overall, the foregoing has identified that the Government will require more integrated research to help implement their new adaptational approach to tackling climate change and sea-level rise. Yet non-government analysts from various sectors such as transport, infrastructure, climate change and coastal management are calling for a single-point authority to co-ordinate and overview the complex interactions and to make sure policies are implemented effectively. There appears to be no framework to achieve this and this presents a barrier in communicating new science/research to those who need it. These problems will have to be tackled in coastal regions all round the UK and, specifically, the far southwest of England as its main railway line is already vulnerable to sea-level rise. Discussions on how to adapt to the increasing threat of long-term sea-level rise and closures of the Southwest's main railway network are primarily impeded by a lack of scientific information of the likely future impacts.

Presenting and analysing the key stakeholders' response to new findings is beyond the scope of this thesis, however, but improving the science and acknowledging the potential problems of its future use, will help identify the region's future vulnerability to climate change issues. This review has presented one such approach that can help address some of the problems discussed, that of scenarios-based forecasts. The use of scenarios has been stated as an effective way to communicate futures of complex interacting (e.g., physical and human) systems to wider audiences and the skills of geographers can be exploited in their construction. The remainder of this project is intended to investigate the future of the railway line and – by using geography-based methods, and scenarios – help the regions decision makers better understand climate science, the potential impacts, and the sustainability of decision making. The following chapter presents the methods needed to achieve the aims and objectives outlined in Chapter One.

Chapter Three

An integrated methodological approach

3.1 Introduction

In the previous chapter it was highlighted that the coastline of the Southwest is of particular interest for research in Holocene sea-level reconstruction as isostatic subsidence in the region is argued to be faster than along any other coastline in the British Isles (Shennan and Horton, 2002). However, the late Holocene relative sea-level changes are poorly constrained and, consequently, it is not possible to infer reliably rates of land and sea-level change during the last few thousand years (Edwards, 2006; Gehrels, 2006; Massey et al., 2008). This has implications for the accuracy of future sea-level predictions and their use in current coastal management decisions. As the region's main railway line is frequently threatened by high tides and storm surges, obtaining accurate data of palaeo-sea level change, future sea-level change, and the likely impacts are essential for future sustainable management. Decision making under future uncertainty has been criticised by researchers and non-government institutions, and calls for research that integrates disciplines and to improve communication cabout omplex futures have been echoed. Finally, scenario-type approaches were identified as being a useful tool for integrating climate and socio-economic data for coastal impact assessments and presenting information that can inform policy decisions. The purpose of this chapter is to present a methodology capable of answering the key research aim and objectives presented in Chapter One.

The second objective presented in the introduction of this thesis (section 1.3.2) contained two research goals. The first of these is to collect historical observations of past vulnerability and impacts on the line to determine the extent to which a relationship exists between sea-level rise and overtopping. Using observations to construct relationships among them is typically referred to as an empirical-based approach, and is a key method in applied geography. The approach carries the assumption that one or more forcing (independent) variables cause changes in a response (dependent) variable (see Lane (2004) for a broad critique of the method). O'Bresail et al.'s (2007) study of the railway line (discussed in the previous chapter) utilised a complex methodology (using numerical models and joint probability) to investigate a number of forcing mechanisms. Overall, they concluded that sea-level rise had the strongest impact on the overtopping of the defence structures during the 21st century. This strengthens the physical basis behind the approach to identifying an empirical relationship between sea-level rise and overtopping at Dwalish. Furthermore, as the Southwest has some of the best maintained tide-gauge records in the UK (see section 2.4.2) it was seen as justifiable from a data perspective. O'Bresail et al.'s (2007) approach lacked consider socio-economic issues however, and a further justification of approach taken here (including the collection of a detailed history of the line) is that it could allow for a more realistic and precise data set to be developed. This, in turn, could allow for the assessment of both the physical and societal impacts of overtopping on the railway. Further discussion of the empirical approach taken to establish the frequency of overtopping is given in section 3.5, along with details of the integration of climate and socio-economic data.

Certain aspects of this methodology are easily identifiable as physical geography based approaches and, equally, certain aspects of the methodology are easily identifiable as human geography approaches. As climate change and sea-level rise unite the environment and society through their impacts so too must the methodologies used to investigate them, and interdisciplinary (or mixed method) approaches have secured their place in applied geographical research (Fielding, 2009). As mentioned in Chapter One, there is an incremental aspect of each objective, thus this chapter is presented in the order in which the investigation took place. The first section of this chapter details the rationale and methodology used to establish late Holocene SLIPs for validating geophysical models and future sea-level projections in the region. The remainder of the chapter outlines the methodology to determine the impacts of the predicted water levels on the railway over the 21st century. This begins by determining the relationship between more recent changes in sea level and past railway incidents and concludes with the method developed to cost overtopping incidents. However, rather than examining the forcing mechanisms (e.g., weather and tidal factors) that cause rail incidents on the line first, this project initially examines the record of incidents before examining the external factors that led to incidents recorded. Finally, the chapter concludes with the approach used to integrate socio-economic impacts and socio-economic scenarios (SES) into climate-based projections of rail problems during the 21st century.

3.2 Sea-level reconstruction

3.2.1 Site selection and salt-marsh sediments as palaeo sea-level indicators

The identification of marine deposits, from stratigraphic investigations, produces a more continuous record of sea-level change than any other method (Lowe and Walker, 1997). Buried marine sequences often contain fossils which can provide additional data for reconstructing sea levels, and it has long been stated that salt marshes provide excellent potential for obtaining records of sea-level change during the late Holocene (Long, 2000; Shennan et al., 2006). Work already undertaken in the Southwest (e.g., Heyworth and Kidson, 1982; Haslett et al., 1997; Healy, 1999; Waller and Long, 2003; Edwards, 2006; Massey et al., 2008) has successfully used buried salt-marsh deposits as indicators of sea-level changes during the early to mid Holocene. Furthermore, salt marshes have the potential to provide new, younger, and more accurate SLIPs (e.g., Gehrels et al., 2005, 2008). Salt marshes are typically found in estuaries and sheltered embayments between intertidal mudflats and the extreme upper limit of the marine influence. They are maintained by regular flooding and these periodic inundations act in two ways. Firstly, they supply sediments and detrital organic material to the marsh surface which, when incorporated with the decaying litter of the plants that colonise the marsh surface, form the emerging salt-marsh platform (Allen and Pye, 1992). Secondly, the height, duration, and frequency of tidal inundation control the submergence – and thus the environmental salinity gradient – of the marsh (Allen, 2000). Interestingly, the flora and fauna that occupy salt marshes have different ecological tolerances and requirements (including salinity) and, as a result, vertical zonation of the species that inhabit the salt-marsh surface is produced.

The cyclic periods of flooding, followed by periods of exposure, that take place on salt marshes have led to the evolution of flora and fauna in order to deal with the stresses these environments produce. While many species have become tolerant to a wide range of variables linked to tidal inundation (e.g., salinity and acidity), some have become more specialised and actively seek out the vertical location that suits them best. The higher the sensitivity of the species, the narrower the vertical range it can tolerate, and this produces an intertidal zonation between different species of some organisms. To maintain their ideal environment, species must migrate up and down the coastal slope in response to changes in sea level. Due to the close interaction between tidal flooding, salinity and sea level, species zonation identified in buried coastal stratigraphies can be used to indicate and track palaeo sea-level changes at a selected location. Furthermore, salt marshes accrete vertically in pace with sea-level rise by filling in the accommodating space created and this can be recorded in stratigraphic sequences.

Within sea-level studies the typical area preferred for reconstructing sea level is the highest part of the marsh. Situated within the high marsh zone is a transitional area where there is a progressive ‘altitude-dependent’ shift from more saline marine conditions to increasing fresh water and terrestrial conditions. This is the most sensitive area of marsh to changes in RSL; any changes in water depth will result in the migration of this narrow transitional zone up or down the coastal slope. These lateral shifts coincide with the vertical accretion of salt-marsh sediments (over time) and both must be measured to establish accurate changes in sea level (e.g., using foraminifera and radiocarbon dating, respectively). Lower in the marsh the relationship becomes less acute to changes in water depth as factors such as an increased sedimentation rates can complicate the transition. As mentioned in the previous chapter, lithostratigraphical analysis of salt-marsh deposits can give a considerable amount of data, but microfossil indicators offer the key tool in reconstructing palaeo sea levels.

One intertidal group of micro-organisms that is known to exhibit intertidal vertical zonation is *benthic foraminifera*, and the sedimentary sequences that make up the modern intertidal zone (salt marshes, tidal flats and tidal channels and creeks) each contain their own characteristic foraminiferal assemblages. Salt-marsh foraminifera are mostly *agglutinated* (i.e. their tests are composed of detrital material kept together by a lining), and they are the only tests that can withstand the acidic conditions associated with salt marshes (Gehrels, 2000). *Calcareous* tests, on the other hand, do not preserve well in acidic conditions and are commonly found on tidal flats and in creeks and channels. Pioneering studies (e.g., Scott and Medioli, 1986) have found that agglutinated assemblages, from the high marsh zone, exist at some sites in areas at the top of the tidal range as narrow as 10 cm. Calcareous species in the lower marsh area (and tidal flats), however, show a much greater altitudinal range and are poorly preserved in the sedimentary record due to dissolution. For this study, therefore, sites containing high-marsh species will be targeted as sea-level indicators. Fossil populations can be analysed and compared with the characteristics of modern distributions of foraminifera to indicate accurately where the fossil population would have existed along the salt-marsh slope. The reconstruction of former sea level, therefore, requires the quantification of an ‘indicative meaning', or the height at which a sea-level indicator (e.g., foraminifera) was deposited in the sediment in relation to a tidal height (van de Plassche, 1986).

The indicative meaning is comprised of two parameters, a reference water level (e.g., MHWS) and an indicative range (e.g., the vertical range over which the sediment was deposited relative to the reference water level). The indicative meaning of fossil salt-marsh sediments in this project is quantified using data from surveys of modern foraminifera and vegetation zonation from sites in the region including South Milton Ley and Dawlish Warren, south Devon (Volkelt-Igoe, 2009). To further improve the accuracy, information was also taken from regional studies of the vertical distribution of modern foraminifera and plant species by Massey et al. (2006). This data set, which includes samples from Gehrels et al. (2001) and White (2001) contains foraminifera between 2.6 m above and 2.6 m below, mean tidal level (MTL), spanning the entire intertidal zone (salt marsh to tidal flat). Samples were taken from the Erme estuary and Frogmore Creek in the Salcombe-Kingsbridge Estuary, south Devon. More details are given in Chapter Four.

3.2.2 Considerations for palaeo sea-level studies

Not all salt marshes will be suitable for obtaining late Holocene SLIPs, however, and careful consideration of what is required for the accurate reconstruction of palaeo sea level is needed before selecting a site. For example, a potential site may contain sediments that are older than those being targeted (i.e. early-mid Holocene). Also, the marsh stratigraphy, and the fossil indicators within, may have been disrupted by human activities such as prolonged sea defence construction, reclamation of land, or the destruction of surface sediments. In addition to anthropogenic activities, meandering of tidal creeks can result in the introduction of material which is non-contemporary to the matrix of the surrounding marsh (Allen, 2000; Massey et al., 2008). It is also necessary to consider the availability of suitable material needed to date the deposits. Traditionally, successful dating involves the sampling of organic rich sediments, however, sediments from the late Holocene can be highly minerogenic (Long, 2000; Long et al., 2006).

Another factor to consider is post-depositional compression, or ‘autocompaction’ of sediments. This is a major cause of error in sea-level reconstruction (van de Plassche, 1982; Paul and Barras, 1998; Gehrels, 1999; Massey, 2004). Autocompaction is particularly significant in Holocene studies of sea-level change as the magnitude of error can be similar to the actual magnitude of change observed (Paul and Barras, 1998). Although there are methods that can be used to estimate autocompaction of sediments (e.g., geotechnical models), there is no common methodology (Bartholdy et al., 2010). The issue is routinely ignored by sea-level researchers (Massey, 2004) and thus creates the potential for considerable error. By making adjustments for autocompaction within the sediments, however, the reliability of RSL histories is significantly improved (Gehrels, 1999; Shennan and Horton, 2002). Figure 3.1 illustrates the varying degree of accuracy obtainable from SLIPs and how targeted selection can reduce the error of compaction in sea-level investigations.

The valley cross-section represents a coastal back barrier system that is typically found along the south Devon coastline (Massey et al., 2008). The early to mid Holocene marine transgression caused the migration of the high salt marsh environment landward and up the Pleistocene slope. By the late Holocene, however, sea-level rise had slowed and widespread barrier closure occurred. This caused the subsequent infilling of the high marsh surface with freshwater peat facies, and stratigraphies indicate a regressive marine influence. These systems are capable of providing a range of SLIPs with varying accuracy (see Figure 3.1).

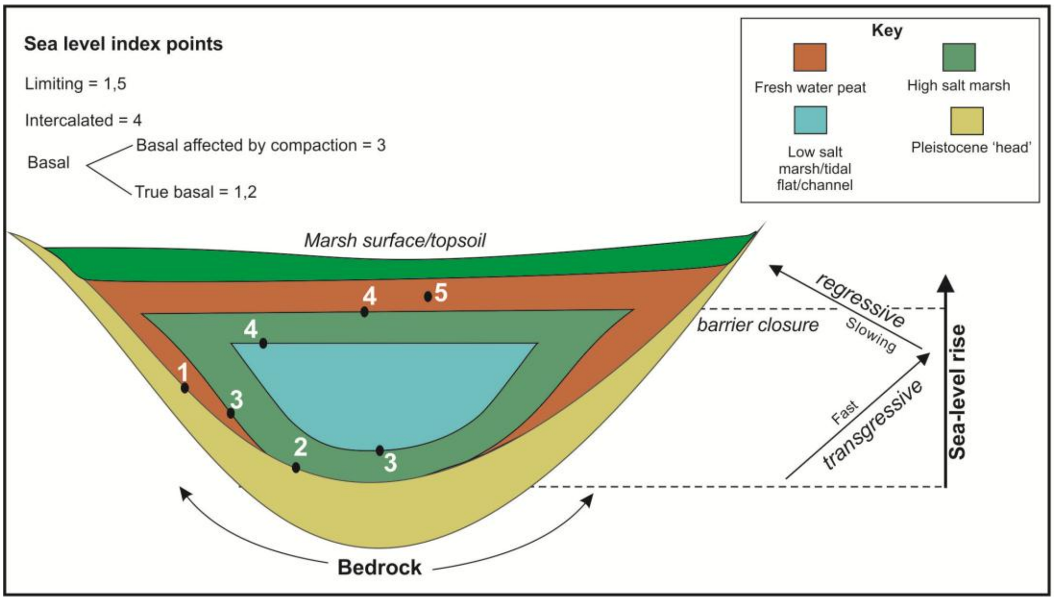

Figure 3.1 Schematic diagram showing the position of sea level index points (SLIPs 1-5) on relation to stratigraphy typical for a back barrier marsh in Southwest England. True basal SLIPs (1-2) lie directly over a hard substrate and are not affected by autocompaction, although 1 is taken from a freshwater peat and therefore is a limiting SLIP only. SLIPs 3 are from the top of a 'basal' unit and will have a vertical error associated with sediment compaction. SLIPs 4 are from intercalated sea-level index points. SLIP 5 is from freshwater peat and represents a limiting SLIP. The valley cross-section illustrated is the result of slowing rates of RSL rise in the mid-late Holocene.

Basal SLIPs obtained from sediments overlying a hard substrate (e.g., Holocene and Pleistocene sands or bedrock) have not been affected by compaction and, for this reason, basal deposits will be targeted to minimise the vertical error and establishing accurate SLIPs for this project. Those that are intercalated or basal (but affected by compaction) will need to include an additional vertical error component in the calculation of SLIPs. The heights of SLIPs in metres relative to mean tidal level (MTL) are calculated using the equation below (Gehrels, 1999):

$$\text{SLIP} = H - D - I + T + A$$

where H is the height of the marsh surface relative to MTL, D is the depth of the core relative to the ground surface, I is the indicative meaning of the sample surface relative to MTL, and T is the difference between present and former mean high water level relative to

MTL (tidal range). Palaeo tidal simulations have shown that changes in tidal range have been relatively small in the last 4000 years (Uehara et al., 2006), and therefore T is assumed to be zero. Finally, A is the autocompaction of sediment typically determined by geotechnical correction (Paul and Barras, 1998). The vertical error margins associated with the altitudinal reference (I) are based on the vegetation and zonation surveys and the regional transfer function (e.g., Massey et al., 2006) and an additional margin of ± 0.06 m is added for levelling errors (Gehrels et al., 1996; Shennan and Horton, 2002; Massey et al., 2008).

3.3 Site selection

Possible locations for a sea-level investigation in south Devon were firstly identified using Ordnance Survey maps, Google Earth, a review of current research literature in the region (e.g., Churchill, 1965; Hawkins, 1971, 1979; Heyworth and Kidson, 1973, 1976, 1978, 1982; Hails, 1975a, 1975b; Morey, 1976, 1983; Edwards, 2000, 2006; Massey, et al., 2008) and investigative walks. Ultimately, two sites (South Milton Ley and South Huish) at Thurlestone (Figure 3.2) were selected to determine their suitability as areas capable of producing basal late Holocene SLIPs.

Two other promising sites immediately near the railway (Cockwood and Coombe Cellars) were also checked for suitability before deciding on the two sites slightly further afield. Preliminary reconnaissance surveying at the two sites established the heights of the marshes relative to the UK Ordnance Datum (Newlyn). These were determined by a differential Global Positioning System (GPS), and temporary benchmarks were created for further surveying.

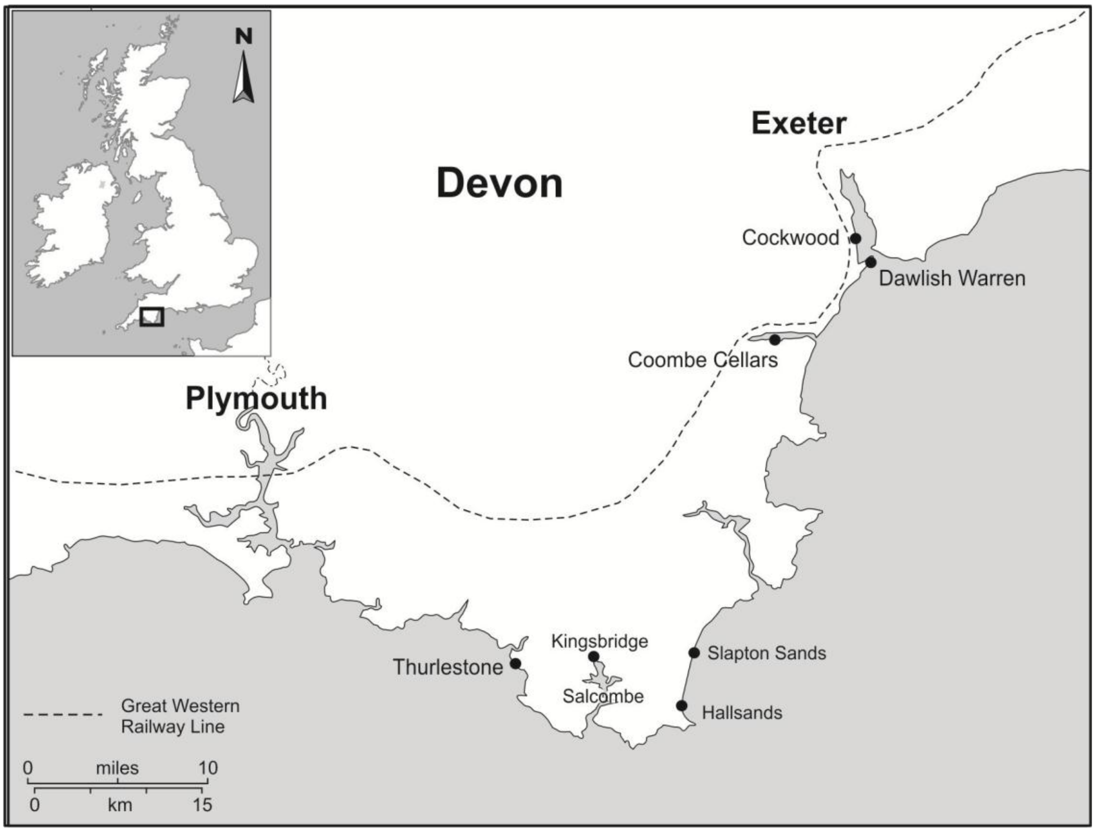

Figure 3.2 Salt-marsh sites investigated for late Holocene sea-level index points (SLIPs) and flora and fauna zonation surveys, including two sites of previous late Holocene studies (Hallsands and Slapton) and sites identified but not included in the study (Cockwood and Coombe Cellars). The route of the main railway line is also illustrated.

The data from reconnaissance work were used to estimate the heights of palaeo sea-levels and, thus, the potential age of the stratigraphic boundaries. At both sites the heights of fossil sediments were surveyed and the heights of palaeo sea-level relative to present MSL were estimated. Coring identified the depth of the underlying bedrock surface, and this was then converted to a palaeo sea level using the equation described in section 3.2.2. For the purpose of estimating the palaeo sea level, MHWS was initially assumed as the indicative meaning of the sediments but microfossil analysis would further constrain the indicative meaning. Palaeo heights were then compared with the current palaeo sea level estimates from geophysical models to estimate the age (Figure 3.3). Sites would be selected for further sampling of lithostratigraphy, microfossils, and analysis if the estimates were younger than 4000 cal yrs BP (late Holocene) It was identified that the two sites at

Thurlestone (South Huish and South Milton Ley) were suitable for this study (Table 3.1). The next sections present the further details of the two sites.

3.3.1 Thurlestone field sites

The marsh at South Huish is situated in a pre-Holocene valley and is barred by the beach and dune system of Thurlestone Sands (Figure 3.4). The southern valley slope is dissected by the road to South Huish village, along which access is available through a large gate. The geology of the area is typical of the Southwest and the local valley fill is known to be Devensian 'head' deposit. A small pond and nature reserve occupy the front of the marsh, and this area remains restricted, therefore, human disturbance is minimal.

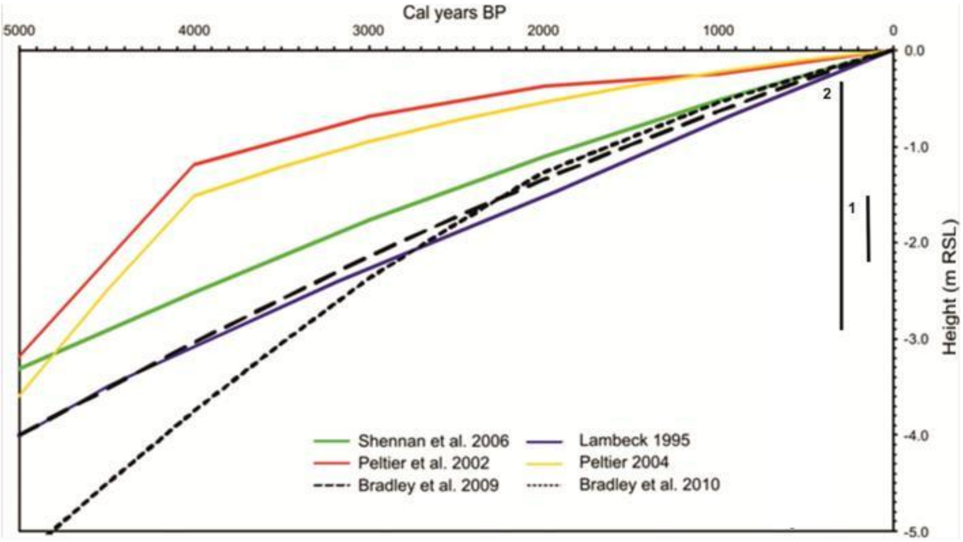

Figure 3.3 Late Holocene sea-level changes predicted by six geophysical models (Lambeck, 1995; Peltier, et al., 2002; Peltier, 2004; Shennan et al., 2006; Bradley et al., 2009 and 2011) and estimated palaeo sea levels of four sites in south Devon: 1 = South Huish; 2 = South Milton Ley (also see table 3.1), based on bedrock depth and an assumed indicative meaning (MHWS).

Site	Palaeo sea-level (m OD)	Age (cal yrs BP)
1. South Huish marsh, Thurlestone	-2.213 to -1.606	1800 – 3400
2. South Milton Ley, Thurlestone	-2.897 to -0.417	1000 – 4000

Table 3.1. Summary of estimated palaeo sea-level data from initial site selection. An estimated indicative meaning (MHWS) and basal contact depth ranges at the site have been used.

The mid marsh has significant evidence of anthropogenic activity, however, and contains <3 m deep man-made drainage channels that allow the land to be used for agriculture in summer months. The drains have effectively lowered the water table which has influenced the local vegetation. Pasture dominates the valley though small patches of cord grass (*Spartina*) fringe the break of the valley slope. The back of the marsh remains untouched and is an undisturbed marsh environment, and a small but dense common reed (*Phragmites)* bed occupies the valley floor.

Figure 3.4 South Huish marsh and investigation area, Thurlestone, south Devon. Source: Google Earth.

Initial coring at the site identified the deepest valley fill to be Devensian 'head' deposits. The 'head' is overlain by estuarine silts and clays and the sequence is capped by freshwater peat. The stratigraphy of the valley system (peat overlying minerogenic deposits) indicates that the site was a salt marsh until the beach barrier cut off the system from tidal exchange. The shallow position of the salt-marsh sediments suggests that this has happened relatively recently, probably in the last 2000 years. An undergraduate study (Taylor, 2004) identified foraminiferal assemblages that are characteristic of a salt-marsh environment at the transition between the mineragenic sediments and the organic-rich peat (Figure 3.5).

The assemblages are indicative of a regressive contact, with lower marsh species (*Miliammina fusca* and *Trochammina inflata*) giving way to higher marsh species (*Balticammina pseudomacrescens* and *Jadammina macrescens*). The minerogenic sediments below the peat lap onto the flanks of the valley to form a shallow basal unit that contains high marsh foraminifera. This unit is highly suitable for obtaining SLIPs due to its position on top of a hard substrate, and the presence of foraminifera for which an indicative meaning can be established. Palaeo estimations indicate that the site could offer dates between 1800-3400 BP (see Table 3.1).

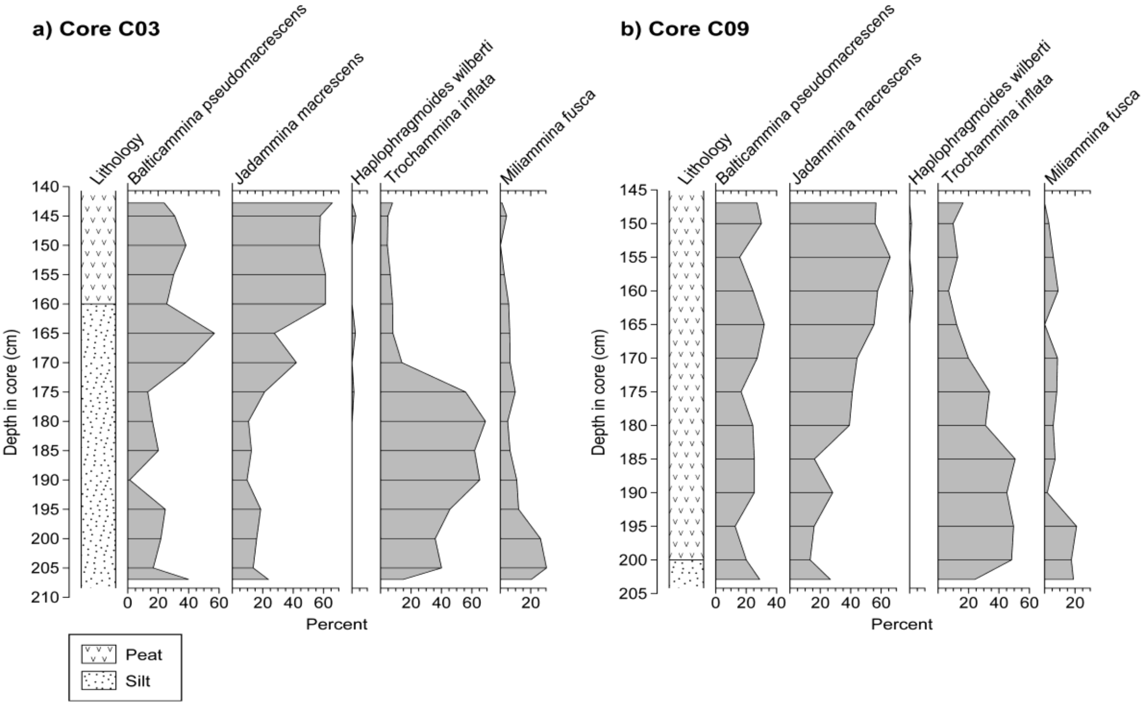

Figure 3.5 Foraminiferal stratigraphy across the silt-peat transition at South Huish marsh. Sourced from Gehrels et al. (2011) and adapted from Taylor (2004). See Chapter Four (Figure 4.3) for core positions.

Situated in the valley north of South Huish Marsh is the second field site, South Milton Ley. It is a small but active tidal freshwater marsh. It lies in a shallow coastal river valley separated from the sea by a barrier dune complex (Figure 3.6). The waters of the Ley directly adjacent to the barrier are slightly brackish due to occasional tidal influence, but upstream they give way to freshwater conditions. The main habitat at the Ley is freshwater reed bed (Phragmites), these habitats are scarce in Devon, and the site was noted as a Site of Special Scientific Interest (SSSI) in 1976 and has since remained undisturbed. The Ley is dominated by Phragmites, while further upstream the vegetation contains a mixture of other tall fen species including hemlock water-dropwort (*Oenanthe crocata*), flag iris (*Iris pseudacorus*), great willow-herb (*Epilobium hirsutum*) and reed sweet-grass (*Glyceria maxima*).

The marsh at South Milton Ley represents a modern analogue of the peat facies found in the cores taken from South Huish. The initial stratigraphic investigation identified shallow 'head' deposits in the valley flanks overlain by a peat unit and topped with a minerogenic layer. The peat layer is not totally basal as a deeper minerogenic layer undermines the unit in the centre of the valley. The presence of freshwater peat suggests a previous and periodic barrier closure, though the barrier is partially open at present. Deeper sediments close to the present channel show an increase in silts and clays, as well as gravels that make up the local bedrock material. The basal depth ranges taken suggest a much younger system than South Huish that is ideal for improving the late Holocene data set (Table 3.1).

Figure 3.6 South Milton Ley and final area of investigation. Source: Google Earth.

3.3.2 Sampling for SLIPs

Cores were taken at one metre intervals using a 20 mm (medium) gouge corer and the lithostratigraphy was logged in the field. Coring extended until impenetrable sediments were reached. When a hard substrate was found a 10 mm gouge corer was used to penetrate deeper and confirm that the unit above was basal in character. The stratigraphy was then traced back to where it fringed the valley sides to obtain the shallowest (youngest) possible basal organic units directly on top of the hard substrate. Additional cores were then taken at higher resolution based on the estimated palaeo sea levels. These cores were taken with a 60mm (large) gouge corer to obtain enough material for laboratory analysis. Cores were positioned so that some overlap between samples occurred to ensure retrieval of a continuous undisturbed stratigraphic section. At Thurlestone, targeted sampling recovered a total of sixteen cores that were taken for analysis back in the laboratory. Sections retrieved were carefully removed from the corer and wrapped in non-PVC cling film and placed in plastic tubing for transportation. All core sections were surveyed to a temporary benchmark using a Trimble 5800 total station, and were labelled with a location identifier, depth and year. Sections were stored in refrigerated conditions until required for sampling.

3.4 Laboratory methods

3.4.1 Lithology

The core sections retrieved were carefully cut in the laboratory. Once exposed to air, sections were promptly logged to avoid error as oxidation occurred. Core sections were logged using a modified Troels-Smith (1955) scheme (see Appendix B -1.1a for core logs), and before sampling the sections were cleaned by carefully removing the surface material. One half of the section was preserved intact for radiocarbon sampling, and the other half was sampled for foraminifera and loss on ignition. Core sections were wrapped in a non-PVC bag, placed in plastic tubing and sealed in PVC plastic sleeves before storing at 4ºC.

3.4.2 Foraminiferal analysis

Fossil species of salt-marsh foraminifera found in the lithostratigraphy are used to reconstruct late Holocene sea-level change along the south Devon coastline. The taxonomy of foraminifera species used in this study is based on de Rijk (1995) and Gehrels (2002). Foraminifera were sampled and analysed using the standard techniques described by Scott and Mediolli (1980) and Gehrels (2002). Samples measuring 2 ml were initially selected at 2 cm intervals across each lithographical contact to locate agglutinated foraminifera. All samples were preserved in an ethanol and distilled water solution and refrigerated to reduce retardation of the tests by biological and chemical action. Samples to be investigated were then sieved between 500 µm and 63 µm and split into eight equal parts using a wet-splitter (de Rijk, 1995; Gehrels, 2002). Foraminifera were wet-picked from a Bergeroff tray under an Olympus SZ40 low power binocular microscope. The sampling resolution was increased to 1 cm intervals where low counts of agglutinated foraminifera were identified.

3.4.3 Loss on ignition

Loss on ignition (LOI) is a widely used method developed to estimate the organic content of sediments (e.g., Dean, 1974; Bengtsson and Enell, 1986). The organic content was measured according to the method described by Ball (1964), and further tested by Dean (1974) and Heiri et al. (2001). Samples for LOI were taken from cores at a 1 cm resolution, and started below the basal unit containing microfossils, continuing up into the overlying sedimentary unit. LOI measurements were taken from the cores to provide calibration with the Troels-Smith (1955) scheme and the foraminiferal records, and to differentiate accurately between basal salt-marsh sediments and the underlying head deposit. This transition can be difficult to discern visually. The change from low organic content (characterised in head) to more organic content (e.g., salt-marsh deposits) represents the leading edge of the initial postglacial transgression induced by RSL rise. For each sample, between 0.3 - 3 grams of oven dried material was placed in a crucible and dusted, weighed and then burnt at 550ºC for a minimum of four hours to establish the percentage of organic matter. The LOI of each sample is calculated using the following equation:

$$LOI_{550} = ((DW_{105}-DW_{550})/DW_{105})*100$$

where LOI_{550} represents LOI at 550 ºC (as a percentage), DW_{105} represents the dry weight of the sample before combustion and DW_{550} the dry weight of the sample after heating to 550 ºC (both in grams).

3.4.4 AMS ^{14}C dating

Radiocarbon analyses are considered the most accurate and widely applicable of the 'absolute' dating methods, particularly for postglacial sea-level studies (e.g., Gehrels, 1999, Edwards, 2006, Massey et al., 2006). Previous studies have shown the usefulness of the Accelerated Mass Spectrometry (AMS) ^{14}C dating method (e.g., Gehrels et al., 1996; Törnqvist and van Ree, 1998; Gehrels, 1999; Massey et al., 2006), which has two main advantages over conventional ^{14}C dating. Firstly, it allows for smaller samples to be selected and, secondly, it allows a more precise average age of plant fossil remains to be obtained. Uncertainties in the age and altitude of a radiocarbon dated sample can result in SLIPs with considerable age and vertical errors. Furthermore, contamination of samples can occur during the sampling stage (Gehrels et al., 1996). Contamination by younger carbon can occur from root penetration through a sediment profile and the downward movement of material through bioturbation. Similarly, the introduction of older carbon can include those from unstable soils and in-wash of local soils and bedrock (Lowe and Walker, 1997). Targeting horizontally embedded plant fragments minimises the possibility that the samples were reworked after deposition, providing a more accurate chronology for basal sections of the cores (e.g., Gehrels et al., 1996; Törnqvist et al., 1998; Gehrels, 1999). From these dated sections an indicative meaning can be established on the basis of the foraminiferal analyses, thus providing basal (compaction free) SLIPs.

Core sections were methodically dissected and examined centimetre by centimetre for suitable dating material. Samples were selected primarily based on the presence of agglutinated foraminifera. To avoid possible contamination (e.g., from in-situ roots and horizontal *Phragmites* rhizomes) only plant fragments that were detrital in nature, broken and away from the core edges, were sampled. Selected material was carefully removed and washed over a 63 µm sieve with distilled water. The material was examined under a low powered microscope to check for contamination by vertical rootlets, and any visible rootlets were removed with tweezers. The datable material was then oven-dried for a minimum of two days at 40ºC, weighed, and stored in airtight plastic containers. Dried samples weighed approximately 3.5 − 15.5 mg (refer to Appendix B -1.1d). Selected fossil plant fragments were associated with foraminifera, were of sufficient weight, and were as near to the base of the section as possible. Samples were then sent to the Natural Environmental Research Council (NERC) Radiocarbon Laboratory in East Kilbride (Glasgow) where they were prepared for dating.

3.4.5 Sea-level methods synopsis

So far this chapter has examined the fundamental methods and concepts needed to establish the primary objective. Two sites at Thurlestone Sands (south Devon), South Milton Ley and South Huish, provide suitable stratigraphies for producing new accurate late Holocene sea-level index points. Details of the practical techniques employed in the field and laboratory, from the core sampling to the retrieval of material for radiocarbon dating, have been described with reference to the relevant literature. The new SLIPs will allow the validation of geophysical models and future predictions of sea-level rise for the region. However, the exact nature of the relationship between sea-level rise and railway impacts is not yet known. The remainder of this chapter presents the methodology used for addressing this, and with alignment to the remaining two objectives of the project. This requires methods from both sides of the geography discipline to determine the impacts of sea-level rise (section 3.5) and the integration of climate and socio-economic futures into scenarios (section 3.6).

3.5 The impacts of future sea-level changes: a semi-empirical approach

A fundamental assumption of the methodology discussed previously is that in reconstructing past trends (e.g., sea level) a likely indication of the future can be established (assuming the trends continue). Attempting to establish the extent to which past changes in sea level have influenced the frequency of incidents on the railway line (if any) could therefore help identify the potential future impacts. This type of exploratory approach allows improvements in the ability to quantify the impacts associated with climate-related hazards (Beniston, 2007). The physical mechanisms that underlie overtopping of defence structures, however, involve a significant number of variables. The principles of the defence structure (e.g. crest height (or freeboard), toe of structure, permeability etc.), and surface run up and surface roughness are major determining factors in overtopping. Other important physical factors include the significant wave height, period and steepness, the local bathymetry and water depth, the severity of weather, and changes in MSL (Geeraerts et al., 2007).

Assessing these interacting mechanisms is another problem would require a complex and sophisticated modelling approach to allow futures to be predicted. Complex models and programs used in climate modelling can often produce ‘nonsense correlations’ or relationships that have no causal basis (Schmith et al., 2007), and these issues have also been raised in sea-level studies. Understanding future changes in sea level is a difficult physical problem, involving complex mechanisms with different time scales (Rahmstorf, 2007a), and the uncertainties in predicting future sea-level changes reflect this (Holgate et al., 2007). Scientists have attempted to reduce the uncertainties and complexities of mechanisms, however, by using observations and past records to establish semi-empirical based relationships. Rahmstorf (2007a), for instance, used a semi-empirical approach to predict future sea-level rise by extrapolating the correlation between global sea-level rise and global mean air temperature change for the last 120 years. The consequences of the relationship could then be explored with future changes in temperature taken from the IPCC scenarios (Meehl et al., 2007). This type of approach allows a known driver (e.g., sea-level change) to be linked to a response (e.g., overtopping frequency) and a future based on empirical evidence to be determined. There can be numerous uncertainties and errors in computer modelled approaches (e.g., future wave conditions, bathymetry, etc.) and a semi-empirical approach can bypass these. Although details of the approach were criticised (not relevant to this study, see Holgate et al., 2007) the example highlights the use of observations and records to establish physical trends involving complex interactions and mechanisms.

For modelling the overtopping of coastal (and estuarine) defences structures, EurOtop have produced a guidance and assessment manual primarily for European coastal engineers (Pullen et al., 2007). By attempting to model key parameters and principal responses of overtopping, the resulting outputs include mean overtopping discharges, maximum overtopping volumes and the proportion of waves overtopping a sea wall, and there are numerous ways of calculating these. Many of the parameters used in engineering models are uncertain, however, and so are the models themselves. Pullen et al. (2007) explains that modelling approaches inherit fundamental and statistical uncertainties from the random process of nature. Furthermore, the data and model used can result in errors and poor representation of the physical processes involved, and there is also the factor of human error. Outputs must also be checked for physical soundness and all parameters must be checked against other variables to highlight any improbable results, both can be time consuming. The fundamental uncertainties of models can never be removed, and other uncertainties can only be reduced by increasing and improving the data, knowledge, and models adopted (Pullen et al., 2008).

With adequate data, however, model approaches can be replicated at coastal locations, and engineering models are a key tool for determining the structural integrity of specific defence structures. Yet the outputs of model approaches (e.g. discharge volumes etc.) may not be able to be directly linked to wider impacts on the line (e.g., damage, traffic restrictions, costs) without extensive expert consultation. As determining the socio-economic impacts of overtopping on the line is a key component of this study, modelling approach may not be entirely satisfactory. Furthermore, O'Breasail et al.'s (2007) study of overtopping on the railway line was based on numerical models, and adopting an alternative approach (i.e. examining empirical-based relationships) could extend current knowledge of the issue in two ways. Firstly, it could allow a more thorough exploration of the wider impacts of line closures that are not considered in their study, and this could also allow the integration of socio-economic scenarios (SES) into the assessment. Secondly, it will allow a comparison of the new estimated impacts of sea-level rise thus providing interesting insights into the science of predicting overtopping on coastal structures. As discussed already in Chapter Two, the observations of MSL in the English Channel are some of the best, and longest, records available from all tide-gauge stations. Establishing a record of overtopping events and line consequences (including wider impacts) would therefore offer data to help identify an empirical relationship between rising sea levels over the last century and a half. This empirical approach based on historical understandings could help to reduce some of the complexities and uncertainties demonstrated in engineering model approaches. The next section discusses the construction of such a record.

3.5.1 Archive and documentary analysis

> *There are no records at all relating to the sea wall. Even in 1916/17, what records had existed had clearly been lost, as the Secretary's report to the Engineering Committee on the history of the wall are sketchy and full of errors.* (Kay, 1993 p. 108).

From this quote it was understood that documentary and archival (secondary) data sources would be the only means of establishing a full empirical history of the line's past vulnerability. However, geographical research often uses historical or documentary data collection in the whole or some part of the methodology (Ogborn, 2004). For instance, in human geography written and numerical materials can tell us about social and economic histories (e.g., Gregory, 1982), and in physical geography coastal maps or historic photographs can inform us of recent landform/shoreline changes (e.g., Morton, 1988). The purpose for gathering or analysing secondary data follows the same principles as in the scientific world of climate reconstruction and, thus, documentary evidence can be used as a proxy – and offer information of high resolution – for investigating local/regional patterns of change (Souch, 2004). Despite the frequent use of archives and documents in research methodologies there are no predetermined rules, handbooks or instructions (Bos and Tarni, 1999).

Documentary data are materials that can be used to provide interpretations and analyses of past periods, histories and events (Ogborn, 2004). However, from the beginning of the research process problems can occur as the necessary data simply may not exist and acquiring information – that may be considered confidential – can require long pathways to access it (Black, 2004). Further complications can occur when sourcing data as archives/records may have changed owners or be stored in various places. Finally, the data themselves may need significant manipulation (scanning, photocopying etc.) to compute information and this can be very time consuming. White (2004) states that negative points must be borne in mind but it is possible to overstress them and, for many geographical investigations, secondary data are indispensible to investigations that seek to make connections between past, present and future events. This was certainly the case for this project, as no definitive record of incidents and disruption had been kept or maintained, documentary sources would be vital in order to create a baseline for analysis.

The potential benefits of using archival or secondary data range from providing the general context and background to a research issue (Creswell, 2009), to drawing specific lessons from past cases or events (Franzosi, 1987; Ogborn, 2004; Woodcock, 2008). Collecting secondary data is often cost effective, and today public opinion, political discourses, policy discussion and commercial actions are increasingly based on the reading (or sometimes misreading) of secondary data (POST, 2009b). Thus, archival data sources can provide information for better informing future policy decisions on the railway (i.e. learning from past experiences). There are numerous approaches to the analysis of secondary documents and their information. The most commonly used for quantitative data is *content analysis*, by which content of a particular media is summarised (Robson, 2002; Scott, 2006). It has been used as an approach to analyse documents and texts, in order to quantify the content with respect to predetermined questions (Bryman, 2008). As this project seeks to establish relationships between rail vulnerability and sea-level changes content analysis would be ideally suited as it could achieve this in a systematic and replicable manner.

Further benefits of documentary data collection are that it is often possible to ‘acquire’ copies of documents of a variety of types to achieve a particular level of understanding and validation. Copies (or sources) can then be used for triangulation purposes and to provide a longitudinal dimension to a study when a sequence of documents is extended back in time (Robson, 2002, Bryman, 2008). Triangulation, to build a coherent history of events, can help validate overall findings and relationships (Gibbs, 2007). Although other methods, such as interviews, and surveys, can provide historical evidence they are time consuming and can ultimately provide indirect, or biased, information (White, 2004; Creswell, 2009). Furthermore, the research produced from interview-based methodologies is often of a more qualitative nature and can be subject to the researcher's own interpretations. The reliability (or replication) and validity (accuracy) of results are therefore questionable (Kirk and Miller, 1986; Marshall and Rossman, 1995; Crewell, 2009). This project requires a precise (quantitative) record of sea wall incidents to be analysed with changes in sea level. Therefore, the qualitative aspect of alternative methods (interviews etc.) are less appropriate for this study. By exclusively using documentary and secondary sources, however, a more robust record of incidents could be established and quantified. The history of line vulnerability is complex and includes engineering problems, railway service changes, displacement of people, and also weather and tidal effects that occur on the line. The cross-clarification and triangulation benefits of using secondary data sources, however, hold the potential for a quantitative history to be constructed in sufficient detail.

3.5.2 Gathering archives and accounts

Initial investigations of industry rail archives, local historians, museums and libraries confirmed Kay's (1993) original analysis of the sea-wall records. It was, therefore, a necessity for the project to collect and create an archive containing all the documented evidence of weather related events on the London-Penzance railway line. Interestingly, UKCIP (www.ukcip.org.uk) recently promoted the use of journalistic archives to help local authorities become aware of the impacts of previous extreme weather events. UKCIP gave guidelines for developing what was called Local Climate Impact Profiles (LCLIP) from a pilot version carried out by Oxfordshire County Council. This essentially involved the sourcing of journalistic evidence, establishing key trends and thresholds, and assembling the information with the relevant future weather and climate data to generate future scenarios. The optional stage of the LCLIP was to gather historical data to explore the patterns of similar events over longer periods (e.g., 50 years) on the basis of its usefulness in informing future trends (UKCIP, 2008). This project uses a similar concept to establish an impact profile on the railway line.

Reconstructing over 150 years of detailed and focused rail history needs careful investigation and planning. Fortunately, many records are available digitally over the internet. However, thought must be given beforehand to the type of research questions wanted to be answered (Ogborn, 2004). Different sources will answer different questions and some are easier to answer than others. For instance, what was the change in sea level along the railway line over the last century? This can be acquired directly using the online records of mean sea level (MSL) from the National Oceanographic Centre (www.pol.ac.uk) and analysed with a simple computer package (e.g., Excel). However, addressing the question: "to what extent is the frequency of overtopping on the line reflected by changes in sea level?" requires consideration and deep archival investigation. As discussed in the previous section the linking of numerous sources can improve consistency and understanding of research questions (Baker, 1997; Black, 2004). Consequently, in order to establish a broader interpretative framework of incidents on the sea wall, a problem-orientated approach was initially adopted with the aim establish a quantifiable record of past vulnerability of the line.

Preliminary internet searches, using carefully chosen search terms (see Appendix A - 1.2), were undertaken to establish the freely available records, books, data etc., regarding the Dawlish-Teignmouth section of the line. Local libraries, online rail forums, newspaper archives and weather records were searched in order to triangulate information based on dates of known incidents. Where records were not freely available to download, or where there were queries in the nature and possible use of data, contact was made with the authors (or owners) directly via letter, email or telephone (e.g., Met Office, Network Rail, National Oceanographic Centre, National Rail Archives etc.). As the data collection was ongoing and involved various sources, records of the data collected, new inquiries and details of their purpose in the project were kept along with the owner's contact details. This enabled a clear overview of the progress being made and the details of the information being sourced to be viewed against the research aim. A number of key documents and sources were obtained from internet searches and direct contact with Network Rail and train operating companies (TOCs). Visits were also made to control centres (e.g., First Great Western) and rail depots to inquire about general information or gather data to be used (if required).

One initial source, however, allowed a pilot study between rail records obtained and MSL to be carried out. In order to establish the changes in recent sea level that have occurred along the section of track, two tide-gauge records (Brest and Newlyn) were taken from the Permanent Service for Mean Sea Level (PSMSL) at NOC (Liverpool). By combining the two data sets, changes in MSL can be observed for the southwest of England and the English Channel for the period 1807-present. This time period spans the entire history of the railway, which opened in 1846 (Kay, 1993), and allows the comparison of changes in sea level to be observed together with a problem history obtained from Network Rail (fully detailed in section 3.5.4). The result suggested an indicative (*prima facie)* positive relationship between sea-level rise and maintenance activity on the line (Figure 3.7). Increases in sea-level appear to coincide with increases in maintenance activity. This does not include, however, the relationship between overtopping and line impacts or other factors that influence overtopping events (e.g., storm surge). It signified, however, the importance of carrying out a full archival search which would, potentially, offer data capable of more in-depth analysis. The main archives collected are now discussed.

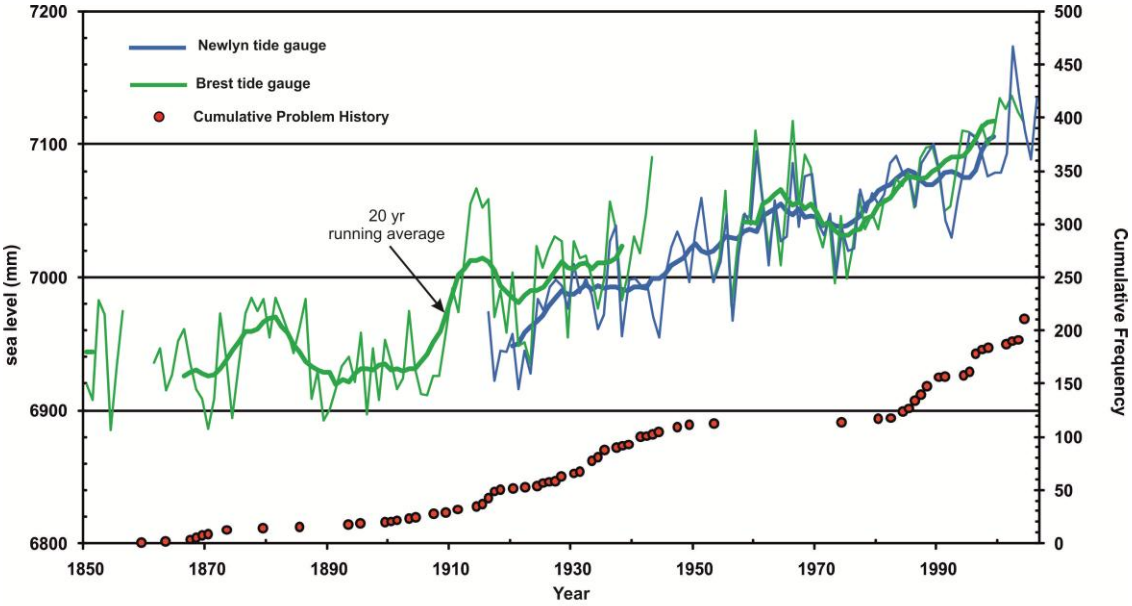

Figure 3.7 Relationship between sea-level change and maintenance activity along the sea defences on the London-Penzance railway line. Periods of frequent repairs correspond with periods of accelerated sea-level rise. Annual tide-gauge data in mm, also showing are 20 year running averages from Newlyn 1916-2007 and Brest 1807-2007 (www.pol.ac.uk). Closed dots show cumulative problem history at Dawlish beginning in 1859 (Rogers and O'Breasail, 2006).

3.5.3 The Published Sources Archive (PSA)

A journalistic record was obtained in order to establish known dates that the railway had been closed or impeded due to overtopping of the defences. These were then quantified and analysed with changes in sea level of the same time period (similar to Figure 3.7). Dates of rail incidents and closures (e.g., from 1846-2009) were collected from historical rail books (e.g., Riley, 1972; Gregory, 1982; Kay, 1993; Marsden, 2009) containing photographs and descriptions of events on the sea wall. Peter Kay – author of *Exeter-Newton Abbot. A Railway History* – was also contacted and copies of his notes where collected for content analysis and further leads. These books offered a base of known incidents which could be investigated and back filled with more extensive searches of local, regional and national newspapers. Microfilms, press cuttings, photo copies, digital articles etc., of the *Western Morning News*, *Evening Herald* and *Express and Echo* were sourced in the libraries of Plymouth, Exeter, Teignmouth, Dawlish and Newton Abbott. Furthermore, online archives of *The Times* and *Guardian* were also searched and provided additional evidence. The National Archives and National Rail Museum were also contacted regarding records. Further useful sources included parliamentary *Hansard* documents (official verbatim of proceedings in both houses) available online, and also the archives of local Members of Parliament (access via personal visit only). These offered additional details of incidents, public opinions (letters etc.) and also further leads for investigation. The microfilms, newspaper cuttings, maps and online archives, however, provided extensive evidence of the known dates and detailed accounts of railway incidents from 1846 – present (2009).

The archive provided details of the days that the railway line has been running a restricted service due to overtopping or damage to the defences (repair works were not included). Once a known incident date was confirmed the newspapers either side of the dates were checked for information on reopening etc. Results were compiled chronologically in a spreadsheet along with the number of days that the incident lasted (based on the report descriptions). This allowed a quantitative account of incident descriptions and known days with line restrictions (known as DLRs) to be slowly constructed. The qualitative descriptions were also recorded and contain varying degrees of details of weather conditions, times of events, wider storm damage and discussion. For instance, information on the effect of DLRs on passenger journey times was recorded (again, with varying degrees of detail) or the location and damage to the infrastructure. The record became known as the *Published Sources Archive* (PSA). Although a lack of consistency and detail among news reports was a disadvantage, the extensive coverage of archives (and thus incidents) provides vital data without which the investigation could not continue.

3.5.4 The Frontage Management Record (FMR)

After initial inquiries at Network Rail and a visit to meet the local Civil Engineer (Peter Haigh) a report was obtained regarding the defences that protect the line (Rogers and

O’Breasail, 2006: *Frontage Management Strategy*). It contained: a problem history (interventions) for the defences (1859-2005); current emergency response initiatives and their trigger levels; and cost analysis of potential line improvements. The intervention history detailed annual damage and repairs to the sea defences between Dawlish-Teignmouth since 1859 (see Table 3.2). The data were categorised and referenced by chainage (location on the track), the date only contained the year of damage, and details of costs or how the problems affected the running of the line were not included. Although the record offered an extensive descriptive source for analysis it was not collected for any analytical purpose, and there was a limit to the depth of analysis achievable from this particular source.

Chainage	Date	Description
204m 59c	1911	Large hole in footpath on seawall near Langstone
205m 44c	1917	A hole 45’ long appeared between the seawall and parapet wall, the ground sank 7’.
206m 6c	1885	High tide and rough sea came over the line at Dawlish Station, East Cliff. Damage to slipway.
207m 50c	2004	Top 50% of wall destroyed including copings and walkway. Replaced to new design standard after storm.
208m 14c	1996	Breakwater demolished

Table 3.2. Excerpt from Rogers and O’Breasail ‘s (2006 p. 10) problem history 1859-2005 detailed in the Frontage Management Strategy. The record is referred to in this thesis as the Frontage Management Record (FMR).

Nevertheless, the record was put in chronological order and the descriptions were analysed and separated into damages and repairs, and four categories (low, medium, high and severe). This became referred to as the *Frontage Management Record* (FMR). Due to the extent of the record, and as the PSA was still under investigation, a preliminary comparison of the FMR’s annual maintenance interventions (Rogers and O’Breasail, 2006) and tide-gauge observations in the English Channel was carried out (Figure 3.7, in section 3.5.2). The authenticity and credibility of the FMR (Rogers and O’Breasail, 2006) was questioned as there was no mention of incidents pre 1859, and it was well established that the first recorded closure occurred in 1846 (*London Illustrated*, 1846; Kay, 1993). After some lengthy investigation, the construction of this problem history was later found to be from a small archive of documents and records in the loft of Network Rail's Exeter depot. The visit, and discussion with engineers, also presented the discovery of Network Rail's more recent digital archive of incidents taken from the TRUST[1] monitoring system.

3.5.5 TRUST Service Data (TSD)

Currently, Network Rail's Weather Strategy Team use a weather matrix based on combinations of wind and tide predictions to alert them to the likelihood of overtopping incidents (discussed in detail in Chapter Five). In 2009-2010 a trial study was carried out using wave height forecasts to alert emergency responses (Network Rail, 2010). This also indicates what emergency response measure should be imposed (i.e. level 1, 2 and 3) and these responses (or alerts) were summarised in Rogers and O'Breasail (2006). Network Rail's Weather Strategy Co-ordination Team archive the records of alerts and these offer an excellent resource for examining more recent line vulnerability (from 1997-2009). The records include the time and location of alert, the level of restriction (e.g., 1-3) and the delay minutes that occurred to the track service (Table 3.3). These records were collected from Network Rail by requesting delays caused by weather events for the Dawlish-Teignmouth section only. The results also contained landslip incidents (and other weather problems) which were not included in any further analysis.

The incidents were put in chronological order and the record was named the TRUST Service Data (TSD) archive. In addition to this, First Great Western's area log files were obtained from the operations and incident control centre in Swindon to establish information on the disruption to traffic during incidents. Over 12,000 files (2002-2009)

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[1] TRUST – Train Running System TOPS: TOPS – Total Operations Processing System.

were searched using the key words and dates already compiled from the newspapers searches and dates from the TSD. The log files contained additional dates along with descriptions of taxi information, train journeys affected on the day, and passenger issues (e.g., missed connections) in relation to the event on the track. The records were input into the TSD archive and any new dates were also checked in the newspaper archives for additional accounts. These archives allowed the average occurrence of alerts to be observed over the last decade. Furthermore, changes to rail user travel times during traffic alerts were established in the data set (using FGW files). These will be utilised in further calculation analysis in Chapter Six. Although consistency and quality varied between the individual incident reports, together, the data give the most detailed incident record for the last decade. Although no long-term trends can be accurately established the frequency of emergency alerts (1-3) and delay minutes for the 13 year period give a accurate record of the recent problems.

Incident No.	***Incident date***	***Description***	***Reason Code***	***Total delay minutes***	***Incident Location***	***Incident Location***	***Text***
272506	08/10/2006	Level 2 working Dawlish	XW	111	Exeter St Davids	Dawlish Warren	*** 08/10/06 19:55 #QDP1036 *** CREATED Pway advise that wind picked up after initial estimate of level 1 so level 2 imposed. Estimate DM reopened by 2300hrs after tide drops & line patrolled.

Table 3.3 Example entry from the TRUST archive (1997 to present) used in this project to construct the TRUST Service Data set (TSD). Source: Network Rail.

3.5.6 Sea surface and weather records

Whilst sourcing dates of incidents, data on factors that influence overtopping (other than extreme water levels), such as tidal and meteorological conditions, were collected. These were cross referenced with dates in the incident archive to determine the conditions under which documented events occur. Along with records of MSL, the PSMSL offers extreme sea level and extreme storm-surge values on a monthly basis. Dates that correspond with incidents were extracted. In addition, daily and monthly wind and pressure archives were obtained from the Met Office from the Channel Lightship Buoy and from the Berry Head recording unit, along with data from the Slapton Field Centre weather station. Together the archives detailed wind speed (duration and direction) dating back to 1961. Although the timescales of the data sources inhibit the construction of a data set spanning the entire life span of the railway, tidal and weather conditions are a crucial factor in determining the thresholds and impacts of individual overtopping events. In addition to these archives, Zong and Tooley (2003) identified historical flood records in the UK during the last few centuries. Their data set was used as another point source as it offered a number of dates when flooding occurred in the Southwest. These dates were then investigated further using other sources to identify if problems on the railway also occurred. Once all the data were collected analysis of the archives (both individually and collectively) was carried out to construct a detailed quantitative and qualitative incident profile for the railway line.

3.5.7 Establishing an empirical baseline

All the quantitative histories of incidents (PSA, FMR and TSD) were kept separate for transparency. Various screenings of the archives were carried out to minimise errors and increase the accuracy of evidence. Only documented incidents with direct mention of the railway were inputted for further analysis. For instance, the newspaper search presented various large (regional) storms over the last one and a half centuries, if the railway was not mentioned it was, therefore, assumed to be unaffected. During the screening process comparisons between the primary data sets were made and analysed. Incidents were cross referenced for clarification and additional information, and the tidal and meteorological data were gathered. Table 3.4 outlines the final archives, the data they contained, and their potential reference with other sources. As mentioned, measurements of annual MSL from Newlyn and Brest were obtained from PSMSL (www.pol.ac.uk/psmsl) and input into an Excel spreadsheet.

Archive	Usable data	Comparison in records
Published Sources Archive (PSA): 1846-present	• Long-term quantification of incidents • Details of disruption to passengers	• TSD's recent events • Long-term tidal data (Mean Sea Level)
Frontage Management Record (FMR): 1859-2005	• Years of damage/repairs • Severity and track location of damages	• PSA's and TSD's description of incidents and dates (annual) of known incidents
TRUST Service Data (TSD): 1997-present	• Recent dates of incidents (1997-2009) • Delay minutes on the track • Average frequency of emergency alerts (1-3) • Delays to passengers during emergency alerts (in correlation with FGW's log files)	• Recent meteorological and tidal data
Meteorological and Tidal data	• Average wind speed/direction during incidents • Tidal heights and surges during incidents	• PSA's and TSD's dates of incidents

Table 3.4 Archives constructed and used in the analysis and impact profile. More detail and discussion are presented in Chapter Five.

The annual Revised Local Reference (RLR) data for both stations were used, as RLR data sets are only calculated if there are at least 11 months of data and each month must have fewer than 15 missing days (Holgate, 2007). A central moving average (CMA) for twenty year periods was computed on the annual data to establish smoothened (average) long-term trends of annual MSL. Twenty year periods were used to coincide with the Moon's full *precessional* cycle (18.6 years), and this has been observed in long-term tidal records (Brown et al., 2002). Unlike Newlyn, the Brest tide-gauge record is not continuous, and this meant that a full record of MSL, from the line opening (1846), was unavailable. Further removal of years with questionable data quality (e.g., 1937, 1939-43) was carried out on the basis of Wöppelmann et al.'s (2005) discussion. The Newlyn record, on the other hand, is near continuous and by combining Newlyn and Brest, the smoothened long-term sea-level data covers the period of 1861-2009.

The data of rail incidents collected were then prepared for analysis with the record (using regression analysis) and extrapolation with the predicted future changes in sea level (e.g., Lowe et al., 2009). Potential projections include known days with line restrictions (DLRs – taken from the PSA), average emergency speed restrictions (utilising the TSD record further), and averages of expected delay minutes. See Chapter Five for more details. The weather records were also observed for any trends and thresholds. Finally, qualitative summaries were made from the observations from the FMR and TSD regarding damages and impacts to traffic (e.g., travel times, trains affected etc.) during DLRs on the line. The next step was to establish the likely costs of incidents and line restrictions (caused during DLRs) to the region and rail industry.

3.5.8 Costing the impacts

It was highlighted in Chapter Two that *more* integrated research – combining both physical and human aspects of science – is needed to inform better coastal management decisions (Turner 2000; Nicholls 2004a; Moser 2005; Nicholls and Tol 2006; Turner *et al.,* 2007; de la Vega-Leinert and Nicholls 2008; Nicholls *et al.,* 2008). The methodology outlined, thus far, has considered the impacts of sea-level rise on traffic running in the form of days with line restrictions (caused by overtopping), but these predictions have major costs for society (e.g., rail users) and the economy (e.g., sectors that require, or rely on, an efficient transport connection). In order to address this it, firstly, required a literature search to identify and examine the link between transport and the functioning (and growth) of the economy (e.g., SACTRA, 1999; OEDC, 2002; Banister and Berecham, 2002; Eddington, 2006). This review, and further justification of the approach, is presented in Chapter Six.

In order to demonstrate the full extent of the predicted increases of incidents and alerts on the region, potential direct costs (to the infrastructure owners) and indirect costs (to rail users and the wider economy) were constructed under a 'business-as-usual' future. To establish the direct costs to the infrastructure owners, the predicted increase in rail incidents was multiplied by the average annual maintenance costs of the defence structures. This assumed a causal link between overtopping, line restrictions and defence damage (outlined in Chapter Five). A further calculation of compensation charges was also calculated based on the contract between Network Rail and train operating companies (Burr et al., 2008) and delay minutes projections (established from previous analysis). All costs and values used in calculations were converted into 2010 market prices to account for inflation using values (e.g., GDP deflators) taken from HM-Treasury (www.hm-tresury.gov.uk). Although the method of calculating these costs is quite simplistic they will illustrate the potential trends of monetary impacts directly to the line. Illustrating the indirect impacts of future rail incidents required a more methodical approach however.

Indirect (socio-economic) costs are often examined in two separate categories: firstly, costs to the rail user (e.g., passengers and freight), which are most commonly attributed to changes in travel time and, secondly, costs to the wider economy (Eddington, 2006). These two costs are outlined in more detail in Chapter Six. Changes in travel time are claimed to have one of the largest impacts on benefits/costs of any transport investigation (Lakshmanan, 2011). They are typically utilised in cost-benefit analysis and option appraisal techniques and were therefore used in the costs calculations. The data required to construct travel time loss are easily accessible, and can be obtained from national transport institutions (e.g., Department for Transport (DfT), Office of Rail Regulation (ORR), Institute for Transport Studies (ITS), Network Rail etc.).

Until recently, very little research has been undertaken regarding the impacts of climate change on transport (Koetse and Rietveld, 2009). However, UKCIP's (2003) *Costing The Impacts Of Climate Change* guidance report provides a case example of the economic valuation of increased flooding on the rail network in Scotland. The method utilises the approach of travel time savings to cost the impacts of future increased delays to rail users. The method can be easily adapted to illustrate the potential costs of future incidents (DLRs) from the following information: change in travel time, the number of passengers, and the time value (in £'s) attributed to each passenger (based on journey purpose and transport mode). Summaries of passenger and train delays (minutes) are available from the rail archives (from the TSD and FGW files) and an estimated daily cost for each day of line restriction (1-3) can be made (e.g., Table 3.5). Using the estimates of future restrictions the cost of passenger time loss for the 21st century can be constructed. A similar concept was carried out to illustrate the costs of freight traffic disruption during the 21st century.

Alert type (1-3)	**Journey purpose**	**Time Loss** (hours/person)	**No. of Persons** (daily)	**Unit Value** (£/hour)	**Total Value** (£)
Level 1	Work	0.33	406	45.50	6,139
	Commuter	0.33	2,830	6.18	5,827
	Other	0.33	2,185	5.47	3,981
	Total	-	**5,421**	**56.95**	**15,948**

Table 3.5 Example of economic cost calculated from increased passenger travel time during emergency speed restriction (in 2010 prices). National average journey purposes and unit values of time are taken from Department of Transport (DfT, 2007) and passenger numbers along the Dawlish-Teignmouth section are calculated from annual journeys recorded by First Great Western (2008-2009).

The costs of lost time to freight traffic is detailed in an ORR recent report (Clarke et al., 2010), and accurate freight loadings along the line can be obtained from Network Rail's TRUST traffic system. Finally, the typical commodity (important in assigning an accurate time value) was established from Network Rail's Great Western Route Utilisation Strategy (Network Rail, 2010). By combining passenger and freight costs the expected impact of increased line restrictions can be calculated. However, the costs should be considered as illustrative and do not include the wider economic impacts (e.g., to loss of business investment, networks and access to labour) of a reduced train service, the methodologies for which are complex and highly contested (Lakshmanan, 2011) and was therefore not attempted. Overall, the indirect (e.g., rail users) and direct (e.g., damages and charges) costs calculated will highlight the potential impacts to the region for the 21st century under a business-as-usual scenario.

Although an empirical approach offers confidence and rigour to forecasts regarding climate change, the chief disadvantage (of these) is that they do not account, or serve as a good basis, for explaining future changes in non-climate factors (e.g., social, economic and political) (Moser, 2005). In Chapter Two, scenario approaches were identified as a way of integrating natural and social-science futures for better informing long-term coastal management issues (e.g., Turner, 1998; Berkhout and Hertin, 2000; Turner, 2000; Berkhout et al., 2002; Tompkins, 2008; Hall et al., 2006; Turner et al., 2007; Torresan et al., 2008). The next, and final, section presents the methodology and rationale for the inclusion of non-climatic futures and the construction of the final rail scenarios.

3.6 Integrating socio-economic futures

The socio-economic uncertainties surrounding future carbon emissions, projections of societal vulnerability, and the long-term nature of climate change have stimulated the use of scenarios in the policy realm (Hall et al., 2006; Gawith et al., 2009). Scenarios can provide plausible descriptions of future trends – such as economic performance, population patterns and forms of governance – and are commonly used in strategic planning (Hulme et al., 2002). The approach is useful in decision making as it can provide policy makers with a more complete description of the range of possible coastal problems (Berkhout and Hertin, 2000; Nicholls et al., 2008). Scenario approaches can also illustrate a range of future consequences, help identify the signposts that flag key decision points, and in turn develop and measure strategic policies (Docherty and McKeirnan, 2008). Essentially, the calculations discussed in the previous section assume that the future is a linear continuation of the past (fixed), and non-climate factors that affect our adaptive capacity to climate change are dismissed. Impact assessments must therefore integrate broader socio-economic changes – that are likely to affect human vulnerability and adaption in the future – in addition to those caused by climatic variation (Berkhout et al., 2002).

In this study socio-economic futures will be used for two purposes, and aid the development of both qualitative and quantitative impact information. As discussed in the previous section the impacts to rail users (e.g., passengers and freight) represents a substantial proportion of the costs of sea-level rise on the railway line. One of the primary assumptions of the calculations is that the number of rail users being affected by incidents today will be the same in 2050. However, passenger demand will alter significantly in the future, for instance, from 1998-2007 Exeter and Plymouth recorded passenger growth increases of up to 50% (Network Rail, 2010). This may be an important consideration when determining the future sustainability of the line. Firstly, therefore, socio-economic scenarios (SES) can be used to demonstrate that patronage (on the rail network) could take a number of different trajectories based on changes in population and transport demand in the future. These will provide quantitative differences, in terms of costs, between futures. Secondly, scenarios are used to illustrate the broader policy and socio-economic futures that the railway may exist in, and that different political decisions regarding coastal and transport infrastructure may be made under each scenario. This represents the qualitative component of the analysis.

The first process, however, regards the integration of socio-economic scenarios and climate (emission) scenarios. This has been described as problematic when dealing with both their assumptions and consistencies (Dalhström and Salmons, 2005) but is crucial for the project. The pairing of the scenarios will inherit unavoidable problems, for instance, emission scenarios used in climate assessments (e.g., IPCC) already contain assumptions about economic, demographic and technological trajectories. This has been a factor in past impact and adaptation assessments. UKCIP (2001) offers guidance on how to minimise inconsistencies but again it remains down to the individual to pair them with consistency and logic (Dalhström and Salmons, 2005). Nonetheless, the importance of considering the non-climatic futures in climate-impact assessment must be stressed in order to acknowledge the effect of socio-economic changes on future vulnerability. In order to illustrate possible non-climate changes in the futures presented in this study, the projected sea-level forecasts (and DLRs) will incorporate socio-economic futures adapted from the Great Western Route Utilisation Strategy (GWRUS) (Network Rail, 2010) and the United Kingdom Climate Impact Programme's (UKCIP) socio-economic scenarios (SES) (UKCIP, 2001). The next section examines the scenarios used in this study in more detail.

3.6.1 Developing the scenarios

UKCIP's (2001) SES help to assess the impacts of climate change by providing non-climatic scenarios in order to highlight the wider socio-economic context in which climate changes will take place. UKCIP's (2001) SES have been developed both to characterise the various drivers of anthropogenic greenhouse gas emissions, which cause climate change, and to characterise the sensitivity and vulnerability of social and economic systems with regard to such change (Dalhström and Salmons, 2005). Essentially, this suggests that modern society has the ability to alter its vulnerability to climate change, for instance, positively by developing into a society that actively seeks to lower carbon emissions (both socially and technologically). Alternatively, vulnerability can be increased by further development without consideration of the long-term implications (e.g., building in areas of flood risk). UKCIP's (2001) fundamental determinants take the form of two dimensions: *governance* and *values*. Changes in these dimensions will lead to different socio-economic futures and consequent vulnerability to climate change. By mapping out these two dimensions UKCIP (2001) have constructed a two-by-two matrix; a future possibility space that segments the future into four quadrants that any region could potentially exist within (Figure 3.8).

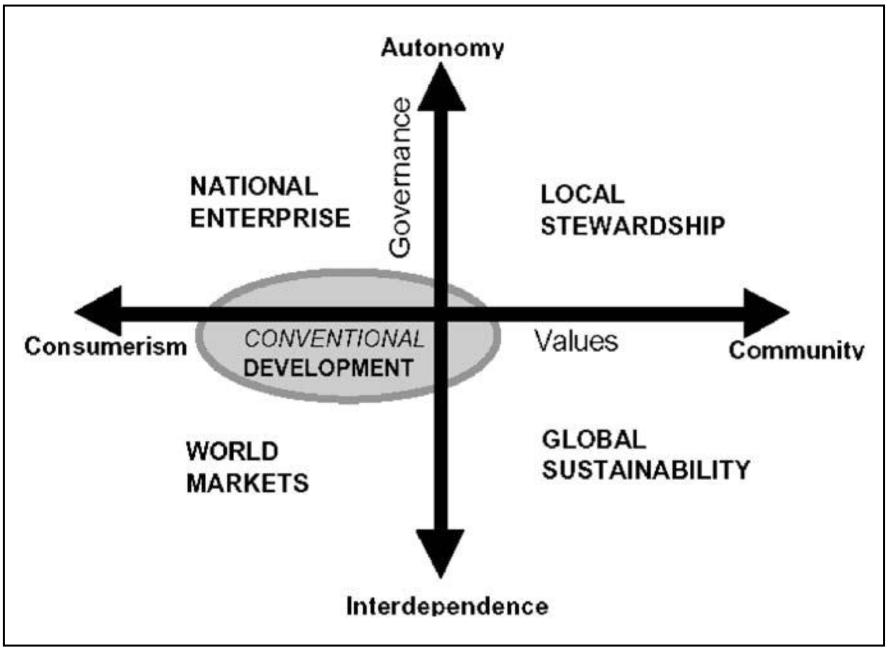

Figure 3.8 UKCIP's (2001) socio-economic scenarios, based on a two-by-two matrix of core socio-economic values (horizontal axis) and alternative structures of economic and political power. Climate emission scenarios can be integrated to give more plausible information for decision making. © UK Climate Impact Programme (2001)

The horizontal axis presents a spectrum of core socio-economic values as represented in choices by consumers and policy makers (UKCIP, 2001). The spectrum ranges from consumerism to community. The 'community' end of the axis signifies a concern for common good and the future (e.g., valuing the environment and acknowledging the risks of climate change), whilst 'consumerism' values private consumption and personal freedom. This implies values with less regard from the environment or the long-term consequences of climate change. The vertical axis presents a spectrum of governance and aims to show alternative structures of political and economic power and decision making. The axis ranges from interdependence to autonomy. This reflects the strengthening power of international economics and politics at one end (interdependence) and, at the opposite end, the retaining of economic and political power at national and regional levels. These alternative futures will have significant implications on the decision making ability of regions and capital investment (e.g., in transport infrastructure and coastal defences). Using this matrix enables the generation of four socio-economic futures which can be applied to the understanding of changes at national, sectoral and regional levels. Each of the four scenarios contains qualitative storylines and quantitative indicators of the socio-economic future and this study will make use of both aspects.

The quantification of socio-economic changes in UKCIP's (2001) SES, however, is limited to a 2020 time frame as (most) socio-economic data (with the exception of demographics) rarely exceeds 20 years (UKCIP, 2001). This time frame issue is a problem for studies attempting to integrate SES with long-term climate scenarios. Some studies have tackled the problem with additional expert consultation. The GWRUS (Network Rail, 2010) contains passenger demand forecasts between Exeter and Plymouth for four future socio-economic scenarios up until 2036. Their scenarios and forecasts were integrated with UKCIP's (2001) SES and to give passenger demand forecasts up to 2060. Details of this process are presented in Chapter Six. The forecasts of passenger demand will be included in the costs of passenger time loss to present a more accurate range of climate impacts. UKCIP (2001) gives descriptions for each future covering socio-economic aspects such as: values and policy, economic development, and settlement and planning. In order to facilitate these in climate impact assessments, however, key impact domains have also been developed including: water, coastal zones (including infrastructure), agriculture, and the built environment (including transport). In this study each scenario will be elaborated and explored with one landscape domain (the coast) and one economic sector (transport) to present a quantitative and qualitative storyline for each future.

There are limitations to the use of SES in climate impact assessments, for example it is not possible to construct SES on the same ‘long-term’ time scale as the climate scenarios (UKCIP, 2001), thus the UKCIP SES are set in a global context for the 2020s and 2050s (see Chapter Two for more details). However, the scenario approach offers a useful tool for presenting complex systems such as climate and socio-economic changes in coastal management decisions (Turner, 1998; Torresan et al., 2008). The scenarios to be presented in this study will combine results from the late Holocene sea-level analysis, the empirical impact investigation and the integration of SES and may provide more accurate and plausible information for future policy debate on the issue of the vulnerability of the main railway line.

3.7 Chapter synopsis

Presented in this chapter is an integrated methodological approach capable of addressing the key research aim outlined in Chapter One: to evaluate the impact of sea-level rise on the London-Penzance railway. Firstly, the methodology and rationale behind objective one – reconstructing late Holocene palaeo-sea levels – was presented. Lithostratigraphical analysis of salt-marsh sediments and microfossil indicators that show vertical zonation (e.g., foraminifera) offer a key tool for identifying palaeo sea-level histories. Basal sediments directly overlying the pre-Holocene surface (e.g., bedrock) offer the most accurate indication of palaeo-sea levels as they have not been subjected to post depositional compression by overlying sediments (autocompaction). From preliminary investigations and previous work (e.g., Taylor, 2004) two sites at Thurlestone (south Devon) were identified as ideal locations to obtain new late Holocene basal sea-level index points (SLIPs). The field and laboratory techniques for indentifying foraminifera, stratigraphic boundaries and accurate ages of sediments found at the sites have also been presented. The collection of new sea-level data will allow the verification of rates of glacial isostatic adjustment (GIA) used in regional predictions of sea-level rise. The results from which are presented in the next chapter. The concept of using past information to inform future trends (as in the sea-level study) transfers directly into the methodology for objective two of this study, namely, establishing the likely impacts of future overtopping on the line.

Empirical based approaches to projecting the future offer a methodology that can bypass the uncertainties and errors of computer based modelling techniques. The method for creating a model capable of extrapolating historical trends of incidents and sea-level change into the future has been outlined. This requires the collection of secondary data, documentary and archive evidence, and correspondence with various experts in the field to acquire an archive of rail incidents along the sea wall spanning over 150 years. Archives of incidents can be compared with records of mean sea-level (MSL) to establish a relationship between the two. This can then be extrapolated with modelled projections of future sea-level change (e.g., Lowe et al., 2009). Predictions will take the form of average days of line restriction per year (DLRs) for the 21st century and can be further adjusted to show the estimated emergency traffic alerts (1-3) and average delay minutes incurred under various sea-level scenarios. The results relating to objective two of this study are to be presented in Chapter Five.

The methodology needed to address objective three of this study, to integrate climate and socio-economic futures, has also been outlined. Monetary impacts can be constructed to highlight the socio-economic impact of future restricted rail travel and overtopping. The most commonly used method for establishing the socio-economic costs of future transport changes takes the form of rail user (passenger and freight) time loss (referred to as the indirect cost). Additionally, direct costs to the defence infrastructure and its owners will illustrate the potential internal cost of the predicted DLRs. Further details and discussion of the aspect of the project are presented in Chapter Six. Finally, the integration of socio-economic scenarios (SES) (e.g., UKCIP, 2001) with future climate scenarios (e.g., UKCP09) was discussed. This follows issues raised in Chapter two of this thesis. In order to illustrate the potential socio-economic changes future rail demand will be used as a quantitative indicator for four socio-economic scenarios. Qualitative descriptions will be used to outline the broader context of changes in vulnerability in the region as a result of the different government structures and societal values. Overall, this will give policy makers a deeper understanding of the relationship between climate change, society and the region's resilience to future climate change.

At present there is little evidence regarding the future of the railway line. The results produced by the methods outlined in this chapter offer data with real practical value for both sea-level studies and policy making in the region. The next chapter is the first of three results chapters, and for consistency these are presented in the order of the project's primary objectives.

Chapter Four

Late Holocene relative sea-level changes in south Devon

4.1 Introduction

The previous chapter established an integrated methodology capable of addressing the core research aim. This chapter begins with the collection of new high quality sea-level index points (SLIPs) in south Devon at two sites at Thurlestone Sands: South Huish and South Milton Ley (Figure 4.1). Both sites were established as being suitable for reconstructing late Holocene sea-level in the area and this chapter presents the results from the study. Furthermore, an independent undergraduate study, including core transects and foraminifera analysis, was conducted at South Huish (Taylor, 2004) and information from the study has been utilised. Firstly, the evidence from each site is described and the late Holocene palaeo-environmental conditions in the region are discussed. A new relative sea-level curve (RSL) for south Devon is then derived, from which the isostatic component is estimated and compared with current geophysical model estimates. Finally, the results are considered in relation to current UKCIP sea-level projections (Lowe et al., 2009) for use in the remainder of this study.

4.2 Thurlestone Sands, south Devon

Tidal heights for Thurlestone Sands are given in Table 4.1 and are interpolated from the River Yealm and Salcombe Harbour tidal station (Hydrographic Office, 2002). The core site at South Huish is situated c. + 2.6 m above MTL, and is barred from the sea by a large dune system. The valley at South Milton contains a small but active tidal freshwater marsh, a large *Phragmites* reed bed (Figure 4.1c), and is barred by the dune system of Thurlestone Sands (Figure 4.2a). A narrow opening is present in the barrier (Figure 4.2b) and allows brackish conditions to develop at the mouth of the marsh. The core site is situated around 2.6 -2.9 m OD and a small channel can be found at 2.10 m OD (Figure 4.3).

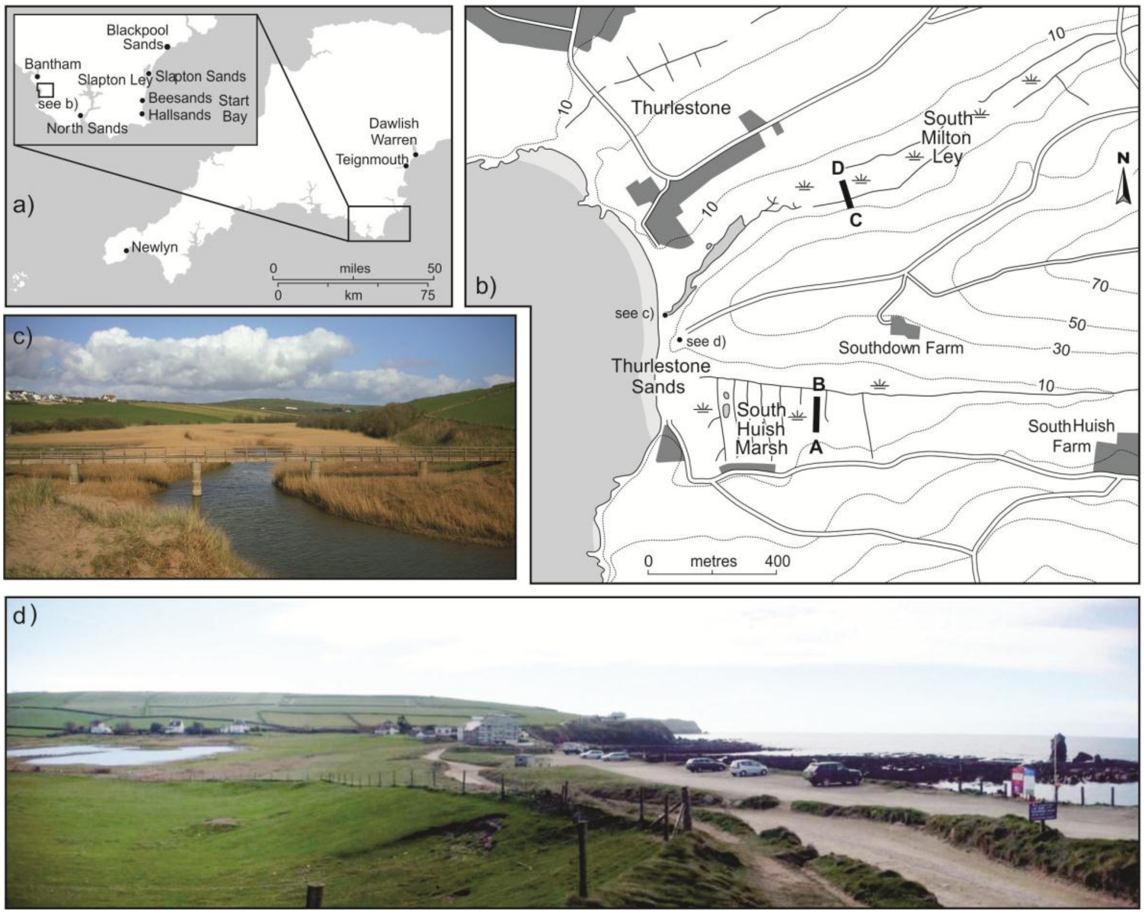

Figure 4.1 a) Regional map showing localities of investigations mentioned in this chapter. b) Location map of study site at Thurlestone, South Devon. Coring transects A-B and C-D corresponds with Figure 4.3. c) The *Phragmites* marsh at South Milton Ley. d) Overview of the Thurlestone barrier beach looking south, showing the South Huish site to the left. Adapted from Gehrels et al. (2011, p118).

Tidal Station / Site	Latitude N	Longitude W	Distance (m)	MHWS (m)	MLWS (m)	Tidal Range (m)	Chart Datum (m)	MSL (m)	MTL (m)
River Yealm (entrance)	50° 18'	4° 04'	15298 west	2.35	-2.35	4.7	-3.05	3.20	0.15
Salcombe Harbour	50° 13'	3° 47'	7600 east	2.25	-2.35	4.6	-3.05	3.14	0.09
Thurlestone Sands	50° 15'	3° 51'	-	2.29	-2.35	4.64	-3.05	3.16	0.11

Table 4.1. Tidal heights for Thurlestone Sands interpolated from nearest tidal stations. All heights are relative to the UK Ordnance Datum. Distance – approximate distance between Thurlestone Sands and Tidal Station (using eastings). Source: Hydrographic Office (2002). See Appendix B – 1.2b.

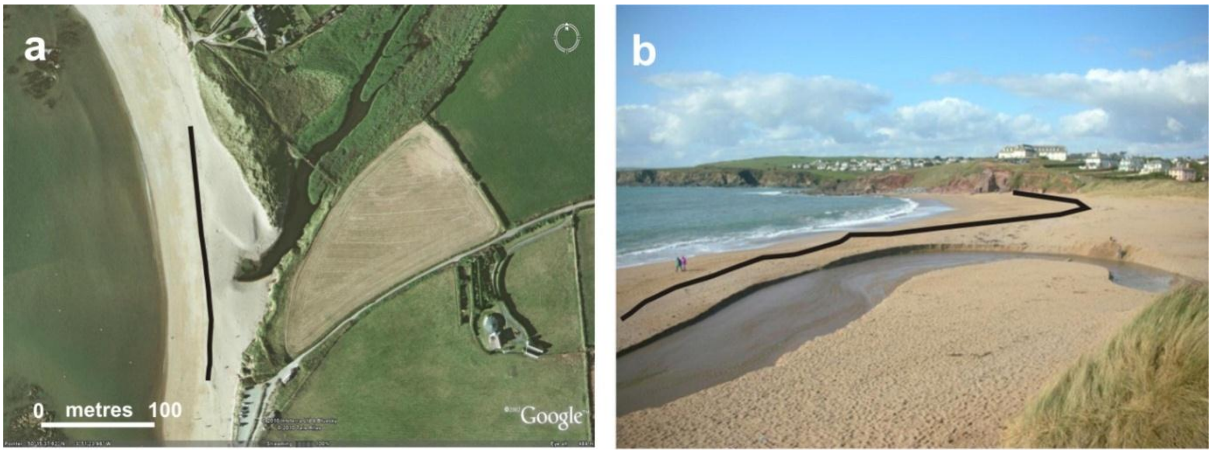

Figure 4.2. (a) A beach bars the entrance to the marsh at South Milton (courtesy of Google Earth ©). (b) A deeply eroded channel cuts through the beach material (March 2007).

4.2.1 Litho- and biostratigraphy

Sixteen cores were collected from a transect taken in South Huish Marsh, and four cores were extracted from South Milton Ley (see Figure 4.1 A-B and C-D, and Figure 4.3). Stratigraphic sections were identified, foraminiferal analysis was completed and 13 radiocarbon samples were selected. Stratigraphic sections were described using a basic Troels-Smith (1955) scheme and are summarised in Table 4.2 and in Figure 4.3. Detailed stratigraphic descriptions of the cores can be found in Appendix B -1.1a. The study at South Huish found Pleistocene head deposits containing a mixture of clay and weathered local bedrock (quartz and schist) from -0.5 m OD (3 m below the surface) up to + 1.5 m OD. The head slopes upward towards the southern valley side and is found at a shallower level of 1.6 m OD (core T-11). In the deeper cores the head deposit can be found (in the centre of the valley) and a sharp transition to a sand-gravel unit is found and this was also identified in a previous study (Taylor, 2004). Overlying the head and gravel is an organic basal silt unit.

The unit varies in thickness from 0.2 - 0.4 m and a reduction in the depth and thickness of the unit is observed southwards away from the valley centre. The deepest basal silt unit (directly over head deposit) is initially found between 0.5 and 1.2 m OD. Above the silt layer, sediments are more organic and peat is found at around 0.20 - 0.25 m below the surface (c. 2.5 m OD), and ranges from 0.5 - 1.5 m thick. The unit is thickest in the northern-most cores closest to the centre of the valley and becomes thinner as it fringes the valley sides. The minerogenic sediments below the peat lap onto the valley sides to form a shallow basal unit that contains fossil foraminifera. Sparse fragments of organic material (*Phragmites* leaves and stems) were found in the silt deposit offering possible material to date.

A-B –South Huish

Unit	Description and components	Nig	Strf	Sicc	Elas	Lim
Peat	Dark organic peat Th3 Dh1 5Y 2.5/1 Black	3	2	3	3	1
Silt	Brown silty peat Ag3 Th1 Dh$^+$ Dg$^+$ 10YR 4/2 Dark grey brown	2	2	2	2	1
Sandy Gravel	Grey sandy gravel Ga3 Ag1 7.5YR 5	2	0	3	1	3
Head	Gold and grey clay and gravel (head deposit) As3 Gg1 2.5Y 6/8 Olive yellow	1	0	0	2	3

C-D – South Milton Ley

Topsoil	Topsoil 7.5YR 4/4 Brown	2	0	3	1	-
Organic silt	Grey brown organic silt Th4 Dh$^+$ 10YR 6/2 Light brownish grey	2	3	3	3	1
Peat	Organic brown peat Th3 Ag1 Sh+ 7.5YR 3/2 Dark brown	3	1	2	3	1
Head	Reddish brown clay As3 Gg1 10R 3/4	2	0	0	3	3

Table 4.2 Facies descriptions from South Huish and South Milton Ley, Thurlestone Sands, Devon. Stratigraphy corresponds to Figure 4.3.Individual log descriptions are also given in Appendix B – 1.1a, descriptions adapted from the basic Troels-Smith (1955) scheme.

Analysis of the basal silt unit found species of agglutinated high-marsh foraminifera between 0.56 and 1.54 m OD (Table 4.3). Foraminifera counts for all the cores are given in Appendix B -1.1b. *Jadammina macrescens* dominates the unit but smaller numbers of *Balticammina pseudomacrescens*, *Miliammina fusca* and *Trochammina inflata* were also identified. The stratigraphy found at South Milton is similar to the South Huish valley (Figure 4.3 cont.).

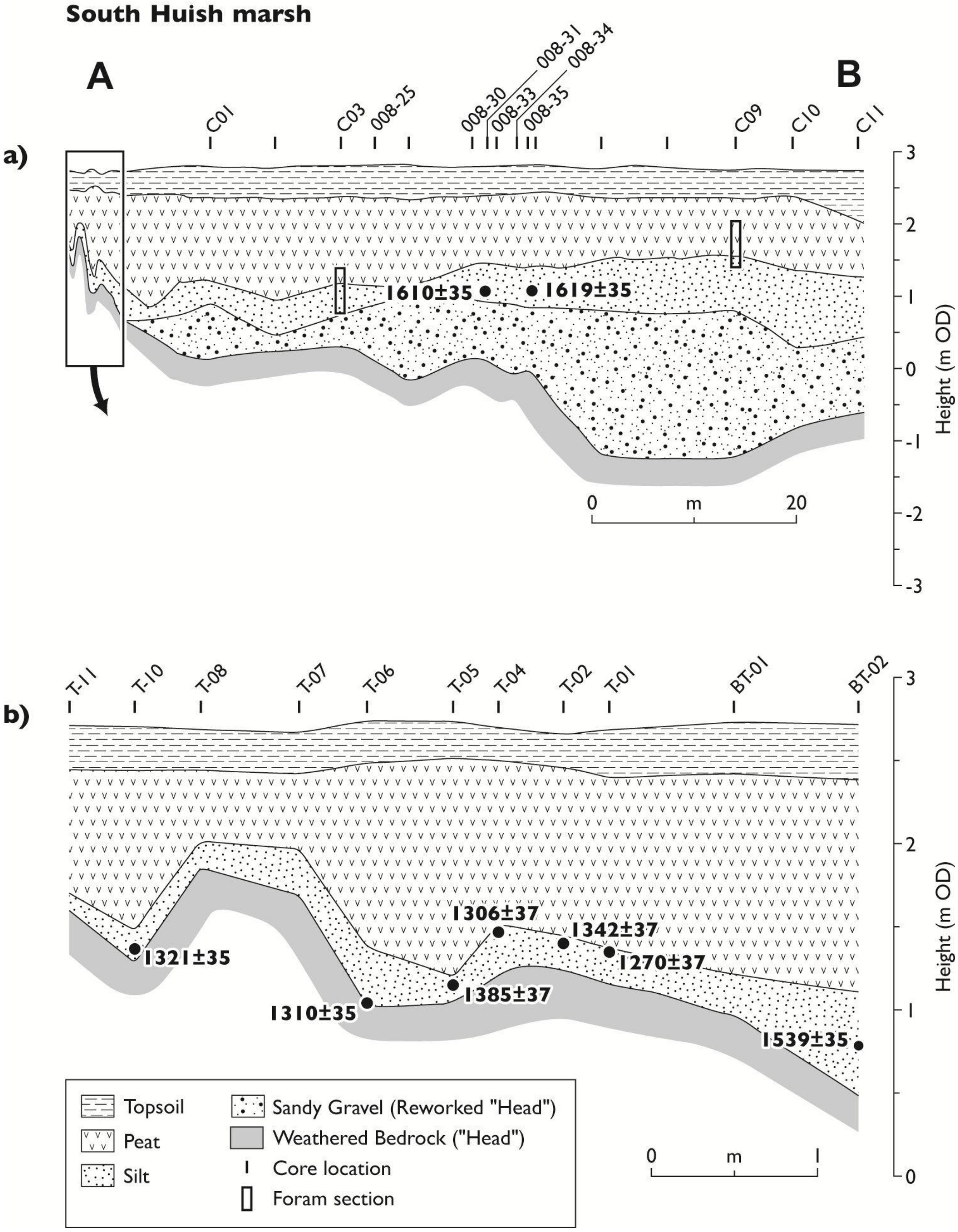

Figure 4.3 Stratigraphic cross section at South Huish showing position of sea-level index points collected from the middle of the valley (a) and the southern valley slope (b). Boxes in (a) show positions of section analysed from foraminifera in a previous study (Figure 3.5). Source: Gehrels et al. (2011, p119).

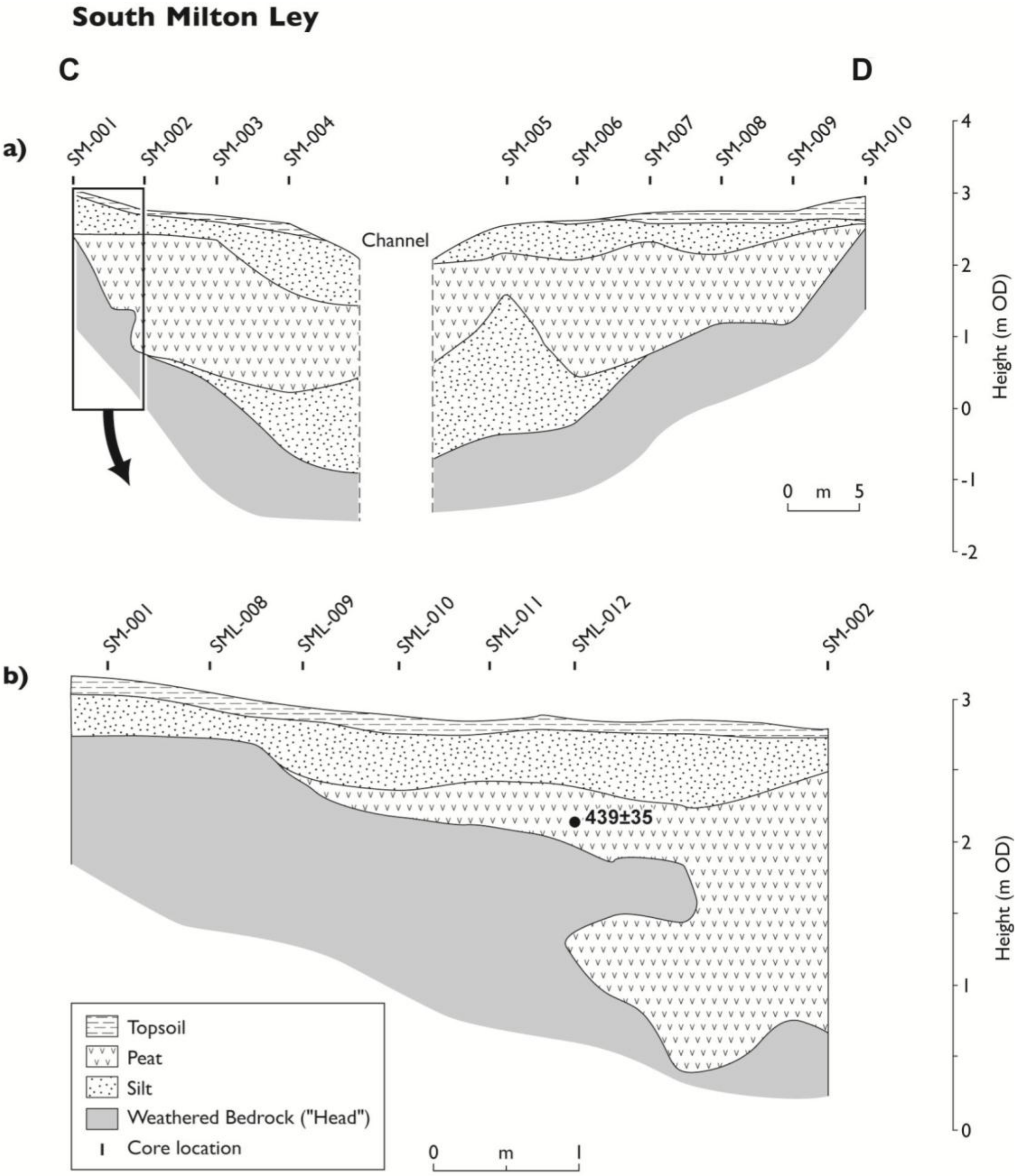

Figure 4.3 (cont). Stratigraphic cross section at South Milton Ley (a) and the position of the youngest sea-level index point collected from the southern valley slope (b). Source: Gehrels et al. (2011, p124)

The valley is floored by head deposits and in the deepest parts silts are found overlying the head. A *Phragmites* peat section, up to 2 m thick, overlays the head and a shallower silt unit can be found above this. Evidence of recent slope movements can be seen in the stratigraphy as the head deposit is found overlying peat in some cores on the southern valley. The head deposit on the southern valley is found from -1.0 – 2.7 m OD, and is overlain by a basal peat unit. Cores were taken for sampling along the base of the head deposit between 1.88 and 2.0 m OD (Figure 4.2). Analysis of the basal peat indentified species of agglutinated high-marsh foraminifera in all but one of the cores and indicates a salt marsh environment between 2.08 – 2.57 m OD at the site. The species were predominantly high marsh species *Jadammina macrescens*. The basal peat unit is ‘fresher’ than the salt-marsh sediments at South Huish, and the presence of foraminifera makes it possible to establish a relationship with tidal levels.

4.2.2 Chronology

At South Huish, from the sixteen cores nine suitable samples were retrieved for radiocarbon dating and, from South Milton, four suitable samples were retrieved. Optimum samples were judged by their weight, foraminiferal association and basal stratigraphic position. All the samples were detrital stems or leaves of *Phragmites* and were sent to the National Environmental Research Council (NERC) Radiocarbon Laboratory (in East Kilbride, Glasgow) to be dated. Dates received from NERC have been calibrated according to Reimer et al., (2004), using IntCal04. Three of the samples from South Milton, however, contained post-bomb radiocarbon concentrations. The samples are in the expected chronological sequence, but are much younger. Sample SML-009 being the most recent, SML-010 approximately covering the bomb-^{14}C peak, and SML-011 either catching the rising part of the atmospheric ^{14}C curve (~1950s) or being a mixture of pre- and post-bomb carbon (Garnett, *pers. comm.*) so these were rejected. Only one radiocarbon dated sample from South Milton Ley is established, and this represents the youngest date obtained from the study. Overall, nine suitable samples were retrieved for radiocarbon dating from South Huish and one from South Milton Ley. This offers ten new late Holocene SLIPs for the region. The combined chronology of the two sites at Thurlestone range from 1619±35 to 439±35 ^{14}C yr BP, and offers a record of ~ 1200 years of sea-level change for the area (Table 4.3). Index points 1-7 and 10 have been collected from basal sediments close to the substrate.

Index number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Radiocarbon laboratory number	SUERC-20170	SUERC-20041	SUERC-20171	SUERC-20172	SUERC-20173	SUERC-20174	SUERC-20175	SUERC-23074	SUERC-23075	SUERC-23081
Core	T-10	T-06	T-05	T-04	T-02	T-01	BT-02	008-31	008-35	SML-012
Material	Plant leaf	Plant leaf	Plant leaf	Plant stem	Plant stem	Plant leaf	Plant leaf	Plant leaf	Plant leaf	Plant leaf
^{14}C age (years BP ±1σ)	1321±35	1310±35	1385±37	1306±37	1342±37	1270±37	1539±35	1610±35	1619±35	439±35
±1σ age ranges (cal. yr BP)	1185-1202	1184-1203	1283-1327	1183-1204	1189-1198	1178-1264	1381-1420	1418-1467	1418-1466	483-521
	1244-1248	1241-1288		1238-1287			1434-1439	1406-1568	1509-1553	335-349
±2σ age ranges (cal. yr BP)	1178-1215	1178-1294	1193-1196	1175-1296	1178-1214	1087-1110	1354-1521	1489-1499	1583-1600	439-536
	1220-1300	1178-1294	1262-1363		1222-1313	1124-1163		1589-1591	1410-1570	
						1166-1287				
Median age (cal. yr BP)	1260	1248	1303	1243	1277	1216	1437	1486	1501	502
Dry sample weight (g)	0.0035	0.0042	0.0212	0.0120	0.0127	0.0079	0.0106	0.0560	0.0219	0.0121
Carbon content (% by weight)	57	26	37	53	52	50	43	49.3	43	48.3
δ^{13}C ± 0.1 (%)	-26.0	-27.8	-27.2	-27.3	-28.2	-28.0	-27.8	-27.9	-27.9	-27.4
Depth in core (m)	1.34	1.69	1.64	1.26	1.32	1.39	1.94	2.01	2.06	0.70
MTL sample height (m)	1.26	0.93	0.99	1.36	1.29	1.23	0.67	0.59	0.52	2.02
Miliammina fusca	0	2	0	0	0	0	0	10	38	0
Trochammina inflata	0	0	0	0	0	0	0	0	0	0
Jadammina macrescens	41	39	1	35	0	3	2	67	32	25
Balticammina pseudomacrescens	6	1	0	2	0	0	0	88	69	0
Indicative meaning (m MTL)	2.20±0.20	2.20±0.20	2.30±0.20	2.20±0.20	2.30±0.20	2.30±0.20	2.30±0.20	2.20±0.20	2.20±0.20	2.65 ±0.15
Estimated autocompaction (m)	0.03	0.02	0.01	0.03	0.05	0.05	0.02	0.01	0.01	0.05
Relative sea level (m MTL)	-0.91±0.26	-1.25±0.26	-1.30±0.26	-0.81±0.26	-0.96±0.26	-1.02±0.26	-1.61±0.26	-1.60±0.26	-1.67±0.26	-0.63±0.21

Table 4.3 New late Holocene sea-level index points from Thurlestone in south Devon with associated data, including foraminifera counts. MTL – mean tide level

Points 8 and 9 are derived from sediments overlying a sandy gravel unit, but can also be considered as basal points due to the un-compactable nature of the gravels (as described by Gehrels et al., 1999).

4.2.3 Loss on ignition (LOI)

Loss-on-ignition (LOI) analysis was carried out on ten cores using the method of Ball (1964) and Dean (1974) to establish the organic content of the sedimentary units found during coring. The reason for this is that the transition between Pleistocene head deposits and overlying Holocene sediments cannot always be determined by visual inspection of the cores alone and can be affected by compaction of the overlying sediments. By accurately differentiating between head deposits and basal sediments the leading edge of the initial postglacial transgression (induced by sea-level rise) can be clearly identified. The exact location of the contact is important in determining the possible compaction of sediments (later in the chapter). The results of the LOI analysis are presented in Figure 4.4 along with locations of dated samples (also see Appendix B – 1.1c). At South Huish, samples were taken between core depths of 1.0 - 2.5 m (0.19 - 1.71 m OD) and analysed at 0.01 m intervals starting in the head deposit and continuing into the overlying units of organic silt and peat.

The percentage of organic matter correlates well with the lithostratigraphy observed showing a decrease in organic material with depth in the cores. The head deposit and sandy gravel unit contains the lowest percentage of organic matter and values range from 2-4%. The values in the overlying silt unit have a much larger range, varying from 4-40% depending on the proximity to the upper peat unit or lower head unit. In the upmost peat unit values are higher and range from 20-70%. These high records represent the abundance of plant microfossils (*Phragmites*) in the layer. At South Milton the Pleistocene surface was impenetrable at 0.90 m (1.88 m OD) in core SML-012, above which an increase in organic material is observed and this marks the exact position of the transition to overlying basal peat.

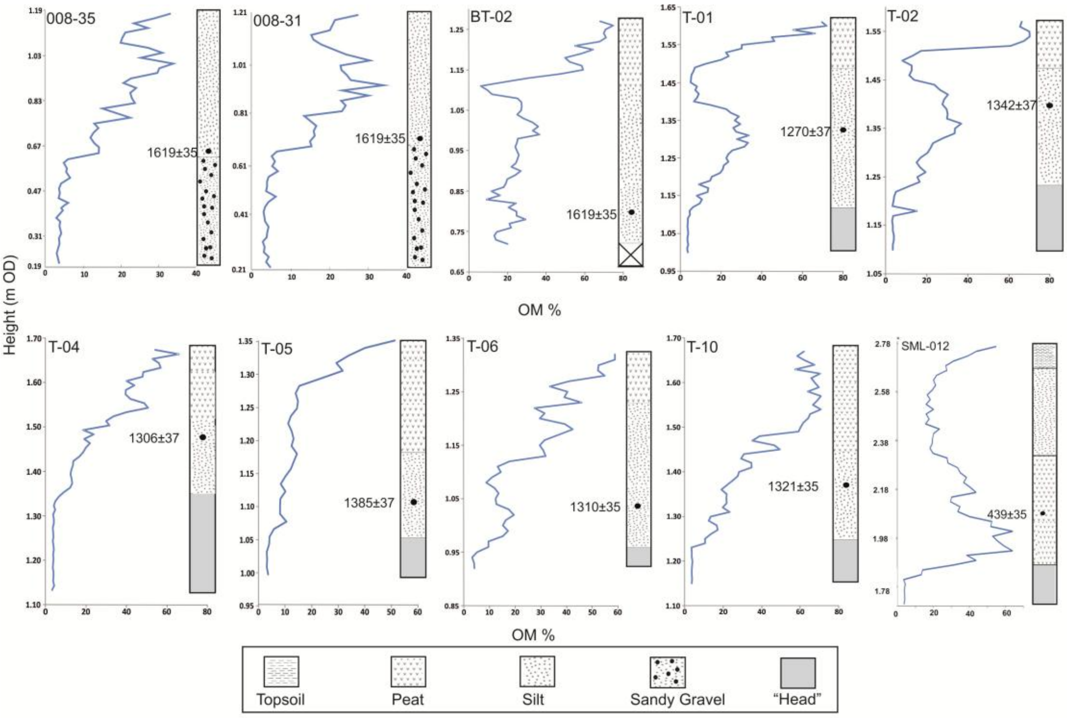

Figure 4.4 Loss on ignition results and locations of samples for radiocarbon dating. Dates are given in year BP calculated to ±1σ.

The basal peat unit fluctuates in organic material between 65-30% but peaks between 1.94-2.06 m OD. It then gradually reduces as the sediments become more minerogenic (silty) towards the surface. This silt unit has distinctly lower organic material than the peat unit, and a much narrow range (15-25%). The results, however, show similar values to the peat/silt units at South Huish Marsh. Finally, towards the surface of the core an increase in organic material can be observed as plant rootlets occupy the upper topsoil surface. Overall, the results from both sites show a gradual increase in organic material from the base of the silt unit towards the surface. This indicates the transition from low organic environments (e.g., head deposit) to more terrestrial based environments (e.g., salt marsh), and the (sea-level induced) transgression of the environments up the Pleistocene slope. The results correlate well with the lithology recorded and also enable us to establish the precise location of each sediment transition and the basal contact. The contact between the hard substrate and basal sediments has been well constrained in all the cores and is found between 0.71-1.23 m OD at South Huish and 1.88 m OD at South Milton.

4.3 Palaeo-environmental interpretation of Thurlestone Sands

The stratigraphy at South Huish indicates that the site was once an open estuary tidal marsh until the beach barrier cut the system off completely from tidal exchange. A number of observations support this. Firstly, the lithostratigraphy at the two sites show a gradual transition from estuarine silts and clays to more organic (terrestrial) peat units, and this indicates a reduction in marine influence. Secondly, the biostratigraphical transition from *ca.* 1.0 - 1.5 m OD indicates a regressive contact between the units, where low marsh species are replaced by the dominance of high marsh species (see Figure 3. 5). This indicates a decrease in tidal influence at the site and the development of high marsh conditions. Previous studies in the region also give evidence of wide spread barrier closure during the Holocene (e.g., Hails, 1975; Morey, 1976; 1983; Massey et al., 2008). Massey et al.'s (2008) records show that throughout the late Holocene the sand dunes of the neighbouring valley at Bigbury Bay (Bantham Sands) gained height and extent along the coastline. This was due to transgression of the barrier system that increased sedimentation rates and eventually blocked the estuary mouth. It is highly likely a similar process occurred at Thurlestone and the dates from the samples collected at South Huish suggest the barrier closure happened relatively recently, probably in the last 1000 years. The similarities between the stratigraphy at South Huish and South Milton Ley suggest that the Ley was once fully open until the dune system began to limit tidal influence. This subsequently allowed the marsh to become less saline and develop a large range of freshwater plant species, and the barrier is now semi-closed. However, Foraminifera are able to survive in the back-barrier due to saline waters that enter the valley during storm events and exceptional high tides. Although the valley is now occupied by reeds, the presence of an organic rich peat layer with high salt-marsh foraminifera (e.g., *Jadammina macrescens*) suggest that high marsh conditions were still present in South Milton Ley as recent as 500 years ago. South Milton has a thin silt unit lying on top of the basal peat, interpreted as a slope-wash deposit.

4.4 Summary of field evidence

Prior to this study no basal late Holocene index points were available from south Devon. A new investigation indentified two sites in the region capable of providing basal late Holocene sea-level data. The lithostratigraphy of the sites indicate that they were once open to tidal influence and the foraminiferal and ^{14}C analyses reveal that a basal salt marsh existed at 0.56 – 1.54 m OD and 2.08 – 2.57 m OD between 1600 and 500 cal years BP at South Huish and South Milton Ley respectively. The sedimentary and foraminiferal analysis carried out on the cores provides evidence of two different marsh zones. Firstly, minerogenic silt sediments with salt marsh foraminifera from South Huish indicate typical high salt marsh elevations. Secondly, high marsh foraminifera found in a peat facies at South Milton Ley represents a slightly higher elevation *Phragmites* marsh similar to the surface environment today (e.g., less saline). Ten potential new sea-level index points can be generated from the two sites. Index points 1-7 and 10 have been collected from basal sediments, and SLIPs 8 and 9 are derived from sediments overlying a sandy gravel unit. These are also considered basal, however, due to the un-compactable nature of the gravels. The next section derives a new Holocene sea-level curve for south Devon, beginning with the identification of an accurate indicative meaning for the palaeo environments found in the cores. The wider implications of the results are then discussed in comparison to current geophysical models and future sea-level predictions for the southwest of England.

4.5 Deriving new late Holocene sea-level data for south Devon

4.5.1 Indicative meaning

Modern tidal environments can be used to estimate the relationship of fossil samples to former sea level (see Chapter Three). A modern salt marsh is not present at Thurlestone however. In order to establish an indicative meaning we therefore combined survey data of foraminifera and vegetation zonation from three sites in the region: Thurlestone, Dawlish Warren and the Erme estuary. The foraminiferal analysis from South Huish showed a dominance of high marsh species *Jadammina macrescens* and *Balticammina pseudomacrescens* (see Table 4.3 and Appendix B - 1.1b). Quantitative work by Massey et al., (2006) in south Devon estuaries indicates that *Jadammina macrescens* typically dominates the highest marsh zone (1.25 - 2.55 ± 0.29 m MTL), and were more dominant between 2.0 - 2.4 m MTL. A number of issues arise in utilising this information to derive indicative meanings for our fossil cores. Firstly, however, *Balticammina pseudomacrescens* was not identified in Massey et al.'s (2006) study, and their study also identified lower marsh *Miliammina fusca* in high numbers with *Jadammina macrescens,* but this was not the case in our cores. Furthermore, the heights from the Erme Estuary (Massey et al., 2006) are not necessarily representative for the indicative meaning of a salt marsh at an open coast setting (as at Thurlestone).

In order to better understand the relationship of the fossil cores to modern sea level surface foraminifera were collected along a surface transect at South Milton Ley. The work was carried out as part of an independent undergraduate project (Volkelt-Igoe, 2009). The surface samples were collected from along the previous coring transect taken at the site (C-D: figure 4.1). The surface of South Milton Ley is found between 2.50 and 2.80 m MTL and represents a modern analogue of the peat facies found above the silt facies (*Phragmites* marsh) at South Huish. The results from the surface transect at South Milton Ley identified species of modern foraminifera between 2.59 - 2.76 m MTL (Volkelt-Igoe, 2009). The foraminifera show similar composition to those found in the fossil core from South Huish, but the silty facies they are found in represent a slightly lower environment than the modern *Phragmites* marsh (i.e. a high salt marsh).

An additional survey of the foraminifera of a salt marsh at Dawlish Warren (see Figure 4.1 and Appendix B 1.2a), the only estuarine salt marsh in south Devon near the mouth of an estuary (the Exe), was undertaken to establish more accurate information. The vegetation and modern foraminiferal assemblages at Dawlish indicate that the high marsh was situated lower down between 1.5 and 2.0 m MTL (Volkert-Igoe, 2009); however, the spring tidal range at Dawlish is smaller than at Thurlestone (3.80 m vs. 4.64 m). This can be accounted for by normalising the tidal heights at Dawlish (e.g., MHWS) to fit within the tidal frame of Thurlestone. The salt-marsh heights at Dawlish occupy the range of approximately 1.70 - 2.30 m MTL (N=10) relative to Thurlestone‘s tidal range (see Appendix B – 1.2b for calculations).

The first indicative meaning (zone one) of 2.20 ± 0.20 m MTL (Figure 4.5) is based on the normalised heights of the marsh at Dawlish and the additional foraminifera study from Massey et al. (2006). The indicative meaning covers the height of the upper marsh at Dawlish, with an added allowance for a higher elevation due to the dominance of *Jadammina macrescens* in our cores. Massey et al.’s (2006) surface study identified a peak of *Jadammina macrescens* ~ 2.40 – 2.00 m MTL, and although there may be uncertainties with using this data alone it provides more confidence to our estimates. A number of the SLIPs from this study, however, contained very small counts of foraminifera (e.g., SLIPs 3, 5, 6 and 7) and could be more indicative of a slightly higher environment on the tidal slope (e.g., towards the fresher *Phragmites* marsh). A second indicative meaning has therefore been estimated for the facies in cores with low numbers of foraminifera. Lower counts of foraminifera (> 5) may indicate sediments at the upper salt-marsh limit, and an indicative meaning of 2.30 ± 0.20 m MTL (zone two) accounts for this.

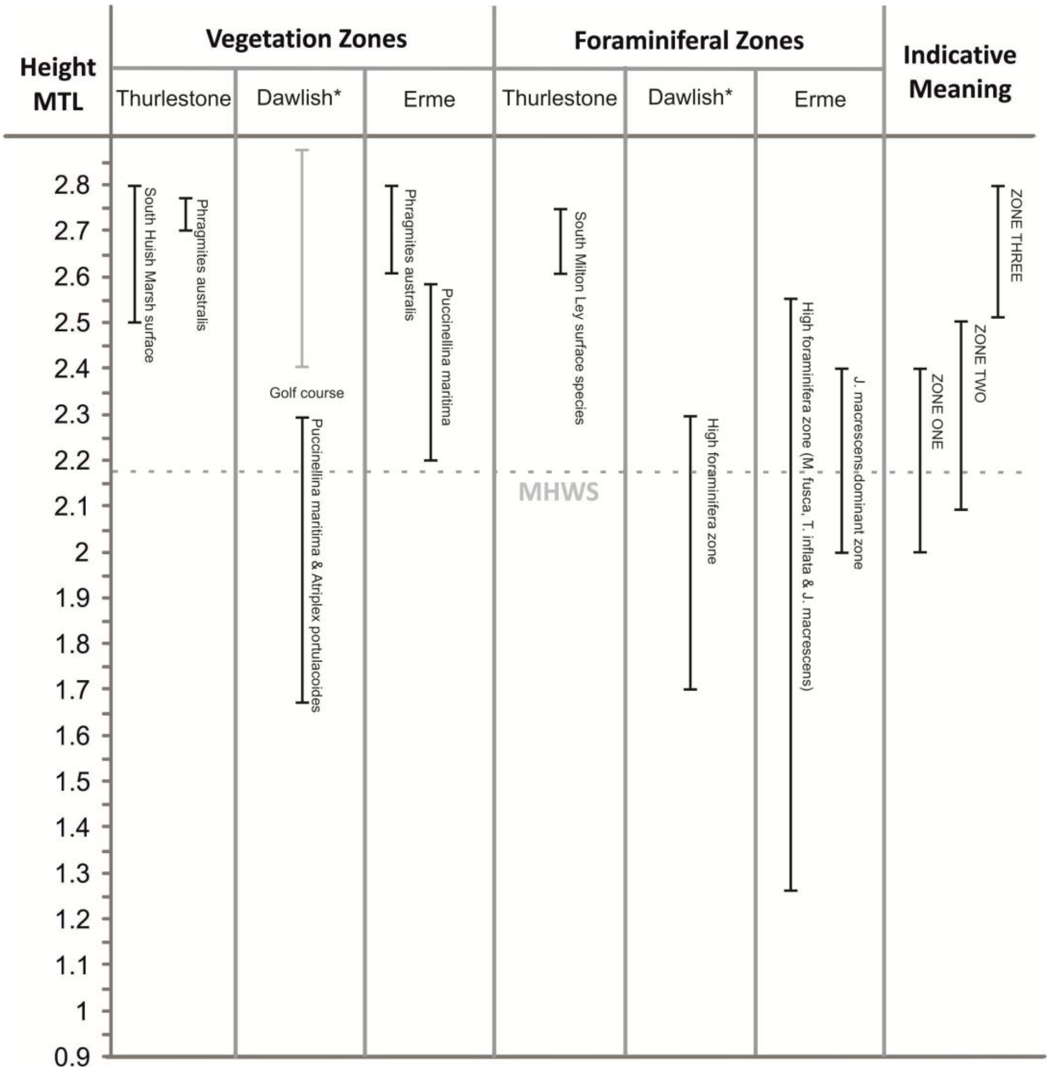

Figure 4.5 Estimates of indicative meanings for new sea-level index points obtained from Thurlestone, south Devon. Three zones have been identified from the facies in the fossil cores. *Zone One*: Salt-marsh facies dominated with *J. macrescens*. Zone Two: Salt-marsh facies with low numbers of foraminifera. Zone Three: Phragmites facies with foraminifera. Estimates are based on surveys from three sites in the region (Volkert-Igoe, 2009; Massey et al.,2006) see text for further details. * Dawlish heights have been normalised to fit the tidal frame at Thurlestone Sands. See Appendix B – 1.2b for normalising calculations.

Furthermore, the upper limit of this zone borders the lower limit of the *Phragmites* zone at South Milton, and is also within the proximity of the high marsh zones on the Erme Estuary and at Dawlish Warren. Finally, the indicative meaning for SLIP 10 from South Milton Ley has been estimated. As the SLIP was taken from a peat facies, the sample was directly comparable with Volkert-Igoe's (2009) survey of the modern marsh (2.50 - 2.80 m MTL). The indicative meaning is therefore estimated at 2.65 m MTL (zone three) based on the height of the modern *Phragmites* marsh with the presence of foraminifera.

In summary, three different elevation zones have been identified from survey heights and data from previous studies. Salt-marsh environments have been estimated to range from ~ 2.0 - 2.4 m MTL, and fresher marsh environments from 2.5 - 2.8 m MTL, this has enabled us to estimate the elevation of the palaeo environments and construct indicative meanings for 10 new SLIPs. The vertical precision of the sea-level estimates is ± 0.26 m (0.21 m for SML-12), a value based on the discussion presented, and levelling errors (0.06 m) (Gehrels et al., 1996; Shennan and Horton, 2002; Massey et al., 2008). With this information, the construction of a new late Holocene RSL curve for the region can now take place, but before this is presented an additional error has to be assessed – that of the possible compaction of underlying sediments.

4.5.2 Basal index points and sediment consolidation

Where sea-level index points are taken from the base of sediments directly overlying a hard substrate (basal) post-depositional compression is not a factor (Gehrels, 1999, 2006). If index points are taken from within a basal peat, however, they will be subject to some degree of compaction from the weight of overlying sediments (Gehrels, 1999; Massey et al., 2006; Shennan and Horton, 2009). Although all the new SLIPs from this study are considered 'basal', they do not directly overlie a hard substrate. Foraminifera were not always present in the lowermost Holocene sediments and samples were collected higher in the sequence where the first foraminifera appeared. It is therefore important to consider effects of autocompaction that may have occurred. Geotechnical tests can establish compaction values of underlying sediments but there are still major limitations to the techniques involved (Massey 2004). There is also a general a lack of empirical research into modelling compression behaviour (Bartholdy et al., 2010). Although authors have been actively involved in modelling compaction (e.g., Paul and Barras, 1998; Massey et al., 2006; Bartholdy et al., 2010; Bartholdy et al., 2010) the decision to which method and model are used is complex and many efforts to apply models have been confounded by logistical and temporal restraints (Bartholdy et al., 2010). Shennan et al., (2000) and Horton and Shennan (2009) did not model the process, but their quantitative assessment highlighted that compaction is affected by the thickness of sediment overburden, and by the depth of sediment below to the base of the Holocene. Shennan et al., (2000) stipulate further that, in basal index points, only the depth of sediment to the base of the Holocene is significant in influencing compaction.

An error for autocompaction was estimated using a geotechnical investigation carried out at Blackpool Sands (Massey, 2004). Core BS-97-02 produced index points 14 and 15 (refer to Table 4.5). BS-97-02 contained a substrate of fractured slates, sandy clayey silts and gravels and it provided the shallowest SLIPs of all the cores that geotechnical tests were carried out on (and is therefore most relevant to this study). Geotechnical tests were computed into a model of autocompaction (based on Paul and Barras (1998)) and it was found that sediments within one metre of the basal contact had undergone a maximum of 0.2 m of vertical compaction, regardless of the type of material (e.g., gravel or minerogenic peat) (Massey, 2004). This estimate was based on sediments with an overburden thickness of 7-19 metres, whereas the SLIPs from this study had overburden thicknesses of 1-2 metres.

Compaction in our cores should therefore be less than 0.2 m. As mentioned, however, the most significant effect of compaction of basal index points is related to the depth of the sample to the base of the Holocene (Shennan et al., 2000; Horton and Shennan, 2009). The trend of compaction in core BS-97-02 from the base substrate to one metre above was calculated using simple linear regression (Figure 4.6). We measured the depth of the SLIPs above the first steady increase in organic content determined by LOI analysis (section 4.2.3) and used the relationship found by Massey (2004) to obtain autocompaction estimates of 0.01 - 0.05 m (given Tables 4.3). With this simple correction included, a new relative sea-level curve from south Devon can be constructed.

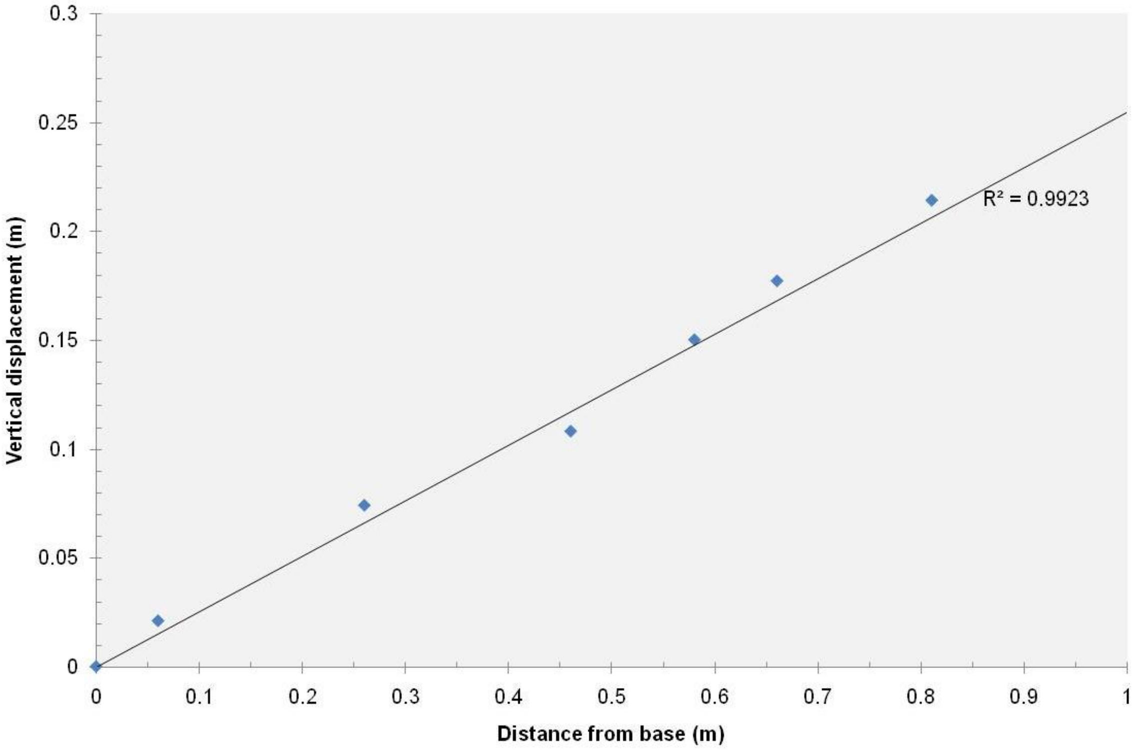

Figure 4.6 Autocompaction from core BS-97-02, from back-barrier sediments at Blackpool Sands (Massey, 2004). Solid line is a linear fit to points within one metre of the basal contact. See Appendix B – 1.2c for the calculation.

4.5.3 Relative sea-level change in south Devon.

The original sea-level curve from Massey (2004) and Massey et al., (2008) contained several basal SLIPs that are rejected in this study (Table 4.4). For example, their index point 17 (NS-97-4: AA-388356) from North Sands is associated with conflicting lithostratigraphical and biostratigraphical data. In the original investigation (Massey, 2004), the SLIP was associated with calcareous foraminifera, indicative of a mudflat environment, but were situated in a minerogenic peat (indicative of a salt marsh environment). In a more recent journal publication (Massey et al., 2008), the disagreement is discussed again. This time, however, the index point is accepted and is assigned an indicative meaning of -1.4 m MTL based on the biostratigraphy (e.g., mudflat). The discussion states further that if the indicative meaning were based on the lithostratigraphy alone then the index point would place ~ 3 m lower. Taking this into account, it would place the SLIP within range of other (compaction corrected) intercalated index points of a similar age. Based on the uncertainty of the indicative meaning (~ 3 m), however, it seems most appropriate to remove the SLIPs from the data set altogether

Massey et al.'s (2008) basal index point 28 (BS-97-3: CAMS -75527) from Blackpool Sands is another critical plot for discussion as it stands over one metre higher than index point 29 of a similar age (and from the same site). Taking the age of the SLIP into more consideration offers a possible explanation as to why this is apparent. Firstly, the age is based on the radiocarbon date from a buried wood fragment, the selection of which was due to an unfortunate '*chronic lack of available plant fragments* [to date] *in the sediments*' (Massey et al., 2008 p 423). Wood fragments are not ideal dating material as they are liable to post-depositional transport, and thus the fragment could actually be older than the sediment it has been entrapped in. Furthermore, the analysis of Massey et al.'s (2008) additional cores from the same site (BS-97-2 etc.) indentified dated horizons that correlate with the stratigraphic position of the SLIP in core BS-97-3, and yet the ages derived from these are ~ 800 cal years younger. Massey et al. (2008) suggested that the age difference could be due to channel erosion or sediment reworking in the system and therefore the SLIPs have been rejected from this data set. Sediment reworking is a significant issue in obtaining sea-level data from back-barrier environments. Furthermore, the water level in back-barrier marsh environments is not only affected by RSL movements but also by significant dynamical and sedimentary processes (Healy, 1995). Massey et al. (2008) suggested that these processes caused the significant spread of published regional sea-level data. Rejecting the questionable index points reduces the spread of data found in previous studies.

^{14}C Lab. no.	^{14}C age (yr BP ±1σ)	RSL (m MTL)	Rejected (R) Accepted (A)	Reference(s)
SRR317	1683±45	3.17±0.66	R	Hails, 1975; Morey, 1983
SRR492	1813±40	-2.16±0.56	R	Morey, 1976
SRR493	2889±50	-4.06±0,27	R	Morey, 1976, 1983
SRR164	4302±45	-5.99±0.73	A	Hails, 1975
SRR165	4767±45	-7.09±0.29	A	Hails, 1975
SRR237	8108±60	-16.50±1.00	A	Hails, 1975
AA-38822	7119±63	-12.85±0.35	A	Massey et al. 2008
AA-38823	7408±59	-15.19±0.35	A	Massey et al. 2008
AA-38824	7359±59	-14.44±0.35	A	Massey et al. 2008
AA-38836	4129±49	-2.95±0.35	R	Massey et al. 2008
CAMS-75525	4949±40	-8.19±0.35	A	Massey et al. 2008
CAMS-75526	4420±40	-7.36±0.35	A	Massey et al. 2008
CAMS-75529	4420±40	-6.35±0.35	A	Massey et al. 2008
CAMS-75530	4020±40	-5.18±0.35	A	Massey et al. 2008
CAMS-75518	7600±40	-14.57±0.35	A	Massey et al. 2008
CAMS-75519	7120±30	-12.97±0.35	A	Massey et al. 2008
CAMS-72401	7980±50	-17.31±0.35	A	Massey et al. 2008
CAMS-72402	7500±40	-17.31±0.35	A	Massey et al. 2008
CAMS-75531	7370±40	-14.78±0.35	A	Massey et al. 2008
CAMS-75527	5880±40	-6.77±0.35	R	Massey et al. 2008
NPL86	8580±800	-25.20±1.66	R	Clarke, 1970

Table 4.4 Previously published Holocene sea-level index points for south Devon and those to be included in the construction of a new Holocene sea-level curve for the region. Source: Gehrels et al. (2011, p117).

This study has added late Holocene SLIPs to the relative sea-level (RSL) record for the region from radiocarbon dated basal salt-marsh sediments containing marine microfossils. Late Holocene RSL changes have been reconstructed from the ten new SLIPs which cover ~ 1000 years between 1500 and 500 cal years BP. The ten index points are taken from sediments overlying the Pleistocene surface, or in-compactable material, but have been corrected for autocompaction for accuracy. Obtaining radiocarbon samples in direct relation to high numbers of foraminifera was always preferred, but a lack of datable material meant that this was not always possible (e.g., index points 3, 5, 6 and 7).

However, all index points are constrained by the presence of foraminifera (despite low numbers) both in the cores and in adjacent samples. With the addition of the new late Holocene SLIPs to previously published SLIPs from studies by Hails (1975) and Massey et al., (2008) (see Table 4.4), the combined data set consists of 25 SLIPs, of which 18 are considered basal in nature, six are intercalated and one is a limiting index point, and where possible SLIPs have been corrected for autocompaction (Table 4.5 and figure 4.7a). The data set covers ~ 9000-4500 cal years BP and suggests a RSL rise of 21 ± 4 m during the last 9000 years. The new SLIPs from this project indicate that RSL in south Devon rose by around one metre between 1500 and 500 cal years BP. RSL has risen ~ 0.7 metres since 500 cal years BP, and combined, RSL rose 1.7 ± 0.2 m since 1500 cal years BP.

This equates to ~ 1.0 ± 0.2 mm/yr ($R^2 = 0.81$) of RSL rise. By including Massey et al.'s (2008) youngest index point (17 - Table 4.5)[2] with our new data, a rate can be calculated from 4500-0 years BP. This suggests sea levels have risen around five metres since 4500 cal years at a rate of around 1.2 ± 0.2 mm/yr ($R^2 = 0.96$). Previous calculations of late Holocene sea-level rise for south Devon and west Cornwall (e.g., Hails, 1975; Morey, 1983; Healy, 1995; Massey, 2004) have shown considerable variation in results (e.g., 0.8 – 1.6 mm/yr between 3200-1000 cal years BP). These estimates were based on intercalated sediments, but our new history of RSL is constructed from basal sediments and is therefore more precise. These new geological data will be used to test model predictions of RSL changes. This will now be examined with particular emphasis on the model used in predicting future sea-level rise in the United Kingdom.

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[2] Not to be confused with index point 17 of Massey (2004) and Massey et al. (2008) discussed previously.

Index No.	^{14}C Lab. no.	Height (m OD)	MTL (m OD)	Indicative meaning (m MTL)	Compaction	^{14}C age (yr BP ±1σ)	Median age (Cal. yr BP)	Age Range (Cal. yr BP 2σ)	RSL (m MTL)	Type
1	SUERC-20170	1.37	0.11	2.20±0.20	0.03	1321±35	1260	1178-1300	-0.91±0.26	B
2	SUERC-20041	1.04	0.11	2.20±0.20	0.02	1310±35	1248	1178-1294	-1.25±0.26	B
3	SUERC-20171	1.10	0.11	2.30±0.20	0.01	1385±37	1303	1193-1363	-1.30±0.26	B
4	SUERC-20172	1.47	0.11	2.20±0.20	0.03	1306±37	1243	1175-1296	-0.81±0.26	B
5	SUERC-20173	1.40	0.11	2.30±0.20	0.05	1342±37	1277	1178-1313	-0.96±0.26	B
6	SUERC-20174	1.34	0.11	2.30±0.20	0.05	1270±37	1216	1087-1287	-1.02±0.26	B
7	SUERC-20175	0.78	0.11	2.30±0.20	0.02	1539±35	1437	1354-1521	-1.61±0.26	B
8	SUERC-23074	0.70	0.11	2.20±0.20	0.01	1610±35	1486	1406-1591	-1.60±0.26	B
9	SUERC-23075	0.63	0.11	2.20±0.20	0.01	1619±35	1501	1410-1600	-1.67±0.26	B
10	SUERC-23081	2.08	0.11	2.65±0.15	0.05	439±35	502	335-536	-0.63±0.21	B
11	AA-38822	-13.68	0.09	-0.91±0.29	0.01*	7119±63	7946	7792-8049	-12.85±0.35	B
12	AA-38823	-13.10	0.09	2.19±0.29	0.19*	7408±59	8247	8050-8371	-15.19±0.35	B
13	AA-38824	-12.80	0.09	1.82±0.29	0.27*	7359±59	8176	8029-8323	-14.44±0.35	I
14	CAMS-75525	-5.74	0.11	2.36±0.29	0.02	4949±40	5676	5596-5842	-8.19±0.35	B
15	CAMS-75526	-5.00	0.11	2.46±0.29	0.21	4420±40	5007	4867-5276	-7.36±0.35	I
16	CAMS-75529	-4.43	0.11	2.16±0.29	0.35	4420±40	5007	4867-5276	-6.35±0.35	I
17	CAMS-75530	-3.34	0.11	2.22±0.29	0.49	4020±40	4487	4414-4782	-5.18±0.35	I
18	CAMS-75518	-11.95	0.11	2.51±0.29	0.00	7600±40	8402	8343-8508	-14.57±0.35	B
19	CAMS-75519	-12.45	0.11	0.41±0.29	0.00	7120±30	7953	7870-8006	-12.97±0.35	B
20	CAMS-72401	-14.76	0.12	2.43±0.29	0.00	7980±50	8850	8648-9000	-17.31±0.35	B
21	CAMS-72402	-14.76	0.12	2.43±0.29	0.00	7500±40	8331	8201-8390	-17.31±0.35	B
22	CAMS-75531	-12.21	0.12	2.45±0.29	0.00	7370±40	8192	8045-8321	-14.78±0.35	B
23	SRR164	-4.32	n/a	n/a	n/a	4302±45	4870	4729-5034	-5.99±0.73	I
24	SRR165	-4.62	n/a	n/a	n/a	4767±45	5512	5328-5594	-7.09±0.29	I
25	SRR237	-16.50	n/a	n/a	n/a	8108±60	9056	8779-9265	-16.50±1.00	L

Table 4.5 Late Holocene sea-level index points from south Devon. 1-10 from this study,11-22 are from Massey et al., (2008), and 23-25 taken from Hails (1975). *includes core consolidation. B = Basal, I = intercalated and L = limiting. Source: Gehrels et al. (2011, p122). Index points correspond to Figure 4.7. Data are also presented in Appendix B – 1.2d.

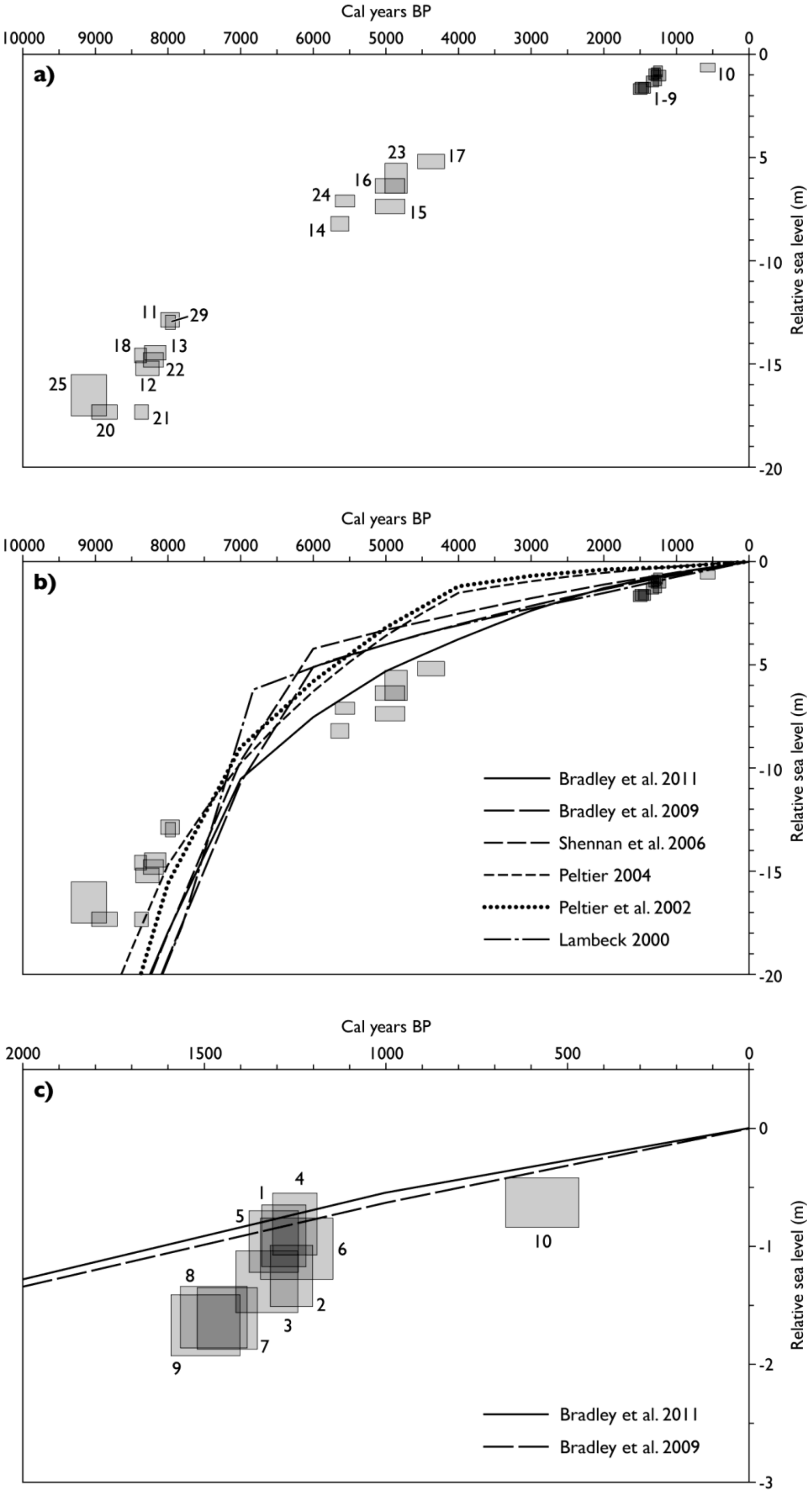

Figure 4.7 (a) Holocene relative sea-level data for south Devon. Details of sea-level index points (SLIPs) appear in Table 4.5. (b) Holocene relative sea-level data for south Devon compared with GIA model predictions. (c) Late Holocene relative sea-level data for south Devon compared with GIA model predictions by Bradley et al., (2009, 2011). Boxes represent associated error margins of SLIPs. Source Gehrels et al. (2011 p124). Data are also included in Appendix B -1.2d

4.5.4 Comparison with geophysical model predictions

Section 2.5 of Chapter Two discussed the application of new geological data, and how a new sea-level curve for south Devon could be used to test current GIA model predictions. Figure 4.7b illustrates the range of geophysical model predictions. These differences are due to the assumed rate of Holocene ice-equivalent sea-level change and the solid Earth parameters used by modellers. The model predictions for south Devon all show a similar trend (i.e. a reduction in the rate of sea-level rise from early-late Holocene). However, modelled estimates of RSL differ by up to 3.5m ca 6000 cal years BP, 2.5m ~ 4000 cal years BP, and sea-level positions for 2000 years BP vary by up to one metre. In comparison with the geological observations, all geophysical models appear to underestimate RSL in the early Holocene (9000-8000 years BP). The best models for estimating early Holocene RSL, appear to be those of Peltier et al. (2002) and Peltier (2004), and the majority of SLIPs plot on, or near, their predicted position. In contrast, all the geophysical models underestimate RSL rise in the mid-late Holocene as the majority of younger index points plot below all of the model estimates. Geological data (SLIPs 15, 16, 17, 23 and 24) show the closest fit with the model of Bradley et al. (2011). Bradley et al.'s (2011) new global ice model differs from Bradley et al. (2009) and other model outputs by up to three metres in places. It contains significantly more ice melt (eustatic) contribution than other models for the period before 2000 cal yrs BP.

Post 4500 cal years BP, all models show a reduction in RSL rates. However, no data are available to test the various model predictions until 1500 cal years BP when they can be compared with the new SLIPs from this study. At around 3000 cal years BP all the models converge, with the exception of Peltier's models, and the differences between model estimates are reduced. The index points from this study plot close to model predictions of Lambeck (1995, 2000); Shennan et al., (2006); and Bradley et al., (2009, 2011) over the period of 1500-500 years BP (Figure 4.7b and c). Peltier's models, however, overestimate late Holocene sea-level change the most, which is likely to be due to the choice of Earth parameters. GIA models suggest around one metre of sea-level change during the last 1500 years and rates of around 0.7 mm/yr. Our data shows around 1.6 ± 0.26 m of change in the last 1500 years, and rates of around 0.9 ± 0.2 mm/yr. Therefore, some additional ice-equivalent sea-level rise in the late Holocene would provide a better fit between GIA model predictions and geological observations. However, based on a comparison with GPS data, it has been suggested that the late Holocene sea-level dataset of the British Isles points at a slight fall in global ice-equivalent sea level (Gehrels 2010). It is anticipated that these discrepancies will be resolved with the advent of 3D Earth models and longer GPS records (Gehrels et al., *2011*).

Bradley et al.'s (2009) model of late Holocene RSL is used to calculate absolute vertical land movement for the UKCP09 predictions of regional sea-level rise (Lowe et al., 2009). It is therefore crucial that the crustal component predicted by the GIA model is tested to verify the rates of land subsidence postulated. It is possible to extract a subsidence component from the new late Holocene relative sea-level data following the methods outlined by Gehrels (2010), and this can then be compared directly with Bradley et al.'s (2009) model outputs.

4.5.5 *Rates of vertical land movement and sea-level projections*

The new sea-level index points obtained from Thurlestone, suggest a sea-level rate of ~0.9 mm/yr. By comparison, the Newlyn tide gauge has recorded an average relative sea-level rise of 1.7 mm/yr since 1916 (Haigh et al., 2009). The difference between the 20th century rate and late Holocene rate of relative sea-level rise reflects the influence of a global acceleration of sea-level rise that started in the early 20th century (e.g., Gehrels et al. 2005, 2008; Kemp et al. 2009; Gehrels 2010). In UKCIP02 (Hulme et al., 2002) late Holocene RSL curves from Shennan and Horton (2002) were inappropriately used to infer trends of vertical land movement (Gehrels, 2006; DEFRA, 2006). This is incorrect, primarily, due to global and regional processes which produce positive sea-level tendencies over the late Holocene period. If these tendencies cancel each other out (i.e. no net change), or are systematically accounted for, RSL curves can be used to approximate for vertical land movements (Gehrels, 2010). Based on this principle Gehrels (2010) presents a new map of vertical land movements extracted from geological evidence from the British Isles (Figure 4.8).

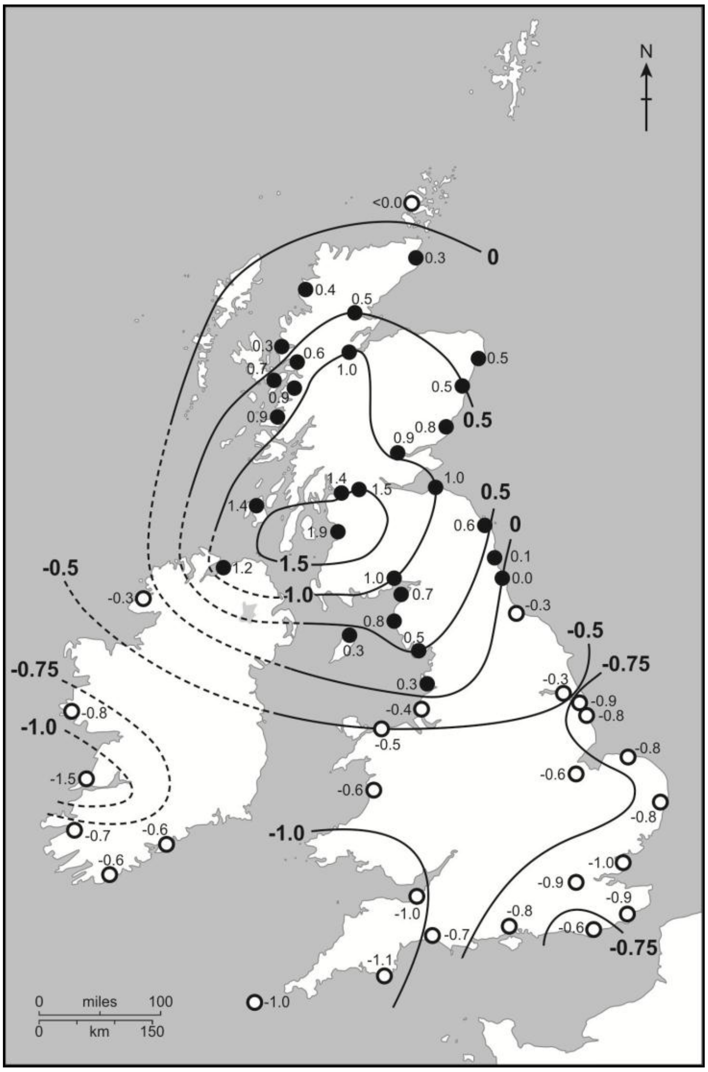

Figure 4.8 Rates of land motion in Britain and Ireland re calculated from Shennan and Horton (2002), open dots represent land post-glacial land subsidence and close dots represent land up lift. Source: Gehrels (2010 p.1649). The figure for south Devon is taken from results from this project (see Figure 4.7).

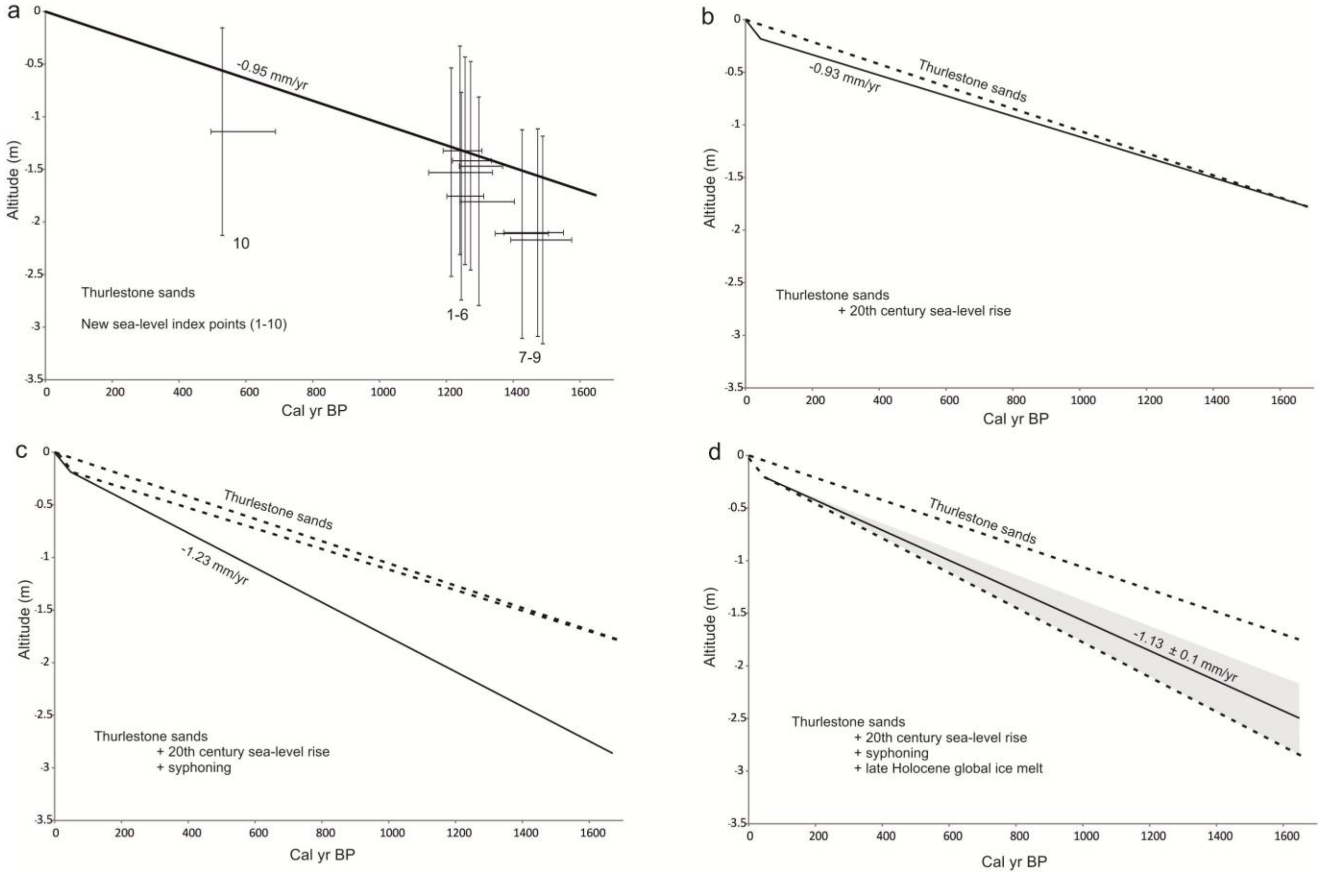

Figure 4.9 A schematic diagram showing how an estimate of vertical land movement (crustal motion) is calculated. A relative sea-level rise from the ten new SLIPs at Thurlestone sands is used (a). When taking account of a 20th century sea-level rise 0.14 m. Including sea-level index points from this study (1-10), numbers relate to Table 4.5 (b), a syphoning value of -0.3 mm/yr (c) and the IPCC estimate of 0.1 ± 0.1 mm/yr for a late Holocene global ice-equivalent sea-level rise, the crustal motion rate can be calculated as -0.67 ± 0.1 mm/yr (d). Adapted from Gehrels (2010). See text for explanation and equation. Refer to Appendix B – 1.3a for calculations.

The map is an improvement on the original by Shennan and Horton (2002) and clearly defines the rates of absolute land movement, rather than relative land movement (as discussed in section 2.5). Using Gehrels' (2010) method a similar process can be carried out on the RSL curve for Thurlestone (Figure 4.9). In order to extract the absolute land motion rates from the new RSL curve, the following must be accounted for, firstly: *regional 20th century sea-level rise (~ 0.14 m)*. The 20th century sea-level trends have deviated significantly from the late Holocene trends (Woodworth et al., 2008).

Woodworth et al., (2009) calculated the difference as 0.14 ± 0.2 mm/yr faster and by choosing 1900 as the 'origin' and an altitude of -0.14 m (as in Gehrels, 2010) sea-level trends can be adjusted (Figure 4.9b). The second factor to be accounted for is: *the process of ocean syphoning (a fall of around ~ 0.3mm/yr)*. The process of ocean syphoning causes a re-distribution of ocean water mass to regions where extra ocean volume is created, either by glacial-isostatic subsidence of the ocean floor or hydro-isostatic loading of the continental shelves (Gehrels, 2009). This produces a net sea-level fall of ~0.3 mm/yr (Mitrovica and Milne, 2002; Gehrels, 2009) and is also accounted for on the sea-level curve (Figure 4.9c) creating a steeper RSL trend.

The final adjustment to the RSL curve is: *global late Holocene sea-level variations (0.0 – 0.2 mm/yr)*, and regards the contribution of global melt water. The IPCC Fourth Assessment Report (Jansen et al., 2007) estimates that in the past 2000 years this contribution is in the range of 0 – 0.2mm/yr (based on geological and archaeological sea-level data from around the globe). As in Gehrels (2010) this value is deduced from the sea-level curve (Figure 4.9d), and allows absolute vertical land movement trends to be extracted. In summary, we extract the late Holocene absolute vertical land-motion rate (VLMR in mm/yr) from the relative sea-level curve by accounting for regional 20th century sea-level rise (SL_{20}), late Holocene global ocean-volume increase (OVI_{LH}), and late Holocene ice-equivalent sea-level change ($EUST_{LH}$), using:

$$VLMR = \frac{x + SL_{20}}{3.9} - OVI_{LH} + EUST_{LH}$$

where *x* is the height of relative sea level at 4000 cal yrs BP (in m relative to present sea level) estimated from the sea-level index points. The values we use for SL_{20}, OVI_{LH}, and $EUST_{LH}$ are 0.14 m, 0.3 mm/yr and 0.1 mm/yr, respectively. The uncertainty is derived from the possible range of $EUST_{LH}$ (0.0-0.2 mm/yr; Jansen et. al. 2007). Based on the approach described, it is estimated that south Devon has undergone -1.13 ± 0.1 mm/yr of land subsidence during the late Holocene, and highlights the major contribution of glacio-isostatic adjustment to regional sea-level change. The new figure of vertical land movement calculated from this study corresponds well with the overall trends from other geological data in the south of England (see Figure 4.8).

Bradley et al.'s (2009) model estimates a subsidence rate of -0.97 mm/yr at the study site. The difference with geological observations (~17%) suggests that the marine projections could contain an underestimate of around 0.16 mm/yr, and this would result in possible additional relative sea-level rise of 0.0016m by 2020, and 0.014m by 2100 (as of 2010). Based on this study the accuracy of current sea-level projections in the region is considered adequate, and the new data validate, for the first time, the values of vertical land movements used by UKCP09 in an area where no high-quality observations were previously available. UKCP09's estimates can therefore be used with greater confidence to inform future coastal management decisions in the southwest of England. The predictions for Teignmouth were presented in Chapter One and show that sea levels are expected to increase by 0.05 m to 0.07 m by 2020 (relative to 2010) and up to 0.53 – 0.79 cm by 2100.

Taking the possible underestimate into account the sea-level predictions for Teignmouth have been recalculated and are presented in Table 4.6 (Appendix B - 1.3b). By 2100, it is therefore estimated that south Devon will have seen 0.55 – 0.81 m of sea-level rise. These are some of the highest prediction in the UK and present a significant challenge for coastal managers and policy makers in the region. As a precautionary approach, the values used are based on Lowe et al.'s (2009) 95th percentile estimates and are therefore the maximum projected increases in sea-level rise in the region.

Scenario	**Year**				
	2020	**2040**	**2060**	**2080**	**2100**
Low	4.7	15.1	26.8	40.0	54.5
Medium	5.7	18.3	32.6	48.6	66.4
High	6.8	22.0	39.3	58.9	80.6
H++	-	-	-	-	93-190

Table 4.6 21st century RSL changes (cm) from 2010 for Teignmouth, south Devon. Values represent the 95th percentiles taken from UKCP09's – user interface (**http://ukclimateprojections.defra.gov.uk**; grid: 25757) corrected for an error of 0.03 mm/yr. H++ scenario is a high impact estimate for the UK. Refer to Appendix B 1.3b for calculations.

4.6 Chapter synopsis

The primary objective of this chapter is to establish accurate late Holocene sea-level index points to validate geophysical models and sea-level projections in the southwest of England. Late Holocene coastal sediments were sampled from back-barrier environments at South Milton Ley and South Huish (Thurlestone Sands). The area contains shallow basal sediments overlying the Pleistocene surface known locally as 'head' and the presence of marine microfossils allow the determination of palaeo sea-levels estimates. Ten new late Holocene SLIPs have been established from basal peat sections and added to the geological data base for the region. In comparison with other studies in back-barrier environments the close proximity of our new SLIPs implies that post depositional transport or sediment reworking have not been a significant factor. A simple correction for autocompaction has also been calculated for all the SLIPs and a late Holocene rate of sea-level rise of 0.9 ± 0.2 mm/yr has been determined.

In comparison with geophysical model outputs, the new data suggest geophysical models underestimate late Holocene relative sea-level rise, however, the models of Bradley et al (2010, 2011) show the closest fit to our data. Geological data can be used to extract rates of absolute land movements (following Gehrels, 2010) and a rate of -1.1 ± 0.1 mm/yr of subsidence has been calculated for south Devon. This rate is in agreement with other geological observations in the south of England. In comparison with the geophysical model used in UKCP09's future estimates of sea-level rise (Bradley et al., 2009), our data suggest that the model under-predicts the subsidence rate by as little as 17%. This could add 1.4 cm of sea-level rise to the predictions for the end of the century. Although this value is small compared to overall uncertainties associated with future sea-level projection, this study has validated estimates in a region where no observations were available to test the high rates of vertical land motion previously postulated. With this minor correction included the accuracy of current sea-level projections in the region is considered satisfactory for the use in this project. In the next chapter these sea-level predictions are put to use and the effects of rising sea levels on the frequency of incidents on the railway line are determined.

Chapter Five

The vulnerability of the Southwest Mainline

5.1 Introduction

In the previous chapter a new late Holocene sea-level curve for the southwest of England was constructed with the inclusion of new geological evidence from which estimates of land subsidence were extracted. The subsidence estimates and glacio-isostatic adjustment (GIA) model used in UKCP09's Marine and Coastal Projections (Lowe et al., 2009) differ by as little as 0.16 mm/yr. Taking this into account sea levels in the region are expected to reach a maximum of 0.81 m in the next 90 years (Table 4.6). These projections will have major implications for the coastline of the southwest of England and the remainder of this thesis is concerned with the analysis of this on the Southwest's main railway line. The mainline is already vulnerable to flooding during high tides and storm events which cause damage, delays and line closures. The future sea-level projections detailed in the previous chapter will have major implications for the functioning of the railway line. In this chapter, the aim is to gain a detailed understanding of the line's past vulnerability to sea-level change and extreme weather. Using this knowledge, an empirical relationship of past sea-level changes and rail incidents will be derived allowing predictions of future rail incidents (e.g., overtopping and consequent traffic restrictions) to be estimated. Before the archival evidence is presented, however, the conditions that result in days with restricted services are presented and discussed.

5.2 Adverse weather and events

In collecting over 160 years of history on the railway line, one phrase is continually repeated: *the combined effect of easterly winds and high tides*…. It corroborates, however, the key meteorological and tidal conditions that cause incidents on the railway. Records of the conditions were collected from known dates of railway incidents (delays or damage –

gathered from the archive investigation). The Slapton Met Station provided recordings of average daily wind speed and direction (1960-2009), and this was also backed up with evidence from newspaper weather forecasts from the region (since 1846). Details on the Slapton Met Station can be found in Burt and Horton (2001). Tidal extremes were also collected from Newlyn tide-gauge station. In 2006, Network Rail’s trigger levels for their (pro-active) Emergency Response Plan (Level 1-3) are based on wind force and direction, and water levels (O’Breasail et al., 2006) and they are outlined in Table 5.1. The record of wind speed and direction during events enables us to examine the accuracy of the adverse weather matrix with actual events (based on observations only).

Wind Force	**Wind Direction**			
	East	***South East***	***South***	***South West***
	Level One Response			
5	NO ACTION	NO ACTION	NO ACTION	NO ACTION
6	Tide > 4.5m	Tide > 4.5m	NO ACTION	NO ACTION
7	Any tide	Tide > 4.5m	NO ACTION	NO ACTION
8	Any tide	Any tide	Any tide	Tide > 4.5m
	Level Two Response			
9	Any tide	Any tide	Any tide	Tide > 4.5m
10+	Any tide	Any tide	Any tide	Any tide

Table 5.1 Adverse weather matrix and the planned emergency response plan. Tide represents high tide above the Lowest Astronomical Tide (LAT). Level 1 = emergency speed restriction (ESR) on the down line. Level 2 = closure of the down line and ESR on the up line. Level 3 (both line closure) occurs if level 2 conditions deteriorate. Adapted from Network Rail’s Frontage Management Report (Rogers and O’Breasail, 2006).

Although evidence of the conditions during incidents is available for older events, the most comprehensive record is for the last 15 years, and also presents the most recent conditions under which line problems occur (Figure 5.1). An in-depth analysis of the full weather data set has not been carried out (as sea-level rise is the principle factor of investigation) but a general historical overview can be found in Burt and Horton (2001). Furthermore, from the observations during events it seems that the characteristics of adverse conditions have changed little in comparison to the changes in frequency of incidents during last century. Nonetheless, a wide range of wind directions has been recorded during incidents, but the dominant directions that cause problems are southerly and easterly winds. The daily wind speeds recorded when actual problems occurred ranged from gentle breezes to hurricane force (e.g., 64 knots), and the average wind speed during past incidents is ~17 knots (Force 4-5).

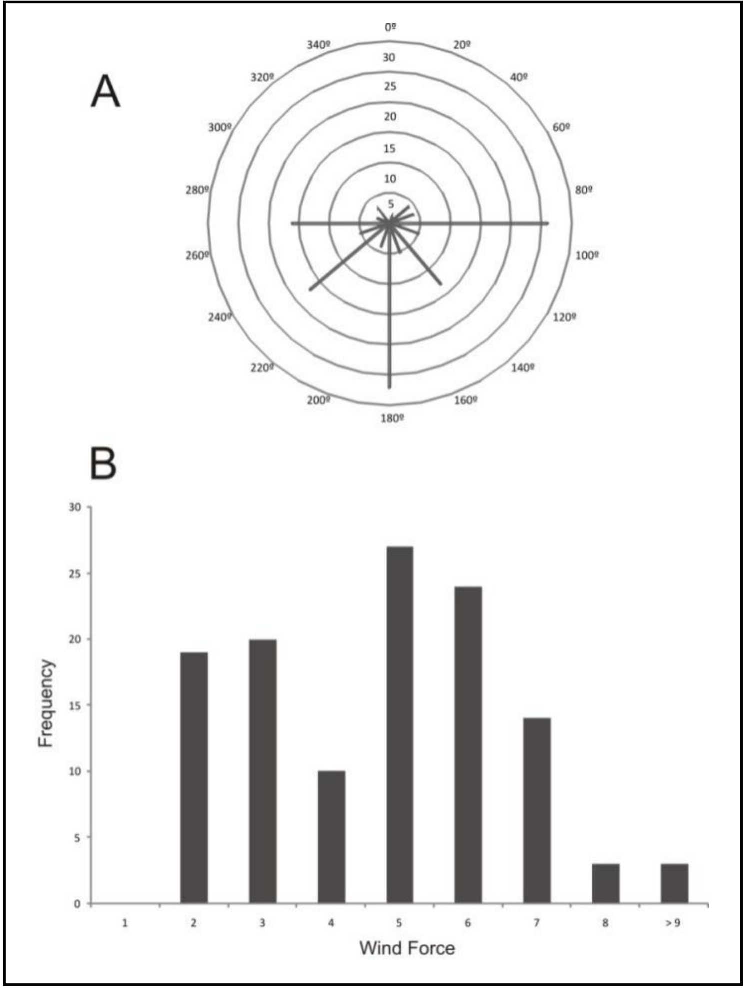

Figure 5.1 a: Dominant wind directions and, b: Wind Force during 124 recorded incidents on the railway line from 1997-2009 recorded in archive observations (presented in section 5.3). Sources of data include: Met Office archives and Slapton Sands weather station (available directly from owners). Data can also be found in Appendix C – 1.1a.

Nearly a quarter of events recorded occurred during a Force 5 but, interestingly, Network Rail's adverse weather matrix would suggest no action is required until wind speeds reach

Force 6. However, this analysis does not take into account the weather characteristics leading up to the incident (or wave climate) but highlights that a number of factors combine to make the 'right' conditions for overtopping. With rising sea levels, Network Rail's weather matrix will likely become outdated and, recently, a trial study of additional wave height monitoring has been included in their response plan to allow for more accurate weather alerts (Network Rail, 2009). Nevertheless, this type of reactionary response still does not address the long-term threat from climate change. Weather and tidal conditions offer further insights into past and current thresholds of the defences (Figure 5.2).

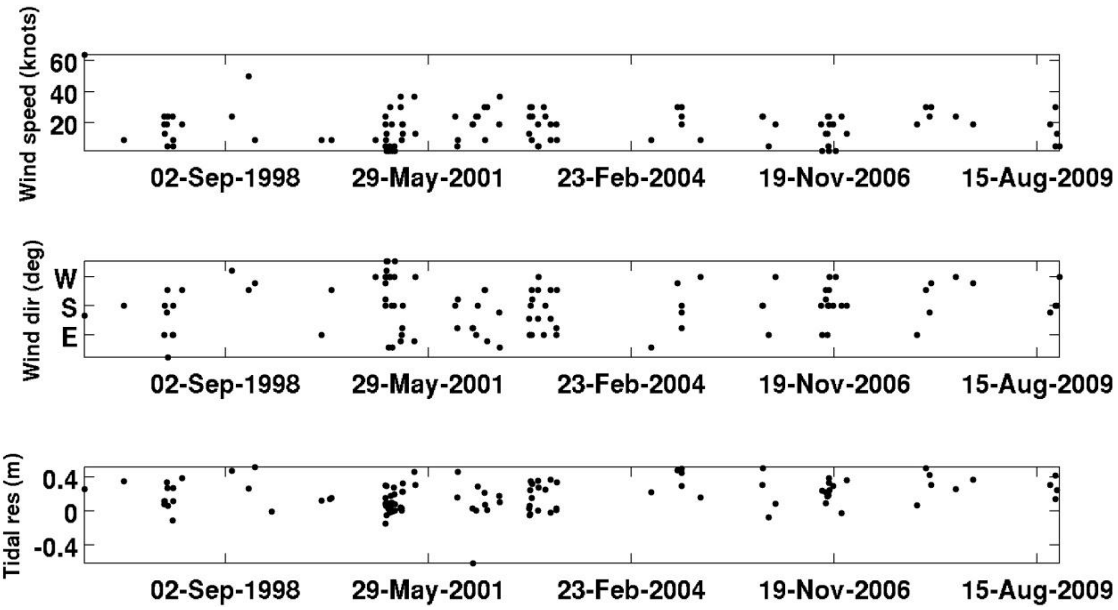

Figure 5.2 Observed meteorological and tidal conditions (from Newlyn, courtesy of the NOC) during all the rail incidents between October 1995 and September 2009. Compiled from the Slapton Field Centre's weather station and tide-gauge data (from the NOC). The correct combination of these factors (and others not recorded) result in an incident

Although large variability can be seen in the data set they highlight that a combination of factors cause most disruptions. For example, if the wind speed is low, the wind direction and/or tide height appears to be adequate enough to cause disruption. The average tidal residual (or surge) recorded during days with incidents was +0.18 m, but it has ranged from below expected values (-0.2 m) to exceptionally high values (over +0.50 m). The record suggests that the average water levels during incidents were around +2.33 m OD (or 5.38 m CD) and this level is around 0.55 m below the highest astronomical tide (HAT). A future with sea levels close to this (0.55 m) level would therefore put the railway at a significantly increased risk from storms. It is important, however, to put these water levels in context with the defence structures on the line. O'Breasail et al.'s (2007) study contains survey heights of known vulnerable sections of the track defences. Six of the crest heights of the track defences have been compared with maximum (still) water levels to illustrate the height needed to completely overwhelm the structures (Figure 5.3). The extent of the current marine projections (Lowe et al., 2009) is also illustrated.

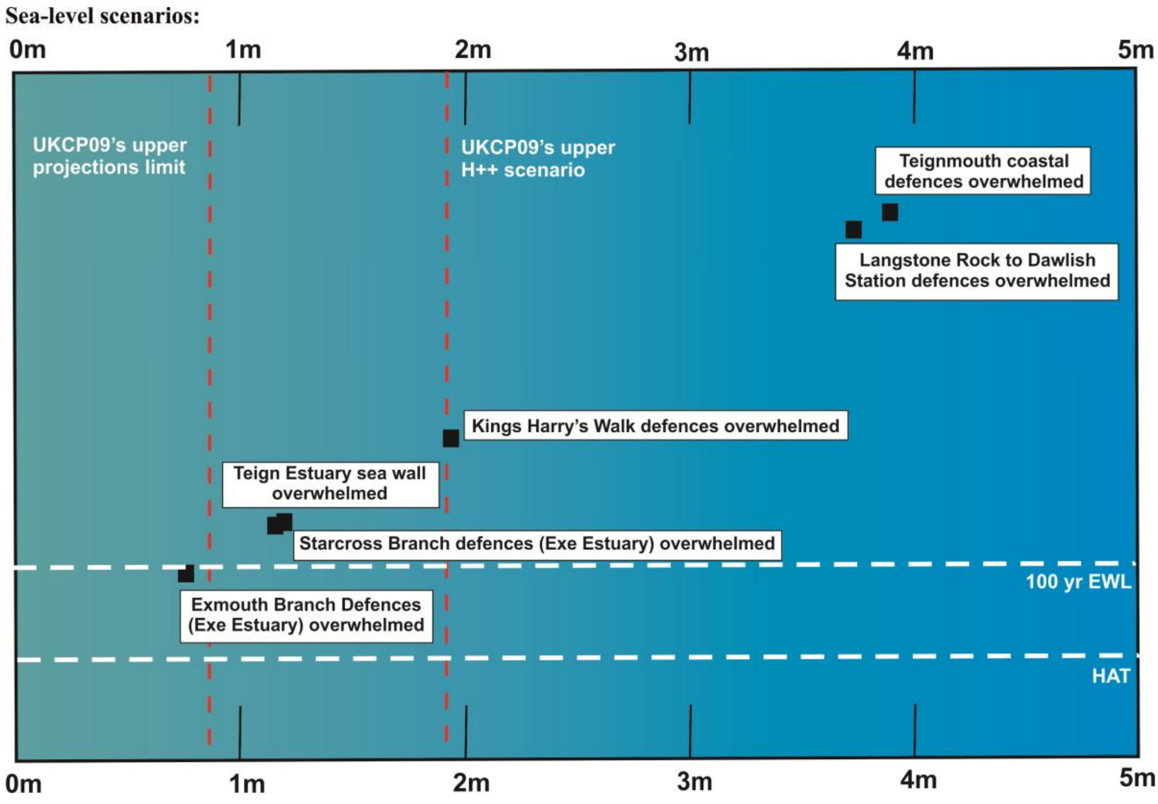

Figure 5.3 Critical defence limits on the Southwest railway network. On the vertical axis: dotted white lines represents the highest astronomical tide (HAT – 2.88m OD) and the current 100 year extreme still water level (EWL) for Teignmouth (3.62 m OD). On the horizontal axis: dotted red lines represent the upper ranges of UKCP09's predictions for Dawlish and Teignmouth (http://ukclimateprojections.defra.gov.uk). The HAT was subtracted from the current defence crest heights to give the extreme water level needed (above HAT) to overwhelm the structures. Defence crest heights courtesy of O'Breasail et al. (2007).

It is evident that a one to two metre rise in sea level would significant impacts on the Southwest’s rail network and the estuary lines (Exe and Teign estuaries) as any structure below +5.0 m OD will be inundated by the HAT. This includes four out of the six sections of the line. Furthermore, the toe level of the defence structures (not illustrated) are also threatened as a 1-2 m rise in sea level (e.g. H++ scenario) could permanently submerge the base of the sea defences. This would make repairing the structures almost impossible. It must be considered that these water levels, although extreme, are representative of standing water conditions only and other factors such as significant wave or surge height would reduce the height of water level needed to inundate the railway line. For example, Newlyn tide gauge has recorded positive surges of up to +1.01 m (Haigh, *pers comm.*) in the past and this highlights the potential vulnerability of the railway line.

For this project, the records of meteorological and tidal data during incidents have provided detailed information of surge and weather characteristics during known sea-wall incidents. It has been shown that weather and tidal characteristics can change significantly between events as the processes involved can change over short time periods (e.g., hours-days). Identifying trends and extrapolating these into the future would be problematic and require significant analytical modelling (Lowe et al., 2005) far beyond the scope of this thesis. Furthermore, in Chapter One it was demonstrated that small changes in sea level can have a significant effect on the future possibility of coastal flooding (e.g., Figure 1.3). Chapter Two also identified the extent of sea-level observations (tide gauges) in the English Channel (spanning a century and a half) that offer continuous evidence of long-term changes. Objective two of the thesis required the collection of a history of incidents on the railway line since it opened in 1846 in order to enable a direct comparison with tide-gauge data (MSL) over the same time period. In the next section records of rail incidents are explored.

5.3 A record of the vulnerability of the southwest mainline

As discussed in Chapter Two, observations of mean sea level (MSL) are extensive, and records from the English Channel date from the 19th century (maintained by the NOC). Chapter Three then outlined the methods and sources used to compile an archival history of problems on the line to compare with tide-gauge records. Three partial histories were constructed from multiple sourcescontaining varying amounts of information in order to examine the vulnerability of the southwest mainline over different time scales. The main characteristics of each data set are given in Table 5.2. The first is referred to as the *Published Sources Archive* (PSA). It was constructed from extensive searches of local and regional newspapers, literature, and libraries and contains a record of all the known days of line restrictions (DLRs) as a result of overtopping.

	Published Sources Archives (PSA)	**Frontage Management Report (FMR)**	**TRUST Service Data (TSD)**
Time period	1846-2009	1859-2005	1997-2009
Units	Years/Days	Chainage miles	Years/Days/Minutes
Years with events	44	38 (Damage) 68 (with repairs)	13
Dates of disruption	66	10	124
Days of disruption	147	-	124
Focus of record	Incidents and impacts	Maintenance interventions	Incidents and traffic logistics

Table 5.2 Summary of the historical archives collected from secondary sources (discussed in Chapter Three), including local, regional, and national newspapers, consultancy reports and digital rail archives. The full archives are contained in Appendix C – 1.2a.

The second account was obtained from Network Rail's defence structure report (Rogers and O'Breasail, 2006) and is referred to as the *Frontage Management Record* (FMR). It provides an account of the maintenance intervention (damages and repairs) on the line's defences along with the year in which they occurred. This record was initially used in Chapter Three to examine a correlation between defence problems and records of mean sea level (MSL) (Figure 3.7). The lack of specific dates of incidents and problems, however, prompted the construction of the more detail PSA (discussed further later). The last account on the railway line is a more recent record of incidents derived from Network Rail’s TRUST service monitoring system (a delay attribution database). This is referred to as the *TRUST Service Data* (TSD). This contains a short, but detailed, record of the daily delays and line restrictions caused by inclement weather between Dawlish-Teignmouth.

In this section, brief discussions of the quantitative trends of the three records are given along with some qualitative descriptions and summaries of past incidents. Furthermore, the data archives are compared in order to draw upon the similarities and differences and enable the construction of a valid record of incidents for analysis in this study.

5.3.1 The Published Sources Archive (PSA-1846-2009)

In Chapter Three it was stated that the early historical records of sea wall repairs were highly fragmented (Kay, 1993). A full journalistic history of incidents between Dawlish and Teignmouth was therefore undertaken (see Chapter Three for details). During the collection of the archive a strict reporting standard was used to ensure the most representative data set, and the record is the most comprehensive collection of rail problems to date. The PSA chronicles over 160 years of railway incidents from multiple published sources. Only direct evidence was included, and large storms (occasionally hurricane force) that affected neighbouring towns (e.g., Exmouth, Paignton, Torquay, Brixham) or extensively impacted the region were excluded unless there was a direct mention of the railway line. Evidence of incidents in the PSA varied, however, from extensive accounts (e.g., full coverage of the damage and restrictions) to minimal descriptions (e.g., single dated photographs with captions of the incident). Single dates could only be attributed to disruption that day, but it is likely that they were a result of poor weather lasting several days. The PSA’s record of DLRs is therefore likely to represent a minimum of actual days when the railway has been interrupted by the action of the sea. The PSA contains a total of 44 years with reported problems occurring and 66 confirmed dates of incidents lasting from one day up to 15 days. In the last 160 years there have been a reported 147 DLRs caused by overtopping. The PSA shows the total days of each year where a restriction on the line occurred and – in quantifying the history into a single time series – basic trends can be identified (Figure 5.4).

Initially, after the line opened high numbers of DLRs were reported in the news but began to decrease towards the 1900s (discussed further later), and between 1900 and 1980 only nine events were reported in total. From the 1980s, however, reported DLRs increased substantially, and over 50% of the incidents in the PSA were recorded in the last 25 years. The PSA also contains qualitative descriptions of some of the past incidents, and these provide eye witness accounts during the last two centuries. The first event to close the line occurred on the 5th October 1846 only months after the line had officially opened, although the line only went as far as Teignmouth at the time (Kay, 1993). There were reported breaches of the sea wall and the track was left hanging. Third class passengers not protected by windows were '*soaked to the skin'*, and the Dawlish residents '*thronged the Marine Parade at high tide to see the majestic mountains of foam thrown up against the wall'* (*The Times*, 1846, p5). A temporary line had to be erected using green fir branches laid on top of the remains of the wall. The line reopened on the 7th October and the blockage was recorded as lasting 50 hours (Kay, 1993). Major line closures (or blockages) have been recorded ever since and have typically occurred every 10 years (Figure 5.4) but smaller events cause problems also. In February 1974, an event occurred that was considered relatively minor by Kay (1993), as both lines were shut for only a few hours, but the news reported the track in ruins and that the eastern end of the Dawlish Station platform was unusable for weeks (*Western Morning News*, 1974, p 9).

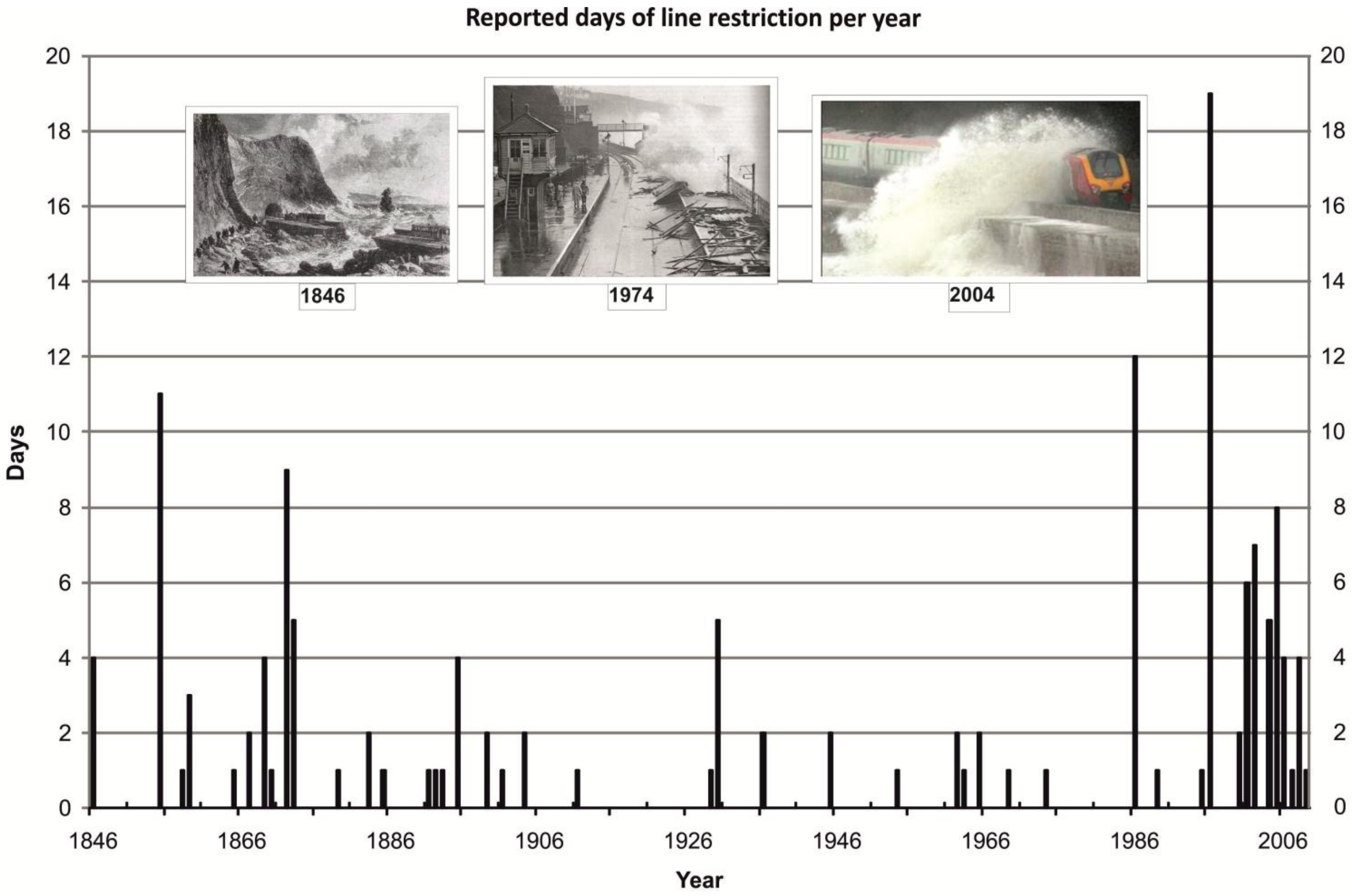

Figure 5.4 Time series of annual days of line restrictions due to overtopping of the sea wall between Dawlish and Teignmouth section of the London-Penzance railway. Reported in Published Sources Archives (1846-2008). Images of events: 1846 - The first storm to hit the line after it opened; 1974 – Dawlish Station down line damaged; 2004 – 21st century problems, as trains, not just the defences, become victim to the sea. From 1980 onwards incidents appear more frequent than any other period. Images courtesy of Kay (1993) and BBC News (2004).

During the last 30 years the problems appear to have intensified and an incident on the 27th October 2004 shut the down-line (closest to the sea) for around five days. One lifetime Dawlish resident (Geoff Lendon, 62) believed it was the worst damage he had seen in 40 years (*Western Morning News*, 2004). The railway had over a foot of standing water on it, and a Virgin Trains spokesman said the line had to be closed as boats had drifted onto it (*The Times*, 2004). The 21st century problems have not only provided damage to the track and defences, but also to the trains, as the newer Voyager trains have begun breaking down due to saltwater spray. This was first reported in 2002 (*The Mirror*, 2002) and, as of 2010, these trains no longer run along the line during heavy seas (BBC News, 08/03/2010). Interestingly, it may be suggested that this is not a problem with the defence infrastructure but with the trains themselves, as the Voyager trains journeys are now curtailed during poor weather conditions. The result is still disruption for the rail passengers, however, as they have to be transferred onto alternative rolling stock (e.g., First Great Western services).

The last major event, in September 2006, left a 10 x 1 metre void in the defences near Dawlish station and caused severe ballast washout and track subsidence, and reportedly closed the line for nearly three days (*Herald Express*, 2006). The extent to which the recent intensification of incidents is directly related to sea-level change remains to be established. However, the history shows that similar periods of intense breaches have occurred in the past (e.g., 1855-1870) and a preliminary analysis of the trend offers interesting comparisons. During the latter half of the 19th century, for instance, high numbers of events were recorded yet sea levels were over 20 centimetres lower than today. This could consequently be a result of other factors influencing the frequency of DLRs. Perhaps the most dominant (large scale) factor that causes breaches and subsequent line restrictions is changes in storminess. Change in the North Atlantic Oscillation (NAO) index, which is a leading pattern of climate variability in the Northern Hemisphere, is an indication of large phases in wind and storminess characteristics.

Zong and Tooley (2003) carried out historical analysis of flooding frequencies in the UK and found steadily increasing frequencies in the Southwest towards the 1940s, and those corresponded with positive NAO indexes (Figure 5.5). The PSA record of line restrictions reduces from the early to middle 20th century (1900-1950), however, and then shows a dramatic increase in the last 40 years (see Figure 5.4). Zong and Tooley (2003) observed lower flood frequencies from 1950-1960 and significant floods in the 1970s after which they declined. For these periods, however, the NAO indexes did not match the records, and their analysis shows an apparent decline in flooding has occurred (post 1970) even though temperature has risen and NAO indexes appear strongly positive. It is suggested that this could be result of significant coastal defence improvements reducing the risk of flooding along the coastline (Zong and Tooley, 2003). This analysis does not correspond with their analysis and PSA record as the last 40 years have been the most intensive. It does, however, correspond with the strongly positive NAO index observed by them. Unfortunately, Zong and Tooley’s (2003) records terminate in 1995 and, therefore, in this study only serve as a reference for investigating possible incidents in other archives (e.g., the PSA).

Furthermore, there is no universally accepted method to describe the temporal evolution of the NAO and all attempts reveal that there is no preferred time scale of variability (Hurrel and Deser, 2010). Therefore, no correlation with past rail problems can be established or projected and another factor (e.g., sea-level rise) may be more significant in influencing the recent trends observed. In conclusion, the PSA record of DLRs and descriptive accounts provide evidence of incident trends during the railway life time. Based on this account, it is apparent the problems on the line have not eased despite 160 years of defence developments. A history of these developments is available from the second archive collected - Network Rail's *Frontage Management Report* (FMR, Rogers and O'Breasail, 2006). It is an empirical history in itself, but it can also help verify the PSA's trends along with offering a more detailed understanding of past damage and maintenance interventions.

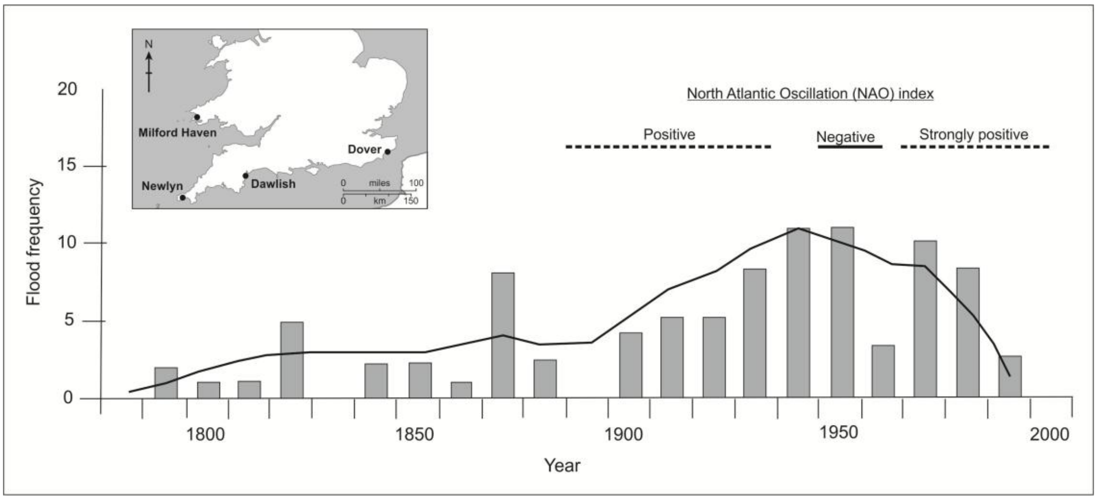

Figure 5.5 Zong and Tooley's (2003) historical coastal flood analysis for the south and southwest of England. Flooding events were recorded between Dover and Milford Haven from 1788 – 1995. The North Atlantic Oscillation index does not correlate with flood frequencies recorded as a decline in flooding post 1980 corresponds with a strongly positive NAO index.

5.3.2 The Frontage Management Report (FMR- 1859-2005)

Whereas the PSA was constructed chronologically, the FMR was originally compiled by track location (not date). However, it contains details of damages and repairs, the year they occurred, and a short summary of the problem. In one year the record may contain multiple locations of damage and repairs to the frontage but as there is no date it is not possible to determine whether one or several incidents took place (without considerable assumptions). Comparison with the PSA record, therefore, is problematic unless only one location and one year is reported (and this would still not provide complete confirmation that the two are linked). The data set is useful, however, for observing the maintenance developments over the last century and a half. As the FMR only contains damages caused by storms, the descriptions contained in the history were screened and divided into damages and repairs[3] (see Appendix C – 1.1a). This enabled any patterns between the two to be viewed against track location. The damage descriptions were screened once more to separate the problems that were substantial but were only represented by a single location (e.g., multiple sections of the sea walls collapsed at 204 m - Langstone).

Network Rail's responsibility for maintaining the defences is between Langstone Rock to Teignmouth Station (204 m and 209 m), after which the areas are managed by the Environment Agency (east of Langstone Rock) and Teignbridge District Council (west of Teignmouth train station) (see Figure 1.1). Figures 5.6 present the information contained in the FMR's problem history. The FMR data has been edited to allow the history to be viewed chronologically, whilst still maintaining the details of location and the extent of invention described in the record. Furthermore, the qualitative descriptions from the FMR were summarised and have been categorised into four types of impacts: low, medium, high and severe (Table 5.3 – refer to Appendix C - 1.2b). Although these cannot be directly related to single events, these impacts provide examples of the typical damages to the defences during the last 160 years. The FMR allows the location and nature of problems to be analysed and interpretations to be made.

For instance, over the railway's first five decades of service some level of damage was reported in nearly half of these years. The damage mainly occurred in single locations and was constrained around the Rockstone – Shell Cove sections of the line (Figure 5.6a: 205 m – 206 m). Damage recorded included coping stones being removed and washouts of the sea walls and footbridges. In 1895, the sea washed a large amount of sand off the beach at Langstone and, subsequently, substantial incidents appear to have occurred more periodically around the Langstone Rock and Rockstone Footbridge area.

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[3] Although 'cause and effect' would suggest that repairs presumably precede the occurrence of damage.

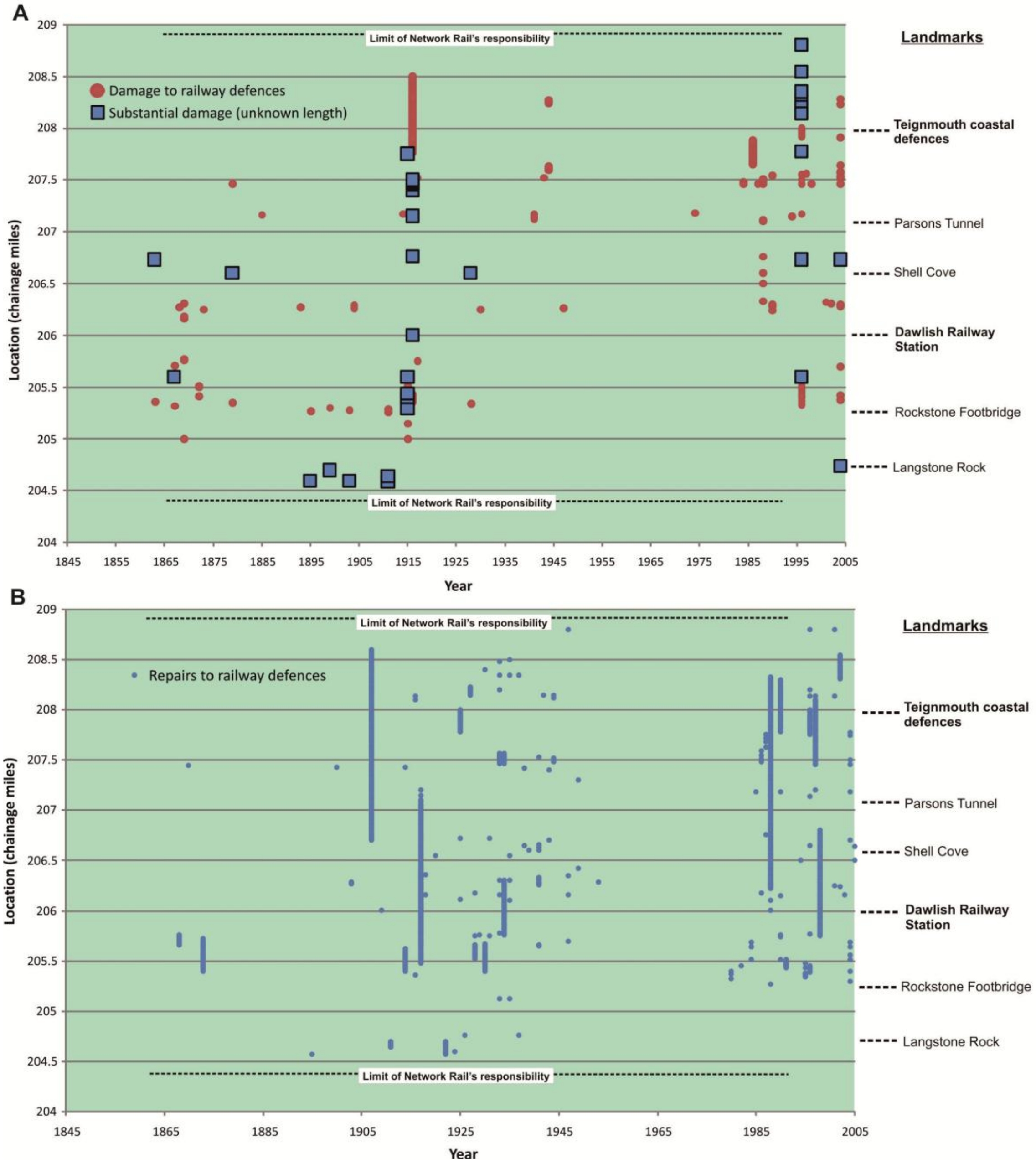

Figure 5.6 The Frontage Management Report's (FMR) problem history (1859-2005) of adapted to show locations of reported damage (a) and repairs (b) (Rogers and O'Breasail, 2006 p. 10). Refer to Appendix C – 1.2b for more details. The landmarks can be located in Figure 1.1.

Washouts and holes in the wall were reported and, as a result, a second heavy concrete wall was erected behind the old one and both were tied together in the same year (Rogers and O'Breasail, 2006). It appears this did not solve the problem, however, as damage continued in the area for over 10 years after. This is not surprising as an additional wall would not help address the erosion of beach material that buffered potential wave energy.

Despite the significant damage reported in the first 50 years the details of repairs between 1859 and the 1900s seem quite minimal (Figure 5.6b).

Impact type	Description
Low	- Localised damage - Masonry damage to defences (cracks and fractures) - Coping stones removed
Medium	- Multiple damage - Ballast washout - Substantial lengths of copings removed or loosened - Beach material removed (foundations exposed) - Damage to groynes and breakwaters
High	- Multiple breaches and flooding (substantial lengths) - Large masonry damage and copings washed away (< 6 m) - Large cavities in sea wall and retaining walls (< 3 m) - Damage to the foundations and toe of the defence - Subsidence or depressions of the track - Dawlish station platform overtopped
Severe	- All of the above damage (for multiple days) - Extensive beach material removed - Multiple voiding in wall and track (3-30 m) - Severe undermining of the foundations - Top sections of wall washed away - Dawlish station roof and platform lifted off - Severe damage to breakwaters/walkways/footpaths (demolished) - Wider rail damage – Starcross, Teignmouth, Paignton, Looe and Penzance

Table 5.3 Categorisation of archive of impacts recorded in the Frontage Management Record (FMR - Rogers and O'Breasail (2006)) and the Published Sources Archive (PSA).

The PSA, on the other hand, reported several line restrictions during this quite period and this suggests that not all repairs and constructions have been recorded. Post 1914, however, was plagued with significant and extensive problems on the sea defences (Figure 5.6). A cross reference with the PSA accounts, however, shows no incidents during this period (Figure 5.4), but as the FMR does not give exact dates of incidents it is not possible to explain the mismatch. One theory that may explain it could be that records are the result of compound damage (i.e. not attributed to any specific event), but this could not be confirmed. Nevertheless, damage was recorded to various sections of the sea wall and the foundations, large sections of copings (< 30 metres) were loosened and, in 1914, Dawlish

Station roof was washed onto the beach. In 1917, large cavities in the wall were found up to 11 metres long and six metres deep and the track subsided seven feet. Following 1917, a substantial section of sea wall was rebuilt from around 205 m – 207 m (Figure 5.6b), 20,000 tons of rock armour was tipped against the walls to prevent subsidence and outer casing and granite aprons were constructed (to protect the toe of the wall). Extensive underpinning and strengthening work was also carried out along with track ballast replacement and the construction of new beach groynes in order to reduce beach erosion.

This period appears to mark the start of extensive repair and construction work along the entire defences (Figure 5.6b). The repair works were continuous till the 1950s and, by this account, appears to have had a positive effect on reducing the number of damages (comparing with Figure 5.6a). The few events that were reported were substantial however. In 1928, for instance, the area around Dawlish suffered substantial damage to the wall in three places. Two years later the tracks were left hanging after significant ballast wash outs, and in 1940 a similar problem occurred near Teignmouth. Post 1950, however, problems and repairs are absent and a review of the original archive data at Network Rail's Exeter depot provides no other explanation for this apparent lack of records. One could assume that the major repairs and constructions were successful in reducing the impacts of storms during this period. This is indeed what rail historian Peter Kay (1993) concludes after his own investigation. Rates of sea-level rise were considerably lower during the 1960s (Woodworth et al., 2009b) and storm frequencies in the Southwest were reportedly lower during the 1950-1970s (Zong and Tooley, 2003). Both rates of sea-level rise and storm frequencies began to increase significantly, however, towards the late 20th century. In 1974, Dawlish Station was once again badly damaged (see insert B in Figure 5.4).

The more recent history from the FMR (the 1980s to 2005) can be easily distinguished as the period with the highest intensity of problems on the line. From the 1980s, the whole track has been impacted periodically (average interval < 10 years) as major events occurred in 1986, 1996, 2004 and 2006. However, unlike the end of the 19th century when damage was isolated to single locations, the impacts appear on the majority of sections of the line and there is clear evidence of reoccurring problems. Similar to the late 1800s, the areas around Rockstone Footbridge and both east and west of Dawlish Station appear to be particularly exposed. The areas around Teignmouth's coastal defences were affected also. From the descriptions it appears that the biggest problem has been undermining of the track foundations (in the soft sandstone bedrock) although large sections of coping have been washed away and voiding has been extensive. As a result, repairs have included full foundation strengthening, concrete spraying to the toe and face of large stretches of the sea wall (which reportedly failed in 1996), groyne renovation, toe-construction, rock armour re-profiling and even new coping designs. It is reported that the capital cost of recent defence works is now estimated at around £9 million since 2004 (Clinnick, 2009).

In conclusion, the problem history has illustrated patterns of damage and engineering response over the last 160 years, and the hold-the-line approach (hard engineering) appears to have improved the situation for a number of decades (e.g., during 1930-1970). But the historical accounts suggest that this approach has proved limited in the long term defence of the railway. Consequently, the most recent period of history identifies the highest number of problems on the line. The FMR's annual summaries give no indication of the actual implications to the railway traffic. However, the contractual nature of the recent privatised rail network and signal improvements have meant accurate records of disruption to rail traffic, albeit on a much shorter time series, are now archived (e.g., *TRUST Service Data* – TSD). Furthermore, these records can be complemented (and cross referenced) with additional data from train operating companies (TOCs) to establish the impact of incidents (DLRs) on trains services and passengers. The next section presents the evidence from the TSD (1997-2009).

5.3.3 TRUST Service Data (TSD-1997-2009)

The TSD record was collected from Network Rail's Weather Strategy Team, and records of adverse weather events between Dawlish and Teignmouth were requested (for more details see Chapter Three). Network Rail manages incidents by dividing its response into three stages of alert - Levels 1, 2 and 3. These are based on predetermined wind and tide levels (Table 5.1) and are typically imposed two hours either side of high tide (twice a day). Additionally, First Great Western (FGW) holds daily performance logs (from 2002 – present) that detail the daily performance of the entire FGW rail network. These can be used to obtain rail user impacts (e.g., changes in travel time) during each alert. The traffic disruption during emergency speed restrictions can vary between incidents, yet Network Rail's traffic protocol is consistent with each level. The information based on an event lasting two high tides (one day) has been collated, and the likely recorded disruption for each restriction level has been summarised based on previous FGW traffic logs (Table 5.4).

Class 2 services (i.e. Exeter-Paignton and Exmouth-Barnstaple), are the first to be restricted during level 1s (20 mph emergency speed restriction ESR) in order to allow intercity trains to run closer to schedule. Previous Level 1s have delayed up to 45 trains (> 5 were Class 1) per day, and during Level 2s all these trains have been cancelled (known as caped). The occurrence of a Level 3 restriction has coincided with delays for up to 80 train services per day (20 of which were Class 1) and has typically added an extra hour to passenger journeys as road transport is required between effected stations. These disruptions continue until the weather or tide subsides enough to open the line, but pending a full engineer inspection of the defence structures and track. Now that the restrictions and impacts have been outlined, the TSD can be examined. Table 5.5 presents the annual numbers of days where a restricted line service has occurred. In the last 13 years there have been 124 recorded incidents (or DLRs).

Restriction	Network Rail Protocol	Recorded impacts to traffic
Level 1	• 20mph Emergency Speed Restriction (ESR) on down line • CrossCountry class 220/221 services on watch and likely to be suspended between Newton Abbot and Exeter • Local stopping services thinned	• Delays to all services between 5-20 minutes • Class 2s services cancelled • < 45 trains affected • Voyager halted (level 2) and train evacuation needed
Level 2	• Up line working only • CrossCountry and Voyagers suspended (bus service only) • Maximum line capacity 6 trains p/hr, and reduced to 3 if ESR imposed on whole track • Emergency timetable imposed • 1 x HST service each way per hour and 1 x FGW local sprinter each way per hour • All Class 1s stop at Newton Abbot • Exeter-Paignton services withdrawn, similarly Exmouth and Barnstaple	• Class 2 services severely affected • Services up to 15-50 minutes late • Up to 80 trains delayed • 45 trains services cancelled • Trains hit by objects, windscreens smashed
Level 3	• No services between Exeter and Newton Abbot • Line will re open as Level 2 • Both line will remain closed until inspection has been completed	• Class 2 service cancelled • Voyagers stranded • < 80 trains affected, of which 20 were Class 1 • Typical Plymouth-Paddington service one hour late

Table 5.4 Network Rail's current adverse weather protocol and the recorded impacts to passenger services during these events. Based on data from 2000-2009. ESR = Emergency Speed Restriction, HST = High Speed Train, and FGW = First Great Western.

The years 2000 and 2002 recorded the highest number of days with line restriction when nearly 25 days during the year saw a limited service. 2006 was also a poor year with 17 days that had a limited service. Network Rail also record the delay minutes associated with each incident, and each minute represents a delay to the functioning of the track (in Table 5.5 also). The delay minutes give a good indication of the possible severity of the event and the possible cost to Network Rail, as a penalty is received for every minute the line is not in full service (this is investigated further in Chapter Six). Annual DLRs and delay minutes (Table 5.5) do not show perfect correlation, for instance, certain years had fewer days with line restrictions but incurred more delay minutes (e.g., 2004) and this reflects the uncertainty of incident impacts. The peak years of delay minutes were 2000-2002 and 2004-2006, and 2002 recorded the highest year of delays with nearly 10,000 minutes over 25 days (Level 1 and 2 ESRs). Alternatively, in 2004 one incident lasted five days, and demonstrates the high level of disruption caused during a Level 3 restriction. The total and average number of incidents has been summarised in Table 5.5 also.

Year	**Days with line restrictions**				**Delay minutes**			
	Level 1	**Level 2**	**Level 3**	***Total***	**Level 1**	**Level 2**	**Level 3**	***Total***
1997	10	1	0	11	809	293	0	*1,102*
1998	3	0	0	3	0	164	0	*164*
1999	4	1	0	5	467	131	0	*598*
2000	3	22	0	25	223	7,267	0	*7,490*
2001	8	4	0	12	4,163	1,459	0	*5,622*
2002	18	5	0	23	3,507	6,414	0	*9,921*
2003	3	2	0	5	77	257	499	*833*
2004	2	1	3	6	104	3,505	7,192	*10,801*
2005	1	4	0	5	21	4,725	0	*4,746*
2006	9	7	1	17	2,116	3,660	1,033	*6,809*
2007	0	1	0	1	9	0	0	*9*
2008	6	0	0	6	1,404	0	0	*1,404*
2009	3	2	0	5	551	9	0	*560*
Total	*70*	*50*	*4*	*124*	*13,451*	*27,884*	*8,724*	*50,059*
Ave	*5.4*	*3.8*	*0.3*	*9.5*	*1,034*	*2,144*	*671*	*3,620*

Table 5.5 Total line restrictions and delay minutes attributed to the sea wall between Dawlish and Teignmouth from 1997-2009. Source Network Rail and the TSD archive. Dated is also available in Appendix C – 1.1a.

The results show that Level 1 alerts were recorded as the most frequent, and instances of total line closure (Level 3) were the least frequent. Total line closures have only been recorded four times in the last 13 years. However, they have caused similar levels of disruption (delay minutes) as 70 Level 1 restrictions. The disruption during complete line closures can thus be described as severe. As identified in the PSA record, the newer Voyager trains are more vulnerable to sea spray than other rolling stock (e.g., First Great Western) and are prone to malfunction as saltwater enters the electrics on the roof of the train. In October 2002, a Voyager train broke down and caused over 4000 delay minutes to the line. Three other services were trapped behind it, and as a result of bad weather further disruption occurred for a number of days. A Voyager breakdown was last recorded in March 2008 and (as mentioned) since 2010 these trains have been excluded from the line during Level 2 alerts (Network Rail, 2009, BBC news, 08/05/10).

The TSD record and FGW's details of passenger delays give the most detailed account of events in the last 13 years and although no long-term trends can be established it provides a excellent control period of recent problems. Having a detailed knowledge of the nature and consequences of past incidents is essential in order to present accurately a likely scenario for the future. As the collective histories are not complete it is not possible to link the exact damage, delays and disruption of all the incidents. However, the three histories can be compared in more detail in an attempt to improving their validity and further use in this investigation.

5.3.4 Comparing the archives of rail history

Figure 5.7 presents an overview of the full quantified record of archives from all three sources. In this section comparisons will be made between them. Firstly, the FMR's record of damage (Figure 5.6a) was quantified to show the collective number of locations (e.g., chainage miles) reporting damage each year (Figure 5.7b).

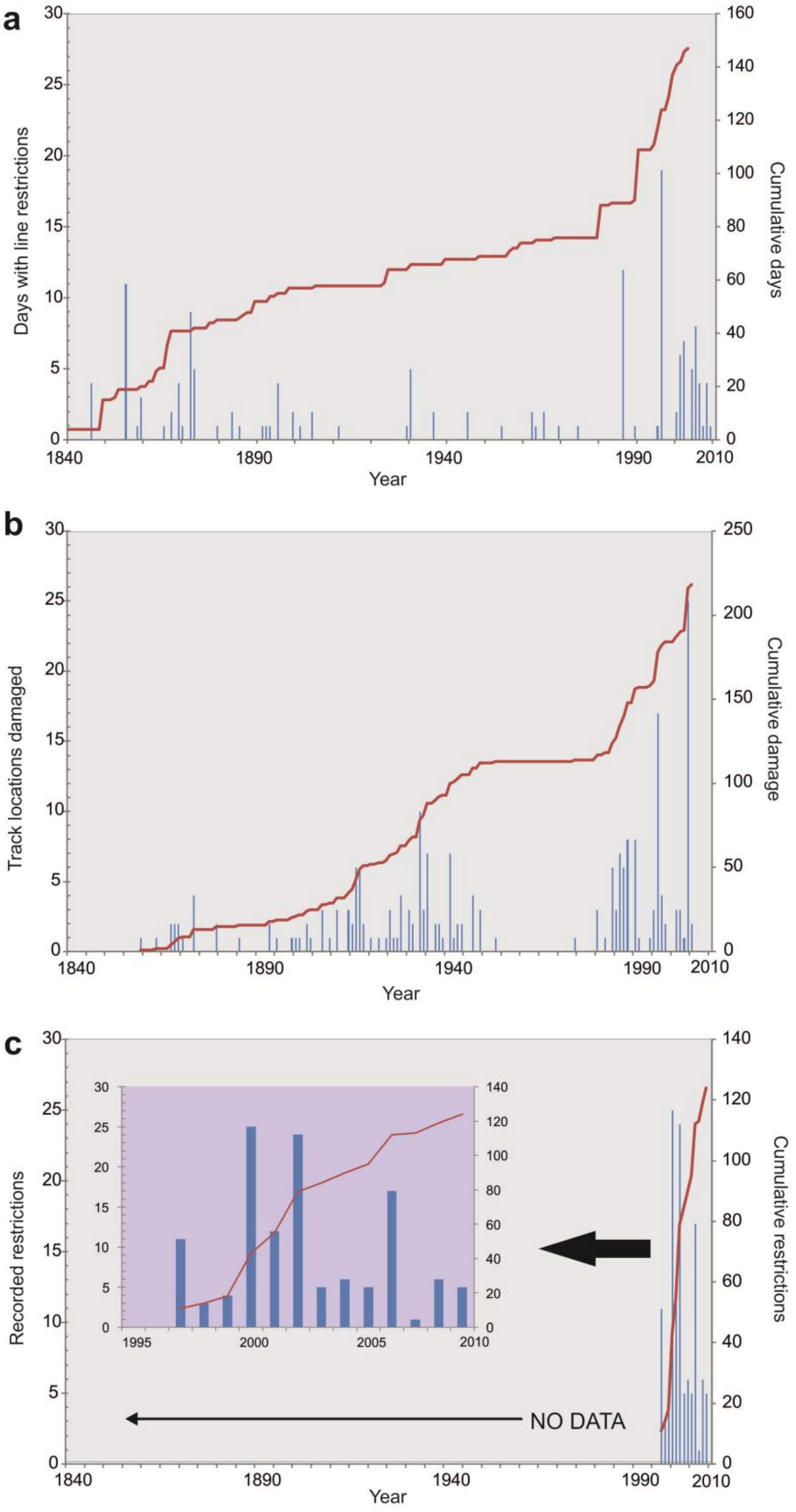

Figure 5.7 Archival history of the Dawlish-Teignmouth railway line. a) The Published Sourced Archive's (PSA) known days of line restriction. b) The Frontage Management Record (FMR) of locations recording damage (annually) and c) the TRUST Service Data's (TSD) record of days with line restrictions. Figure data is contained in Appendix C -1.1c.

Initial, comparison with the PSA's (Figure 5.7a) frequency of DLRs illustrates that both records show similar patterns over the last 160 years. However, the two are certainly not identical. The FMR and the PSA have been further compared to investigate the differences in more detail (Figure 5.8).

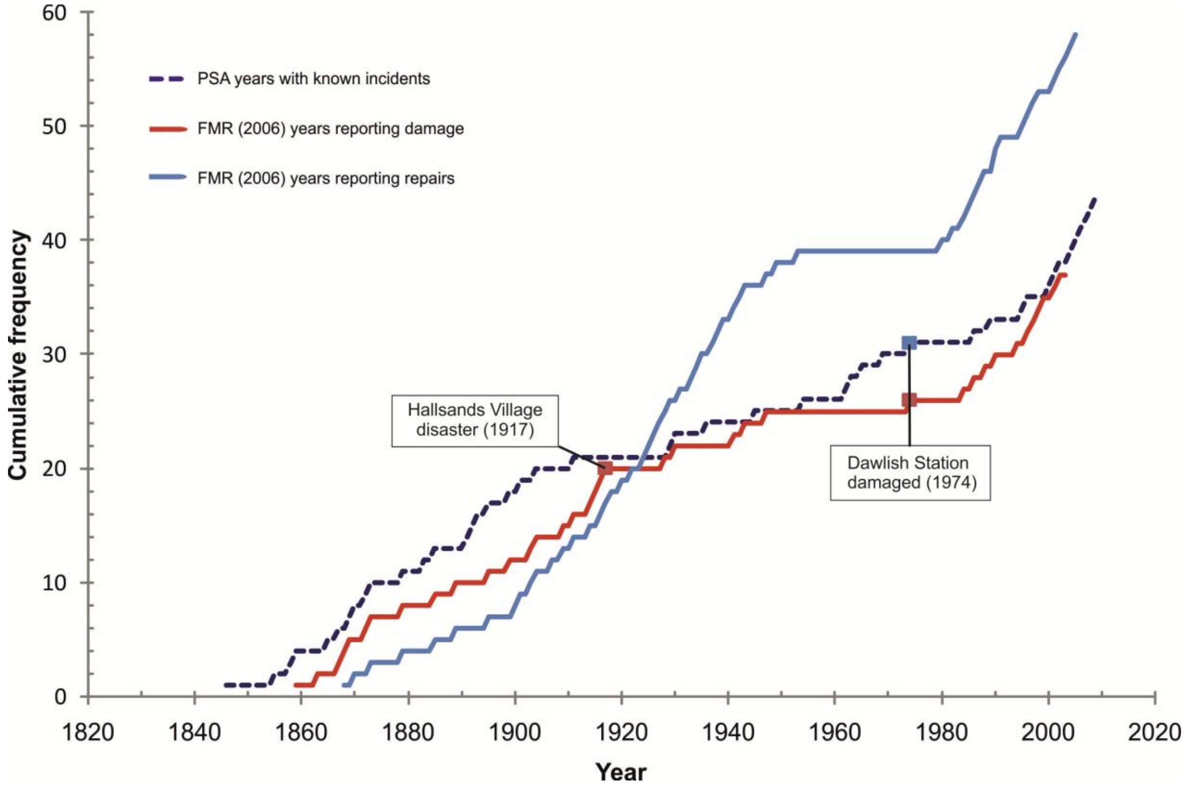

Figure 5.8 Cumulative records of annual disruption/damage/repairs on the railway line. Taken from Published Sources Archives (PSA), and the Frontage Management Record (FMR). The significant increase in repairs and construction observed after 1920 can be seen in Figure 5.7b.

The historical accounts show similar cumulative trends initially, and with a steady frequency of yearly events up until the 1900s. The PSA identifies the first incident free period from 1911-1930 but, in contrast, the FMR records damage to the defences up until 1917. However, 1917 was significant in the region as it was the year of the famous Hallsands village disaster. Hallsands is situated around 35 miles west of Dawlish, and on 26th January 1917 a huge easterly storm battered the south Devon coastline and destroyed the seaside village. Although this is not the first year to have a mismatch with the PSA[4], late 1916 and 1917 had extensive damage reported in the FMR and preceded an extensive period of repairs and construction work. The regional news reported the storm yet the railway was not mentioned. This example highlights one of the issues with using journalistic archives (and secondary data). As the FMR clearly states that a large amount of damage was recorded in 1917 it could be assumed that the PSA and FMR are connected. The news is constructed for the public and will likely report the areas of most concern, and in this case, the usual problems on the railway went unreported in favour of the unforeseen destruction of the village of Hallsands. On the other hand, from 1950-1975 the FMR gives no evidence of damages yet evidence in the PSA reports single line working due to ballast washout in 1954 (*The Times* 28th Nov. 1954, p4).

Additional news reports describe similar damage in 1962 and 1963, and in 1969 a 12 foot (3.7 m) hole in the wall caused two days of restrictions. These events would have caused significant problems to the public (e.g., rail traffic) and were extensive enough to be reported in the news, but no evidence is recorded in the FMR. In 1974, however, both records are clearly synonymous as Dawlish Station was severely damaged and the FMR describes a '*13 chainage [mile] length of platform deck [Dawlish station] lifted by a storm in February*' (also see Insert B, Figure 5.4). This represents one of few events when the FMR records the actual month of the incident in its accounts. There are numerous mismatches between the annual accounts of problems on the line; therefore another quantitative comparison of the records was made to examine broader trends in the observations. Figure 5.9 compares the trends of total known DLRs from the PSA (Figure 5.7a) with known years of damage or repairs (Figure 5.7b) over twenty year periods from the opening of the railway.

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[4] The PSA record has an additional eight years of events unrecorded in the FMR records, and similarly the FMR contains eight additional years of damage unreported in the PSA.

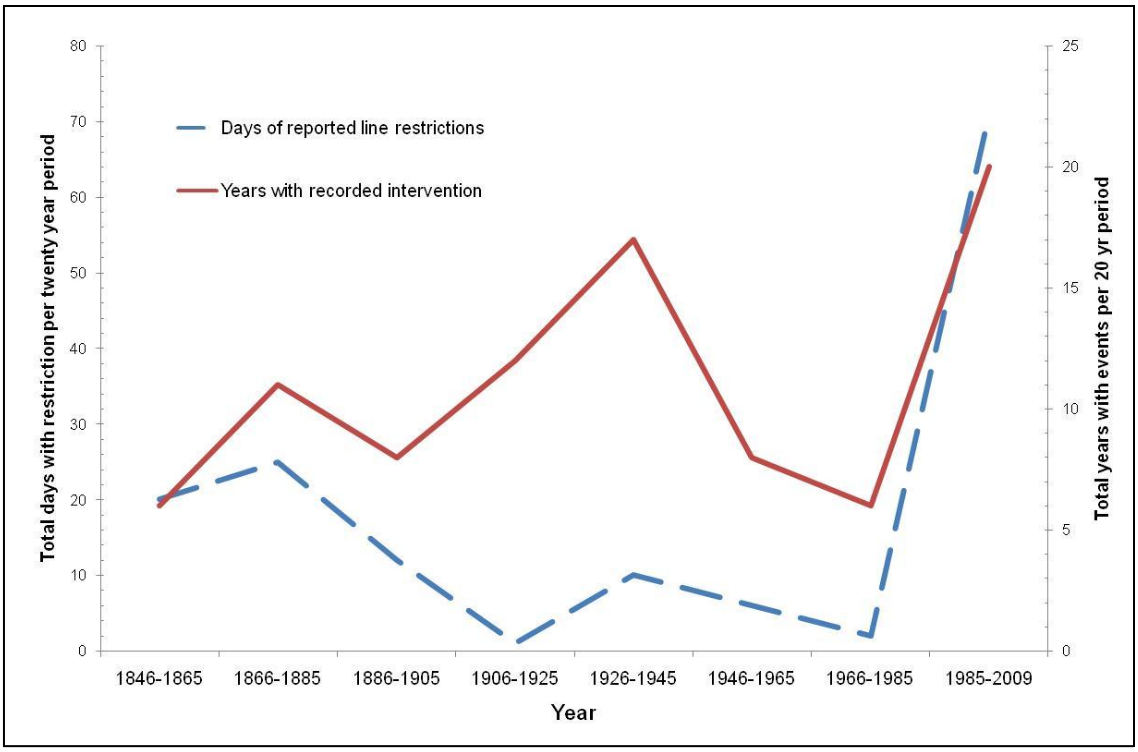

Figure 5.9 Comparisons of total days of line restrictions (from PSA) and maintenance interventions (from the FMR) over twenty year periods. Periods with increased days of line restriction coincide with periods of increased maintenance inventions. The FMR's interventions combine the years of damage and years of repairs.

The DLRs are noticeably higher as one event can restrict the traffic for several days but the result shows that the trends over twenty year time periods are very similar. Periods with higher recorded maintenance interventions correspond with high numbers of days with line restrictions. Furthermore, the most recent period (1985-2009) of the line's running is recorded as being the most disrupted and damaged. From the trends identified by the PSA, and based on these discussions, the following can be stated:

- The *Published Sources Archive* (PSA) contains additional incidents compared with the *Frontage Management Report* (FMR) that have - or are likely to have - caused damage to the defences.
- The FMR contains additional accounts of damage to the defences compared to the PSA that are likely to have resulted in disruption to the traffic on the railway.

In using either of the histories as a baseline, these conclusions should be considered and a causal link between the line restrictions and damage to the defences could be assumed. Overall, the long-term trends of the PSA and FMR have been independently verified by one another. The lack of dates in the FMR, however, means the two can never be combined without including large assumptions. In choosing one of these for extrapolation, the PSA would be more suitable as days of line restriction (that affect rail users) could be projected along with the causal relationship (with damages and repairs) described above.

Finally, validation of more recent incidents (1997-2009) can be achieved using the TSD. The TSD contains directly comparable recording units as the record from the PSA, but for less than a tenth of the line’s history (refer to Figure 5.7c and section 5.3.3). Over the last 13 years Network Rail has recorded incidents to the railway traffic every year. The PSA record, however, only reported incidents in nine of these years (Figure 5.10) and only provides evidence of 47 DLRs, whilst the TRUST data recorded over 100 (almost 70% more). Only during two of the years (2004 and 2007) did days of disruption reported in the news correlate exactly with service data and, interestingly, these were not the same incidents. Furthermore, taking the actual incidents into account the PSA recorded an additional 14 dates which were not recorded in the TSD, and contains additional DLRs every year except 2003. This suggests that the service record does not record every single incident on the line, and void days (total closures can go unrecorded as the system resets itself), routine maintenance or technical problems in bad weather could be a reason for this.

From 1997-2000, however, there were particular mismatches between records, and by examining the nature of events (e.g., the response level) it highlights (further) the inconsistency of journalistic records. The majority of events from 1997 - 2000 were recorded by the TSD as Level 1 or 2 restrictions and, thus, caused less disruption to rail traffic than a Level 3 restriction. The year 2000, for example, recorded 25 DLRs and nearly all were Level 2, yet only two restrictions were reported in the news (and were actually not recorded in the TSD). The results from the newspaper archives in 2000 found that the majority of headlines and articles discussed the line’s future. The focus of concern was not on actual incidents but how to tackle the problem, and this was likely to be stimulated by the frequent seasonal closure of the line. Overall, the PSA’s record during the period under-represents the actual number of line restrictions, but in comparing the two it has shown that the TSD is not totally accurate either.

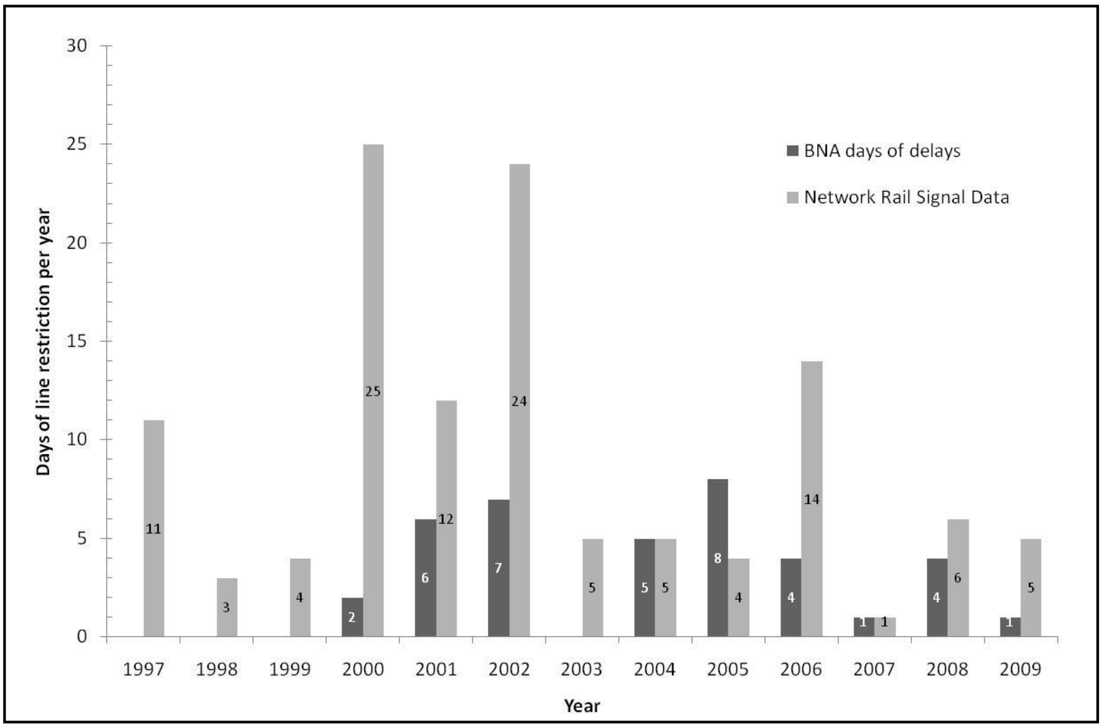

Figure 5.10 Comparison of days of line restriction from TRUST Service Data (TSD) and Published Sources Archives, 1997-2009 (Appendix C -1.2d).

In summary, this section has presented the historical archives collected from secondary data collection outlined in Chapter Three. Three partial histories have been collated (summarised in Figure 5.7 a-c), discussed, and compared, and the collective histories suggest that in the last three decades the railway has become significantly more vulnerable.

The PSA record of days with line restrictions (DLRs) is the longest and most continuous account of incidents on the line to date. The 19th, 20th and 21st century quantitative records of DLRs observed have been validated by the Network Rail FMR record (Rogers and O'Breasail, 2006) which offers further details of the location and damage during events. Finally, the TSD's detailed record of incidents and delays provides a recent history of the frequency of track alerts and delays but there are significant differences with the PSA. This section has provided a fragmented record of incidents, damages, delays, etc. Nonetheless, they can be used to demonstrate the past (empirical) vulnerability of the line. Unfortunately, the different reporting standards used in each archive inhibit them from being combined. However, due to the detail and length the PSA's record of DLRs offers it the best empirical baseline to compare with changes in mean sea level (MSL) over the last one and a half centuries.

5.4 A semi-empirical relationship of rail problems and sea-level change

Using empirical data to model the future is an approach that has been used in sea-level studies in recent years. Rahmstorf (2007a) presented a method of projecting sea-level rise based on a linear relationship observed between global mean surface temperature and the rate of global mean sea-level change. He argued that, at present, a poor understanding of the processes and dynamics involved in global sea-level change (e.g., thermal expansion and ice melt contributions) limit the capability of physics based models to calculate future scenarios, or even replicate recent sea-level rise. A semi-empirical approach, therefore, provided a pragmatic alternative to complex process-based models of future predictions. The numerous parameters that influence overtopping of defence structures on the track (e.g., wave processes, hydraulic processes, geometric designs and structure types etc.) are complex and difficult to model accurately, particularly over long time scales. Furthermore, the majority of engineering and computer modelling methods (e.g., EurOtop, 2008) produce estimates of overtopping discharge and velocities (e.g., O'Breasail et al., 2007) and would require further analysis to relate these outputs directly to the impacts on the traffic (e.g., service disruption). In this study, the assumed physical driver of change in overtopping and DLRs is sea level, and a relationship between the two is sought. Firstly, an empirical relationship is explored using observed changes in MSL and the PSA records of line restrictions.

Records of MSL were smoothed by calculating central moving averages over twenty year periods (in alignment with the lunar nodal cycle, see Chapter Three also). Smoothing the data set removes the fluctuations of annual sea-level change but allows a clearer trend of MSL to be observed, analysed and compared. Only periods with continuous MSL observations were used from the Brest (1861-2009) and Newlyn (1916-2009) tide-gauges records. To enable a continuous comparison, the PSA data were adjusted to show a continuous yearly record of restrictions (see Chapter Three). The two data sets have been plotted individually first, and observing the individual trend of the records identifies some initial correlations (Figure 5.11). Over the railway's life span there has been around 0.20 m of sea-level rise in the English Channel, and nearly half of this has occurred in the last 40 years. Similarly, the highest numbers of restrictions recorded have been in the last three decades (see previous sections). Since the 1970s both water levels and the number of DLRs per year have risen simultaneously.

The continuous record of total DLRs (from Figure 5.11) was recalculated to establish an average number of DLRs for each year. This was then plotted against the averages of MSL change in the English Channel (Figure 5.12). DLRs were compared with the Brest tide gauge up until 1916, and from then onwards the Newlyn tide gauge is used as it represents a more continuous and proximal record for correlation[5]. The results show two distinct periods, the first corresponds with the period between 1860 and 1964 and shows a fluctuating relationship with no clear trend between the variables. Periods with high numbers of line restrictions are associated with lower sea levels, and vice versa, and this lasted nearly a century. The extent to which sea level affects the trend of average DLRs is minimal in this period and the residuals show an almost downward trend, thus, sea level change has not been the dominant influence affecting incidents. During this time, more influential factors could have been periods of higher storm intensity or, more dominant, human intervention (e.g., hard engineering and defence improvements).

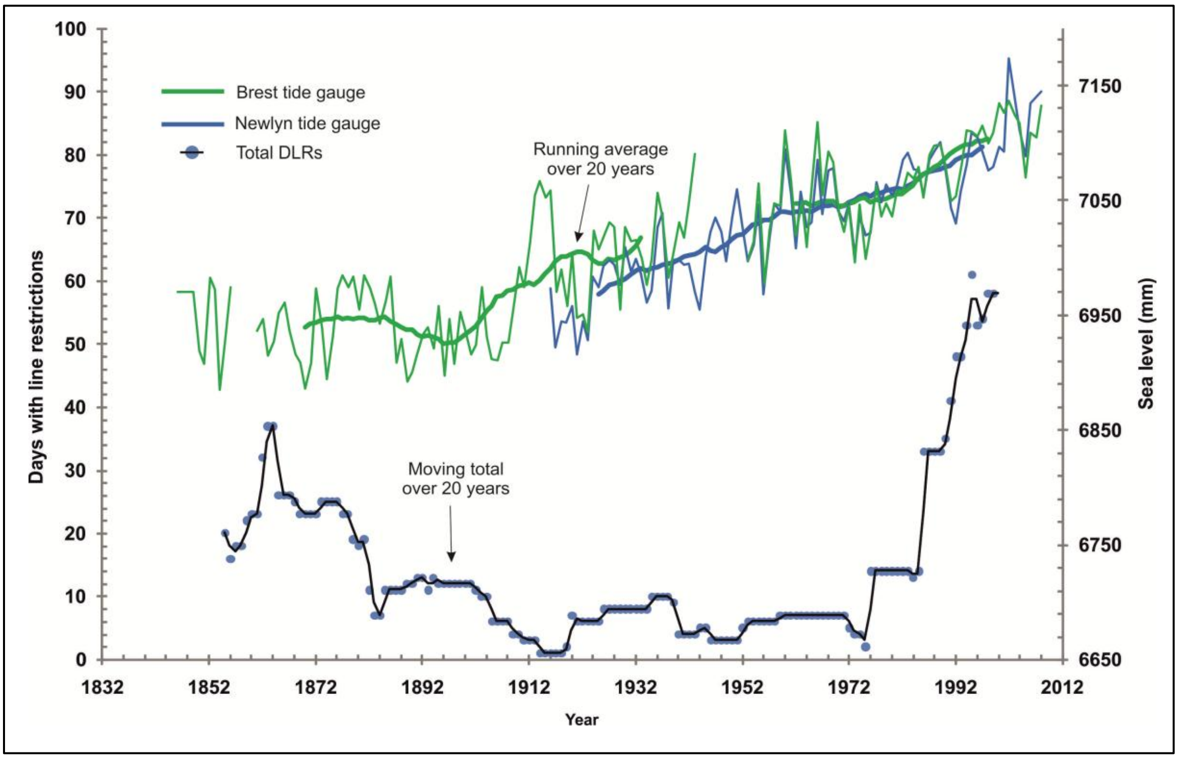

Figure 5.11 English Channel sea-level observations from tide gauges, including smoothened running average and compared with days of line restrictions (DLR) from the PSA. DLRs presented as smoothened running totals for 20 year periods.

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[5] By using an all Brest tidal input the difference to the relationship observed is minimal.

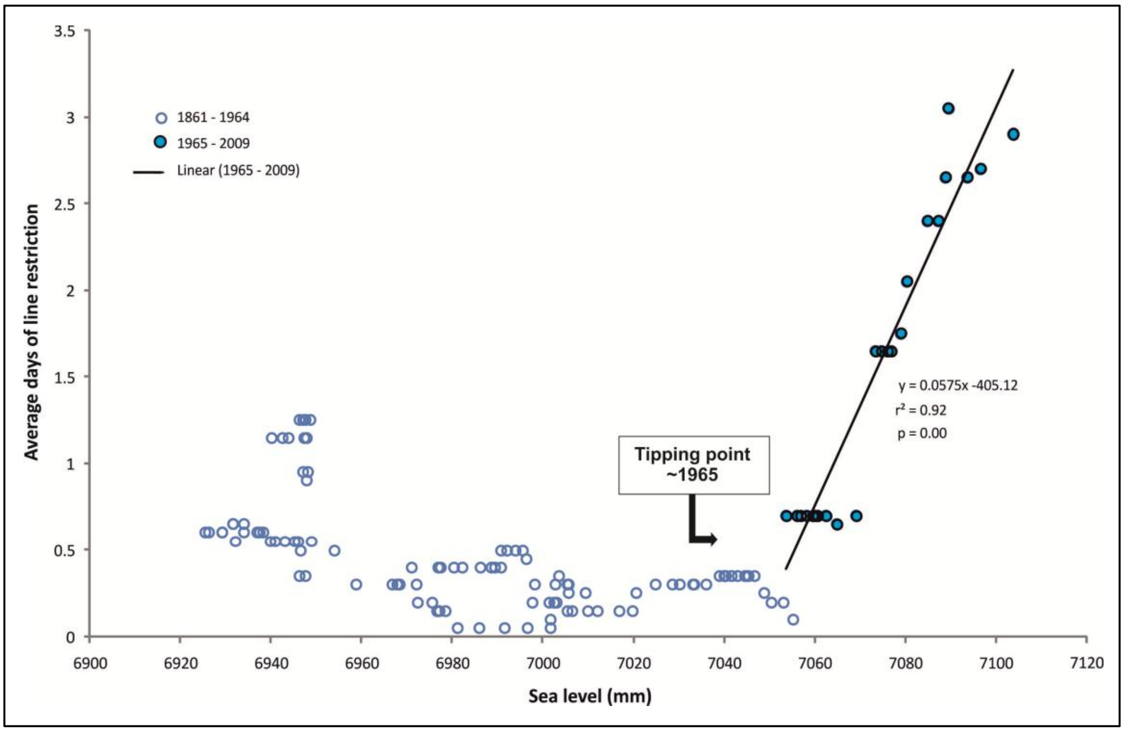


Figure 5.12 Correlation of annual mean sea level (MSL) taken from the English Channel (smoothed 20 year averages) and average days of line restriction (DLRs) per year (average incidents over 20 year periods). A clear tipping point can is identified, in which, rising sea levels have a positive effect on average days with line restrictions recorded from ~1965 – 2009. The linear trend (y = 0.0575x -405.12) can be used to estimate future averages of DLRs/yr. Data taken from the *Published Sources Archive* (PSA) and Newlyn and Brest tide-gauge records (courtesy of NOL).

A clear inflection (or tipping point) is seen in the records after the mid 1960s (when sea level had reached 7050mm), since then the influence of the recent high frequency of DLRs is apparent. The trend between average line restrictions per year and MSL post 1965 is clearly positive, linear (r^2 = 0.92) and significant (p = 0.000 at 95% confidence limit). At present, average sea level is around 7100mm (based on smoothened trends) and the average DLR (from the PSA) is estimated to be around three days per year. The correlation suggests that a 0.04m rise in water level nearly doubled the average DLRs per year from 1964-2009. This apparent inflection point could be explained by a number of factors. For instance, the early 1970s were recorded as being a time of higher than average wind speeds in south Devon (Burt and Horton, 2001) and Zong and Tooley (2003) describe positive NAO indexes (associated with more storminess) around this period also. Perhaps the most indisputable factor is that the height of the water level today is closer to the crest of the defences than has ever been recorded. Consequently, the most conceivable explanation for the trigger point is that the rise in water levels over the last century and a half have significantly reduced the available freeboard along the sea wall (i.e. height of the crest of the defences above the water level). This has in turn allowed more frequent overtopping that has caused increased DLRs to be observed.

It must be acknowledged, however, that multiple factors, including non-climatic impacts, could have influenced this apparent trend (occurring simultaneously). For instance, changes in management approaches and expenditure on the defences during the 20th century may have resulted in an increased vulnerability to overtopping. A review of the UK coastal management practice during the 20th century, indeed, highlights a reduction in hard engineered approaches during the 1970s (and onwards) as environmental concerns increased and softer approaches became favourable (French, 2004). This national trend may not be relevant on a local scale, however, and unfortunately details of the long-term annual expenditure on the defences at Dawlish were not obtainable to test this further.

Although engineering intervention cannot be completely accounted for, the FMR's problem history (Figures 5.6 & 5.8) provides some evidence of maintenance developments on the line. Indeed, after extensive improvements on the track during the early 20th century little or no repairs are recorded during the 1960s and 70s, and historians believe (Kay, 1993) the defence improvements were successful as no damages were reported (see section 5.3.2). Further trends of external factors (other than sea-level rise) have been examined and offer some extra confidence in the assumed sea-level influence on overtopping, a fuller discussion of this is given in section 5.3. In addition to this, it could also be argued that using trends from journalistic records is not conclusive or reliable. For example, trends could be more representative of current public concerns, and the inflection could be a result of the rising climate change debate in the last few decades. But the apparent correlation between the PSA trends and the FMR trends (described in section 5.3.4) would suggest that the history is reliable. On the basis of these points, there is a strong argument that the relationship is indeed significant, and that the last few decades indicate a reliable baseline of what is likely to continue for the remainder of the century. It must be acknowledged, however, that multiple factors (including human influences) could have influenced this apparent trend but are not accounted for in this study.

Assuming the linear relationship between sea-level change and DLR frequency from 1964-2009 (Figure 5.12) will continue, the trends can be extrapolated with the accelerated projections of 21st century sea-level rise. Similar to Rahmstorf's (2007) method, the use of an empirical based model circumvents the complex, and poorly understood process models (e.g., wave set up, sea defence characteristics, sea-level changes etc.) needed to calculate the principle responses of sea-level change. In accepting this baseline, however, the issues of the data set discussed must be acknowledged and other potential drivers of overtopping, such as non-climatic changes (e.g. coastal management practice and expenditure on the defences), are assumed to be less dominant.

Averages of water levels and line restrictions are used in the analysis to allow direct extrapolation with future sea-level projections. However, the predictive capacity of the model cannot be directly validated against the recent observations (TSD) due to the difference in units (average and actual events). The semi-empirical approach adopted by Rahmstorf (2007a) was critiqued by Holgate et al., (2007) and Schmith et al., (2007). One of the issues raised regarded the possibility of 'nonsense correlations', that is, real correlations that do not have causal basis (Schmith et al., 2007). This can never be ruled out, but similar to Rahmstorf (2007a), the starting point of this analysis was the physical reasoning that sea-level rise should have an effect on the frequency of overtopping and consequent line restrictions (i.e. reducing the available freeboard). The analysis shows that the data from the past 50 years is consistent with this expectation and is statistically significant.

In the last 13 years, however, the PSA identified up to 70% fewer line disruptions in comparison to dates recorded by the TSD. Again, a difference between the reporting standards of the different data sets. Network Rail's new Adverse Weather Protocol (Network Rail, 2009) and the RSSB's climate change report (O'Breasail et al., 2007) both state that the current frequency of incidents is ~ 9 per year. Yet the PSA estimates averages of around three per year. Extrapolating the trend just from the PSA alone would consequently lead to estimates that under predicted the future frequency of DLRs. For accuracy, therefore, the model should be calibrated to present day averages. The period from 1997-2009 has been used to compare the DLR model's output with total averages calculated from Network Rail's service observations (TSD – Table 5.5). Table 5.6 presents the calibration of the DLR model estimates for the present day (2010).

Average MSL (mm)	Predicted average/yr (PSA)*	Average observations/yr (TSD)	Obs./pred.
7115	4.0	9.5	2.4

Table 5.6 Comparison of model outputs (Figure 5.12) and observations for 1997-2009. Present day average mean sea level (MSL) has been calculated from observations from 1997-2009 courtesy of NOC. Average observations of days with line restriction (DLR) for the same period are taken from Network Rail's *TRUST Service Data* (TSD) from 1997-2009. * The empirical trends from *the Published Sources Archive* (PSA), using the formula: $y = (0.0575x) - 405.12$ (where $x = 7115$mm), underestimate the annual average DLRs from observations. Based on this difference an adjustment of 2.4 can be added to the PSA's formula to improve the accuracy of projections.

A sea-level height of 7115mm was used in model calculations to represent the present day water level and, for consistency, is an average of tide-gauge observations from 1997-2009. The DLR model calculates an average of four line restrictions per year in comparison to the TSD's 9.5. By simply adjusting the DLR model to fit the observations (by 2.4) the outputs are more consistent with recent service data (TSD). Table 5.7 presents a comparison of model outputs and observations of line restrictions from the TSD. With the adjustment (from Table 5.6 above) estimates compare well with observations. Overall, the (adjusted) empirical trends offer a good baseline to illustrate the predicted increase in traffic restrictions on the Southwest's mainline during the remainder of this century. A linear trend from over 40 years of observations, calibrated to more recent service observations, can be used to estimate the future average DLRs per year by extrapolating it with current predictions of sea-level rise from UKCP09 (Lowe et al., 2008).

Restriction type	MSL (mm)	Observations (from TSD)	Modelled predictions*	Calibrated model predictions**
Level 1	7115	5.4	2.2	5.2
Level 2	7115	3.8	1.5	3.6
Level 3	7115	0.3	0.1	0.3
All	**7115**	**9.5**	**4.0**	**9.5**

Table 5.7 Comparison of modelled and observed days with line restriction (DLR). Mean sea level (MSL) from Newlyn tide-gauge station (average from 1997-2009) courtesy of NOC. Track observations taken from Network Rail's *TRUST service data* (TSD) from 1997-2009. * calculated based on the equation y = (0.0575x) - 405.12. ** calculated based on the same equation with a multiplier of 2.4 (see Table 5.6).

5.5 The future of the Dawlish to Teignmouth railway line

Sea-level predictions for a 25 km grid (25727), covering the entire section of railway, have been corrected for an error of 0.16 mm/yr (Tables 4.6), and the empirical trends outlined in the previous section have been extrapolated with sea-level estimates for the 21st century (Lowe et al., 2008). In order to do this, present day sea level was set at 7115 mm (based on the 1997-2009 average), and units were converted from millimetres (as in the observations) to centimetres (as provided in the projections.

Figure 5.13 presents the results of this procedure. The empirical-based model suggests that a 0.05 m rise in sea level will increase average line restrictions by 7 per year, and this trend can be directly compared with current sea-level estimates (in metres from 2010). Figure 5.14 and Table 5.8 present the future running restrictions on the railway based on low-high scenarios of sea-level rise. Each DLR represents a day when Network Rail may be obliged to impose traffic alerts due to overtopping of the defences. Based on the empirical evidence (from the PSA and FMR), however, it could be suggested that some level of structured damage will occur simultaneously (see section 5.3.4). It is estimated that a 0.047 - 0.069 m rise in water level will have occurred by 2020, and this will double the average DLRs resulting in 16-19 restrictions per year. Looking at the archive of events, the average predicted restrictions from 2020 are synonymous with those actually observed during 2006.

By 2060, 0.27 - 0.39 m of sea-level rise will cause 46-63 DLRs a year, and by the end of the 21st century it is estimated that 84-120 DLRs will occur every year (0.55 - 0.81 m). This is more than five times the maximum annual DLRs recorded in the archives (e.g., 2000 and 2002). Based on the observations of restrictions recorded by the TRUST service system (in the TSD archive, see Table 5.5), the total estimated DLRs can be divided (by the ratio of occurrence during 1997-2009) to indicate the likely track restrictions during the 21st century. This assumes no change in the ratio of restrictions over the 21st century and the results are presented in Table 5.8. Current observations indicate that an average of up to five Level 1 alerts occur per year, four Level 2s, and Level 3 alerts have occurred once every four to five years

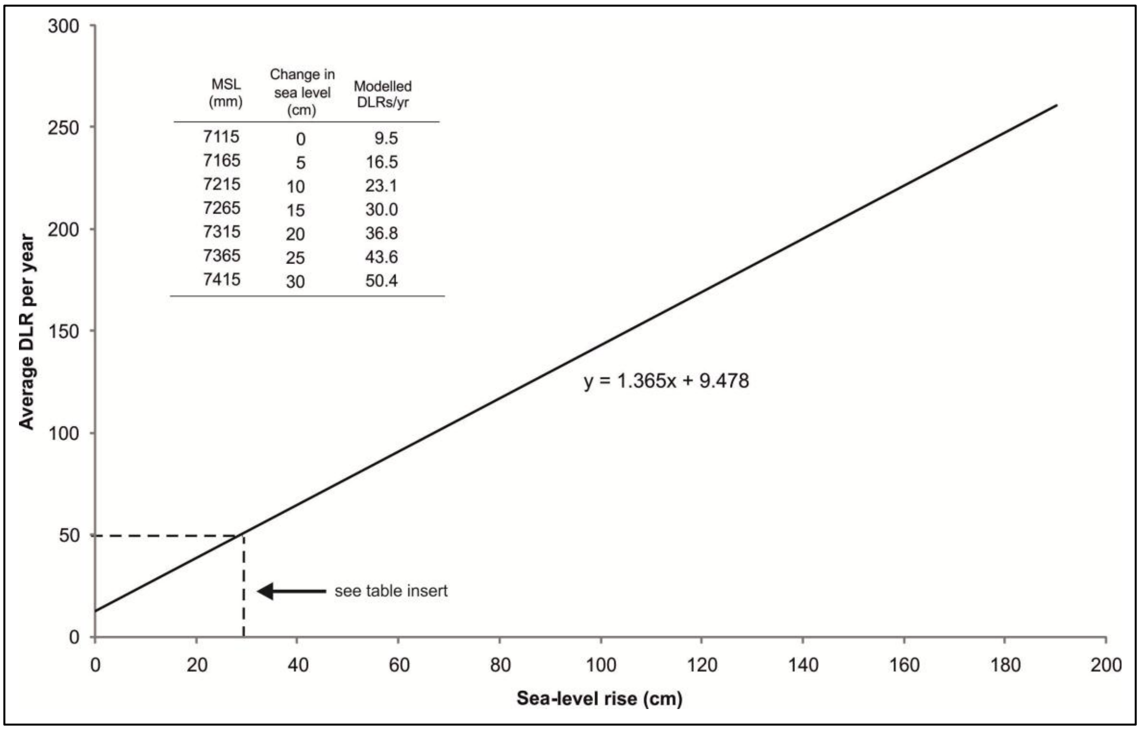


Figure 5.13 Converting the empirical trend line (y = 0.05x -405, Figure 5.12) to account for changes in sea level from present. This is required in order to align days with line restriction (DLR) with UKCP09's marine estimates (Lowe et al., 2009). In plotting the estimated DLRs against a rise in sea level (see nested table also) a trend line is established (y = 1.4x + 9.5). Also see Appendix C – 1.4.

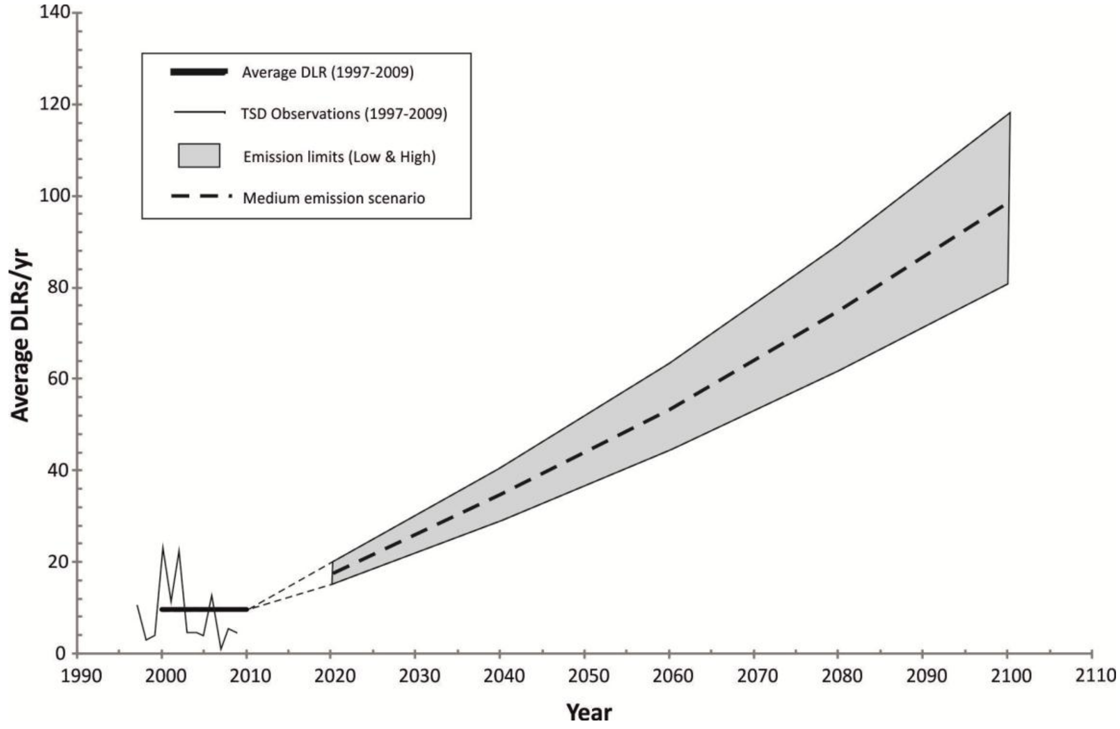


Figure 5.14 Projections of days with line restrictions (DLRs) for the Dawlish-Teignmouth section of railway line. Projections are based on the empirical model presented in Figure 5.12 and 5.13, adjusted to recent service observations (TSD), and sea-level projections from UKCP09 corrected for an underestimate of vertical land movement. See Table 5.8 also. Calculations are presented Appendix C – 1.4.

Year	*Sea-level rise (cm)**	*Average days with line restrictions***	Level 1	Level 2	Level 3
1997-2009	-	*9.6*	5.4	3.8	0.3
	Low Emissions				
2020	4.7	16	8.4	7.2	0.5
2040	15.1	30	16.0	13.6	0.9
2060	26.8	46	24.4	20.7	1.4
2080	40.0	64	34.0	28.8	1.9
2100	54.5	84	44.5	37.7	2.5
	Medium Emissions				
2020	5.7	17	9.1	7.8	0.5
2040	18.3	34	18.3	15.5	1.0
2060	32.6	54	28.6	24.3	1.6
2080	48.6	76	40.2	34.1	2.3
2100	66.4	100	53.1	45.1	3.0
	High Emissions				
2020	6.8	19	9.9	8.4	0.6
2040	22.0	40	20.9	17.8	1.2
2060	39.3	63	33.5	28.4	1.9
2080	58.9	90	47.6	40.4	2.7
2100	80.6	120	63.3	53.8	3.6

Table 5.8 Predicted sea-level rise and rail problems for the 21st century. *Sea-level predictions for the Dawlish area (relative to the present day 2010) and corrected for a 0.3mm/yr underestimate of vertical land movement. ** Predictions of rail disruption (relative to 2010), based on the empirical relationship identified in Figure 5.13 table insert (equation: $y = 1.4x + 9.5$).

The results for high sea-level estimates suggest that by 2020, Level 1 restrictions will occur, on average, 10 times a year, Level 2 alerts will occur 8.4 times a year and Level 3 alerts will occur once every two years. By 2060, around 34 speed restrictions and 28 down line closures will be imposed yearly, whilst Level 3 alerts (total line closures) are estimated to occur twice a year. By the end of the century, however, line closures will occur around 3.6 times a year and Level 2 and 1 alert will occur over 53-63 times respectively. Figure 5.15 illustrates the average estimated increase of traffic restrictions during the 21st century (for high emissions). The frequency of Level 2 alerts are predicted to increase more than Level 1 and 3 events, and our model suggests that by 2020 closures of the down line (Level 2) will increase by over 120% from the present day, and over 1300% by 2100.

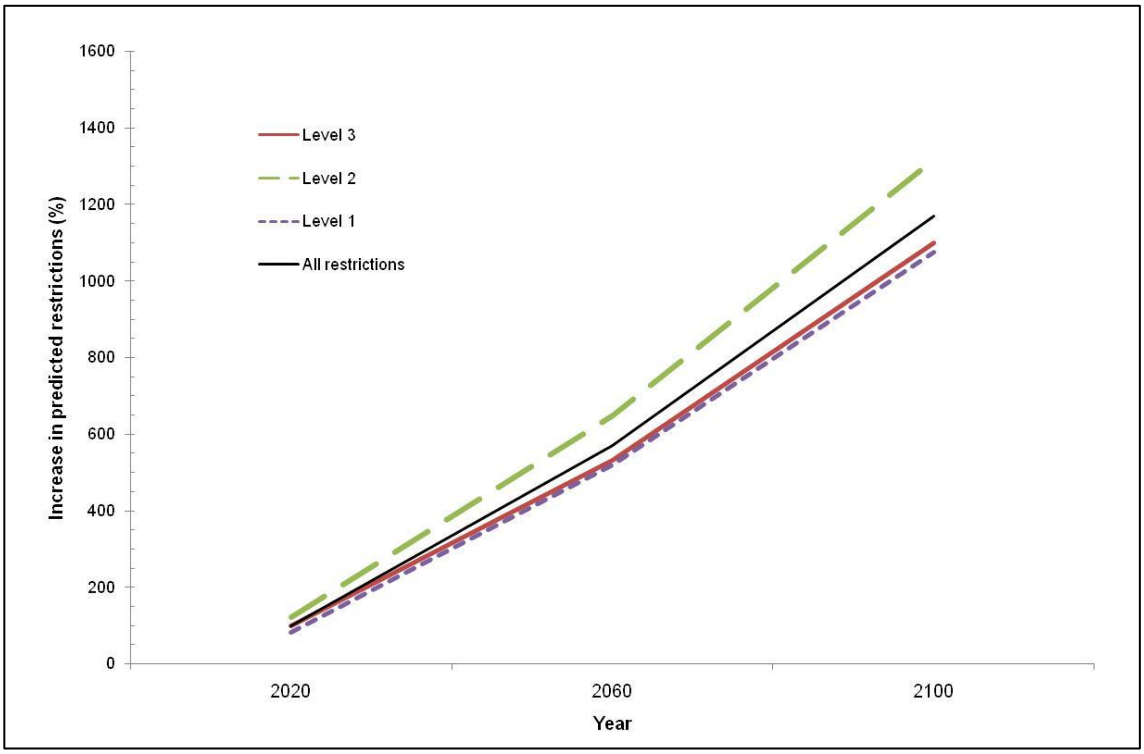


Figure 5.15 Predicted increase in emergency restrictions in the 21st Century. Based on the new empirical model, present day averages calculated from 1997-2009 service observations and assuming the high emissions sea-level estimate.

By assuming that all restrictions recorded in the PSA have coincided with damage to the defences, the severity of impacts summarised in Table 5.3 can be linked to the increased frequency of events. Impacts recorded as high to severe, and associated with Level 3 incidents, for example, will increase in likelihood by nearly 100% in the next ten years. This could involve multiple breaches, undermining and subsidence to the track with extensive damage to footpaths and offshore breakwaters. By 2060, high impact damage may occur twice a year, and when analysing the historical impacts of Level 3 events, the likelihood that the railway will be able to withstand up to two high impact events every year is questionable. One may argue that, from 2060 onwards, even one of these events in this period could close the line for a considerable length of time. Lowe et al. (2009) provide an additional marine scenario however. The high impact low probability scenario

(H++) project sea-level rise of +1.9 m. The estimates of DLRs associated with UKCP09's H++ scenario are given in Table 5.9.

Extreme sea-level rise (cm)	***Average DLRs/yr***	***Level 1***	***Level 2***	***Level 3***
90	132	70.1	59.6	4.0
110	160	84.6	71.8	4.8
130	187	99.1	84.1	5.6
150	214	113.5	96.4	6.4
170	242	128.0	108.7	7.2
190	269	142.5	121.0	8.1

Table 5.9 Estimated days of restricted line running based on H++ scenarios of the 21st century based on the empirical relationship identified in Figure 5.12.

The model predicts that a +1.9 m rise in sea level would shut the railway as nearly 270 days of restricted running would occur each year. This equates to over 260 Level 1 and 2 alerts each year, and 8 Level 3s. This level of water would also inundate the estuary defences of railway (see Figure 5.3) further highlighting the impact of this level of sea-level rise. In observing the dates of incidents contained in the PSA and TSD archives it highlights that most the incidents occur during winter storms (September-April). The total DLRs have therefore been adjusted to show the percentage of the winter train services that will be running with some level of service restriction. Figure 5.16 presents the findings of the analysis.

During the baseline period (1997-2009), traffic restrictions caused by overtopping affected nearly 5% of the winter service. By 2060, under high carbon emissions, it is estimated that over a third of the winter will be run under restricted service. By the end of the century up to 65% of the winter could expect some level of service disruption. This highlights the level of disruption estimated by our projections and the impact of these (i.e. economic and defence costs) will be investigated in the following chapter. However, from the archive constructed in this study it is possible to estimate the average delay minutes for the 21st century based on observations (from the TSD) estimates of DLRs and level restrictions.

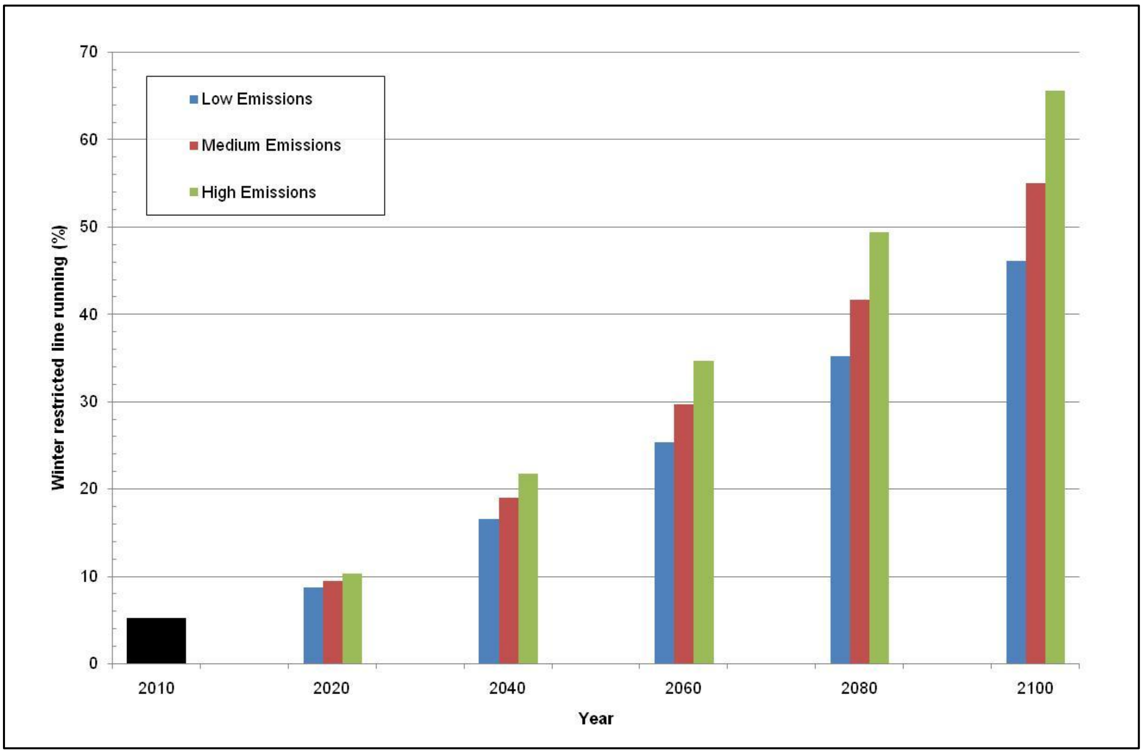
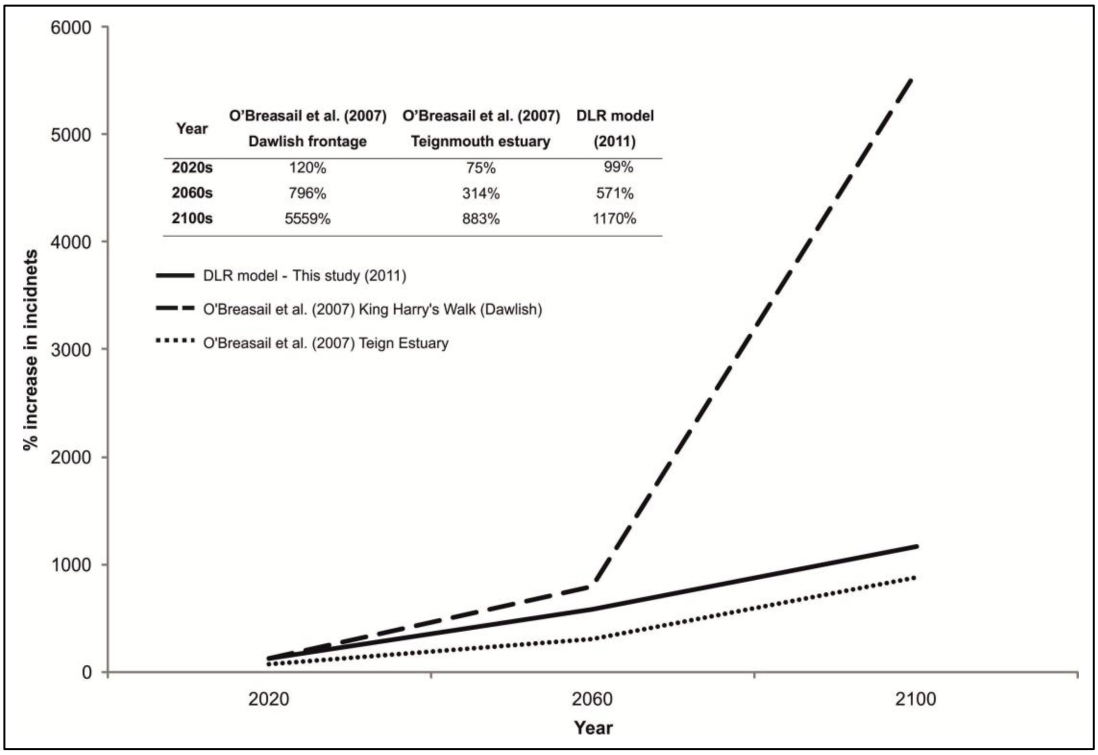


Figure 5.16 Estimates of winter restricted line running (September-April) based on three sea-level estimates (Lowe et al., 2009 – 95th percentiles) and empirical trends established in this chapter. 2010 data represent average observations from the TRUST service data (TSD) collected (1997-2009), courtesy of Network Rail.

However, as discussed in section 2.7.1 O'Breasail et al. (2007) carried out an investigation on overtopping of the track defences (for the Rail Safety Standards Board - RSSB). O'Breasail et al. (2007) used a very large numerical modelling programme to obtain their predictions based on changes in extreme water levels relative to 2006 levels. Figure 5.17 presents some of their findings for predicted overtopping under high sea-level estimates at King Harry's Walk and the Teign estuary (see Figure 1.1 for locations), and are compared with the empirical-based predictions from this study. O'Breasail et al. (2007) utilised the sea-level estimates from UKCIP02 (Hulme et al., 2002) which predicted higher sea levels than the subsequent UKCP09 estimates (Lowe et al., 2009). Their approach is capable of estimating the increased impact of 1 in 1 year overtopping (that would affect the operation of the line) and 1 in 100 year overtopping (that would impact the structural integrity of the defences). Results between the two levels are similar at both sites.



Year	O'Breasail et al. (2007) Dawlish frontage	O'Breasail et al. (2007) Teignmouth estuary	DLR model (2011)
2020s	120%	75%	99%
2060s	796%	314%	571%
2100s	5559%	883%	1170%

Figure 5.17 Comparison of predicted increases in incidents from this study and the predicted increase in 1 in 1 year overtopping by the Rail Safety Standards Board (O'Breasail et al., 2007). Estimates from this study used land movement corrected high emission scenarios of sea-level rise (adapted from Lowe at al., 2009). O'Breasail et al., (2007) use high sea-level estimates from UKCIP02 (Hulme et al., 2002). There are other differences also (see discussion in text).

In comparison with the empirical-based projections (e.g., percentage increase in total days with line restrictions) from this study, the results are well constrained with the RSSB's projections adding a level of credibility to our projections. After 2060, however, O'Breasail et al.'s (2007) model estimates considerably more overtopping at King Harry's Walk (see Figure 1.1) in comparison to this study (and their estuarine estimates), and this highlights an important consideration. The elevations of the defence structures along the Dawlish-Teignmouth frontage vary considerably from estuary (Exe) to estuary (Teign).

Figure 1.1 (Chapter One) and Figure 5.3 (this chapter) illustrate that the crest height of the King's Walk section (4.82 m OD) is lower than other sections of the coastal frontage by almost a metre making the lower section is clearly more vulnerable to overtopping than other areas of the coastal frontage (and estuary sections). The potential, therefore, for non-linear trends of future overtopping on the more vulnerable sections of the coastal defence structures are not reflected in our estimates. The estimates from this study, however, are based on documentary evidence of overtopping over the entire frontage, and do not share the spatial resolution of more sophisticated model approaches (see Chapter Three for more discussion). O'Breasail et al. (2007) also provide estimates of traffic restrictions (e.g., level 1-3) and these can be compared with the outputs from this study also (Table 5.10).

	Present		2020		2080	
Alert Response	RSSB (2007)*	TSD (2010)**	RSSB model (2007)	DLR model (2010)	RSSB model (2007)	DLR model (2010)
Level 1	5.8	5.8	n/a	8.8	n/a	40.7
Level 2	1.2	3.4	1.3	7.4	2	34.5
Level 3	0.25	0.3	0.28	0.5	1	2.3

Table 5.10 Comparison of predicted annual events per year. * Present day predictions based on rail data from (2000-2005) used in RSSB study (O'Breasail et al., 2007).** Annual averages from service data (1997-2009) used in this study. Estimates from this study used land movement corrected medium emission scenarios of sea-level rise. O'Breasail et al. (2007) use estimates from the Met Office model W5B-029/TR (e.g., Hume et al., 2002).

Again there are some large differences between projections from this study. This time, however, the empirical approach produces considerably higher traffic restrictions than the method used by O'Breasail et al. (2007). They used observations of weather data and predicted tidal levels to establish trends of closure based on Network Rail's trigger levels (see Table 5.1). The weather data collected in this chapter (section 5.2) highlighted that events have occurred below Network Rail's pre-judged trigger levels. This could explain the low estimates projected by the RSSB study. What is not clear from their conclusions, however, is how a 5000% increase in overtopping (that are stated to have an impact on the track services and the structures) predicted at Dawlish can result in just two level 2 events per year. Furthermore, the RSSB report gives no further consideration of the impacts of sea-level rise on the railway line. The average DLRs projected from this study, however, can be directly related to impacts on the traffic services (based on empirical trends calibrated by service observations). As presented in section 5.3.3, the TSD also gave average delay minutes per year on the line (Table 5.5) and these are an indication of the level of disruption during incidents. By using the percentage increases in expected incidents (e.g., Figure 5.15) increases in average annual delay minutes (due to overtopping) can be projected for the next century. Table 5.11 presents the results.

Year	***Level 1***	***Level 2***	***Level 3***	***Total delay minutes***
2020	1,889	4,508	1,740	8,198
2060	6,398	15,238	5,507	27,114
2100	12,126	28,886	10,440	51,432
H^{++}190	-	-	-	110,283

Table 5.11 Average delay minutes per year predicted from increases in emergency speed restrictions in the 21st century, based on high emission sea-level rise estimates and the empirical model trends.

As the results are averages, they are not indicative of the range of minutes recorded year to year, which can be considerably large (see Table 5.5). Nonetheless, they do indicate changing trends and according to the high emission scenario the total average delay minutes are predicted to reach over 50,000 a year by 2100. These minutes represent the time Network Rail would be expected to compensate train operating companies (TOCs) for not providing time-tabled train paths, and this information is valuable for indicating possible future costs to the company. The projections in this chapter will be used as the basis for estimating the socio-economic impacts (e.g., costs) of increased rail closure in the next chapter (Six). Overall, it is hoped this information will enable strategic decisions to begin and evolve into an effective strategy for the future of regions transport network.

5.6. Chapter synopsis.

This chapter began by presenting three separate accounts of rail histories (Published Sources Archive, Frontage Management Report and TRUST Service Data). The history established from the PSA contained a 160 year record of overtopping and impacts to traffic in the form of known days with line restrictions (DLRs). The FMR (Rogers and O’Breasail, 2006) contained a 150 year history of maintenance intervention along the defence structures and the TSD contained a recent decadal record of track delay minutes and detailed passenger impacts. The two most extensive accounts (PSA and FMR) showed a similar pattern of incident frequency over the last 150 years, and indicate a level of reliability in the long-term trends observed. Tide-gauge observations show that there has been ~ 0.20 m of sea-level rise since the railway opened, however, nearly half of this occurred in the last 40 years. Similarly, both the long-term rail histories show that the most extensive period of disruption and damage occurred in the last 40 years. The rail history was also compared with storminess on the south coast (Zong and Tooley, 2003) and overall rates of sea-level change (Woodworth et al., 2009b), and both support the recent increase in incidents. As the long-term predictability of storms is limited, the influence of mean sea level (MSL) on the line offered the potential for a more reliable statistical comparison.

A more detailed investigation of past line restrictions and changes in MSL was conducted and the results suggest that - after an initial period when changes in sea level had a minimal effect on the frequency of DLRs – a tipping point occurred. After which, a clear, positive and linear relationship was identified between increases in MSL and observed line restrictions at Dawlish. One interpretation of this is that, previous to the inflection point, the frequency of line restrictions was influenced less by MSL and more by other factors such as periods of storminess and maintenance intervention (e.g., new defence structures).

By the 1970s, however, the increasing water level reduced the available freeboard of the defences enough to significantly affect the frequency of overtopping and line restrictions. Since then sea levels have risen continuously, and this trend is mirrored in the observation of DLRs. The influence of the maintenance regime on the 20th century trends is not fully considered, but confidence of the trend is improved using observations of trends from several sources. The empirical based trend between MSL and DLRs taken from 1965-2009 has been used as a baseline relationship between sea level and rail events. The smoothing of both data sets (over a full lunar cycle) however, unfortunately means that modelled predictions cannot be directly validated against recent observations (from the TSD). But the trend was calibrated with recent observations of emergency traffic alerts from the TRUST system (or TSD) in order to give a more accurate representation of baseline incidents.

The relationship from 1965-2009 was extrapolated with UKCP09 (Lowe et al., 2009) sea-level scenarios (corrected for an underestimate of GIA by up to 0.16 mm/yr). The results from the analysis show that by 2060, up to 35% of the winter period will be run with emergency speed restrictions (ESRs - level 1 to 3). This corresponds to an average of two level 3s (total line closures) a year, and up to 530% increase from the present day averages. Based on the empirical evidence collected these events could correspond with high to severe impacts to the defences and significant impact to the rail traffic. For example, Class 2 services could be cancelled up to 30 days a year and passengers would be severely affected. Substantially more delay minutes and penalty charges to Network Rail are associated with these impacts (discussed further in Chapter Six). However, based on the crest heights of the current defences (O'Breasail et al., 2007), the region's estuary and branch lines are at a much greater risk from sea-level rise and are likely to cut off from the network during storms by 2080.

The H++ scenarios suggest water levels of up to 1-2 m higher than at present, however, and if this occurred it would effectively cut the railway off along the Exe and Teign Estuary sections. The empirical based investigation has shown clear indications that trigger points have occurred in the past. The next tipping point could regard the line's safety or expense to run, and discussions on the future are currently impeded by a lack of long-term information. Presented in this chapter is information that will help in addressing this problem as the expected restrictions to traffic and extent of sea-level rise can be clearly seen. Although other projections are available on the line (e.g., O'Breasail et al., 2007) they do not consider the wider implications to region (i.e. to traffic and the economy). Furthermore, they utilise older sea-level projections and rely on the projection of extreme water levels (caused by storms) and the predicted return period of them. This chapter has presented a simpler empirical approach that correlates incidents directly with mean sea level change and by incorporating other sources (e.g., TSD) can identify the effects to rail users. This offers more meaningful projections for policy makers.

Climate change is not the only threat however. Large cuts are expected as a consequence of the economic problems of 2010 and there are increased fears for the funding of planned improvements to the Southwest's transport infrastructure (BBC News, 18/05/10). Addressing the future vulnerability of the railway has never been more pressing. A reactionary, or business-as-usual, approach to managing the coastline will be costly and unsustainable for the rail companies and the regions socio-economic functioning. The next chapter will utilise these data further to look at the costs and socio-economic impacts implied in these projections but also, and importantly, it will present the integration of socio-economic futures to further elaborate future scenarios of rail problems in the region.

Chapter 6

Costing the impacts of future line closure

6.1 Introduction

Climate change is considered an issue of global concern and debate, particularly when it comes to the impacts on the economy. In recent years there have been numerous large scale analyses of the possible damage and implications of climate change to global socio-economic functioning (e.g., The Stern Review, 2007; Meehl et al., 2007). Less discussion, however, is given to the effects of climate change and the transport sector (Koetse and Rietveld, 2009). This is unexpected considering that transport's functioning plays a critical role in economic and social networks (SACTRA, 1999, OEDC, 2002, Eddington, 2006) and its breakdown can lead to a series of chain reactions in multiple sectors (Murray et al., 2008; ICE, 2009a; Koetse and Rietveld, 2009). Furthermore, by its nature transport infrastructure is almost always exposed to weather and climate. It is estimated, for example, that present-day adverse weather conditions (temperature, rain, sea level) cause 20% of all unplanned delays on the rail network (Thornes and Davis, 2002; Eddowes et al., 2002; Dobney et al., 2009). Despite this, few examples consider the impacts of these delays or the impact of future socio-economic changes on flood risk, and this is a growing issue for effective policy making.

In the last chapter, the empirically-based predictions of future rail impedance under various increases in mean sea level (MSL) were presented. By 2100, it is predicted that up to 65% of the winter service (33% of the entire year) could be run under with some level of traffic restrictions (e.g., level 1-3). The expected days with line restrictions (DLRs) and increased delay minutes projected can be used to illustrate the associated future impacts as direct costs (to the rail industry) and indirect costs (to the Southwest economy). However, before this is discussed further the historical newspaper archives gathered – in conjunction with quantifying an empirical record of incidents – also documented various views and events on the railway line. These accounts are important as they provide some of the broader social-political context of the empirical history of the line.

6.1.1 A century and a half of regional rail problems

In previous years problems of the sea wall were tackled with the used of additional lines. For instance, from 1903-1958 the Teign Valley line was used as a diversionary route until 1958 when the Southern Railway line (Okehampton-Bere Alston) took over. This line was closed in 1968, however, and since then the only diversionary route during floods and closures is via road and cause significant inconvenience to rail users (see Table 5.4). Not surprisingly, this has prompted public and political calls for a complete re-route. Recent arguments for re-routing the line are not unique to the 21st century, or even the 20th century however. Evidence from the *Published Sources Archives* (PSA), although often entertaining, highlight that the discussion on the line’s future is far from contemporary:

> *The whole property is not worth a shilling if evil be not cured', Stephen Matterface (Dawlish Orator) said that this is the first of 3 degrees 'this' he said to James the Blacksmith 'is Neptune's youngest son; next he will send the eldest; and if that won't do, next time he will come himself and sweep them all away. As a main trunk line between London and Land's End it is utterly preposterous, and is now so considered by every man between those termini’.* (*The Times,* Saturday, October 31, 1846 p 5).

Talk of building a new line began in the late 1800s and by the late 1920s – early 1930s – construction had commenced on the Dawlish Avoiding Line (DAL). However, a lack of funds (and WWII) halted the plan and the solution to the problem was postponed. The PSA and *Frontage Management Record* (FMR) both highlighted that DLRs and maintenance intervention were low during the 1930s-1950s, and this may have influenced the decision not to build an avoiding line at such a high cost. But even in 1986, after the worst event since the 1930s, discussions of re-routing the line were dismissed on the total unit cost of the procedure (The Guardian, February 28th 1986). Ten years later, in January 1996, another particularly bad event occurred and cost Railtrack an extra £220,000 (Railtrack, 1996). Once again a decision was dismissed, but contrasting views on the line remained, even within the same company:

> *Tracy Bailey, Railtrack spokesperson, commented 'It's the most beautiful bit of track in the country but, in the year we have been operating we have had to close it four times! .... Martin Reynolds Railtrack's boss said that the annual income of Great Western Railway is £30-40 million, and it makes no sense to reroute the line. (Western Morning News,* 24/1/1996).

A further ten years later the situation is little different and the views and discussions of the solutions have become as seasoned as the railway. Members of Parliament in the region have raised the issue several times. The then Conservative MP for Totnes, Antony Steen, long lobbied the call for a closure of the line and a reroute to be made on the basis that the line will one day be washed away. However, Richard Younger-Ross, a Lib Dem MP for Teignbridge Council, is against permanently closing the line, as the cost of a re-route would be phenomenal (although no estimate was given). His suggestion was the opening of previously closed routes to serve (again) as an alternative during bad storms (Clinnick, 2009). Most recently, Conservative MP Anne Marie-Morris secured a debate in Westminster Hall (Hansard, 10th November, 2010), to confirm three things:

> *A statement on the Government's behalf that it is their priority to keep the line running; confirmation that there is no plan to resurrect a debate about the alternative inland route at a cost of £100 million; and for the Minister and the Government to direct Network Rail and the Environment Agency to work together to find a way forward, putting this route and its long-term viability and infrastructure at the heart of the plan going forward* (Morris, 2010).

The under-secretary of state for transport (Norman Baker) acknowledged the importance of the railway to the regional economy, but also stated that the railway's proximity to the coast had long been its Achilles heel. Furthermore, he stated that any solution could not ignore the needs of south Devon, and although a re-route would be welcome it would not be a substitute, as this would not meet with their primary objectives. The overall stance of the state is that it falls to Network Rail to continue monitor the operational integrity of the line (Baker, 2010). Among the diverging opinions on the solution to the future of the line, the owner's perspective is clear. Network Rail's operating licence requires it to maintain and renew its infrastructure to keep the line running and their infrastructure engineers suggest that the call for re-routing is a discussion for another day (Rail, 2006).

The overall aim of this chapter is to combine socio-economic and climate scenarios in order to generate future rail scenarios for the region. In doing so, provide scientific evidence for discussions and policy debate. To achieve this, firstly, the link between transport and the economy will be evaluated in order to identify the potential costs of increased rail delays in the region. Secondly, the costs of projected incidents will be constructed for three marine projection scenarios over the 21st century (having established that the H++ scenario would leave parts of the mainline fully inundated – see Figure 5.3). Thirdly – and in order to provide more plausible futures for the region – the costs will be integrated with four socio-economic scenarios (SES). The extent to which the different socio-economic futures impact on the region, and society more broadly, will be determined and discussed. Finally the potential use of the new scenarios (or science in general) in policy making will be considered, and this aligns with the original (applied geography) debate outlined in Chapter One of this thesis.

6.2 Transport and the economy

If sea-level rise continues, during the next century the Southwest faces increased periods of time without a fully functioning main railway network. The impact of a reduced transport system on the region's economy is a vital consideration for stakeholders and decision makers. The fundamental basis of the link between transport and the economy is embedded in the history of economic development and the long-term growth of transport networks. The rail network has long been a key to growth and development, and economic historians have attempted to measure the impact of railways on cities and regions worldwide (e.g., O'Brien, 1983; Foreman-Peck, 1991; Lakshmanan, 2010). More recent literatures on the role of transport in the United Kingdom (e.g., SACTRA, 1999; OEDC, 2002; Eddington, 2006) offer resources for examining the economic benefits of transport investment. In these studies, the major benefits are commonly demonstrated through improvements in accessibility (and time and cost), reliability and network coverage. For instance, almost 47% of UK firms depend on a significant proportion of staff to commute to work (CBI, 2005) and transport reliability is therefore crucial to their performance. Freight operators also rely heavily on the reliability of the transport networks for optimum efficiency (Eddington, 2006), to which a network of other businesses will also depend on. Business is not the only sector to be affected, however, and transport also influences peoples quality of life (e.g., allowing better use of leisure time). This reflects that all journeys, not just the business-related, are important as non-work and leisure travel contribute directly to a population's 'welfare' (and in turn public spending).

Transport networks not only allow people and goods to reach destinations, but they also open up new opportunities. For example, new destinations (and business links) or new combinations of journeys, which can feed through into productivity and economic growth (Eddington, 2006), and eventually filter into the Gross Domestic Product (GDP) of a region. This impact on GDP can be felt through two channels, and the first is by improving inputs (Eddington, 2006). For example, transport networks affect employment through changing the access to labour (e.g., commuter travel) and the potential creation of new businesses, without which it may be difficult to access labour markets (i.e. skilled or un-skilled) or develop competitive links with other businesses (e.g., supply chains etc.). Both of these can impact the number of goods and services produced and lead to changes in GDP in a region. The second channel, however, involves the improvement of journey time. Reduced journey times can benefit the costs of production, for example, by assisting to lower vehicle operation costs (e.g., fuel and rolling stock etc.). This can eventually stimulate greater demand and promote effective competition even when economic activity is geographically dispersed (SACTRA, 1999). Banister and Berechman (2001) analysed the link between transport investment and economic growth in detail and suggested a further spatial aspect to the link. Nationally, for instance, well developed transport infrastructure is needed to compete on the global scale and this has a direct measurable output on annual GDP. On a regional scale, however, accessibility changes and the redistribution of employment activities between areas are key factors, and measurable outputs include spatial relocation, competitive advantage and industrial clustering. Finally, on a local level, network considerations – for example employment level, labour and productivity (time allocation) – are argued to be most affected. These can be measured directly by the growth of jobs, welfare improvements and agglomeration economies. All these benefits, to an extent, are measurable in terms of impacts on GDP and are thus discussed in most transport appraisal schemes to justify the level of investment in transport improvements (SACTRA, 1999; OEDC, 2002; Eddington, 2006; Lakshmanan, 2010).

It can be argued that new transport investment in areas with well established transport networks will not necessarily create new economic growth (SACTRA, 1999; Banister and

Berechman, 2002). Maintaining existing transport infrastructure, however, is a key component in sustaining long-term growth, promoting more, and allowing the existing economy to better adapt to structural changes (Eddington, 2006). Consequently, there are widely accepted associations between the quality of transport infrastructure and the level of economic development within regions (MacKinnon et al., 2008). From history it is evident that transport is instrumental – and a key facilitator – to the performance of the economy (O'Brien, 1983). Investment in improving it (e.g., reducing travel time, congestion, unreliability etc) can, therefore, have some level of benefit to a regions socio-economic functioning and GDP. It is logical that disinvestment or poor maintenance of existing transport infrastructure is likely to have the opposite effect on the economy (i.e. negative). Based on Banister and Berechmam's (2001) analysis, on a national level international competition could be affected or impeded, whilst on a regional scale accessibility, employment and industry are likely to be constrained and, at the local level, networks of labour, productivity and welfare could be restricted. Consequently, the closure of a fully operational railway can have considerable penalties in terms of GDP loss, and this has been shown historically (O'Brien, 1983; Lakshmanan, 2010). But how can the expected impacts of the predicted rail restrictions (from this study) be illustrated in terms of GDP loss?

Of the measurements of impacts, travel time costs are the most commonly used to assess transport changes on the economy (OEDC, 2002; Lyons, 2003; Eddington, 2006; Metz, 2008; Batley et al., 2008; Banister and Thurstain-Goodwin, 2010). Indirect costs, based on changes in travel time, are compared to the overall investment costs using cost benefit analysis (CBA), and this forms the basis of the majority of transport appraisal projects and planning strategies (e.g., Burr et al., 2008; Network Rail, 2010). In the Southwest region, for example, Network Rail analysts' suggest that improving journey time by one minute can support a maximum level of capital expenditure of £9 million (Network Rail, 2010). However, it has been argued that improved travel time savings is a contested approach (see Metz, 2008 etc.), and there are a number of benefits that are not entirely assessed by conventional measures of GDP output, for example, welfare and network effects. Tackling the broader economic impacts (e.g., network effects, agglomerations, etc.) is difficult and the models used to estimate them are conflicting and devoid of clear linking mechanisms between transport and the broader economy (Lakshmanan, 2010).

Notwithstanding these issues, the travel time approach commonly used splits transport users into four broad groups: *business travel*, *freight traffic*, *commuter travel*, and *non-work and leisure*. The first three are important because of their direct contribution to GDP, for instance, to labour markets and productivity. Non-work and leisure are also important, however, for economic welfare and tourism, retail, etc. On this basis, reducing the users' travel time is assumed to have direct impact on GDP. Conversely, and in light of what has been discussed already, it could be argued that increasing the travel time will have a similar, but negative, effect (UKCIP, 2003). Sea-level rise and overtopping will cause an increase in the frequency of line restrictions on the track that will, consequently, increase the journey time for rail users in the region. The extent to which this could affect GDP and the wider economy would be an important consideration in any future investment decision. As stated in Chapter Three, this approach to economic valuation has been utilised in UKCIP's (2003) climate costing guidelines to cost the delays caused by the flooding of Central-Busby Junction (Glasgow) in 2008. The potential increase in these extreme weather events was then explored using future probabilities of their occurrence. The same framework has been utilised in this Chapter but with the addition of the potential impacts to the rail industry. The next section presents the potential costs of projected future line restrictions.

6.3 Costing the impacts of future rail incidents

Between 2006 and 2007, 800,000 rail incidents on the UK rail network led to a total of 14 million delay minutes and an estimated minimum cost of £1 billion/yr in the time loss to passengers (Burr et al., 2008). The National Audit Office's (NAO) report on UK passenger delays states that there has been a 45% increase in the delays caused by external factors (e.g., weather, fatalities and vandalism) in the last decade (Burr et al., 2008). Each external incident caused, on average, around 45 minutes of delay, twice that of infrastructure failure and four times the costs of incidents caused by train operating companies (TOCs). The costing of external rail incidents is becoming more significant, especially with the apparent increases in extreme weather in the UK (e.g., 2010). As discussed previously, the expected increase in overtopping incidents will have implications for the Southwest's rail users and the wider economy (indirectly). However, there are also going to be significant costs directly to the infrastructure operators. Thus, in order to illustrate the full extent of future rail incidents, the impacts can be divided into direct and indirect costs. Direct costs are identified as the impacts to the infrastructure owners (Network Rail) as an immediate result of an incident and can include the costs to infrastructure (track, defences etc.), compensation costs to TOCs, and additional compensation to passengers (which is paid by the TOCs). The indirect costs, on the other hand, represent the impacts to the economy, and in this project only the travel time impacts are quantified (e.g., from the effects on rail users). Generally, quantifying the wider indirect costs would involve an additional multiplier of the rail user costs (typically of one or two), but the methods of their calculation are complex and conflicting (Lakshmanan, 2010) and have not been included in this study.

6.3.1 *Direct costs of sea-level rise*

This section is intended to present estimates of the internal costs of operating the line under the future restrictions projected. Not all costs have been accounted for as it was not possible to obtain detailed defence expenditure resulting from even the most recent events on the line. However, it is important to emphasise the potential cost of maintaining the line under future sea-level scenarios. In 1996, Railtrack published a public information leaflet on the state of the sea wall (Appendix D – 1.4) and it detailed the costs of the extreme weather in the January of that year. It stated that the inclement weather had cost the company an extra £220,000 in repairs. It was not possible to determine exactly how this cost is broken down, but by referencing the incident in the *Published Sources Archive* (PSA, from this project) more information was obtained. Only one incident was recorded in January of 1996, and it was described as a Level 3 event (The Herald Express, January 9th, 1996). Wind speeds reached over 60 knots and a residual tide height of +0.26 m was recorded bringing the tide to 5.4 m CD (or 2.2 m OD). Further archive data, cross examined (with the FMR and other news sources), reveal that the seawall was demolished in two places (Rogers and O'Breasail, 2006) and the line was running a restricted service for over two weeks (The Times, January 24th 1996). Although a significant level of detail of the incident was obtainable, the circumstances that led to this scale of incident are highly variable. Therefore, it did not seem appropriate to assume all Level 3 incidents predicted during the 21st century will be of a similar magnitude (and cost).

Nevertheless, there are costs that can be examined to give indicative estimates of the likely impacts of expected incidents. Firstly, the increase in preventative maintenance will be examined in relation to increases in average annual line incidents. The justification for this calculation was identified during a comparison between the FMR problem history (Rogers and O'Breasail, 2006) and the PSA's record of incidents (DLRs) presented in Chapter

Five. A link was found, implying that the frequency of recorded DLRs was proportional to the frequency of defence intervention (damage or repairs) in the FMR (see Figure 5.9). As mentioned, detailed and extensive records of defence expenditure were unfortunately not available to test this relationship further. However, Network Rail state that the annual maintenance cost for the defences (at Dawlish) are around £500,000[6] or ~ £65,000 per/km (for the ~7.6 km section). As this is additional to general track maintenance, this is one of the most expensive stretches of infrastructure to maintain in the country[7] (Clinnick, 2009). Thus, assuming that the costs of preventative maintenance are proportional (to a degree) to the amount of overtopping, the costs can be analysed with the predicted increase in DLRs during the 21st century[8].

The total predicted increases in DLRs (%) were, therefore, multiplied by the average annual maintenance cost for the defence structures. For accuracy, the published annual maintenance cost was converted to 2010 prices by applying the Treasury’s GDP deflator (see Appendix D - 1.1a) and is estimated to be ~ £612,000/yr (or £78,000 km/yr). Table 6.1 presents the results of the procedure (see Appendix D - 1.1b for the calculations). Based on the figures obtained, the average additional expenditure on maintaining the defences from 1997 - 2009 was £0.5 million per year (or £0.61 million in 2010). By 2020, 5-7 cm of sea-level rise is expected to increase the predicted DLRs by 69 - 99%, and Network Rail could see annual defence costs of £1.0 - £1.2 million a year. During the second half of the century sea levels are predicted to increase by over a third of a metre, the extent to which will cause between 389% – 571% more DLRs than present. The cost of these increases on annual maintenance is estimated to reach from £3.0 - £4.2 million per annum. By the end of the century, however, the costs are in the range of £5.5 - £7.9 million per annum as

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[6] This figure was obtained directly from Network Rail, however, it has been quoted in numerous news reports since 1996 (Railtrack, 1996 (Appendix D -1.4), Clinnick, 2009).

[7] Maintenance on an average stretch of track is estimated around £62,000-£94,000 km/yr

[8] Detailed records of expenditure were not available to test this assumption.

incidents are estimated to increase between 800% - 1100% from present. These figures represent averages based on a business-as-usual approach to the line management and do not include major defence damage or any large investments that may be needed during the century. There are, however, further direct costs that can be taken into account in the future, and these relate directly to future delays minutes.

Network Rail is responsible for all external impacts on the track operation. During an incident Network Rail's staff liaise with the TOCs to examine the evidence that is collected during incidents in order to determine the key responsible party (who are then obliged to pay compensation). During emergency speed restrictions along the sea wall, for instance, money can be transferred between Network Rail and the TOCs under 'Schedule 8' of the franchised passenger operators' track access contract (Burr et al., 2008). These charges, if necessary, are then used to refund passenger ticket costs if a threshold in time loss is reached (set by TOCs). It was not possible to acquire the exact nature of the penalty charges (e.g., from the contract), as it is commercially sensitive (Network Rail, *pers comm.*). The National Audit Office (Burr et al., 2008), however, suggests that the average value per delay minute is £73.74 for each train (though this average is described as an underestimate). This is based on an average train carrying 282 passengers, of which, 14 are business travellers, 195 are commuters and the remainder are described as others. Using this value of time, it is possible to estimate the future delay charges based on the forecast delay minutes from Chapter Five (see Table 5.11, section 5.5).

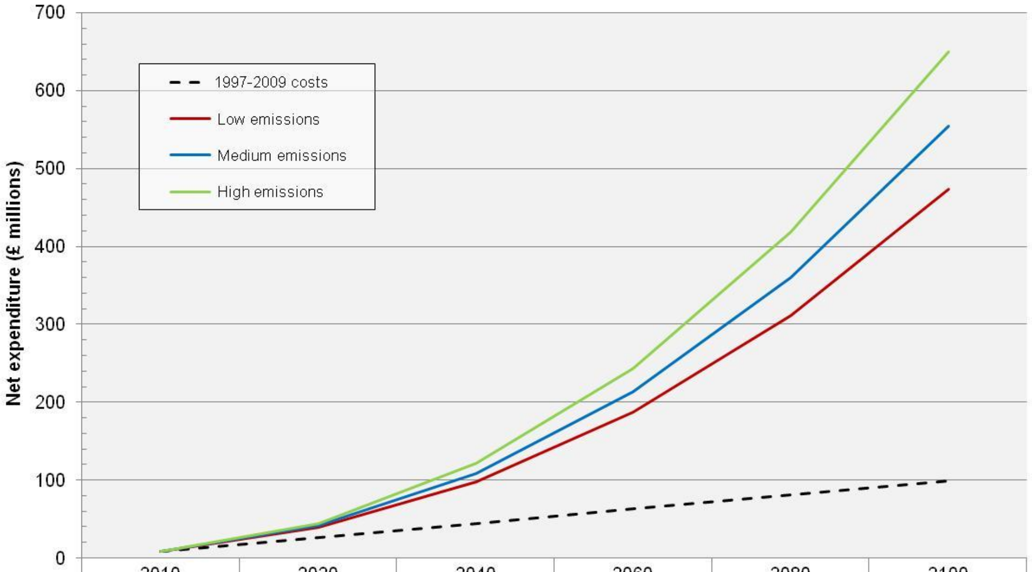
Network Rail's record of delay minutes (in the TSD) do not distinguish which passenger or freight trains were delayed during the incident, and only detail the total delay that occurred. Therefore, the possible freight penalty charges have not been included in the costs. Nonetheless, by using the prediction of average delay minutes for the 21st century and a standard cost of £73.47 per minute, indicative costs of charges due to future incidents can be made. Again, the value of time used was converted from 2008 to 2010 market values by applying a GDP deflator (Appendix D -1.1a), and thus a figure of £90.06/min is used in the calculations. The resulting values are presented in Table 6.1 (see Appendix D -1.1c for calculations). The predicted increases in delay costs show a similar magnitude of increase as maintenance expenditure. The average delay minutes recorded from 1997-2009 suggest that a cost of £0.35 million per year was attributed to overtopping and line restrictions between Dawlish-Teignmouth. By including the impacts of sea-level rise, however, by 2020 the increased line restrictions will raise the average annual cost to £0.6 - £0.7 million per annum. By 2040, a combined estimate of over one month of DLRs will cost the company from around £1.1 to £1.5 million per annum, and between 2060 and 2080 the annual costs per year will rise to £1.7 - £2.4 million. These results are average estimates only and should not be considered for their exactness. For example, the incident in 1996 caused £220,000 of damage to the infrastructure alone, another incident in 2004 caused 5097 delay minutes which would equate to some £459,036 in delay charges. The results, however, clearly identify the future impact climate change may have, and Network Rail (and to an extent TOCs) will face increasing economic consequences of a business-as-usual approach. These figures have been combined to illustrate the total direct costs over the 21st century (Figure 6.1 – see Appendix D – 1.1d for calculations).

The cumulative costs are presented over 20 year periods. This time length is synonymous with the average sea-level calculations in Chapter Five. It also reflects the fact that, empirically, annual fluctuations in sea level have had minimal impact on average DLRs. The net costs for 2020, 2040 etc., include the annual impacts for the remainder of the 20 year period (e.g., 2039). They therefore represent the maximum expenditure expected. The 2010 values are estimated at £8.64 million for all scenarios, and this assumes the average annual delay and maintenance costs observed during 1997-2009 (e.g., £960,000 per year) will continue up to 2020. This cost has also been extrapolated to represent a scenario with no further sea-level change during the remainder of the century, and is estimated to reach around £100 million by 2100.

Year	**Sea-level rise (cm)**	*Average DLRs/yr*	*Increase in DLRs (%)*	*Delay (minutes/yr)*	*Delay value (£ millions/yr)*	*Preventative maintenance (£/yr million)*
1997-2009	3	9.5	-	3,900	*0.35*	*0.61*
Low Emissions						
2020	4.7	16	69	6,510	0.59	1.04
2040	15.1	30	220	12,326	1.11	1.96
2060	26.8	46	389	18,836	1.70	3.00
2080	40.0	64	581	26,232	2.36	4.17
2100	54.5	84	792	34,360	3.09	5.47
Medium Emissions						
2020	5.7	17	83	7,049	0.63	1.12
2040	18.3	34	266	14,098	1.27	2.24
2060	32.6	54	474	22,110	1.99	3.52
2080	48.6	76	710	31,047	2.80	4.94
2100	66.4	100	964	40,985	3.69	6.52
High Emissions						
2020	6.8	19	99	7,665	0.69	1.22
2040	22.0	40	320	16,178	1.46	2.57
2060	39.3	63	571	25,847	2.33	4.11
2080	58.9	90	856	36,825	3.32	5.86
2100	80.6	120	1170	48,920	4.41	7.78

Table 6.1 Estimated direct costs of incident projections based on estimates from three sea-level scenarios. Results are based on the predicted increases in days with line restrictions and delay minutes (see Chapter Five). 1997-2009 results are based on actual observations, and all costs are presented in 2010 market prices.

Sea-level rise, however, appears to cause an exponential increase in costs during the 21st century. Cumulative expenditure is estimated to reach over £40 million during the 2020s as sea levels rise by up to 0.21 m (by 2040), and by 2060, expenditure could rise to between £187 and £244 million (emission dependent). By the end of the century, however, it is estimated that incidents could cost Network Rail a net gross of £474 to £650 million and this is without considering the costs of major damage during single events. The highest estimated costs of sea-level rise are over six times the cost of the baseline scenario (1997-2009). Future sea-level rise has a significant impact on the direct costs on the line, and they appear to become more extensive towards the latter half of the century. All alternative defence schemes (see Table 2.2), or investment plans, in the coming decades must consider these potential impacts in long-term strategic planning. The next section examines the indirect costs, and by utilising the concept of changing travel time for rail users discussed in section 6.2, it is possible to quantify the potential impacts of future rail closures on the Southwest economy.



	2010	2020	2040	2060	2080	2100
1997-2009 costs	8.64	26.88	45.12	63.36	81.60	99.84
Low emissions	8.64	39.46	97.82	186.99	311.19	473.86
Medium emissions	8.64	42.01	108.76	213.44	360.42	554.46
High emissions	8.64	44.93	121.52	243.89	418.23	649.84

Figure 6.1 Cumulative expenditure (£ millions) as a result of sea-level rise on the Dawlish-Teignmouth section of the London-Penzance railway line. Results based on annual results from Table 6.1 and figures assume a fixed cost per year for a 20 year period. The 1997-2009 costs assume (baseline) the observed trends over the period continue for the remainder of the century.

6.3.2 Indirect cost of sea-level rise

In this section the estimated indirect economic costs of rising sea levels and increased restrictions of the mainline are presented. This process required the collection of passenger and freight information including: the time losses caused during restrictions, accurate unit values of time, journey numbers, and journey purposes on the line. UKCIP's (2003) climate costing guidelines methodology (outlined in section 3.5.8) was adapted along with standard industry-used documents including: The Department for Transport's (DfT) *Transport Appraisal Guidance* – unit 3.5.6 (DfT, 2007), the *Great Western Route Utility Strategy* (Network Rail, 2010) and the Office of Rail Regulation's (ORR) *Rail Freight User Values of Time Reliability* (Clarke et al., 2010). Information was integrated with data from the rail archives collected and the projections of future incidents during the 21st century (detailed Chapter Five). Average passenger time losses, during predicted incidents, were calculated first.

The total annual passenger journeys that pass through the Dawlish-Teignmouth section of the mainline were obtained from First Great Western (FGW) using the MOIRA[9] modelling tool which derives its data directly from LENNON[10] (see James et al., 2010 for details on the system). The total number of journeys (per year) was divided (by 365) to establish an average number of passengers per day on the line. Annually, nearly 4 million journeys are made along the section and this equates to around 11,000 journeys each day. To establish the likely journey purposes along the section, the DfT's *Transport Appraisal Guidance* report (DfT, 2007) was used to calculate the average purpose splits for rail travel. The results are based on a national survey from 1999-2001 and work by the Institute for Transport Studies (ITS). However, they are likely to be skewed by London (south east) journey figures. Nevertheless, the *all week average* values of person trips were used to

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[9] MOIRA is the rail industry's tool for forecasting the impact of time tables on passenger revenue (James et al., 2010)

[10] LENNON is the rail industry's ticket and revenue system

estimate the proportion of business, commuter and other passengers (i.e. work and non-work) on the line (Table 6.2).

	Journeys			
Unit	*Total*	*Business*	*Commuter*	*Other*
Annual	3,957,168	296,788	2,065,642	1,594,739
Daily	10,842	813	5,659	4,369

Table 6.2 Passenger journeys and journey purposes splits between Dawlish-Teignmouth on the Southwest mainline. Numbers calculated from rail industry models (MOIRA and LENNON) and purposes constructed using the Department for Transport's national proportion of rail trips (DfT, 2007).

It is estimated that nearly 8% of national rail journeys made in the UK are for work (business), whilst the other 92% are made for commuting and other purposes (e.g., 52% and 40% respectively). This relates to an estimated 813 business related journeys and 10,000 non-business related journeys each day. The division of passenger journey purposes' is necessary in order to apply a more accurate unit value of time for each passenger. The DfT (2007) suggests that the value of working time per rail passenger is £36.96 per hour whilst the non-working value time for a commuter is £5.04/hr per passenger and £4.46/hr per passenger for other travel users. It is assumed that this hourly rate is fixed and, therefore, the figures have been divided to calculate the unit value of time per minute (e.g., 60p, 9p and 8p per minute respectively). These figures, however, are in 2002 market prices and have, therefore, been converted to 2010 market prices using the Treasury's GDP deflator (see Appendix D - 1.1a). The values of passenger time are therefore estimated at £45.91, £6.18 and £5.47 (for business, commuter and other respectively).

With the average number of passengers, their purpose, and their unit value gathered, it is possible to construct an average daily cost of Network Rail's line restrictions (level alerts), based on previous incidents. The First Great Western (FGW) archives (discussed in section 5.3.3) have been used to estimate the loss of time (minutes) to trains (and passengers) during each level alert. The national average for all external delays is around 45 minutes, however, the archive evidence suggests that Level 1 incidents at Dawlish cause up to 20 minutes delay per train, Level 2s cause ~50 minutes, and a Level 3 can add up to 80 minutes to the journey[11]. For the best representation of incidents only half the daily passengers are estimated to be affected during Level 1s, as emergency speed restrictions only affect one half of the track (e.g., the line closest to the seawall). Level 2 and 3 incidents, however, affect both lines and are thereby assumed to affect all passengers. Based on the information from Table 6.2 the expected daily economic cost per restriction can be made (Table 6.3 see Appendix D -1.1e).

Alert type	***Average delay (min/person)***	**Passenger type**	***No. of daily journeys***	***Total value of alert (£)***
Level 1	20	Business	407	6,139
		Commuter	2,830	5,827
		Other	2185	3,981
Level 2	50	Business	813	30,699
		Commuter	5,659	29,136
		Other	4,369	19,905
Level 3	80	Business	813	49,119
		Commuter	5,659	46,618
		Other	4,369	31,849

Table 6.3 Estimated indirect cost of current days with line restriction (DLR), based on time loss to passenger per day. Present day unit time values (DfT, 2007) and data collected from First Great Western's area log files. All costs are in 2010 prices.

The results show that Level 1 incidents are estimated to cause up to £15,950 per incident (per day), whilst Level 2 incidents could cost nearly five times more (over £79,700). Level 3 incidents, however, have the highest cost per restriction (eight times Level 1) and are

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[11] Although, the track service data has recorded individual events that have caused over 1000 delay minutes, and up to a maximum of 5000 minutes, every year from 1999 – 2006.

estimated at around £127,590 per day. These indicative incident costs can be combined with the predicted number of incidents (1-3) to estimate the costs during the 21st century for the three climate scenarios (low, medium and high). The results are presented later (along with the considerations of the approach). Firstly, however, the potential impacts of incidents to freight traffic must be determined.

Although the overall methodology is the same (e.g., UKCIP, 2003) the inputs for the costs for freight differ slightly to the passenger travel time calculations. Firstly, regarding freight flows in the region, Network Rail's Great Western Route Utilisation Strategy (Network Rail, 2010) suggests that the traffic through Dawlish - Teignmouth is a maximum of 12 trains per day. This was confirmed with observations of Network Rail's TRUST data base (i.e. TSD) that recorded 12 trains in 24 hours (six up, six down), although this may not be the case for every week (Network Rail, *pers comm.*) as freight is heavily influenced by patterns of demand. The commodity type is also needed to calculate an accurate value of time and the flow of goods in the Southwest region are mainly metals, aggregates (china clay) and specialist materials[12] (Network Rail, 2010). The ORR's Rail Freight Users' Time and Reliability report (Clarke et al., 2010) details the likely values of unexpected delays to freight operating companies (FOCs) in the UK. They investigated the value of costs of unexpected lateness (reliability) on loaded trains by conducting over 30 interviews with national FOCs. Their costs take into account changes to various procedures involved with the freight delivery process (e.g., collection and delivery, equipment, handling, time, road substitution etc.) estimated during the interviews they conducted. Their results present the value of unexpected lateness per train (subdivided by commodity) and are based on typical weights of cargo carried (e.g., tonnage). Table 6.4 presents some of their conclusions.

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[12] Specialist materials are likely to include defence manufacturing heading to the navy ship yards in the region (e.g. Devonport).

In Clarke et al.'s (2010) investigation, metals and aggregates are considered as bulk traffic, specialist traffic is not identified and, consequently, calculations presented here assume it to be included in the bulk traffic value. The cost of unexpected lateness to bulk traffic ranged between £0 and £9,080 depending on the delay time, but the averages they recorded ranged from £23 to £2,838 (see Table 6.4 below).

Sector		***Up to 30 mins***	***30-60 mins***	***1-2 hours***	***2-4 hours***	***4-12 hours***	***12-24 hours***	***24-48 hours***
Bulks	*Min*	£0	£0	£0	£0	£0	£0	£0
	Avg	£23	£46	£122	£900	£1,311	£1,674	£2,838
	Max	£116	£231	£462	£4,455	£4,455	£9,080	£9,080
Coal	*Min*	£0	£1,500	£1,500	£1,500	£1,500	£1,500	£1,500
	Avg	£600	£1,640	£1,796	£1,972	£2,159	£2,402	£2,890
	Max	£1,475	£2,700	£4,030	£5,360	£5,400	£5,400	£5,400
Domestic intermodal	*Min*	£0	£0	£0	£60	£60	£1,060	£1,060
	Avg	£0	£459	£2,164	£3,335	£8,994	£12,164	£16,424
	Max	£0	£3,075	£12,150	£15,300	£30,300	£44,300	£44,300

Table 6.4 Value of unexpected lateness in £s per train for freight traffic. Taken from The Office of Rail Regulation's (ORR) Rail Freight Users Time and Reliability report (Clarke et al., 2010). Values in 2010 market prices.

The variance in the values of time for unexpected lateness is a representation of the diverse types of freight traffic and demand in the UK. Clearly, the costs of perishable goods, or deliveries for just-in-time productions, are more expensive than non-perishable goods (e.g., aggregates). Some FOCs, however, incorporate safety margins in their timetables (known as slack time) and this has an obvious effect on the impact of unexpected delays. Bulk traffic is suggested to accommodate, on average, around 105 minutes of lateness, but this ranged from 30 minutes to 3.5 hours (Clarke et al., 2010). Despite this variance, the values are useful as they help to indicate the extent to which incidents could impact the region directly (and the FOCs). In order to acknowledge the uncertainty in values, however, Clark et al.'s (2010) average values per train were used, but with minimal slack time. This information was fitted directly to the current freight usage in the region (e.g., trains affected) and the details of the line restrictions obtained from the archive investigation (e.g., time loss incurred).

The newspaper and service archives, however, gave little indication of the impacts of incidents on commercial freight traffic[13]. Therefore, informed estimates of the delays that occurred were made based on the delays to passengers and TOCs. Level 1 and 2 incidents have recorded between 20 – 50 minutes of delay to services and, in order to align with the time units of Clarke et al.'s (2010) results (Table 6.4), these incidents were combined. A maximum impact of up to 60 minutes delay per train is, therefore, used in the calculations, and an average cost of £46 per train, per incident (Clarke et al 2010). The extent of Level 3 alerts differ, however, as the line is closed completely and, unlike passenger trains, during a complete closure freight trains cannot shuttle their cargo between the nearest unaffected stations (e.g., Exeter and Newton Abbott). Thus, freight trains are likely to be held until the line opens under a Level 1 or 2 working, unless other modes of transport are utilised (at additional cost of time and expense).

During previous Level 3 incidents, the worst of the impacts occurred 2 hours either side of high tide (when the water level was highest) – although this is likely to be extended in the future – and delayed the track for both the daily high tides (e.g., 24 hours – or the duration of the storm surge). Theoretically, a minimum of eight hours of total closure would occur, although previous Level 3s have caused delays for several days (e.g., 1996, 1998, 2002, 2004, 2005, 2006), and on this basis the best estimate time frame (from Table 6.4) to represent a single Level 3 incident is 12-24 hours. The delay to bulk traffic during a Level 3 is, therefore, predicted to cost an average £1,674 per train (Clarke et al., 2010). With this

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[13] TRUST data from 2009 now records the delays to each train and provides evidence that freight traffic is affected by days with level restrictions.

information it is now possible to estimate the costs of each incident. The estimated time delay for each train was multiplied by the daily freight trains on the line (Network Rail, 2010) and the average unit value of unexpected lateness for bulk traffic (Clarke et al., 2010). Table 6.5 presents the results (see Appendix D - 1.1f). The costs of a Level 1 and 2 alerts, causing between 30 – 60 minutes of delay, is estimated at an average of £798 per day and Level 3 alerts are estimated to cost £20,000 per day. These costs can be combined with the results from Table 6.3 to present the estimated cost of future DLRs to all rail users. Before these are presented, however, a number of considerations must be outlined.

Alert type	Time loss per train	Trains affected per day	Unit value of reliability	Cost per alert per day
Level 1	30-60 minutes	6	£46	£276
Level 2	30-60 minutes	12	£46	£552
Level 3	12-24 hours	12	£1,674	£20,088

Table 6.5 Estimated costs of line restrictions (alerts) for bulk freight traffic between Exeter-Plymouth per day. Based on freight traffic numbers and commodity types from Network Rail (2010), and values of reliability taken from Clarke et al., (2010).

Firstly, the predictions of DLRs taken from Chapter Five, assume that each incident lasted all day and affected all passengers and trains equally. Actual DLRs, however, often have a mix of alerts and varying delays. For instance, a Level 1 can deteriorate to a Level 2, or even level 3, if the conditions worsen. Similarly, a Level 3 can be downgraded to a Level 2 if the conditions improve, hence, varying delays per day can be expected. Furthermore, evidence has also shown that individual rail services are also affected differently. Class 2 (local) passenger services are reduced first, to make way for intercity services, and are often completely cancelled during Level 2 and 3 events. But as incidents and impacts are dependent on a number of factors (weather, tide, wave, time of day, train service etc), it is impossible to model the full variance of actual incidents. Therefore, as opposed to using one single event as an analogy for all future incidents, the average trends of potential impacts and costs, based on the empirical evidence collected, are used. It must also be acknowledged that the estimates are based on empirical findings and impacts recorded in the last few decades. The nature of the incidents and their impacts (e.g., magnitude and frequency) are likely to increase as a consequence of sea-level rise. Thus, factors that caused previous level 1 incidents are likely to become cause Level 2 and, eventually, Level 3 incidents.

The second consideration regards the values used in the time loss calculations (also based on averages). For instance, using average passenger journeys creates a uniformity of rail travel that does not take into account seasonal variations in passenger demand, such as summer holiday traffic, which can make up a major element of overall demand in the region (Network Rail, 2010). As the majority of alerts recorded in the past have occurred during the winter months it could be argued that the passenger numbers would be reduced. Furthermore, the use of the DfT’s all week average journey splits (DfT, 2007) assumes an average proportion of purpose trips and does not account for any variance in travel. For instance, the cost of lost time on a peak rush hour train (full of business and commuter traffic) or the complete cancellation of Class 2 services (during level 2s) would alter the costs calculated. Furthermore, passenger numbers are likely to increase but this will be dealt with in later sections with the integration of socio-economic scenarios (SES). Finally, although these results are developed and extrapolated from industry recognised data sources they represent informed estimates only. As such, they are constructed to help illustrate the impacts of sea-level rise and potential socio-economic costs to enable effective stakeholder dialogue to begin. The final indirect costs are now presented.

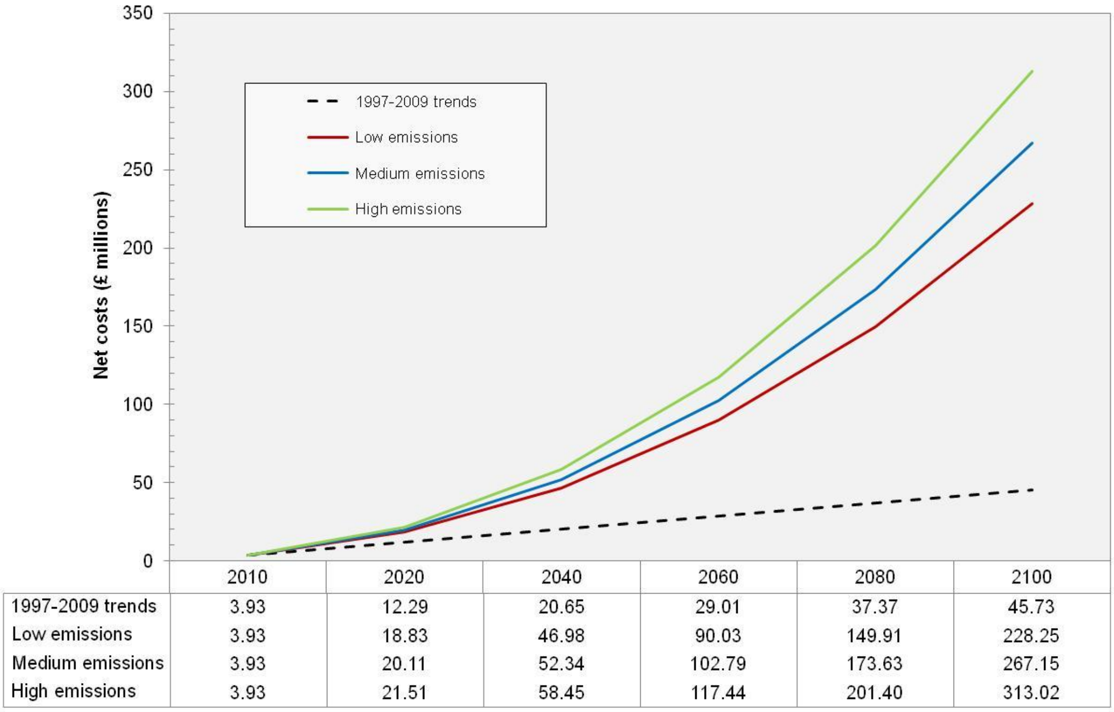
6.3.3. The combined indirect costs of sea-level rise

The 21st century estimates of economic impacts from three sea-level scenarios have been calculated using the data from Table 6.3 and Table 6.5 and the estimated projections of incidents (DLRs). Table 6.6 presents the results (see Appendix D - 1.1g). The TRUST service data (TSD) recorded an average of 9.5 DLRs per year between 1997-2009, during which period sea levels rose around three centimetres, and based on the data presented in the two previous sections cost the economy £437,033 in time loss. During the next ten years, however, 0.047 m – 0.068 m of sea-level rise is expected to double the current average of DLRs (16-19/yr). The total value of time lost is thus estimated to increase to £788,242 - £933,351 per year. By 2040, however, the costs rise significantly and 0.15 m - 0.22 m of sea-level rise will cause impacts in the region of around £1.4 - £2.0 million per year. This increase eventually reaches a maximum of £3.13 million by 2060, over eight times the present day estimates. By 2100, between 0.5 m and 0.8 m of sea-level rise is predicted to cause 84-121 DLRs/yr. This is the equivalent to over three months of restricted rail operation. Consequently, the average costs to the economy are estimated from £4.15 - £5.94 million per year. Observing the individual alerts, however, indicates that the highest costs will result from the increase in Level 2 alerts as these affect both lines, and are predicted to occur almost as often as Level 1s (as today).

The net impacts for the 21st century have been calculated assuming that the costs per year (from Table 6.6) will occur every year. For comparison, a baseline estimate based on the 1997-2009 trends of incidents (and costs estimates) is also presented, and Figure 6.2 presents the results (see Appendix D -1.1g for calculations). By extrapolating the 1997-2009 trends to 2020, all the scenarios estimate the average cost of time loss will be ~ £3.9 million.

Year	SLR (cm)*	Estimated ESR/yr		*Estimated line closures/yr*	Passenger time losses (£/yr)			Freight time losses (£/yr)			Total time loss impacts (£ per year)
		Level 1	Level 2	Level 3	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3	
1997-2009	*3*	*5.4*	*3.8*	*0.3*	*86,122*	*303,021*	*38,276*	*1490*	*2098*	*6026*	*437,033*
					Low Emissions						
2020	4.7	8.4	7.2	0.5	134,348	570,347	60,837	2,325	3,948	9,578	781,384
2040	15.1	16.0	13.6	0.9	254,351	1,079,794	115,178	4,402	7,475	18,134	1,479,333
2060	26.8	24.4	20.7	1.4	389,355	1,652,921	176,312	6,738	11,442	27,759	2,264,527
2080	40.0	34.0	28.8	1.9	541,666	2,299,527	245,283	9,374	15,918	38,618	3,150,387
2100	54.5	44.5	37.7	2.5	708,978	3,009,813	321,047	12,269	20,835	50,547	4,123,490
					Medium Emissions						
2020	5.7	9.1	7.8	0.5	145,887	619332	66,062	2,525	4,287	10,401	848,494
2040	18.3	18.3	15.5	1.0	291,275	1236546	131,898	5,041	8,560	20,767	1,694,087
2060	32.6	28.6	24.3	1.6	456,280	1937036	206,617	7,896	13,409	32,531	2,653,768
2080	48.6	40.2	34.1	2.3	640,900	2720800	290,219	11,091	18,834	45,693	3,727,537
2100	66.4	53.1	45.1	3.0	846,289	3592738	383,225	14,646	24,870	60,337	4,922,106
					High Emissions						
2020	6.8	9.9	8.4	0.6	158,580	673,216	71,810	2,744	4,660	11,306	922,316
2040	22.0	20.9	17.8	1.2	333,969	1,417,792	151,231	5,780	9,814	23,811	1,942,396
2060	39.3	33.5	28.4	1.9	533,589	2,265,237	241,625	9,234	15,681	38,043	3,103,409
2080	58.9	47.6	40.4	2.7	759,749	3,225,349	344,037	13,148	22,327	54,167	4,418,776
2100	80.6	63.3	53.8	3.6	1,010,140	4,288,329	457,422	17,481	29,685	72,019	5,875,076

Table 6.6 Indirect (economic) costs of 21st century sea-level rise based on increased passenger and freight time loss between Dawlish and Teignmouth. Sea-level predictions, corrected for vertical land movement, are given relevant to present day (2010). ***** The English Channel tide gauge records indicate average sea-level rise of ca. 3 cm of during this period. The past sea levels from UKCP09's model (Lowe et al., 2009) estimate around 5-8 cm. ESR = emergency speed restrictions, imposed by track operators during storm events (see Chapter Five for details).



	2010	2020	2040	2060	2080	2100
1997-2009 trends	3.93	12.29	20.65	29.01	37.37	45.73
Low emissions	3.93	18.83	46.98	90.03	149.91	228.25
Medium emissions	3.93	20.11	52.34	102.79	173.63	267.15
High emissions	3.93	21.51	58.45	117.44	201.40	313.02

Figure 6.2 Net external costs based on user time loss as a result of sea-level rise and increased line restrictions for the 21st century. Current estimates of passenger and freight flows (2008-2009) and national averages of journey purpose and unit time values (DfT, 2007) are used. Total costs assume a fixed cost per year for a 20 year period, and relative to 2010 market prices.

During the 2020s, however, changes in journey times could cost the economy over £20 million, and nearly double the extrapolated baseline trends (1997-2009) over the next two decades. During the 2040s travel time losses could potentially have cost the economy up to £62 million. From 2060-2080, the total impact could range from £90 - £117 million and the net economic impacts of closures by the end of the century (up to 2120) are estimated between £228 and £313 million. In light of the baseline projections the costs of a business-as-usual management approach on the economy rise exponentially during the remainder of this century. These costs are illustrative and do not take into account the wider economic consequences of deteriorating transport infrastructure. It was stated in section 6.2, however, that the wider economic costs are generally calculated using a region multiplier (typically of one or two), thus the impacts calculated could double the estimated presented here. The next section will present the combined direct and indirect costs of future incidents.

6.3.4 Total costs of rail incidents

The results presented in the two previous sections can be combined to give estimates of the total direct impacts for three sea-level projections, and a baseline scenario using the past observations (1997-2009). These total costs combine the estimated impacts to rail users (passenger and freight) and the estimated impact on the maintenance expenditure on the track. Some researchers suggest internal costs, such as infrastructure maintenance, should be excluded from climate impacts assessments on the basis that they are less of an economic issue (Koetse and Rietveld, 2009). The increased internal costs, however, are likely to be an important factor in the future climate change and are included in the estimates presented in this thesis. The penalty charges are not included in these calculations as these charges may eventually be passed on to the customer via compensation of rail tickets (Burr et al., 2008). Including them may have resulted in double-counting of the costs. Table 6.7 and Figure 6.3 present the results (see Appendix D 1.1h for calculations).

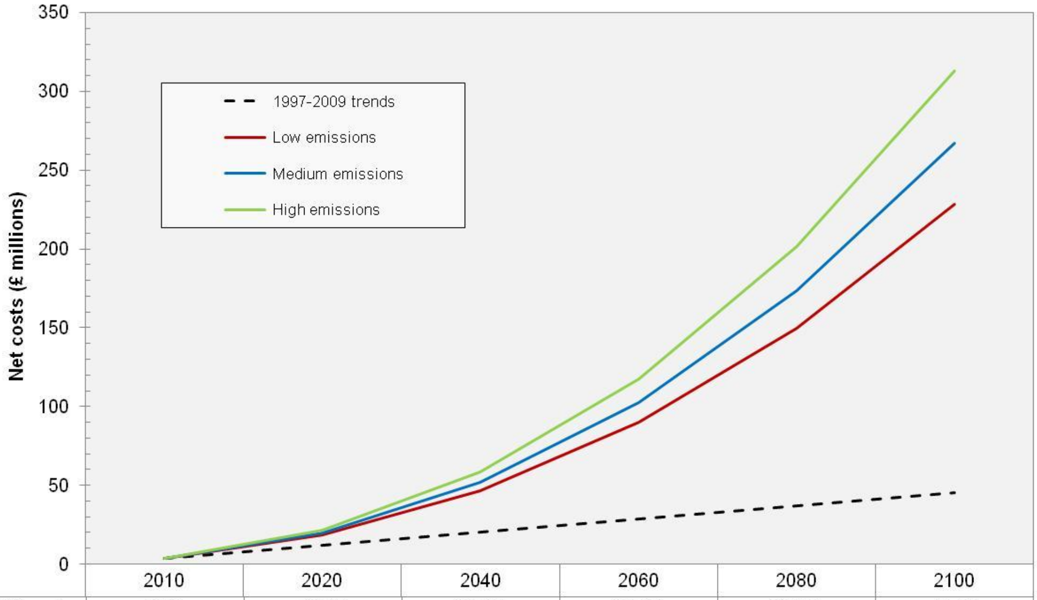
Based on the calculations from this chapter, the period between 1997 and 2009 is estimated to have cost a total of around £12.6 million (£1.05 million/yr), although this does not include the major events or defence works (e.g., new sea walls and foundations strengthening) during this period. If these annual costs continue up till 2020, the cost from present (2010) will be around £9.45 million. During the 2020s, the annual expenditure is predicted to be from £1.82 - £2.14 million per year and sea-level rise could raise the net cost to the region to nearly £51 million over the 2020-2039 period. By 2060, average costs could reach around £6 million annually and by 2080 attain a maximum of £10 million per year.

Year	***Sea-level rise (cm)***	***Annual time loss (£ million)***	***Annual maintenance (£ million)***	***Total annual costs (£ million)***
1997-2009	3	*0.44*	*0.61*	*1.05*
2010	-	*0.44*	*0.61*	*1.05*
			Low Emissions	
2020	4.7	0.78	1.04	1.82
2040	15.1	1.48	1.96	3.44
2060	26.8	2.26	3.00	5.26
2080	40.0	3.15	4.17	7.32
2100	54.5	4.12	5.47	9.59
			Medium Emissions	
2020	5.7	0.85	1.12	1.97
2040	18.3	1.69	2.24	3.94
2060	32.6	2.65	3.52	6.17
2080	48.6	3.73	4.94	8.67
2100	66.4	4.92	6.52	11.44
			High Emissions	
2020	6.8	0.92	1.22	2.14
2040	22.0	1.94	2.57	4.52
2060	39.3	3.10	4.11	7.22
2080	58.9	4.42	5.86	10.28
2100	80.6	5.88	7.78	13.66

Table 6.7 Future climate impacts estimates for the Dawlish-Teignmouth railway line. Impacts predicted for three emissions scenarios from 2010. Estimates of sea-level rise are relative to 2010 and include allowances for vertical land movements calculated in Chapter Four of this study. All costs are relative to 2010 market values.

During the second half of the century the increases in annual incidents will have caused a cumulative impact of £210 - £275 million. By the end of the century, a minimum of half a metre of sea-level rise is predicted, and the collective impacts on the mainline could range from £532 million to £732 million, and this is a result of over four months of DLRs and four Level 3s a year. Based on the damages recorded in the *Frontage Management Record* (Rogers and O’Breasail, 2006), when level 3s averaged ~0.4 per year, the possibility of the railway defences withstanding an average of four level 3 events per year is questionable.

If there were no changes in DLRs from 2010, however, the estimates suggest the net costs would reach £110 million during this century. Climate change will amplify the costs significantly, and the results have shown that rising sea levels during this century will be coupled with higher average DLRs, longer delays to rail users (directly impacting the economy) and higher maintenance expenditure.



	2010	2020	2040	2060	2080	2100
1997-2009 trends	3.93	12.29	20.65	29.01	37.37	45.73
Low emissions	3.93	18.83	46.98	90.03	149.91	228.25
Medium emissions	3.93	20.11	52.34	102.79	173.63	267.15
High emissions	3.93	21.51	58.45	117.44	201.40	313.02

Figure 6.3 Estimated cumulative costs of sea-level rise on the Dawlish-Teignmouth railway line. Costs combine those to the economy (in the form of delays to rail users) and those to the rail industry (in the form of maintenance expenditure). 21st century sea-level predictions used are corrected for vertical land movement and are given relevant to present day (2010). Results based on annual results from Table 6.7 and figures assume a fixed cost per year for a 20 year period. 1997-2009 costs represent the baseline impacts on the line without any future sea-level change.

Economically, costs directly to the region are going to increase as a result of increased travel time, and a decrease in freight reliability, affecting labour markets and productivity. This will also inhibit the region's ability to adapt to economic changes and increase the wider economic costs to society (e.g., welfare), and although not quantified these impacts will eventually be felt in terms of regional GDP output. Comparing a future without sea-level rise with the high emission projections estimates shows that climate change is expected to cost an additional £623 million during this century. In alignment with the results from Chapter Five this section has illustrated the extent to which future sea-level projections are likely to impact the economy and rail industry. Although these results are only illustrative, it is clearly evident that the Southwest railway line will become increasingly unsustainable during the remainder of the century.

The analysis so far, however, is based upon the assumption that current socio-economic trends will continue in the future, rather than forming coherent views of the kind of future that they may influence upon, or vice versa (Berkhout and Hertin, 2000). There are complex interactions between humans, climate, and impacts, and these must be considered in any impact assessment. Current management practices will be modified by changing risks and society's expectation of those risks. Management of flood protection and transport policies are therefore scenario-dependent (Hall et al., 2006). The next section presents the integration of socio-economic futures, with the climate impacts projected in order to provide more plausible scenarios for stakeholder consideration.

6.4 Integrating socio-economic scenarios (SES)

In addition to climatic futures, society's vulnerability to climate change is shaped by economic, institutional and political factors that are themselves dynamic (Adger, 1996), and are consequently inter-related. It is important to consider the impacts of socio-economic futures in climate impact assessment and acknowledge the effect of changes in governance and values on the capacity of a regions' ability to adapt. Scenarios are often used to integrate socio-economic and climate changes to help deal with the complexities of the relationship between the two (Berkhout et al., 2002; Hulme and Dessai, 2008). UKCIP's (2001) Socio-Economic Scenario's (SES) help to assess the impacts of climate change by providing non-climatic scenarios in which climate changes will take place

(Dalhström and Salmons, 2005). In this assessment, projected sea-level rise, closures and impact costs will be linked to storylines of the UKCIP's SES (2001): *National Enterprise, Local Stewardship, World Markets and Global Sustainability* (discussed in section 3.6 of Chapter Three).

These futures must be considered, in order to present a wider range of possible outcomes of the future impacts of sea-level rise in the region. In this study the SES impacts are explored qualitatively using one landscape domain (the coast) and one economic sector (transport). To assess the impact of socio-economic change, however, the SES must firstly be paired with the UKCIP climate emission scenarios (Hulme et al., 2002) and the marine sea-level projections (Lowe et al., 2009). This pairing reflects the assumptions between the UK and the rest of the world in terms of future socio-economic and emission characteristics (trends). However, it also reflects the assumptions concerning the future ability of technology and society to reduce greenhouse gas emissions (Dalhström and Salmons, 2005). Thus, a future in which society is concerned for the environment may strive to invest in better technology to reduce carbon emissions, or vice versa. As in other studies, the outcome of the integration is based on consistency and logic, and the pairing has followed the examples of UKCIP (2001), Dalhström and Salmons (2005) and Hall et al., (2006).

It must be noted, however, that the UKCIP's climate emissions scenarios are based on trends from the Intergovernmental Panel for Climate Change (IPCC) and, therefore, automatically include assumptions of future socio-economic conditions (emissions). The integration in UKCIP's examples (e.g., Shackley et al., 2001; Dalhström and Salmons, 2005) has, therefore, been followed as closely as possible to reduce any added complications. It was not possible to follow the integration exactly, however, as

UKCIP02's (Hulme et al., 2002) climate scenarios split the medium emission climate forecast into two separate futures (medium-high and medium-low). The UKCP09 Marine Projections of sea-level rise (Lowe et al., 2009) have adopted the original three scenarios in their outputs (high, medium and low) and, therefore, the medium marine projections are used for two of the SES (Table 6.8).

UKCIP02 Climate change scenarios	**UKCP09 Marine Projections**	**UKCIP Socio-economic scenarios**	**GWRUS (2010) scenarios**
Medium-low emissions	Medium SLR	Local Stewardship	*Local Awareness*
Medium-high emissions	Medium SLR	National Enterprise	*Insularity*
Low emissions	Low SLR	Global Sustainability	*Global Responsibility*
High emissions	High SLR	World Markets	*Continued Profligacy*

Table 6.8 Integrating the socio-economic scenarios (SES) and climate emission and sea-level rise (SLR) projections. These pairings will be used in the final scenarios of rail impacts.

The future with high growth, technological advancements and environmental awareness (Global Sustainability) is linked to the lowest carbon emissions and sea-level rise. Whilst the future with the highest consumption values, growth and lowest environmental awareness (World Markets), is linked to the highest carbon emissions and consequent projections of sea-level rise. Each SES will have a different effect on the region in the future and, although the qualitative storylines provide detailed analysis, it is important to quantify these effects where possible (UKCIP, 2001). One easily quantifiable effect is population change and – by extension – demand on public transport (or rail patronage). By incorporating quantitative indicators the influence of socio-economic change on the costs of future climate projections can be clearly demonstrated. The SES (UKCIP, 2001) give estimates for trends in national transport modes for the 2020s and 2050s but there is little indication of how these trends might be applied to the study site in Devon. It is suggested that studies looking into finer scale phenomena need to account for more detailed information by the process of downscaling (van Vuuren et al, 2010) but this is complex procedure and the outcomes are often flawed. The GWRUS (Network Rail, 2010), however, contains passenger demand forecasts for the next 30 years based on four scenarios: *Global Responsibility, Continued Profligacy, Insularity and Local Awareness* (Figure 6.4).

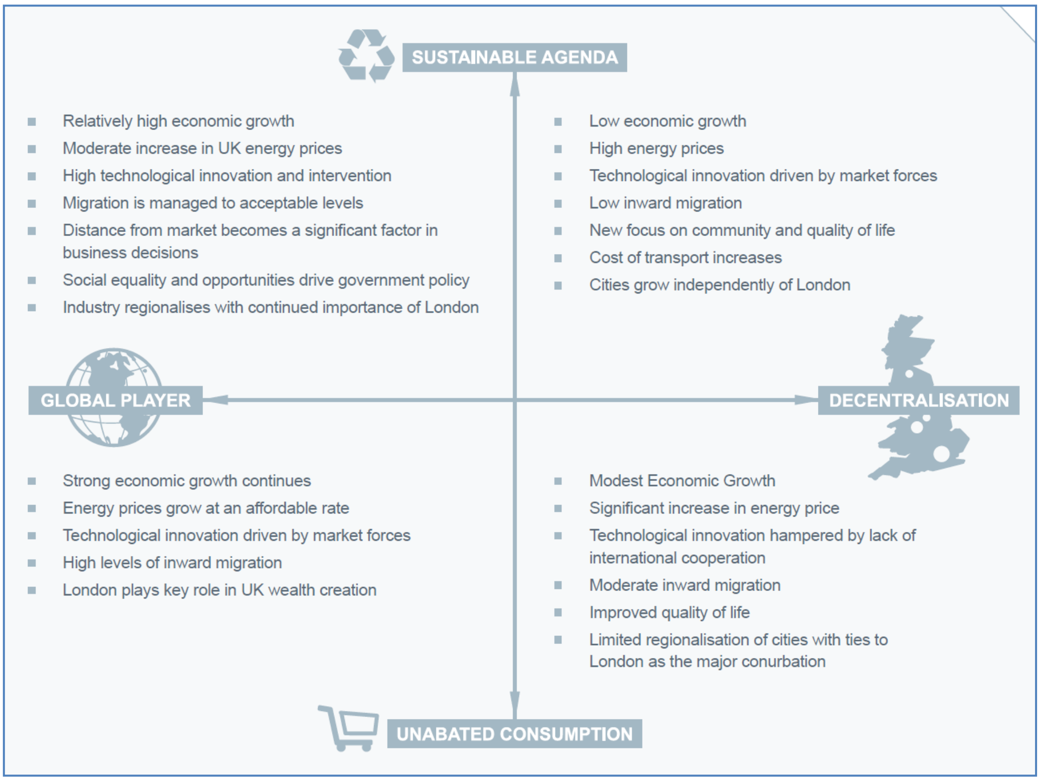


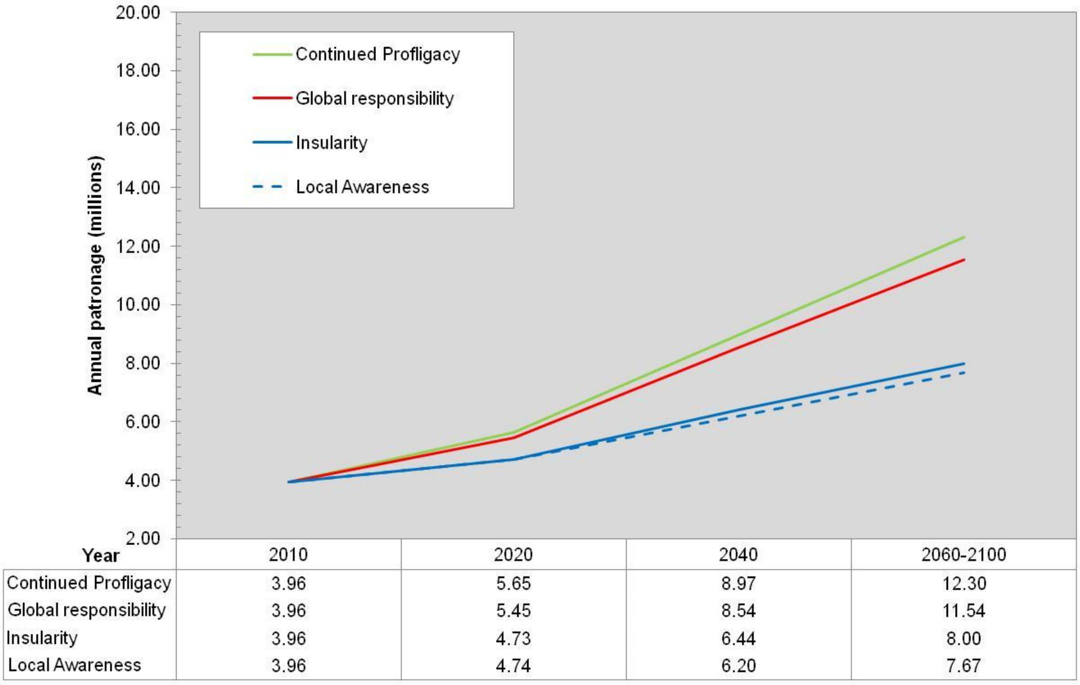
Figure 6.4 The Great Western Route Utilisation Strategy's (GWRUS) (Network Rail, 2010) socio-economic scenarios (SES) used to develop long-distance passenger demand forecasts for Plymouth-London and along the Dawlish-Teignmouth section of the Southwest mainline. Clockwise from top left: *Global Responsibility, Local Awareness, Insularity and Continued Profligacy*. © Network Rail (2010).

Under each scenario long distance passenger demand has been predicted based on the impacts of economic growth, demographic changes, energy prices and society's attitude to greener transport (Network Rail, *pers comm.*). Despite no direct acknowledgement, the descriptions of these scenarios show striking similarities to UKCIP's SES (2001), and the futures described in the GWRUS (Network Rail, 2010, p. 129) are easily comparable as they utilise the same two-by-two matrix of governance and values (outlined in Chapter

Three). On the basis of this comparison, the forecasts of passenger demand can be integrated with the marine climate projections (Lowe et al., 2009). The inclusion of the GWRUS's (Network Rail, 2010) passenger forecasts, therefore, enables the most plausible forecasts of passenger demand in the region to be incorporated into the regional economic analysis. The integration of these forecasts, UKCIP's SES (2001), and the final climate emission scenarios are also presented in Table 6.8.

The GWRUS (Network Rail, 2010) forecasts are limited to 2036, however, and are not conclusive with the time scales of the future projections in this project. Further analysis was therefore required to fit them to the time scales of sea-level projections (e.g., 2020 - 2100). Firstly, the 2009 annual journeys between Exeter and Plymouth were used as the present day values (2010) which were then simply multiplied by the forecast increase in long distance journeys between Plymouth and London for 2036 (from the GWRUS (Network Rail, 2010)). These results were then used to represent the forecasts for 2040. Secondly, a line was fitted using linear regression (of passenger demand) from 2010 to 2040 and was then extrapolated up to 2060. From 2060, however, no increase was predicted, partly as the accuracy of socio-economic trends become increasingly contested over longer time scales (Dalhström and Salmons, 2005), and this also avoided the inclusion of unrealistic passenger journeys. Figure 6.5 presents the results of the process for each scenario.

The high growth scenarios of Continued Profligacy (or World Market) and Global Responsibility (Global Sustainability) have the highest predicted increase in passenger demands with over 11 million journeys a year by 2060 (over 210% from present). The scenarios of Insularity and Local Awareness (National Enterprise and Local Stewardship) are predicted to have the least increases in journeys, between 7.5 and 8 million by 2060 respectively (more than 95% from present). These figures, however, represent the forecast increase in long distance travel only and, as they have been applied to all passenger journeys and therefore assume the same increase in inter-regional travel. Having established the integration of the climate scenarios and SES – and identified an accurate quantitative indicator to represent them – the final direct costs of railway can be accurately presented and discussed for four futures.



Year	2010	2020	2040	2060-2100
Continued Profligacy	3.96	5.65	8.97	12.30
Global responsibility	3.96	5.45	8.54	11.54
Insularity	3.96	4.73	6.44	8.00
Local Awareness	3.96	4.74	6.20	7.67

Figure 6.5 Forecasts of potential long distance passenger demand between Plymouth and London for four socio-economic scenarios. Predictions adapted from the Great Western Route Utilisation Strategy (Network Rail, 2010). See Appendix D – 1.2 for calculations.

This study utilises an incremental approach to present the future costs (similar to Shackley et al., 2001) through the process of determining, firstly, the effects of socio-economic costs (SEC) without the influence of climate change (in this case no sea-level rise from the present baseline). These costs are constructed by extrapolating the 1997-2009 trends of incidents (e.g., 9.5 DLRs/yr) with the potential future passenger demand changes for the remainder of the century (from the SESs). Secondly, the integrated future costs (FC) are calculated to illustrate the impact of both the socio-economic futures (e.g., passenger demand) and climate change scenarios (e.g., sea-level rise). These are calculated by combining the predicted increase in rail incidents for the relevant climate scenario (high-low), with the associated increase in passenger demand from the SES (see Table 6.8). Finally, the overall cost of climate change (CCC) is determined by subtracting the SEC from the FC (i.e. it is assumed the SEC occur without any change in sea-level and overtopping frequency). The final CCC thus demonstrates the additional financial impact of sea-level rise on the region with no adaptational response. Figure 6.6 illustrates the method for costing the final scenarios in this chapter. The next section presents the results and the final scenarios.

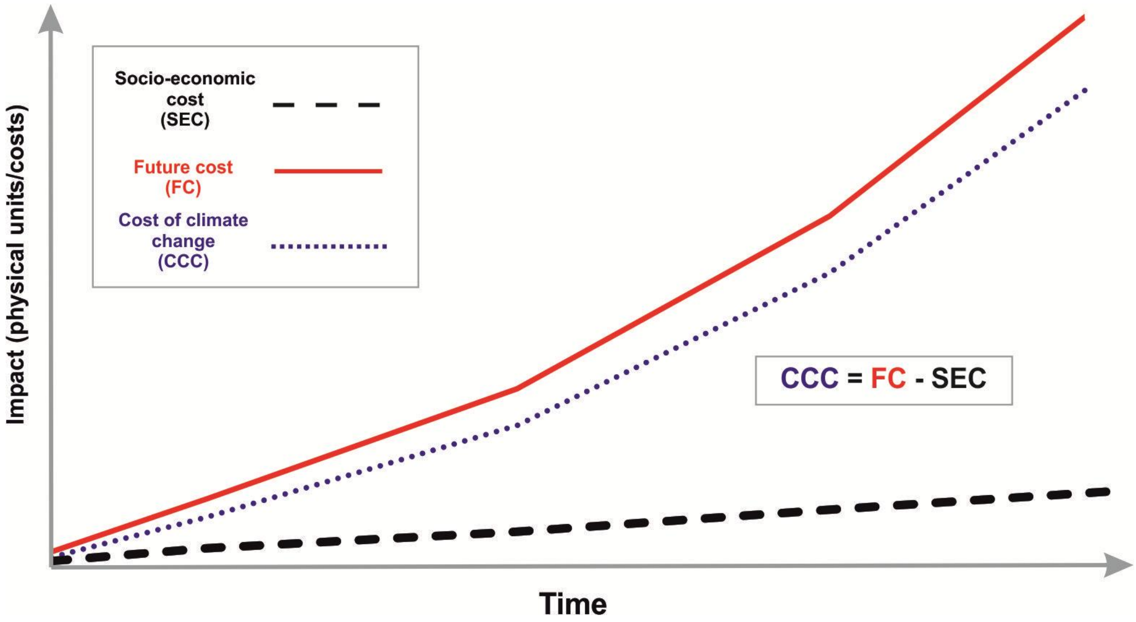


Figure 6.6 Illustration of the approach to integrating, and presenting, the future costs of climate change (CCC) on the London-Penzance railway line in this chapter. Socio-economic cost (SEC) illustrated using current baseline trends (1997-2009) and changes in passenger demand. These are subtracted from the future cost (FC) that combines both climate and socio-economic impacts. The result is the CCC for each integrated scenario.

6.5 Scenarios of future rail problems

Shackley et al. (2001) point out that when linking climate change and socio-economic scenarios it is necessary to consider the point at which mitigation actions will start to take effect. The quantitative costs of the scenarios in this study have been calculated by assuming that mitigation will be minimal (i.e. business-as-usual). The empirical relationship between overtopping and rail impacts, therefore, remains constant during the 21st century; with a decreasing reliability of rail services. Each scenario will be presented individually, firstly, with a narrative storyline of the future expanded from UKCIP's descriptions (e.g., Shearlock, 2001; Shackley et al, 2001; Dalhström and Salmons, 2005) and with a focus on coastal environments and transport infrastructure in the region.

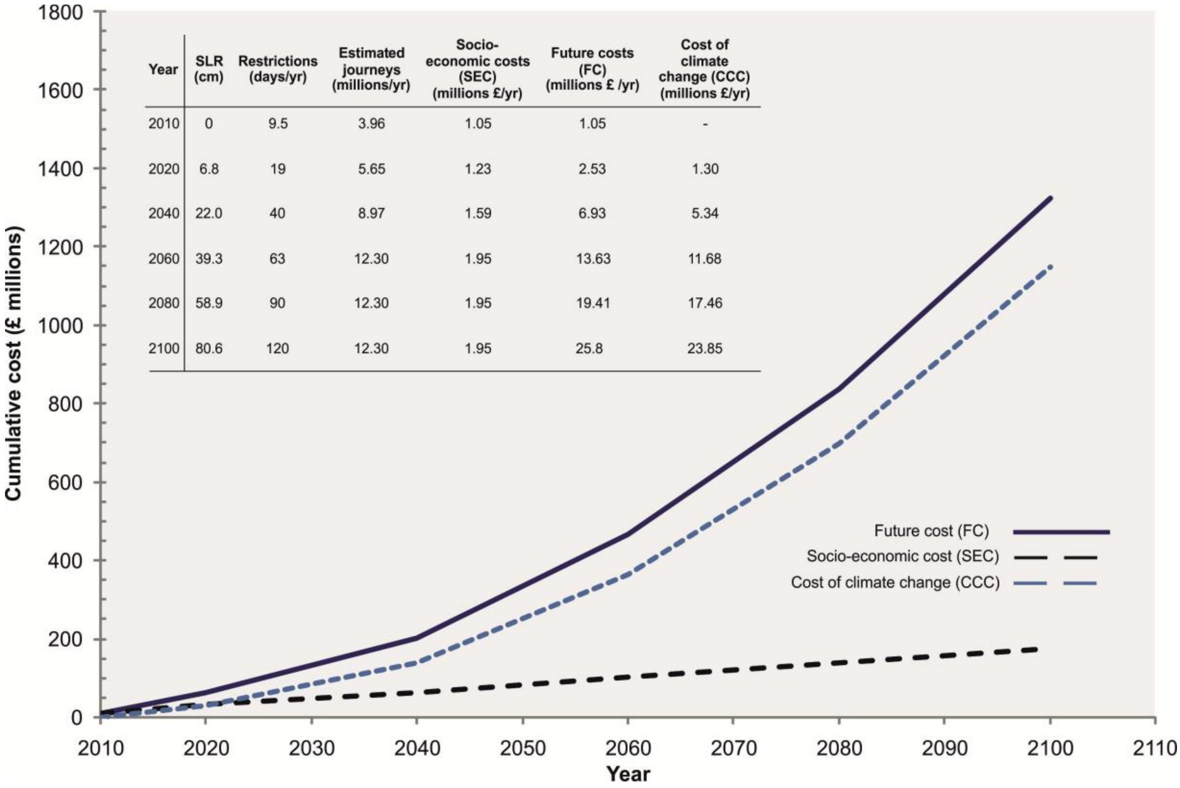
Secondly, the combined (indirect and direct) costs will be presented for each scenario to illustrate that the impacts (quantified using patronage) could take a number of trajectories. Finally, the scenarios will be used to discuss the possible trajectories of broader policy/socio-economic context that the railway may exist in, and in each scenario different decisions for the railway may be made. Each scenario begins with a number of headline points that describe the scenario's key characteristics.

6.5.1 World Market scenario

- Highest threat from sea-level rise
- Highest growth, innovation and demand
- Unwillingness to plan ahead and adapt
- Government's responsibility for climate change not well defined
- Low decision maker credibility

A World Market orientation is one based on the pursuit of high, and sustained, growth within a global context, and has the highest (and fastest) rise in national GDP. In the Southwest, society will aspire to personal independence, material wealth and mobility all to the exclusion of the environment. Economic development is linked strongly to the proximity, and connection, to the capital (i.e. the main driver of growth). Efficient transport networks will be vital to remain economically competitive. Regional institutions will therefore be responsible for attracting inward finance to secure jobs through investment in transport and other infrastructures. This scenario is also characterised by the highest increases in (coastal) population and households and, by 2050, the region's households could have increased by 1 million (from 2001 figures) to over 3 million (Dalhström and Salmons, 2005). Current transport links will be under pressure to support this, and a high level of transport investment will be crucial. Society's unwillingness to plan ahead and cut carbon emissions, however, leads to an increased vulnerability to climate change (e.g., high emission scenarios). Sea levels will consequently reach a maximum of 0.81 m higher than at present by the end of the century, and will put coastal transport infrastructure at maximum risk of failure. In terms of coastal defence, it is suggested that economic benefits are the main driver for investment, and defence will be mainly privately funded as the public sector will withdraw. Consequently, this may lead to an uneven approach to coastal management that does not take long-term sustainability into account. The national annual coastal investment is estimated to be the largest of the scenarios at around £350 million by 2020 (UCKIP, 2001), but the increase in population and coastal development will put the largest pressure on this resource. Figure 6.7 presents the quantified results.

The highest passenger growth, sea-level estimates, and the predicted incidents on the line result in the highest costs calculated in this study. In terms of traffic incidents, between 2020 and 2100 the results (Chapter Five) suggests there will be on average from 19 to 120 days with line restrictions (DLRs) per year and by 2060 it is estimated ~20% of the year (35% of winter) will be run under some level of line restriction. From this level of rail impedance the future costs (FC) of rail user time loss and average defence maintenance are estimated to range from £58 - £1307 million during the next nine decades. This results from annual costs of £2.53 - £25.80 million per year. In comparison with baseline costs (SEC) sea-level rise is estimated to increase the costs in the region from 75% - 650% over the century. The annual CCC are therefore estimated to be £1.30 million/yr during the 2020s and by the second half of the century the impacts on the line are expected to create additional costs of between £11.68 - £22.85 million/yr.



Year	SLR (cm)	Restrictions (days/yr)	Estimated journeys (millions/yr)	Socio-economic costs (SEC) (millions £/yr)	Future costs (FC) (millions £ /yr)	Cost of climate change (CCC) (millions £/yr)
2010	0	9.5	3.96	1.05	1.05	-
2020	6.8	19	5.65	1.23	2.53	1.30
2040	22.0	40	8.97	1.59	6.93	5.34
2060	39.3	63	12.30	1.95	13.63	11.68
2080	58.9	90	12.30	1.95	19.41	17.46
2100	80.6	120	12.30	1.95	25.8	23.85

Figure 6.7 Average annual and cumulative costs of sea-level rise in a World Market (high emission) future. The estimates of sea-level rise, line restrictions (DLRs) and passenger increases are also presented (see table insert) along with the average annual costs for the remainder of the century. The cumulative total of the annual costs are illustrated for the proceeding two decades assuming a fixed cost per year (from the table). All estimates are relative to 2010.

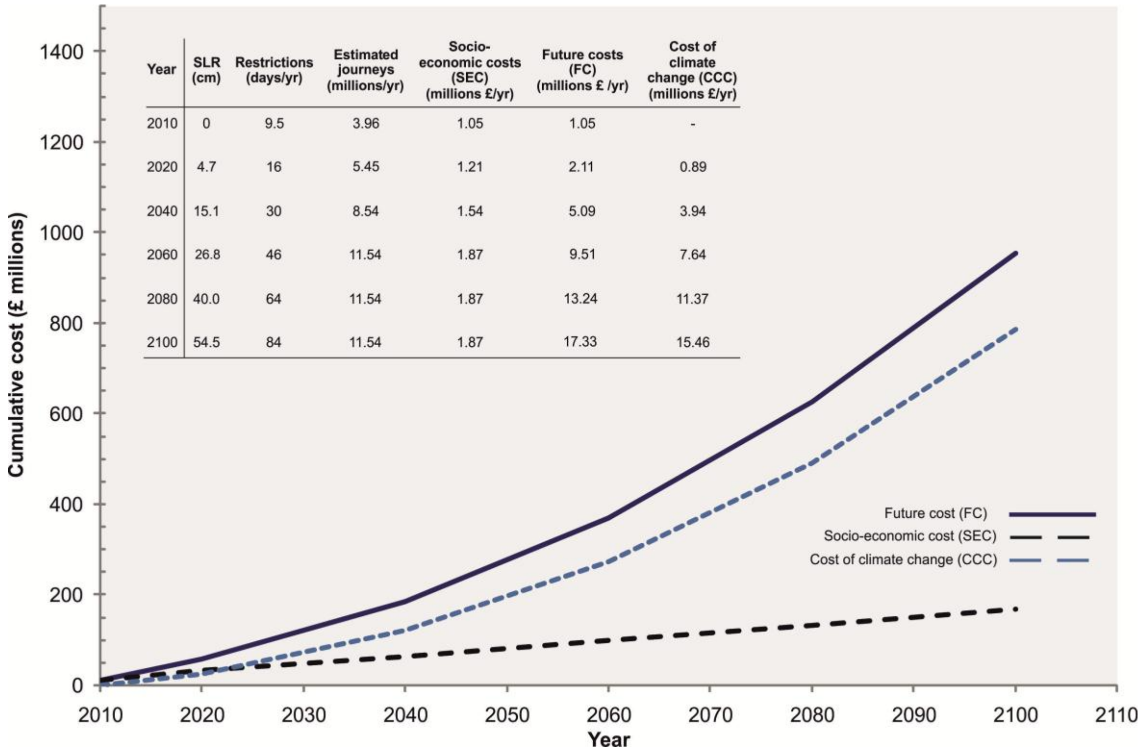
As a result, the cumulative total CCC is estimated to reach up to £23.85 million during the 2020 period. By the end of the century, however, the increased problems on the line will have reached a net total of £1.13 billion. There are wider impacts of this scenario to consider however. In this future there is more patronage, economic growth, and capital available for transport and coastal defence investment. Planning for the future and adaption, however, are not major priorities, thus the capital for investment may be spent on less sustainable (quicker 'fixes') to the problem (i.e. on road building to support the high population and households). This would result in socio-economic exclusion for coastal communities that rely on the railway and its trade particularly as local services are thinned. In the long term Plymouth and Cornwall could be significantly impacted as the region's competiveness, productivity, and local and inter-regional labour networks may be affected. The regions airports and roads, however, may become more viable transport options for travellers (i.e. business and leisure).

6.5.2 Global Sustainability scenario

- Lowest sea-level threat
- Medium high growth, high innovation and demand
- Coastal protection judged as most vulnerable by the nation
- Clearly defined roles and responsibility for climate change adaptation
- High decision maker credibility – value experts

In this scenario, the global environment is a political priority and regional climate vulnerability is, therefore, considered lower than alternative scenarios. Sea-level rise, along the Southwest's mainline, will reach a maximum of 0.55 m by 2100, ~0.15 m lower than the World Market projections. Despite lower sea level forecasts, the Southwest's population will still require extensive protection in coastal areas as populations and household growth continues to increase (e.g., 2.8 million households by 2050). The annual coastal defence expenditure, however, will be mainly public funded and is estimated to be significantly lower than the World Market future, at around £200 million a year by 2020. National growth is expected, but not as much as the World Market scenario, and there is a trend towards eco-economic growth with opportunities being felt most in areas offering eco-efficient goods and services (i.e. transport). The scenario implies that, nationally, the modernisation and restructuring of freight and passenger transport will be carried out with the longer-term aim of increasing public road and rail transport. Thus, the demand for rail transport in the Southwest is one of the highest as the economy needs a mobile work force and society requires greener transport links (to reduce road congestion). Transport investments are carried out with the strong emphasis on minimising environmental impacts and private transport. The cost of travel and transport (e.g., fuel), therefore, rises to guarantee minimal environmental impacts. With the emphasis on the natural environment the local government's role is strengthened with increased open democratic partnerships. Furthermore, institutions and decision makers are themselves considered credible and a balanced approach to coastal management may offset flood risks (UKCIP, 2001). The future costs to the region remain high, however, as the demand for passenger transport increases, similar to World Markets, and by 2060 nearly 11.5 million journeys are made in the region annually (over 100% more than present). Figure 6.8 presents the estimates.

With the lowest emissions and sea-level projections, DLRs are estimated to range from 16-84 days per year during this century (2020-2100). By 2020, 5% of the days of the year could be affected by restrictions and by 2060 this could reach around 13% (or 25% of the winter). Without the effects of sea-level change the cumulative SECs are estimated between £32 and £168 million (£1.21 - £1.87 million/yr). The impact of sea-level rise, however, is estimated to increase these costs by up to 240% by 2060. Consequently, the future cost (FC) are estimated to reach £327 million (£9.51 million/yr) and, over the century (2020-2100), range from £50 to £907 million (£2.11 - £17.33 million/yr). From these figures, the estimated CCC (from increased DLRs and maintenance) is expected to range from £0.89 million/yr, during the 2020 period, to £15.46 million by 2100. Cumulatively, these annual costs will reach £17 -£740 million respectively.



Year	SLR (cm)	Restrictions (days/yr)	Estimated journeys (millions/yr)	Socio-economic costs (SEC) (millions £/yr)	Future costs (FC) (millions £ /yr)	Cost of climate change (CCC) (millions £/yr)
2010	0	9.5	3.96	1.05	1.05	-
2020	4.7	16	5.45	1.21	2.11	0.89
2040	15.1	30	8.54	1.54	5.09	3.94
2060	26.8	46	11.54	1.87	9.51	7.64
2080	40.0	64	11.54	1.87	13.24	11.37
2100	54.5	84	11.54	1.87	17.33	15.46

Figure 6.8 Average annual and cumulative costs of sea-level rise in a Global Sustainability (low emission) future. The estimates of sea-level rise, line restrictions (DLRs) and passenger increases are also presented (see table insert) along with the average annual costs for the remainder of the century. The cumulative total of the annual costs are illustrated for the proceeding two decades assuming a fixed cost per year (from the table). All estimates relative to 2010.

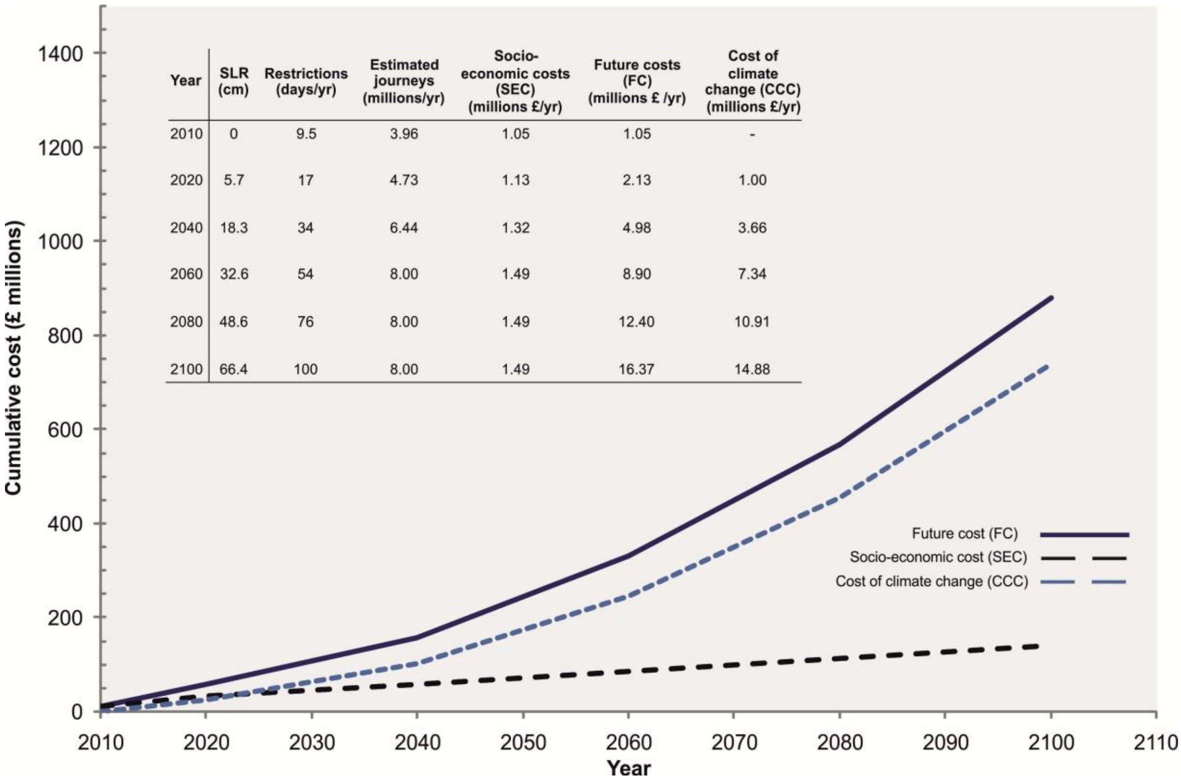
Under this scenario, the costs of climate change are estimated to become prominent slightly later than the World Market future and, by 2060, are £118 million lower. This difference is significant when accounting for the cost of defence expenditure (i.e. Table 2.2) In terms of the broader context, however, the railway will be in high demand and the importance of sustainable public transport in the region is recognised. With greater awareness and less severe climate impacts a long-term decision may be made sooner allowing the region to better adapt to change in both sea level and socio-economic trends. Finance for coastal investment in this future, however, is low and the quality of the infrastructure, if threatened, may not allow the region to capitalise on the greener transport demands required by the sustainability led economy. Access to less affluent coastal communities may become difficult, resulting in greater regional and local disparity and increased congestion on the roads.

6.5.3 National Enterprise scenario

- Medium sea-level threat
- Medium-low growth, innovation and demand
- Society has a lack of cooperation toward climate
- Clear responsibilities towards CC but and based on personal responsibility
- Medium-low decision maker credibility

In this scenario people aspire to personal independence and material wealth regardless of the environment. It is similar to a World Market future, however, it is set within a national based cultural identity rather than global (UKCIP, 2001). Furthermore, The Government has a lukewarm view and commitment to climate change and adaptation with decision making being made at the national level public participation is somewhat reduced. Sea-level rise along the Southwest coast is predicted to be higher than in a Global Sustainability future but less than a World Market future, and a maximum increase of 0.67 m is predicted by 2100. Economically, the Southwest will exist in a medium-low growth future, coupled with poor technological innovation and little additional investment for public transport. This affects the quality of transport infrastructure, and road demand increases to full capacity.

Population and household demand grows relatively slowly and, therefore, rail passenger demand grows relatively slowly – in comparison with more interdependent governance scenarios – as society use personal transport more. Policies are made at the national level and the economic and organisational capacity to protect coastal zones is therefore weakened. Annual investment in coastal protection is estimated at £230 million by 2020, higher than today, but is limited by a range of economically justified spending. Furthermore, a general lack of national cooperation leaves the individualistic society vulnerable to climate change and large differences in impacts are felt regionally. The estimated implications of this scenario are presented in Figure 6.9.



Year	SLR (cm)	Restrictions (days/yr)	Estimated journeys (millions/yr)	Socio-economic costs (SEC) (millions £/yr)	Future costs (FC) (millions £ /yr)	Cost of climate change (CCC) (millions £/yr)
2010	0	9.5	3.96	1.05	1.05	-
2020	5.7	17	4.73	1.13	2.13	1.00
2040	18.3	34	6.44	1.32	4.98	3.66
2060	32.6	54	8.00	1.49	8.90	7.34
2080	48.6	76	8.00	1.49	12.40	10.91
2100	66.4	100	8.00	1.49	16.37	14.88

Figure 6.9 Average annual and cumulative costs of sea-level rise in a National Enterprise (medium emission) future. The estimates of sea-level rise, line restrictions (DLRs) and passenger increases are also presented (see table insert) along with the average annual costs for the remainder of the century. The cumulative total of the annual costs are illustrated for the proceeding two decades assuming a fixed cost per year (from the table). All estimates relative to 2010.

Medium sea-level projections associated with this scenario are expected to cause 17-100 DLRs per year over the next nine decades. Consequently, by 2060 around 30% of the winter service could be affected (15% of the year). The estimated SEC are only fractionally lower than the previous scenarios, and over the century the cumulative cost is estimated from £31 to £140 million. However, the results suggest that sea-level rise will increase regional costs by 60% - 510% during the remainder of the century. The expected annual FC of increased incidents is lower than the Global Sustainability future and range from £2.13 to £16.37 million/yr. The cumulative FC is estimated from £50 million by 2020 to £859 million by 2100, and around £312 million during the latter half of the century (2060 onwards). The calculated CCC is therefore predicted to reach a total of £19.03 million during the 2020s, £228 million during the 2060s, and £718 million by the end of the century. These cost estimates are the third highest but are some £418 million lower than the World Market estimates. However, these annual estimates are reasonably close to the Global Sustainability cost despite the difference in the climate emission scenario used and this clearly highlights the impact of socio-economic trends on the future cost of climate change.

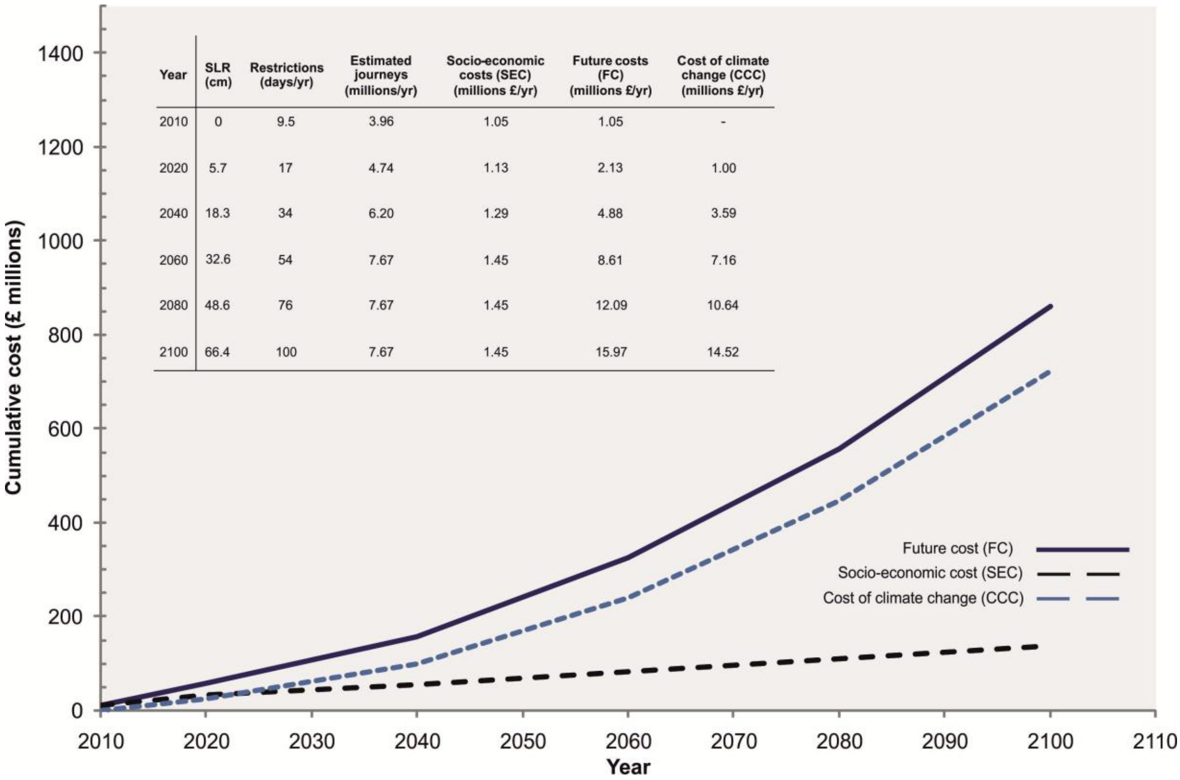
In other regional analyses of this scenario it was described as presenting a very poor future as higher climate impacts are exuberated by poor protection of the environment, lost opportunities and lagging regional economies (Shearlock, 2001). The results here would align with that statement in that the Southwest faces increased economic stresses with a slow growth economy and rising annual closures on the mainline and inter-regional services. A lack of investment for public transport and coastal defences mean the railway infrastructure may be left to deteriorate without an alternative. Roads may become the cheaper alternative and congestion will increase as a result. Coastal communities will be left isolated and the region, as a whole, may see greater disparity in its production and labour markets creating an inability to react efficiently to changing economic markets.

6.5.4 Local Stewardship scenario

- Medium sea-level threat
- Lowest growth, innovation and demand
- Threats of climate change clearly understood locally/regionally
- National responsibility less well defined
- Medium-high decision maker credibility

The final scenario is characterised by the recognition of conserving the local assets and accepting that this might result in significantly reduced economic growth. Furthermore, the commitment to climate change is high with decision makers acknowledging the risks between technology and the environment. A lack of growth (nationally) and innovation, however, means the ability to tackle climate change and carbon emissions is not sufficient enough to lower the impacts of sea-level rise in the region and, by 2100, 0.66 m of sea-level rise is predicted (thus it aligns with medium sea-level projections). By 2020, annual investment for coastal infrastructure is the lowest of all the scenarios (£150 million per year) as public bodies try to keep maintenance investment low. In the coastal zone, 'managed retreat' becomes an increasingly important policy option, especially where sea-defences are costly. As investment is reduced the quality of sea defences are threatened and this significantly increases the risk of economic loss through defence failure (nationally). The long-term average of populations and households seize to grow as rapid as in other scenarios and the lower growth also affects the transport sector (trade and demand) as investment will be reduced resulting in poor quality infrastructure. Regionally, policy-making will involve extensive public and stakeholder consultation (surveys, focus groups etc.) and will tend to turn policy attention inward (reflecting public concern) but the egalitarian system slows down decision making process. The costs calculated for this scenario are the lowest of all the scenarios and are presented in Figure 6.10.

The physical impacts to the railway under this scenario are identical to the National Enterprise estimates and thus a maximum of 30% of the year (55% of the winter) will be run under some level of line restriction by the end of this century The future estimates with no climate are close to the National Enterprise scenario also, and range from £30 million to £138 million during this century. Factor into these the medium sea-level projections, however, and the net FC range from £50 to £840 million. This century, the annual CCC is expected to range from £1.00 - £14.52 million/yr and, assuming no adaptational measures are undertaken, this will equate to a total cost of £19 - £701 million over the next 90 years. These climate impacts are the lowest estimated despite the medium climate emissions and are very close to the National Enterprise scenario. However, important differences must be outlined.



Year	SLR (cm)	Restrictions (days/yr)	Estimated journeys (millions/yr)	Socio-economic costs (SEC) (millions £/yr)	Future costs (FC) (millions £/yr)	Cost of climate change (CCC) (millions £/yr)
2010	0	9.5	3.96	1.05	1.05	-
2020	5.7	17	4.74	1.13	2.13	1.00
2040	18.3	34	6.20	1.29	4.88	3.59
2060	32.6	54	7.67	1.45	8.61	7.16
2080	48.6	76	7.67	1.45	12.09	10.64
2100	66.4	100	7.67	1.45	15.97	14.52

Figure 6.10 Average annual and cumulative costs of sea-level rise in a Local Stewardship (medium emission) future. The estimates of sea-level rise, line restrictions (DLRs) and passenger increases are also presented (see table insert) along with the average annual costs for the remainder of the century. The cumulative total of the annual costs are illustrated for the proceeding two decades assuming a fixed cost per year (from the table). All estimates relative to 2010.

Although this scenario shares the same climate impacts used in National Enterprise (e.g., medium emissions) the broader political and socio-economic context of this scenario has several differences. The future is characterised by effective decision making and, structurally, local governance and policy making are better set up to tackle issues effectively. Investment, however, is the significant problem and is the lowest for coastal defences. This is coupled with a more ‘managed retreat’ policy action leaving defences and transport infrastructure at risk of deterioration. As the region’s transport is reduced (lower demand is also predicted), the local and regional economies, for which smaller businesses and communities will rely upon, will see a reduced ability to generate investment (which is already low nationally). Although extensive consultations may take place to establish the action needed to tackle climate changes at the local and regional level, the funding and investment will be difficult to obtain due to the general slower economic growth both regionally, and nationally. Consequently, the railway may be left to deteriorate and the socio-economic isolation described in other scenarios may be felt. Now all the scenarios have been presented a final summary is given.

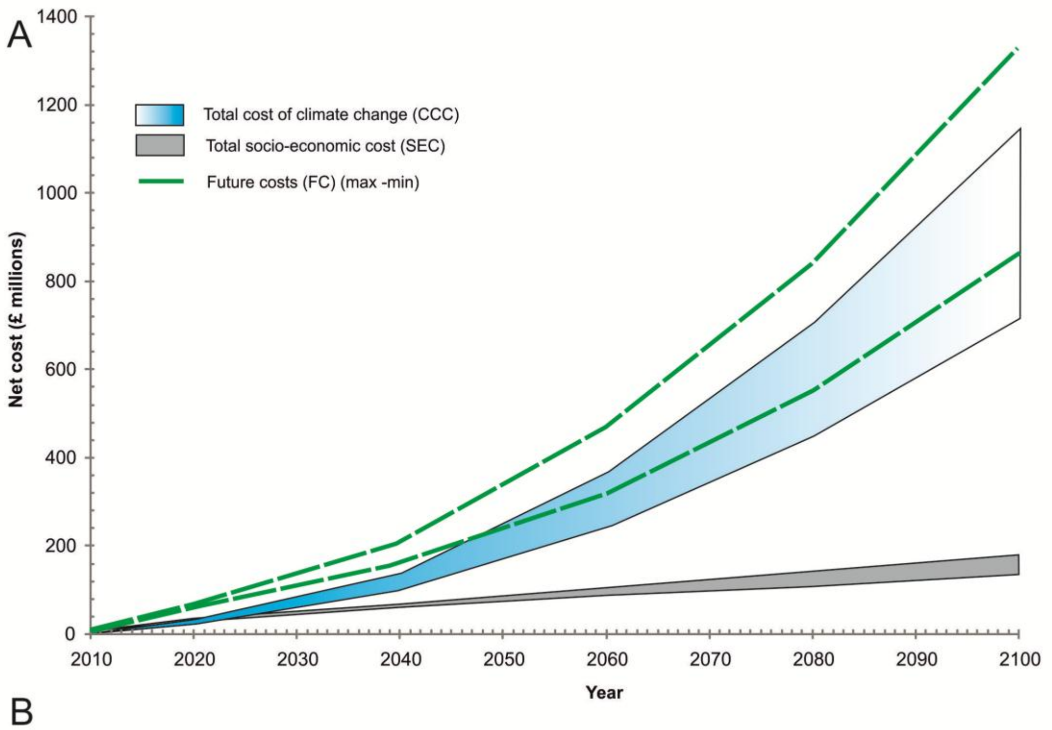
6.5.5 *The future impact of sea-level rise*

The empirical-based evidence has shown that, regardless of the scenario, the Southwest faces increased closures of the main railway line during the 21st century. Figure 6.11a summaries the impacts in terms of costs (indirect and directly) constructed in this study. It is estimated that the cost of increased incidents and defence damage will become prominent during the 2020s, from which the impact to the region will increase substantially. The impact of rising sea levels and overtopping could increase annual costs by up to 350% by 2060, and these costs will need to be considered when evaluating the sustainability of potential line options in future transport strategies. It is beyond the scope of this study to discuss and analyse (i.e. cost/benefit) all the potential options, however, some potential line options were presented in Chapter Two of this thesis (Table 2.2). These were gathered from Network Rail's *Frontage Management Report* (Rogers and O'Breasail, 2006) and an unpublished MSc dissertation (Phillips, 2009). This information was adapted to present the capital cost of two future line options (Figure 6.11b).

The first option (Option 1) is to carry out all the major defence improvements to reduce overtopping on the existing line. This includes new sea walls, heightened sections, new rock revetments and offshore breakwaters amounting to a capital cost of over £150 million

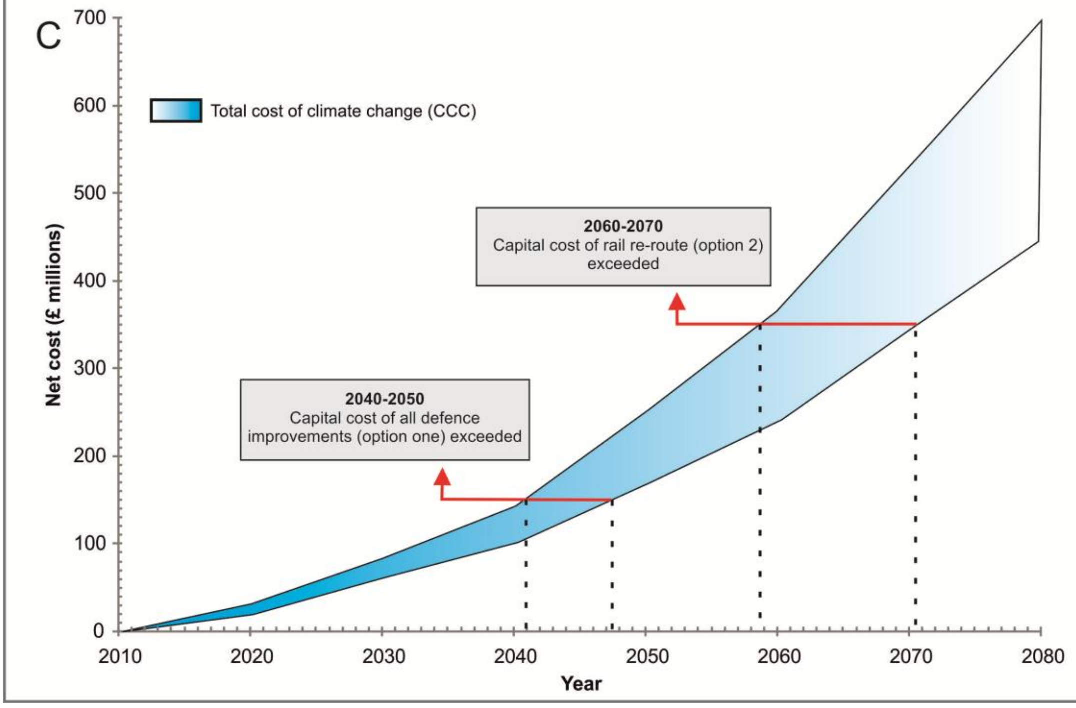
(Rogers and O’Breasail, 2006). This would potentially reduce the amount of overtopping of the line (and consequently offset the future economic impacts). The long-term implications of this in terms of structure integrity and annual maintenance would be questionable, however. The second option (Option 2) regards a completely new inland route and requires two new tunnels at an estimated cost of ~ £330 million (see Appendix A - 1.1b). This would solve the problem of increased overtopping, however, the coastal communities (Dawlish, Teignmouth, Starcross etc.) would be left with a deteriorating section of coastal defence that would still require regular maintenance for the projection of the population. By comparing the capital cost of these major line options with the estimated cost of climate change (CCC) constructed in this thesis the importance of a long-term planning perspective is illustrated (Figure 6.11c). Assuming there are no major changes to the defence structures on the Dawlish-Teignmouth section of line (i.e. a do-nothing scenario) the estimated additional cost as a result of sea-level rise (e.g., the CCC) will exceed the capital cost of constructing all the major defence structures (option 1) by the period 2040-2050.

These estimates suggest that, under a do-nothing scenario, the CCC will outweigh any potential defence improvements in the next 30 years. Similarly, the proposed re-route (option 2) has a capital construction cost of £330 million, assuming the empirical trends in this study the average cost of incidents will exceed the capital cost of a new line by 2060-2070. From this brief analysis it is demonstrated that any delay in decision making regarding the line’s future will be costly, and by 2060 these costs may equal the most expensive line option (e.g., a re-route). At the beginning of this chapter, a recent discussion in Parliament outlined that the Government has no plans to make a decision on the line until 2025 (Hansard, 10th November, 2010).



B

Example decision options	Description/implications	Estimated capital cost
Option 1: Improve all existing defences along the track	Heighten sea wall, extend rock revetment, new sea wall, offshore breakwaters. Reduce overtopping and line closure (temporarily). However, may lead to the structures becoming unstable and more prone to collapse. Also, significant recreational and environmental issues.	£155,824,900 *(Rogers and O'Breasail, 2006)*
Option 2: Re-route the line via tunnels inland	This would solve the coastal defence problem and enable upgrading of the network system to higher specification. However, issues relating to cost and socio-economic importance of the line would cause major conflict.	£330,000,000 *(Phillips, 2009)*



2060-2070
Capital cost of rail re-route (option 2) exceeded

2040-2050
Capital cost of all defence improvements (option one) exceeded

Figure 6.11 a – Estimated cost of sea-level rise on the London-Penzance railway line 2010 to 2100. Maximum and minimum costs represent the range of scenario used in the study. b – Two examples of potential line options adapted from Roger and O'Breasail (2006) and an unpublished MSc dissertation – Philips (2009). c - comparison of potential line options and the estimated costs of climate change (CCC) 2010-2080). All costs values are relative to 2010.

However, during this discussion it was suggested that the cost of a re-route would be more in the region of £100 million (source not given). If this were the case, the CCC would exceed the capital cost of constructing a new line would be exceeded during the 2030s-2040s. It must be noted that any short-term improvement of the defences will have the potential to offset these costs to some extent. However, in the long-term, the future of the railway will remain the same, and there is a real need to begin planning the region’s transport network as the sustainability of the main railway line will be significantly reduced over the next few decades.

It should be noted that the figures presented in Figure 6.11 do not incorporate future discounting of the costs of climate impacts or the adaptation options considered. However, future discounting is nearly always used in investment decisions and climate-change policy in order to reflect the relative weight of future and present payoffs of climate-related liabilities and response actions (Nordhaus, 2007). The practice takes place because individuals attach less weight to a cost-benefit in the future than they do to the cost-benefit at present (UKCIP, 2003). Furthermore, in a detailed financial appraisal of the options, it would be necessary to include the financial costs borne by the implementing agency (i.e. public or private). These are primarily likely to take the form of annual interest payments on loans required to finance capital expenditures.

To illustrate the potential size of the borrowing costs for the two options, the costs associated with interest rates of between 5-10% are presented in Table 6.9. These rates are illustrative, but reflect typical financial market interest rates over the last 20 years. The period of the loan is assumed to be for 20 years from the present and equal payments are made annually to repay the loan in full by the end of this period. The interest payments on such large capital costs are substantial and can result in payments comparable to, or exceeding, the original capital sum. As demonstrated, the new tunnels estimated to cost

£330 million would incur interest repayments of £173 million with a 5% interest rate over twenty years. A 10% rate, however, would raise this figure to £347 million, which exceeds the original capital sum borrowed.

Line option	Capital cost (£)	Interest payment (£) 5%	Interest payment (£) 10%
1	152,000,000	79,800,000	159,600,000
2	330,000,000	173,250,000	346,500,000

Table 6.9. Interest payments on capital investment costs of two line options (discussed in this Chapter and Chapter 2), assuming a 20 year repayment and 5% and 10% rates of charge. Note: based on the equal annual repayments .

At the same time, the financial costs to Network Rail associated with the future impacts of climate change (that would be avoided if the line was re-routed) will be discounted at a similar market rate of interest to that charged on borrowing. To illustrate this, discount rates of 5% and 10% have once again been used (see Table 6.10), though the current historically low rate of 2.5% could also be used[14]. The financial costs include the increased maintenance and penalty charges, as a result of overtopping, taken from section 6.3.1 (Table 6.1), under a high emission sea-level scenario.

Year	Financial costs (cumulative 2010 prices)	Discounted financial costs (d.r. 5%)	Discounted financial costs (d.r. 10%)
2020	11,508,315	8,954,706	7,223,896
2030	19,100,540	9,054,564	4,524,911
2040	21,221,756	6,049,518	1,866,113
Total	**51,830,610**	**24,058,789**	**13,614,921**

Table 6.10 Financial costs of annual rail impacts (e.g. increased maintenance and delay minutes) under high sea-level scenarios and discounted using an illustrative rate of 8.5% (representative of the current market). Financial costs (impacts) are taken from Table 6.1 of this chapter.

The cumulative financial cost estimated by 2040 is ~ £52 million; however, taking into account the annual discount rate of 5% the cumulative cost in present values is reduced to

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[14] Commercial interest rates in the UK tend to be about 2% higher than the Bank of England Base Rate. (See Bank of England, 2011)

~ £24 million, and a 10% rate reduces the costs further. This example has assumed that the implementing agency is a private organisation motivated primarily by financial profit and, thus, interested mainly in financial costs that would be incurred by the organisation.

If the adaptation option is undertaken by a government agency, however, then this is assumed to be motivated primarily by social welfare objectives. Consequently, appraisal would need to be subject to a social cost-benefit analysis. In this case, the appropriate discounting regime is that given in the project appraisal guidance published by H.M. Treasury (HMT, 2003)[15]. This rate is currently set at 3.5% for the first 30 years, declining thereafter. In a social cost-benefit analysis, interest payments are not included since they represent a transfer between groups within society rather than a net economic cost. Capital cost is discounted in the year that it is incurred whilst benefits are discounted in all years that they arise. These are illustrated in the Table 6.11. The impact avoided by an adaptation option (or incurred without) is reduced under the notion that individuals value welfare more today than in the future. Therefore, by 2040 cumulative impacts are estimated at £67,989,018 based on 2010 prices, these cumulative impacts in present value (discounted) terms are estimated to be £37,869,026.

Year	Impacts avoided (Cumulative, 2010 prices)	Present value impacts avoided (d.r. 3.5%)
2020	13,027,592	9,005,904
2030	25,281,121	12,125,421
2040	29,680,306	9,988,395
Total	**67,989,018**	**31,119,719**

Table 6.11 Impact costs of annual overtopping incidents under high sea-level scenarios and discounted using a rate of 3.5%. Discount factors taken from HM Treasury's Green Book (2003).

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[15] Note, however, that there remains significant controversy over the appropriate social discount rate, as highlighted by Stern (2006), who argued for a lower rate, and the subsequent commentaries e.g. Weitzman, (2007) and Nordhaus (2007) who argue for a higher rate.

It must be noted, however, that the financial costs presented Table 6.10 are lower than the impacts presented above. These costs (Table 6.11) include the indirect socio-economic impacts based on passengers affected by overtopping under a World Market scenario where passenger numbers are estimated to increase significantly. The financial costs presented in Table 6.10, on the other hand, include 2000-2010 delay minutes extrapolated with a standard charge per minute, and thus have no consideration for future demand changes. Finally, Table 6.12 presents an illustrative example of a basic cost-benefit calculation assuming that a new inland route is built in 2011, and thus reduces the impacts of sea-level rise to zero.

Average annual costs of maintenance are assumed to be £500,000 for the new stretch of track. The results presented in the table indicate that the net balance of discounted benefits and costs is negative, suggesting that the option is not justified on the grounds of economic efficiency. The assumptions in this example are large, however, and there are also large uncertainties in the costs used. For example, the capital cost of investment may be too high (e.g. the cost recently discussed in Parliament (Hansard, 10th October, 2010)), and the benefits of having an unimpeded fully functional main railway may be too low. Furthermore, this benefit-cost example only examines the period up to 2040 and, therefore, ignores the benefits for the remainder of the century.

As shown, the extent to which discount rates are used in climate impact assessments is an important consideration in economic studies. Most notably, climate-impact costs are less likely to be substantial further into the future since the application of conventional discount rates reduces these costs substantially. There has been significant discussion of the use of discounting rates in long-term climate studies (see Nordhaus, 2007 for a critique) but it is not in the scope of this study to address this, other than to highlight its potential effect on decision making under future uncertainty. Due to its importance in economic evaluation, however, it is useful to highlight the effect and implications for climate-change and policy making, and to stress the need for further economic analysis.

Year	Discount factor (rate = 3.5%)	Scheme costs (Annual, 2010 prices)	Present value costs	Scheme Benefits (Annual, 2010 prices)	Present value Benefits (d.r. 3.5%)	Present value: Cost - Benefits
2011	0.97	330,000,000	318,840,580	1,049,948	1,014,442	-318,840,580
2012	0.93	500,000	466,755	1,049,948	980,138	466,755
2013	0.90	500,000	450,971	1,049,948	946,993	450,971
2014	0.87	500,000	435,721	1,049,948	914,969	435,721
2015	0.84	500,000	420,987	1,049,948	884,028	420,987
2016	0.81	500,000	406,750	1,049,948	854,133	406,750
2017	0.79	500,000	392,995	1,049,948	825,250	392,995
2018	0.76	500,000	379,706	1,049,948	797,343	379,706
2019	0.73	500,000	366,865	1,049,948	770,379	366,865
2020	0.71	500,000	354,459	1,049,948	744,328	354,459
2021	0.68	500,000	342,473	2,528,112	1,731,620	342,473
2022	0.66	500,000	330,892	2,528,112	1,673,062	330,892
2023	0.64	500,000	319,702	2,528,112	1,616,485	319,702
2024	0.62	500,000	308,891	2,528,112	1,561,822	308,891
2025	0.60	500,000	298,445	2,528,112	1,509,006	298,445
2026	0.58	500,000	288,353	2,528,112	1,457,977	288,353
2027	0.56	500,000	278,602	2,528,112	1,408,674	278,602
2028	0.54	500,000	269,181	2,528,112	1,361,037	269,181
2029	0.52	500,000	260,078	2,528,112	1,315,012	260,078
2030	0.50	500,000	251,283	2,528,112	1,270,543	251,283
2031	0.49	500,000	242,785	2,528,112	1,227,578	242,785
2032	0.47	500,000	234,575	2,528,112	1,186,065	234,575
2033	0.45	500,000	226,643	2,528,112	1,145,957	226,643
2034	0.44	500,000	218,979	2,528,112	1,107,205	218,979
2035	0.42	500,000	211,573	2,528,112	1,069,763	211,573
2036	0.41	500,000	204,419	2,528,112	1,033,587	204,419
2037	0.40	500,000	197,506	2,528,112	998,635	197,506
2038	0.38	500,000	190,827	2,528,112	964,865	190,827
2039	0.37	500,000	184,374	2,528,112	932,237	184,374
2040	0.36	500,000	178,139	2,528,112	900,712	178,139
Total		**344,500,000**	**327,553,511**	**61,061,721**	**34,203,844**	**-293,349,666**

Table 6.12. An illustrative example of benefit-cost analysis of a potential new line inland railway line (option 2), in which the new line is determined to be uneconomical over the next 30 years (not representative of the 21st entire century). The calculation assumes the scheme costs and benefits (impacts) already discussed in this chapter.

Notwithstanding the uncertainties in the estimates presented, the results provide important new insights for policy makers in the region. But the question of how this scientific data will be utilised in the future planning for the region remains unknown. The concern of non-government analysts, discussed in Chapter Two, regarding the significant barriers (or gaps) to the use of scientific evidence in UK policy making has important implications for the issues on the railway line. The integrated scenarios presented here may have an influence on such gaps and, consequently, the region's vulnerability to climate change. However, the final section of this chapter examines the boundary between science and policy in the UK with reference to the broader socio-economic futures discussed under each scenarios.

6.6 Connecting the science to society

Recently, in 2006, the House of Commons' Science and Technology Committee welcomed the Government's progress in integrating scientific evidence into decision making (HoC, 2007). This move towards evidence-based policy making has been justified by assertions that scientific understanding makes better informed and more effective legislative and regulatory decisions (Oreskes, 2002; Lagace et al., 2008; Oreszczyn and Carr, 2008). The Government has produced documents that lay out the principles and guidelines for scientific analysis to help policy makers make better use of the available information (HMG, 1997, 2000, 2005; HoC, 2007). The actual impact of these guidelines has been questioned, however, and the challenges of transmitting/translating science to policy makers are real (Ballantine, 2005; Lagace et al., 2008). Over the years the connection between science and policy has been viewed by various conceptual frameworks of knowledge production. Traditionally the process was viewed as linear, unidirectional and mechanical (e.g., Elzinga and Jamison, 1995; Jasanoff and Wynne, 1998) in that research findings are shifted from the 'research sphere' to the 'policy sphere', and then has some impact on policy makers' decisions (de Vibe et al., 2002). A better appreciation of the complexity of the policy process led to a move away from the linear models towards more alternative, participatory, and inclusive models (e.g., Jasanoff, 2004). These models looked beyond formal government policy making to informal relationships and networks that constitute a wider policy process (Oreszczyn and Carr, 2008). The models tackled the assumptions created with the linear view in that, firstly research influences policy in a one-way process, secondly, that there is a clear divide between policy makers and researchers, and finally that the production of knowledge is confined to a set of specific findings (e.g., a positivistic model) (de Vibe et al., 2002). These models emphasised the complexities of producing science/research that can cross the policy gap – and the external/internal pressures that influence its production, analysing differences between scientists and government cultures (Grande and Peschke 1999; Salter and Martin 2001; de Vibe et al., 2002; van Kerkhoff 2005; Lagace et al., 2008; Pohl 2008).

Levin (1991) and Quevaviller et al., (2005) state that the two communities lack clear co-ordination mechanisms. The review scheme of scientists discouraged, until the recent change to the Research Excellence Framework (REF), policy orientated work in favour of producing publications in narrow audience, high quality, journals in order to maximise funding generated (Shaw and Matthews, 1998; Pacione, 1999; Peck, 1999; Lagace et al., 2008). This issue was raised by geographers in the relevance debate decades ago and connects with the broader problem. Policy makers, on the other hand, are often elected officials and are consequently pressured by public opinion, political agendas and scientific advice. Their need for science (evidence) is spontaneous (reactive) and issue-based to keep pace with the rapid concerns raised by stakeholders and the public, and they generally do not have time to read lengthy reports (Stone et al., 2001; Lagace et al., 2008). Many argue it is the role (or moral responsibility) of the scientist to address this, for example, by re-organising science for its effective use in society (Schoenberger 1998; de Vibe et al., 2002;

HM Treasury, 2004; van Kerkhoff 2005; Lagace et al., 2008; Pohl 2008) or to improve communication (engagement) and methodological approaches (Gopen, 1990; Cash, 2003; Lagace et al., 2008). Effective communication, not only with policy makers, but also across disciplinary divides is a significant issue regarding the science to policy debate. Differences in spatial and temporal scales, not to mention complex political structures, can throw up difficult puzzles for interdisciplinary research (Turner, 2000; van Kerkoff, 2005; Turner, 2007; Tompkins et al., 2008; Pohl, 2008).

These issues parallel the concerns of non-government analysts raised early in this thesis (Chapter Two), as poor communication between sectors and complex governance structures can militate against effective delivery of solutions (Berkhout and Hertin, 2000). For instance, DEFRA, and Tyndall Centre technical reports call for integrated research, improved communication, a simpler national framework, and increased stakeholder involvement in the coastal management of climate change (O'Riordan et al., 2006). Hassol (2008) calls explicitly for better communication of climate change research for policy makers. Hulme and Turnpenny (2004) and Gawith et al., (2009) suggest more guidance and ongoing dialogue between producers and end users are needed for UKCIP studies. Finally, the Institute of Civil Engineers (2009a, 2009b) call for a single point authority to communicate new interdisciplinary research more efficiently. The problem of communication and engagement is raised with issues outlined in the debate of relevance and geographical research (e.g., Shaw and Matthews, 1998; Castree, 2002; Jones and MacDonald, 2007). More broadly, the science to policy agenda concludes similarly, calling for a 'boundary facilitator' to manage inter-disciplinary research so that it is communicated effectively to stakeholders and policy makers. It seems that with adaptation and mitigation being key agendas for the future coastal management, decisions that will inevitably affect a wide range of processes, systems, and societies may be made without sufficient information that, in many instances, is available. The work of geographers would be ideally suited to help tackle these issues in a logical and well informed manner, particularly in issues of coastal management (McFadden, 2008).

When coupled, socio-economic scenarios and impact scenarios provide policy makers with a more complete picture of possible future coastal conditions (Nicholls et al., 2008). The analysis presented here indicates clearly that a ‘business as usual’ approach to coastal management will be accompanied by increased vulnerability from damage, delays and rising costs. The magnitude of this will depend on the trajectory of sea-level rise and broader socio-economic trends, and the delay taken by decision makers to plan adequate adaptation strategies. Each socio-economic scenario (SES) presented in the previous section outlines different futures for decision-maker credibility and, to an extent, scientific evidence used by them. The World Market and National Enterprise futures, for instance, poorly values experts and policy makers and, under these scenarios, key information may not be acknowledged, sought, or incorporated into future strategies. Their futures are economically driven and coastal protection may be provided by the market rather than through government. Thus, decisions will likely be determined by the immediate solution, and the ability to pay, rather than what is understood to be appropriate for the long-term sustainability of the region. On the other hand, examining the Global Sustainability and Local Stewardship futures provides an example of a more conscious socio-economic environment where future impacts may be reduced by long-term planning and sustainable adaptation. These are supported by clearly defined governments that value experts (e.g., research and evidence) and decisions makers highly, and with transparency regarding the roles towards climate change and adaptation. Although funding may be an issue a Local Stewardship futures it provides a potentially beneficial environment for the use of scientific information in adaptation decisions. These scenarios, resultantly, serve to highlight the need to develop effective integrated and informed policy making in the region and the UK more extensively. However, there still remains considerable debate regarding the process of connecting science to policy, much of which is embedded in the issues of applied geography.

Van Kerkoff (2005) concludes that there is little doubt that methodologies that enhance the learning of research for evidence based policy-making are an important step forward addressing the science/policy gap. Using scenarios to improve stakeholder engagement and participation is one option for improving the link between science, policy and practice (Berkhout and Hertin 2000; Berkhout et al., 2002; Nicholls 2004a; Fletcher, 2007; Hulme and Dessai 2008; Oreszczyn and Carr, 2008; Wright et al., 2008). This does not guarantee effective engagement, however, and Tompkins et al., (2008) used 'novel' method of scenario-based stakeholder engagement (SBSE) to explore the trade-offs of coastal management decisions. This involved stakeholder workshops, a method also adopted by Oreszczyn and Carr (2008), and both highlight the benefits of such approaches in implementing research into decision making and policy in areas of future uncertainty.

> '*the* [SBSE] *approach is essentially an adaptive, learning-based management approach which encourages coastal stakeholders to reflect on how decisions are made…. and the implications of the decisions, in terms of their impacts on risks, costs, and participation in decision making… It could become an important decision-support tool to facilitate coastal planning in the UK*' (Tompkins et al., 2008, p.1592).

The complexities of addressing the Southwest's rail issue under potential sea-level rise are high and the costs of failing to do so have been outlined in this chapter. The integrated scenarios presented have been constructed with the intention of providing useful information for stakeholder dialogue and regional decision making. But it is clear that this is the first step of the process and effective communication and engagement with the results will be the next challenge.

6.7 Chapter Synopsis

In combination with the predictions of future line incidents, this chapter has integrated climate and socio-economic scenarios to present four scenario futures for stakeholder consideration. These are formed on the basis of a series of indicative costs indirectly - to the economy, and directly - to the rail industry. The results are illustrative, however, as a full range of impacts was not possible to determine, and it is recommended that they are not used for their exactness without further detailed consideration. A number of conclusions can be made however. Firstly, by examining the link between transport and the economy the connections between future rail closures and the potential socio-economic impacts have been outlined. The increased future closure of an already well developed rail network will affect travel time, reliability and socio-economic networks. This will, ultimately, have a number of impacts on Gross Domestic Product (SACTRA, 1999; Eddington, 2006). Before estimates were constructed, however, the potential costs directly to the Network Rail were examined, in order to illustrate the internal impacts of future rail problems. The cost to the rail industry was constructed using evidence from the rail archives (presented in Chapter Five) and correspondence with Network Rail. These took the form of preventative maintenance costs and penalty delay charges along the sea wall. At present (and in 2010 market values) the evidence used suggests these impacts have cost Network Rail an average of ~£960,000/yr (since 1997). By the end of the century, however, the increased number of annual incidents (DLRs) would result in annual costs of ~ £12.3 million/yr. These are average costs, however, and do not account for major damages or repairs resulting from severe events.

Thirdly, to illustrate the potential indirect impacts of increased rail problems (on the economy) the effects on passenger and freight travel were estimated (in the form of the cost of lost time). Using this method, and recent observations (1997-2009), the evidence suggests that the average time lost during incidents has cost the economy ~ £437,000/yr. By the end of the century, however, and as a result of 0.81 m of sea-level rise, the indirect costs to the region will be around £5.9 million per year. Although, these costs do not account for the wider socio-economic impacts (e.g., loss of new business investment, economic welfare etc.) they give a good indication of the extent of the increasing impact of incidents on the economy. Presented next, was the combination of rail user impacts and maintenance costs, and the penalty charges were excluded on the basis of potential double counting. By 2060, the average annual cost of sea-level rise will be around £5.3 - £7.3 million/yr with a maximum of £13.8 million/yr by the end of the century. Cumulative estimates suggest that the cost will reach up to £215 million during the 2060s and ~£540 million by the end of the century (low emissions). A future without the inclusion of the empirical trend of sea-level rise and incidents, however, would see costs in the range of £70 -£110 million respectively. All of these costs represent the extrapolation of present day socio-economic conditions. However, in order to demonstrate the potential effect of socio-economic futures, the costs were integrated and examined with four socio economic scenarios (SES) (UKCIP, 2001). Changes in rail passenger demand were used as a quantitative indicator for each future (e.g., a quantitative indicator) and were adapted from the Great Western Route Utilisation Strategy (Network Rail, 2010). Qualitative storylines, provided in the SES (UKCIP, 2001), were also used to give some additional wider social/economical/political context.

The total future cost (FC) (combing climate and socio-economic scenarios) calculated are estimated to range from £850 million to £1.3 billion by the end of the century. These were then compared with socio-economic costs (SEC) with no climate change to establish the overall (additional) cost of climate change (CCC). The results suggest that the average annual CCC will range from £1.01 - £1.32 million during the 2020s, and £15 - £24 million by the end of the century. The total cumulative CCC could reach £352 million by 2060 (under a World Market scenario). The broader socio-economic context in which these estimates may exist in was also examined for each scenario. The storylines illustrated the potential consequences of different values and governance on the future rail vulnerability in the region. The World Market future presents the highest risk of impacts and cost for the Southwest and the Local Stewardship future the least (despite having medium emission impacts). However, decision maker credibility and investment for future transport projects differs between all the scenarios and these result in alternative outcomes for the future. For example, the Local Stewardship and Global Sustainability scenarios are characterised by strong government structure with a long-term perspective that value experts and policy makers more than alternative scenarios.

These futures are interesting when considering the current issue (barriers) of connecting science to policy. Communication and engagement are the key barriers to effective management in issues of uncertainty, and the scenarios demonstrate the potential aggravation of these problems based on government structure and decision maker credibility. Using the scenarios approach can help address these barriers and create open and informed dialogue between key decision makers. The integrated scenarios have been constructed to help tackle this present problem and provide credible storylines of the potential future uncertainties. However, on their own, they may not necessarily achieve this but by combining the scenarios with stakeholder engagement the uptake of the findings may be improved.

Transport infrastructure is integral to continued regional economic growth (Mackinnon et al., 2008), and without effective engagement (and further development) with these storylines the quality of the regions transport network and economy will be threatened. During the latter half of this century, after over 0.30 m of sea-level rise, the railway will become significantly more costly in terms of maintenance and economic loss. The length of time taken to plan an adaptational response is directly proportional to the sustainability of the current management approach. By 2060, for example, the highest cost estimates (World Market and high emissions) will have exceeded the capital cost of a new inland railway line. Furthermore, the estuary defences, and the populations that are protected by them, will be at significant risk before this. Preparing for this, in the coming decades, is critical for sustainability and the long-term stability of the region. How policy makers communicate and engage with one another to tackle this will be a key process in adapting to future climate change effectively.

Chapter Seven

Conclusions

7.1 Original aims

The central aim of this thesis is to establish the extent to which future sea-level change will impact upon the Southwest's main railway line. This aim carries three objectives:

1. To establish accurate late Holocene sea-level trends in order to validate geophysical models used in current future sea-level projections in southwest England

2. To establish the likely impacts of future sea-level change on the functioning of the Dawlish-Teignmouth section of the London-Penzance railway line.

3. To integrate climate and socio-economic futures (scenarios) to construct a plausible range of information for future use in policy debates in the region.

In seeking to achieve these objectives, significant scientific and societal issues have been raised and are summarised here. All transport is dependent on the weather and climate (Thornes and Davis, 2002) and impacts on the functioning of the transport network will have deeply embedded regional consequences; transport connects people and services and has a strong social and economic function (Eddington, 2006). Geographers have the necessary skills to understand complex interactions between the environment and society and at its core; this project represents what is commonly understood as applied geography. There has been long debate regarding the use of applied geography in informing future policy decisions (Crisholm, 1971; Berry, 1972; Coppock, 1974; Stoddart, 1975; Pacione, 1999; Peck, 1999; Martin, 2001; Berry, 2002; Johnston, 2004; Ward, 2005). However, steps taken to improve coastal impact assessment (e.g., integrated scenarios) have resulted in conclusions that will be helpful to the wider scientific community and, hopefully, the region's key stakeholders and policy makers.

7.2 New sea-level data for southwest England

In Chapter Four of this thesis a new Holocene relative sea-level (RSL) history for the Southwest was presented based on 25 sea-level index points (SLIPs). Fifteen were taken from previously published early-mid Holocene studies (e.g., Hails, 1975; Massey et al., 2008) and 10 additional late Holocene index points obtained during this project. The 10 new index points were obtained from cores extracted from two coastal valleys at Thurlestone Sands, south Devon. The cores – containing basal salt-marsh units and marine foraminifera – were dated and their combined chronology range from 1619±35 to 439±35 cal. years BP. Prior to this study no basal late Holocene sea-level index points were available from south Devon, and this study has provided the youngest basal index points for the Southwest region. The data suggest that sea level has risen 1.7 ± 0.2 m along the south Devon coastline since 1600 cal years BP. This equates to an average RSL rise of ~ 0.9 ± 0.2 mm/yr. During the last century, however, sea has been rising in the region at ~ 2.0 mm/yr (Haigh et al., 2009). This difference highlights the extent of the present and pending threat of sea-level rise. Importantly, the construction of a new Holocene sea-level history was critical to verify discrepancies between glacio-isostatic adjustment (GIA) models (i.e. objective one). One such model (Bradley et al., 2009) is used to estimate the vertical land movement component in the current 21st century sea-level projections (e.g., Lowe et al., 2009). The new SLIPs from this study were used to extract estimates of vertical land movements for direct comparison with this model.

During the last 2000 years the coast of south Devon has subsided at a rate of ~1.1 ± 0.1 mm/yr. This corresponds well with overall trends of geological data in the south of England, and previous estimates in the Southwest region (although based on unreliable data). In comparison, Bradley et al.'s (2009) model predicts a subsidence rate of -0.97 mm/yr. The difference of 0.16 mm/yr (~17%) would result in an additional sea-level rise of 0.014 m by 2100. This discrepancy is negligible when considering the overall range of the current marine projections scenarios (e.g., 0.25 m by the end of the century, or 1 m under the H++ scenario). Based on this study, however, the new data validate, for the first time, the values of vertical land movements used by UKCP09 in an area where no high-quality observations were previously available. Furthermore, southwest England is predicted to have some of the highest increases in sea-level rise this century and the accuracy of projected water levels is important for coastal management. New sea-level estimates were therefore constructed with an additional 0.16 mm/yr of crustal subsidence for accuracy and use in this study. Overall the outputs of this objective have improved the accuracy of Southwest palaeo sea-level studies and have validated vertical land movements and future sea-level projections in the region. Objective two was to establish the nature and extent of these projections on the functioning of the Southwest main railway line.

7.3 The vulnerability of the Southwest Mainline

At present, Network Rail's service records show there are around nine days with line restrictions (DLRs) per year (O'Breasail et al., 2007; Network Rail et al., 2010). During the period of observation (1997-2009) an average of 5.4 level 1s (speed restrictions and monitoring), 3.8 level 2s (closure of down line and monitoring) and 0.3 level 3s per year (total closure and full inspection) have occurred. Projections based on an empirical relationship between sea-level rise and incidents suggest that a 0.05 - 0.07m rise in water level (estimated by 2020) will double the current amount of DLRs causing an average of

16-19 annual incidents per year. By the end of the century, however, up to 0.81 m of sea-level rise is estimated, and DLRs are expected to reach from 84 – 120 per year (emission dependent). This would be the equivalent of 46% – 66% of the winter period running with some level of emergency speed restriction or closure. By 2020, level 1s are expected to increase by over 83% from present, level 2s by 121%, and level 3s by 100%. By the end of the century, however, the situation is predicted to get much worse. Level 1s and Level 3s are predicted to increase by ~1100%, and level 2s by over 1300%. This equates to an overall increase of all incidents by 1170%. The figures assume a linear increase in incidents. However, it has been highlighted that non-linear trends may occur as a result of more vulnerable sections of track (e.g. King Harry's Walk, Dawlish).

In terms of the impact to traffic, increased and extended disruption (i.e. delays and restrictions) to services and passengers on the line during high tides will be expected. Local (class 2) rail services will be affected more frequently as they are thinned (or cancelled) to allow intercity travel schedules to be maintained. Major events (e.g., level 3s) are typically the focus of discussion of problems in the future due to their high impacts. By 2060, the average occurrence of these events will be two per year, an increase of 530%, and the integrity of the defence structures to withstand this is uncertain. However, analysis in this study identifies a further problem for the region, and regards future level 2 alerts. Although less severe in terms of impacts (empirically), they are expected to occur at a similar frequency to level 1s in the future. Level 2s restrict traffic on both lines and cause significant disruption to passengers (e.g., up to 50 minutes delay). The impact of more frequent passenger disruption, in comparison to the likelihood of a single large scale event, is an important consideration for policy makers. Furthermore, as Voyager trains no longer run during level 2s they will be halted from service more often (during the remainder of their service life) and this may have repercussions for the both train operating companies and passengers.

Finally, Lowe et al. (2009) H++ scenario predicts up to 1.90 m of sea-level rise in the region, and under the occurrence of this level of rise the crest of the defences at Exmouth, Starcross, and Teign estuary defences would be permanently inundated. Furthermore, the highest predicted increase in sea level would reach the top of the sea wall at Dawlish (King Walk). Evidently these levels of sea-level rise, although improbable during this century, would cut off the railway network from the rest of the UK. It was based on this evidence that no further inclusion of the H++ scenario was included in the analysis. From the model, DLRs are expected to reach 270 annually, or 70% of the year, and level 3s will occur 8 times per annum (on average). These figures do not include the influence of waves (e.g., of several metres) or storm surges (that can reach over 0.5 m), the impacts of which are also likely to change in the future. The reality of the railway being cut off completely in the future is clearly evident, and the extent of predicted sea-level rise by 2060 is of serious concern for these areas. Furthermore, if the defences are not altered, sea levels would threaten Dawlish, Teignmouth, Starcross and their coastal populations (around 40,000). Thus, the issue of future sea-level rise and the main railway line is a real concern for the regions coastal communities (not just rail users). Over the line’s history hard engineering has been shown to improve the situation (e.g., 1930-1970) but it is not a long-term solution and we are now beginning to experience this directly.

7.4 The impact of increased rail problems

From the archives collected to quantify problems on the line, an interesting history of public and political response has been documented. Debates on how to address the issue – beginning after the first closure in 1846 – have come to no real conclusion. There is considerable opinion both for and against immediate action to the problem, from the initial plans to re-route the line in 1930 (see Kay, 1993), to the recent discussions in Westminster (Hansard, 2010). Direct actions (e.g., re-routes and re-opening old diversionary routes) have been dismissed based on the capital costs of investment and the prospect of leaving parts of south Devon without sufficient public transport. The discussions over the years appear reactive, typically following a poor winter period or a significantly large event, and have been hampered by a lack of information in order to form a respectable case for any future decision. The results gathered to achieve objective two (Chapter Five) contribute directly to this knowledge gap. However, forecasted overtopping frequencies give little consideration to the effects and subsequent costs of incidents to the region. The finally objective of this project is to provide integrated research combining climate impacts with socio-economic changes (and costs) in order to present the most plausible futures for discussion.

The analysis in Chapter Five discussed the increases in damages and disruption on the railway. Chapter Six therefore began by examining the potential impacts of predicted damage and disruption on direct costs (e.g., to Network Rail) and indirect costs (to the economy). Directly, a business-as-usual approach will result in a dramatic increase in the additional costs of preventive maintenance and delay related penalty charges during the 21st century. Based on the projections of DLRs the average costs are expected to double by 2020, from £0.96 million/yr (in the last decade) to ~ £1.9 million/yr (high emissions). By 2060 they are estimated to reach £5.51 million/yr and could have reached a cumulative total of ~ £213 million (medium emissions). The context of annual maintenance costs per kilometre of track, these could reach ~ £570,000/yr during the second half of the century. In comparison to a typical average track cost of £64,000 - £94,000 km/yr this will remain one of the (if not the) most expensive stretches of track in the country to maintian. Indirect costs to the economy have been calculated based on the increases in journey time during incidents as a result of sea-level rise. The costs of passenger/freight time loss are expected to increase significantly during the 21st century, from the present average of ~ £0.44 million/yr to £3.10 million/yr by 2060 (under high emissions). These estimates assume current socio-economic conditions will continue, however, and do not account for the influence of human interaction on climate futures. Therefore, the projections and costs were integrated with four socio-economic scenarios (SES) constructed by UKCIP (2001) and Network Rail (2010) to illustrate the potential implication of different passenger demand forecasts.

The Global Sustainability (low emissions) and World Market (high emissions) scenarios both present futures with large growth increases (e.g., GDP, population etc.) in the region. This will result in increased numbers of people and business using the railway line resulting in higher economic costs during predicted incidents. The 2020s, for instance, the cost of climate change (CCC) (i.e. increased closures) could cause and additional £0.89 - £1.30 million per year respectively, and could reach £16 - £24 million per year by the end of the century (depending on the emissions). Under Local Stewardship and National Enterprise futures (medium emissions) passenger demand increases are slower, but the climate change impacts are high enough to place the likely costs within range of a Global Sustainability future (with low emissions). This emphasises that socio-economic trends must be considered in climate change assessments to demonstrate more plausible rages of potential impacts. In the Southwest, the cumulative CCC is expected to cause an additional £17 - £24 million during the 2020s, and during the 2060s these costs are expected to range from £223 - £348 million. The wider economic impacts of rail closures (not quantified) could multiply these estimated values significantly, however. Although these costs are illustrative it is crucial that they are considered in future sustainable decision making or investment proposals on the line. For example, the cumulative CCC in the next 30 years will exceed the capital cost of a major defence renewal, and by 2060 these costs will have exceeded the capital cost of constructing an entire inland route (not taking into account discounting). To an extent, the delayed planning for the future of the transport network will have a direct relationship with the amounting costs of climate change.

The illustrative costs, however, assume present coastal management practices will continue in the future. They will, in fact, be modified in response to changing socio-economic trends which are outlined in each future (from UKCIP, 2001). Coastal management policies and practice are, thus, scenario-dependent (Hall et al., 2006). For instance, a World Market scenario presents the wealthiest society which can afford to protect against the risks it is exposed to. Investment will be made through markets and not government however. Thus, protection (predominately hard engineered) may be determined by the ability to pay rather than what is sustainable. In the short term, the transport infrastructure could potentially receive significant investment, but the 'quick fix' mentality of society in this future may not solve the long-term problem and the issue will rise again in a number of decades. This, coupled with poor decision maker credibility suggests that the future uncertainty of sea-level rise will not be fully acknowledged or gained upon either. Global Sustainability, however, is the polar opposite in terms of emissions, but the government in this future play leading roles in providing coastal management and maintaining transport infrastructure. Decision maker credibility is high and soft engineered approaches that are more resilient to future uncertainty are emphasised. This future is likely to have the infrastructure in place to develop long-term strategies for future coastal management. National Enterprise is less wealthy than the previous scenarios but economic development is regarded higher than environmental protection. A reactionary approach to coastal protection with poor decision maker credibility is characterised, and a lack of investment will result in deterioration of coastal and transport infrastructures. The Local Stewardship scenario on the other hand is characterised by a clear understanding of the threats from climate change and decision making regarding coastal infrastructure is likely to include expert knowledge. A lack of investment for coastal protection and adaptation will be a major disadvantage for developing sustainable transport strategies.

In addressing objective three of this thesis, it has been outlined that socio-economic trends will have a significant influence on the impacts of climate change, not only by affecting emissions (through technology, innovation and values) but also the overall cost of climate impact. The migration of populations and industry to our coastlines increases the possible future economic costs of climate change, not just in the UK but also worldwide (Anthoff et al., 2010) and coastal management (policy and practice) needs to evolve to adapt to this.

7.5 Summary of investigation

This analysis provides important new insights for policy makers and aligns with current debates regarding evidence-based policy making. Communication and engagement are paramount to effective management of complex issues with high uncertainty, such as the railway. As outlined in Chapter Two and Chapter Six, many sectors are calling for improved national frameworks to establish effective communication and engagement within coastal, transport and infrastructure management in the UK. The findings from this study present impacts that are easy to communicate to wide audiences (e.g., delays directly to services) and offer a single point of discussion for policy makers. Furthermore, they reduce the risk of misunderstanding when discussed, in comparison to frequencies of return period for instance, which can lead to all manner of interpretations if not explained correctly (Bell and Tobin, 2007).

It is clear from the findings that a ‘business-as-usual’ approach to managing the main railway line will be accompanied by an increased vulnerability to overtopping, closures, disruption and damage. The extent to which will be part-dependent on the severity of climate change, but also the trajectory of broader socio-economic change and, more importantly, the time taken to make adequate adaptation plans. Policy makers therefore have an equal, if not extended, role in limiting the impacts of sea-level rise in the future, by developing a long-term strategy to address the region’s transport issues. History has shown that decision making on the line has been mainly reactive, in that only after an incident is the potential need for action discussed. As sea levels change and adapt our coastlines, decision making will need to change and adapt also. A precautionary or pro-active, rather than reactive, approach will help address such problems (and other coastal issues more broadly) earlier before a major catastrophe. It is vital that this is developed in the next few decades before the impacts become severe.

Sea-level rise is not the only problem on the line however. Rock fall and land slips at Dawlish also cause significant problems and are threatened by changes in precipitation and temperature. It was not the scope of this thesis to consider the impact of these on the line, but the two often occur simultaneously. However, the findings have additionally acknowledged the potential problems associated along the estuary sections of the line on the River Exe and Teign. The defences along these sections are not under Network Rail’s jurisdiction, however, and are the responsibility of Teignbridge Council and the Environment Agency (Rogers and O’Breasail, 2006). This could potentially raise further conflict in the future coastal management strategies if not tackled in an integrated manner. Those calling for an immediate re-route of the line (e.g., via Okehampton or the South Devon Railway) must understand that the current Parliament will not be planning to build any alternative in the next 15 years. In light of the evidence in this thesis, the sustainability of this decision is questionable based on the cumulative costs of impacts in the region. Any investment plans must factor these issues into their evaluations, as until a long-term strategy is compiled the regions transport network remains in a very vulnerable position.

Regional decision makers must acknowledge that, from this evidence, it is not a case of ‘if’ but more a case of ‘when’ the railway will be severely disrupted (and even closed). Protocols are in place to limit the disruption during events (e.g., buses etc.), but now is the time to begin communicating this eventuality, as by the middle of this century the railway will be at significant risk from major closure. The cumulative costs of this could potentially outweigh many major defence options and reduced the resilience of the region to climate change further (although discounting must be considered more explicitly). As a geographer, and researcher, it is easy to see the potential escalation of these problems, but how effective this research is in stimulating decision making regarding the railway’s future is unknown and engagement with these data is an important next step. If the barriers of communication are not tackled in the Southwest there will be an increased risk of socio-economic exclusion for many coastal communities that rely on the railway and its trade. In the longer term, Plymouth and Cornwall could be significantly impacted as their competiveness, productivity, and local and inter-regional labour networks are affected.

Overall, the empirical approach used in this study identified the occurrence of a clear tipping point (e.g., when sea-level reached 7050 mm), within which the relationship between sea-level rise and disruption on the line became positive and linear. It is likely that there will be further tipping points in the future, where changes in sea-level will have more impact on rail services and the wider region. Particularly on lower sections of track (e.g. King’s Walk) where non-linear trends could be possible in the future. But the key tipping point regards the decision for the long-term future of the line. Who will be involved in making the decision? Will it be reactive - and wait till the railway network is cut in half? Or will it be strategic – and acknowledge all the potential cost involved to make a well balanced and justified decision? These questions are focused on the uncertainty of decision making and much, if not all, of the issues discussed are parallel to wider questions of science, policy and practice in the UK. The issue is distinctively geographical in nature, and the knowledge of the world as seen through the eyes of a geographer provides a logical tool to address it.

7.6 Further research, recommendations, and reflections

This study has been successful in achieving the primary aim outlined in Chapter One, and the approach enabled both quantitative and qualitative information on the future of the Southwest mainline to be presented. In comparison with more sophisticated numerical approaches (e.g. O'Breasail et al., 2007), this study has been able to extend more sophisticated analysis of overtopping estimates to emphasise likely disruption to rail services and socio-economic costs. The simplified approach and illustrative information can be clearly understood and utilised by non-expert decision makers. Thus, beyond this case study the consideration of the end-user and their need for information should be emphasised in future climate impact assessments. For example, the scenarios presented here have the capacity to be used in option appraisal studies, and further research into the possible adaptation options for decision makers is recommended next step to address this issue. Additionally, the Dawlish – Teignmouth coastal railway is not unique. The UK rail network has over a hundred coastal (and estuarine) sections of track. The future of these lines have not be not been considered in detail by Network Rail, although it intends to address this issue as part of wider climate impact programme in the next five years (Dora, 2011).

Successful adaptation and avoidance of the incurred costs in these areas, however, relies on application of the robust decision-making processes. The findings of a recent report by HM UK Government (2011) suggested that the key future challenges relate to the facilitation and communication of scientific information. Whilst the Treasury has recently released a budget of £200 million for the Infrastructure UK (IUK) team to tackle long-term infrastructure resilience and sustainability, it was clearly outlined in Chapter Two of this thesis that poor communication between sectors and complex governance structures currently act against the effective delivery of solutions. This could result in failed decisions, poor investment and maladaptation to future climate risks. With the existence of precise estimates of sea-level rise and, now, improved understanding of the wider socio-economic costs, the transport sector provides a good example where the communication of, and engagement with, information on new climate risks are real barriers to improving decision making and the delivery of future adaptation. In addition, it provides a good arena to develop applied interdisciplinary research.

Further research therefore needs to establish the key ‘barriers in practice’ to reducing the risks to critical transport infrastructure in the UK from the effects of future climate change. This could include the following:

- The up-scaling of a unique approach, developed on a local case study, which will derive integrated climate and socio-economic scenarios for future risks to critical transport infrastructure (e.g. the UK rail infrastructure).
- Conducting focus groups and semi-structured interviews with key stakeholders (elites) using the integrated scenarios as a support tool.

- Assessment of stakeholder responses and attitudes towards the socio-economic implications of increased railway closures and distinguishing of generic and local factors that may impeded the effective delivery of a solution.
- Utilisation of the findings to derive a better process of engagement and communication that can be applied to national and international critical infrastructure risk management.

Finally, with respect to the specific case study in this thesis, several short-term recommendations can be made for the region:

- Workshops and focus groups, involving key stakeholders and independent facilitators, should be held to discuss the findings of this thesis with the aim of developing scenarios further and beginning a long-term strategy (decision pathway) for the region (i.e. post 2025).
- Potential adaptation options should be investigated in consultation with key industry groups (comparing experiences with similar railways world-wide). The feasibility (cost-benefit) of each option should be expertly evaluated. The passenger time loss estimates from this study can be used directly in this assessment.
- It is also recommended that a dedicated record of sea-wall incidents is maintained by Network Rail. This will allow accurate reviews to be made (i.e. 5-10 years) in order to track and observe changes in recent trends – this echoes recent Government recommendations that regular reviews (3-5 years) should be adopted as standard practice for building resilience to climate change (HMG, 2011). In this respect, the findings and data presented here represent a starting point for such a record.

Finally, it is worth reflecting on the strengths and weaknesses of the applied research approach used in this thesis and the insights the project provides for future applied geography research. As Frazier (1982) and Pacione (1999) stated, applied geography uses the principles and methods of the wider discipline of geography but with the more explicit agenda of seeking to evaluate and inform policy and planning. In doing so, applied geography contributes to, as well as utilises, wider geographical concepts and methods and seeks to develop new relationships between sub-disciplines within geography (Frazier, 1982). This ultimately provides researchers with new opportunities to place their research in the critical proving ground of real-world policy and planning (Pacione, 1999). In the original discussions on the emergence of applied geography (reviewed in Section 1.2), the ability of geographers to cross into the policy realm was a key issue of the so-called 'relevance' debate (e.g. Chisholm, 1971; Berry, 1972; Coppock, 1974; Stoddart, 1975, 1987; Pacione, 1999; Peck, 1999; Martin, 2001; Berry, 2002; Ward, 2005). Central to this was the idea that geographers should be more involved in policy making (or at least informing policy making) due to their particular blend of skills (Chisholm, 1971; Berry, 1972; Clark, 1982; Peck, 1999; Berry, 2002; Johnston and Sidaway, 2004; Martin, 2001; Yeates, 2001; Pelling et al., 2008), and this idea raised further debate of how to achieve policy influence (e.g. Chisholm 1971; Eyles 1973; Blowers 1974; Coppock 1974; Harvey 1989; Martin 2001; Massey 2001; Johnston 2004).

Some argued that a failure by academics to communicate their work effectively – and to make it easily accessible – was a problem (Shaw and Matthews, 1998; Jones and MacDonald, 2007). Others discussed the cultural differences between academia and the policy realm (Chisholm, 1971; Martin 2001; Massey 2001; Lagace et al., 2008) and, in this thesis, these issues were linked to recent concerns in the wider science-policy debate (see Section 6.6). Despite these discussions, the principal rationale of applied geography has remained centred on the application of geographical knowledge and skills to the resolution of social, economic and environmental problems (Pacione, 1999). Geography, in its broadest definition, provides an interface between the human and natural worlds, and this integration has become a key agenda within debates on climate change and society (Liverman, 1999, 2002; Daniels et al., 2008). Analysis of the policy and management implications of climate change also represents an important research area that can help to shed further light on ways to apply geography to contemporary environmental, social and economic problems (Hulme and Turnpenny, 2004; Bailey, 2007, 2008).

However, it is still argued that geographers must engage – now more than ever – in applied research to link knowledge and science to practical concerns and practice in climate research (Moser, 2010a). Applied geography approaches provide several benefits for addressing this issue. Key among these is that it crosses academic boundaries and highlights linkages between different geographical phenomena (Pacione, 1999). This is illustrated by the broad range of applied and interdisciplinary geographical research on climate change impacts and adaptation, such as: natural hazards and extremes (e.g. Nicholls et al., 1999; Montz and Tobin, 2011); politics and economics (e.g. Fankhauser, 1995; Hilmer-Pegram et al., 2012); and human behaviours (Anable and Shaw, 2007; Donovan, 2010). Clearly, those hoping to utilise applied geographical approaches have a strong research base upon which to build. It can also allow research to be taken beyond analysis and theoretical advancement into the realms of application by placing greater emphasis on the use of knowledge to achieve problem-orientated goals (Pacione, 1999).

In doing so, integrated research can be developed to improve interactions between the physical and social sciences. As has been demonstrated in this project, environmental (sea-level science) and socio-economic methods (socio-economic scenarios and travel costing) have been linked in an innovative manner. Furthermore, it has been shown that local-scale assessments can be useful tools for planning possible adaptation measures (Torresan et al. 2008). Geographical knowledge applied to local and regional problems are therefore well-placed to challenge compartmentalised approaches to decision making and contribute productively to the future planning and management of climate issues. This has been particularly noted in transport studies (e.g. Keeling, 2008; MacKinnon et al., 2008) and research on sea-level rise (Nichols and Klein, 2004).

In this thesis, empirical-based impact analysis was carried out largely from an atheoretical perspective that, by avoiding theoretical silos, enabled the utilisation of a broad range of geographic thought. This approach has further contributed to research that is more accessible to wider audiences than is generally the case with more theoretical research. This has obvious benefits for the dissemination of research findings and addressing recent government concerns about the communication of complex scientific issues (such as critical infrastructure and interdependencies) to decision makers, government agencies and other practitioners. Improving communication, being more proactive in reaching out to practitioners, building relationships, and actively engaging with policy and practitioner communities as part of a knowledge co-production process are important in building on the historical accomplishments of applied geographical research (Moser, 2010a). Achieving such interconnections requires detailed understanding of temporal, spatial and sectoral considerations (Bailey, 2008), and geographers have benefitted by a long established history of investigating and evaluating such interactions (Liverman, 2004).

Amongst the calls for new forms of research, applied geography approaches often develop (or seek to develop) new relationships between social, economic and environmental research issues at various scales and, as the approach emphasises its real-world applications, the process often requires significant external (stakeholder) engagement (as occurred in this project). In addition to the direct benefits for the development of research outputs, this type of engagement also helps to maintain, promote, and facilitate the impacts of research (sea-level rise, climate change, cost, etc.) among key stakeholders and wider audiences. Equally, it can encourage new relationships and new types of discussion within practitioner organisations (e.g. Network Rail or Devon County Council). Moser (2010) and Montz and Tobin (2011) agree that this type of engagement can help to improve communication and understanding of future climate impacts and further promote the use of applied geographical information in other arenas. Overall, applied geography promotes the construction of research that can focus on addressing societal issues such as climate change and on expressing them in more accessible ways.

Despite the potential benefits of utilising applied geography, it is not without its limitations (Chisholm, 1971; Harvey, 1989; Johnston, 2004). Some interesting accounts have been produced recently by early career researchers (e.g. Aalber and Rossi, 2007; Lau and Pasquini, 2008; Evans and Randall, 2008; Donovan et al. 2010). Many of the issues raised relate to the original 'relevance' discussions. One of the initial concerns of applied geography debate was the apparent success of certain research areas (e.g. natural hazards) compared with others (Ward, 2005; Montz and Tobin, 2011), and the consequent risk of the discipline splitting into other subjects (Peck, 1999; Castree, 2002; Ward, 2005). Palm and Brazel (1992) discussed the division within geography into so-called 'pure' and 'practical' geographers, and stressed the potential for this separation to weaken the discipline. Peck (1999) and Thrift (2002) also commented that practically-oriented research risked diluting 'pure science' in geography. Nearly two decades later, studies of cognitive approaches describe similar concerns and interdisciplinary (applied) geographers are referred to by some academics as 'jack of all trades and master of none' (Lau and

Pasquini, 2008, p560). Furthermore, there is no single method for doing applied geographical research (Pacione, 1999). It must be acknowledged, therefore, that applied geography projects complement rather than replace existing approaches.

However, a more fundamental consideration for applied geography approaches is that geographers are not exclusive in their desire to study socially relevant issues with the aim of producing applied research. Geographers seeking to influence public policy must inevitably compete with more clearly defined ‘experts’ working on similar themes (Pacione, 1999). Challenges clearly exist in becoming an expert in multiple research areas whilst working within the boundaries of a single project. Furthermore, addressing specialist audiences in both the scientific and policy realms requires communication skills (see Shaw and Matthews, 1998) and investigative approaches that are not suited to all researchers. Despite the importance of communication in engaging wider audiences and policy makers (described in numerous disciplines and by non-governmental analysts – see Chapter Two for calls related to this project), there remains a lack of training for researchers to hone these skills (Moser, 2010b). This is a deficit that will need to be addressed if applied geography and applied research more generally is to prosper to its fullest.

This highlights one of the key weaknesses of applied geography projects, the issue of time. Engaging with multiple aspects of physical and human geography in a robust way may require extensive training and reflection that stretches beyond the time available for the completion and communication of research to decision makers. In this study, barriers to decision making on critical transport infrastructure were not investigated, but were instead highlighted as an area for further research. This omission must be recognised as placing limitations on the policy impact of the research but, equally, only so much can be achieved in time-bound projects. But however one judges this particular piece of research, applied geography approaches have helped to steer it towards a more user-orientated outcome, an achievement aided by the relevance debate and other debates on the strengths and weaknesses of applied geographical research.

Developing research that addresses at least some of the issues raised in the relevance debate offers one avenue for stimulating and increasing the use of applied geography in policy making. Furthermore, the recent focus on ‘impact’ in the UK’s *Research Excellence Framework* (REF), (HEFCE, 2010) means that projects with an applied dimension may be valued more highly than has historically been the case. Equally, Pacione’s (1999) critique of applied geography found that socio-political environments had a significant effect on the balance between pure and applied research, and that when external pressures are greater, disciplines tend to emphasise their problem-solving capacity (or value). In light of this observation, and the current economic climate, applied projects may become more desirable. Competition from other disciplines (and groups of experts) aiming to inform policy makers is a significant challenge that applied geographers will face. However, despite major advances in scientific understanding of climate issues, considerable scope remains to improve the preparation of knowledge for decision-making and the effective communication of scientific insights to stakeholders (Moser, 2010a; Rodima-Taylor et al., 2012). There are still significant improvements to be made within applied geography, particularly in relation to the climate change agenda (Moser 2010a).

The key argument of the ‘relevance’ debate was how best to penetrate the policy realm, yet simply producing societal relevant research does not guarantee that it will be taken up by decision makers. Similarly, even if research is read by decision makers, this provides no assurances that they will act upon it. These remain priority issues for future applied geographical research. Moser’s (2010b) work on communication and climate change highlights some potential future research directions. These include the need for research focused on audience-specific messaging, reviews of the contextual influences on communication, and the effectiveness of different communication efforts. Applied geography approaches are currently developing decision-support tools linked to these areas (e.g. Schwilch et al., 2012), and the beginning of this section suggested strategies (i.e. workshops and focus groups) to tackle them for climate change and critical transport infrastructure issues. There is a need to develop projects that encompass the effective and ethical use of visualisation in cross sector dissemination (e.g. Nicholson-Cole, 2005; Sheppard, 2005). Understanding public perceptions of climate change and adaptation to climate change are also research priorities, the findings of which could be used to improve geography’s interaction with decision making.

Furthermore, little is known about how to communicate climate issues in ways that engage societal actors over longer time periods (Moser, 2010b). Strategies that make use of novel methodologies to improve stakeholder engagement (e.g. Berkhout et al., 2002; van Kerkoff, 2005; Tompkins et al., 2008; Schwilch et al., 2012) are recommended, and research that includes the empirical exploration of the role of dialogue for engagement and decision making could offer further vital benefits (Moser, 2010b). In this thesis a scenario-based stakeholder engagement method was utilised (Chapter Six – Section 6.6) to communicate issues related to coastal management and policy making (Tompkins et al., 2008). Even if all the issues discussed here were addressed, however, it does not guarantee research will influence decision-making processes.

A core challenge for applied geographers, therefore, is to ensure they think carefully about how their research (beyond the thesis or research output) may be communicated to improve interactions with the policy arena. Projects that place communication and engagement (e.g. workshops, consultations, external collaborations etc.) among their principal aims may stand a greater chance of influencing future policy decisions. Furthermore, improving the visibility of applied geography research by developing scientific publications in more public and political arenas (e.g. the media or Parliamentary Postnotes), and by directly engaging with policy makers, for instance, informing Chief Scientific Advisors and parliamentary debates may further assist in extending the impact of applied geographical research. Society will always need user-oriented research to help make decisions on complex issues such as climate change. Applied geographers have a long history of contributing to this issue, but identifying – and working out how to combat – the barriers to influencing policy making is an important area for further study. Further efforts in this direction are an essential part of enabling geographers to be more successful in breaking into the policy realm, and could contribute to the design of specific training and teaching strategies for future researchers who wish to apply the principles of applied geography to their research.

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