UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT
Civil, Maritime and Environmental Engineering & Science

The Historic Evolution of Coastal Flood Exposure in the UK

by

Andrew J. Stevens

Thesis submitted for the degree of Doctor of Philosophy

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ABSTRACT

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Coastal flooding is a serious and growing threat, with 200 to 300 million people estimated to live within the coastal floodplain worldwide today. This exposure is not static and it is increasing globally due to rising populations and sea level rise. While there have been scenario-based investigations of future exposure, there is a knowledge gap concerning historic analysis of how exposure to coastal flooding has evolved. Understanding what drives changes in exposure can help us to better predict how exposure may evolve in the future under the combined pressures of climate change induced sea level rise, growing populations and increasing development within coastal floodplains.

This thesis developed a quantitative methodology to evaluate the detailed historic evolution of exposure with regards to changing coastal population and other drivers of exposure. This includes formal definitions of exposure with and without defences. The occurrence of damaging coastal and river flooding over a >100 year period in the UK was evaluated which showed that reported flooding has been increasing significantly. Subsequently a framework was developed for quantification of exposure with and without defences: new GIS methods were developed to spatially distribute census population data across the indicative floodplain based on residential development patterns observed on historic maps and a rapid inundation model. A time series dataset on changes in defence heights was compiled from historic and contemporary records. A computational FAE (Fraction of Attributable Exposure) technique was used to evaluate the effect of flood drivers on the changing exposure.

As a demonstration of the methodology, population exposure to a range of flood events was evaluated at 10 year intervals between 1801 and 2011 for Portsea and Hayling islands in the UK's Solent region, representing a city with significant flood risk, and a more rural location, respectively. 1801 represents the first UK Census, while sea level data is available at Portsmouth since 1960 and this is extrapolated back to 1801. The results show that exposure has grown significantly at both sites. Annual average people exposure (averaged across a range of recurrence intervals) increased from 176 and 27 to 6,911 and 692 over the study period in Portsea and Hayling, respectively. Most of the exposure in Hayling developed after 1931 when residential areas started to encroach on the coastal floodplain. In Portsea, the exposure grew until 1931 and then decreased until 1981 and is now growing again, following changes in the Portsea population. Population growth and residential development have been much bigger drivers of increased exposure to coastal flooding than sea level rise in the region studied, accounting for 71% and 85.5% of the growth in exposure in Portsea and Hayling, respectively, with sea level rise explaining the balance.

The methods presented are generic and could be readily extended to a national level analysis. It could also be repeated elsewhere in the world where the necessary data on population and flood characteristics (land elevation, flood levels, sea level change) are available. By understanding historic changes in exposure, an improved understanding of changes in flood risk can be developed, including a reality check on scenarios to inform future flood risk management.

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Declaration of Authorship

I, Andrew J. Stevens, declare that the thesis entitled *The Historic Evolution of Coastal Flood Exposure in the UK* and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- Where I have consulted the published work of others, this is always clearly attributed;
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- Parts of this work have been published as:

  Stevens, A. J., Clarke, D., and Nicholls, R. J. (2016). Trends in Reported Flooding in the UK: 1884-2013. Hydrological Sciences Journal. 61(1), pp. 50-63 (See Appendix J)

  Stevens, A. J., Clarke, D., Wadey, M. P., Nicholls, R. J. (2015). Estimating the long-term Historic Evolution of Exposure to Flooding of Coastal Populations. NHESS Discussions. 3 (2), pp. 1781-1715 (See Appendix K)

Signed:..

Date:...

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My closing remarks are also the ones I am most eager to share. In the thesis of life science is most definitely in the methodology, but God is the author. As a scientist and a Christian I acknowledge that science does not replace God; science reveals him. I am thankful for the privilege of my PhD journey, for the things I have learnt and for the adventures I have had along the way. I am thankful for God's faithfulness throughout.

Chapter 1

Introduction

This chapter gives a background and a context to flooding (Section 1.1) and evaluates the following questions; **what** is exposure? (Section 1.2), **why** study exposure? (Section 1.3), **who** has previously studied exposure (Section 1.4) and **how** will exposure be evaluated? (Section 1.5). The content of the subsequent chapters is outlined in Section 1.6.

1.1 Flooding: Background and Context

Throughout history flood events have had a diverse range of significant impacts on society (Pielke Jr., 2000). Flooding from different sources (tidal, river and rainfall) is evident over more than one-third of the world's land area, in which some 82% of the world's population resides (Dilley et al., 2005). The most severe impacts that have been recorded are known of for China in 1931 when a combination of cyclones, heavy rainfall and snow melt caused a series of floods that killed up to four million people (Pietz, 2002; Redd, 2012), whilst 80 million were left homeless as 34,000 square kilometres of land was inundated. Northern Europe (within which this research case study is located) has a long history of severe floods. In 1099 high tides and storms caused floods responsible for the deaths of approximately 100,000 people in the Netherlands and England (Redd, 2012). The North Sea storm of 1953 led to the deaths of over two thousand people across the United Kingdom and Northern Europe (HR Wallingford et al., 2006).

More recently, major flood events have illustrated that despite adaptation (e.g. due to defences and forecasting) a large population can be affected by floods. Over the last 30 years Doocy et al. (2013) estimated that 2.8 billion people were affected by flooding worldwide. For example the coastal storm surge event which impacted the whole city of New Orleans (and other areas of the Gulf coast) during Hurricane Katrina in 2005; Cyclone Nagris (Myanmar in 2008), Storm Xynthia in 2010 (Atlantic coast of France), 'super storm' Sandy (New York in 2012) and Typhoon Haiyan (Philippines, 2013). In the UK, the summer floods of 2007 (river and rainfall) (e.g. Chatterton et al., 2010) and coastal floods of 2013-14 (e.g. Sibley and Titley, 2015) are recent reminders of the exposure to flooding. For example in the 5-6 December 2013 UK surge event, over 2,800 properties were flooded and 10,000s people evacuated and many more people were protected by defences that were upgraded since the devastating east coast floods of 1953 (Wadey et al., 2015).

With projected sea level rise (e.g. Church et al., 2013) and increased coastal development (e.g. Hallegatte et al., 2013), the exposure (i.e. people or places that could be theoretically flooded from extreme sea levels and waves, with or without defences) to flood events will rise (Stevens et al., 2015). In the UK, this is illustrated by the prevalent coastal development since the events of 31 January-1st February 1953. For example on Canvey Island (Essex, outer Thames Estuary) 58 people died from the floods, of a population of 12,000. Over the following decades, defences have been improved, but population is now in excess of 40,000. This highlights a complex and globally relevant risk paradox (where risk is a product of flood probability and consequence). Regardless of measures taken to protect an area that could be flooded (i.e. known to be susceptible historically, because it is low lying, or is in the path of large surges etc.), understanding the extent, drivers and consequences of this 'exposure' is an important step towards sustainable future coastal development.

1.2 Defining Exposure in the context of the SPR

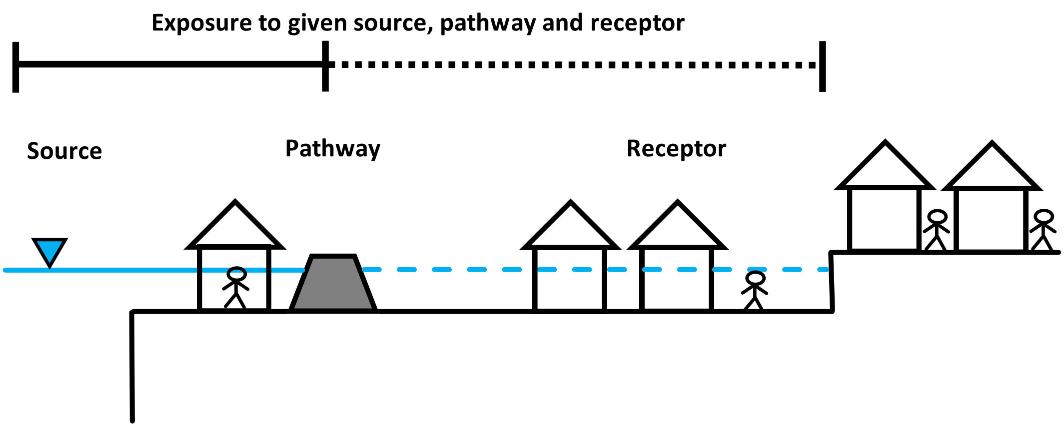

Figure 1.1: Exposure in the context of the Source-Pathway-Receptor (SPR) model

Exposure has not been consistently defined or applied and the term is often confused with risk (this is explored at depth in Chapter 2). In some studies defences are included (Koks et al., 2014; Mokrech et al., 2014; Früh-Müller et al., 2014) and in other studies defences are ignored (Jongman et al., 2012b; Lugeri et al., 2006; Stevens et al., 2015).

This lack of consistent terminology makes the comparison of exposure between different studies challenging.

In this work we attempt to remove this ambiguity by defining the term exposure more explicitly using the Source-Pathway-Receptor concept. The Source-Pathway-Receptor-(Consequence) concept links the physical source of flooding (e.g. coastal storm surge, high river flow, and groundwater) to the entities that can be harmed (e.g. people, property, habitat and economic value) via flood mechanisms termed pathways (e.g. the presence of defences, elevation and characteristics of the floodplain):

> Exposure is defined in the context of the SPR as the **receptors** at risk from a given **source** and **recurrence interval** of flooding and a given **pathway** (Figure 1.1). The extent of flooding and the entities within the floodplain determine the exposure to the flood event.

It is important that the source, pathway and receptor are clearly defined so that exposure estimates are consistent and comparable between studies. The SPR concept is further discussed in Chapter 2, and the chosen Source, Pathways and Receptor to be evaluated are presented in Chapter 3.

1.3 Role and Relevance of Flood Exposure Research

Exposure is an important part of risk, where flood risk is the interplay between the probability of a given event occurring, the people and property exposed to the flood event, and the vulnerability of those at risk (e.g. Samuels and Gouldby, 2009; Blaikie et al., 1994; Gwilliam et al., 2006; Kron, 2005; Fielding, 2007; UNDRO, 1982; United Nations, 2006b; USACE et al., 2011; IPCC, 2012; Koks et al., 2014; Sayers et al., 2015b). At any given location, flood events are often classified probabilistically (e.g. by referring to the recurrence interval/return period of sea or river levels). In UK flood management the level associated with a 1 in 200 year coastal and 1 in 100 year fluvial annual probability are generally used for flood risk management as 'extreme' events to generate flood maps and define required defence heights.

Assessments of flood risk are frequently limited to direct economic damages due to the complexity of factors affecting risk (Merz et al., 2007). Contemporary analysis of risk is increasingly taking account of additional risk factors including 'indirect' economic losses (e.g. disruption of services or business), damage to habitat, danger to people, and risk to life (Jonkman and Vrijling, 2008; Asselman and Jonkman, 2007; Penning-Rowsell et al., 2005b, 2013). In the UK the Multi-Coloured Manuals provide comprehensive guidance for evaluating flood risk from many different factors. This approach has enabled an economic analysis of risk in the UK; although an accurate assessment requires detailed data. Specific datasets are also required to estimate or quantify risks to population and properties, whilst flood defence data (e.g. crest height and fragility) is also a fundamental component of flood risk assessments. This data is increasingly available today however it is lacking for historic study, in particular quantitative information on flood defences. Therefore it is difficult to apply contemporary risk analysis to historic studies.

A meaningful alternative to full risk assessment which has lower data requirements is an analysis of flood exposure (Table 1.1). Exposure analysis is useful for comparison of exposure between areas either spatially or temporally. This lays a firm foundation for future, more detailed risk analysis. It identifies areas where further detailed assessments are required and can be used to identify and prioritise management recommendations (USACE, 2013).

Metric	Risk Analysis	Exposure Analysis
Context in SPRC	S-P-R-C	S-P-R
Drivers	Sea level rise, precipitation, surges and waves, land-use change, coastal morphology/subsidence, development/urbanisation, population, demography, stakeholder behaviour, Flood Risk Management	Sea level rise, precipitation, surges and waves, *(land-use change), coastal morphology/subsidence, development/urbanisation, population, *(Flood Risk Management)
Level of Details	Feasibility of specific project	High level variation
Repeatability	Detailed analysis to describe risk in a particular location with defined conditions	Systematic and repeatable method to describe and compare exposure across diverse regions
Data requirements	High data and time/budget requirements	Low data and time/budget requirements
Complexity	Accounts for complex interactions among flood water, floodplain, defences, property and people using depth-damage relationships, evacuation modelling, depth-mortality relationships and other functions	Simplifies description of inundation by describing people as exposed or not to flood water

Table 1.1: Comparison of exposure analysis and risk analysis (partly based on (USACE, 2013)). *Brackets indicate that the factor is partially considered. SPRC = Source-Pathway-Receptor-Consequence. See Sections 1.2 and 2.2.1

The relative importance of drivers of flood risk can be explored by evaluating the historic changes in exposure to flooding, where socio-economic indicators (e.g. population, development) can be observed. Historic records increase our knowledge of the variability in a given variable (Glaser and Stangl, 2004) which helps to frame future predictions, providing a 'reality check' on values obtained. For instance future predictions may otherwise be discarded as 'too extreme' when in fact they fall within historic variability.

Conversely future predictions of exposure may be seen as too conservative when in fact analysis of historic variability shows the predictions are quite reasonable.
Further, the analysis of the effect of historic developments in built up areas gives useful indicators of how future development in currently under developed areas can affect exposure. The future case is likely to be unprecedented in some ways (for instance the acceleration of climate driven sea level rise), however other factors are likely to fall within levels historically observed, for instance the rate of development in some urban areas is actually slowing due to the lack of space, discussed later in the thesis. Whilst the quantity of changes in individual drivers (e.g. sea level rise, development) is likely to be different to those observed historically, the relationship between these drivers and exposure can be used to scale these effects and predict future changes in exposure.

Despite its limitations historic data remains the best way to forecast the future as it helps to validate underlying assumptions in future prediction (The Economist, 2009). For instance the assumption of stationarity in exposure or risk may translate to sub optimum management (Jain and Lall, 2001). Hence the observation and analysis of historic changes in exposure could provide useful information to inform future flood management policies and practice.

1.4 Evaluating changes in Exposure

Evaluation of changes to flood exposure is an active research topic. For instance on an international scale, the 'CLIMSAVE' project considers future impacts from flooding across Europe (Pataki et al., 2011; Mokrech et al., 2014; Kebede et al., 2015); whilst in the UK the Foresight study assessed flood exposure (and risk) at the national scale over the next 100 years (Evans et al., 2004), with a government response including 'Making Space for Water' which stipulated the importance of planning for future development in and around the floodplain (DEFRA, 2005). Similarly in the Netherlands 'Room for the River' is a strategy which aimed to create a system that accounts for future flood exposure. The study uses projections of climate change to the end of the 21st century (Dutch Cabinet, 2006). At a local scale the T2100 plan explored management of the Thames barrier and associated defences to protect the city of London to the end of the 21st century (EA, 2012b).

However, historic changes to flood exposure have not yet been studied in detail. In many scientific and management disciplines, understanding the past is a standard part of understanding the future (Glaser and Stangl, 2004). Changes to both flood risk and exposure are driven by factors such as population, development, sea level rise, rainfall and river flow, land use and construction of defences. Analysis is hindered by a lack of data to characterise and quantify changes in these drivers. Historic time series on flood defences is poorly recorded and depth-damage relationships, which relate physical conditions (i.e. sea levels, river flow) to consequences (economic damages or people injured/killed), are highly variable and uncertain through time and space (Stevens et al., 2015; Jongman et al., 2012a). We have a handle on environmental drivers (i.e. sea level rise, storminess) and they are well researched (Pugh, 2004; Butzengeiger and Horstmann, 2004; Purvis et al., 2008; Nicholls et al., 1999; Nicholls and Leatherman, 1995; Nicholls, 2010). However socio-economic drivers of risk and exposure (such as floodplain population rise and development) are not as well studied (or in existence as time series data) compared to flood sources (e.g. sea levels and river flow). This allows an imbalanced perspective upon the changing risks associated with climate change - which may be incorrectly estimated if no account is taken of people's exposure and vulnerability (The Royal Society, 2014). Hence it is important to increase our understanding of socio-economic drivers of flood exposure.

1.5 Thesis Aims and Objectives

Research Gap

There have been several studies which consider how flood exposure (and risk) may change in the future (Evans et al., 2004; Pataki et al., 2011; Mokrech et al., 2014; Kebede et al., 2015), but historic changes in exposure have not yet been assessed. This misses an opportunity to gain knowledge from evaluating historic changes in exposure to flooding which would help to evaluate the role of different drivers and test our understanding against empirical observations. Such studies can inform our understanding of today and likely future trends (Glaser and Stangl, 2004). The identified research gap is summarised as follows:

- A need to characterise and quantify historic changes in exposure to flooding;
- A need to understand the impact of socio-economic drivers (population rise, residential development) on exposure;
- A need for a transferable generic method to evaluate exposure which can be applied consistently in time and in space.

Aims and Objectives

The goal of this work is to fill the identified research gap in answering the following research question:

How can the temporal evolution of flood exposure be characterised and quantified?

The aims are as follows:

- To develop and apply repeatable methods to evaluate historic flood exposure and associated flood drivers
- To interpret the results of this analysis for improved management of exposure

These aims will be achieved by evaluating how exposure to flooding has evolved historically, what has driven the changes in exposure and the effect that flood defences have had on exposure. This work will evaluate how the current flood exposure profile came about. It will expand on the Foresight study by looking at the historic evolution of flood exposure, facilitating a 'reality check' on scenarios of future changes. The objectives of the thesis are as follows:

1. Characterise and evaluate the historic evolution of flood events
There is a need to evaluate historic changes in flooding. The aspiration is to do this at the national scale. This will help to give context to the evolution of flood exposure.

2. Develop a framework to quantify the historic evolution of flood exposure
There is a need to quantify the evolution of exposure to flood risk. The datasets which are needed to evaluate flood exposure, and the time-frame over which such datasets are available, must be determined. Historic "data mining" is required to produce long term datasets which quantify this system.

3. Attribute the changes in flood exposure to the underlying drivers
The next step in understanding how flood exposure evolves is to determine the key variables that drive the changes in flood exposure. The impact of each driver and the relative effect on flood exposure must be identified.

1.6 Thesis Structure

The structure of the rest of the thesis is as follows:

Chapter 2 gives a background to flooding and its management, and how exposure has been defined in the literature. The drivers of exposure are explored and frameworks for describing the flood system are reviewed. Key messages from the literature are evaluated.

Chapter 3 presents the research approach for quantifying the evolution of exposure to flooding. The relative strengths of different techniques and rationale behind choices are explained, and approaches selected. Datasets required and available for quantifying exposure are determined.

Chapter 4 gives a national context to the work by evaluating the occurrence of flood events in the UK from all sources over the last 100+ years.

Chapter 5 sets out the quantitative model of coastal flood exposure evolution at the local scale. The repeatability of the method is demonstrated by application to two coastal case studies in the UK. An assessment is made of changes in exposure through time from coastal sources with and without defences in place for a range of recurrence interval flood events.

Chapter 6 presents a method for attributing flood exposure to the underlying physical and socio-economic drivers using the quantitative model. The relative contribution from each driver of flood exposure is evaluated for the two case studies from Chapter 5.

Chapter 7 sets the thesis work in the context of the wider literature and discusses the findings and novelty of the work presented. The outcomes of the thesis are discussed in the context of national flood management and other work done in the area.

Chapter 8 provides a summary of the key messages of the work and evaluates whether the thesis objectives were achieved. Suggestions are made for future work in this research area and key messages for the management of exposure are discussed.

Chapter 2

Literature Review

This chapter explores the concept of flood exposure and appraises the importance of evaluating changes in exposure. Frameworks for evaluating the flood system, the drivers of exposure, and exposure evolution within the literature are evaluated, and flood events and their management are assessed. The key messages from the literature are summarised and a conceptual model of the flood system presented.

2.1 Exposure in the Context of Risk

In this section definitions of exposure and risk within flood research and the wider literature is explored. The terms are evaluated to produce the working definition of exposure and risk used in this thesis. The concept of exposure with and without defences is developed to reconcile fundamental differences in the definitions of exposure and risk.

2.1.1 Defining Terms

In defining key terms there is a need to agree precise definitions (Samuels and Gouldby, 2009), with unambiguous and consistent definitions important for scientific discussion (Kron, 2005). Yet a key finding of the European CLIMSAVE project was that key words, despite being used extensively by policy documents, were rarely defined thus "leaving room for ambiguity" (Pataki et al., 2011). The literature on risk throws up a complex array of terms, summarised in Figure 2.1.

The Language of Risk was one of the first deliverables of the European Community funded FLOODsite project (Samuels and Gouldby, 2009). The project integrated terminology from documents both from the EU and from non EU sources to produce a glossary of terms intended as a common dictionary for use in Flood Risk Management. The project discussed what it describes as "the risk of language", with the concepts and meanings of technical terms varying between professional communities or national practices. The work drew together a wide literature on risk, with particular focus and discussion on defining risk and vulnerability, seen as the overarching concepts.

The work of Blaikie et al. (1994) pulled together a wide literature on vulnerability and natural hazards. The work championed the idea of coping capacity as a tenet of vulnerability, arguing that those with fewer resources were less able to respond to hazards and were therefore more vulnerable. This idea of coping was adopted by several key reports (e.g. IPCC, 2001; UKCIP, 2003; Omann et al., 2010).

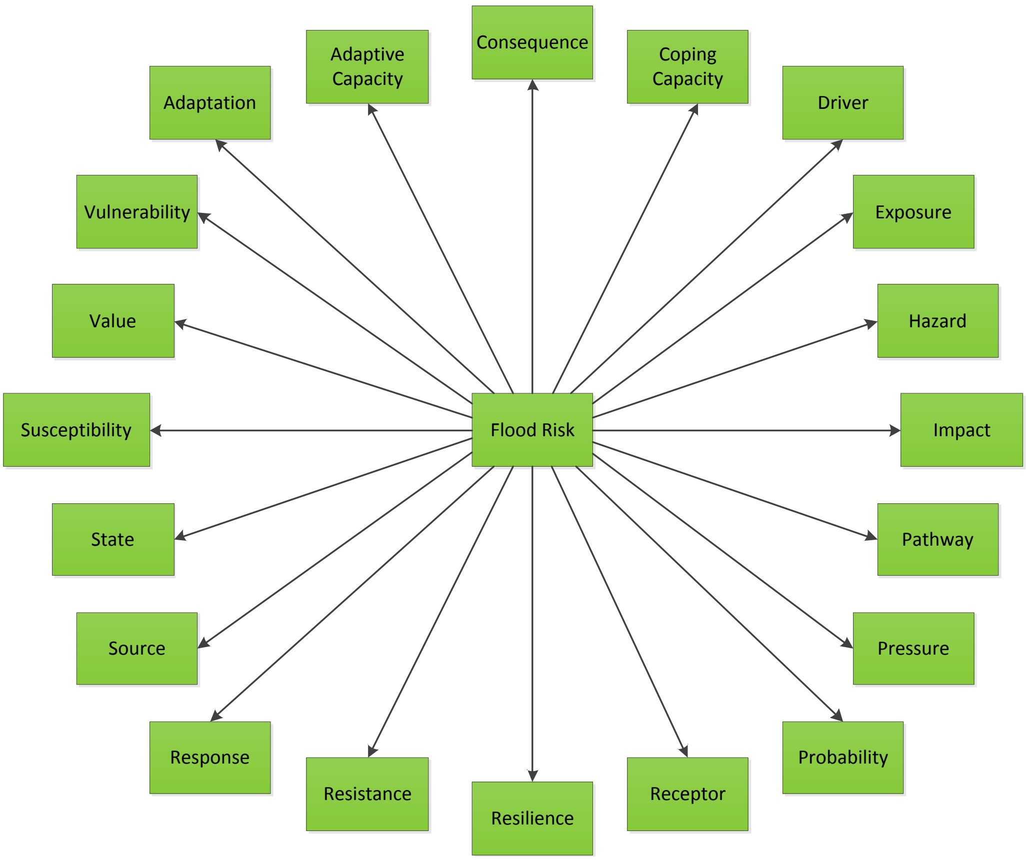

Figure 2.1: Key terms relating to risk from the literature

The term risk is understood in different ways by different people (Kron, 2005). Whilst the disaster literature considers risk to be a complex combination of hazard and vulnerability (Blaikie et al., 1994; Woltjer and Kranen, 2011; Fielding, 2007; Thrush et al., 2005), elsewhere value is considered to be an integral part of risk (Kron, 2005; Samuels and Gouldby, 2009; Gwilliam et al., 2006; UNDRO, 1982). There is no consensus in the literature on what constitutes risk.

Depending on the context risk can have a range of meanings (Samuels and Gouldby, 2009). Risk is seen to be a function of probability and consequence (Evans et al., 2004; Samuels and Gouldby, 2009; USACE et al., 2011; Sayers and Meadowcroft, 2005; UNISDR, 2009). Probability is generally taken as the probability of the hazard, which has purely physical characteristics (Brooks, 2003). However it is important to note that the consequence is equally dependent on probability (such as probability of defence failure, or loss of life). Indeed Turner et al. (2003) define risk directly in terms of the probability and nature of the consequences.

A review of 21 key papers and reports published between 1982 and 2010 indicates a wide array of terms used to describe risk including “exposure”, “sensitivity”, “susceptibility”, “vulnerability”, “value”,“resources” and “resilience”. A visualisation of the most common terms used to describe risk is presented in Figure 2.2. Papers which do not define the components of risk cannot be displayed and are hence excluded.

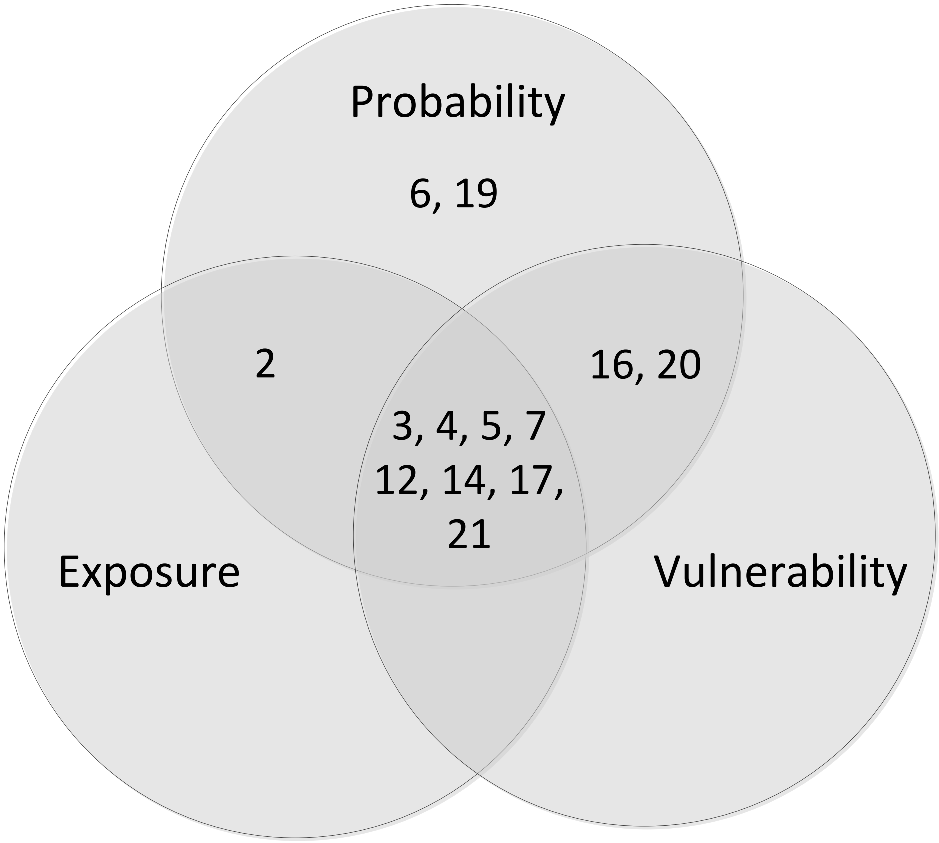

Figure 2.2: Mapping the components of risk as defined in the literature. References 1. (Evans et al., 2004), 2. (Linnerooth-Bayer, 2005), 3. (Samuels and Gouldby, 2009), 4. (Blaikie et al., 1994), 5. (Gwilliam et al., 2006), 6. (Sarewitz et al., 2003), 7. (Kron, 2005), 8. (Sayers et al., 2003), 9. (UKCIP, 2003), 10. (ASC, 2010), 11. (Pitt, 2008), 12. (Fielding, 2007), 13. (UNISDR, 2009), 14. (UNDRO, 1982), 15. (Turner et al., 2003), 16. (United Nations, 2006a), 17. (United Nations, 2006b), 18. (Pelling, 1999), 19. (Cutter et al., 2003), 20. (Thrush et al., 2005), 21. (USACE et al., 2011)

There is some level of agreement that risk is a function of probability, exposure and vulnerability:

$$Risk = f(Probability,\ Exposure,\ Vulnerability) \tag{2.1}$$

In this context probability is defined as both probability and nature of a (flood) hazard (Evans et al., 2004; Samuels and Gouldby, 2009; Linnerooth-Bayer, 2005; Gwilliam et al., 2006; Kron, 2005; Fielding, 2007). Probability tells us the chance a given flood event will occur. For example heavy rainfall or high tide levels will increase the chance that flood waters will be of an given height. There is also a probability associated with defence failure and hence the extent of flooding (Turner et al., 2003).

Exposure is a measure of the total number of receptors in a given area and the proportion of these that will be exposed to the flood water (Samuels and Gouldby, 2009).
It is generally determined by the extent of the system affected by the hazard (Turner et al., 2003; Gwilliam et al., 2006; Omann et al., 2010; UNISDR, 2009; Samuels and Gouldby, 2009). Exposure encompasses everything on the floodplain (termed 'receptors') that will be affected by a given flood. Commonly exposure is an economic value (for example the cost of damages) but exposure can include receptors without an economic value such as people or habitat.

Vulnerability determines the consequences for a given exposure - i.e. how much harm will occur for a given flood. The vulnerability to a given flood event is further affected by the emergency response, such as availability of pumps for removing water, search and rescue by emergency services and other responses.

Physical and Socio-economic Systems
It is useful to evaluate risk in terms of a closed system. A system is defined in the broadest sense as the social and physical domain within which risks arise and are managed (Sayers et al., 2003; UKCIP, 2003). The flooding system therefore entails all physical and human systems that cause, influence, or are influenced by, flooding (Evans et al., 2004). The flood system can be thought of as an assembly of elements and the interconnections between them (Samuels and Gouldby, 2009). The physical and socio-economic systems, in relation to flood risk, is shown in Figure 2.3.

Probability is predominantly a component of the physical system. Vulnerability is predominantly a component of the socio-economic system. Exposure forms the interface between the physical and the socio-economic system domains.

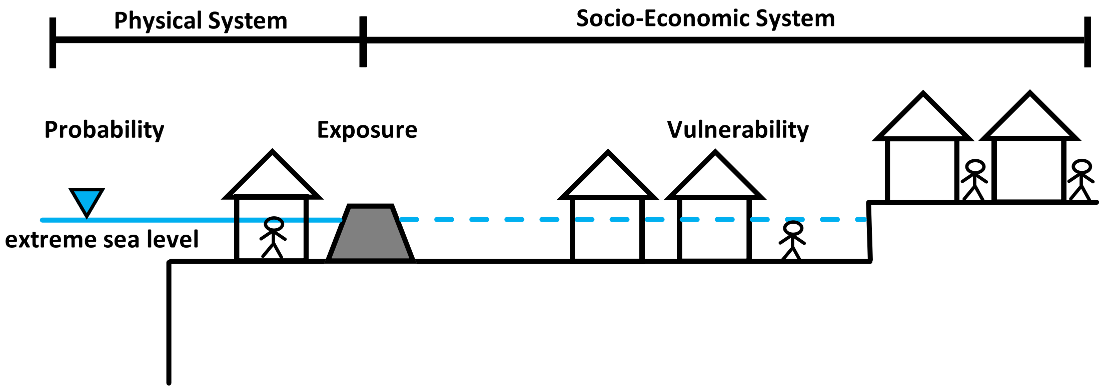

Figure 2.3: The physical and socio-economic systems in relation to flood risk. Note that this is a simplified concept; in reality the 'physical' and 'socio-economic' domains are not entirely limited to the regions defined in the figure

2.1.2 Importance of Human Interventions

The capacities of countries or regions play a key part in the extent and magnitude of consequences following flooding (and hence flood risk). For example the lack of organisation in New Orleans following the flooding caused by hurricane Katrina was widely cited as a reason for the delayed pace of recovery (Olshansky et al., 2008; Cigler, 2007; Nigg et al., 2006). In 1996 the Environment Agency of England and Wales were condemned by MPs for the lack of public awareness of warning systems and poor communication with emergency services following the Easter floods of 1998 (BBC, 1998). In Bangladesh a lack of resources poses a challenge for measures such as river flow monitoring as they require continued government and donor interest (Agrawala et al., 2003). Further, countries such as Bangladesh lack comprehensive national policy on climate change (Agrawala et al., 2003), causing concern for adaptation and therefore their ability to limit future risk. These human responses to flood risk must be evaluated for risk to be fully understood.

Past management decisions can leave a legacy of increased risk. For example lack of regulation in the 1930s and 1940s in the UK led to unplanned growth spilling onto floodplains (Werritty, 2006). The idea of flood defences breeding positive feedback loops whereby the safety of a defence means more development (and hence higher risk) thus more defence is well established (Parker, 1995; Evans et al., 2004; Tobin, 1995; Khatibi, 2011; Filatova et al., 2011). In England the phenomena was coined the 'escalator effect' (Parker, 1995). The presence of flood defences facilitate increased development which in turn encourages upgraded defences to mitigate the increased exposure, seen in mega cities across the world (Nicholls, 1995; World Bank, 2010). Thus the risk to the area behind the defences escalates over time, with higher and higher potential consequences should the defences fail or should a design storm higher than defence standard occur. In the USA the effect is coined the 'levee effect' whereby under certain circumstances the building of levees can exacerbate flood losses by facilitating increased exposure within flood plains (Tobin, 1995). This increase in development encouraged by construction of defences makes cost-benefit analyses "flawed" (Parker, 1995). A similar effect is noted in coastal zones where increased economic value creates the need for defences which further attract economic value to the 'improved safety' of the protected coastal zone (Filatova et al., 2011).

The feedback between flood management decisions and future flood risk can be extended to other aspects of flood risk management. For example river straightening in the UK to facilitate floodplain development is linked with increasing flow velocities and flood risk to urban areas (Purseglove, 1988). These feedbacks can have long time-scales, for instance the decision in the 1600s to drain the fens of East Anglia (Purseglove, 1988) shapes the modern day flood risk profile. Further, the presence of defences may raise the public's perception of flood risk (Botzen et al., 2009). This is because the presence of defences highlights the flood risk (i.e. they are defending against a flood hazard).

Dawson et al. (2008) formalised the influence of responses on flood risk by defining the flood system (denoted X) in terms of a vector of loading variables S and a vector of variables that describe the flood management variables (resisting variables) R . The basic variables are written as thus:

$$X = (S,\ R) \tag{2.2}$$

The loading variables (Dawson's S) give the *potential* risk given physical conditions (probability and exposure) and socio-economic conditions (exposure and susceptibility). This definition of risk is important because it tells us the potential harm if the flood risk is not managed. It also indicates the potential exposure to flooding should defences fail. This definition of risk is equivalent to that used by the UK Environment Agency's Indicative Floodplain Map (IFM) which does not take account of flood defences. However it is also important to know the risk with defences or other management responses in place (Dawson's R).

Responses to manage flood risk are designed to modify the relationship between the physical system (the flood hazard) and the socio-economic system (people and property). Exposure is a measure of the people and property potentially affected by a flood hazard and therefore forms the interface between these systems. Hence in this work responses are considered as part of the exposure term.

2.1.3 Exposure with and without Flood Defences

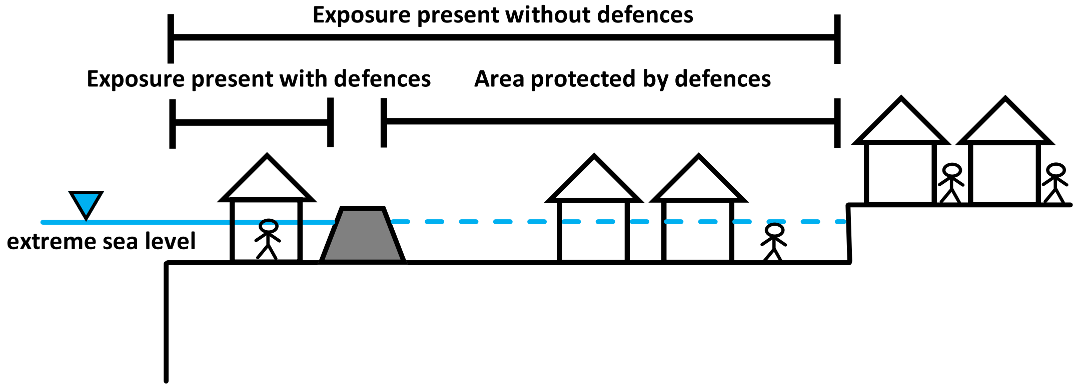

Figure 2.4: Concept of exposure with and without defences

Exposure can be evaluated as part of the Source-Pathway-Receptor-(Consequence) model (described in detail in Section 2.2.1.1). Although the SPR is presented as a linear relationship there are several possible sources and pathways and hence several unique floodplains (Narayan, 2014). As exposure is determined by the extent of the floodplain it follows that for multiple floodplains (based on recurrence interval, flood source, defences) there are multiple exposures. There is a need to distinguish between these different exposures so that results from different studies are consistent and comparable. It is possible to analyse all likely sources and pathways using a case study approach, as demonstrated for the Solent region (Wadey, 2013). However this approach is site specific and has high data requirements, and results in a range of exposure estimates that may make interpretation difficult. There is a research gap in developing an approach to exposure that can be applied consistently across different spatial locations, and is easily interpretable. Perhaps the most useful information for flood risk managers to know is the 'worst-case' exposure (what do they need to plan for in an extreme event where defences fail?) and the most likely or best-case exposure (what are they likely to face given the presence of defences?). Following this logic it is possible to evaluate just two different exposures:

- Exposure if no defences/defences fail. The exposure that would occur if defences were to fail (or in project appraisal, the exposure if defences are not constructed).
- Exposure if defences are fully effective. The exposure that is likely to occur given the presence of defences under the assumption that they do not fail.

The first definition incorporates the environmental factors (termed the physical system: flood hazard, land elevations) and socio-economic factors (termed the socio-economic system: placement of people and property within the floodplain) - equivalent to Dawson et al. (2008)'s loading variable S.

The second definition is defined as a function of this exposure without defences considered and responses (i.e. management interventions which aim to reduce or remove risk - equivalent to Dawson et al. (2008)'s R). This gives us an equation for exposure with defences:

$$Exposure_{with\,defences} = f(Exposure_{without\,defences}, Responses) \tag{2.3}$$

This concept formalises work on this approach for example Koks et al. (2014) who differentiate between flood hazard in unembanked and embanked zones in the Netherlands. The Language of Risk report (Samuels and Gouldby, 2009) defines exposure as the total number of receptors in a given area and the proportion of these that will be exposed to the flood water. We formalise this by differentiating between the whole population at risk (exposure without defences) and the subset which is exposed to an event where defences are in place (exposure with defences). Both of these definitions are important for evaluating exposure and hence risk:

Exposure without defences

- Holistic assessment needs to consider situations where the potential solutions can fail (Zoran Vojinovic and Abbott, 2012). Defences may fail or not behave as expected. Defence failure has led to huge losses in previous flood events, such as the North sea flood in 1953, and flooding following hurricane Katrina in New Orleans in 2005 (see below). The sea defences protecting Herne Bay in East Kent, built following the North Sea surge of 1953, were recently found to have an undefended gap due to an access road (Canterbury City Council, 2015, personal communication).
- It is important to quantify the increase in potential exposure due to the 'escalator' effect of defence construction (Parker, 1995; Tobin, 1995; Khatibi, 2011; Filatova et al., 2011) - see Section 2.1.2.
- Exposure without defences is vital for project appraisal where both "Do Nothing" (i.e. no defence) and "Do Something" (i.e. with defence) are required.

Exposure with defences

- This gives information on the exposure expected if defences do not fail, or for an area with no defences the exposure should defences be constructed.
- It is vital in project appraisal of flood defence projects that both exposure with and without defences are known.

- Informs risk managers of the expected extent of flooding if the defence behaves as designed/expected.

The exposure concept presented can be explained by applying the terms to historic flood events.

The 1953 North Sea Flood Event
On the night of the 31st January 1953 an abnormal tidal surge moved down the east coast of England. The 1953 north sea flood was the largest natural disaster in the UK twentieth-century history (Hall, 2011). It led to the deaths of over 2,500 people across the UK, the Netherlands, Belgium and Germany (HR Wallingford et al., 2006). In England 1,200 breaches along 1,000 miles of sea defences led to large scale inundation with over 300 deaths and 24,000 dwellings lost (National Archives, 1997). In the Netherlands an estimated 400,000 hectares of land was inundated and 40,000 buildings damaged (V&W, 2008). More than 1,800 people lost their lives and a further 70,000 were evacuated (V&W, 2008).
The exposure 'with defences' was low as defences were in place across a lot of the East and South-East coast. It was (falsely) believed that they were 'safe'. However the exposure 'without defences', the people and property at high risk should defences fail, as they did, was unknown and unpalatably high.

The 2005 New Orleans flood event
Hurricane Katrina hit the Gulf coast of the USA on August 29th, 2005, causing over 1,100 deaths throughout the state of Louisiana (Jonkman et al., 2009; About US Economy, 2011). The estimates of economic damage vary, however an oft quoted figure is around $125 billion (USA Today, 2005; About US Economy, 2011). Worst hit was the city of New Orleans, which had an ageing set of defences that had evolved over a 280 year period (Rogers, 2008). A series of defence failures increased the damage from the storm (Sills et al., 2008).
Analysis conducted soon after the event suggested that Katrina was of magnitude 1 in 15 - 1 in 20 year return period storm (Elsner et al., 2006). This highlights the huge exposure present, even for a small return period flood event.

The concept of exposure with and without defences allows responses to flooding to be evaluated. The evaluation of exposure is further reviewed in the following section.

2.2 Evaluation of Exposure

In this section existing frameworks to characterise the flood system are evaluated, drivers of flooding are explored and the evaluation of exposure evolution in the literature is reviewed.

2.2.1 Frameworks to Evaluate the Flood System

The flood system has been defined in the broad sense as the interplay between the socio-economic system (population, development) and the physical system (hazard) (Sayers et al., 2003; UKCIP, 2003; Evans et al., 2004). Different frameworks exist that can be applied to evaluate the flood system, and are described in the following section.

2.2.1.1 Source-Pathway-Receptor-Consequence Model

The Source-Pathway-Receptor-Consequence (SPRC) model (Figure 2.5) is commonly used for flood risk analysis. It is a useful conceptual model since it is documented that a source - pathway - receptor linkage must exist for risk to occur (EA, 2004; FloodSite, 2009). The SPRC originated in the environmental sciences where it was used to describe the propagation of pollutants (Holdgate, 1979). The model has been in common use in the UK since the government publication of Guidelines for Environmental Risk Assessment and Management (DETR, 2000). It is widely used across government to "assess and inform the management of environmental risks" (Sayers and Meadowcroft, 2005).

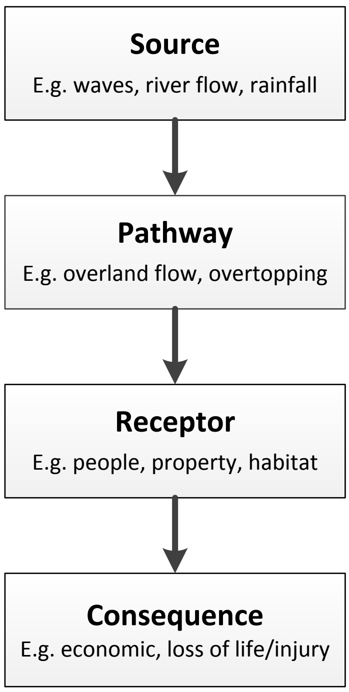

Figure 2.5: The Source-Pathway-Receptor-Consequence (SPRC) model

The source term describes the origin of the hazard (Samuels and Gouldby, 2009). In terms of flooding, this is the weather related phenomena that generate water that could cause flooding (Evans et al., 2004). For example marine storms, rainfall or river flows.

The pathway provides the connection between a particular hazard and the receptor (UKCIP, 2003). In flooding this can be described as the mechanism by which water travels from its source (i.e. marine storm, rainfall) to places where it may affect receptors (Evans et al., 2004). For example the land over which water moves to reach a settlement and the effect of flood defences.

The receptor is the entity that may be harmed by a given hazard (UKCIP, 2003). This could be people, industries or natural environments that flooding can affect (Evans et al., 2004).

The consequence term denotes the impact of the hazard event. This could be an economic, social or environmental impact, either positive or negative (Samuels and Gouldby, 2009; UKCIP, 2003).

Application of the SPRC to Risk and Exposure

The model was adopted by both the Foresight project and the EU FLOODsite project (Evans et al., 2004; Samuels and Gouldby, 2009). It is used widely in flood risk analysis (Evans et al., 2004; Narayan et al., 2012; O'Connell et al., 2011). Narayan et al. (2012) adapt the linear SPRC into a two dimensional model for assessing flood risk in complex systems. Floodplain systems are divided into elements which are modelled as both receptors and pathways to other receptors. This approach gives the SPRC credibility in representing a complex system spatially.

The SPRC model provides a snapshot of risk for a given event, i.e. the risk at a specific point in time. Consequences are determined for the exposure (through pathways) of a given set of receptors to a given hazard (e.g. a specific, defined flood event). The model is used probabilistically by modelling for numerous events and working out an overall probabilistic risk value. However it does not explicitly deal with time, and therefore does not in itself evaluate the *evolution* of exposure.

The SPRC provides a useful framework for assessing static probabilistic risk. However, as a static construct the source-pathway-receptor-consequence model would be inappropriate, without adaptation, for use in evaluating the *evolution* of risk and exposure. This thesis is based on a changing world and so temporal changes need to be accounted for.

2.2.1.2 Driver-Pressure-State-Impact-Response Framework

An alternative framework is the Driver-Pressure-State-Impact-Response (DPSIR, Figure 2.6), which encompasses time by introducing the idea of drivers and pressures, which are time dependent. DPSIR studies have been heralded for providing effective solutions to "real world problems" (Tscherning et al., 2012). The framework was promoted to show the cause-effect relationships between environmental and human systems (Tscherning et al., 2012; EEA, 2007). Although the DPSIR framework is often presented in linear or circle form, interrelations between the parts cause the framework to actually resemble a complex web of many interacting, non-linear factors (Gabrielsen and Bosch, 2003).

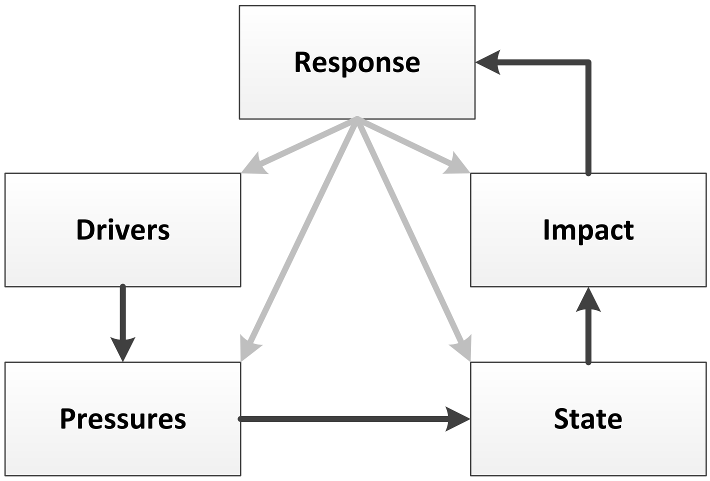

Figure 2.6: The Drivers - Pressures - State - Impact - Response (DPSIR) Framework

Drivers, or driving forces, describe the social, demographic and economic developments and corresponding changes in lifestyle in societies (Gabrielsen and Bosch, 2003). More generally, they can be described as phenomena that may change the state of a system, for example climate change, urbanisation or changing agricultural practices (Evans et al., 2004).

Pressures are described as direct stresses to the environment (Pirrone et al., 2005), exerted by human activities (Kristensen, 2004). They are defined in terms of climate change research as the release of emissions, physical and biological agents, the use of resources and the use of land by human activities (Omann et al., 2010; Gabrielsen and Bosch, 2003). For the flooding system pressures would also entail natural stresses to the human-environment system, i.e. coastal/river/groundwater flooding.

The state of the system reflects its condition at a point in time (UKCIP, 2003; Samuels and Gouldby, 2009; Pirrone et al., 2005). The condition can be thought of as the quality of an "environmental compartment" (i.e. air, water, soil etc.) in relation to the function that compartment fulfils (Kristensen, 2004). For the flooding system, this could translate as the (physical) condition of a flood embankment compared to that required to fulfil its function in keeping water out.

Impacts in the DPSIR describe changes to the functions of the environment (Pirrone et al., 2005; Gabrielsen and Bosch, 2003). It can be directly related to impact as used in the risk definition to mean a consequence, either beneficial or detrimental (UKCIP, 2003).

Responses are described as attempts to prevent, compensate or adapt to changes in the state of the environment (Gabrielsen and Bosch, 2003). They entail the evaluation of actions taken to solve environmental problems (Pirrone et al., 2005). A response can affect any part of the framework (i.e. be designed to combat drivers, pressures, impacts or affect the state of the system directly) (Kristensen, 2004). In terms of the flooding system, a response would be a change to the flood system implemented to reduce flood risk (Evans et al., 2004), or the reaction of a defence or system to environmental loading (e.g. high sea level or large river flow) or changed policy (Samuels and Gouldby, 2009; UKCIP, 2003).

Application of the DPSIR to Risk and Exposure

The DPSIR model was used in the Foresight project as a framework for projecting flood risk into the future (Evans et al., 2004). The study used projections of different flood risk drivers (such as sea level rise, increased storminess, population rise) to estimate the future state of the flood system and potential future impacts from flooding. The response component of the DPSIR allows the framework to explicitly evaluate responses to managing flooding (and hence exposure with defences).

The DPSIR approach does not allow the flooding system to be evaluated in terms of risk (Evans et al., 2004). It can, however, be used to evaluate exposure and hence is applicable to this work.

The Driver-Pressure-State-Impact-Response model is applicable to exposure since it can facilitate the effects of both environmental factors and human responses. An advantage of this framework over the SPRC is that the DPSIR inherently includes time. This gives the model direct application to long term modelling of a system. Hence the model could be adapted to evaluate the evolution of exposure. Such an adaptation is discussed in the following section.

2.2.1.3 SPRC-DPSIR Hybrid Framework

Combining the risk-compatible SPRC and the time-compatible DPSIR frameworks allows the flooding system to be more effectively modelled than using either framework independently. For this reason the combined approach was adopted by the Foresight project (Evans et al., 2004). A hybrid model is useful because it allows point risk estimates (from the SPRC model) to be evaluated over time (using the DPSIR) (Merz et al., 2010). The state variable from the DPSIR represents the flooding system at a given point in time, and therefore equates to the SPR terms from the SPRC (Figure 2.7). The consequences from the SPRC equates to impact from the DPSIR. Changes in risk over time are modelled as changes to the state variable (i.e. the state of the flooding system) as a result of changing pressures led by drivers (for instance sea level rise, urbanisation or population rise).

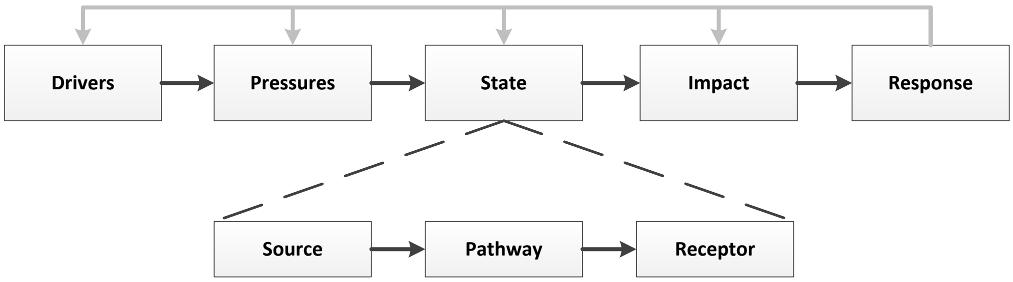

Figure 2.7: A hybrid SPRC-DPSIR framework for assessing risk over time

In summary the flooding system incorporates everything that affects or is affected by flooding, for instance sea level or the people and property within floodplains. The flooding system is an important concept for providing a comprehensive understanding of exposure to flooding. The Source-Pathway-Receptor-Consequence (SPRC) framework is useful for quantifying flood risk for a unique point in time (i.e. a point estimate of flood risk). It is widely used in flood risk management studies for this quality. The Drivers-Pressure-State-Impact-Response (DPSIR) allows the dynamics (i.e. the changes in time) of the flood system to be captured.

A unified model combining the SPRC and DPSIR frameworks is useful for assessing risk and exposure in time. This hybrid model can be used to predict flood risk in the future given the effects that drivers (such as sea level rise, urbanisation) will have on flood risk. Exploring these drivers is important for understanding how the flooding system changes in time and therefore evaluating historic and future changes in risk and exposure.

2.2.2 Drivers of Flood Risk and Exposure

Flood risk and exposure and not static. Risks vary with time, as the probability of, and exposure and vulnerability to flooding, change. The things that influence these changes are known as drivers - phenomena that may change the state of the flooding system in time (Evans et al., 2004).

The Foresight study identified 19 drivers of flood risk which were categorised as either source, pathway or receptor drivers (Evans et al., 2004). They cover physical processes (such as sea level rise, waves and precipitation) and anthropogenic (socio-economic) processes (such as urbanisation, land use, stakeholder behaviour) - Figure 2.8. The key drivers are summarised in Table 2.1.

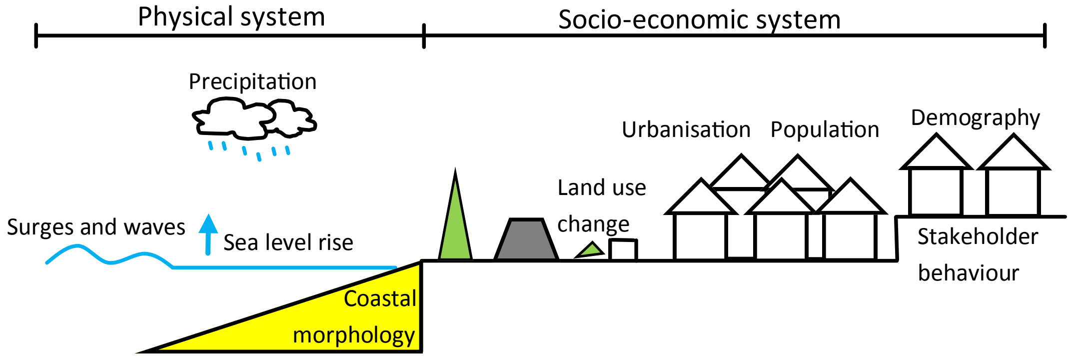

Figure 2.8: Drivers of flooding in relation to the physical and socio-economic systems

Drivers can also be categorised by the component of risk (Probability, Exposure or Vulnerability), and the SPR component (Source, Pathway or Receptor) that they influence (Table 2.2). In this way the drivers are grouped by both their effect on flood risk and the part of the flooding system that they affect. The drivers are discussed in more detail in the following section.

2.2.2.1 Physical Drivers

Physical drivers are caused by climate change driven by rising global temperatures. Climate change is linked to sea level rise, increased intensity of precipitation, increased waves and surges, and changing morphology. Physical drivers tend to affect the probability and exposure to flooding.

Relative Sea Level Rise. Global sea levels rose by 17cm through the 20th century (Nicholls, 2011) and are expected to rise by 9-69cm by the 2080s (Hulme et al., 2002). A collapse of the western Antarctic ice sheet could cause sea level rise of 5-6m resulting in almost £100 billion in flood damages in the Thames estuary during "frequent inundations" (Dawson et al., 2005). Rising global temperatures cause sea levels to rise by a combination of the physical phenomena that a warmer sea will take up a greater volume and by the melting of ice sheets (Butzengeiger and Horstmann, 2004). Even should the greenhouse gas concentration be stabilised sea levels will still rise over the next few centuries due to the extremely slow response of oceans to changes in air temperature (Hulme et al., 2002). Relative sea level rise is a function of both the mean global sea level rise discussed and local conditions such as coastal morphology and sediment supply. Land levels may sink in response to geological processes (Hunt, 2002) or subsidence caused by groundwater pumping in coastal areas (Nicholls, 2011).

Precipitation. Changes in precipitation intensity in the UK are expected over the next

Domain	Drivers	Description	Identified in
Physical System	Relative Sea Level Rise	Rising sea levels and sinking land levels contribute towards an increase in water levels thus increasing the risk of flooding	(Evans et al., 2004; Nicholls, 2011; Dawson et al., 2005; Butzengeiger and Horstmann, 2004; Hulme et al., 2002; Hunt, 2002)
	Precipitation	More intense precipitation events will increase the potential for flash floods and saturation of catchments	(Evans et al., 2004; Hunt, 2002)
	Surges & Waves	An increase in surges will increase extreme water levels, combined with more energetic waves there is in increased likelihood of defence overtopping and coastal flood events	(Evans et al., 2004; Hulme et al., 2002; Nicholls, 2011)
	Coastal Morphology	A change in coastal morphology can increase potential flood pathways by for instance reducing land levels due to cliff erosion	(Evans et al., 2004; Nicholls, 2011; Hunt, 2002)
Socio-economic System	Population	A rising population will increase the number of people residing in floodplains and the pressure on emergency responses to flooding	(IPCC, 2012)
	Development / Urbanisation	An increased density of development reduces the drainage capacity of catchments and can place more development within floodplains	(Evans et al., 2004; Woltjer and Kranen, 2011; National Audit Office, 2011)
	Land Use Change	Changes in land use can change the size and position of floodplains with either positive or negative influences on flood risk	(Evans et al., 2004; Garcia-Bajo, 2011)
	Stakeholder Behaviour	The attitudes of stakeholders to flooding will shape the responses to flooding both on a personal and societal level with corresponding consequences for flood risk	(Evans et al., 2004)
	Demography	An ageing population increases the risks of injury and mortality during flood events and increasing the pressure on emergency response for instance by making evacuation more difficult	(Kim et al., 2009; Fernandez et al., 2002; HPA, 2011; Thrush et al., 2005; Tapsell et al., 2002)

Table 2.1: Summary of the key drivers of flood risk

Driver	Risk (P = Probability, E = Exposure, V = Vulnerability)			SPR (S = Source, P = Pathway, R = Receptor)		
	P	E	V	S	P	R
Sea Level Rise	X	X		X		
Precipitation	X	X		X		
Surges and Waves	X			X		
Coastal Morphology		X		X		
Population Size		X			X	X
Development/Urbanisation		X	X		X	X
Land Use Change		X	X		X	X
Stakeholder Behaviour			X			X
Demography			X			X

Table 2.2: Drivers of flood risk categorised by the component of Risk definition and SPR concept

century, with as much as a 30% increase in winter rainfall by the 2080s (Hulme et al., 2002). More intense rainfall can exacerbate damages from flood events (IPCC, 2007). Further the likelihood of flash flood events is likely to increase (IPCC, 2007; Stern, 2007).
Surges and Waves. In coastal areas changes in storm characteristics may influence extreme water levels and therefore flood risk (Nicholls, 2011). Increased energy from waves and storm surges can increase the chance of breaching or overtopping of coastal defences (Evans et al., 2004).
Coastal Morphology. Flooding in coastal areas is affected by changes in coastal morphology (Hunt, 2002). Coastal erosion can lead to loss of beach front and cliff top building and related infrastructure (Nicholls, 2011).

2.2.2.2 Socio-Economic Drivers

Socio-economic drivers are a result of human interaction with the physical flood system, for instance development and population within the coastal floodplain. These drivers tend to affect the exposure and vulnerability to flooding.

Development/Urbanisation. In conventional development planning 20 years is considered long term (Zevenbergen et al., 2008). However development has a far longer term legacy. For instance in England 38% of all present day dwellings were built before 1944 (DCLG, 2009a). Past development decisions can therefore influence future flood risk over long time scales of many decades or more. Woltjer and Kranen (2011) hypothesise that "the fixed character of buildings and infrastructure makes it difficult to undo unsustainable developments from the past that add to the risk in present conditions". In England 12-16000 homes are built per year in high risk flood zones, in some local authorities development within floodplains occurs at a higher rate than for the locality as a whole (ASC, 2011). Preventing inappropriate development on floodplains is seen as key to risk management (National Audit Office, 2011). However floodplain development can have wider environmental benefits such as protection of the green belt or agricultural land (Parker, 1995).

Population Size. Worldwide population growth between 2010 and 2050 is estimated at around 2.2 billion (DESA, 2011). In the UK there is a similar picture, with population projected to grow to 70.9 million by 2031, an increase of almost 10 million people since 2009 (Beaumont, 2011). This increase in population will have implications for flood risk (IPCC, 2012).

Land Use Change. Changes in land can cause the position and size of floodplains to be heavily modified (Garcia-Bajo, 2011), affecting flood pathways. Data on land use in the UK is variable in scope and quality (Bibby, 2009) making changes in land use hard to assess.

Stakeholder Behaviour. A stakeholder (in terms of FRM) is an individual or organisation responsible for and affected by flood risk. The behaviour of stakeholders affects the responses taken to flooding and is therefore a major driver of future flood risk either positively (i.e. reducing future risks) or negatively (i.e. increasing future risks). For example a large number of stakeholders are involved in influencing flood risk management decisions (Ramsbottom et al., 2012; Thorne et al., 2007). In the UK ICE (1996) estimate there are over 200 organisations within an interest in management of the coast. The behaviour of stakeholders can be linked to their risk perception (i.e. how the individual or group will react to and tolerate risk). This risk perception and the reality of the flood risk do not necessarily correlate (UKCIP, 2003; Hooijer et al., 2004). The extent to which flood risk is tolerated will determine societies willingness to fund risk reduction or risk pooling measures (Dawson et al., 2011a). The behaviour of people who knowingly reside in floodplains due to the high amenity value is well documented (BBC, 2012b; Burningham et al., 2008).

Demography. The elderly are seen to be at increased risk from the effects of flooding both physically and mentally (Kim et al., 2009; Fernandez et al., 2002; HPA, 2011; Thrush et al., 2005; Tapsell et al., 2002). Of the fatalities following hurricane Katrina between 60-70% of the victims were over 60 (About US Economy, 2011; Jonkman et al., 2009). A similar trend was evident for both the 1953 North sea storm surge event and a 2010 event in France caused by hurricane Xynthia (Lumbroso and Vinet, 2011), and for victims of the Japanese tsunami in 2005 (The Hindu, 2011; Daily Yomiuri, 2011; NPR, 2012). The elderly population of the UK increased by almost 5% between 1971 and 2009 (Beaumont, 2011). With this trend expected to continue population ageing will continue to drive vulnerability to flooding into the future.

2.2.3 The Evolution of Exposure

Exposure has been the focus of flood studies which evaluate the exposure to flooding of population (Fielding, 2007; Walker et al., 2003; Thrush et al., 2005; Martin et al., 2011; Koks et al., 2014), land-use (Lugeri et al., 2006; Früh-Müller et al., 2014; Rosca et al., 2014) or economic value (Woodruff et al., 2013; Hallegatte et al., 2013; Barredo, 2009; Jongman et al., 2012b).
Census population data has been combined with an existing flood map to evaluate the exposure of people to flooding in England and Wales (Fielding, 2007; Thrush et al., 2005; Walker et al., 2003) and Northern Ireland (Martin et al., 2011). Koks et al. (2014) used similar population data to evaluate exposure in Rotterdam in the Netherlands. Exposure to flooding in 13 European countries for different land uses was studied by Lugeri et al. (2006). These studies estimate flood exposure at a single point in time, however they do not look at how exposure has *evolved*.

Research which evaluates changes in exposure (and risk) have tended to focus on *future* changes to exposure (Evans et al., 2004; Pataki et al., 2011; EA, 2012b; DEFRA, 2005; Dutch Cabinet, 2006). Evaluation of the future has been carried out at multiple spatial scales:

International studies and approaches
CLIMSAVE is a pan-European project developing a web based tool that allows stakeholders to assess climate change impacts and vulnerabilities across a range of sectors such as agriculture, biodiversity and water (Pataki et al., 2011). It uses two independent time slices, predicting flood risk in the 2020s and in the 2050s. The future changes to flood risk as a consequence of flood risk adaptations are not accounted for since the time slices are independent.

National studies and approaches
The UK Foresight Future Flooding study was undertaken in order to understand how flood risk and its management may change in the long term future (up to 100 years). It produced four qualitative "extreme" but plausible future scenarios entailing differing degrees of climate change and different socio-economic futures (Evans et al., 2004). The study provides a sound backdrop for further research, and demonstrates that investment in adaptation to increased flooding is essential. The study raised the idea of adaptability of flood management measures, allowing future generations to not be tied into costly defence options unsuitable for future risk. This highlights the influence of flood risk management on future flood risk.
Room for the River is a strategy of the Dutch government launched in 2006 and due to run until 2015. Its aim is to create a system that accounts for future risk, such as higher design river discharges. The study uses projections of climate change to the end of the

21st century. Work includes future-proofing FRM by lowering river channels, creating water storage, relocating dikes inland, removing obstructions and lowering groynes, depoldering and strengthening dikes (Dutch Cabinet, 2006).

Regional studies and approaches

In the UK, the government has undertaken a series of regional forward looking studies, coined strategic flood risk assessments (SFRAs). These studies evaluate the present-day situation and the situation after 80 years, with increased peak flows to account for projected climate change (East Staffordshire Borough Council, 2008). A weakness of these studies is the simplistic approach to assessing future flood risk. No account is taken of the rate of change of flood risk (i.e. the timescale and speed over which risk increases), or of changes to how the risk is managed (i.e. it is assumed that management is static over time).

Further studies are carried out at the regional scale for planning purposes. Shoreline Management Plans (SMPs - coastal areas) and Catchment Flood Management Plans (CFMPs - inland areas). These reports inform management at the regional and local scales (Canterbury City Council, 2015, personal communication).

Local studies and approaches

The TE2100 Plan is a forward looking study that details flood risk management strategies for the Thames Estuary over the next 100 years (EA, 2012b). The study considers future changes in flood risk and possible responses to manage these risks. Most importantly it gives the time-scales at which different interventions should happen (for instance raising the Thames barrier in the 2070s). However such strategies tend to have a local or regional focus and are not consistently produced at either national or international levels.

Historic Evolution of Exposure

Understanding of current and future conditions can be driven by knowledge of the past (Glaser and Stangl, 2004). Historic trends in exposure can inform us of potential future changes. Historic analysis gives a unique opportunity to quantify exposure using observed empirical data. However previous work evaluating the historic evolution of exposure to flooding is limited.

Früh-Müller et al. (2014) analysed historic development in North Bavaria, Germany using a 1km land cover map, however they did not account for historic changes in the flood extent. Glaser and Stangl (2004) evaluate the potential of written historical documents to reconstruct hydrological and climatological parameters and events. Doocy et al. (2013) analysed natural hazard events worldwide between 1980 and 2009. Using primarily the CRED International Disaster Database (EM-DAT) and the Dartmouth Flood Observatory (DFO) Global Archive of Large Flood Events database they estimate that 2.8 billion people were affected by flooding between 1980 and 2009.

In general historic analysis of exposure and risk has focused on a single location or point in time. For instance Marsh et al. (2005) used historic evidence and modern computational techniques to study the 1984 Thames flood. Historic data (topographic profiles and hydrometric) and a basic land use map were used to evaluate flood risk for a fluvial case study in Romania (Rosca et al., 2014).
There is a need for the historic evolution of flood exposure to be evaluated in a generic framework that can be applied to multiple locations. This will facilitate wide analysis of changes in exposure and hence will inform proactive management of the exposure.

2.3 Flood Events and Management

In this section methods for the evaluation of flood events are explored and the management of flooding is characterised using three national case studies.

2.3.1 Evaluation of Flood Events

Recurrence Interval

It is useful to evaluate the probability of a flood event in terms of its recurrence interval (or return period) (Figure 2.9). The recurrence interval refers to the amount of time, on average, between floods of a given extent or magnitude. For instance a flood that would be expected (statistically speaking) to occur every 5 years is termed a '1 in 5 year' flood. In the same way a rarer flood that would be expected to occur every 1000 years is termed a '1 in in 1000 year' flood. Exposure can be assessed for floods of different recurrence interval. Figure 2.9 shows a simple example without flood defences. As there are no buildings within the floodplain for the in 1 in 25 year flood the 'exposure' of people and property is zero. For the 1 in 50 year flood eight properties are within the floodplain (four on the upper bank and four on the lower bank) and so the 'exposure' is equal to eight properties and any people within.

Hydrological vs Damaging flooding

Flood studies in the academic literature typically evaluate changes to river flows and tides but not necessarily the impacts of these changes (e.g. Marsh and Harvey, 2012; Robson et al., 1998). However Flood Risk Assessments performed by engineering consultancies typically perform flood mapping, which does provides a visual assessment of exposure.
Flood impacts are a result of a combination of high river flows/tidal levels and the people/properties exposed to flooding. However, the relationship between river flows/tidal levels and the impact of the resulting flood is weak (Pielke Jr. and Downton, 2000; Pielke Jr., 2000). It is important therefore to differentiate between a hydrological flood

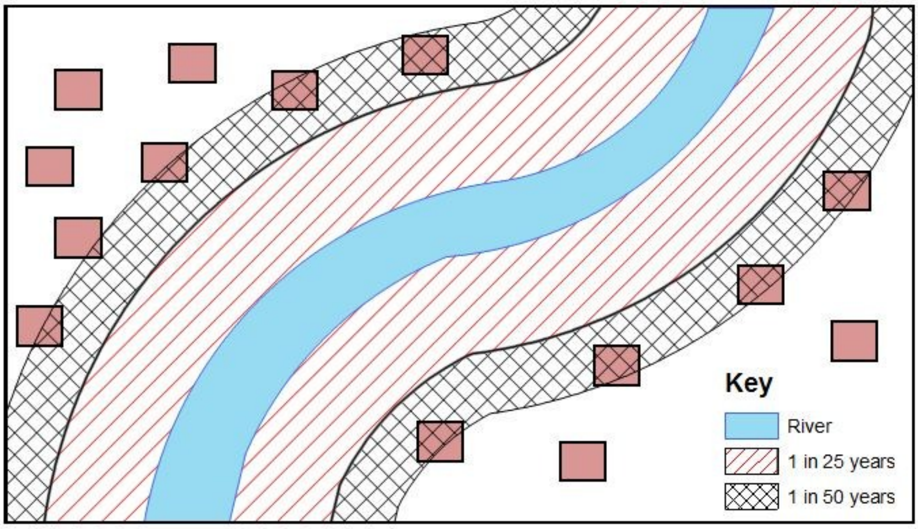

Figure 2.9: Plan-view of a floodplain showing the extent of floods of different recurrence interval

(a purely physical event) and a damaging flood event (one that impacts on society by causing damages). The difference between a hydrologic and a damaging flood is that a hydrologic flood occurring in an unpopulated area may cause no damage (Barredo, 2009).

Floods events have typically been evaluated using river flow data and the analysis of the frequency of peak flows (e.g. Delgado et al., 2010; Petrow and Merz, 2009; Macdonald et al., 2010; Marsh and Harvey, 2012; Robson et al., 1998; Robson, 2002; Haigh et al., 2010; Menéndez and Woodworth, 2010; Murphy et al., 2013; Wilby and Quinn, 2013). Long term studies include Delgado et al. (2010) who studied 70 years of data on the Mekong river and Petrow and Merz (2009) who analysed river flow data for 145 sites in Germany between 1951-2002. However consistent long term river flow or flood records (>100 years) are rare (Macdonald and Black, 2010) and are almost always reported for a single gauging station or river. In the UK only the Thames at London the River in Ireland have flow records >100 years (CEH, 2015a).
Some studies have supplemented the hydrometric flow data with historical sources such as flood marks and descriptions (Macdonald, 2006), documentary records Macdonald and Black (2010) or paleoflood hydrology such as geological records (Costa, 1986). Studies into the frequency and distribution of coastal flooding have used high sea level data combined with local records to judge when tidal floods have occurred (Ruocco et al., 2011). These studies evaluate hydrological flood events.

However extreme flows do not necessarily cause damage (Pielke Jr., 2000); changes in the hydrological regime are only one driver of flood risk. As populations grow and development expands onto the floodplain, there is a higher exposure to flooding and in many cases this is "managed" by construction of flood defences. The outcome is that although a flood is caused by meteorological and tidal climatic drivers, the impact of the flood event is a function of multiple socio-economic drivers (e.g. IPCC, 2012; Hooijer et al., 2004; Evans et al., 2004). Flood events that lead to damages or that impacts upon society are termed damaging flood events.

2.3.2 Management of Flooding

Flooding can be managed at many different scales and many strategies exist for achieving this. The umbrella term for these measures is Flood Risk Management; a collection of policies, plans and measures designed to reduce flood risk. The goal of flood risk management can be defined as "to minimize flood risk by implementing measures that reduce risk most efficiently" (Hooijer et al., 2004).

Flood Risk Management (FRM) can be achieved in a variety of ways; the Foresight study identified 80 possible responses for reducing flood risk (Evans et al., 2004). For a given country or region, the resultant mix of policies and measures adopted is dependent on characteristics and consequences of flooding, the desired level of risk, available budget and cultural aspects (USACE et al., 2011).

The complexity of FRM is shown using the examples of Flood Risk Management systems in England and Wales, the Netherlands and the USA (Figures 2.11 to 2.13). The background literature and evaluation of these diagrams is provided in Appendix A. The figures show flood policies and management schemes that drive responses to flooding in the three countries respectively.

Flood Risk Management measures can be grouped into three components; structural measures to prevent or control flow (Sayers and Meadowcroft, 2005; Sayers et al., 2003; CIRIA, 2012), planning policies which limit development in certain areas (Mori and Perrings, 2012; Parker, 1995); and flood event responses by flood managers/the emergency services (Dawson et al., 2011b). Examples of structural measures are seawalls, surge barriers such as the Thames barrier, or river flow control such as weirs or sluices. Examples of planning policies are ones that prevent houses being built within floodplains, or within a certain distance of the coast. Flood event responses include warning, evacuation, temporary barriers and pumps, or recovery from flood damages.

In this work we define these components as Structural Intervention, Spatial Planning, and Flood Incident Management (Table 2.3). This is consistent with the Environment Agency who categorise flooding into capital investment in flood defences, development control, and warning and preparedness (EA, 2009a). These are underpinned by risk analysis; the process by which risk assessment is used to develop risk management options (UKCIP, 2003). For example flood hazard maps which show possible extents, depths and velocities of flow for different recurrence interval flood events (i.e. information on probability of and exposure to flooding) (Morris and Flavin, 1996; Borga et al., 2011; DOST, 2012). Indicative maps of vulnerability contribute towards risk analysis in highlighting areas that are particularly susceptible to flooding (Fielding and Burningham, 2005; Fielding, 2007; Kim et al., 2009). Forecasting and predictions of flood which lead to flood warnings (and possible evacuations) inform the flood incident management component and are considered part of risk analysis.

Structural Interventions affects the probability of and exposure to flooding, Spatial Planning affects exposure and vulnerability, and Flood Incident Management affects vulnerability (Figure 2.10).

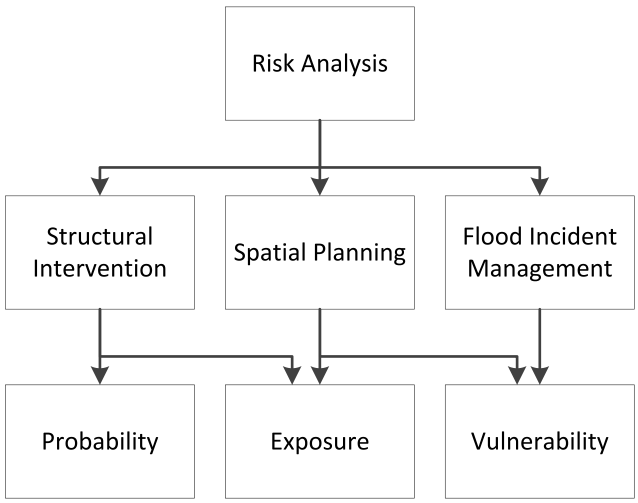

Figure 2.10: Flood Risk Management components based upon their effect on flood risk

Flood Insurance

In some countries flood losses are compensated through risk pooling (i.e. insurance schemes). Risk pooling does not reduce flood exposure or risk since damages are not prevented, however it spreads the financial burden of flood events both spatially and in time (i.e. premiums are paid each year regardless of whether a flood event occurs). Insurance can be a significant factor in recovering from flood incidents (RICS, 2012). However it has been criticised for hiding rational economic signals in cross-subsidising (i.e. home-owners in low risk flood areas subsidise high risk flood areas) which could result in failure if costs increase (Huber, 2004). In this way insurance may not serve the long term interests of floodplain residents (Lamond and Proverbs, 2008). The 'winners and losers' of UK flood insurance are discussed in detail in (Penning-Rowsell and Pardoe,

2012).
Although insurance may reduce the impacts of flooding for individuals or businesses, it does not reduce the exposure to flooding and so is not considered in this work.

A History of Flood Risk Management in the UK
Flood management in the UK has gone through two widely recognised shifts from land drainage (considered as structural intervention in this work) in the early 20th century to flood defence (structural intervention) around the 1970s-1980s (e.g. Johnson and Priest, 2008) and from flood defence to flood risk management (incorporating risk analysis, structural intervention, spatial planning and flood incident management) around the 1990s-2000 (e.g. Johnson and Priest, 2008; Tunstall et al., 2009; Butler and Pidgeon, 2011; Khatibi, 2008; Newman et al., 2011).

The changes in Flood Risk Management between 1900 and 2012 in the UK are shown in Figure 2.14. Structural intervention was been dominant throughout the 20th century and remains a part of FRM today. Risk analysis (which underpins the other components) developed from the 1970s with the introduction of the 1973 Water Act. Spatial planning was considered but non-statutory (represented by a dashed line) from the 1970s, and became a more prominent part of FRM with the introduction of PPG25, spatial planning policy aimed at reducing development in flood risk areas (this policy was replaced by

Component	Description
Structural Intervention	This is primarily flood defences such as sea walls, embankments or levees and flow control measures such as culverts. In England there are over 10,500 km of flood control structures including culverts, raised defences and sea defences (EA and DEFRA, 2011). Structural intervention can be described as a source measure as the primary function of defences is to prevent flood water from entering human settlements. Structural intervention therefore affects the probability of a flood event occurring and the exposure to the event (Figure 2.10).
Spatial Planning	This entails the siting of development and land use planning, in regards to flood risk management this is the primarily the placement of property within and deciding the land use of floodplains. The presence of people and property within floodplains (both traditional riverine/tidal floodplains and areas susceptible to surface water flooding, for example urban areas) affects the exposure term of the risk equation (Figure 2.10). The land use within the floodplain affects the vulnerability to flooding.
Flood Incident Management (FIM)	This encompasses preparing for and responding to flood events. The Environment Agency describe the "core processes" of FIM as detection and forecasting potential flood conditions, issuing and dissemination of flood warnings, and planning and implementation of responses to flood emergencies (EA, 2009b). FIM activities contribute towards removing people from the floodplain and reducing consequences by responding effectively to emergencies. In this way FIM measures affect the vulnerability term of the risk definition (Figure 2.10).

Table 2.3: The Components of Flood Risk Management to be used in this thesis

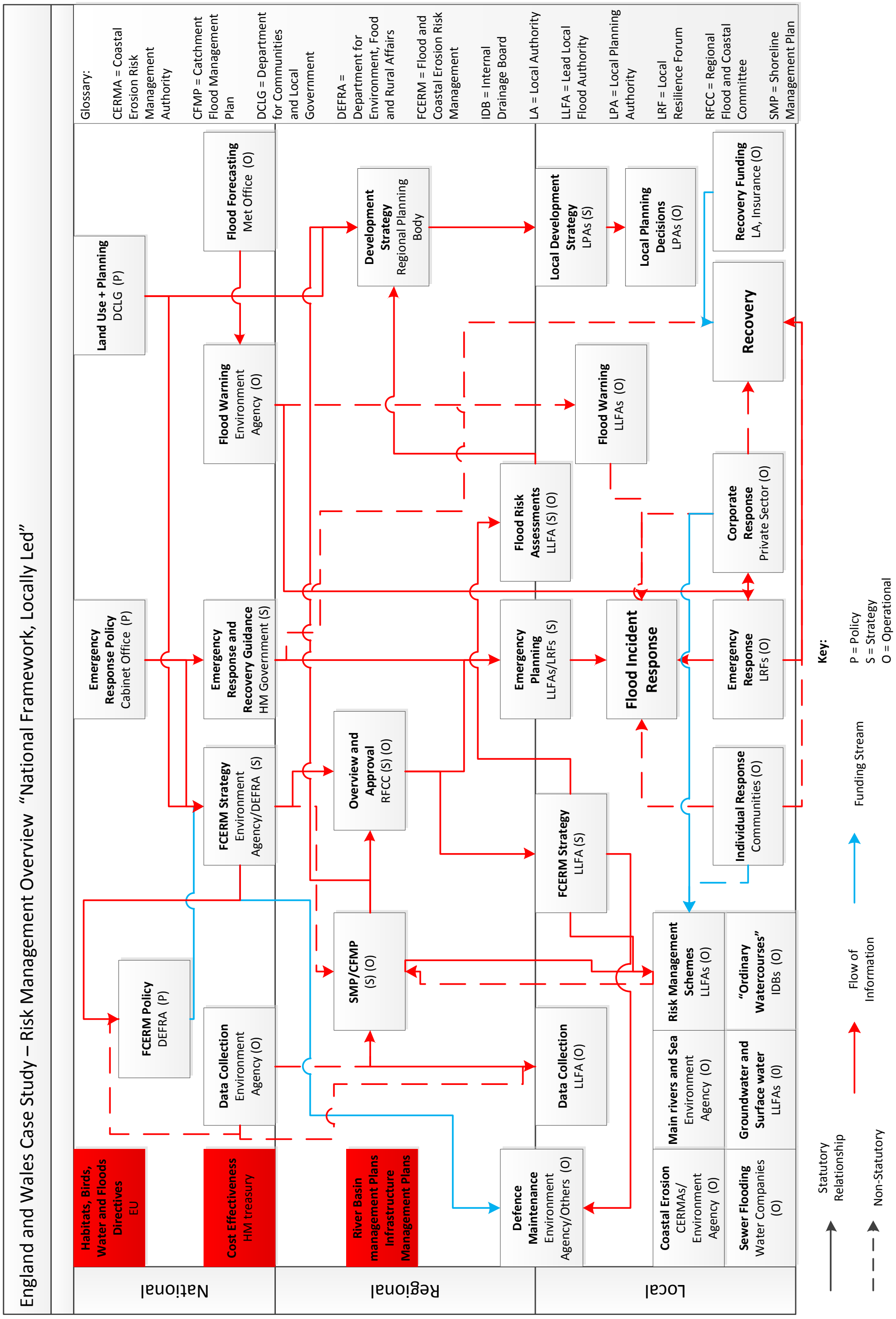

Figure 2.11: The Flood Risk Management System in England and Wales. Key References: (EA and DEFRA, 2011; HM Government, 2010a; DCLG, 2009b, 2010; DEFRA, 2011; HM Government, 2010b; European Commission, 2011; HM Government, 2004; CCS, 2010; USACE et al., 2011)

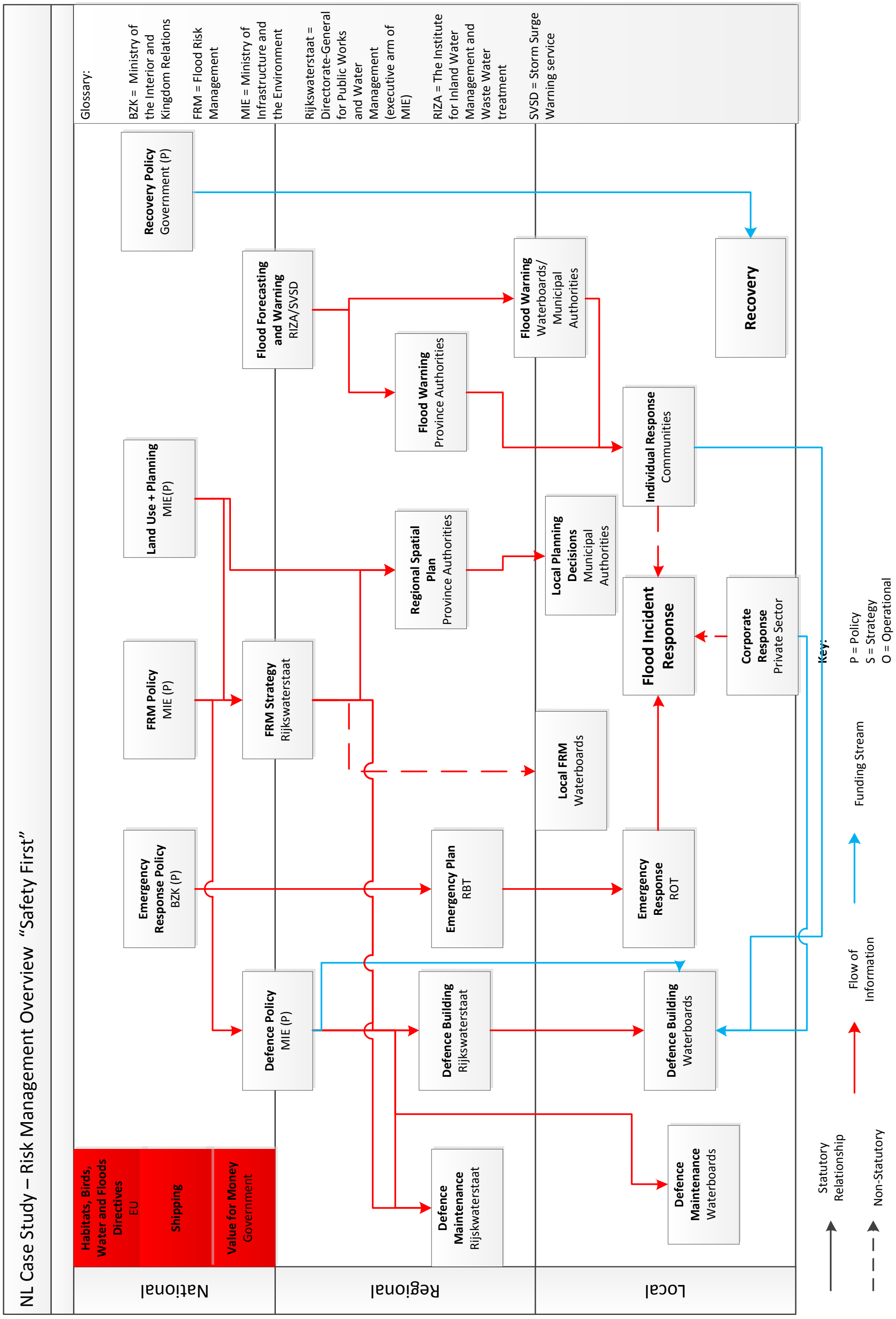

Figure 2.12: The Flood Risk Management System in the Netherlands. Key References: (Van der Valk, 2002; Dutch Government, 2010; Parker and Fordham, 1996; Steenhuisen et al., 2007; Neuvel and van den Brink, 2009; Rijkswaterstaat, 2005)

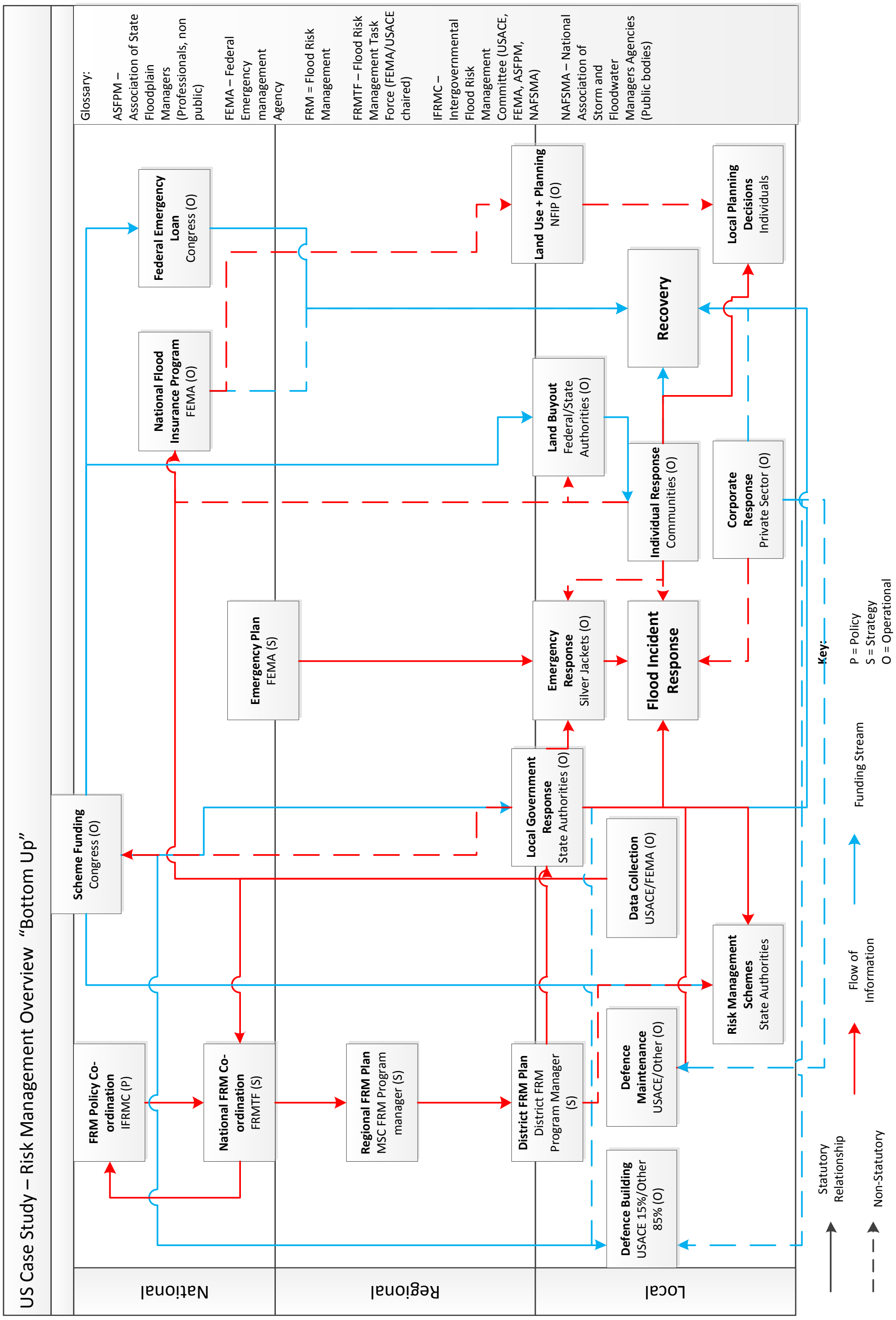

Figure 2.13: The Flood Risk Management System in the USA. Key References: (USACE, 2009; USACE et al., 2011; Rabbon, 2008; FEMA, 2004, 2008; ASFPM and NAFSMA, 2007; Rogers, 2008)

PPS25 and late the National Planning Policy Framework). Flood incident management was first introduced in the 1950s when storm warnings for the east coast were developed following the 1953 North Sea flood event. The history of FRM in the UK is evaluated in Appendix B.

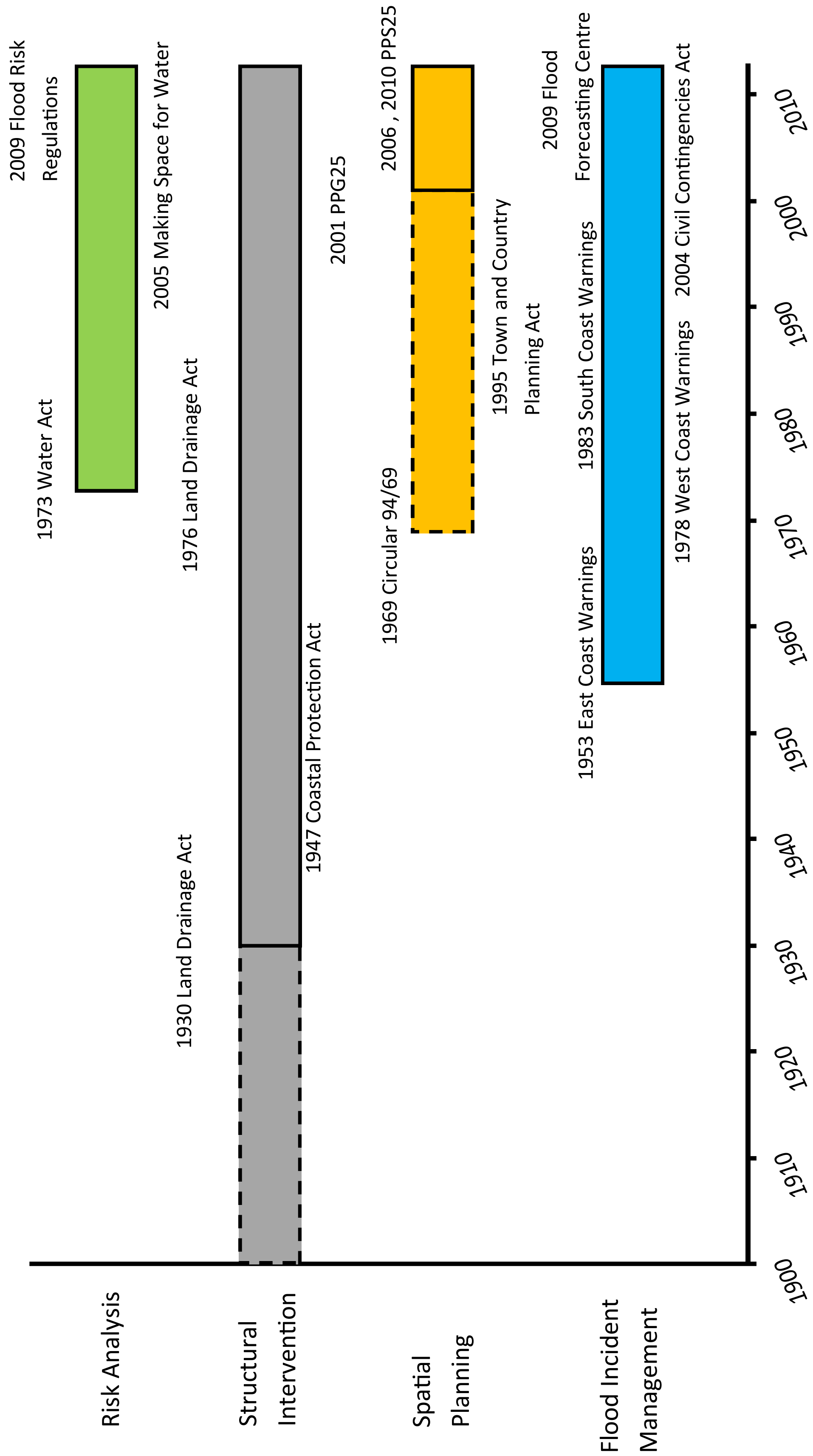

Figure 2.14: A summary of the UK FRM system between 1900 and 2012

2.4 Key Messages

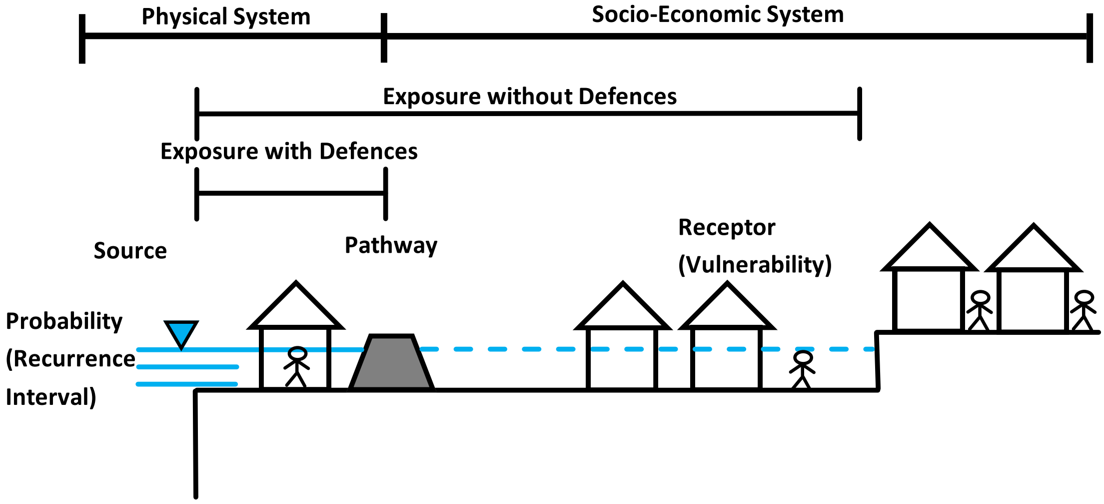

Figure 2.15: Exposure in the context of the risk definition and Source-Pathway-Receptor model

Exposure has been shown to be a vital part of risk, which is a function of probability, exposure and vulnerability. However the term exposure has not been consistently defined or used. It was found that fundamental differences in definitions/usage can be reconciled by defining exposure in terms of its source, pathway and receptor.

Changes in exposure are driven by physical (or environmental) and socio-economic (human) drivers and it is essential to understand the influence of these drivers to assess the evolution of exposure over time. Whilst future changes in exposure have been studied, historical analysis is limited. However knowledge from the past is a key to understanding the current and the future (Glaser and Stangl, 2004).

Exposure is modified by defences and in this work this issue is overcome by separately evaluating exposure without defences (which also describes exposure if defences fail), and exposure with defences (assuming that they do not fail), whereby:

$$Exposure_{with\,defences} = f(Exposure_{without\,defences}, Responses)$$

Flood events give context to the evolution of exposure; these are evaluated in terms of hydrological floods (high river/sea level) or damaging floods (events that impacts society).

These key messages from the literature are summarised in a conceptual framework (Figure 2.16) based upon the DPSIR-SPRC hybrid framework. Drivers of flooding, physical and socio-economic in nature, drive changes in source and receptor terms respectively. A given source, pathway and receptor result in the realisation of exposure, which leads to flood events and impacts. Flood events and impacts lead to management responses, as seen in the England and Wales, Netherlands and USA examples. These responses modify the flood pathway and hence exposure. This framework is consistent with the concept of exposure with and without defences. The linear Driver-SPR-Exposure linkage gives the potential exposure of flooding due to physical and socio-economic drivers, defined as the exposure without defences - responses are not considered in this evaluation. Adding the Responses loop evaluates the exposure of flooding given human responses to flooding, defined as exposure with defences.

In the following chapter this is explored further and the research approach to the thesis is developed.

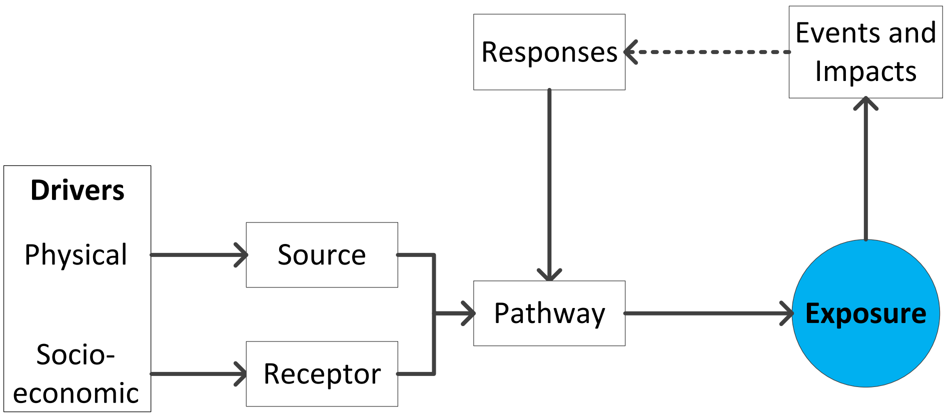

Figure 2.16: Conceptual framework of the flood exposure system

Chapter 3

Research Approach

This chapter sets out the research approach for the thesis. It gives an overview of the methodological framework; the individual methodologies are described in Chapters 4-6. Here the approach for achieving the research aims and objectives is described and approaches for modelling exposure are evaluated. The approach for evaluating exposure is to be applied to a case study. In this chapter the case study sites are selected and the spatial and temporal scales of the work are set out. The data requirements and data availability for the case study site are discussed and assumptions to be made in the modelling process are stated.

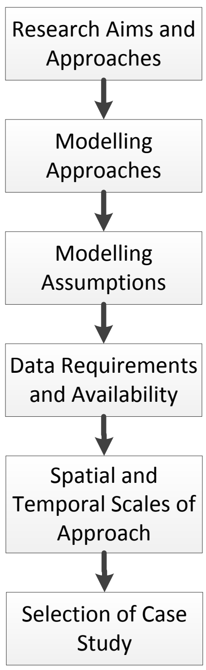

Figure 3.1: The structure of the Research Approach chapter

3.1 Research Aims and Approaches

There is a need to characterise and quantify exposure to flooding in order to ensure sound management of flooding over the next 100 years. Chapter 2 demonstrated the gaps in knowledge in evaluating historic changes in flood exposure. The key messages from the literature review are a) changes in historic exposure over time have not been fully evaluated and b) flood drivers and responses to manage flooding need to be evaluated. Exposure changes in response to both physical drivers (e.g. sea level rise, precipitation) and socio-economic drivers (e.g. development, population rise). As a result of these key messages the thesis aims were identified as:

1. To develop and apply methods to evaluate historic flood exposure and associated drivers

2. To interpret the results for improved management of exposure

In order to achieve these aims this work seeks to provide a methodology that can be applied nationally. The following research objectives will be fulfilled:

1. Characterise and evaluate the historic evolution of flood events
Exposure to flooding is defined as the potential to be harmed by flood events, and hence the occurrence of flood events can give a context to exposure. In order to evaluate the historic evolution of flood events it is necessary to have information on historic instances of flooding and if possible, the impacts.

2. Develop a framework to quantify the evolution of flood exposure
The quantitative model approach requires an understanding of the floodplain, and understanding of what is exposed (i.e. people, property, economic value), and how these have changed though time. In this thesis the quantitative model will determine a numerical value for flood exposure.
Quantification of exposure is needed because a) it gives knowledge as to how exposure has changed over time and b) it facilitates comparison between different management responses. This contributes towards proactive management of flooding. We evaluate the potential exposure without management or should defences fail (exposure without defences) and the moderated exposure given flood management measures (exposure with defences).

3. Attribute the changes in flood exposure to the underlying drivers
Attributing flood exposure to its underlying drivers allows a better understanding of how future changes to drivers (such as climate change, population dynamics) will drive future exposure (and hence risk). Changes in exposure are associated with several physical (environmental) and socio-economic (human) drivers including sea level rise, population

and development. In this work the attribution approach requires understanding and data for changes in the drivers over time, such as historic sea levels and population change.

The rest of this chapter is presented as follows: (Section 3.2) The modelling approaches and assumptions are explored; (Section 3.3) The issues of spatial and temporal scales are discussed; (Section 3.4) Case studies at the specified scale, to which the methodology is applied, are selected; (Section 3.5) The data requirements and availability for modelling are evaluated; (Section 3.6) The thesis approach to assess flood exposure is presented.

3.2 Modelling Approaches and Assumptions

3.2.1 Objective 1: Evaluate flood events at national scale

The realisation of exposure is felt in flood impacts (or consequences). These are caused by flood events which will have an impact relative to the size of event (typically measured in terms of its recurrence interval), the people and property present within the floodplain, and the presence of defences and the vulnerability of the system. In this work we do not consider the complex changes in vulnerability over time; only exposure is assessed.
For the most extreme 'worst case' flood events, such as the 1953 North Sea Flood, defences can be overwhelmed and hence exposure without defences is approximately equal to the observed impacts or damages. For flood management such extreme events are considered; typically a 1 in 200 year recurrence interval for coastal flooding. Where defences are present and do not fail, impacts from flood events are moderated and hence equivalent to the exposure with defences. Hence flood events can give a meaningful context to exposure both with and without defences, as evaluated in this work (see Chapters 1 and 2).

In the literature review two metrics for evaluating flood events were introduced; hydrological flooding (the occurrence of extreme water levels or flows) and damaging flooding (flood events that affect people). Therefore we have two potential approaches for evaluating flood events:

- Approach (1) Evaluate damaging flooding
- Approach (2) Evaluate hydrological flooding

Earlier flood event studies were based on river flows or tide levels (e.g. Marsh and Harvey, 2012; Robson et al., 1998). However there is only a weak relationship between extreme flows/water levels and the occurrence of damaging floods (Pielke Jr. and Downton, 2000; Pielke Jr., 2000). Hydrological flooding only gives information on the *physical* component of exposure (i.e. source component of the SPRC - the water levels present and therefore likely extent of the floodplain). However hydrological flooding does not account for either pathways or receptors within the floodplain. Flood defences may provide protection against high water levels and therefore in reality a large hydrological flood event does not necessarily cause damages (Pielke Jr. and Downton, 2000). Damaging flooding is a good indicator of exposure as it considers the impacts of flooding (i.e. Consequences from the SPRC, which result from Source, Pathway and Receptor terms). For an event to be damaging there must be a Source (e.g. high water, rainfall), a Pathway (defence failure/no defences) and Receptors (i.e. people or property) exposed to flooding. If a defence is present (and does not fail) then the flood event will not cause damage, or the damages will be moderated. A damaging flood event therefore gives information on both exposure with and without defences. Crucially, it characterises the effect of flooding on people, which hydrological flooding alone does not.

The chosen approach is therefore approach (1): to evaluate damaging flooding. This is because damaging flooding is a better indicator of exposure than hydrological flooding. Damaging flooding accounts for the interaction between the flood source (i.e. hydrological flood) and the people and property (receptors) exposed. Damaging flooding also accounts for the moderating effect of flood defences (i.e. events may be less damaging than if not defended) and the effect of defence failure (flood events will be more damaging). The methodology for evaluating the evolution of damaging flooding is described in Chapter 4 of this thesis.

3.2.2 Objective 2: Quantify the evolution of flood exposure

In Chapter 2 it was shown that exposure has not been consistently defined or quantified in previous work. As a result exposure has been evaluated differently at different case study sites and comparison between studies is often not possible.
In order to improve the consistency in exposure evaluation a method is required that is applicable at the national scale, or be repeatable at the local scale to build a consistent national dataset. Further it must facilitate historical analysis by accounting for changes in exposure over time. Therefore the research approach to quantify exposure must adhere to the following:

- A definition of exposure that is consistent in space and time
- Use data sets to quantify exposure that are available nationally (e.g. census data, sea levels etc.)
- Need for a consistent approach that can be applied to any local case study

In Chapters 1 and 2 exposure was defined in terms of recurrence interval, source, pathway and receptor. Changes in exposure over time are driven by both physical and socio-economic drivers. In this section the approaches for modelling and quantifying each of these components are discussed.

Flood Source

The main sources of flooding are coastal (tidal) flooding and fluvial (river) flooding, however other forms are becoming increasingly prominent such as surface water flooding and groundwater flooding. Other forms of flooding include *surface water* (Hickman, 2011; Kaźmierczak and Cavan, 2011; MWH, 2011), *sewer* (Penning-Rowsell et al., 2006a), *groundwater* (Adams et al., 2010; Bricker et al., 2011; Macdonald et al., 2008), *reservoir failure* (Charles et al., 2011), and other less common forms such as *ice jam flooding* (USACE, 2011). These are less well characterised than fluvial and coastal flooding with less data available to quantify them. Therefore the following two approaches are compared:

- Approach (1) Fluvial Flooding
- Approach (2) Coastal Flooding

Fluvial Flooding has been the focus of many studies (e.g. Robson et al., 1998; Macdonald, 2006; Marsh and Harvey, 2012; Delgado et al., 2010; Petrow and Merz, 2009; Barredo, 2009). Major fluvial events affected the Netherlands in 1993 and 1995 leading to dike heightening across the country (Van Boetzelaer and Schultz, 2005). Major floods in the UK in 2007 had an estimated £3.2 billion economic cost in England (Chatterton et al., 2010). It is anticipated that with climate change winters will become wetter with a greater frequency of fluvial winter flood events (Hulme et al., 2002; IPCC, 2007). However there are no discernible long term historic trends in river flows either globally (IPCC, 2007) or in the UK (Robson et al., 1998; Macdonald, 2006; Marsh and Harvey, 2012). Delgado et al. (2010) found an increasing likelihood of extreme events in the Mekong river - however the probability of an “average flood” has decreased. Significant trends in floods were detected in some German basins, however some were positive and others negative with no overall increase in flows demonstrated (Petrow and Merz, 2009). Barredo (2009) showed that trends in fluvial flood losses in Europe were removed when normalised by exposure (population and wealth) suggesting a lack of trend in river flow. This means that for historical studies changes in fluvial flood exposure are socio-economic (i.e. human) driven. The lack of historic trend in river flow limits our ability to compare historic physical and socio-economic drivers of fluvial flooding.

Coastal Flooding is a growing threat with coasts containing a large and growing population (Nicholls, 2015). Exposure to flooding is increasing in coastal cities across the globe (Hallegatte et al., 2013). In Thailand devastating floods in 2011 led to inundation of more than 5.5% of the total land area affecting more than 13 million people with

over 680 deaths (GFDRR and The World Bank, 2012). In 2005 hurricane Katrina highlighted the flood exposure in the USA causing more than 1,100 fatalities in the state of Louisiana (Jonkman et al., 2009). These events highlight the increased risk of coastal regions due to the combined effects of more intense and more frequent natural events, whilst having the highest concentration of people and economic value (Kron, 2008). One tenth of the world's population live within 5km of the coast, with the number exposed even higher due to temporary residents from coastal tourism (Kron, 2008). More than 200 million people are at risk of flooding from extreme tide levels as a result of storms (Nicholls, 2010). In addition, in the 136 port cities worldwide with a population of more than one million habitants an estimated $3,000 billion of assets are exposed to the 1 in 100 year coastal flood event (Nicholls et al., 2007).
More recently, the Winter 2013/14 storm season in the UK was seen to be the most extreme on record (Wadey et al., 2015). There were more than 295 flood warnings in force across England and Wales and 1,400 homes were flooded due to a North Sea tidal surge on December 5th 2013 (Sawer, 2013).
Historic changes in mean sea level have been measured across the world (Church et al., 2013). Historic changes in exposure to coastal flooding have been driven by both physical (i.e. sea level rise) and socio-economic (population rise, coastal development) factors (e.g. Lin et al., 2012; Aerts and Botzen, 2012). Therefore the physical and socio-economic drivers can be compared. There is a need to characterise the effect of these drivers of flooding on the coastal system (Sanchez-Arcilla et al., 2008; Nicholls, 2015). The evolution of fluvial flood exposure could be similarly studied; however less insight will be gained into the drivers of the changes in exposure. Coastal areas are likely to be more vulnerable than inland areas due to changes in sea level, wave heights and accelerated erosion (Zsamboky et al., 2011). Further, in England and Wales the coastal floodplain contains a much higher proportion of deprived households than fluvial floodplains (Walker et al., 2003).

From this brief overview, it is clear that coastal zones are the most vulnerable places to flooding due to the high degree of development coupled with the intensity of natural events. Further, historic changes in sea level have been observed making coastal flooding conducive to historic analysis. Hence coastal flooding (Approach (2)) is the focus of this thesis.

Flood Pathway

Flood pathways are affected by several responses to manage flooding, which have been grouped into three main sections: structural intervention, spatial planning and flood incident management. Structural Intervention describes measures to prevent or control flow (such as a seawall or a levee). Spatial Planning describes policies which limit development in certain areas, such as restricting coastal development. Flood Incident Management (FIM) describe responses to manage flood events and include warning, evacuation, temporary barriers and pumps, or recovery from flood damages. The possible approaches for considering flood pathways in the quantitative model are as follows:

- Approach (1) Model all three groups of flood management response
- Approach (2) Model Structural Intervention only
- Approach (3) Model Spatial Planning only
- Approach (4) Model Flood Incident Management only

The first two of these groups will affect flood exposure; for instance defences reduce possible flood pathways and spatial planning can remove receptors from the floodplain, however flood incident management can reduce impacts such as loss of life or damages, which are related to vulnerability and not exposure as defined in this work. Further, each of these interactions with the flooding system requires a different approach with its own assumptions, data requirements, and individual complexities. Approach (1) can therefore not be achieved in a meaningful way since it would require several distinct methodologies and so could not be done at a high level of detail in the context of a thesis. Further, not all components of Flood Management directly affect exposure. Spatial planning can remove exposure, structural intervention determines the exposure with defences (as defined in this thesis), and Flood Incident Management directly affects the vulnerability of the flood system, not exposure.
Approach (2) facilitates quantitative analysis, as it can be applied to a numerical model as a boundary condition (i.e. defence height), and was identified as a key intervention in the literature (i.e. see the management diagrams for the USA, Netherlands and England and Wales in Chapter 2). In the UK structural intervention has been the dominant response to flooding over the last 100 years (See Appendix B). Further, it allows comparison of exposure with and without defences. Approach (3) does not directly affect exposure to flooding, and has already been covered in major work by Fontaine (Fontaine, 2010), and advanced models such as the Sleuth urban growth model (Clarke et al., 1997; Silva and Clarke, 2002; Bihamta et al., 2015). Approach (4) was considered within academic research using agent based modelling (Dawson et al., 2011b) and government research projects (EA, 2006, 2013). Further, national policies in Flood Incident Management have only existed for a few decades and so historical analysis of this response is limited (Appendix B).

The selected approach is therefore approach (2): to model for Structural Intervention only. This is a key response to flooding and has a direct effect on exposure, it can be considered within the numeric model, and it reduces the complexity of the thesis to an achievable level. Consideration of structural intervention allows comparison of exposure with and without defences (see Chapters 1 and 2); highlighted as an important facet of flood exposure studies.

Flood Receptor

The most commonly evaluated receptors in flood exposure studies are people, property and economic value. Monetary or economic losses are commonly evaluated in project appraisal of flood defences and in national and global analysis (e.g. Nicholls et al., 2013; Hallegatte et al., 2013; Dawson et al., 2009). In some previous studies, population data has been used to spatially locate population within the floodplain (e.g. Fielding and Burningham, 2005; Thrush et al., 2005). Other studies evaluate the number of properties exposed to flooding (e.g. Wadey, 2013; Wadey et al., 2012). The following approaches to flood receptors are compared:

- Approach (1) Economic Losses
- Approach (2) Population (number of people in the floodplain)
- Approach (3) Property (number of buildings in the floodplain)

Approach (1) is to evaluate economic losses. These are vital for analysis of the cost benefit (value for money) of defence options. However economic losses are difficult to assess historically because depth damage curves, which relate land/building type and flood depth to damages are highly uncertain in time. Further, they are sensitive to assumptions in historic discount rate. An alternative flood receptor is people (Approach (2)). This may offer an alternative for historical analysis as census data exists >200 years in time in the UK and this offers a more consistent approach through time. Using people as the chosen receptor eliminates the need for depth-damage curves as people are a constant metric through time. Uncertainty in discount rates for historic analysis of monetised exposure becomes irrelevant.

The number and spatial location of people exposed to a flood event is vital information for emergency planning. The approach for evacuating 1000 people from an urban apartment block is very different to the approach for evacuating 100 people from dispersed rural villages, perhaps with limited access routes.

The number of buildings within the floodplain is also a consistent metric of exposure; however there is not the same consistency in historic data as for population. Whilst historic populations are known (for instance, census data in the UK goes back to 1801, which will be discussed later), there is not the same data available for number of buildings. The location of developed areas can be extracted from historic maps, however the resolution is too low to pick out individual properties. The exposure of property gives information on potential commercial losses as well as exposure of residential properties which can be used with average occupancy rate of residential properties to estimate the exposure of people. However it is not always possible to distinguish between residential and non-residential properties especially with older lower resolution data such as

OS maps. Using the exposure of properties as an indicator of exposure to people then becomes highly sensitive to the assumptions used to translate number of properties into number of people.

The chosen approach is therefore approach (2): to use population as the flood receptor. This is because the metric of people exposed is consistent through time, an important metric to be quantified for emergency planning, and historic data is available nationally. It is acknowledged that financial damages and properties are also important metrics; and future work could seek to quantify these. For example a human life is valued at £1.49 million in UK climate change risk assessment (Ramsbottom et al., 2012), which could be used as a starting point to monetise the evaluation of people exposure.

Drivers of Flood Exposure

There are several drivers that broadly can be categorised as physical (or environmental) drivers, and socio-economic (or anthropogenic) drivers. Physical drivers include relative sea level rise, waves, coastal morphology and precipitation. Socio-economic drivers include population, development and land use. The two overall approaches to modelling flood exposure drivers are to consider all known drivers, or to use the literature to unpick the key coastal flood exposure drivers and concentrate on these:

- Approach (1) Consider all exposure drivers
- Approach (2) Concentrate on key/representative drivers

Approach (1) was undertaken by the Foresight study at the national scale (Evans et al., 2004). Foresight identified 19 drivers of flooding, using scenarios and expert judgement to apply a weighting factor to each driver to determine how it will change future flood risk. For instance the sea level rise driver was predicted to multiply present day (2004) national flood risk by between 4-10 times by the 2080s (Evans et al., 2004). However, not all drivers of flood risk drive exposure. For instance stakeholder engagement identified in Chapter 2 affects vulnerability, and surges and waves affect the probability of a flood event, and hence in this work it is not necessary to evaluate all drivers. The identified flood exposure drivers in Chapter 2 were sea level rise, precipitation, coastal morphology, population size, development/urbanisation and land use change.
We can concentrate on a fewer number of key drivers in order to gain meaningful insight into the effect that each has on the evolution of exposure.

The three key physical drivers of exposure identified are sea level rise, precipitation and geomorphology. In this work we focus on tidal flooding, and hence can eliminate precipitation as a driver. Although rain-driven fluvial and pluvial events may affect coastal locations, precipitation is not a cause of tidal flooding. Coastal morphology is difficult to quantify - Stuiver (2013) studied the evolution of this driver. Relative sea level rise does take account of both global rises in sea level, and local subsidence/uplift for instance as a result of isostatic rebound. This can be a compromise between fully characterising the coastal morphology and ignoring this driver outright. Fully characterising coastal morphology would introduce additional uncertainties and is beyond the scope of this research, and ignoring changes entirely could lead to poor results. Therefore relative sea level rise will be modelled as the physical driver of flood exposure.

The key socio-economic drivers of flooding identified are population size, development/urbanisation and land use change. The quantification of these drivers can be achieved by considering the size and location of the coastal population at potential risk. Population is defined as the number of people in the coastal environment, which drives the number of people within the floodplain and so this driver will be considered as part of the framework. Development/urbanisation relative to the coastal population can be characterised by the location of people within the floodplain. High urbanisation equates to high population density, for instance coastal mega cities across the globe (Nicholls and Klein, 2005; Kaufmann et al., 2010). Land use change is an important driver of exposure, however for consideration of the coastal population it can be described as land use relating to residential development. Residential development is defined in this work as the spatial location of the population - i.e. where residential development is sited. Residential development does not include other land uses such as agriculture, commercial or industrial. The term Residential Development is used throughout this thesis instead of urbanisation and land use change in order to make this distinction clear.

The chosen approach is therefore to quantify the following drivers:

- Sea Level Rise
- Population (size)
- Residential Development (location where houses/people exist)

These drivers represent both physical drivers (sea level rise) and socio-economic drivers (population, residential development). Population determines the density of people within the coastal floodplain, and Residential Development determines the expansion of residential area. This approach maintains a balance between meaningful analysis (i.e. not over-simplifying the modelled system), and meaningful understanding (i.e. not over-complicating the modelled system).

Recurrence Intervals

In UK flood management the 1 in 200 year coastal flood event is typically used to define an extreme event; however smaller, more likely events can still have an impact and so are also important to consider. Two potential approaches to recurrence intervals are therefore compared:

- Approach (1) Evaluate the 1 in 200 year coastal flood event
- Approach (2) Evaluate a range of recurrence interval coastal flood events

The first approach is consistent with current practice and so results are comparable to other studies. For instance the Environment Agency's indicative floodplain map (IFM), available across England, evaluates the 1 in 200 year coastal flood event. The current range of regional beach management plans also focus on the 1 in 200 year event (Canterbury City Council, 2016, personal communication). However, evaluation of only the 1 in 200 year event gives no information on smaller but still significant events. Current research on 'flood memory' suggests that a series of concurrent low recurrence interval flood events may be as damaging as a single rarer, higher recurrence interval event (Haigh et al., 2016, In Review). Further, some coastal flood defences are designed to a standard of protection less than (or in uncommon cases, such as the Thames barrier, more than) 1 in 200 years.

Evaluation of a range of recurrence intervals gives more meaningful information on exposure and the effect of defences on smaller/larger flood events. It also provides the foundation for further study on risk - calculation of annual average damages requires data on a range of recurrence intervals. The drawback of evaluating a range of recurrence intervals is that it requires data on still water levels and corresponding flood extent for each recurrence interval considered. This increases the complexity of modelling and the time taken to undertake the methodology, and means that existing sources that evaluate a single recurrence interval (such as the Environment Agency's IFM) cannot be used.

In conclusion the positives outweigh the drawbacks and so a range of recurrence intervals (Approach (2)) will be evaluated in this work. A supplementary analysis will be undertaken for the 1 in 200 year coastal flood event for comparability with existing work: this analysis will form an appendix to the main thesis.

Flood Extent

Previous studies which evaluate flood extent can broadly fall into two categories; conceptual or qualitative models (such as the SPRC or DPSIR frameworks discussed in Chapter 2), and maths based or quantitative or numerical models (such as hydrodynamic models). Maths based models can be used to describe flood extent, such as the quantified SPRC (Narayan et al., 2012; O'Connell et al., 2011), hydrodynamic flood models (Dawson et al., 2005, 2009; Smith et al., 2012) or Bayesian networks (Mojtahed et al., 2012; Manning, 2011). Exposure can be quantified at the local level by numerical modelling (e.g. Mokrech et al., 2011; Wadey et al., 2012; Dawson et al., 2005). Maps of the floodplain extent are produced in England and Wales by the Environment Agency; however these maps are only for a single recurrence interval (the 1 in 100 year fluvial floodplain and 1 in 200 year coastal floodplain). These different sources give different levels of detail.

- Approach (1) Conceptual model (e.g. SPRC)
- Approach (2) Use existing flood map (i.e. EA IFM)
- Approach (3) Hydrodynamic/Numeric Model

Approach (1) was studied in a recent major body of work (Narayan, 2014) which built upon the SPRC concept to develop a rapid appraisal of flood risk. This approach is based on risk, not exposure, and so is not suitable for this thesis. The use of an existing flood map (Approach (2)) would make the methodology easier, however this restricts the analysis to the 1 in 200 year floodplain in the modern day; limiting historic analysis and analysis of different recurrence intervals (see previous section). This thesis aims to evaluate multiple recurrence interval flood events. Further, the Environment Agency's IFM is considered inconsistent as it it based on several distinct sources of data that vary in scale and precision (Porter, 2009). Approach (3) - the use of a hydrodynamic model (e.g. Bates and De Roo, 2000; Bates et al., 2005, 2010; Wadey et al., 2012) would allow greater flexibility for recreating the historic floodplain (i.e. modelling for a lower historic sea level). Flood inundation models are a major tool for mitigating the effects of flooding and there have been major advances over the past decade (Mason et al., 2010). A numeric model also facilitates the inclusion of flood defences in the analysis, allowing the effect of flood management measures to be evaluated. Hence both exposure with and without defences can be evaluated.

For these reasons the chosen approach is to use a hydrodynamic model to model the flood extent (Approach 3). This gives the thesis flexibility to explore historic flood exposure accounting for changes in sea level and for a range of recurrence intervals, and allows scenarios with and without defences to be modelled.

The methodology for quantifying the evolution of exposure is described in Chapter 5.

3.2.3 Objective 3: Attribution of flood exposure to drivers

Attribution is the act of identifying the underlying factors behind some phenomenon, for instance attributing rising global temperatures to anthropogenic greenhouse gas emissions. Attribution gives information on what has *caused* observed changes the factor under consideration. The current state of flood trend attribution is poor and either based on qualitative reasoning or speculation (Merz et al., 2012). Attribution of river flow data tends to be based upon statistic methods, for instance Kjeldsen et al. (2012) use statistic tests of hydrometric flow data to attribute trends in UK flooding. Harrigan et al. (2014) used statistical tests on multiple hypothesised drivers to determine the drivers attributed with increased stream flow in the Boyne catchment of East Ireland. In the climate change research community the Fraction of Attributable Risk has been recent established (Merz et al., 2012). This method has its roots in epidemiological science (Levin, 1953) and is a measure of the amount of risk attributable to underlying drivers of change. Kay et al. (2011) use FAR to attribute the Autumn/Winter 2000 flood risk in England to anthropogenic climate change. Hence the following two approaches can be used to attribute flood exposure and risk:

- Statistical Methods
- Fraction of Attributable Risk

Statistical methods are widely used to study trends in river flow using hydrometric flow data (e.g. Kjeldsen et al., 2012; Harrigan et al., 2014) and have been used to attribute flood risk to different risk management organisations (Dawson et al., 2008). However there is limited application outside of flood hazard (i.e. the physical system). In this research we assess exposure due to both physical and socio-economic drivers. A benefit of FAR is that it is widely applicable (Jaeger et al., 2008) and hence is likely to be better suited to this study. FAR is a consistent quantitative approach to the attribution problem (Merz et al., 2012), and is applicable to the analysis performed in this thesis. Statistical methods are more appropriate for analysing raw data, particularly in larger datasets such as hourly rainfall or river flow records. However for the scale and methods of this thesis FAR is a simpler approach that is easily repeatable and consistent for multiple case studies.

The chosen approach for attribution is therefore the Fraction of Attributable Risk (FAR). The methodology for attributing the drivers of flood exposure is described in Chapter 6 of the thesis.

3.3 Spatial and Temporal Scales of the Approach

Analysis of flood exposure can be conducted at a range of spatial scales, ranging from the global scale (Nicholls and Tol, 2006; Nicholls et al., 1999; Vafeidis et al., 2008; WEF, 2014; Hinkel et al., 2014), national scale (Evans et al., 2004; EA, 2009a; Hall et al., 2006; Stevens et al., 2016), regional scale (Gouldby et al., 2008; Bosom and Jimenez, 2011; Bates et al., 2005; Wadey et al., 2012), down to the local scale (Stevens et al., 2015; Wadey et al., 2012; Rogers, 2008; Meding and Oyedele, 2008). A decision on the spatial and temporal scale of modelling depends on what output we want to achieve. A comparative national assessment of exposure for different regions would require a series of assessments through time, whereas an emergency evacuation plan for a local area would require a more detailed assessment for one fixed point in time (i.e. using the most up to date information).

In this section the spatial and temporal scales of the approaches developed in this chapter are discussed.

3.3.1 Spatial Scale of the Model

The scales at which flood exposure can be managed are shown in Table 3.1. The highest scale is national scale at the level of governance. Here policy and national strategy are achieved, as discussed in the case studies in the literature review.
The regional scale is defined as sub-national areas containing several towns or cities, in which flooding is managed. Here strategic decisions on funding and management are made. Local scale is defined as local authority areas such as towns or cities. At this level flood management operations take place, for instance spatial planning decisions or flood defence works.

Scale	Geographic Size	Examples
National	Country	Netherlands, USA, England
Regional	County/State	Lousisiana, Hampshire
Local	City/Town	New York, London, Amsterdam

Table 3.1: Definition of the spatial scales considered in the thesis

There is a trade off between resolution and data requirements/computational resources in choosing the spatial scale at which to model. The larger the scale of the work, the lower the resolution of the output. For example a flood model from a global study of flooding would necessarily be coarser than a flood map produced for a local area.
Local studies at the catchment scale make hydrologic sense and allow more detailed flood data to be used. However they can be difficult due to administrative boundaries not matching catchment areas. This makes the local analysis less meaningful to flood management at higher spatial scales (for example regional and national policies). On the other hand more regional approaches lack local perspective and offer a lower resolution analysis (EA, 2012a). For quantitative analysis the local scale is more robust and meaningful.

The benefits of a national level study which is useful for management, and the local scale which offers higher resolution, can be combined. A series of local studies at higher resolution can be combined to give national coverage (Figure 3.2). This approach maintains the benefit of local study whilst giving a wider regional and national perspective.

In this approach the national and regional scales are combined into a “strategy” or policy level. The local level is the scale at which policies and strategies are enacted. Therefore a national scale study will be used to give context at the level of governance. Exposure will be quantified at the local level.

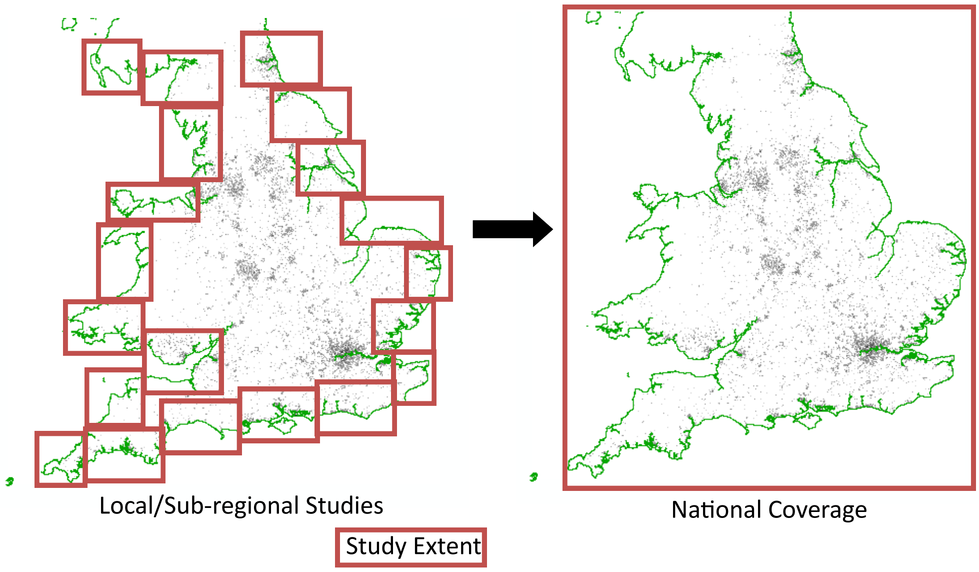

Figure 3.2: Combining local/sub-regional scale coastal flood exposure studies to give national coverage (size of local studies exaggerated for display). Contains public sector information licenced under the Open Government Licence v3.0.

3.3.2 Temporal Scale of the Model

Flooding and flood management acts over several timescales. Development planning in the UK typically considers a 10-15 year period (Khatibi, 2011). However climate change is felt over a much longer timescale. The UK government's Foresight study considered flood risk over a 100 year period (Evans et al., 2004). The TE2100 plan looked at changing conditions in the Thames estuary until 2100 (EA, 2012b). The hundred year timescale allows the long term evolution of flood exposure to be evaluated.
Foresight considered three "time slices": the 2050s, 2080s and 2100 (Evans et al., 2004). The UK Climate Impacts Program publish climate change scenarios for similar time periods, the 2020s, 2050s and 2080s (Hulme et al., 2002).

This work will use a temporal scale of one-two centuries. The historic analysis will be dependent on the presence of datasets to estimate exposure to flood risk. The number of unique analyses to be undertaken (i.e. the time-step of the analysis, roughly 30 years for Foresight) will be determined by the availability of data. The aspiration is to consider a smaller time-step than Foresight by using higher resolution local data, rather than the national approach taken by the Foresight analysis. This will be discussed in Section 3.5.

3.4 Selection of Case Study Sites

In order to prove the concept of this approach, a national case study, and two local studies are selected.

3.4.1 National Case Study: England and Wales

England and Wales represent an effective case study region for evaluating exposure for several reasons:

- **UK Flood History**. The UK has a long history of nationally significant flood events (i.e. the Great flood of Sheffield 1864, North Sea flood 1953, more recent events such as the 1998 Easter floods, 2000 Autumn floods, 2004 Boscastle flood, 2005 Cumbria flood, 2007 Summer floods, floods across Great Britain and Ireland in 2009 and 2012 and coastal storms in Winter 2013/14)
- **Availability of National Datasets**. Data is available across England and Wales relating to population (census data), flood events (Met Office publications, Centre for Ecology and Hydrology reports), topography (Environment Agency LIDAR data) and extreme water levels (McMillan et al., 2011).
- **High Exposure**. The UK has a high exposure to flooding, as illustrated by the quantity of flood warnings issued by the Environment Agency (Figure 3.3). This event was described by the UK's Met Office as "exceptionally wet weather" however it was not unprecedented, with a further notable rainfall event and notable winter storms in the same year, and several notable flooding events in the majority of years on record (Met Office, 2017).

The UK national case study is presented in Chapter 4 where damaging flooding is evaluated at the national scale.

3.4.2 Local Case Study Sites: Portsea and Hayling islands

Portsea and Hayling islands sit within the North Solent region on the South UK coast (Figure 3.4). The Solent encompasses urban semi-metropolitan areas such as the cities of Southampton and Portsmouth, along with rural conurbations in the New Forest, and the Isle of Wight. The area extends from Hurst Spit in the west, to Selsey Bill in the East. There is a high level of flood risk in the Solent, with an estimated 24,138 properties (excluding the Isle of Wight) exposed to a 1 in 200 year coastal flood (NFDC, 2010). The Solent is well suited for a study of flood exposure for several reasons:

- The range of topography, population and land use (particularly the rural/urban split) is representative of many European areas;
- Flood extent data for different recurrence intervals of flood events exists from EA flood maps, and from a validated model which incorporates defence failures and the dynamics of flood spreading (Wadey et al., 2012), allowing for a more detailed analysis of vulnerability to different threat levels;

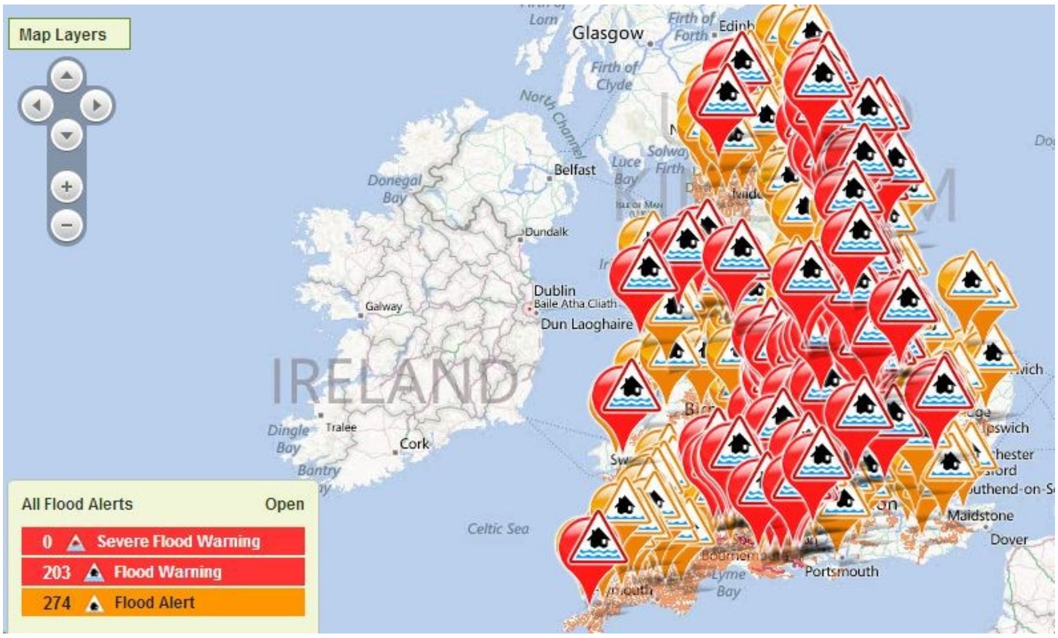

Figure 3.3: An illustration of the high level of exposure to flooding in England and Wales (flood alerts and warnings as issued in November 2012). Flood warnings indicate “Flooding is expected, immediate action required”, and Flood Alerts indicate “Flooding is possible, be prepared” (see https://flood-warning-information.service.gov.uk/)

- The Solent region faces residential and commercial development pressures due to its strategic trade location (road and sea transport routes) and tourist / environmental attractions (Atkins, 2007; NFDC, 2010). Sea levels have been rising at an average rate of 1.7 mm/year across the past century (Bindoff et al., 2007; IPCC, 2013) increasing the probability of extreme events (Haigh et al., 2011; Wadey et al., 2013) and are expected to accelerate over the coming century (e.g. NFDC, 2010), and increase flood risks (Evans et al., 2004);
- Portsmouth is a city of national flood significance, only behind London and Hull in terms of the amount of property exposed to coastal flooding (RIBA and ICE, 2008).

The Solent is at risk of significant and increasing flood impacts as a result of expected sea level rise and socio-economic changes (including increased development and population). Flooding is moderated by flood defence systems which includes managed habitats. The low residual risk in the region poses challenges for coastal and flood management as risk awareness may be reduced and there may be complacency regarding the need to prepare for future flooding (Shackleton et al., 2011). However the Solent is at risk of significant flood impacts as a result of expected sea level rise and socio-economic changes including increased development and population rise. These are expected to be felt most severely in Portsmouth (Havant Borough Council, 2014, personal communication).

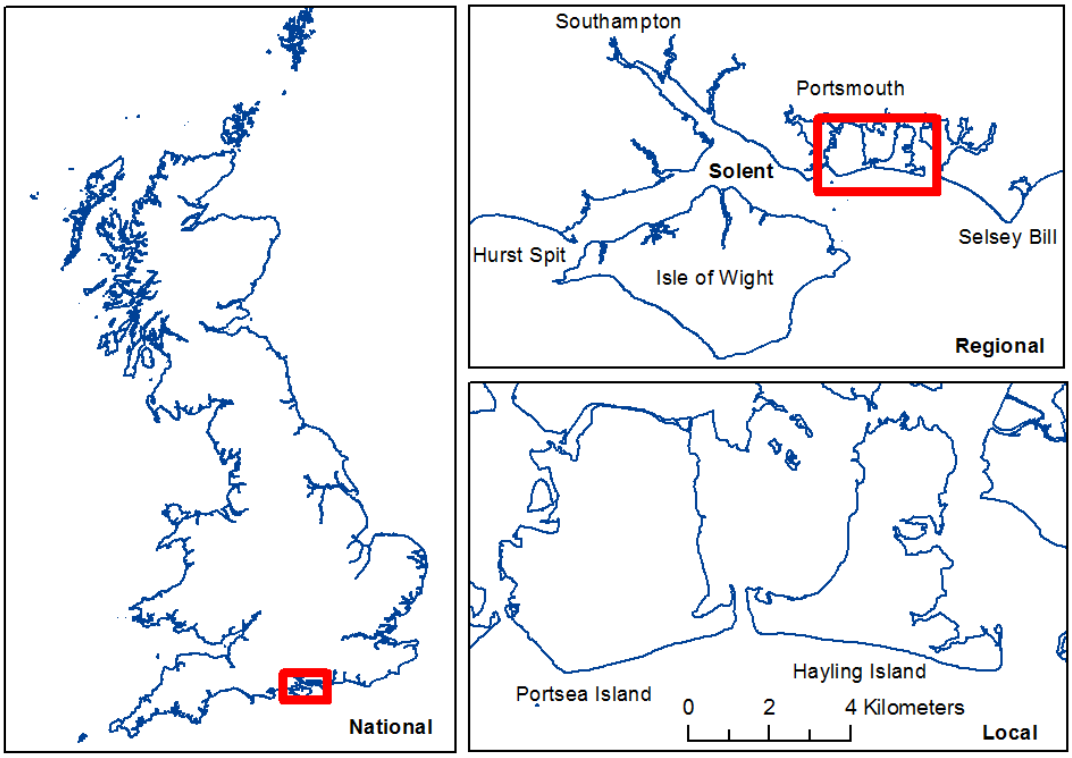

Figure 3.4: Portsea and Hayling islands within the UK's Solent region. Contains public sector information licenced under the Open Government Licence v3.0.

Quantifying the respective roles of the main socio-economic (population, development) and physical (sea level) drivers behind exposure, and the dynamics of this over time will inform sound management of future exposure and hence is valuable as a research tool. This will benefit coastal management, both to disseminate an understanding of risk to the public and developers, and for long term coastal planning.

Within the Solent region the two locations were chosen to represent a densely populated and highly developed urban area, and a sparsely populated and less developed rural area. The chosen locations are Portsea and Hayling Islands, located in the eastern part of the North Solent region. This will facilitate comparison of how well the approach works for low and high population studies. Further, this can test the hypothesis that the underlying drivers in a typical rural area and typical urban area may be different.

Portsea Island is the urban case study. It forms the majority of the city of Portsmouth which has a population of 205,100 and a density of 5082 people per square kilometre according to the 2011 census, the highest in England and Wales outside of London. Portsea Island has a long history of flood risk management (Easterling, 1991) with large areas of the Island protected by artificial or managed natural defences. Hayling Island is the rural case study. It has a much lower population than Portsea (17,379 according to the 2011 census) and has been subject to a lower degree of active intervention, although sea defences do exist on the Eastoke peninsula and the beach is reshaped following storms

(HR Wallingford and Havant Borough Council, 2009). The evolution of exposure of the coastal population in these two areas will offer insight into the effect of flood defences on long term changes in flood exposure.

3.5 Data Requirements and Availability of the Modelling Approach

In this section the data requirements of the methodological approach, data availability and the assumptions adopted in the approach are discussed. The approach requires data to characterise the following components at key steps in time over 100+ years:

- Hydrodynamic model (sea levels, tidal curve, ground elevations)
- Population size
- Distribution of population (residential development)
- Structural Intervention data (defence heights, location)

The availability of the data required for applying the model in the UK is shown in Figure 3.5. Data for the hydrodynamical model (e.g. sea levels, tidal curves) are available 1960-2011 from sea level records (Haigh et al., 2011). Population size data comes from the UK census and is available from 1801-2011 at 10 year time intervals. Development data comes from historic OS maps, which are available from 1870-2011 at irregular time intervals averaging 20 years from Digimap© (https://digimap.edina.ac.uk/). Digimap© hosts mapping for the whole UK, however the exact dates of the maps can vary for the region under consideration. The dates in Figure 3.5 represent the dates of maps for the Portsea and Hayling case studies. Data on defence heights comes from contemporary research and historic engineering reports and is available for the case study from circa 1960-2012 (Easterling, 1991; Wadey et al., 2012).

Uncertainty is "an unavoidable aspect of scientific endeavours" (Lewandowsky et al., 2014). Uncertainties are inherent in both our understanding of real world systems (i.e. data/knowledge uncertainties), and in our representations of these systems (i.e. model uncertainties). These uncertainties are managed by the use of assumptions. The modelling assumptions in this work are shown in Table 3.2.

The hydro-dynamic model to be used in Lisflood-FP, a 2d inundation model that has been proved for coastal use (Bates et al., 2005). This method is more accurate than 'bathtub' or planar water level models as mass conservancy and hydraulic connectivity accounted for. In a bathtub model the floodplain is determined by land elevation and water level - pathways are not accounted for and hence defences cannot be evaluated.

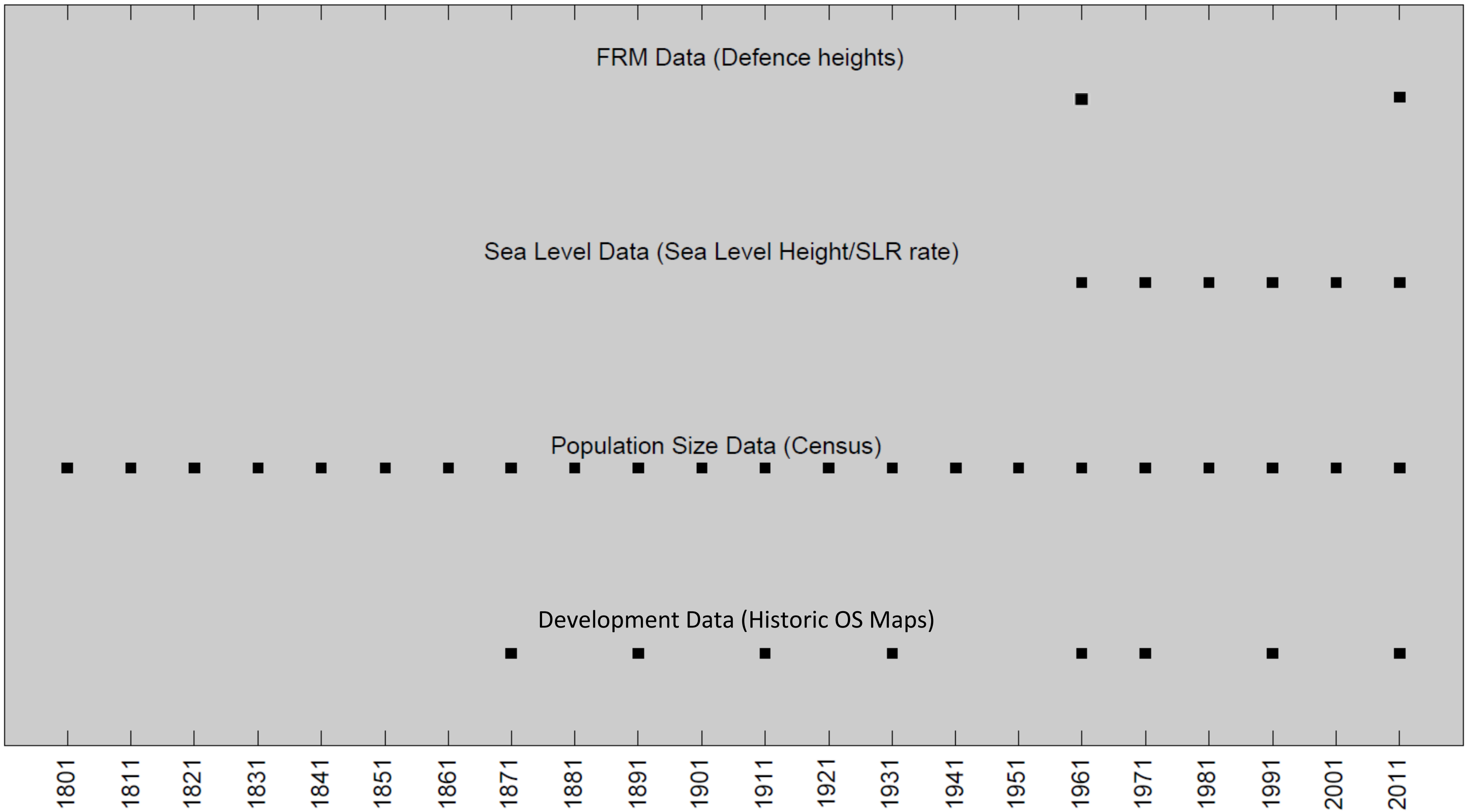

Figure 3.5: Data Available for Quantifying the Evolution of Flood Exposure in the UK. See text for explanation of data availability

The use of 'full' 3d or more complicated models is expensive in terms of both cost & computationally. Without extensive validation full models do not offer any benefit over simpler approaches (Wadey, 2013). A validated Lisflood-FP model exists for the Solent region (Wadey et al., 2012) which is run for historic water levels and a range of recurrence intervals within this work.
An assumption is made that extremes of still water level are the dominant physical driver of exposure in the case study site and waves (and hence wave driven overtopping) are excluded. Wadey (2013) demonstrated that breach scenarios with inundation a result of still water levels gave a much higher exposure than wave driven overtopping scenarios. In this work we consider a 'worst' case event and hence extreme water levels are the dominant mechanism for such an event. Waves, although important to some coastal flood events, are contentious in an inundation modelling framework as they are difficult to predict and to validate. Further, modelling of wave propagation and overtopping value calculation are highly uncertain (Wadey, 2013; Smith et al., 2012). However it is recommended that waves are included in future work as uncertainties are reduced by further research in that area. There is a lack of data to characterise historic coastal morphology in the case study and hence without further assumptions this cannot be achieved. Further assumptions would introduce unnecessary uncertainty to the approach and is outside of the scope of this work (see Section 3.2.2).

The temporal resolution of the available population data constrained the time step to 10 years. This corresponds to census years, where it is possible to get high resolution spatial population data. To reduce the time step with less sufficient supplementary would limit the reliability of the study. Whilst this time step may miss shorter term changes (i.e. seasonal/yearly variations in hydrology), it captures the longer term dynamics of population change and development, and sea level rise which occurs over a long time period. Further, the high spatial resolution and quality of the census data used gives the study greater reliability than if supplementary data (perhaps with a smaller time step) was used. Census data is available for a 200 year period and is the longest dataset available. A period of 200 years allows for a clear long term trend to propagate.
From 1971 onwards census data is available as centroids, which provide a single georeferenced point for a ward/enumeration district. Centroids are the highest resolution data readily available and are provided to protect the privacy of individual households by aggregating several across an output area (an area of census geography, see Table 5.3 in Chapter 5 for a description of different census geographies). Centroid data allows the creation of high resolution population surfaces, with the assumption that a centroid's population is distributed in the surrounding area according to some distance decay function, which has finite extent (Martin, 1989). This method offers stability through time and ease of integration with non-population data sources (Martin et al., 2011) - both essential parts of the methodology.

Component of Approach	Modelling Assumption	Justification
Hydrodynamic Model (Lisflood-FP). See (Bates et al., 2010)	Simplified hydraulics compared to 'full' 2D models	Offers a compromise between crude 'bathtub' method and expensive full model
		Model proven for coastal use (Bates et al., 2005) and with a validated model for the case study region (Wadey et al., 2012)
	Extremes of still water level are dominant physical driver (waves excluded)	Still water level breach dominant flood mechanism
		Waves uncertain and hard to validate
	Coastline static (no morphological changes)	Lack of data to characterise coastal morphology
Population	Population size does not change between 10 year time step	Highest resolution method, based on availability of census data
	The dates chosen are representative of population change	200 years allows long term trends to propagate
	Centroid population distributed by distance decay function	Most accurate method for distributing centroid points (Martin, 1989; Bracken and Martin, 1989; Martin et al., 2011)
Residential Development	Developed residential area does not change between 20 year time step	Best available method, based on availability of historic maps

Table 3.2: Key modelling assumptions and justifications

The 20 year time step for characterising residential development is based on the availability of historic maps for the case study site. 20 years is appropriate as it is typical of long term spatial planning time horizon (e.g. Zevenbergen et al., 2008). Constraining population to residential area using historic maps improves spreading over uniformly distributing population and so this is the best available method (this will be discussed in Chapter 5).

3.6 Thesis Approach for Assessing Flood Exposure

In this chapter the methodological approach for modelling coastal flood exposure has been evaluated. The chosen approaches are shown within the conceptual model in Figure 3.6.

Exposure will be evaluated as the number of people exposed to flood events of a given recurrence interval coastal flood event and given pathway (with or without defences). The physical driver of flood exposure over time is sea level rise, and the socio-economic drivers are population (size of coastal population) and residential development (location of coastal population). Flood source will be modelled using a flood inundation model, and the size and location of the population will be modelled using historic OS maps and census data. Data on flood defences will be used to evaluate exposure with and without defences.

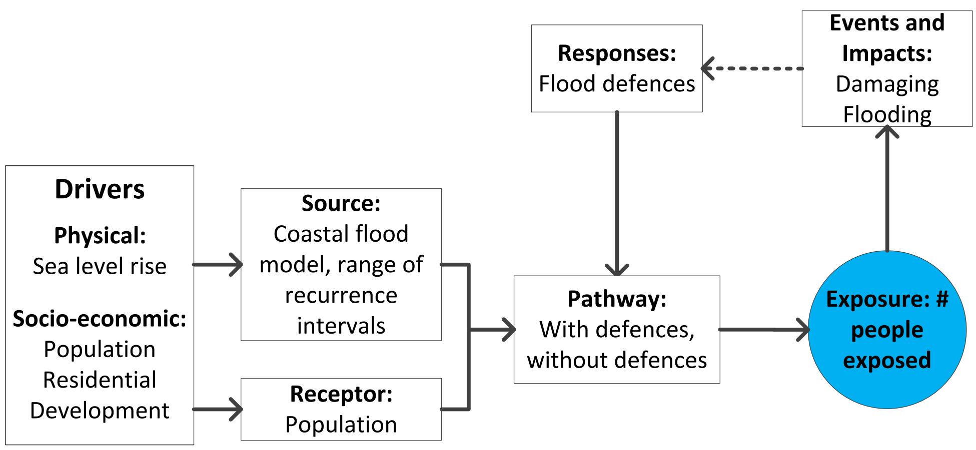

Figure 3.6: Conceptual framework to evaluate exposure to flooding

Chapter 4 evaluates flooding in the UK and gives a national context to the work. Chapter 5 describes our quantitative model of exposure and applies it to a local case study. The changes in distribution of people over time are mapped and the historic floodplain recreated. The method for quantifying exposure at the local scale will expand upon previous work (Fielding and Burningham, 2005; Thrush et al., 2005), introducing a new method. The physical flood model, which calculates the extent of the floodplain, will make use of previous work on floodplain inundation modelling (Wadey, 2013). Each component used within the model can be adapted or improved depending on the resolution of the data available. Using the concept of exposure with and without defences described in Chapters 1 and 2 the reduction in exposure as a result of flood defences will be assessed (Figure 3.7). Chapter 6 describes the methodology for attributing exposure

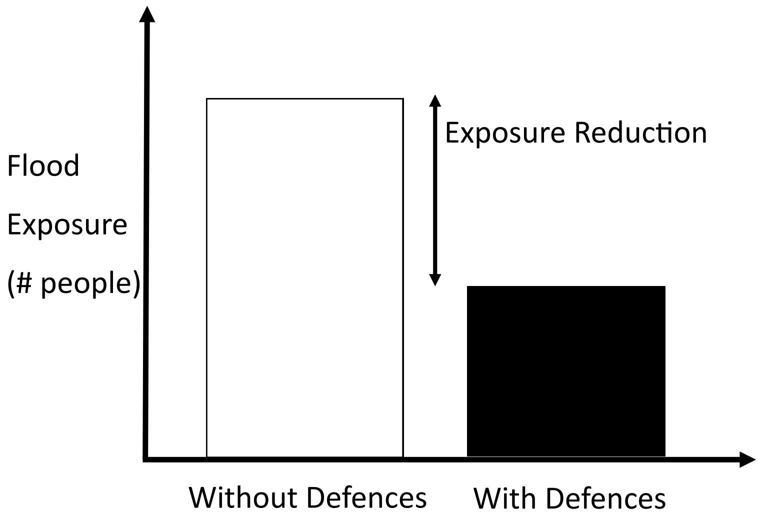

Figure 3.7: Evaluation of the reduction in exposure due to defences

to the underlying drivers, using the quantitative model to evaluate the influence of each driver on the changes in exposure.

Chapter 4

An Evaluation of Flooding at the National Scale

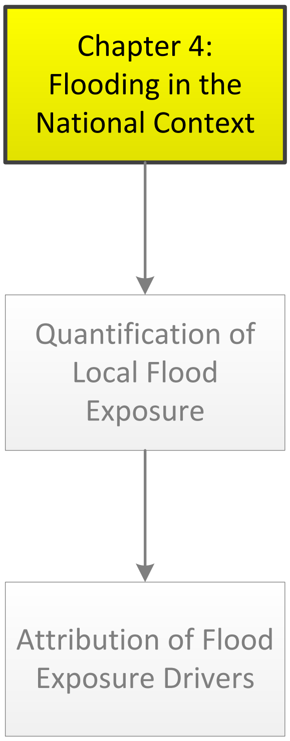

Figure 4.1: Chapter 4 within the general research design

(Note: Much of the material in this chapter was published in (Stevens et al., 2016))

4.1 Introduction

The aim of this chapter is to characterise and evaluate the historic evolution of flood events (Objective 1). This will be achieved by evaluating the following outputs:

- Develop a consistent record of reported flood events in the UK
- To ascertain trends in flooding in the UK over the 20th century
- Evaluation of the frameworks used to report flood events (i.e. how good it is to enable us to extract consistent knowledge)

Damaging flooding (i.e. flood events that affect *people*) is used to give a context to exposure at the national scale. A dataset of flood events in the UK between 1884-2013 is created and used to evaluate trends in flooding in the UK and also to identify periods of significant damaging flooding. The work is set out as follows: (Section 4.2) the methodology is described; (Section 4.3) results of the analysis presented; (Section 4.4) a discussion of the findings and critique of the method; (Section 4.5) the work is summarised and put into the context of the wider thesis.

4.2 Methodology

Approaches to evaluating flood events

Floods events have typically been evaluated using river flow data and the analysis of the frequency of peak flows (e.g. Delgado et al., 2010; Petrow and Merz, 2009; Macdonald et al., 2010; Marsh and Harvey, 2012; Robson et al., 1998; Robson, 2002; Haigh et al., 2010; Menéndez and Woodworth, 2010; Murphy et al., 2013; Wilby and Quinn, 2013). Long term studies include Delgado et al. (2010) who studied 70 years of data on the Mekong river and Petrow and Merz (2009) who analysed river flow data for 145 sites in Germany between 1951-2002. However consistent long term river flow or flood records (>100 years) are rare (Macdonald and Black, 2010) and are almost always reported for a single gauging station or river. Further, the consistency and precision of data can be a major problem with many earlier hydrometric records (CEH, 2015a). Some studies have supplemented the hydrometric flow data with historical sources such as flood marks and descriptions (Macdonald, 2006), documentary records Macdonald and Black (2010) or paleoflood hydrology such as geological records (Costa, 1986).
However, whilst historic sources can be used to extend records, these are not always consistent or reliable. Robson et al. (1998) state that long datasets are needed to identify trends, yet older data can be “sketchy”. For instance in European studies it was found minor flood events were reported more widely in recent times (Barredo, 2009). It is

clear that a trade-off exists between increasing the length of record with multiple data sources and maintaining consistency and quality of the record.

Studies into the frequency and distribution of coastal flooding have used high sea level data combined with local records to judge when tidal floods have occurred (Ruocco et al., 2011). The use of reported flood event data is beneficial because extreme flows do not necessarily cause damage (Pielke Jr., 2000). In Chapter 2 a distinction was made between hydrological flooding caused by a high water level/flow and damaging flooding which causes impacts. In this study only floods which have been reported as having an impact are considered and hence *damaging* flooding is evaluated. This gives a national context to the evolution of exposure: damaging flooding is a useful indicator of exposure because it accounts for flood source, pathway and receptor, and the performance of flood defences. Hydrological flooding on the other hand only accounts for flood source.

Data sets used for the long term study of damaging flooding

The datasets used to characterise damaging flood events are the Met Office Monthly Weather Reports (Met Office, 1993) and UK Climate Summaries (Met Office, 2015) (© Crown Copyright). These records span the period 1884-present (Figure 4.2) and are probably the longest regular set of national reported flood events in the world.

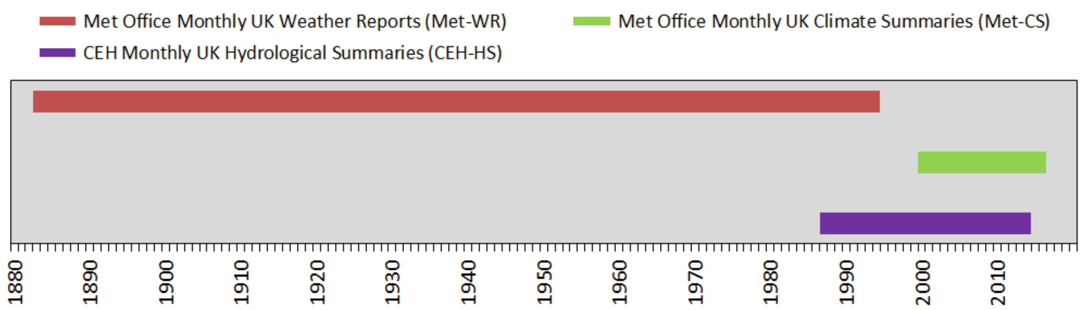

Figure 4.2: Lengths of the datasets used within this study

The Met Office monthly weather summaries report on the Meteorological "highlights" for the UK each month. Where flood impacts as a result of Meteorological processes (such as rainfall, storm surges, high tides and gales) occur these are reported in the summaries. The Met Office monthly weather summaries ended in 1993 and the UK Climate Summaries started in 2001. In this work, these reports are supplemented with the CEH (Centre for Ecology and Hydrology) monthly Hydrological Summaries (CEH, 2015b) for 1988-2012 (© NERC - Centre for Ecology & Hydrology). These are a comparable resource which report damaging flood events, and they overlap with the Met Office reports, allowing comparison for consistency.

In order to create an unbroken record of records from 1884-2013 the datasets were combined. A total of 785 reported flood events were identified in the combined dataset. For the period 2001-2013, the Met Climate Summaries are used as they describe impacts

Classification	Description
Class 3	The most significant or damaging flooding as estimated from the reported record. For the Met record these are floods described as 'Widespread', 'Serious', 'Extensive' or 'Disastrous'. In the CEH record these are floods described as 'Devastating', 'Substantial' or 'Protracted'. Where quantifiable impacts are reported a flood event involving loss of life, >1000 people evacuated or severe structural damages (such as hundreds of homes flooded, >£100 million in material damages)
Class 2	Floods events described in the Met reports as 'Severe' or 'Worst in xx' and in the CEH as 'Widespread', 'Serious', 'Severe', 'Considerable', 'Extensive', 'Significant', 'Disastrous', 'Worst in xx', 'Major' or 'Notable'. Quantified impacts less severe than class 3 such as a handful (or unspecified number) of buildings destroyed, >£1 million material damages, some evacuations, substantial loss of livestock)
Class 1	Floods events either not described or with perceived low magnitude impacts: such as those described as 'Localised'.

Table 4.1: Classification of flood events according to estimated severity of event

more comprehensively than in the CEH reports. For the period 1993-2000 the CEH hydrological summaries are used, and the Met Weather Reports are used to extend the record from 1993 back to 1884. For a full account of the method used to create the record, including consistency of the terminology used, partial validation of the record against global flood event databases and an evaluation of the reported impacts in the record, the reader is referred to Stevens et al. (2016), included in Appendix J.

Classification of flood event descriptors

The descriptive phrases and information on flood impacts used in the CEH and Met reports were used to classify floods into groups which indicate the impact of the flood event (Table 4.1). Three flood impact classes were created; Class 1 for low magnitude events, Class 2 for intermediate magnitude events, and Class 3 for high magnitude events. Floods where 'Localised' is the only description given were assigned to Class 1 (low magnitude of impact) because the use of 'Localised' as a descriptor was considered to be uncertain and inconsistent. Less than 15% of all floods described in the dataset were described just as 'Localised' so the effect of this assumption is minor.

4.3 Results: Trends in Reported Flooding

The annual totals of reported flood events in each severity category are shown in Figure 4.3. There is an upward trend in reported flooding over time and flood events appear more frequently towards the end of the 20th century. The start of the record is 'flood poor' but the number of events rose sharply through the 1910s and the 1920s. The number of reported events is lower between 1930 and the mid-1960s. This is most noted for 1939-1945 when there were government restrictions on reporting due to the Second World War. Reported events increased noticeably in the 1960s with a peak in the early 1990s. 2012 was an exceptional year for floods in the UK, where annual rainfall was the second highest in over 100 years (Met Office, 2013). Well known events such as the floods of 1947, 1953, 2001, 2007, 2012, etc. were readily identified.

Clusters of 'Class 3' (high magnitude) flooding (as defined in Table 4.1) appear in the 1920s, 1960s and the 1990s. 'Class 2' (intermediate) flood events appear more uniformly though time. The number of 'Class 1' (low magnitude) events is highly variable. There is a fall in 'Class 1' floods between 1930 and 1960 but the frequency of 'Class 1' floods increases sharply after 1968.

Wilby and Quinn (2013) identified three hydrologically flood rich episodes in river catchments since the 1870s as follows: 1908-1934, 1977-1988 and from 1998 onwards. The first period is visible in Figure 4.3, and the second and third periods are characterised by higher numbers of flood events (fluvial, pluvial and coastal) in the 1980s and post 1998. However the reported flooding dataset also indicates a peak in the early 1970s which differs from the Wilby and Quinn (2013) analysis.

There is no data available in the UK at a national scale that records changes in natural defences, artificial defences and other management. Natural defences are important and they may have declined, but data is poor (Jones et al., 2011). There have been significant upgrades to artificial defences, most notably following the 1947 Thames floods with a sustained effort to improve conveyance of rivers, and the 1953 North Sea storm surge which led to a major upgrade of flood defences on the East Coast, including the Thames Barrier and London's flood defences. Hence subsequent extreme sea level events on the East Coast had much lower impacts even if the hydraulic conditions were similar; compare the major consequences of the 31 January/1 February 1953 event including more than 300 deaths (Steers, 1953) with the 11 January 1978 event (Steers et al., 1979), and the recent 5/6 December 2013 event with similar or higher water levels and much smaller consequences. As well as defences, flood warnings have improved substantially and are now routine components of flood risk management (Horsburgh et al., 2008). We cannot normalise the reported flooding dataset for defences, but we note that the last peak of (Wilby and Quinn, 2013) is not apparent in Figure 4.3. This may represent the effect of improved defences reducing impacts and therefore "reportable" flood events.

The causative mechanism of the floods (coastal, pluvial, fluvial) was rarely described and only 47 coastal flood events were identified from the records; therefore it is not possible to discriminate between flood sources. This is a limitation of the approach which is discussed later.

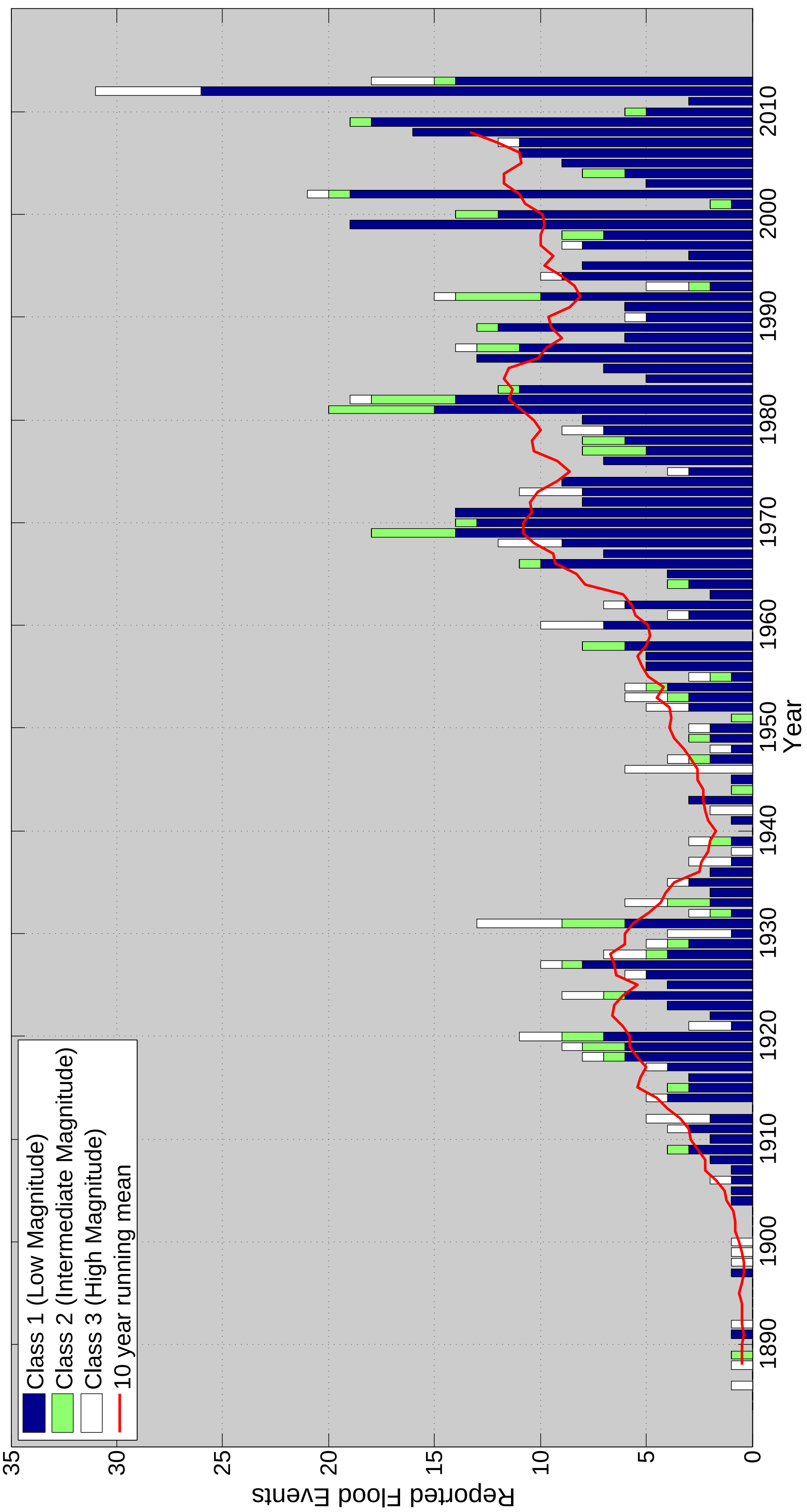

Figure 4.3: Instances of reported flooding in the UK each year 1884-2013 using combined Met Office/CEH data

4.4 Trends in Reported Flooding: Normalised for Population and Residential Development

Estimating changes in population and residential development

Over the 20th Century, the UK population grew from 38.2 million to 59.1 million and the number of dwelling houses grew from 7.7 million to 24.8 million (Figure 4.4). As a result there were more properties with the potential to be exposed to flooding and also more people to report flooding. This is likely to result in a larger number of reported flood events and larger potential consequential damages.

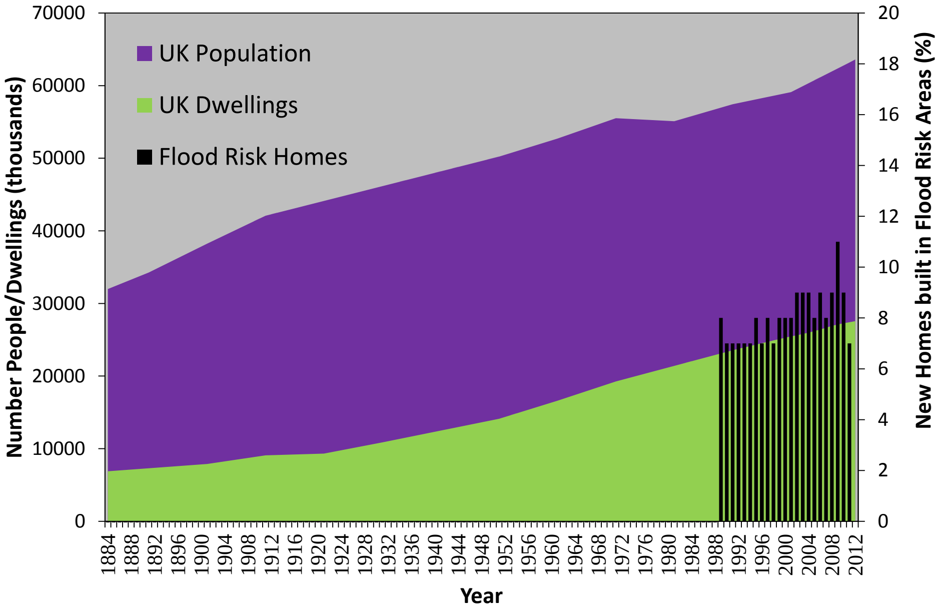

Figure 4.4: UK population counts (NISRA, 2012; NRS, 2012; ONS, 2012a,b), dwelling counts (DCLG, 2013) and the proportion of new homes built in areas of flood risk (DCLG, 2012b)

The reported flood events from the Met Office and CEH were normalised using the UK population and the number of dwellings, which represent the Population and Residential Development drivers. The reported flood events were not normalised by the Sea Level Rise driver as the dataset contains flooding from all sources. This is acknowledged as a limitation of this method for coastal flooding which is discussed later (see also Section 4.3). The population and dwelling counts were used as a proxy for socio-economic drivers of flooding assuming that the percentage of the population in floodplains is proportional to the total population. There is not sufficient data on floodplain households over the length of the record to support this assumption. Data for the percentage of new households built on floodplains in England from 1989-2010 shows a similar percentage of homes throughout the 20 year record (DCLG, 2012b, shown in Figure 4.4). However there is no data to validate the assumption pre 1989 and so this is a limitation discussed later. The population and dwelling data were used to scale the aggregate yearly flood totals using:

$$FSP_i = (F_i/P_i) \cdots\cdots (1)$$

$$FSD_i = (F_i/D_i) \cdots\cdots (2)$$

Where:

FSP_i is the flood count scaled for population in year i
FSD_i is the flood count scaled for dwellings in year i
F_i is the count of reported flood events in year i
P_i is the UK population in year i
D_i is the UK dwellings count in year i

Results normalised by population and residential development drivers

Reported flood events normalised by population and number of dwelling houses in the UK are shown in Figures 4.5 and 4.6. The normalised data suggests that there is a diminished upwards trend compared to the raw data in the number of reported floods per head of population or number of dwellings during the 20th century. This suggests that Population and Residential drivers of exposure may be dominant in the upwards trend of reported damaging flood events seen in the raw data (Figure 4.3). However there is significant decadal variability in both the raw data and normalised counts, and the results are driven by the assumption that on/off floodplain development was constant over time. Therefore the analysis presented is insufficient to prove or disprove the hypothesis that socio-economic drivers have been the main cause of damaging flood events in the UK. The findings, limitations, and wider implications of this study are discussed in the following section.

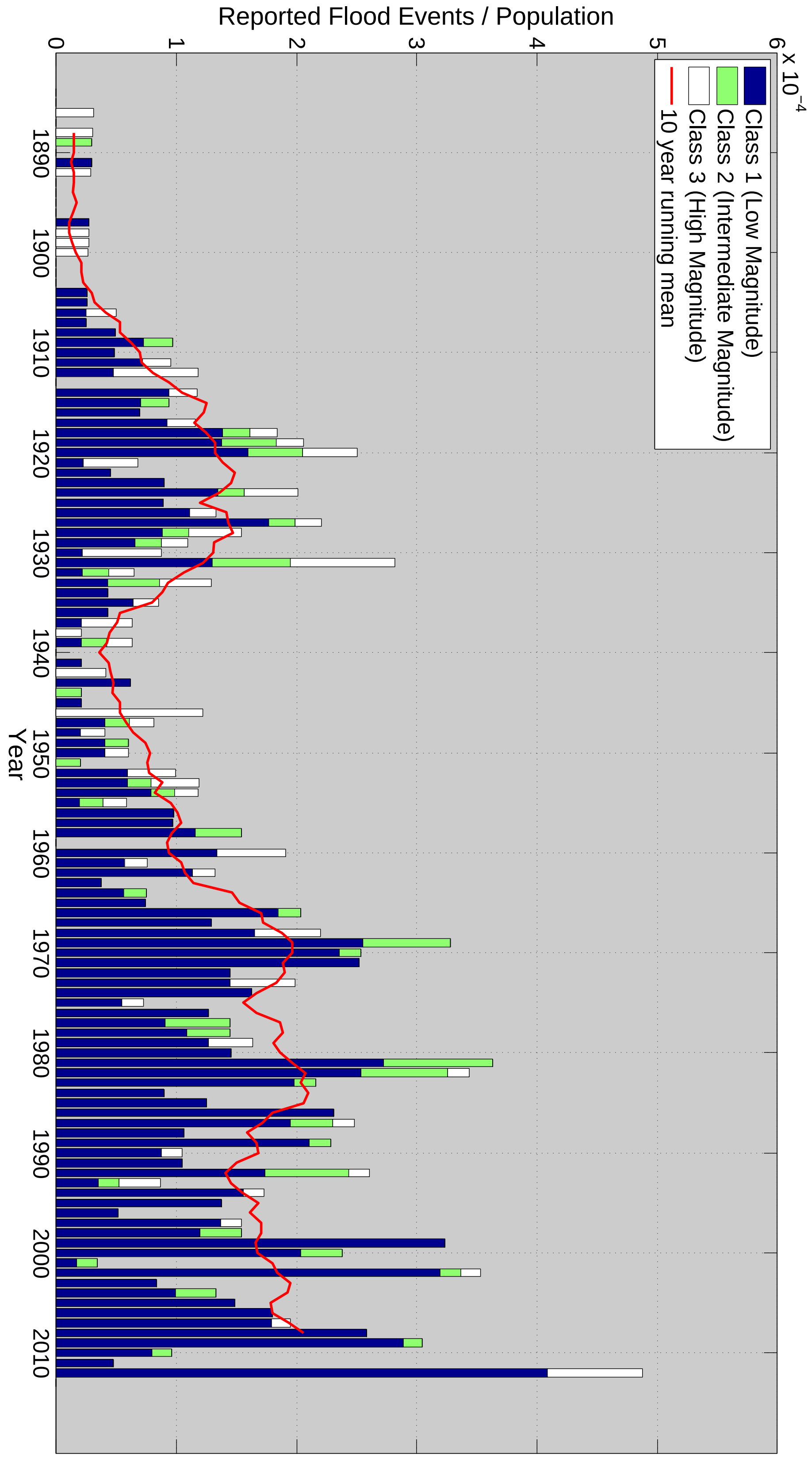

Figure 4.5: UK Flooding normalised by population (note: normalised data plotted to 2012 due to lack of 2013 normalisation data)

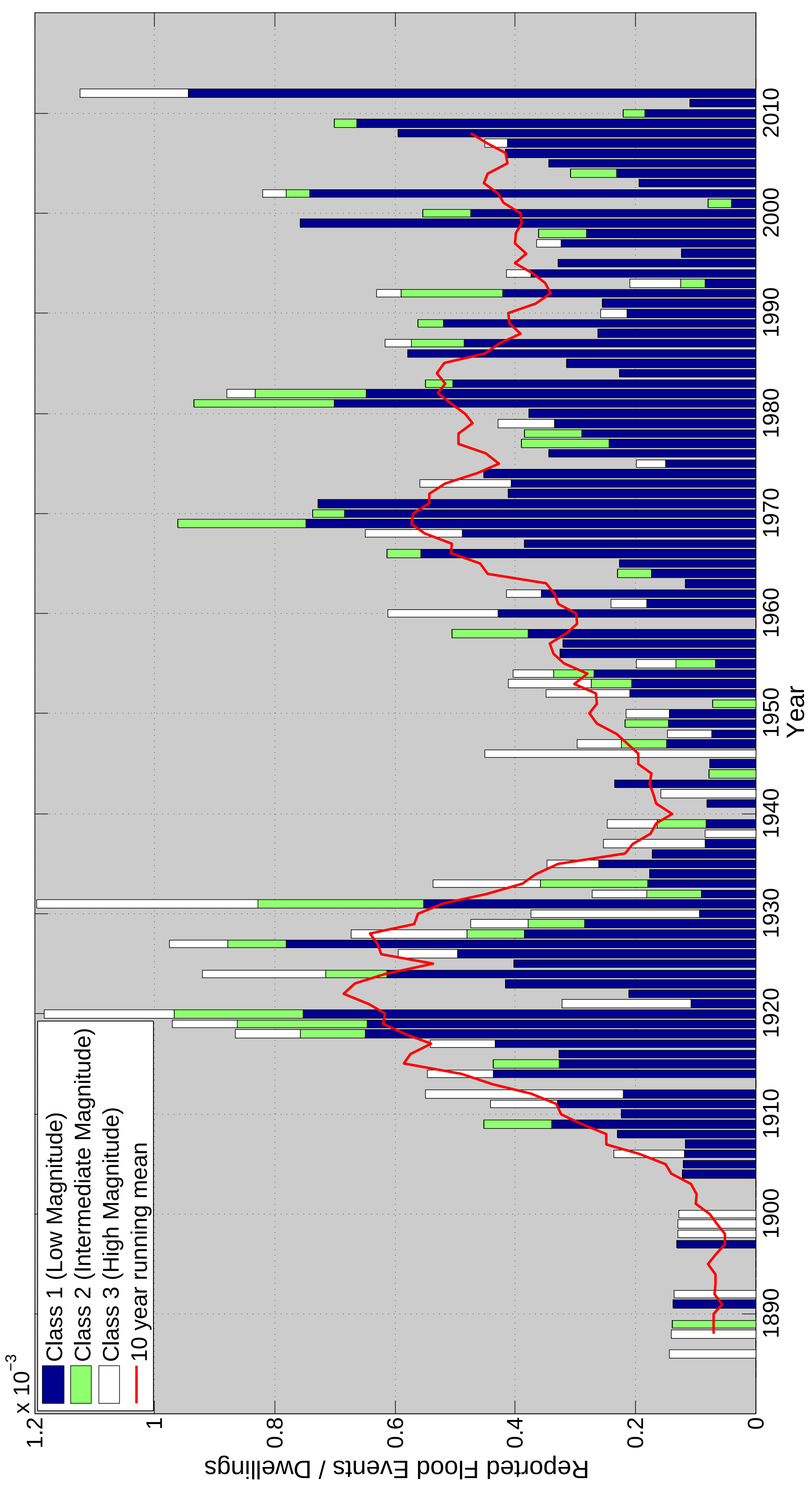

Figure 4.6: UK Flooding normalised by number of dwellings (note: normalised data plotted to 2012 due to lack of 2013 normalisation data)

4.5 Discussion

The lack of a systematic trend in the normalised UK total flood count mirrors earlier findings on hurricane damage in the USA. Pielke Jr. and Landsea (1998) found that normalising damage reports to take account of exposure removed the upward trend of losses over time and only left a large decade to decade variation in losses. It is also in agreement with studies of trends in river flows in the UK (Robson, 2002). These observations do not preclude concern about the role of physical drivers on future flood events, especially in coastal areas where sea-level rise is being observed and faster rises are expected (Haigh et al., 2011), and in areas potentially exposed to higher rainfall intensities (Hulme et al., 2002; Stern, 2007).

There are a number of limitations of the approach and the data used; the inherent assumption that the ratio of on/off floodplain development is constant, potential biases and changes in reporting over time, lack of descriptions of flood source and recurrence interval, and a lack of data on flood defences. These are discussed in turn.

The analysis suggests that the increase in the total number of reported flood events in the 20th century in the UK appears to be a function of the gradual increase in exposure due to urban expansion and population growth. However the normalised results rely on the assumption that the ratio of on/off floodplain development was constant over time at the national level. Whilst this assumption was supported by evidence available on new developments from 1989-2010, there can be no certainty in extrapolating this assumption over 100+ years. Therefore the hypothesis that socio-economic drivers have been dominant in the increased trend cannot be categorically proven or dis-proven using the methodology described. Further work is needed, as will be undertaken in subsequent chapters.

The reporting may be biased towards urban areas where reporting of flooding is more likely. There are also likely to have been changes in the Met Office's reporting capabilities over the timescale of the work, meaning the number of reported flood events and the actual number of flood events may differ. In a study in Europe Barredo (2009) found that minor flood events have been more widely reported in recent years. This 'reporting bias' may lead to a higher proportion of flood events being reported towards the end of the record in this study. Similar limitations exist in evaluating hydrological flooding, as less river and sea level gauges existed in the past as compared to the present day.

The reported flood events included flooding from all sources of flooding including coastal, fluvial, pluvial and groundwater flooding and the reporting framework rarely provided the opportunity for classification of flooding by source. Therefore it was not possible to normalise the counts by the physical drivers of flooding which is is a limitation of this methodology. Socio-economic drivers and physical drivers of exposure cannot be directly (and quantitatively) compared. This highlights the need for higher resolution study at the local level where the sources of flooding can be unpicked, and exposure and its drivers can be quantified. A further study linking the date of occurrence of flood events from this record with rainfall/river flow data could make the assessment of flooding 'type' possible. Complementary analysis of the recurrence interval of events within the record could provide further information on the magnitude of events, which is lacking in the data sources used.

The number of reported 'Class 3' flooding events has remained static or decreased slightly over the 20th Century. This is despite the UK population almost doubling and the number of dwelling houses tripling over the same time period. This may be a function of improved defences, however the lack of defence data over the timescale of the work means that this hypothesis cannot be proven. This demonstrates a need for better recording of flood defence data at the national level.

Despite these drawbacks the dataset opens the possibility of considering flood occurrence over a long timescale using reported information (and thus likely effects on society) rather than just changes in extreme hydrological events. The reporting framework used by both the Met Office and by CEH has been shown to be an effective resource for a national scale study of reported flooding. The consistency of the data is a key asset with the length of record giving useful insights into flood trends at a national level. Care must be taken with the use of multiple data sources and variations in the terminology used to describe floods, however this caveat should not prevent qualitative information being used in similar studies.

As a tool for reviewing the changes in flood impacts through time supplementary data is needed (such as local newspaper reports, post-hoc academic or professional reviews) as key events are typically mentioned, but underplayed in the data (e.g. the North Sea Flood of 1953 was condensed to a report of 'unprecedented coastal damage and floods'). Additional data can be gathered for individual flood events, for example, the Environment Agency report on the costs of the summer 2007 flood events (Chatterton et al., 2010), Met Office reviews of the 2005 and 2008 flooding (Met Office, 2011, 2012) and an appraisal of the 1947 fluvial event (RMS, 2007).

The dataset presented here serves as a 'catalogue' of national level flood events in the UK over the last 125 years. The study could be complemented or extended further in time by using ancillary data sources such as The Chronology of British Hydrological Events (Black and Law, 2004). However care must be taken to ensure the quality of additional information sources, considering the limitations of qualitative data sources as discussed in this chapter. This work highlights the need to maintain the reporting framework of flood events in order to provide continued information on long terms trends in flooding, and a need for collection of time series data on flood defences.

Reports of damaging flood events, as evaluated in this work, are not a proxy for exposure and the methodology and datasets presented are insufficient to quantify changes in exposure over time. However instances of damaging flood events do give a useful national context to exposure, with the high number of reported events illustrating the large degree of exposure to flooding present in the UK. On balance, descriptive datasets of reported flooding are insufficient in themselves to characterise exposure, however they can complement existing hydrological analysis, especially for combined descriptive/quantitative datasets such as the CEH Hydrological Summary of the UK.

4.6 Chapter 4 Summary and Conclusions

This work has developed a 100+ year national dataset of 785 damaging flood events in the UK. It is an unusual if not unique dataset. The data indicates an increase in reported flood events during the 20th/21st Century and significant variation from decade to decade. Normalising the data by population and number of dwellings appears to reduce any long term temporal trend and leaves a strong decadal variability. This suggests that socio-economic drivers of flood exposure have affected trends in flooding, however this cannot be proven using the methodology presented. Further, the effects of increasing and improving defences on the number of reported flood events is unclear, and reporting bias may exist meaning the number of *reported* events and the number of actual events may differ.

Due to these limitations the effect of exposure on the number of damaging flood events cannot be *quantified* using the datasets and methods presented. Further, there are regional differences in flood sources (the contributions of coastal, fluvial, pluvial and groundwater flooding), pathways (floodplain geometry, defences), and receptors (population size and location, development) which cannot satisfactorily be unpicked in a national scale study. The lack of comprehensive information on flood defences make it impossible to differentiate between exposure with and without defences. There is a need therefore to quantify exposure at the local scale where population size, location, floodplain geometry and defence locations and heights can be evaluated.

Despite the limitations the analysis represents a forwarding of knowledge with regards to national flood trends. The work is novel in its consideration of *reported* flood events, which are a better indicator of flood exposure than hydrological records alone (Pielke Jr. and Landsea, 1998; Pielke Jr., 2000). The methodology offers a foundation on which further studies can expand and improve.

This chapter gives a national context to the next objective of this work: to *quantify* the historic evolution of exposure, which is undertaken in the following chapter.

Chapter 5

A Quantitative Assessment of Flood Exposure Evolution

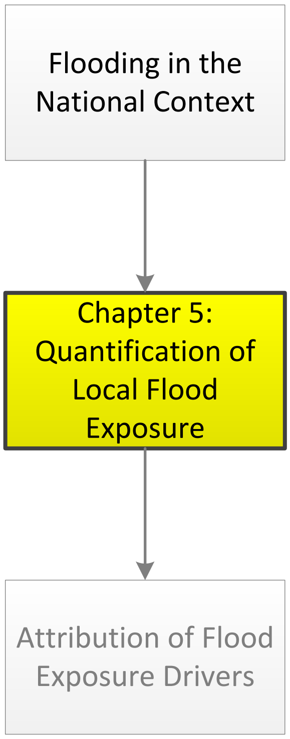

Figure 5.1: Chapter 5 within the general research design

(Note: Material based on the first part of this chapter was published in Stevens et al. (2015))

5.1 Introduction

The aim of this chapter is to develop a framework to quantify the historic evolution of flood exposure (Objective 2). This aim will be achieved in two parts:

- An investigation of how historic changes in sea level and population may have affected the evolution of exposure without defences (Section 5.2)
- An assessment of the evolution of exposure with defences and hence the effectiveness of defences (Section 5.3)

A historic analysis will be conducted looking at how exposure with and without defences has evolved in two case study areas. In this work flood exposure will be quantified by calculating the number of people exposed to coastal still water level flooding under different conditions that change through time. An annual average exposure is calculated at each 10 year time step from a range of different recurrence intervals, taking into account temporal changes in sea level, population and location of residential development.

5.2 A Quantitative Assessment of Exposure Without Defences

This section intends to fill the identified gap in the assessment of the evolution of exposure of coastal populations to flooding. This has implications for the current assessment of coastal flood events, and also for future planning decisions. The aim is to assess the exposure of the coastal population in a case study, and how this has evolved over a long timescale (200 years). The model development will be illustrated by a study of a local scale area of the UK for a rural and an urban case study. The following section is based upon work published in Stevens et al. (2015).

In this section the following actions are undertaken:

- Estimate the extent of the coastal floodplain for a range of recurrence intervals, at 10 year time steps
- Recreate the size and spatial distribution of a coastal population at discrete time steps
- Characterise and model the interaction between the physical flood system and the coastal socio-economic system
- Calculate the number of people within the floodplain for each recurrence interval

- Quantify exposure as the annual average people exposure across a range of recurrence intervals at each time step
- Model how exposure changes in time over a 200 year period using historic sea level, population and mapping data

5.2.1 Methodology

The model structure is shown in Figure 5.2. Drivers of flood exposure (sea level rise, population change and development; orange box) modify the physical and the socio-economic systems (grey box). The physical system is defined here as the sea and coastal interaction which includes the water level, tidal curve and land elevations. The socio-economic system is defined as the coastal population and residential development (the area where population reside). The physical system datasets drive the floodplain extent model (blue box) which produces the floodplain extent. The socio-economic system datasets drive the population distribution model (yellow box) which produces the spatial population density. The floodplain water depths from the physical model and spatial population density are combined within the exposed population model (beige box). The exposed population model produces estimates of the number of people exposed to flooding, for each given recurrence interval of coastal flood. The calculations are repeated over time for changing sea levels, population and residential development.

Portsea and Hayling Case Study

The method is to be applied to two case studies in the UK's Solent region (Figure 5.3), chosen to demonstrate the applicability of the method to 'typical' urban and rural locations. Portsea island is a highly developed area that contains the majority of the city of Portsmouth and has a large residential population. Neighbouring Hayling island is mostly undeveloped and by contrast has a much smaller residential population.

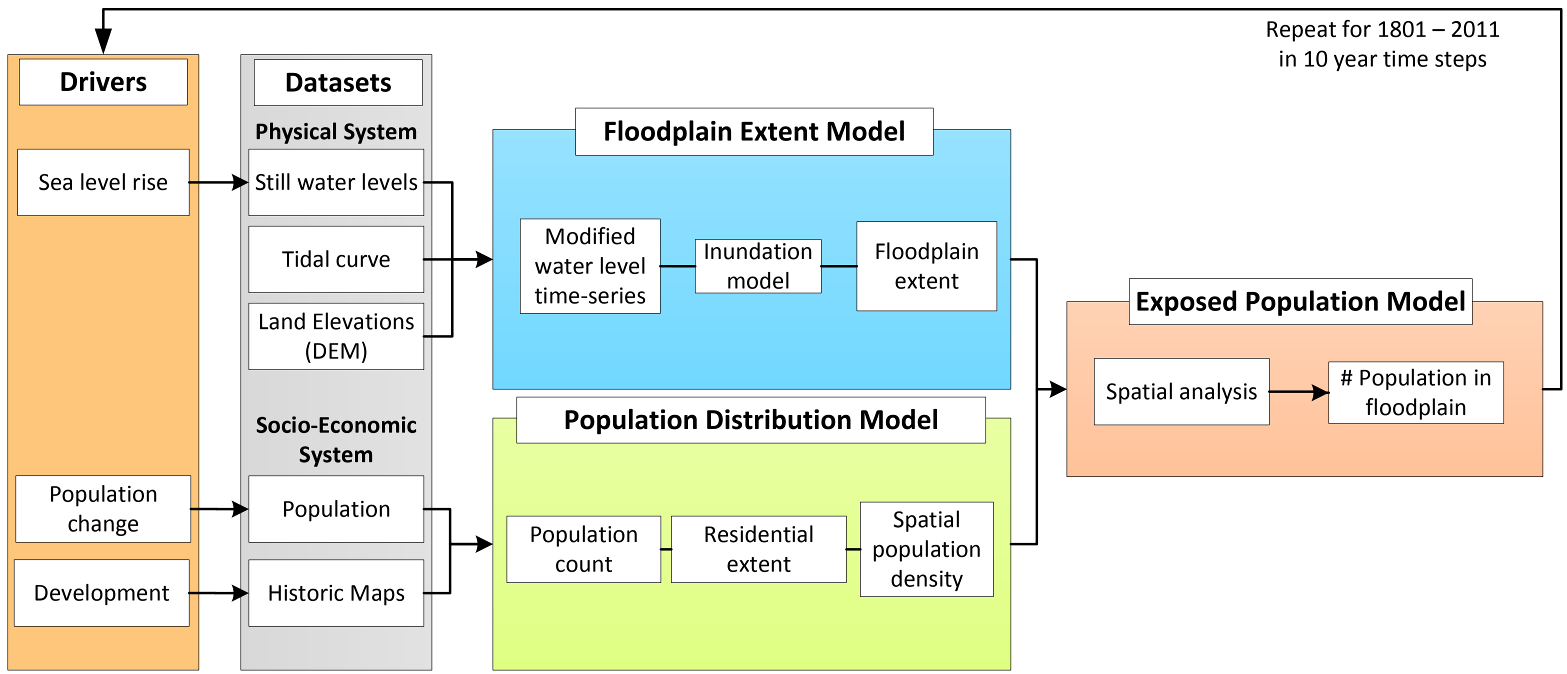

Figure 5.2: Flowchart showing the quantitative model structure. The method is used to calculate exposure of people for a range of recurrence intervals, at 10 year time steps between 1801 and 2011

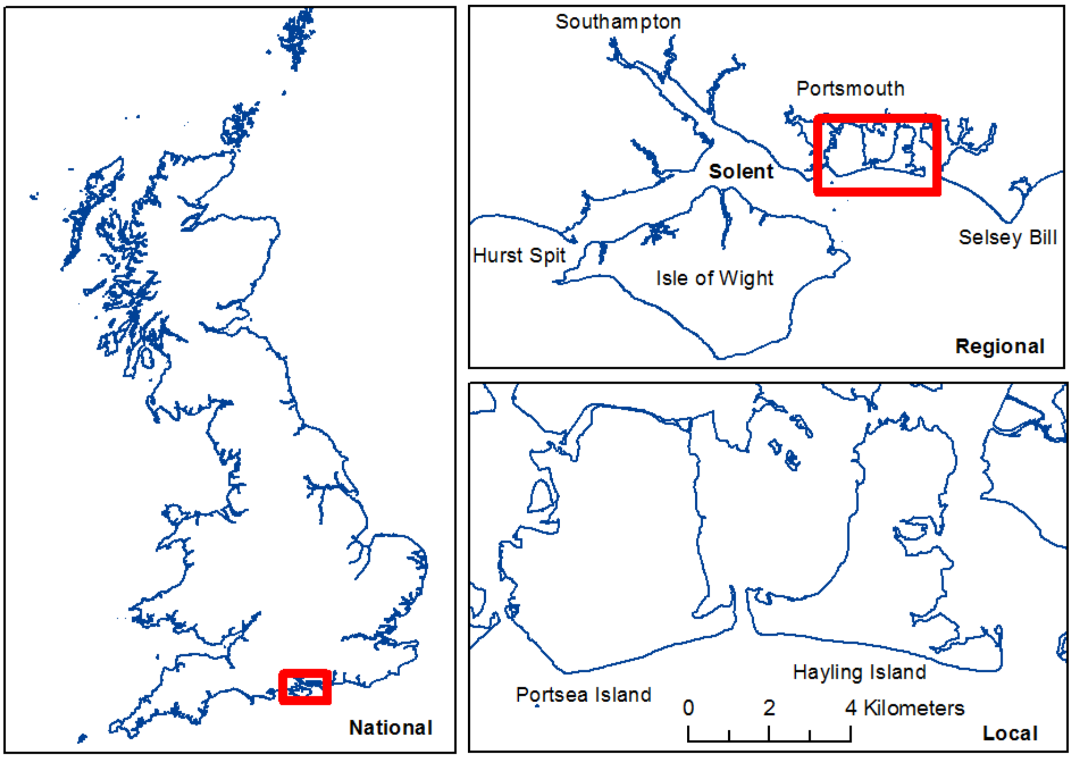

Figure 5.3: Portsea and Hayling islands within the UK's Solent region. Contains public sector information licenced under the Open Government Licence v3.0.

Model Variables for case study

The model considers a range of variables which relate to the uncertainty of sea levels, probability of flooding (recurrence intervals) and population location in the floodplain (Table 5.1). These variables will be discussed in the following sections.

Variable	Method	Value(s)	Description
Sea level rise (SLR)	No Change	0 mm/yr	Baseline scenario assuming no changes in sea level
	Uniform rate of change	1.48 mm/yr	Upper rate from (Haigh et al., 2011)
		1.21 mm/yr	Mean rate from (Haigh et al., 2011)
		0.94 mm/yr	Lower rate from (Haigh et al., 2011)
Still Water Level Recurrence Interval (RI)	Range considered	1 in 1, 10, 20, 50, 100, 200, 1000 years	A range of recurrence interval water elevations representing the probability of a flood event of that magnitude occurring (see Table 5.2)
Tidal Cycle	Time variable water level	1 tidal cycle (12 hours)	Storm surges are temporary and will not last more than one tidal cycle (e.g. Wadey, 2013)
Population Spreading Method	Distributed from centroid	50m, 100m, 200m, 300m, 400m, 500m search radii	Range of distributions from the most realistic spreading method (Martin et al., 2002)
	Uniformly distributed over residential area	-	Method for constraining population to developed areas where spatial population data does not exist
	Uniformly distributed over total land area	-	A baseline method used in previous studies (e.g. Fielding, 2007; Thrush et al., 2005)

Table 5.1: Model variables and the values used within the model

Recurrence interval (years)	1	10	20	50	100	200	1000
Elevation (mOD)	2.56	2.81	2.88	2.98	3.05	3.12	3.28

Table 5.2: Still water levels corresponding to different recurrence interval flood events for Portsmouth (adapted from McMillan et al. (2011))

Physical System: Floodplain Extent Model

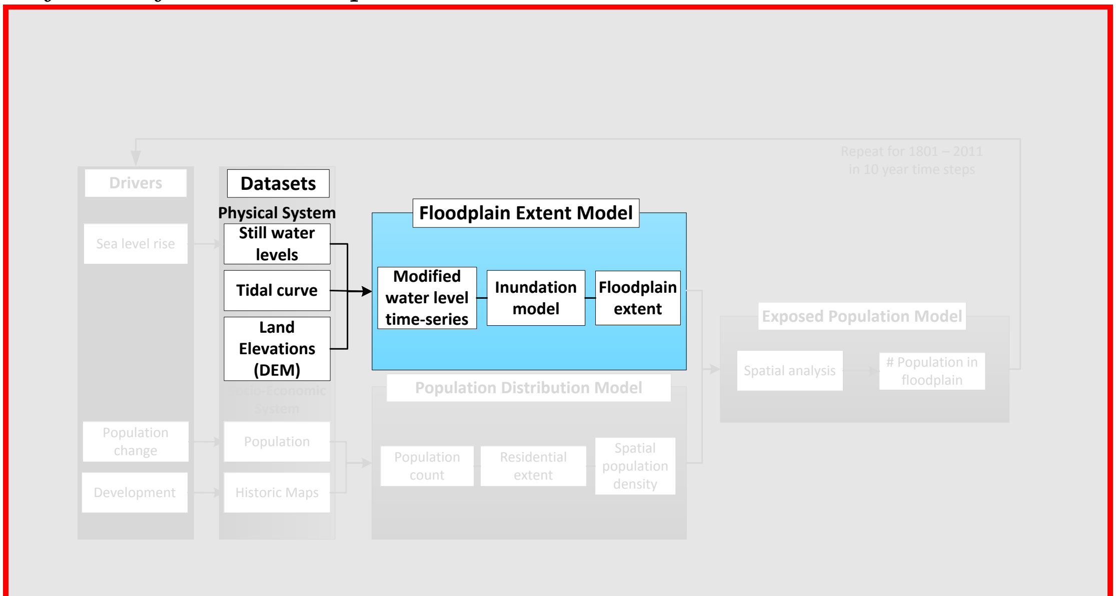

Figure 5.4: Physical system within the model structure

Datasets that describe the physical system are still water levels for the case study area, a 'typical' tidal curve (data from December 1989) which gives time dependent water levels, and datasets on land elevation at 50m spacing (Wadey, 2013). When calculating exposure without defences the natural land elevation is used - defences will be considered later when exposure with defences is evaluated. This data drives the inundation model which produces the floodplain extent (blue box in Figure 5.2).

Modified water level time series

The still water levels for each recurrence interval under consideration are shown in Table 5.2; these are the expected peak water levels for a range of design storm surges. The tidal curve input into the model is based on the monthly average for December 1989. This was chosen as it represents a typical storm tidal cycle for the case study: the high tide level falls between mean high water springs (MHWS) and highest astronomical tide (HAT) which is the common approach in coastal flood modelling (Wadey et al., 2012). Tidal curves are important because they allow inundation to be evaluated over time. The still water levels were used to adjust the synthetic tidal curve to a modified still water time series for each specific flood event (e.g. 1 in 100, 1 in 200 year event). The adjustment is done as follows:

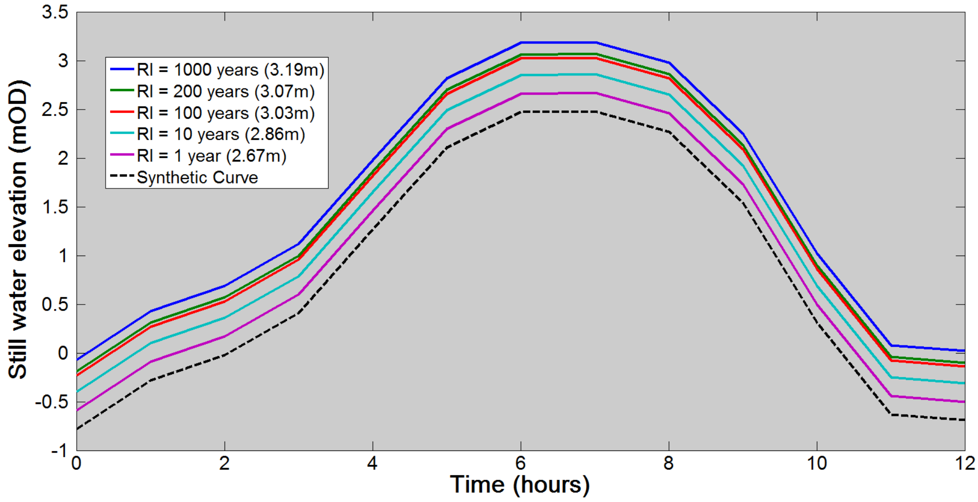

Figure 5.5: Portsmouth tidal curve based upon average monthly data for December 1989 adjusted for different recurrence interval water levels

$$Y_i = y_i + (Y_{max} - y_{max}) \tag{5.1}$$

Where:
Y_i = Modelled still water level at time i
y_i = Dec 1989 tidal curve still water level at time i
Y_{max} = Maximum still water level for recurrence interval considered
y_{max} = Maximum still water level in Dec 1989 tidal curve

Tidal curves for different recurrence intervals are shown in Figure 5.5. The sea level change is applied to each point on the tidal curve, as shown in Figure 5.6. Sea level change is deducted from the known modern day levels (2011) to estimate the likely values for historic sea levels using a constant annual rate of change. The results presented in this chapter use the average rate of change of 1.22mm/year (Haigh et al., 2011). For comparison a scenario of no change in sea level (i.e. assuming that historic sea levels are equal to today's sea levels), and scenarios using the lower and upper sea level change estimates (0.98mm/year and 1.48mm/year respectively) were modelled. The results for these scenarios are presented in Appendix E.

Inundation Model

A hydrodynamic flood model (LisFlood-FP, see Chapter 3) was used to calculate the inflow of water onto the land. This is achieved by evaluation of overtopping of natural land elevations at the model boundary. Flood water is then propagated across the model domain according to the water and land elevations in grid cells at 50m spacing. The model calculates flood water depths at each raster cell. Natural land elevations in Portsea and Hayling and the 1 in 200 year still water level are shown in Figure 5.7.

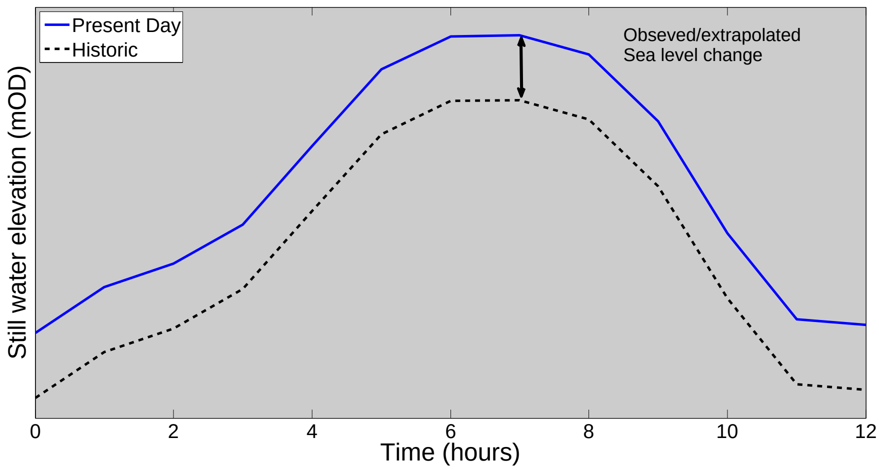

Figure 5.6: Method for recreating historic tidal curve accounting for historic sea level change

Around 30% of each island is situated below the 1 in 200 year still water level.
The study made use of flood data from a combined hydraulic and digital elevation model (DEM), presented in Wadey et al. (2012). The DEM assumes that there are no flood defences in place. Modelling without sea defences allows a “worst case” storm event to be modelled, where it is assumed that all of the defences fail. This is important in terms of holistically assessing exposure of people to a flood event since potential defence failure (as approximated by exposure without defences) will increase the level of exposure and decrease the propagation to receptor time.
Wave overtopping was not included in the physical model due to the high uncertainties involved (Pullen et al., 2009), as discussed in Capter 3. This could be added to future inundation modelling once current overtopping approaches are improved.

Floodplain Extent

The output from the hydrodynamic model is an inundation map for each recurrence interval at each time step. As an example the 2011 floodplain extent for the 1:200 year recurrence interval is shown in Figure 5.8. This map is an estimation of the extent of the floodplain for a given recurrence interval of flood.

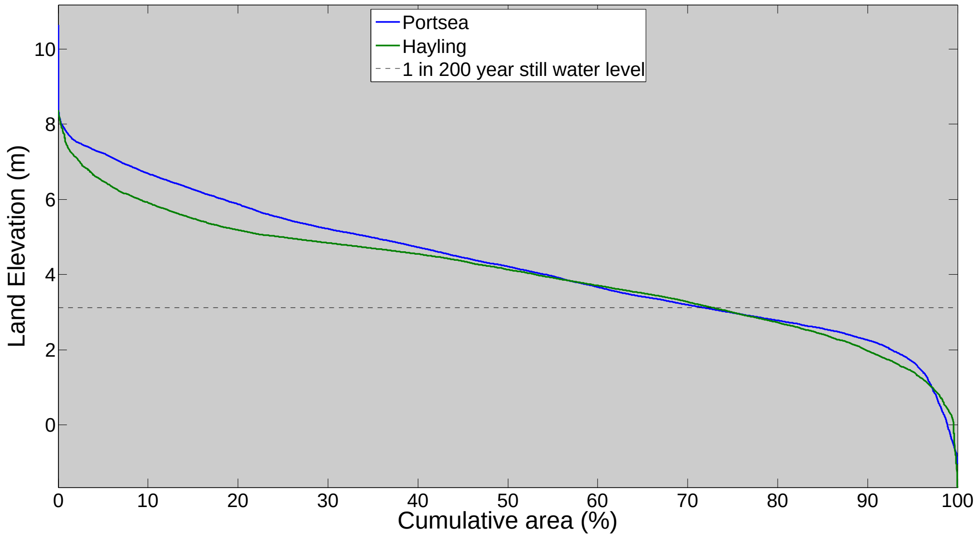

Figure 5.7: Hypsometric curve showing natural land elevation in Portsea and Hayling

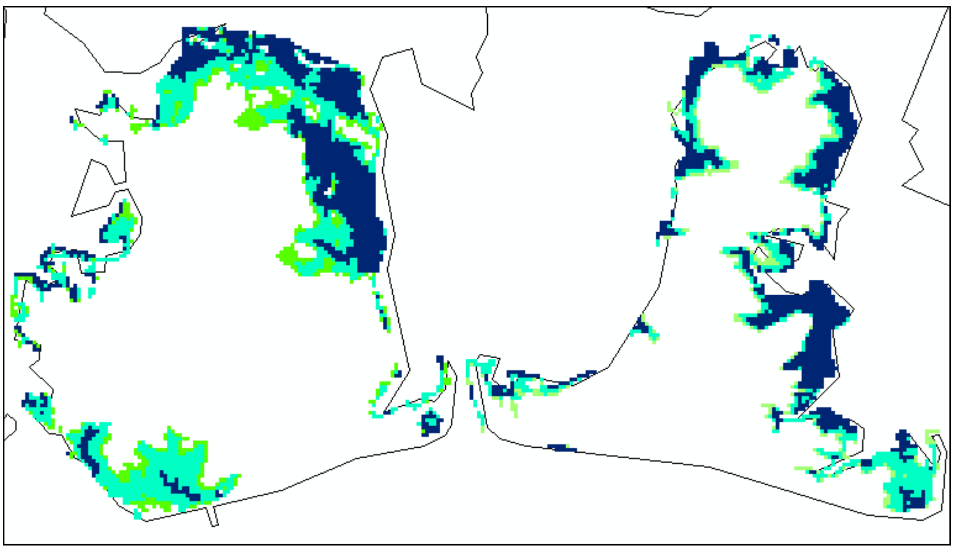

Figure 5.8: Modelled Flood extents for the 1 in 1 year (dark blue), 1 in 100 year (light blue) and 1 in 1000 year (green) coastal flood events in Portsea and Hayling islands (assuming no defences). Contains public sector information licenced under the Open Government Licence v3.0.

Socio-economic System: Population Distribution Model

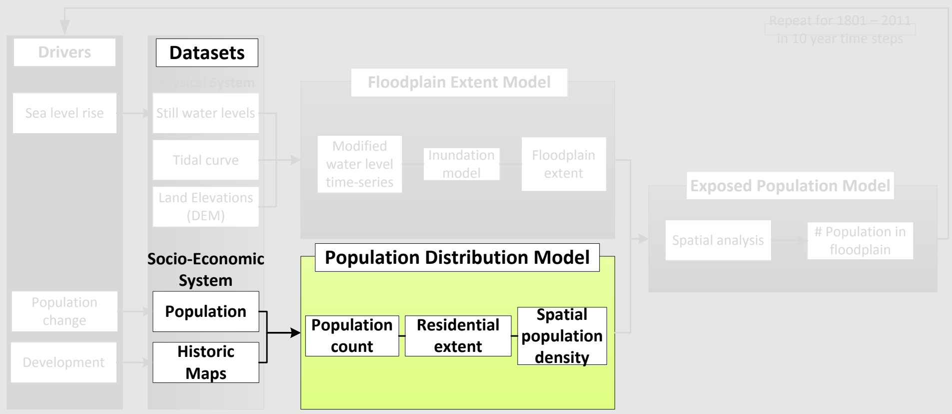

Figure 5.9: Socio-Economic system within the model structure

Census population data is used to give a population count at each time step. Historic maps are used to evaluate the location of the population and these are combined to estimate the spatial population density. The location of the population is important as it will determine where it intersects the floodplain.

Population data is extracted from demographic data from the UK census, which is conducted every 10 years. The data is presented spatially for "modern" censuses (1971 onwards) however the regions have changed through time (Table 5.3). For the 1971-2011 censuses this data exists in the form of weighted centroid points for each census area (e.g. Figure 5.10). Centroids provide a single georeferenced point for an output area/enumeration district and are provided to protect the privacy of individual households.

Census Year	Smallest Census Area available	Description	No. in Portsea
1801-1961	Total Count	Non spatial data	1
1971 1981 1991	Enumeration District	Areas used for collection and output of census data, size determined by requirements of data collection and to match administrative boundaries at the time	312 314 303
2001 2011	Output Area	Lowest level of output geography from 2001 onwards, designed to have population of comparable size, containing an average of 300 people (min. 100)	504 522

Table 5.3: A description of available census geographies through time and their relative size

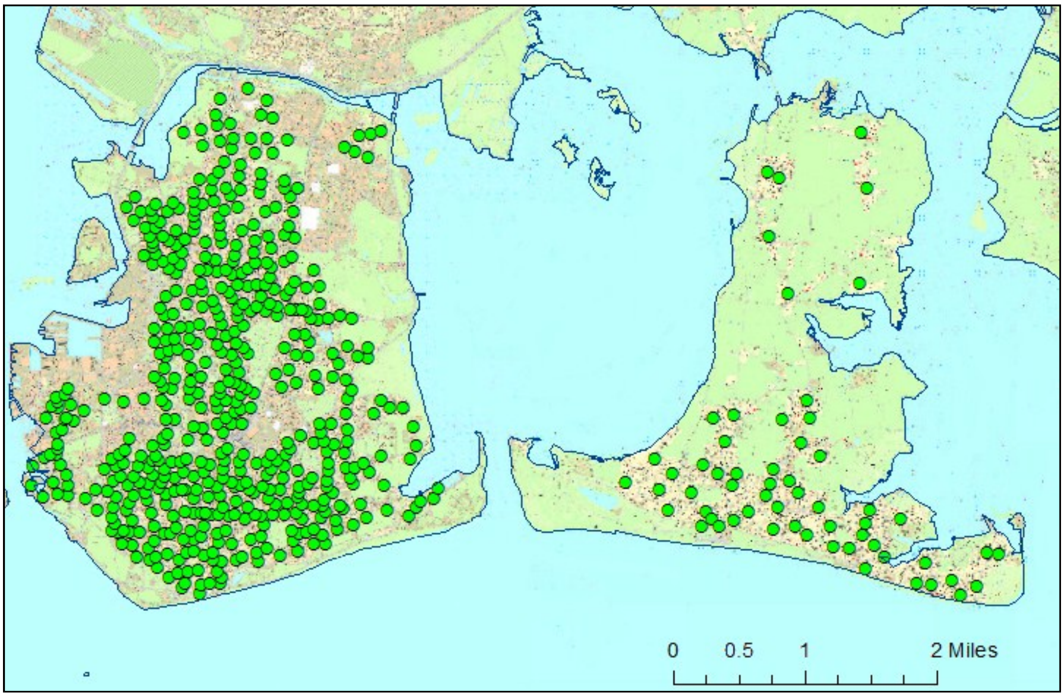

Figure 5.10: Portsea and Hayling islands showing 2011 population centroids (green circles). Underlying map is 2012 MasterMap®. Crown Copyright/-database right 2015. An Ordnance Survey/EDINA supplied service.

The different geographies between censuses make long term studies problematic as the areas are not directly comparable (Langford, 2007; Martin et al., 2002). The solution is to use appropriate area interpolation techniques to transform the data values to a **common** set of zones (Langford, 2007). For small spatial areas, such as output areas and enumeration districts, remodelling of the data to an underlying surface-based representation may prove the only alternative (Martin et al., 2002). Further, gridded population models offer ease of integration with non-population data sources (e.g. raster flood maps as used in this study) (Martin et al., 2011).
The processing of the population data from 1801-2011 for Portsea and Hayling is described in the following section.

Portsea Population

The aggregate population counts for the city of Portsmouth from 1801-1961 were scaled to represent population in the case study area (Portsea island). Scaling the total counts in this way deals with the problem of changing geographies through time (e.g. changing administrative boundaries). The populations were scaled using aggregate counts for the city of Portsmouth for census years 1801-1961 and the modelled (spatial populations from centroid points) for census years 1971-2011, as per the equation:

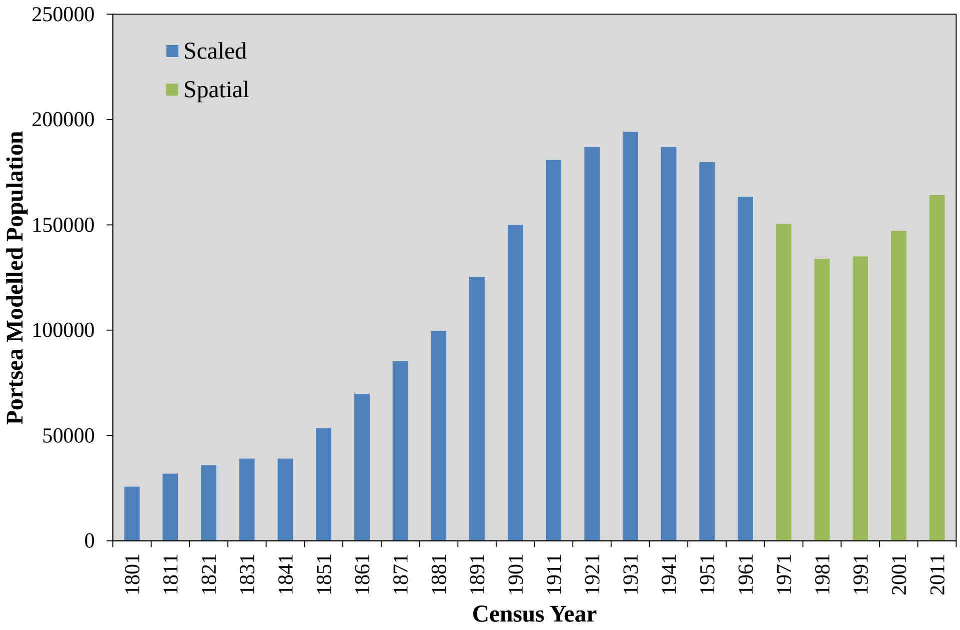

Figure 5.11: Portsea Population used within the model and the type of data used

$$Pop_{scaled_t} = Pop_{Portsmouth_t} \times \frac{\sum_{n=1971}^{2011} \frac{n_{Portsea}}{n_{Portsmouth}}}{n_{years}} \tag{5.2}$$

Where:

Pop_{scaled_t} = The scaled population for Portsea Island used within the model at time step t

$Pop_{Portsmouth_t}$ = The total population for Portsmouth from the census data at time step t

$n_{Portsea}$ = The modelled population used in the spatial census study (1971-2011)

$n_{Portsmouth}$ = The total population for Portsmouth from the census data (1971-2011)

n_{years} = The number of years where spatial data exists (= 5 for the Portsea case study)

Raw census data and scaled populations from 1801 to 2011 are shown in Figure 5.11. The population in Portsea rose at a high rate from 39,000 in 1841 to a peak of 194,000 in 1931. The population then falls to a local low of 134,000 in 1981 before rising again to a value of 164,000 in 2011. The modelled populations from 1801-1961 were scaled, and 1971-2011 used spatial census data.

Hayling Population

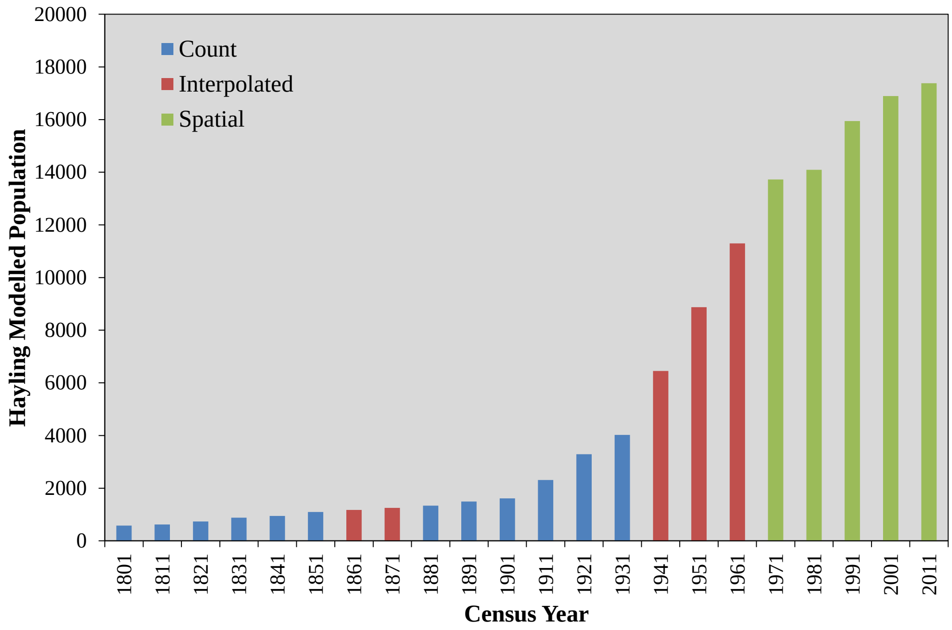

Figure 5.12: Hayling Population used within the model and the type of data used

Historic census data for Hayling parish (which covers the spatial area of Hayling island) extends to 1801 however it is not complete due to changing administrative boundaries during the 19th and 20th centuries. Therefore it was necessary to interpolate the counts for missing years (Figure 5.12). The population in Hayling rose steadily from just under 600 in 1801 to 4,000 in 1941. Population continued to increase at a higher rate until the maximum of 17,400 in 2011. Modelled populations in 1801-1851, and 1881-1931 are formed from raw counts from census data, with values in 1861-1871 and 1941-1961 interpolated from these counts. Between 1971 and 2011 spatial census data for Hayling was used.

These scaled populations counts were used within the model to simulate coastal population.

Method for recreating the residential extent

Historic maps of Portsea and Hayling islands were used in order to evaluate which spatial areas were populated. Maps were sourced from Digimap© from the University of Edinburgh for the 1870s, 1890s, 1910s, 1930s, 1960s, 1970s, 1990s and 2012; their use is summarised in Table 5.4. Developed areas were hand digitised within GIS (Geographical Information System) software in order to create a 'development layer' showing where population is situated, with population allocated only to populated areas. This allowed population to be spread more realistically as opposed to distributing centroids

Census Year	Map used to create population mask
1801-1871	County Series Edition 1 (1870s)
1881-1891	County Series Revision 1 (1890s)
1901-1911	County Series Revision 2 (1910s)
1921-1931	County Series Revision 3 (1930s)
1941-1961	National Grid imperial Edition 1 (1960s)
1971	National Grid Metric Edition 1 (1970s)
1981-1991	Latest National Grid (1990s)
2001-2011	MasterMap® (2012)

Table 5.4: Historic maps used to create residential masks for each census year

with no regard for the spatial location of residential areas. Non-residential features such as schools, hospitals and industrial units were removed from the residential development layer in order to increase the accuracy of the population spreading. This prevented population from being distributed to non-residential areas. The vector layer was converted to a 50m raster grid to match the resolution of the flood model. A 50m resolution includes adjacent roads in residential masks; however the spatial resolution of census data makes higher resolution (e.g. 10m grid cells) unrealistic.
Use of a development layer addresses the problem of differing census geographies by constraining population to the area developed for each census year (Martin, 1989). The digitised residential areas are seen in Figure 5.13. Development has increased on both islands between 1870 and 2012. On Portsea early residential development (1870s) was centred near the dockyards area to the West of the Island with small pockets of residential development elsewhere. The centre and East of the Island began to be developed between the 1890s and 1910s and by 1930 the Island was largely developed. Major developments since the 1930s include Anchorage park to the North-East of the Island (seen in the 1990s map and expanded in the 2010s map), and developments in the Eastney area in the South-East corner of the Island (seen from 1960 onwards).
Hayling was sparsely developed from the 1870s through to the 1910s. In the 1930s development increased, mostly in the South of the Island. As for Portsea, the picture in the 1930s is similar to that of the modern day, although noticeable development did occur in the Eastoke peninsula (South-East corner of the Island) seen in the 1960s through to the 2010s map. Portsea Island remains more developed than Hayling throughout the record.

The development in km^2 is shown in Figure 5.14.

Methods for recreating spatial population distributions
The use of non spatial data presents a problem for population spreading due to the inherent sensitivity to how the population is spread. In order to perform a limited sensitivity analysis three different population methods were compared; a method using

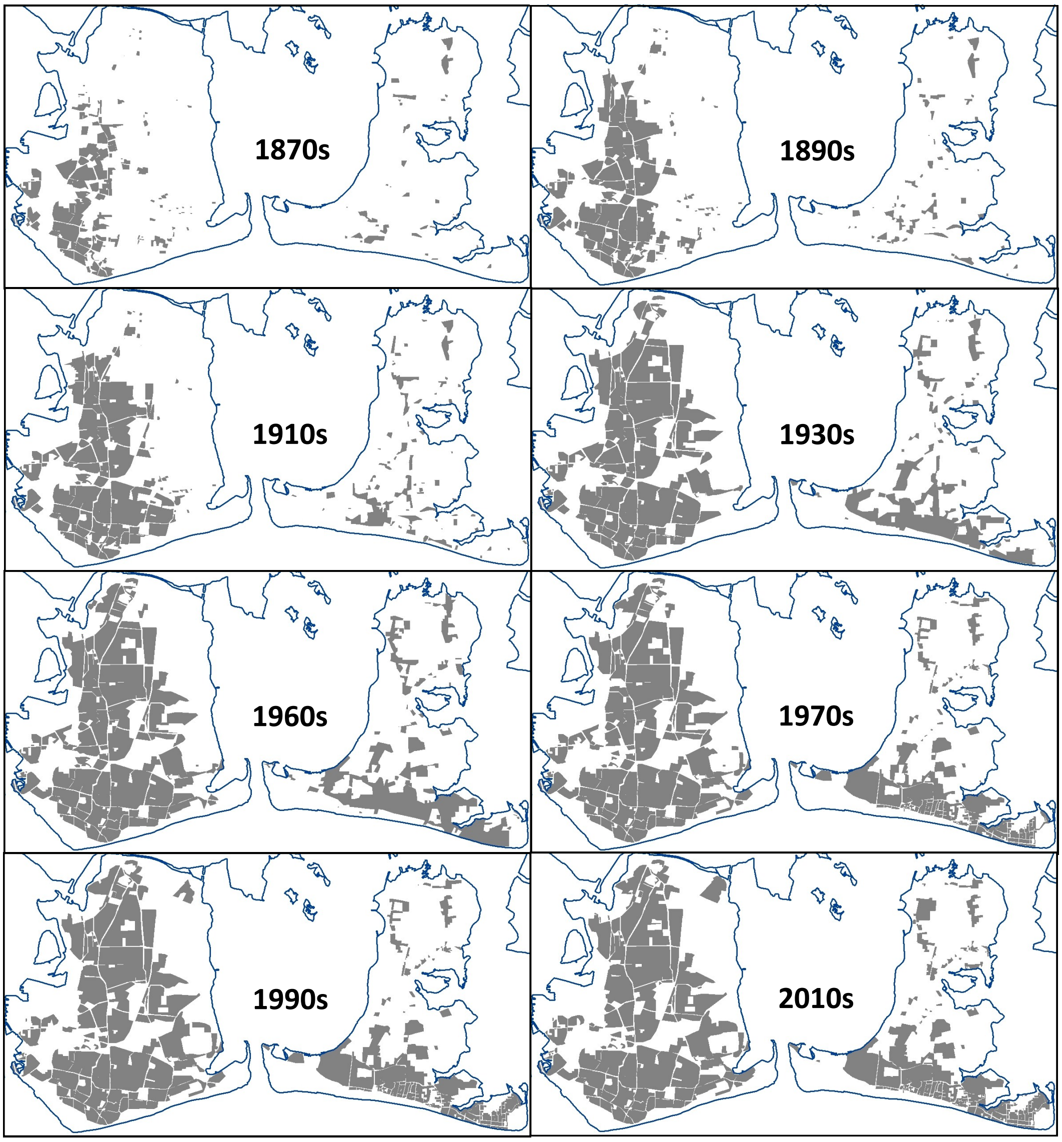

Figure 5.13: Developed areas in Portsea Island (left) and Hayling Island (right), 1871-2011. Contains public sector information licenced under the Open Government Licence v3.0.

population centroids (A), a method using historic mapping to distribute population to residential areas (B) and a simpler method where population is uniformly distributed across the model. A summary of the data required for each method and the length of data availability is shown in Table 5.5.

Method A uses a combination of spatial census data and historic maps to distribute population as realistically as census data allows. Population is distributed from census centroid points to nearby residential areas thus conserving the spatial population density of the underlying data. The population is distributed according to a distance-decay function as evaluated in SurfaceBuilder^{TM}, a surface population model widely used in studies using census data (Martin, 1989; Smith et al., 2014, 2015, e.g.). This raster based method has been demonstrated to be more reliable than other methods (Martin

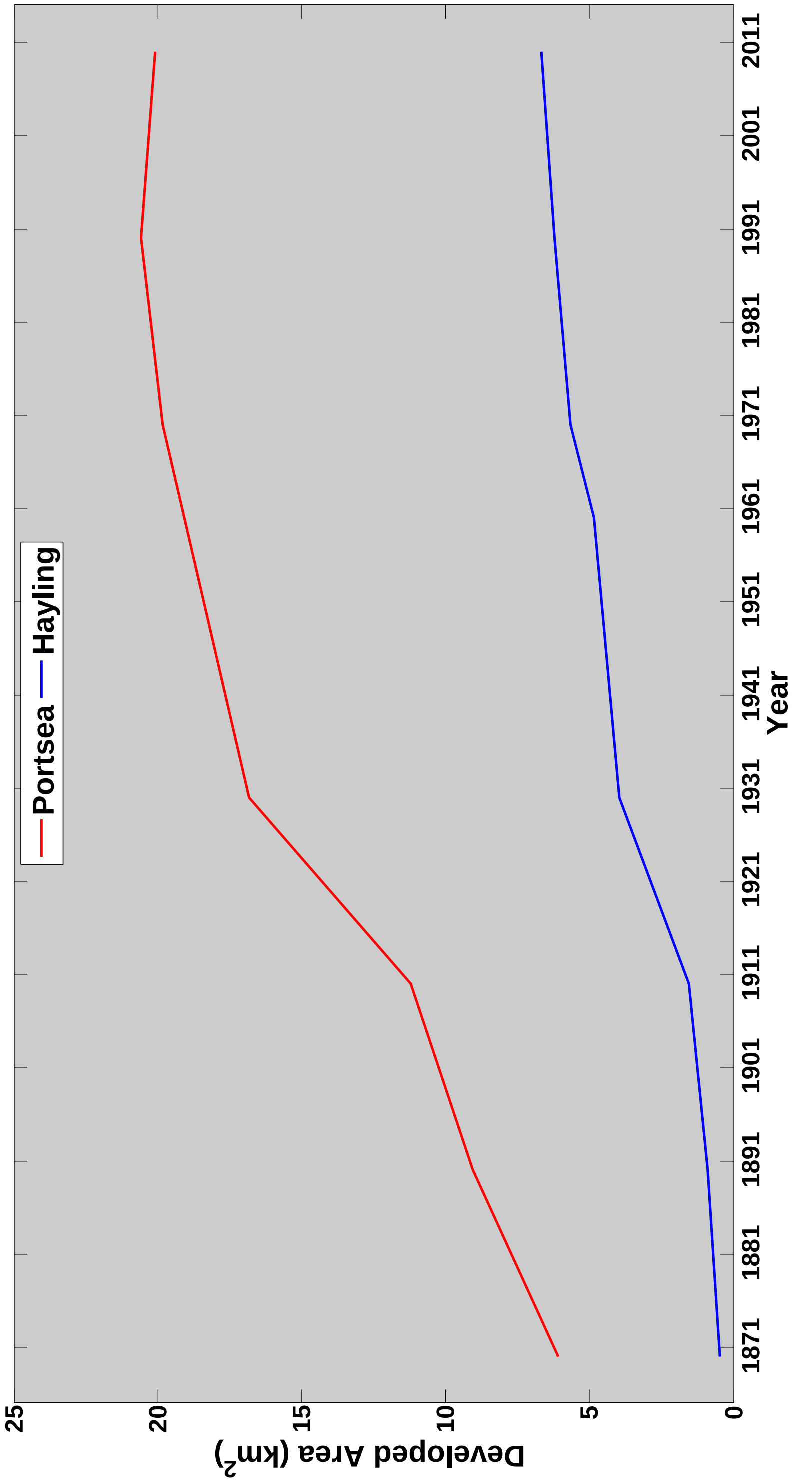

Figure 5.14: Area of development in Portsea and Hayling islands, 1870-2010

et al., 2002, 2011). However this method is only viable where spatial centroids exist (1971-2011).
Method B uses a more concise distribution in which population is constrained to the residential extent as per the historic maps. The population density is assumed to be spatially uniform within the residential areas.
Method C presents a 'crude' method of distribution where the population is evenly distributed across the model extent. This method assumes the population density is spatially uniform and allows population to be spread into non residential areas such as green space, industrial land or inland water bodies. It is intended as a baseline against which to judge the other methods.

The chosen method is B, which is a trade-off between the highly detailed but limited A (only 40 years of centroid population data exists, whereas non-centroid data exists over 200 years), and the simplicity but inaccuracy of method C. Each method is described more fully, and results using each method are compared in Appendix D.

Technique	Data Required			Data available
	Population Centroids	Population Count	Map	
A: Centroid	Y	Y	Y	1971-2011
B: Residential Distributed	-	Y	Y	1870-2011
C: Uniformly Distributed	-	Y	-	1801-2011

Table 5.5: Comparison of population spreading techniques

Impacts: Exposed Population Model

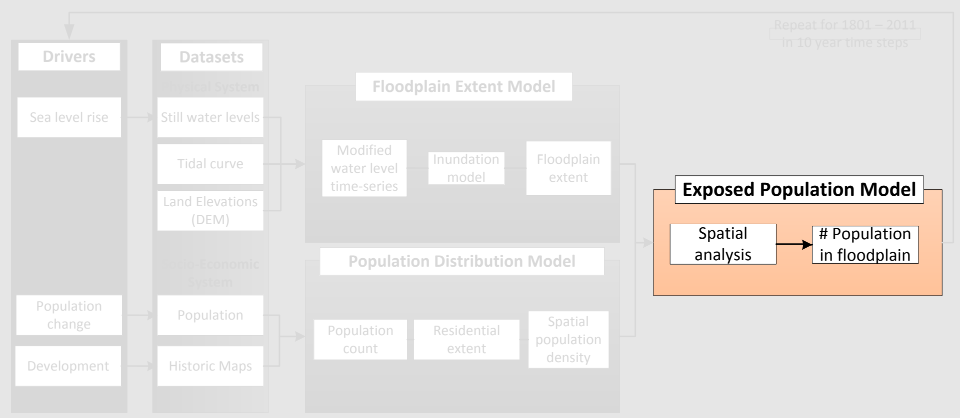

Figure 5.15: Impacts within the model structure

The human impacts of flooding are considered in the model by calculating the number of people exposed to each flood event at each discrete time step. An annual average exposure is calculated from a range of recurrence interval events as described in the following section. This allows a comparison of exposure between different scenarios. The method for extracting exposed population is shown in Figure 5.16.

The exposed population in each grid cell is summed to give a total exposed population for each time step. The change in exposure over time is then calculated.

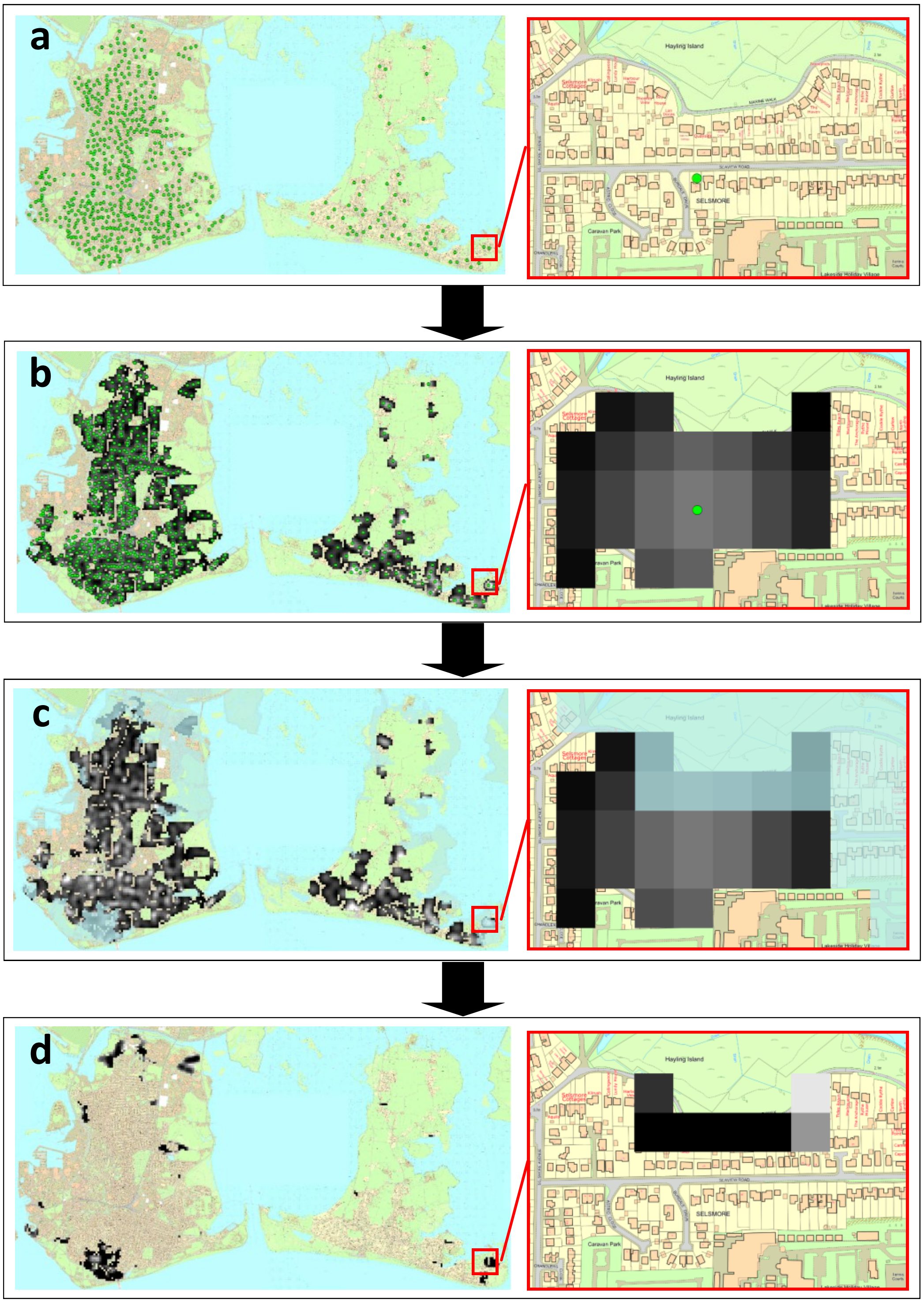

Figure 5.16: Methodology for extracting floodplain population from population centroids and flood extent data. (a) Spatial census data are overlain onto historic map. (b) The population is distributed onto a raster surface constrained by residential development from the map. (c) Floodmap of known recurrence interval is overlain onto the raster population surface. (d) Population intersecting the floodplain is extracted. Underlying map is 2012 MasterMap®. Crown Copyright/database right 2015. An Ordnance Survey/EDINA supplied service

Calculating Annual Average Exposure from a range of Recurrence Intervals

In risk analysis damages from a range of recurrence interval flood events are used to calculate an Annual Average Damage (AAD, sometimes expected annual damage EAD) which can be defined as the statistically expected (economic) damages that will occur each year, for a given area, due to flooding (Penning-Rowsell et al., 2005b). This is calculated as a weighted average of damages across a range of flood events of known probability. AAD can be represented graphically by integrating the area underneath a damage-probability curve (Figure 5.17).

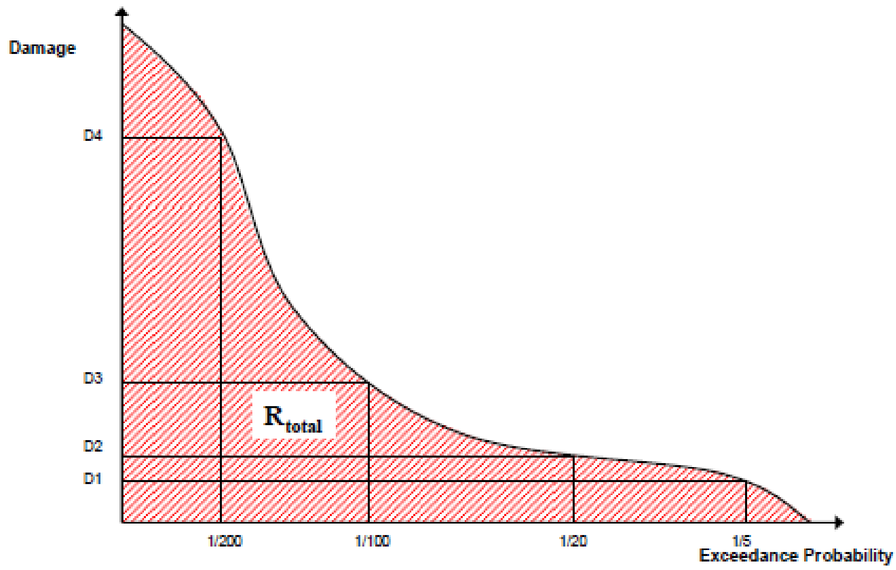

Figure 5.17: The graphical calculation of AAD as the area by a damage versus probability graph. Reproduced from Floodsite (Messner et al., 2007)

In this work the AAD equivalent for people exposure is calculated as the number of people, on average, expected to be exposed to flooding in any given year. The annual average number of people exposed to flooding is termed 'annual average people exposure' to differentiate it from economic annual average damages (AAD). The annual average people exposure is calculated from the number of people exposed to a range of recurrence intervals at each time step (10 year intervals) as thus:

$$Annual\ Average\ People\ Exposure = \int_{1:1000}^{1:1} f(x)\,dx \tag{5.3}$$

where f(x) is the equation of the curve of recurrence interval plotted against exposure of people for the 1:1 year, 1:10 year, 1:20 year, 1:50 year, 1:100 year, 1:200 year and 1:1000 year coastal flood events.

The measure of annual average people exposure is designed to condense a lot of information into a single number, which will aid coastal managers in interpreting the results of the exposure analysis. The results of this analysis are presented in the following section.

5.2.2 Model Results: Exposure Without Defences for a range of Recurrence Intervals

Variable	Value	Rationale
Sea level rise	1.22 mm / yr	Mean rate of sea level change (Haigh et al., 2011)
Recurrence interval	1 in 1, 10, 20, 50, 100, 200, 1000	Range of RI used to calculate the annual average exposure of people
Tidal cycles	1 cycle (12 hours inflow)	Used in previous study (Wadey et al., 2012; Wadey, 2013)
Population method	B - Residential Distribution	Best available method (see Appendix D)
Defences	None (natural ground elevation used)	Evaluation of exposure without defences

Table 5.6: Model variables used for the Portsea and Hayling without defences model

The model was ran for a range of recurrence intervals (Table 5.6), and from these individual model runs an annual average people exposure was calculated as described in the previous section. The annual average people exposure is presented for the mean rate of sea level change from the previous section (1.22 mm/yr), applied from 2011 to 1801, for the scenario without defences.

Portsea Without Defences

The exposure without defences increases between 1801 and 2011 for all modelled recurrence intervals; for the smallest event modelled (RI = 1 year) exposure increases 175-fold from 21 people in 1801 to 3,677 people in 2011, for the most extreme modelled event (RI = 1000 years) exposure increases by a magnitude of 8.6 from 2,777 people in 1801 to 23,987 people in 2011. The estimated exposure to the annually expected flood event (RI = 1 year) is >100 people from 1891 onwards and >1000 people from 1991 which demonstrates the importance of defences in managing the potential exposure in Portsea and the severe consequences if defences fail.

The annual average people exposure (without defences) increased from 176 people in 1801 to 6,911 people in 2011 (a magnitude of 39.3, 3,827%). Between 1801 and 1921 this increase was gradual, with a large increase between 1921 and 1931. This is likely to reflect post-war development and population rise on the island. There is another period of gradually increasing exposure between 1931 and 1971 with a small reduction in exposure in 1981. Post 1981 there is a higher rate of increase in exposure (exposure doubles between 1981 and 2011) which reflects an increased rate of development and population rise over this period, particularly in the coastal environment.

Probability versus exposure is presented for the time steps at 1801, 1901, 2001 and 2011 in Portsea (Figure 5.19). The population expected to flood in 1901 every 10 years equates to the population expected to flood in a 1000 year recurrence interval flood in 1801. Similarly the population expected to flood every 200 years in 2001 equates to that expected to flood once every 1000 years in 1901. Over a 10 year period between 2001 and 2011 the expected exposed population for given probabilities increased and this is more pronounced for the more extreme (higher recurrence interval) flood events. A 1 in 200 year flood would be expected to expose approximately 16,950 people in 2001, and approximately 19,800 people in 2011. For a 1 in 1000 year flood the exposed population increases to 20,900 and 24,000 people for 2001 and 2011 respectively; an increase of over 2,000 people. For the 1 in 1 year recurrence interval (the 'annual' flood) the estimated number of people exposed increases from 2,400 people in 2001 to 3,700 people in 2011. In 1801 it is estimated that only 21 people would be exposed to the annual flood event, increasing only modestly to 193 people in 1901.

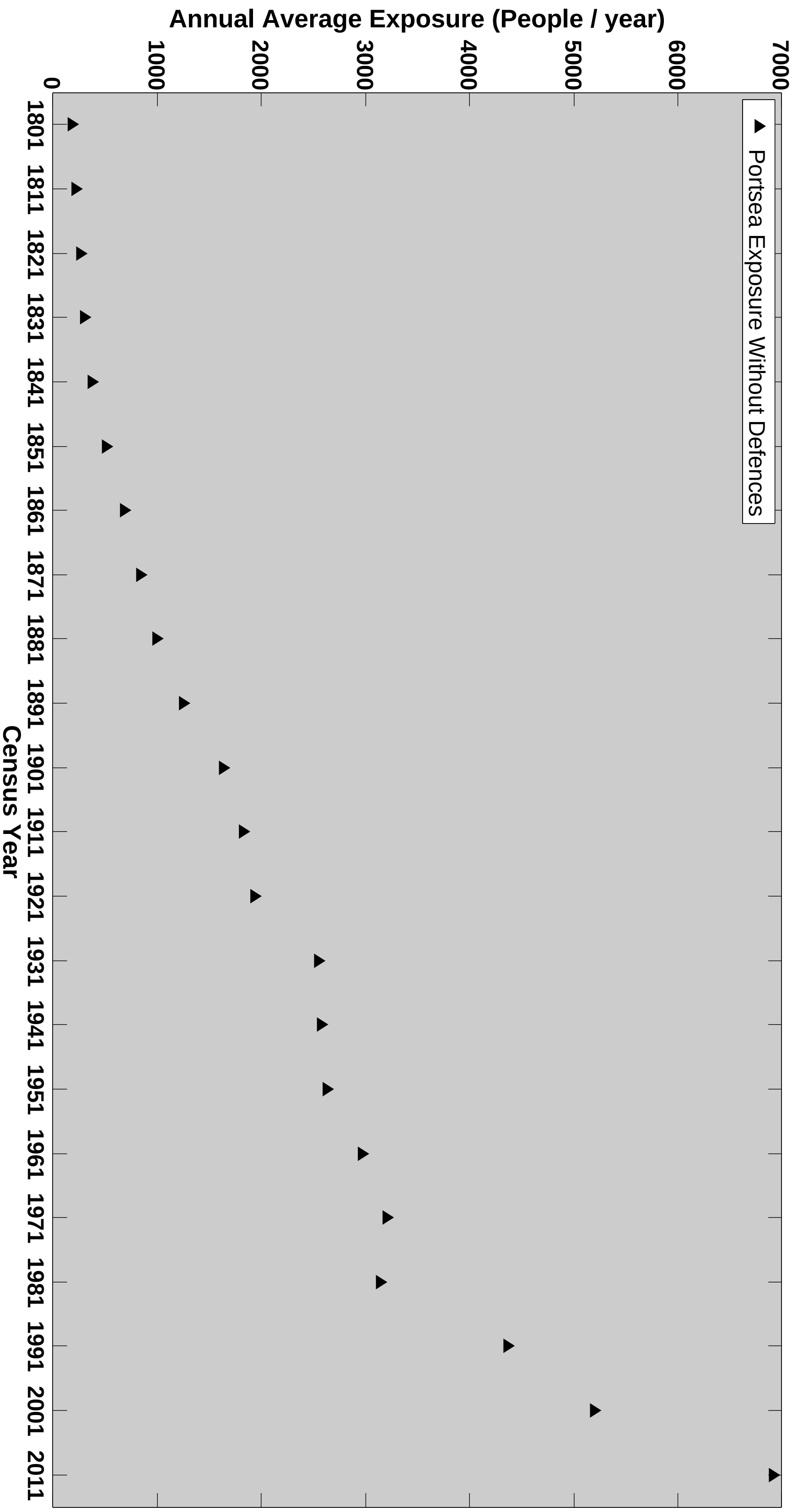

Figure 5.18: Annual Average Exposure of people to flooding in Portsea, without defences, 1801-2011 (1.22 mm/yr sea level change rate applied)

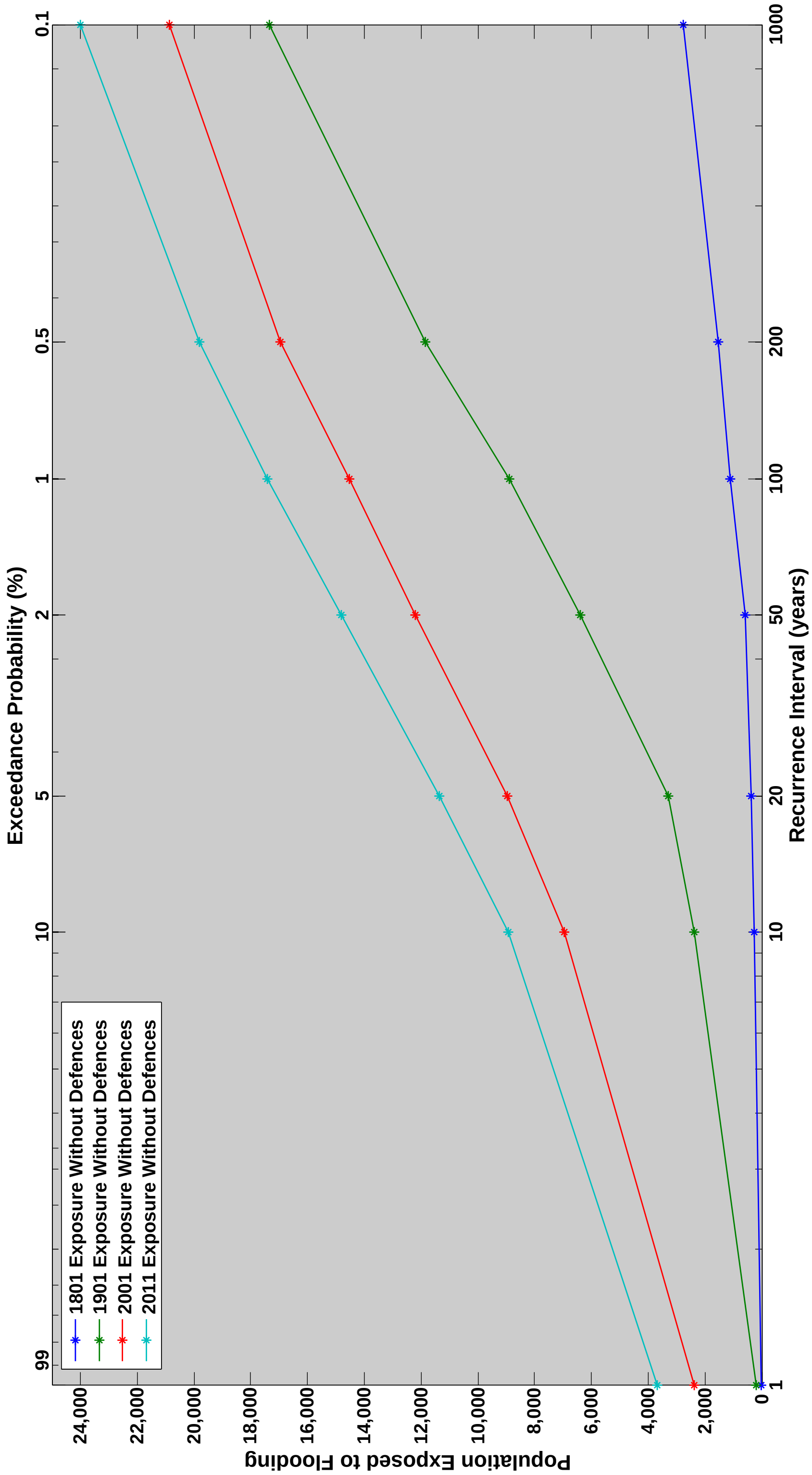

Figure 5.19: Probability vs exposure graph of population exposed to events of different recurrence intervals, 1801-2011 for Portsea (mean SLR rate 1.21 mm / yr applied, logarithmic scale)

Census Year	Number of people exposed/Recurrence Interval (1 in x years)						
	1	10	20	50	100	200	1000
1801	21	252	358	568	1,094	1,536	2,777
1811	26	313	443	730	1,408	1,956	3,547
1821	29	383	501	883	1,649	2,297	4,329
1831	32	416	607	1,279	1,982	2,590	4,796
1841	32	544	703	1,407	2,014	2,846	4,892
1851	44	744	1,006	2,144	3,063	3,938	6,913
1861	57	973	1,430	3,090	4,177	5,264	9,154
1871	70	1,187	1,746	3,771	5,238	6,914	11,243
1881	82	1,387	2,122	4,734	6,447	8,406	13,384
1891	162	1,778	2,640	5,227	6,897	9,268	14,387
1901	193	2,386	3,289	6,384	8,899	11,865	17,346
1911	244	2,682	3,719	6,645	8,778	12,192	17,313
1921	252	2,837	4,161	7,186	9,456	12,923	18,344
1931	282	3,801	5,912	9,244	11,730	14,546	20,833
1941	316	3,795	6,190	9,172	11,612	14,730	20,514
1951	348	3,910	6,039	9,080	11,644	14,728	20,072
1961	529	4,308	6,727	10,166	12,585	15,344	20,219
1971	730	4,658	6,987	9,664	11,993	14,391	18,424
1981	897	4,485	6,341	8,816	10,888	13,177	16,549
1991	1,782	5,950	7,944	10,753	12,777	15,223	18,999
2001	2,369	6,943	8,950	12,208	14,511	16,946	20,861
2011	3,677	8,924	11,351	14,813	17,419	19,811	23,987

Table 5.7: Number of people exposed to flooding in Portsea for a range of recurrence intervals (exposure without defences, 1.22mm/year sea level change rate applied)

Hayling Without Defences

The exposure without defences in Hayling increased across all recurrence intervals between 1801 and 2011; for the annually expected flood (RI = 1 year) exposure increased by a magnitude of 27.5, and for the most extreme modelled event (RI = 1000 years) exposure increased by a magnitude of 46.8. The exposure without defences in the early 1800s in similar across all recurrence intervals, which suggests that some inappropriate residential development took place near to the coast (within the 1 year RI floodplain), with the rest occurring outside of the 1 in 1000 year floodplain.

The annual average people exposure (without defences) increased from a value of 27 people in 1801 to 692 people in 2011 (an increase of 2,463% or magnitude 25.6). Following a gradual increase in exposure between 1801 and 1881, exposure oscillates between increase and decrease from 1881-2921. The reductions in exposure are likely a result of the method; an increase in non-coastal development causing a reduction in modelled population density near to the coast which is discussed later. Post 1921 exposure increases up to its peak in 2011. The largest single increase in exposure occurs between 1951-1961 (almost 200 people, a 100% increase). The average annual people exposure in Hayling is around an order of magnitude lower than in Portsea, which is due to the much smaller population in this rural location.

Probability versus exposure is presented for the time steps at 1801, 1901, 2001 and 2011 for Hayling (Figure 5.21). The population expected to be flooded in a 1 in 1000 year event in 1801 is eighteen times lower than that expected to be exposed to a 1 in 1 year flood in 2011. This represents a significant increase in exposure in Hayling over the last 200 years. Exposure even to the most extreme floods was low through the 19th and 20th centuries in Hayling. The exposure to the 1 in 1000 years recurrence interval was 44 people in 1801 and 139 people in 1901, compared to 1,945 people in 2001 and 2,060 people in 2011.
The rise in exposure between 2001 and 2011 is uniform across all recurrence intervals.

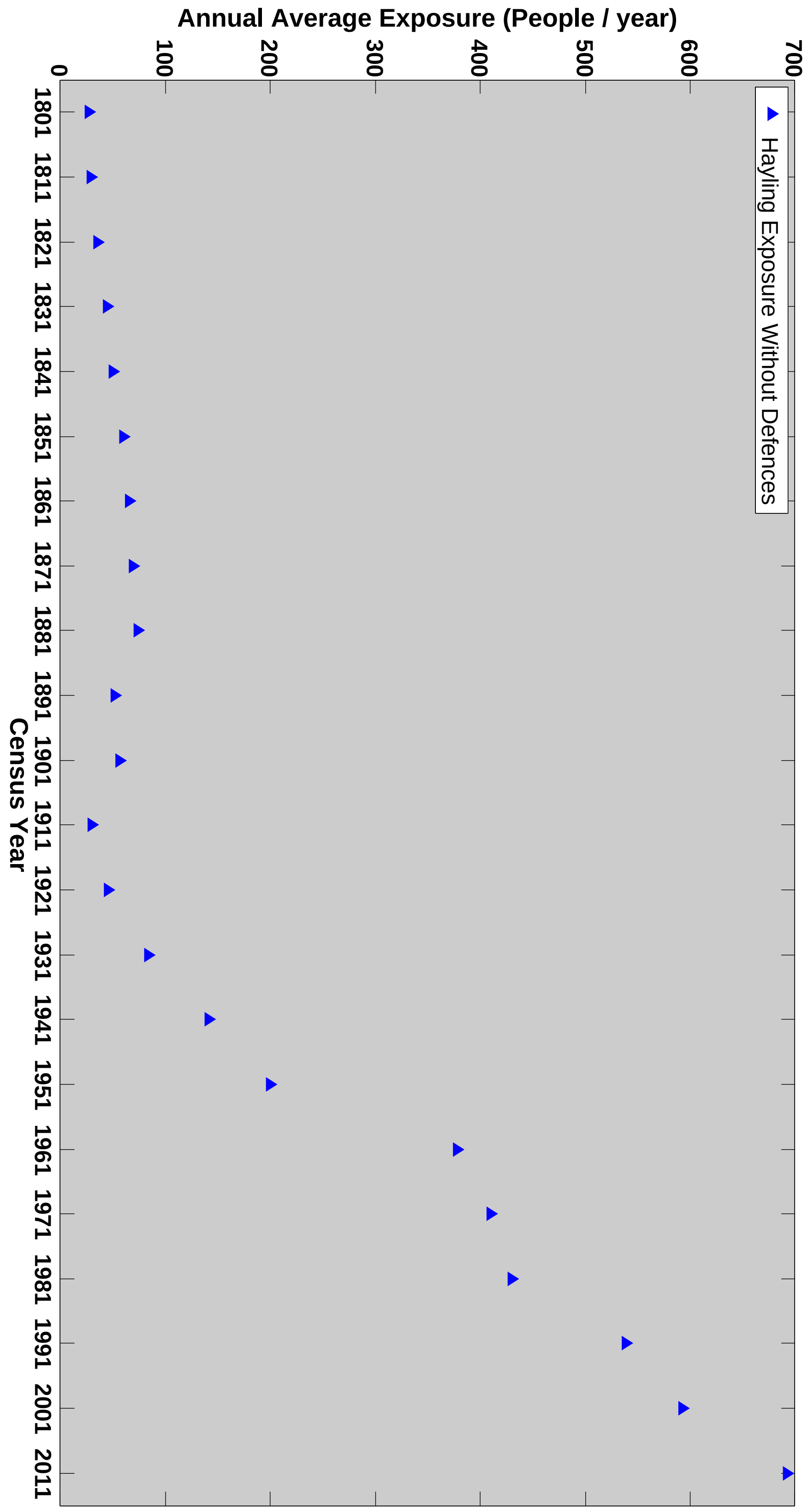

Figure 5.20: Annual Average Exposure of people to flooding in Hayling, without defences, 1801-2011 (1.22 mm/yr sea level change rate applied)

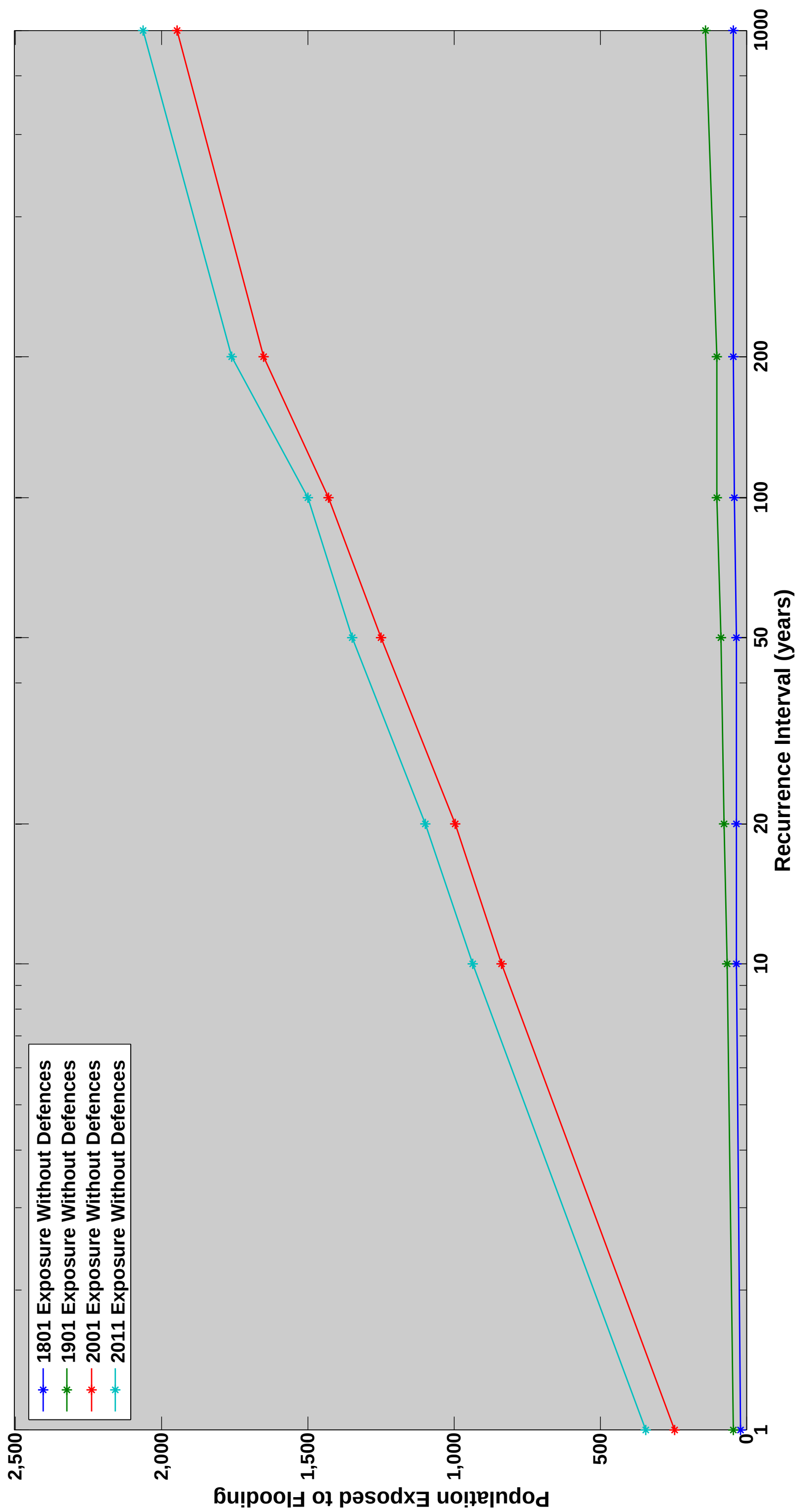

Figure 5.21: Probability vs exposure graph of population exposed to events of different recurrence intervals, 1801-2011 for Hayling (mean SLR rate 1.21 mm / yr applied, logarithmic scale)

Census Year	Number of people exposed/Recurrence Interval (1 in x years)						
	1	10	20	50	100	200	1000
1801	19	34	34	34	41	44	44
1811	20	37	37	40	47	47	47
1821	24	44	44	48	56	56	56
1831	33	52	52	62	67	67	72
1841	41	56	56	66	72	72	77
1851	53	65	65	77	83	83	95
1861	57	70	70	83	89	89	102
1871	61	75	75	95	95	95	109
1881	65	79	79	101	101	101	115
1891	40	59	69	79	89	94	129
1901	43	64	75	85	101	101	139
1911	13	40	53	71	80	85	125
1921	19	63	76	101	114	120	184
1931	38	116	141	176	188	217	286
1941	60	196	237	287	312	352	463
1951	83	284	333	395	450	492	651
1961	153	540	613	766	854	942	1,190
1971	178	569	684	871	986	1,110	1,421
1981	192	593	711	912	1,049	1,158	1,468
1991	229	748	908	1,157	1,317	1,527	1,816
2001	243	835	994	1,247	1,427	1,649	1,945
2011	342	935	1,096	1,347	1,498	1,759	2,061

Table 5.8: Number of people exposed to flooding in Hayling for a range of recurrence intervals (exposure without defences, 1.22mm/year sea level change rate applied)

5.2.3 Discussion

The local scale results for Portsea and Hayling presented in this Chapter support the limited conclusions from Chapter 4, which suggested that normalising flood events by population and dwelling counts removed most of the upward trend in flood exposure. However the national scale results could not be substantiated and hence it is unclear whether socio-economic drivers are dominant at both local and national scales in the UK. It is also not yet clear whether the relative effects of population change and sea level change on the exposed population will show a similar trend at local level across the UK as regional differences may exist. The datasets used and the approach developed here could be applied to any UK case study in order to test this hypothesis and to improve the limited conclusions of the national scale analysis in Chapter 4.

Some reductions in exposure were recorded despite no overall decrease in coastal population or development. This is likely caused by a sudden increase or reduction in population or development causing a change in the modelled population density (which is calculated as total population divided by total residential land area). If this development occurs outside of the floodplain then the total people estimated to be exposed may be underestimated. This is highlighted as a limitation of this methodology. However there is still confidence in long term trends as these short term effects are evened out. The estimated exposure using the chosen population spreading method showed good agreement with the exposure estimated using higher resolution population data (available for modern censuses, 1971-2011) which gives confidence in its application.

Wadey (2013) simulated the 1 in 200 coastal flood event using the exposure metric of number of buildings within the floodplain. Their results for an all breach scenario are comparable to the results presented here as both assume there are no defences present (and therefore natural ground levels are used). Unfortunately only the results for the 1:200 event for the current day (2011 time step)can be validated, as Wadey (2013) did not look at a range of recurrence intervals or evaluate the historic evolution of exposure as in this work. Wadey (2013) estimate that there are 8,099 buildings exposed to flooding for the modern day 1 in 200 year floodplain. If we assume an occupancy rate equal to the national average (2.3 people per dwelling) the number of people exposed is equal to 8,099 * 2.3 = 18,627. Here it is estimated that 19,800 people are exposed to the 1:200 year event. This shows good agreement (within 6.1%) with the published results of Wadey and gives limited validation of the technique. Full validation of the estimates are not possible, as no previous studies have considered recurrence intervals other than the 1:200 year event, or evaluated the evolution of the exposure of the coastal population in this location.

It is possible that the large time step used in this analysis (10 years) may mask changes in coastal population over shorter time scales. However the high quality of census data and the length of data availability (>200 years) outweigh the benefits of using alternative

or supplementary, lower quality data to reduce the time step. This highlights the need for regular high quality data on both physical variables (land elevations, sea levels) and socio-economic variables (population size and density, residential extent). Availability of such data will allow continued assessment of changing exposure to flooding.
The nature of population distribution changes in the future is likely to have a significant effect on the number of people exposed to flooding and therefore the potential consequences of flood events.

5.2.4 Summary and Conclusions

Exposure has been estimated from 1801-2011 using nationally available (census) population data. The length of this study is unprecedented, and demonstrates the strength of the methodology for historic study. The method was applied to Portsea and Hayling islands on the UK's south coast, which represent an urban and a rural area. The study found that exposure in both areas to a range of recurrence intervals has risen significantly from 1801 to 2011 due to a combination of sea level rise, population rise and expansion of residential development into flood risk areas. This work has demonstrated that:

- Exposure to flooding of the coastal population to a range of recurrence intervals can be estimated
- Exposure to flooding has been increasing in case study area
- Approach can be used in any coastal region in the UK

In both case study regions exposure to flooding has increased. This is more pronounced in the urban case study, Portsea, which had a greater growth in population between 1801 and 2011.
The approach developed can be used in any coastal region in the UK, or elsewhere where sufficient data exists. This allows the evolution of coastal exposure across the UK to be assessed.

In Chapters 1 and 2 a distinction was made between exposure without defences (as studied here, where defences are ignored or assumed to fail) and exposure with defences (which accounts for the moderating effect of defences, assuming that they do not fail). It is useful to evaluate both of these concepts in order to give a holistic assessment of exposure and to quantify the effectiveness of defences. This section has developed a methodology for assessing the exposure *without defences* in a coastal location, and investigating how historic changes in sea level and population have affected the evolution of exposure. The next step in the method is therefore to evaluate the effect of flood defences on the exposure and hence evaluate exposure *with defences*. This will be done by building a dataset of defences through time in the case study and applying the defence data to the exposure model. This is undertaken in the following section.

5.3 A Quantitative Assessment of Flood Exposure With Defences

This section analyses the effect of flood defences on exposure in the case study area. The proportion of the population protected by defences over time is analysed which sheds light on the effectiveness of management at the local level. The objectives of the study are to (1) to develop a methodology to recreate the flood defence history of the case study area, (2) to explore how historical changes to flood defences have modified flood exposure and (3) to evaluate the effect of flood management on flood exposure in terms of the number of people protected by defences.

In Section 5.2 a method was presented for quantifying the exposure *without defences* to the coastal population. This is defined as the population potentially at harm if defences are not present or fail. Responses to manage this potential flood exposure will affect the impacts on the coastal population. The interaction of management responses and potential exposure is defined in this work as exposure *with defences.* In this section we examine this interaction between flood management responses and exposure in a coastal area. Flood exposure with defences will be quantified using the equation introduced in Chapter 2:

$$Exposure_{with\,defences} = f(Exposure_{without\,defences}, Responses)$$

The analysis is presented for Portsea island only, as Hayling only has minimal formal defences in Eastoke and hence analysis is limited. The defences at Eastoke were constructed in 2008 and hence only represent the current condition. Portsea on the other hand has a long history of structural intervention and the majority of the island has hard defences, with historic datasets to describe their evolution. The following actions will be undertaken:

- Build a dataset of historic flood defences in Portsea
- Characterise and model the interaction between flood management and exposure
- Calculate the proportion of people protected by defences in the case study area
- Evaluate the effectiveness of defences through time

5.3.1 Methodology

In Chapter 3 it was decided that management responses will be evaluated by considering structural intervention. Structural intervention is defined here as physical measures designed to prevent coastal flood-water inundating the land. These measures are modelled in this work as defence heights at the model boundary (i.e. the coastline). This work uses defence crest heights from a dataset described in (Wadey, 2013). This dataset provides modern day defence heights (true to 2008) for the entire Solent region. Historic defences are recreated using a 1991 report by Portsmouth's then city engineer (Easterling, 1991) for the area of Portsea, which contains extensive information on when the defences were constructed starting in circa 1960. Although modern day defence data is available for Hayling island a history of structural intervention is not available, and therefore analysis is presented for Portsea only.

A dataset of historic defence heights

Easterling (1991) gives defence heights for the majority of the East, South and North of Portsea island (Figure 5.22). Defence heights for the west coast of Portsea island (W1-W7) are not available in the report as the area is controlled by the Military of Defence and was not surveyed by the city engineer. The defence elevations in this area (W1-W7 in Figure 5.22) are assumed to be equal to the elevations in the 2008 dataset and so static in time over the last 50 years. This assumption is reasonable because no recent defence works have been carried out in the area. Further, the area is mostly military and commercial dockyard and the seaward land elevations are far higher than design storm levels and hence will not be inundated. This assumption is also made in Section S2. The defences in this area are formed of historic military fortifications, built hundreds of years previously and far higher than the design storm still water levels considered (defence heights >5mOD). Hence the assumption that the defence heights are unchanged has no effect on the modelled exposure.

The report details the date defences were constructed, modified or upgraded. The majority of defences (with the exception only of those in S3) were constructed during or prior to the 1960s. The seawall present in section S3 was constructed in the 1970s, however prior to this a promenade (constructed in 1848) was present. Several sections (S1.3, S, 1.4, S3.1, S5, E3) were restored between 1970 to 1990, however they were not raised in height and so it is a reasonable assumption that the height is unchanged. This thesis does not attempt to calculate the probability of defence failures, either in the modern day or for the historic defences. The assumption regarding exposure with defences is that defences do not fail, as stated here and in earlier chapters. Therefore the analysis is based upon the defence heights as stated in the Easterling report; the implications of this assumption are discussed later.

The defence heights are shown in Table 5.9. There are 17 unique heights for the Portsea coastline, which is a sufficient resolution to recreate Portsea's defences at the 50m resolution of the hydrodynamic model. Where a range of heights are given the average defence elevation was used to represent the section. Whilst the lowest height is more critical, applying this across the whole section would likely overestimate the exposure.

General Location	Wall Levels in 1960 (mOD)	Location in Fig. 5.22
+*Promenade Sea Wall	2.9	S1.1
+*Old Fish Quay Timbers	3.2	S1.2
+*Garden at rear of Still and West	2.9	S1.3
+*Bath Square Slipway	3.2	S1.4
+*Portsmouth Sailing Club	2.7	S1.5
+*Tower House Walls	3.9	S1.6
+*Old Car Ferry Slipway	2.7	S1.7
Clarence Beach	3.2 - 3.6	S3
*Bullnosed Walls	4.2 - 4.4	S3.1
Southsea Castle to Lumps Fort	4.3 - 4.5	S4,S5,S6
*Pyramids Bullnose	5.6	S5.1
Eastney Beach	4.5 - 5.0	S7
Eastney Lake	2.7 - 3.3	E1
Milton Bund to Eastern Road Bridge	3.3 - 3.7	E2,E3
Tipner Lake east of M275	2.6 - 3.3	W7,W8
Portcreek west of railway	2.5 - 2.6	N1
Anchorage Park north shore	3.2	N2

* Specific defence(s)

\+ Part of Portsmouth Point

Table 5.9: Defence heights in Portsea island in 1960, adapted from Easterling (1991). Location in Fig. 5.22 refers to the map in Figure 5.22

Similarly applying the maximum defence height may under-predict exposure. In the absence of high resolution data for the whole of Portsea as exists for certain sections (for example S1.1:S1.7) the use of the average defence height is the most reasonable assumption. A sensitivity test was ran for the minimum/maximum heights and showed negligible change (<5%) in estimated exposure. This is likely because most defence heights are higher the 1 in 1000 year extreme still water level (3.28mOD) and hence will not be inundated when either the maximum or minimum value is used for any of the recurrence intervals evaluated in this work.

The Bullnosed walls and Pyramid Bullnose were located using scanned maps and Geographical Information System (GIS) software (Figure 5.23). The main sections were digitised by overlaying the scanned sections map onto a GIS Portsea layer and manually digitising the spatial location where each defence section is located. A GIS dataset of defence crest heights for points around the Portsea coastline was produced.

Calculation of Exposure reduction due to Defences

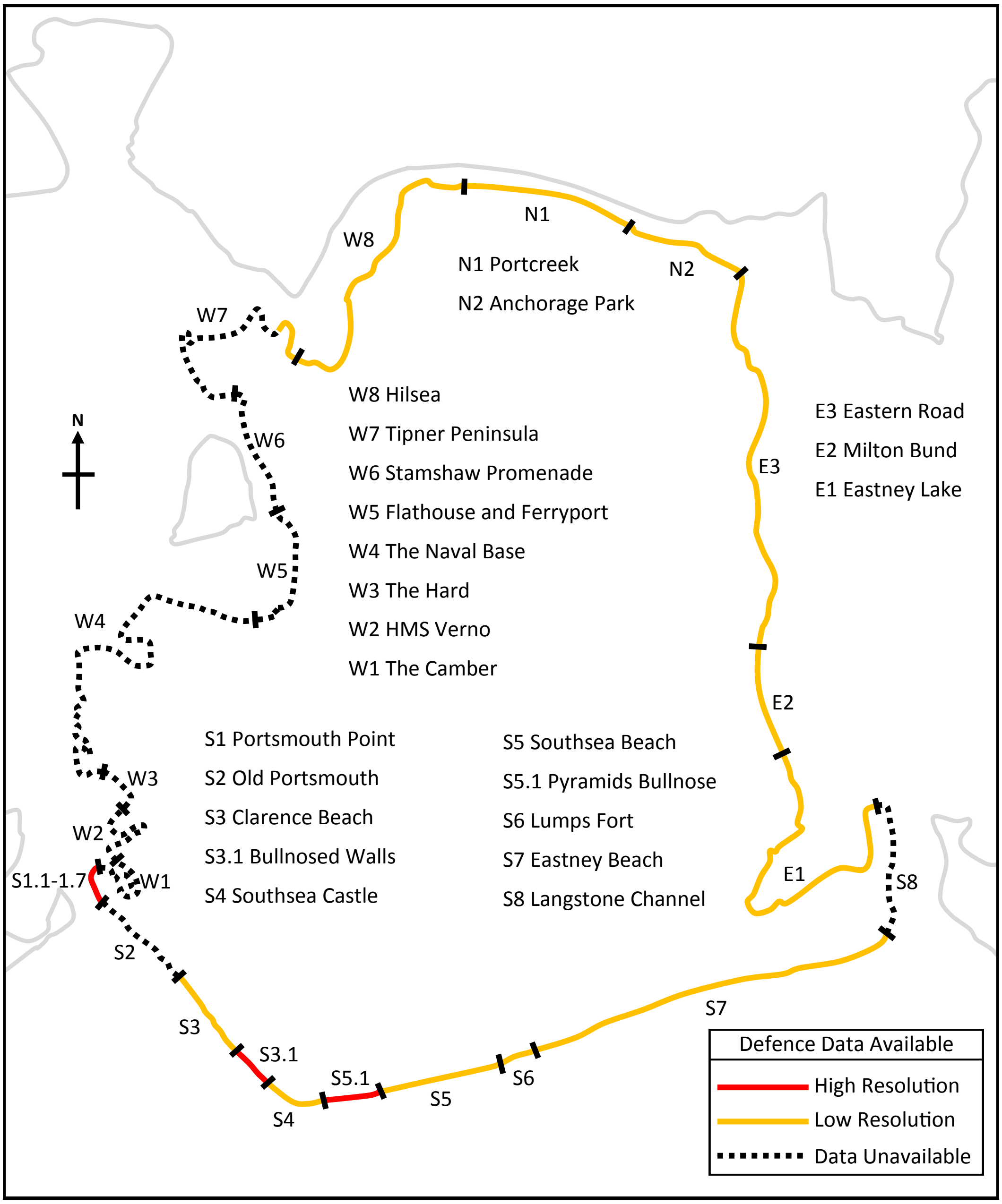

Figure 5.22: Portsea defence sections and data available (sections adapted from (Easterling, 1991))

The analysis in Section 5.2 estimated the exposure to flooding without defences, defined as the number of people residing within the coastal floodplain when natural ground levels are assumed (i.e. defences are not considered). When defence heights are accounted for the exposure with defences (number of people exposed to flooding, under the assumption that the defences do not fail) can be calculated. Investigation of the complex interactions of defence failure mechanisms is beyond the scope of this research; instead the percentage of the exposure to flooding that is removed by the presence of coastal defences is calculated. Exposure reduction is defined in this work as the proportion of

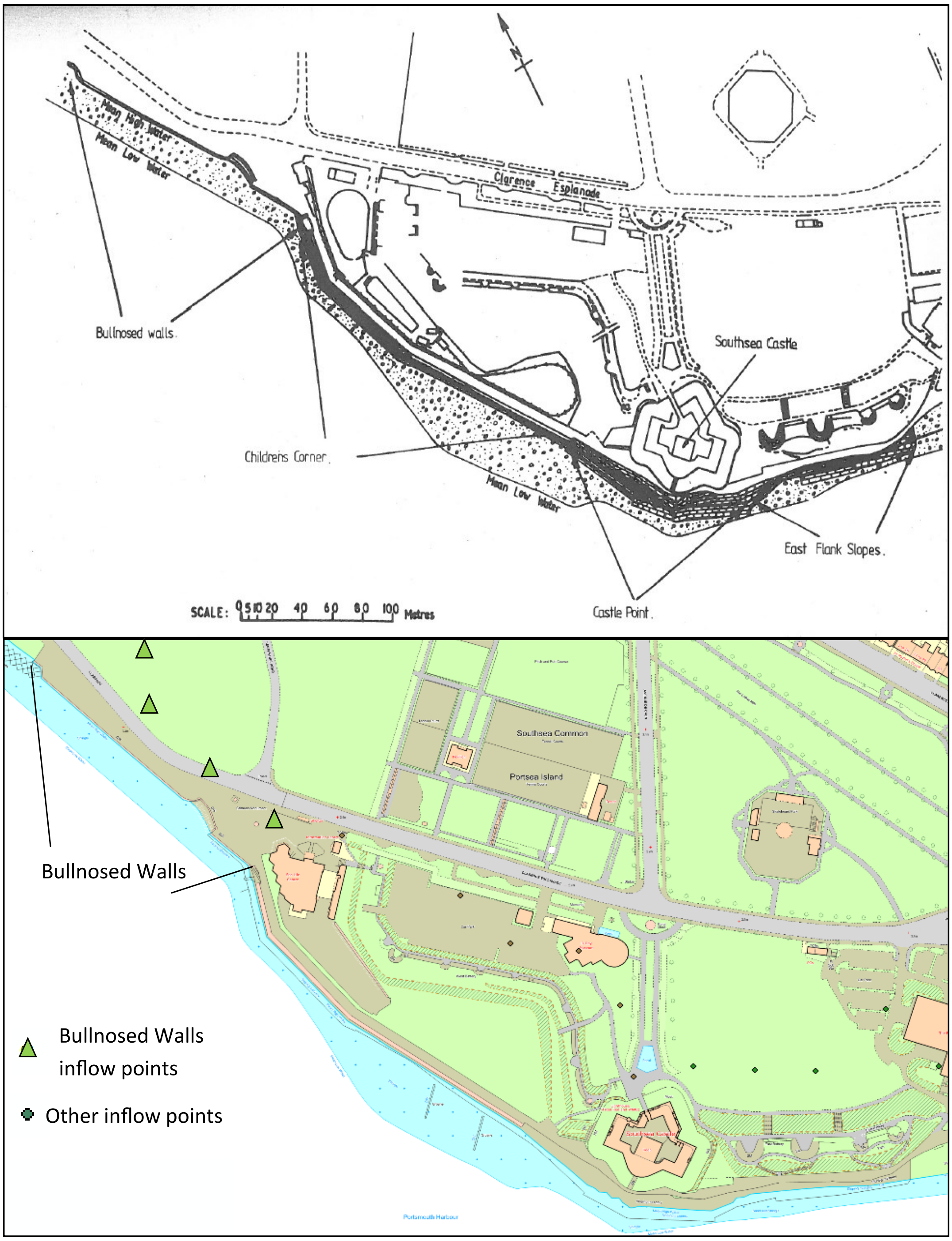

Figure 5.23: Inserting the Bullnosed walls into the GIS system (above) based on the scanned map (below) from (Easterling, 1991). Underlying map is 2012 MasterMap®. Crown Copyright/database right 2015. An Ordnance Survey/E-DINA supplied service

the *potentially* exposed population that are removed from the floodplain by the presence of defences:

$$Exposure\ Reduction_{People}\ (\%) = \frac{Exposure_{Without\ Defences} - Exposure_{With\ Defences}}{Exposure_{Without\ Defences}} \tag{5.4}$$

Exposure with and without defences are measured as the number of people exposed to a range of recurrence interval flood events; the primary metric used is annual average people exposure. Most of the modern day defences in Portsea are designed to a 1 in 200 year standard of protection (SoP); however notably some have a SoP less than this standard and so some exposure will occur for smaller recurrence intervals. Hence this measure of people exposure reduction is a way of evaluating the effectiveness of defences in reducing coastal flood exposure. Results of the analysis are presented for the period 1961-2011, where defence data exists. Defences are known to have existed before the 1960s, however there cannot be confidence in extending the analysis as there is not a consistent record of defence crest heights present before this time.

5.3.2 Model Results: Exposure With Defences for a range of Recurrence Intervals

Variable	Value	Rationale
Sea level rise	1.21 mm / yr	Mean rate of sea level change (Haigh et al., 2011)
Recurrence interval	1 in 1, 10, 20, 50, 100, 200, 1000	A range of RI used to calculate the annual average exposure of people
Tidal cycles	1 cycle (12 hours inflow)	Used in previous study (Wadey et al., 2012; Wadey, 2013)
Population method	B - Residential Distribution	Best available method (see Appendix D)
Defences	Observed Defence heights	Defence heights from historic datasets (Wadey et al., 2012; Easterling, 1991) to evaluate exposure with defences

Table 5.10: Model variables used for the Portsea with defences model

The estimated number of people exposed to flooding in Portsea for a range of recurrence intervals are shown in Table 5.11. The exposure with defences to the annual expected flood (RI = 1 year) is zero until 2011 when around 300 people become exposed. For the other small to intermediate flood events (RI = 10:100 years) the exposure reduces between 1961 and 1981, which reflects a reduction in overall population in Portsea, and then increases from 1981 to 2001, and then drops between 2001 and 2011. For the most extreme events (RI = 200-1000 years) exposure follows the same trend but increases between 2001 and 2011. These results reflect the interaction between coastal development in this time period and improvement of defences between 1961 and 2011, particularly improvements between 2001 and 2011 to low to medium return period events. A potential limitation of the method is that the 50m resolution of the model may miss localised defences or raised elevation of new developments, which is discussed later.

From the exposure values to RI 1:1000 years an annual average people exposure was calculated as in Section 5.2.2. The annual average people exposure with defences for Portsea is shown in Figure 5.24; the annual average people exposure without defences is displayed for comparison.

The people exposure with defences decreased from a value of 592 people in 1961 to 451 people in 1991, increasing to 1,027 in 2011 (an increase of 128%). The exposure

Census Year	Number of people exposed/Recurrence Interval (1 in x years)						
	1	10	20	50	100	200	1000
1961	0	907	1,323	2,381	3,893	4,573	5,669
1971	0	695	1,182	2,051	2,990	3,511	4,380
1981	0	681	1,114	2,011	2,753	3,124	3,898
1991	0	1,812	2,447	4,198	5,014	5,618	6,403
2001	0	2,139	2,830	4,837	5,660	6,219	7,206
2011	286	1,356	2,035	3,605	5,890	6,996	12,600

Table 5.11: Number of people exposed to flooding (1961-2011) in Portsea for a range of recurrence intervals (exposure with defences, 1.22mm/yr sea level rise rate applied)

increased between 1991 and 2001, and decreased between 2001 and 2011, which reflects improvements in defences over this period. The average annual people exposure with defences is significantly lower than the exposure without defences with an average reduction of 81%. This is higher than the reduction for the 1 in 200 year event (65%, see Appendix F) which demonstrates that the defences in Portsea significantly remove exposure to smaller events. The apparent reduction in effectiveness of defences between 1981 (86%) and 1991 (74%) is likely a product of the rise in population during this time; annual average exposure with defences rose by 750 and exposure without defences rose by 1,200 which suggests that the majority of development was within the unprotected floodplain during this period.

The overall increase in annual average exposure shows that despite improvements to defences over this period, the combined effects of rising population, location of residential development within the floodplain and rising sea levels have driven a modest increase in the exposure with defences to coastal flooding in Portsea. Whilst the reduction in exposure with defences between 2001 and 2011, and the increase in defence effectiveness during this time (an increase of 10% from 75% in 2001 to 85% in 2011) does show that recent improvements in defences have kept up with rising populations and coastal development; the high annual average exposure as measured without defences (6,900 people) demonstrates the potentially significant impacts should defences fail.

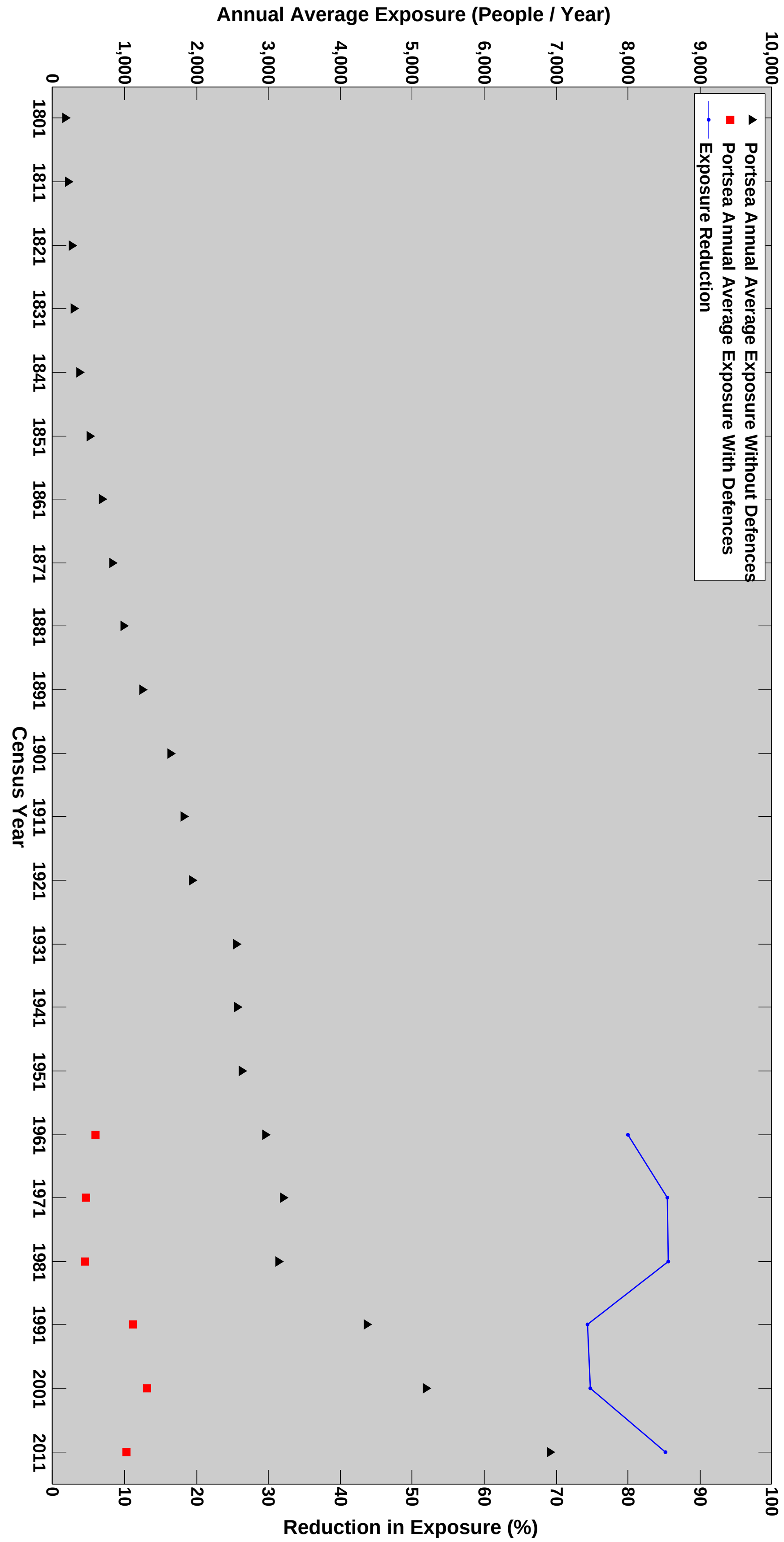

Figure 5.24: Annual Average Exposure of people to flooding in Portsea, with and without defences, 1801-2011 (1.22 mm/yr sea level change rate applied)

5.3.3 Discussion

An important assumption in calculating exposure with defences in this work is that defences do not fail. However the restoration and rebuilding of sections of Portsea's sea defences in the 1970s and 1990s (Easterling, 1991) is evidence that defences either had failed, or there was a risk of failure. This suggests that calculation of exposure with defences may underestimate the actual exposure present. This does demonstrate the strength of the method in calculating both exposure with and exposure without defences. Exposure without defences gives a 'maximum' potential exposure, and exposure with defences gives a 'minimum' exposure with all defences performing as expected (with the important caveat in both cases that the actual storm event is equivalent to the idealised design event modelled here). Hence between the two calculations the 'exposure range' is calculated. With further information on probability of defence failure this information could be used as a foundation for the study of risk - this is explored in Section 8.2.2.

The merit of the exposure without defences analysis is that the effect of the defences can be quantified, as the Environment Agency is beginning to do with each flood event that is experienced (i.e. highlighting the numbers protected as opposed to the numbers flooded).

Partial validation of these results is possible by comparison with the Portsea Strategy Approval Report (STAR) (Portsmouth City Council and EA, 2011). The report calculated the number of residential properties at risk of flooding in 2009 for a range of recurrence intervals. The Portsea STAR results are based upon an assumption of partial defence failure (both breach and overtopping) and so should be within the with/without defences exposure range. Using average occupancy rates the number of residential properties from the Portsea report is converted to an estimate of the population at risk of flooding which is comparable to the results from the 2001 and 2011 time steps in this work (Table 5.12). The comparison shows that for all recurrence intervals compared the Portsea STAR results are between the range of exposure with and without defences. This validates the recurrence intervals compared for the most recent time steps (2001 and 2011); validation of the historic results and for the whole range of recurrence intervals modelled is not possible.

In their work on flood exposure in the Solent Wadey (2013) also evaluated scenarios with and without defences. They used the number of buildings exposed as the metric of exposure and estimate that 1,110 buildings are exposed to the 1 in 200 year floodplain in Portsea in the current day (equivalent to the 2011 time step in this work) when accounting for defences (assuming no waves, as for this work). When a scenario is considered equivalent to the no defences scenario here they estimate the exposure at 8,099 buildings. Therefore we can estimate the percentage reduction in building exposure due to defences from Wadey's work. This is comparable to the percentage of people removed

	Population Exposed				
Recurrence Interval	Portsea Study (2009)*	With Defences (2001)	Without Defences (2001)	With Defences (2011)	Without Defences (2011)
1:200	9,896	6,219	16,946	6,996	19,811
1:75	8,942	5,248^{+}	13,359^{+}	4,747^{+}	16,116^{+}
1:20	4,124	2,830	8,950	2,035	11,351

*Calculated using an assumed household occupancy rate of 2.35 which is an average of the 2001 and 2011 censuses (ONS, 2012a).

$^{+}$ The 1:75 values are averaged from results for the 1:50 and 1:100 year recurrence intervals modelled in this work and are only indicative

Table 5.12: Comparison of population exposed with results from the Portsea Strategy Approval Report (Portsmouth City Council and EA, 2011)

from the floodplain by the presence of defences as calculated in this work. Using equation 5.4, the exposure reduction can be calculated:

$$Exposure\ Reduction_{Buildings}\ (\%) = \frac{Exposure_{Without\ Defences} - Exposure_{With\ Defences}}{Exposure_{Without\ Defences}}$$

$$Exposure\ Reduction_{Buildings}\ (\%) = \frac{8,099 - 1,110}{8,099} = 86.3\%$$

This value is close to the exposure reduction calculated here (85% for the 2011 time step) - however Wadey (2013) only considered the 1:200 event whereas in this work a range of recurrence intervals were modelled. The exposure reduction for the 1:200 event alone is this work is calculated as 65% (see Appendix F). This is of the same order of magnitude as Wadey's results which gives confidence in the analysis. The percentages are likely to differ because using Wadey (2013)'s results to model population assumes a uniform occupancy rate across all buildings whereas in this analysis population is constrained to residential areas only. Unfortunately there are not currently comparable results to fully validate the annual average people exposure results at the local level. The collection of flood event data (namely number of people affected, an estimate of the return period of the event, and the extent of the floodplain) could be used for further validation of the results, and this is a key recommendation of this work.

Portsea's main coastal defences were digitised and used within the flood model to calculate exposure with defences (Section 5.3.1). However the 50m resolution of the model may miss localised defences around new development, such as clay bunds or soak-away/drainage systems, and does not account for property level protection measures which may prevent water ingress into properties. Modern building codes state that new development in flood risk zones should be resilient and not increase flood risk elsewhere (e.g. PPS25, National Planning Policy Framework, CIRIA guidance): which means that properties may not be damaged by flood events which they are exposed to. However, if streets are flooded then the population within residential properties will still be negatively affected by the event, and hence it is still reasonable to consider them 'exposed', even if there is no significant damage to the property itself. The estimation of flood extent may be improved by higher resolution flood modelling, however this requires high resolution input data which is lacking for historic study.

5.3.4 Summary and Conclusions

The evolution of exposure with defences in Portsea has been evaluated from 1961-2011. The work has shown the following:

- Historic defences can be quantified using available data in Portsea
- Defences have reduced the annual expected people exposure (averaged across all modelled recurrence intervals) by an average of 81% between 1961 and 2011
- The magnitude of exposure reduction calculated is similar to previous studies at both local and national scales

A dataset of flood defence heights in the recent history of Portsea was created (1961-2011). It is likely that similar datasets could be created from local authority data across the UK and hence the methodology can be repeated across the UK. The historic dataset was low resolution (17 unique heights for the Portsea coastline) and this is a potential limitation of the study. It highlights the need for recording of high resolution defence data in order to improve estimates of exposure with defences for future work.

The presence of defences in Portsea reduces the potential exposure of the coastal population across a range of recurrence intervals by an average of 81%. This shows the moderating effect that structural intervention can have on flood exposure. However this is under the assumption that defences do not fail which is not always valid, especially for historic study (for instance the 1951 north sea surge caused the failure of several defences across the East coast of England). It is important to know the potential range in exposure, between a totally undefended floodplain (exposure without defences) and a defended floodplain (exposure with defences).

The exposure values for the most recent time steps (2001 and 2011) are consistent with previous estimates (Portsmouth City Council and EA, 2011), and the magnitude of the exposure reduction calculated using this methodology is similar to that of a previous study on the area (Wadey, 2013). This gives strength to the reliability of the method, however further validation would be useful.

These results have implications for management elsewhere in the UK, especially densely populated coastal areas such as Portsea. They demonstrate that evaluation of exposure both with and without defences are essential to estimate the potential range in exposure and calculate the effectiveness of defences in reducing exposure to flooding. Evaluating the *evolution* of exposure gives a longer term view and can be used to compare historic defences to existing or planned sea defence changes.

5.4 Chapter 5 Summary & Conclusions

This chapter has presented a method for evaluating the evolution of exposure to tidal flooding of a coastal population. The method was applied to two case studies in the Solent region of the UK: Portsea, a highly developed urban area, and Hayling, a sparsely populated rural area. The population distribution was recreated using census population data and historical maps. Time series and extrapolated sea level data was then used to force an inundation model to recreate the historic floodplain. Population and floodplain layers were created at 10 year time-steps from 1801-2011. The two layers were overlain to estimate the exposure of the coastal population to flooding without defences (Section 5.2). This exposure model was combined with defence data from 1961-2011 in order to evaluate exposure with defences (Section 5.3). However this presents significant challenges for historical analyses, as we found that information on flood defences at Portsea before circa 1960 is poorly recorded, and high quality data for high resolution flood modelling is not available historically. This emphasises the importance of documenting defences and vulnerability characteristics over time, such as seen in the UK's Strategic Regional Coastal Monitoring Programme[1] and recent advances in asset inspection methodologies (this will be discussed further in Chapter 8).
The method developed could be applied elsewhere in the UK, or in the world where population and hydrological data exists. The work has demonstrated that:

- The evolution of exposure without defences to coastal flooding can be estimated over a 200 year period, and exposure with defences where defence data is known (a 50 year period for Portsea)
- Exposure to flooding has increased from a value of 176 people per year in 1801 to 6,911 in 2011 in Portsea, and 27 people per year in 1801 to 692 in 2011 in Hayling, due to a combination of rising sea levels, population and residential development in the coastal area
- In Portsea the exposure calculated with defences has increased from a value of 592 people per year in 1961 to 1,030 in 2011. Defences have reduced exposure of population to flooding by an average of 81% across the range of flood events modelled

[1] http://www.channelcoast.org/

The conclusions of this research support analysis of AAD in England and Wales which shows that damages have been steadily increasing over the last 10-15 years (e.g. Penning-Rowsell et al., 2006b; Penning-Rowsell, 2013; Evans et al., 2004). Unfortunately data does not exist on AAD over the 200 year timescale considered in this thesis so long term trends cannot be compared.

The result of the analysis with defences showed that defences have significantly moderated the exposure to flooding in Portsea. How flooding is managed in the future will have implications for how future flood exposure and hence risk evolves. Allowing defences to degrade, or keeping them at current levels, is likely to lead to a large increase in flood exposure by the end of the 21st century. A large £44 million investment in defences in the Portsea case study was recently announced (Dredging Today, 2015) which highlights the degree of flood risk in this case study, and the importance of good quality research to inform flood managers as they make decisions.

The exposure without defences in Hayling over the last 10-20 years is similar to the exposure with defences in Portsea. The trends suggest that within 10-20 years the exposure in Hayling may become higher than the exposure with defences in Portsea, and more structural defences may be required in Hayling. This finding appears to be supported by recent completion of a defence scheme in Hayling (Havant Borough Council, 2013).

These outputs contribute towards increased understanding of exposure in the coastal environment. However this work has not yet identified whether it is changes in population size and location or changes in extreme sea levels that have the biggest influence on the calculated exposed population. The next stage of the work is to *quantitatively* attribute the exposure to these underlying drivers of change: this analysis is undertaken in the following chapter.

Chapter 6

Attribution of Flood Exposure Drivers

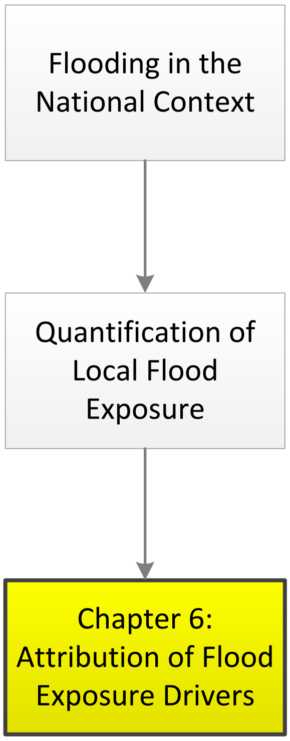

Figure 6.1: Chapter 6 within the general research design

(Note: Material based on the work presented in this chapter was published in (Stevens et al., 2015))

6.1 Introduction

The aim of this chapter is to examine an important gap in the attribution of flood exposure to its underlying drivers (Objective 3). Attribution is the act of identifying the underlying factors behind some phenomenon, for instance attributing rising global temperatures to anthropogenic greenhouse gas emissions. Attribution gives quantitative information on what has *caused* observed changes in the factor under consideration. Quantifying the effect that physical drivers (sea level change), and socio-economic drivers (population size, residential area) have on exposure to flooding increases the knowledge base on how exposure has evolved, providing a reality check for scenarios of future change. This will be achieved in two stages:

- Attribution of the observed change in exposure to its underlying drivers
- Determination of the relative exposure from socio-economic (human) versus physical (environmental) drivers

The current understanding of flood exposure attribution is poor and generally based on qualitative reasoning or speculation (Merz et al., 2012). Computational scenario modelling is used here to give a unique insight into the issue of attribution by its ability to be (a) *deterministic* - i.e. cause and effect and (b) *focused* - the ability to 'turn off' external drivers such as sea level or population changes to look directly at the effect each individual driver has on the exposure to flooding.
This is an important advance in flood science and especially useful for flood managers seeking to learn from the past. The quantitative model developed in Chapter 5 is used to give insight into the relative effects of each of these drivers on coastal flood exposure. These results can be used to inform decision making for the management of exposure.

6.2 Methodology

Drivers of flood exposure include Sea Level Rise, Precipitation, Surges and Waves, Coastal Morphology, Population Size, Development/Urbanisation, Land Use Change, Stakeholder Behaviour and Demography. In Chapter 3 the application of each driver to coastal flooding was discussed and from this list three drivers were identified to be modelled in this work:

- Sea Level Rise - change in relative sea level
- Population - the size of the coastal population
- Residential Development - the location of the coastal population

Historic data to quantify these drivers is available in approximately 20 year time-steps in the Portsea and Hayling case study areas (Figure 6.2). The modelling system from Chapter 5 (which calculates annual average people exposure from a range of recurrence intervals) is run for this data in the 20 year time-steps. Each driver in turn is "turned off" by keeping it constant between time steps. For instance a model run using the 1870 population, 1870 residential development location and the 1870 sea level is compared to a model run using the 1870 population, 1870 residential location and 1890 sea level. This information allows exposure to flooding to be evaluated both *with* and *without* each driver considered. We can then attribute the change in exposure to these underlying drivers and evaluate their relative importance.

Attribution is carried out on exposure without defences so that (a) The attribution of exposure in Portsea and Hayling can be compared and (b) attribution can be carried out over the 200 year timescale. The effect of defences on flood exposure was assessed in Chapter 5. A full historic attribution is not possible because the probability of defence failure, and the presence and characteristics of defences are not known over the 200 year timescale. This is acknowledged as a limitation of this work.

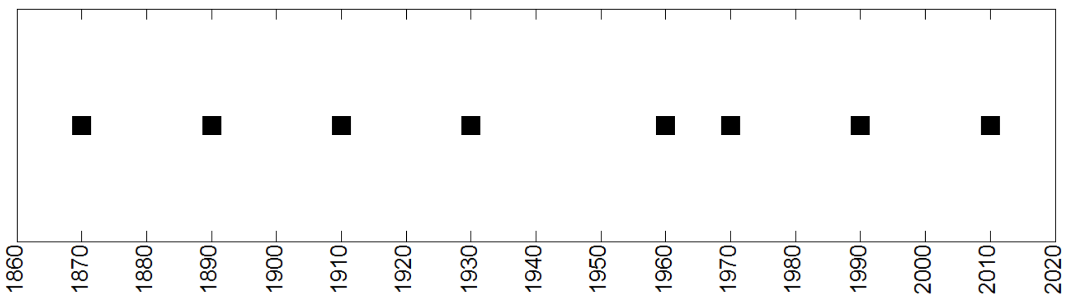

Figure 6.2: Time-steps where data for flood exposure attribution is available for Portsea and Hayling, based on the dates of historic maps

6.2.1 Fraction of Attributable Exposure

The method of attribution used here stems from the Fraction of Attributable Risk (FAR) approach - a measure which has its roots in epidemiology (Levin, 1953). The Fraction of Attributable Risk is defined in epidemiology as the difference in disease rate between an exposed and an unexposed population (Coggon et al., 2003). "Exposure" in this context is an environmental factor that affects the chance of infection by the disease. FAR has been used in the literature to attribute the risk resulting from climate driven events to human induced climate change (e.g. Jaeger et al., 2008; Stott et al., 2004). In this work it is translated to the context of flood exposure. FAR is used instead of statistical methods because it offers a simple, repeatable methodology that can be used with the available data to attribute exposure for a given case study. The benefits of FAR are discussed in Section 3.2.3.

The FAR approach can be used in this study of exposure by considering the probability of exposure to flooding in a population exposed to some driver (e.g. population change, sea level rise) as opposed to a population not exposed to that driver. For clarity the term Fraction of Attributable Exposure (FAE) is used as this work evaluates exposure, not risk.

Considering a single driver denoted i at time t:

$$FAE(i)_t = P(driver_i)_t - P(no - driver)_t \tag{6.1}$$

Where:
$FAE(i)_t$ = Fraction of exposure attributable to driver i at time t
$P(driver_i)_t$ = Probability of flooding at time t when driver i considered
$P(no - driver)_t$ = Probability of flooding at time t when driver i not considered

The FAE can be expressed as a percentage by dividing by the exposed probability - i.e. in this case $P(driver_i)$. In this work we have considered the population exposed to a flood event of known probability. We are dealing therefore with **absolute** populations - rather than the probability that an individual will be exposed to flooding. For simplicity we use the notation FAE interchangeably as either a fraction or a probability. This makes our equation:

$$FAE(i)_t = \frac{E(driver_i)_t - E(baseline)_t}{E(driver_i)_t} \tag{6.2}$$

Where:
$E(driver_i)_t$ = Population exposed to given flood event at time t when driver i considered
$E(baseline)_t$ = Population exposed to given flood event at time t when driver i not considered

Using the calculated FAE for each driver the relative importance of each driver can be estimated. This is done using the measure of relative exposure - where the sum of each drivers FAE is equal to 100%. This measure allows easier interpretation of the relative importance of each driver through time.

For the general case with n different drivers at time-step t the relative exposure (RE) for driver i can be expressed as:

$$RE(i)_t = \frac{FAE(i)_t}{\sum_{a=i}^{n} FAE(a)_t} \tag{6.3}$$

Where:
$RE(i)_t$ = Relative Exposure from driver i at time t
$FAE(a)_t$ = Fraction of Attributable Exposure for each case

In this work we considering three drivers; sea level rise, population and residential development. Hence the relative exposure of each driver is equal to the FAE of that driver divided by the sum of all three added together. For example in the case of Population in 2011 the RE is calculated as thus:

$$\frac{FAE(Pop.)_{2011}}{FAE(SLR)_{2011} + FAE(Pop.)_{2011} + FAE(Res.\,Dev.)_{2011}} \tag{6.4}$$

Where:
$FAE(Pop.)_{2011}$ = Fraction of Attributable Exposure due to Population in 2011
$FAE(SLR)_{2011}$ = Fraction of Attributable Exposure due to Sea Level Rise in 2011
$FAE(Res.Dev.)_{2011}$ = Fraction of Attributable Exposure due to Residential Development in 2011

Historic data to characterise each driver (Sea Level Rise, Population and Residential Development) was collated as part of the methodology in Chapter 5. We can use this data to keep one or more drivers as variables, and make the others constant (i.e. fixed in time) in order to quantify the effect of a single driver. For instance we can run a model using the 1891 population and residential development distribution, but use the 1871 sea level. This will tell us the effect on exposure if sea levels had not risen historically over that 20 year period. Similarly we could run a model for the 2011 sea level and residential development distribution, and the 1991 population. We can then run the same model but consider the 2011 population (change over a 20 year period). By fixing each driver in time (or fixing two drivers and keeping one as a variable) we can quantify the relative effects of each driver.
Hence the FAE calculation is carried out for each flood exposure driver at the time steps shown in Figure 6.2, for the Portsea and the Hayling case studies. The change is exposure for each period is attributed to the underlying drivers, presented in the following section. The analysis is ran for the **annual average people exposure**, calculated from the 1 in 1, 1 in 10, 1 in 20, 1 in 50, 1 in 100, 1 in 200 and 1 in 1000 year recurrence intervals.

6.3 Attribution of Annual Average Flood Exposure: Results for Portsea and Hayling

Variable	Value	Rationale
Sea level rise	1.21 mm / yr	Mean rate of sea level change (Haigh et al., 2011)
Recurrence interval	1 in 1, 10, 20, 50, 100, 200, 1000 years	Range of RI used to calculate the annual average exposure of people
Tidal cycles	1 cycle (12 hours inflow)	Used in previous study (Wadey et al., 2012; Wadey, 2013)
Population method	B - Residential Development	Highest resolution method available (see Appendix D)
Defences	None (exposure without defences)	Allows Hayling and Portsea to be compared using the same method and over the same timescale

Table 6.1: Model variables used for the results of the Attribution model

The quantitative model from Chapter 5 was ran for four cases for Portsea and Hayling between 1871 and 2011:

- All Drivers (as in Chapter 5)
- Sea Level Rise turned off
- Population the only turned off
- Residential Area only turned off

The change in exposure as a result of each driver is calculated by deducting the exposure with that driver "turned off" from the all drivers case (the best estimate of actual exposure as presented in Chapter 5). This gives the change in exposed population as a result of each individual driver. A positive change in population exposed denotes that changes in the driver contributed towards increased exposure, a negative change denotes that the driver contributed towards decreasing the exposure (for instance in years where the total population in Portsea dropped). The following outputs were produced:

- The absolute change in population exposed for each case. The attribution method is applied to the annual average people exposure which gives a broader quantification of exposure as opposed to a single recurrence interval.
- The Fraction of Attributable Exposure (FAE) for each case. This quantifies the effect that each individual driver has on changes in exposure. It can be used to compare the effect of each driver across different regions.
- The Relative Exposure (RE) from each driver. This is calculated from the FAE as described previously. It is designed to facilitate an easier comparison between different drivers.

6.3.1 Attribution Results for the Urban Case Study: Portsea

The change in the number of people exposed to flooding for Portsea under the influence of each driver is shown in Figure 6.3. The figures presented are for the **annual average people exposure** as described in Chapter 5. This is a measure of exposure across a range of recurrence intervals from the 1 in 1 year to the 1 in 1000 year flood events. Results are presented for the 1 in 200 year flood event (the 'industry standard' used in UK FRM) in Appendix F. The final results for Relative Exposure are presented for each individual recurrence interval for comparison (see Table 6.2).

The change in exposure as a result of sea level rise in Portsea is lowest at the start of the record (an increase of 150 people 1871-1891) and highest towards the later timesteps (1971-1991 changes are +550 and 1991-2011 changes are +600). Changes in exposure due to sea level rise between 1971 and 2011 are increasing; this is likely as Portsea was highly developed by this point in time and so as the coastal floodplain increases in size (due to higher sea levels) an increasing number of people become exposed to flooding (rather than green space or non residential land providing a buffer to rising seas).

The change in exposure due to population size has a degree of variability as the population of Portsea changes both positively and negatively; whilst the long term trend is increasing their is decadal variability such as the reduction in population between 1931 and 1991. This is reflected in the calculated exposure. At the start of the record there is an increase in exposure between 1871-1891 (+400) and 1891-1911 (+550). There is a large decrease in exposure due to population 1931-1961 (-550) and a large increase 1991-2011 (+1,200). The negative changes are caused by the reduction in the total population of Portsea observed between 1931 and 1991.

The change in exposure due to residential development is variable which is due to the sporadic nature of housing construction (i.e. see Figure 5.13 in Chapter 5 which shows changes in development patterns over time). Large increases in development are reflected in large positive changes in exposure between 1971-1991 and 1991-2011 (both approx. +950). There are decreases in exposure as a result of the residential development driver between 1871-1891 (-162) and 1891-1911 (-501).

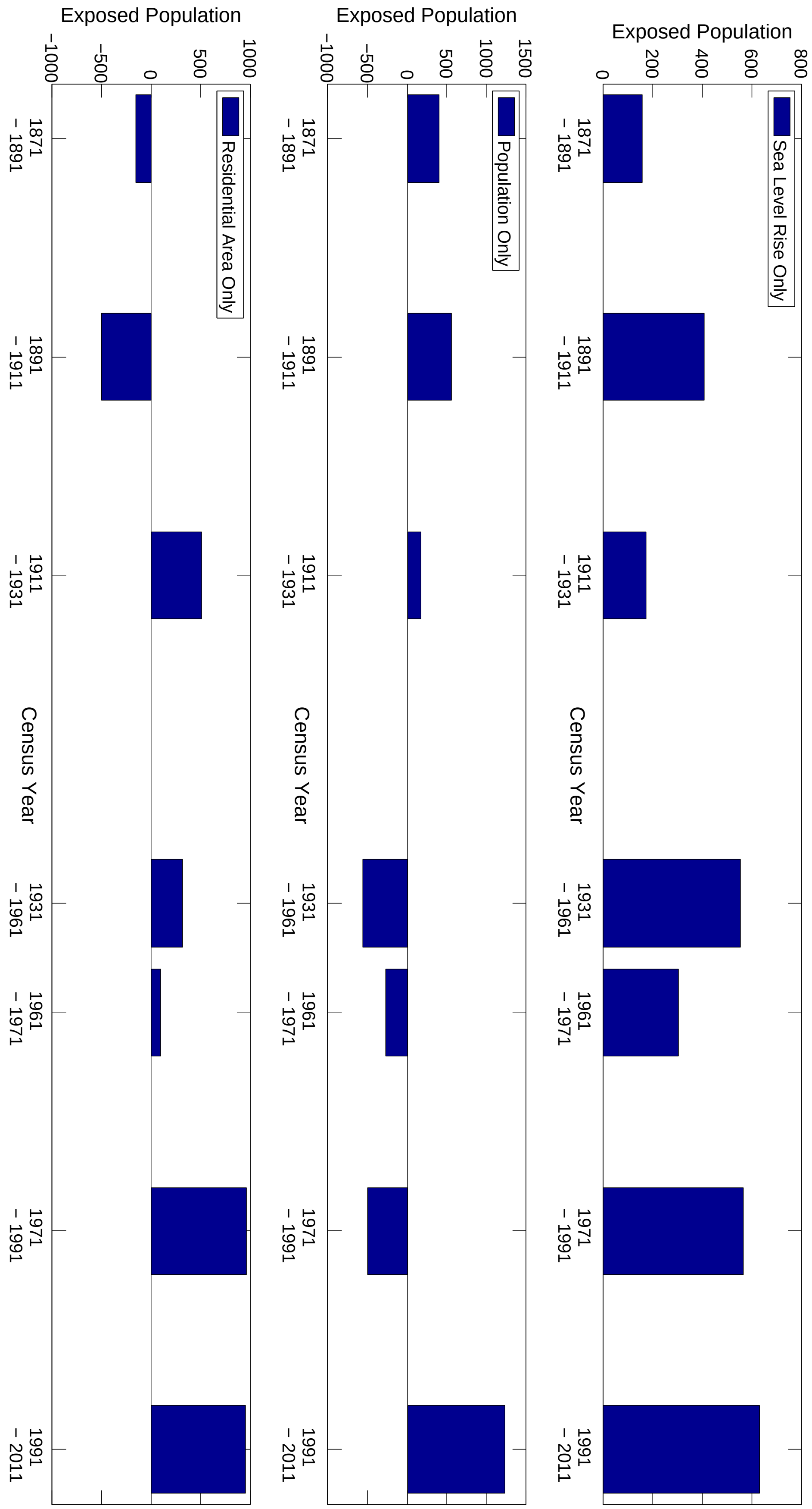

Figure 6.3: The change in annual average people exposure due to sea level rise, population and residential development in Portsea (note that the axes have different scales)

A reduction in exposure due to the residential development driver does not necessarily mean that coastal development was moved inland or abandoned during these periods; this is believed to be a function of the population spreading methodology and is discussed later.

Fraction of Attributable Exposure

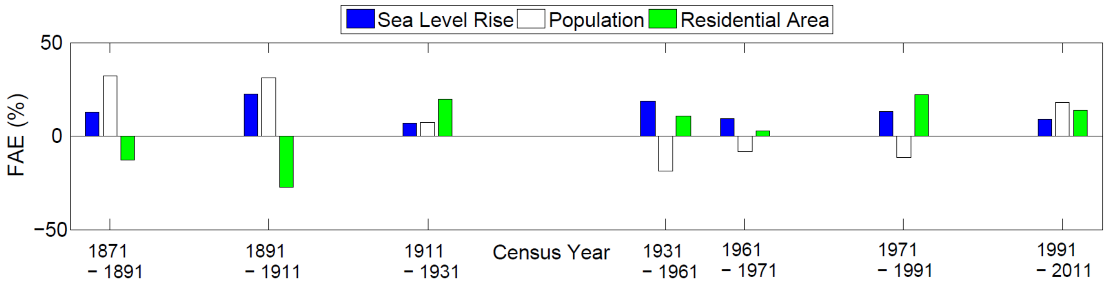

Figure 6.4: The Fraction of Attributable Exposure due to sea level rise, population and residential development, calculated for the annual average people exposure in Portsea

Sea level rise has been a relatively constant component of exposure over the last 100 years as shown in the calculated FAE (Figure 6.4). The average FAE due to sea level rise over the period 1871-2011 is 13%. The total population in Portsea has varied, with a decrease in the 1960s-1990s but has grown post 2001 and this is reflected in the FAE. The highest FAE for population is in the periods 1871-1891 (32%) and 1891-1911 (31%) where total population change was highest. Pre 1931 Portsmouth was expanding and most of the development was outside of the floodplain (negative bars - Figure 6.4). Residential Development between 1911 and 1931 contributed moderately towards increased exposure to flooding (FAE of 9%) and by 1961 Portsmouth was mostly covered in development and expansion onto the floodplain increased (+ bars, highest is between 1971 and 1991 at 10%). The relatively larger contribution of Population to exposure between 1931 and 1971 (white bars), compared with the much smaller contribution of Residential Development (green bars), shows that during this period the *area* within the floodplain that was developed did not change, however the population density did increase. The FAE for Residential Development towards the end of the record is low as the pace of additional development reduced following rapid expansion in the early 20th century.

Relative Exposure

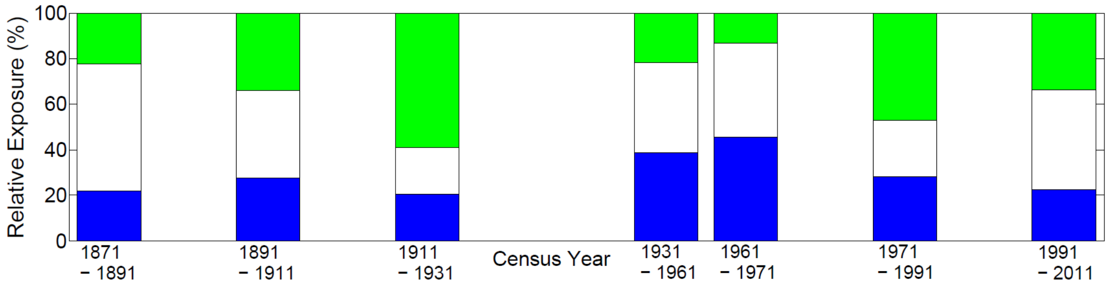

Figure 6.5: The Relative Exposure due to sea level rise, population and residential development, calculated for the annual average people exposure in Portsea

Socio-economic drivers (population and residential development) have had a larger effect on flood exposure (either positively or negatively) than physical factors (sea level rise) in every time-step (Figure 6.5).

The relative exposure from sea level rise is highest in 1961-1971 (45%); in all other time steps it accounts for less than 40% of the total changes in exposure. Large changes in population led to a higher relative effect from population size - as seen in 1871-1891 (56%), 1991-2011 (44%), and 1961-1971 (41%). The relative exposure from the residential development driver was lowest in 1961-1971 (13%), suggesting that there were only small amounts of residential development change in the floodplain during this period.

On average 38% of the change in exposure between 1871 and 2011 is a result of population size, 33% a result of residential development, and 29% a result of sea level rise. We can therefore attribute 71% of the changing exposure in Portsea to socio-economic (human) drivers of flood exposure, and 29% to physical (climate) drivers over the period 1871-2011.

The relative exposure from each individual recurrence interval, averaged across all time steps, is presented in Table 6.2. Physical drivers have been found to have a larger relative effect on exposure for smaller return period events, responsible for 33% of the changes in exposure for a 1:1 year (annual) flood event, compared to just 11% for the 1:1000 year flood event. When the changes in exposure are averaged across all recurrence interval events Sea Level Rise accounts for 29% of the changes in exposure. The Population driver accounts for a higher proportion of the exposure in the larger recurrence interval events; 59% for the 1:1000 year and 53% for the 1:200 year events, compared to 31% for the 1:1 year event and 38% for the annual average. Residential development is relatively stable across all recurrence intervals, varying between 26% and 35%, with an annual average of 33%.

Recurrence Interval (years)	Sea Level Rise (%)	Population (%)	Residential Development (%)
1:1	33	31	35
1:10	27	39	34
1:20	27	42	31
1:50	22	46	31
1:100	21	49	30
1:200	21	53	26
1:1000	11	59	29
AAE	29	38	33

Table 6.2: Attribution of Relative Exposure (%) to underlying drivers for a range of recurrence intervals in Portsea, averaged across all time steps. AAE denotes Annual Average Exposure. Note that due to rounding the percentages may not add up to 100%.

6.3.2 Attribution Results for the Rural Case Study: Hayling

Changes in exposure due to each driver for Hayling are presented in Figure 6.6. The values are approximately an order of magnitude lower than those in Portsea, due to Hayling's smaller population. The changes in exposure due to sea level rise are negligible in the late 19th and early 20th centuries. This is due to early development being located away from the coastal floodplain and so the population was not susceptible to modest rises in sea level. The change in exposure from rising seas is more pronounced from 1931 onwards due to an increasingly developed coastline in Hayling. However throughout the record the sea level driver only increases exposure by less than 75 people between each time step (average 20 year time step).

The change in exposure due to the population driver is small through the start of the record, reaching a peak in 1931-1961 when the population exposed increased by 250 people; this time step is larger (30 years compared to 10-20 years) however the changes are still larger per year than the other time steps considered. The changes in consecutive decades are smaller in magnitude and relatively stable through time accounting for around 60-70 people each time-step. This demonstrates that population growth in Hayling has mostly been outside of the floodplain.

The change in exposure due to residential development are negative between 1871-1891 (-31) 1891-1911 (-50) and 1961-1971 (-55), suggesting that the majority of development was outside of the coastal floodplain during these times.

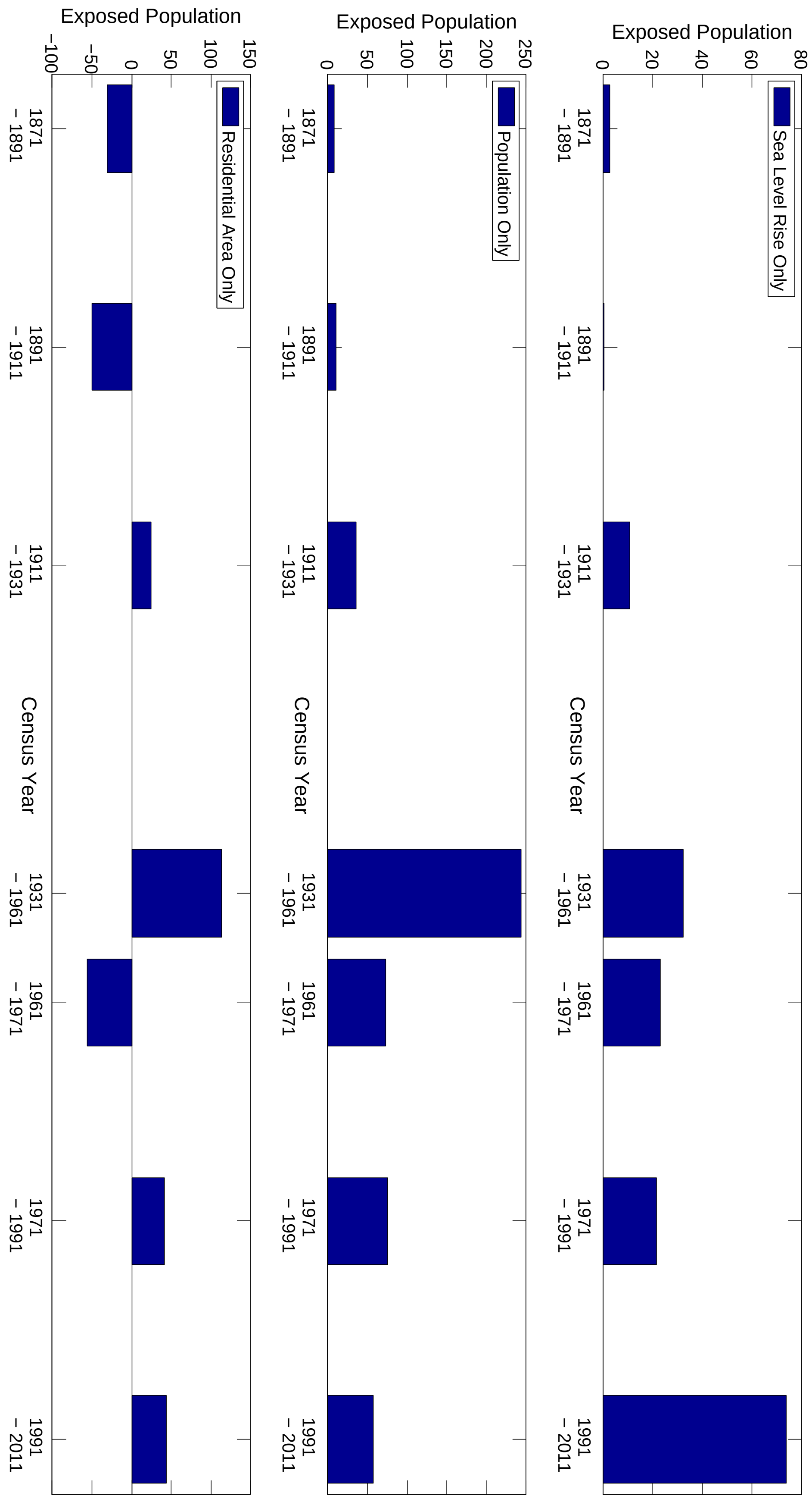

Figure 6.6: The change in annual average people exposure due to sea level rise, population and residential development in Hayling (note that the axes have different scales)

Between 1931-1961 the change in exposure is the highest in the record (+100) which suggests encroachment of residential areas into the floodplain during post war development. This correlates with the rise in exposure due to the population driver during 1931-1961. The change in exposure due to development post 1961 is variable and of a smaller magnitude which suggests only modest development within the coastal floodplain tool place during this time period.

Fraction of Attributable Exposure

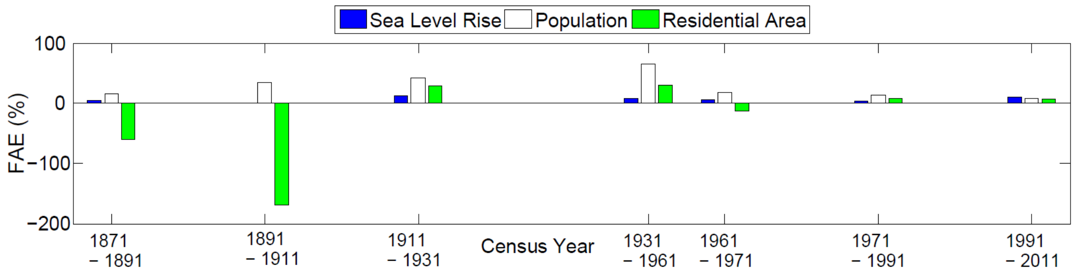

Figure 6.7: The Fraction of Attributable Exposure due to sea level rise, population and residential development, calculated for the annual average people exposure in Hayling

In Hayling sea level rise has been a relatively small and constant component of exposure (Figure 6.7) with an average FAE of 7%. This shows that modest rises in sea level between 1871 and 2011 did not have a big effect on Hayling's floodplain population. The FAE for the population driver is significantly higher. Between the late 1800s and the 1960s population became an increasingly important driver of exposure - accounting for over half of the changes in exposure 1931-1961 (64%). The magnitude reduces in later time-steps as the total population stabilised.

The FAE from residential development is variable as a result of development both within and outside of the floodplain. The FAE for residential development is negative between 1871-1891 (-60%) and 1891-1911 (-169%) which suggests that the majority of development was outside of the coastal floodplain during this period. Development has the largest positive effect on exposure in 1931-1961 (30%) and 191-1931 (29%). During this time urban expansion on Hayling led development onto the coastal floodplain. Increases in population density on the island are evident from the large contribution of Population throughout the record.

Relative Exposure

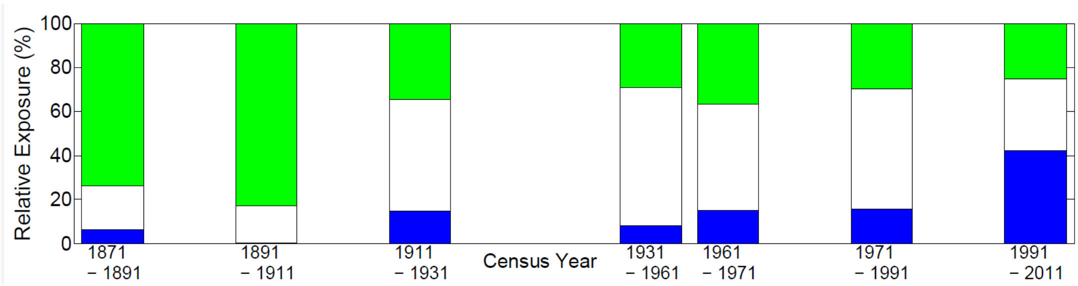

Figure 6.8: The Relative Exposure due to sea level rise, population and residential development, calculated for the annual average people exposure in Hayling

The relative exposure from socio-economic (human) drivers at Hayling is high throughout the record and accounts for almost the entirety of the change in exposure observed (85%, with sea level rise explaining the balance, see Figure 6.8). The effect of physical drivers (sea level rise) are almost negligible until the 1900s when the relative exposure increases. The relative exposure from sea level rise is highest in 1991-2011 (42%). This is a combination of the reduced rate of population rise and development reducing the relative effect of human drivers, and an increasingly large coastal population driving the exposure from floodplain expansion due to sea level rise.
On average 41% of the change in exposure between 1871 and 2011 is a result of population size, 44.5% a result of residential area, and 14.5% a result of sea level rise. We can therefore attribute 85.5% of the changing exposure in Hayling to socio-economic (human) drivers of flood exposure, and 14.5% to physical (climate) drivers.

The relative risk from each individual recurrence interval, averaged across all time steps, is presented in Table 6.2. As in Portsea, physical drivers have a larger relative effect on exposure for smaller return period events in Hayling, responsible for 21% of the change in exposure for a 1:1 year (annual) flood event, compared to just 9% for the 1:1000 year flood event. When changes in exposure are averaged across all recurrence interval events Sea Level Rise accounts for 15% of the changes in exposure. The Population driver accounts for a higher proportion of the exposure in the larger and medium recurrence interval events; 65% for the 1:1000 year and approximately 50% for the 1:50, 100 and 200 year events. The annual average is higher than Portsea at 41%. Similarly to Portsea the residential development driver is relatively stable across all recurrence intervals, with a value of 44.5% for the the annual average people exposure. However the value for the 1:1000 year event is lower at 26%, suggesting that for the most extreme events changes in population size and sea level rise have a larger relative effect than development on Hayling, compared to the smaller recurrence interval events.

Recurrence Interval (years)	Sea Level Rise	Population	Residential Development
1:1	21	39	39
1:10	13	41	46
1:20	12	46	43
1:50	11	51	38
1:100	11	52	37
1:200	8	53	39
1:1000	9	65	26
AAE	15	41	45

Table 6.3: Attribution of Relative Exposure (%) to underlying drivers for a range of recurrence intervals in Hayling. AAE denotes Annual Average Exposure. Note that due to rounding the percentages may not add up to 100%.

Attribution Summary

This analysis has shown that in both Portsea and Hayling the relative exposure (measured as annual average people exposure) as a result of socio-economic drivers (i.e. population size and residential area) is higher compared to physical drivers (i.e. sea level rise), accounting for 71% and 85.5% of the changes in exposure in Portsea and Hayling respectively. When calculated for each individual recurrence interval the smaller recurrence intervals (1:1 year) were found have a higher relative exposure from physical drivers (accounting for a third of the exposure in Portsea and a fifth in Hayling), whereas for the more extreme events socio-economic drivers are even more important (accounting for approximately 90% of the exposure to the 1:1000 year event in both Portsea and Hayling).

Whilst in Portsea the influence of sea level rise appears to be relatively stable in time, in Hayling it is increasing with time (especially as development encroaches closer to coastal floodplain areas) and so the risks posed by climate change cannot be ignored. These findings show that a holistic analysis of coastal adaptation must consider both environmental and socio-economic factors.

6.4 Discussion

In both the Portsea and Hayling case studies socio-economic factors have been the dominant drivers of exposure between 1871 and 2011. The Royal Society (2014) warn that the risks from climate change can be underestimated if no account is taken of people's exposure and vulnerability. This statement is supported by the results in this chapter; between 1871 and 2011 71% of the change in exposure in Portsea and 85.5% in Hayling were attributed to socio-economic factors.
Portsea and Hayling were chosen as case studies as they represent typical UK coastal sites (see Chapter 3). Portsea is a highly developed urban area with a large presence of hard (structural) sea defences. Hayling is a less well developed rural area with little in the way of structural sea defences, although some beach management does take place including a new scheme in 2013 (Havant Borough Council, 2013). Hence the trends seen in these areas may be representative of trends in the UK at the national scale. This assertion appears to be supported by previous studies; Barredo (2009) found that in Europe flood losses are a result mainly of socio-economic factors. At the global scale increasing exposure of people and economic assets has been the major cause of long-term increases in economic losses (IPCC, 2012), and population rise and urbanisation are the greatest drivers of increased exposure of people worldwide (Hanson et al., 2011). This hypothesis could be formally tested in future work using the generic methodology described in this chapter.

A potential limitation of the method is that the approach uses a uniform distribution of population across all residential areas. If new development takes places without a corresponding rise in population then the modelled population density will decrease across all residential areas. If this development is away from the floodplain then the overall exposure modelled within the floodplain will be reduced. This limitation of the method must be accepted for historic study as there is no high resolution spatial population data available pre 1971. An apparent reduction in exposure will only occur in periods where off-floodplain development occurs, and floodplain development does not take place, and hence will correctly suggest that changes in development over these periods were not significant in increasing flood exposure. This gives confidence that the method will correctly attribute changes in exposure to the correct drivers. The implication of this is that the FAE values are only a guide, and should not be used as precise figures. Relative Exposure (i.e. the relative importance of each driver) is a better metric for reporting the attribution results, so the conclusions will only be drawn from these values.

The method presented in this chapter is designed to be generic and not specific to the case study presented. The only prerequisite of the method is the quantitative model described in Chapter 5. The quantitative model used nationally available datasets describing relative physical coastal characteristics (sea levels, tide curves), population (census data) and residential development (historic maps). These datasets are not unique to the UK; similar data is likely to exist around the developed world. Flood drivers can therefore be assessed elsewhere in the UK or the world. This ability to understand drivers tells us what factor, or combination of factors, has been responsible for the largest historic increases in exposure, and allows exposure to be consistently compared across case studies and time periods. Understanding the relative risks between areas helps to target investment (SEPA, 2015; EA, 2010) and this method can contribute towards high level analysis, which then leads to more in-depth modelling and analysis for the most exposed areas.

Whilst historic changes in sea level have been relatively small (1.22mm/yr is the average rate used in this work), future changes are expected to accelerate (Church et al., 2013; Nicholls, 2011). Hence increases in exposure due to sea level rise are likely to have a more significant impact in the future (Zsamboky et al., 2011). This work demonstrated that in Portsea and Hayling the Population driver had a much greater effect on exposure compared to Sea Level Rise historically, however as the rate of sea level change increases this could become an increasingly important driver of changes in future exposure. In densely populated areas such as the Portsea case study (which makes up the majority of the city of Portsmouth) the rate of development slows as the island becomes 'full' with no further room for development, and hence in coastal mega-cities Sea Level Rise may become relatively more important compared to Population in the future (Nicholls and Leatherman, 1995; World Bank, 2010).
The increases in exposure due to Sea Level Rise in Hayling suggests that in the future "safer" inland development will become more susceptible to flooding as sea levels increase, even in locations where coastal development has mostly been avoided in the past. Further, the large increases in FAE due to Residential Development in Hayling demonstrate the danger posed by developing the coastline in rural, relatively undeveloped locations. Unlike urban Portsea, the more rural Hayling island has a lot of room for additional development and hence Residential Development may increase exposure in the future. This is likely to be generic amongst rural coastal locations across the UK. This is a helpful finding as Hayling is mostly undefended, as is typical of rural locations at 'low' risk. Decisions on coastal management and defences may need to be taken imminently on future challenges facing such locations (Wadey et al., 2012).

A key message of this work is that increases in population and residential development have contributed towards towards the majority of the increases in exposure to flooding in Portsea and Hayling, and this may be typical of other coastal the UK. Flood exposure is likely to increase in the future as a result of climate change, population growth and urbanisation (Queensland Government, 2011), and flood defences and other management measures will need to evolve to manage future exposure. Predictions of sea level rise and hence likely lead time on flood defence improvements is improving (e.g. University of

Southampton, 2016); however this work demonstrates that there is also a need to ensure that consideration of socio-economic drivers is central to any holistic future plan.

6.5 Summary & Conclusions

This chapter has presented a method for attributing flood exposure to it's underlying drivers for an urban defended area and a rural mostly undefended area in South England. A historical analysis was undertaken with flood drivers considered separately to calculate their relative effect on exposure. This allowed the exposed population to be attributed to the underlying drivers, and the relative contribution to exposure from each driver to be assessed.

This work has demonstrated that:

- Using the FAE approach we can attribute coastal flood exposure to the underlying drivers of change (Sea Level Rise, Population and Residential Development)
- Over the last 150 years socio-economic drivers (Population, Residential Development) have had a bigger influence than physical drivers (Sea Level Rise) in Portsea and Hayling

These outcomes contribute towards an increased understanding of flood exposure and its drivers. It has been shown that for the two case studies considered, socio-economic drivers (population rise, residential development) have historically had a much larger effect on exposure compared to physical drivers (sea level rise). Due to limitations in the Fraction of Attributable Exposure (FAE) methodology and the historic datasets available is is proposed that the measure of Relative Exposure is a better metric for reporting the attribution results. There is confidence that the model attributes exposure to the correct drivers.

The results of this analysis support the Parker (1995) escalator effect. However the attribution of exposure without defences alone is incomplete without knowledge of the probability of defence failure. This analysis of exposure attribution could be improved by analysing the current and historic probability of defence failure. This is recommended as future work.

These case study areas are typical of many coastal UK areas so the method can be easily applied elsewhere in the UK. It is likely that these results will have implications for management decisions across the UK. Whilst maintenance of defences and other flood management measures will be vital for the effective management of flood exposure in the future, it is essential that socio-economic drivers are also considered to ensure holistic future planning.

Chapter 7

Discussion

This chapter discusses the novelty and context of the research and its contribution to original knowledge. The research is compared to existing methods, and the strengths and limitations of the work are discussed. Future improvements are suggested and the applicability of the methodology to other sites and scales is discussed.

7.1 Novelty and Context

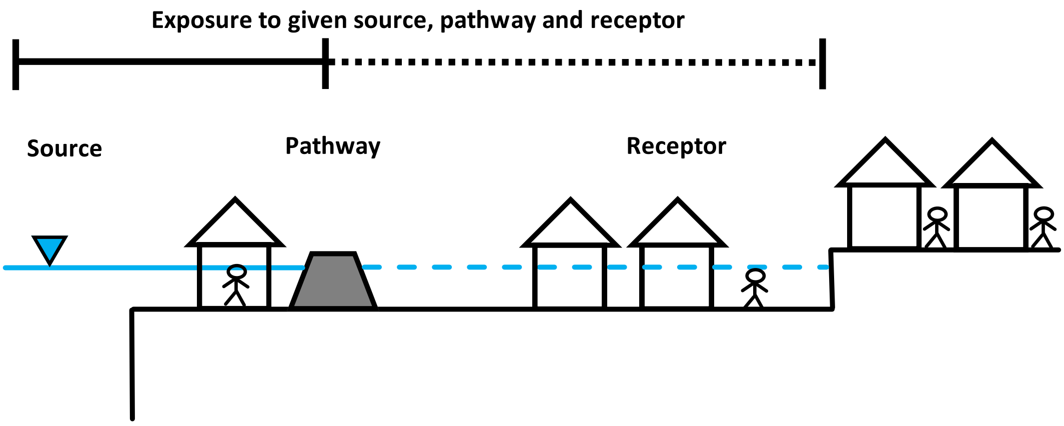

Figure 7.1: The context of Exposure within the Source-Pathway-Receptor (SPR) model (reproduced from Chapter 1)

Exposure is a component of risk, alongside probability and vulnerability (Samuels and Gouldby, 2009; Blaikie et al., 1994; Gwilliam et al., 2006; Kron, 2005; Fielding, 2007; UNDRO, 1982; United Nations, 2006b; USACE et al., 2011; IPCC, 2012; Koks et al., 2014; Sayers et al., 2015b). In this thesis exposure is defined in the context of the Source-Pathway-Receptor model as the **receptors** at risk from a given **source** and **recurrence interval** of flooding and a given **pathway** (Figure 7.1). The chosen source is tidal flooding and the receptor is people, rather than economic value as used by Evans et al. (2004). This is a better approach for historic study because the number of people exposed is a consistent measure through time and is not influenced by assumptions on discount rates and depth damage curves.

Two pathways are evaluated; one in which defences fail or are not present (exposure without defences), and the other in which defences are present and fully effective (exposure with defences). The use of these two pathways is consistent with current practice in evaluating exposure both with and without defences in place, which allows a more comprehensive understanding of the risks present (this will be discussed in Section 7.3.3). Exposure has been calculated for a range of recurrence intervals from the 1 in 1 year (annual) flood to the 1:1000 (extreme) flood, and from these values an annual average people exposure has been calculated. This is an improvement on previous work which consider only a single recurrence interval of flood event (e.g. Jongman et al., 2012b; Smith et al., 2012; Früh-Müller et al., 2014), as these studies present only a limited view of exposure.

A novelty of this work is in its *quantification* of the historic evolution of flood exposure. Previous studies of flood exposure evaluated a “snapshot” of exposure for a single point in time either in the current day or for a future year (e.g. Evans et al., 2004; Dawson et al., 2005), however the evolution of exposure over time has not been quantified before. Further, whilst previous studies have evaluated changes in exposure qualitatively (e.g. Evans et al., 2004), none have quantitatively attributed exposure to its underlying drivers. Exposure is at the interface between the physical and socio-economic systems and hence understanding what drives changes in exposure allows the relative importance of physical drivers (sea level rise) and socio-economic drivers (population rise, residential development) to be evaluated. The assumptions made and strengths and weaknesses of the historic study are discussed in Section 7.3.2.

A novel feature of this work is the use of both qualitative and quantitative data sources to characterise and evaluate flood exposure over time periods of up to 200 years. The time series of damaging flooding in the UK from 1884 to 2013 in Chapter 4 is believed to be the longest consistent record of its kind worldwide (Stevens et al., 2016). Census data dating back to 1801, historic maps dating to 1870, and sea level records extrapolated from 1960 were used in Chapter 5 to quantify historic exposure to flooding in Portsea and Hayling islands. The methods developed in this thesis demonstrate that historic data sources, often overlooked in contemporary analyses, can be used to give insight into the evolution of exposure.

The historic data required by the approach (population size and map showing residential development, and information on sea levels) are readily available in the UK and other countries, and so the method is widely repeatable. Recent work to develop consistent extreme water levels for the entire UK coastline (at 2km spacing) will contribute to applying this approach consistently across the UK (McMillan et al., 2011).

7.2 Contributions to Knowledge

The key contributions to knowledge from this work are as follows:

- Reported instances of damaging flooding from all sources of flooding in the UK have increased over the last 130 years. The flood event database on its own is insufficient to characterise exposure as the number of people exposed and the sources and drivers of exposure could not be quantified at the national scale. However the dataset can be used as a check for future studies examining trends in flooding in the UK, and could be linked to other datasets such as the Dartmouth flood observatory or SurgeWatch. The length of the record is greater than in any previous work on flood trends and forms a foundation for future work.
- The increase in exposure to coastal flooding in Portsea and Hayling has been quantified. Wadey (2013) evaluated exposure in the current day in these locations however did not quantify changes in exposure over time. The quantitative model used nationally available datasets describing physical coastal characteristics (sea levels, tide curves), population (census data) and residential development (historic maps) to quantify changes in exposure and so is repeatable across the UK. A consistent local scale method represents a step forward in flood exposure research; whilst exposure models unique to case studies have been developed (Dawson et al., 2011b; Früh-Müller et al., 2014; Wadey, 2013) the data and approaches are not necessary repeatable elsewhere.
- The evaluation of drivers of historic flood exposure developed in this work meets the need to understand the effect of flood drivers on the coastal environment (Sanchez-Arcilla et al., 2008; Nicholls, 2015). The finding that calculated increases in exposure are not uniform and are a function of changes in population, location of new development, rising sea levels and construction of sea defences was qualitatively described in Evans et al. (2004) however it has not previously been quantified. It was found that socio-economic drivers were dominant in exposure changes at the local level, however this does not preclude concern for the future, where sea level rise is predicted to play a more important role in increasing damages than population rise (Sayers et al., 2015b) due to the increased magnitude of climate change that is expected (Church et al., 2013).

An understanding of the historic evolution of flood exposure allows evidence based decisions on management to be made, which is discussed in Section 7.3.2. Recommendations for the management of exposure are explored in Section 8.3.

7.3 Strengths and Limitations

In this section the assumptions inherent in the approach are discussed in the context of the thesis and wider research, and the strengths and limitations of the approach are critiqued. Improvements to the approach for further research are suggested, with specific future work described in Section 8.2.
The exposure of people to coastal flooding has not been evaluated at this scale before; Evans et al. (2004); Fielding (2007); Thrush et al. (2005) evaluated the exposure of people at the national level, and Wadey et al. (2013) evaluated the exposure of buildings at the local level. The method is repeatable and has low data requirements, however the low resolution also has limitations compared to other studies, as discussed in the following section.

7.3.1 Data requirements and computational effort to quantify exposure

The approach for quantifying flood exposure only requires a flood hazard map and a land use map, and not a depth damage curve as in previous approaches (Evans et al., 2004). This is a strength as lower data requirements are conducive to historic analysis and a wider application of the methodology (Section 7.4). However the lack of detail can also be a limitation. For example the 50m resolution of the flood inundation model may miss localised changes in defences or land elevations such as property level protection schemes, which higher resolution case study approaches will evaluate (e.g. Wadey et al., 2013). The lack of a depth-damage curve in the methodology is also a limitation, as it restricts our ability to assess the economic consequences of flooding and hence assess economic flood risk (Evans et al., 2004). Future work to evaluate risk is discussed in Section 8.2.2.

The data required (at 10-20 year intervals, smaller if available) for the local scale methodology is:

- Population size (population datasets, available from the UK census at 10 year intervals)
- Residential development location (maps, available from the Ordnance Survey at approximately 20 year intervals, and aerial photography such as from the Regional Coastal Monitoring Programme (RCMP)[1] at five year intervals from 2003)
- Floodplain location or data to calculate it (extreme sea levels available from (McMillan et al., 2011), tide curves from the RCMP or Admiralty, land elevation such as from Environment Agency LIDAR data[2])

[1]http://www.channelcoast.org/
[2]http://environment.data.gov.uk/ds/survey/#/survey

- Flood defence data (crest elevations, available from local authority records) to quantify exposure with defences

Over the last decade there has been a huge increase in the availability of data to parametrise flood models (Mason et al., 2010), and digital census and map data is becoming increasingly available.

The methodology developed here can be rapidly applied to other sites in the UK. The time required and software used to undertake each component of the quantitative methodology is shown in Figure 7.2. The method is not dependent on the exact software used; although LisFlood was used for the Portsea and Hayling case studies the method would also work for other flood models, or flood map inputs. For a local scale urban case study (e.g. Portsea, approximate size 25km^2) the method (from data collection to analysing results) takes a total of approximately 15 days. For a rural case study (e.g. Hayling, approximate size 16km^2) the method takes approx. 12 days. The smaller time for the rural study is a function of a smaller population in the rural location which makes population data easier to process, and less development and a smaller total land area which decreases the time taken to manually digitise historic development maps. The hydrodynamic inputs to the model (sea levels, tide curves) are provided at the regional/sub-regional level - so for geographically close locations (e.g. Portsea and Hayling for the UK study) these inputs remain the same. Processing time can therefore be reduced when adjacent local case studies are undertaken. The most time consuming step in the methodology is the creation and validation of a flood model. For locations where a validated flood model is available (as for the Portsea and Hayling case studies and several other UK locations), the time taken will reduce significantly.
Some steps in the methodology could be automated; reducing the estimated time even further. For example a technique is available that automatically digitises developed areas on monochrome OS map (Visser, 2014). Wider application of the method is discussed in Section 7.4, and the estimated time to undertake a full national analysis is presented in Section 8.2.

Method step	Software/ Source	Time taken: Urban Case Study	Time taken: Rural Case Study
Collection of Input Data	Internet, Local Authority Records	1-2 days	1-2 days
Processing of DEM and flood model inputs	GIS/Matlab (manual)	~ 1 day	~ 1 day
Calibration and validation of flood model, model error checks	LisFlood	7 days	7 days
Creation of floodmap	LisFlood/Matlab (automated)	~ 5 seconds	~ 5 seconds
Population data processing	GIS/Excel (manual)	~ 1 day	~ 0.5 days
Map data processing (digitisation of residential area)	GIS (manual)	~ 0.5 days per map (3-4 days total)	~ 0.25 days per map (1.5–2 days total)
Creation of population grid	GIS/Matlab (manual)	~ 0.5 days	~ 0.5 days
Spatial analysis of floodmap/ population grid	Matlab (automated)	< 1 second	< 1 second
Run model for each driver case	Matlab (automated)	< 1 second	< 1 second
Synthesise results\ produce output graphs	Matlab (automated)	< 1 second	< 1 second
		13.5- 15.5 days	11.5-13 days

Figure 7.2: Research approach for quantitative evaluation of exposure in an urban and rural location: methodological steps, software used and time taken. Note that for locations where a validated flood model exists the time taken is significantly reduced.

7.3.2 The Historic Evolution of Exposure

A century ago Santayana wrote the now famous phrase “Those who cannot remember the past are condemned to repeat it” (Santayana, 1906). Gathering information on historic floods is a standard part of flood risk management plans (SEPA, 2015; Queensland Government, 2011; Canterbury City Council, 2015). Information on the evolution of exposure complements this information; whilst flood events demonstrate that exposure must have been present, it is possible that areas may have been historically exposed to large recurrence interval events that were never realised (e.g. the 1 in 200 or 1 in 1000 year still water levels never occurred). In addition, flood events with small recurrence intervals (such as the 1:1 year ‘annual’ flood event) may not have been widely reported due to the low impacts. Therefore an analysis of historic exposure to a range of events gives valuable information on historic exposure that may otherwise be lacking [in this work exposure to the 1 in 1, 10, 20, 50, 100, 20 and 1000 year recurrence intervals were evaluated].

Sustainable Flood Management
The first step in sustainable flood management is to identify the areas that are most exposed or vulnerable to flooding (SEPA, 2015). This can be done relatively quickly using the method in this thesis. Investment can then be targeted to the most exposed areas, including further in depth analysis of the exposure and risks present in the current day, and exposure and risks that existed historically.

The way in which exposure has evolved can give managers valuable insight into which strategies have worked, which haven’t, and how changes in physical and socio-economic conditions have driven changes in flood exposure. For instance if exposure has existed for 100 years in a given area, then recent development decisions may not be at fault; equally if it can be demonstrated that historic development was not within the floodplain when constructed but is now exposed (due to changes in sea level, flood defences or geomorphology of the land), this information can aid contemporary planners in making wise future-proof (or at least future-resilient) decisions. Land zoning for historic developments is generally not possible (with the exception of as yet untested large scale urban managed realignments, which are discussed in section 8.3), but the retro-fitting of property level flood resilience measures to historic developments has been demonstrated (Queensland Government, 2011). With increasing urbanisation currently rural locations are likely to face the same planning challenges that denser urban areas have already faced decades before. For instance this work has shown that the level of development in Hayling is at the same level as Portsea in the 1910s. Hence knowing the historic evolution of exposure in Portsea may help planners to understand how exposure in Hayling may evolve in the future and therefore to make better informed decisions.

Floodplain Development

A key assumption in the methodology presented is that population density of development on and off the floodplain is assumed to be equal. This assumption was made in the absence (pre 1971) of spatial census data which is the best available data used in census population and flood exposure studies (e.g. Martin et al., 2002; Smith et al., 2014). Spatial census data exists for the UK from 1971 to 2011; over this 40 year period the analysis presented in this thesis agree very closely with the spatial population spreading method (see Appendix D). Crucially, the spatial method predicts on average 60-70% less exposure than the cruder assumption of spreading population over the entire land area, an assumption used in previous studies (Nicholls et al., 1999). Therefore the method developed in this thesis improves the estimation of historic exposure.

Historic and Future Exposure Studies

There is a lack of high resolution population, mapping and land elevation data available historically which leads to a lack of detail in historic study. However the strength of historic study is that it is based on observations (i.e. of sea levels, development patterns and population size), whereas estimates of future exposure are far more sensitive to the assumptions made regarding these variables (rate of sea level rise, population growth and urbanisation).

It is important to note that historic study alone is not sufficient to inform future management options. Future scenarios are likely to be unprecedented due to the influence of sea level rise acceleration (Church et al., 2013; Nicholls, 2011) and changes in population and development patterns. The attractiveness of future exposure evolution studies is that they allow management decisions and potential future scenarios to be explored. The attractiveness of historic exposure evolution studies is that they give information on how the current exposure came about, and provide a baseline and grounding for future scenarios. For instance historic development trends have been used as a baseline to compare modelled urban expansion scenarios in flood exposure work in the USA (Song et al., 2016) and in Italy (Sekovski et al., 2015). Historic and future studies are both important and indeed are complementary.

Learning from the Past

The most damaging coastal flood event in the UK is the 1953 North Sea storm surge (Hall, 2011). Learning from this event led to improvement in coastal defences across the UK's east coast which are credited in part with reducing damages to a storm of similar magnitude in December 2013 (Wadey et al., 2015). Similarly learning from fluvial flooding events in Summer 2007 led to numerous changes to flood management in England and Wales (Pitt, 2008) (see Appendix B for other similar examples throughout the history of flood management in the UK). There is a clear benefit from learning from the past and on balance the historic evolution of exposure is important information because it provides another much needed instrument in the decision makers' tool-kit (Hall et al., 2012).

7.3.3 Exposure with and without defences

There is a need for clear, concise terminology relating to risk and associated concepts such as exposure (Samuels and Gouldby, 2009). Koks et al. (2014) make a distinction between exposure in embanked and unembanked areas in the Netherlands. They found that potential exposure in embanked areas (i.e. exposure if defences fail) is far higher than the exposure in unembanked areas. Hence the potential exposure 'without defences' in areas where defences exist is a critical concept. Exposures with and without defences are also differentiated by Mokrech et al. (2014) who estimates exposure in Europe firstly with no defences, and then with defences. However neither study defines the distinction between exposure with and without defences. In this thesis this distinction is clarified by differentiating between exposure with fully functioning defences and exposure without defences.
Jongman et al. (2012b) and Lugeri et al. (2006) evaluate exposure without defences, and Koks et al. (2014), Mokrech et al. (2014) and Früh-Müller et al. (2014) evaluate exposure with defences. However these studies compare different information, as both use the undefined term 'exposure', and it could be concluded that they are comparing like for like. Using the term exposure to describe both of these estimates is confusing and misleading. For example in Portsea the exposure with defences is 80% lower than the exposure without defences when averaged across a range of recurrence intervals (Chapter 5). Explicitly differentiating between exposure with and without defences facilitates comparison between different studies.

A limitation of this exposure study is the lack of data on defences, which limits the timescale over which exposure without defences can be evaluated. In their work on exposure in Bavaria in the 1850s and in 2011 Früh-Müller et al. (2014) use a current day flood map which excludes areas that are protected through flood control measures (i.e. they evaluate exposure 'with defences' as defined in this thesis). Areas that would be flooded without these measures in place are not included which leads to an under-estimation of flood prone properties for the historic study. Conversely, in Chapter 5 the estimated exposure without defences in Portsea may overestimate the people at risk, as although crest height data on defences pre circa 1960 is not recorded, sea defences of some form are known to have existed then. Smith et al. (2012) were able to extract historic defence heights from Water Authority records for a fluvial case study in the UK, however they faced a similar limitation to this work in the length of data available.

A potential limitation of the analysis of exposure with and without defences is the binary nature of the approach. For a place with defences they are either considered to work fully (exposure with defences), or they are considered to have all failed or not exist (exposure without defences). In reality there are likely to be several distinct failure mechanisms and several different defences which may or may not fail - and hence several distinct pathways and hence 'exposures'. In their evaluation of defence failure in Portsmouth Wadey (2013) formulated multiple scenarios in which defences failed including full breach (all defences fail), partial breach (some defences fail) and wave driven overtopping of defences. In addition the failure of pumps for removing flood water was considered. Each of these pathways will lead to a different flood extent and hence has an exposure associated with it. Exploration of all (expected) failure mechanisms and associated exposure facilitates the estimation of risk, which is discussed in Section 8.2. However, this approach will require extensive data on defence characteristics and failure mechanisms which is lacking in our historic dataset.

7.3.4 Population as a metric of exposure

In the UK, census population data is available at 10 year intervals from 1801 to 2011. Fielding and Burningham (2005) and Thrush et al. (2005) used census data from 2001 to estimate the population exposed to flooding across England and Wales, and Smith et al. (2014) used census data to estimate exposure for a local study in Cornwall. This estimation of people exposure is a pre-requisite for assessment of fatalities during flood events (Asselman and Jonkman, 2007; Jonkman et al., 2008, 2009). The relationship assets = 5 * GDP (per capita) * Population (£140k / person in the UK, 2015) is an assumption widely used in the insurance industry to estimate the economic assets at risk (Hanson et al., 2011).
The length of census data available in the UK (1801-2011) makes population an attractive metric for historic study. However a limitation of using census data in flood exposure analysis is that it does not capture daily changes in population. There are differences in the 'night time' population (as depicted by census data), and day time population due to the influx of commuters, tourists and other temporary visitors (Smith et al., 2014; Smith, 2015). To analyse exposure at different times of day (i.e. exposure for a daytime flood event versus exposure for a night time flood event) changes in population need to be quantified. For disaster management information on daytime populations may be less critical, as the worst-case flood event is likely to be one that occurs at night when awareness is lower and responses are harder, such as the 1953 North Sea flood in which over 300 people in England lost their lives (Steers, 1953). For such an event the exposed population will resemble the census population. However it is possible that large events could occur during daytime hours when the population differs from the census estimate, and it is recommended that for a full risk analysis this is considered.

Alternative methods to quantify exposure include the number of buildings at risk (Wadey et al., 2012; Wadey, 2013) or classification of land use (Lugeri et al., 2006; Rojas et al., 2013). This gives additional information on commercial, industrial and environmental assets which are likely to improve subsequent estimates of risk which should take account of damages from all sources (Penning-Rowsell et al., 2013). The number of residential dwellings from the census is available; however there are not consistent historic datasets on other building types and land use over a 200 year period. Whilst it is possible to extract residential area from historic OS maps, the resolution of these maps is too low to count the exact number of buildings.

For a full risk assessment it is important to consider exposure to flooding of multiple receptors including people, buildings, habitat and commercial assets. However within the context of a thesis it is not possible to fully evaluate multiple receptors over the 200 year timescale used in this work. Disruption to transportation and commerce has a much smaller impact than flood damages to homes and hence people are a more valuable metric to evaluate. In order to improve estimations of people exposed to flooding the collection of high quality population data at the sub 10-year time step (to supplement census data) is recommended for future work (see Section 7.3.6).

7.3.5 Drivers of Coastal Flooding

In this work the drivers of flood exposure were defined as either physical (those that change the physical flood system) or socio-economic drivers (those that change the human system exposed to flooding).

Previous approaches to estimating changes in exposure have assumed that physical drivers are constant over time. Früh-Müller et al. (2014) used a current day flood map to evaluate exposure in a German river catchment in 1850 and in 2011. However in this thesis it was found that there was a 56% reduction in the number of people exposed when changes in sea level since 1801 were evaluated. Hence assuming that physical drivers are constant over time over time may lead to overestimation of historic exposure, or conversely an underestimation of future exposure (Jongman et al., 2012b).

Physical Drivers of Exposure

Physical drivers of exposure include sea level rise, waves, precipitation and coastal morphology. In this work changes in sea level and coastal morphology were considered together as relative sea level rise, and waves are precipitation were not modelled.

Land Elevation

A limitation of this historic study is the absence of time series data of land elevation. Dornbusch et al. (2013) used historic mapped lines of mean high water, mean low water and beach toe (level of the foreshore) to estimate beach volumes and create simplified Digital Elevation Models (DEM) for the UK's South-East coastline for the 1870s, 1890s, 1910s and 1930s. This approach is valid for estimating historic elevation changes in the tidal environment (between the beach toe and high water mark); however the method is not applicable to inland areas beyond the high water mark. It is not possible to digitise historic topographic maps to obtain changes in elevation due to the low resolution of the maps (also OS maps typically use the 5m contour as the "first" line, which is above the extreme 1 in 200 year still water level elevation).

Waves
For low lying islands such as Portsea and Hayling surge driven extreme water levels are typically the most critical flood mechanisms (Wadey, 2013). Waves were ignored in the analysis presented in this thesis. However for other coastal areas this assumption may not be valid. For example in mostly high-lying cities such as Brighton on the South coast of England the critical flood mechanism is wave driven overtopping of seawalls (Canterbury City Council, 2015, personal communication).
Changes in wave climate over the 200 year timescale of this work were not quantified. Surge Watch[3] is an online database of historic and contemporary coastal flood events which could be used to estimate changes in wave climate in coastal areas. This could help characterise changes in the wave driver, however the level of detail is not consistent across the country, a limitation shared with the flood event database created in this thesis. Further, there are inherent uncertainties in the prediction of wave driven overtopping rates and hence for future study the benefits of quantifying the wave driver will have to be weighed against this limitation.
Fluvial Flood Events
Fluvial flood analysis require evaluation of a different set of physical drivers which include precipitation, changes in river profile and both upstream and downstream land use change. Smith (2015) looked at exposure and risk for a fluvial case study in the UK. They found that accurate estimation of socio-economic drivers is potentially as important as changes in future hazard. This demonstrates that for both fluvial and coastal studies, it is important to evaluate changes in both physical and socio-economic drivers.

Socio-economic Drivers of Exposure
The socio-economic drivers used in this work were population and residential development. Residential Development accounts for land use change and urbanisation specific to population. Globally population rise and urbanisation are among the biggest drivers of exposure (Hanson et al., 2011).
Population
Thanks to recent efforts to digitise historic maps and census data, the data used to evaluate the size and location of the population exposed to flooding is available (Digimap©, Casweb, Infuse). A limitation of pre 1971 census data is that it is low resolution, with only aggregate population counts of wards available. However, the use of historic development maps (OS in the UK) allows the location of the population to be estimated, and hence allows exposure of people to be quantified over the century timescale (Früh-Müller et al., 2014; Stevens et al., 2015).
Früh-Müller et al. (2014) digitised human settlements from a 1850 historic map in their analysis of the River Main in Germany. The location of the population (represented by the Residential Development driver in this thesis) is important as differing estimates of the coastal communities in the floodplain lead to inconsistent estimates of the population at risk (Ache et al., 2015). If the coastal population at risk were defined as the

[3] www.Surgewatch.org

number of people within 5km of the coast then the 'at risk' (exposed) population in Portsea in 2011 would be 164,000 people. When exposure is defined as those within the 1 in 200 year extreme water level floodplain, and population location is accounted for using census data and mapping, the population exposed is calculated as 19,800 people without defences and 7,000 people when defences are accounted for (Appendix F). This shows the importance of accounting for the spatial location of the coastal population.

Land Use Change

Changes in land use were not considered in this thesis. This is a limitation of the work as changes in land use and ground cover can modify the roughness and hence extent of the floodplain. In their Solent inundation model Wadey (2013) found that at the 50m resolution the estimated floodplain is insensitive to changes in the floodplain roughness. However this may not be the case for other locations and so it is recommended to evaluate the effect of land use changes on exposure in future studies.

A summary of recommendations to improve the thesis methodology are presented in the following section.

7.3.6 Recommended Improvements to the methodology

Suggested improvements to the methodology developed in this thesis would include:

- Additional flood event data to allow characterisation of exposure. Flood event data required for characterising exposure includes the number of people affected by events, the source of flooding (tidal, fluvial, pluvial, combination), the extent and exact location of flooding, the presence and behaviour of defences (i.e. did defences fail) and an estimated return period of the flood event. This data could come from multiple sources; for instance newspaper records (Ruocco et al., 2011), online databases or flood records (Black and Law, 2004; Brakenridge, 2015), or local authority or Environment Agency records. Data on events can be 'crowd-sourced' such as the approach used by SurgeWatch[4] which collects photos of historic coastal flood events to improve understanding of the extent/impacts of past events. Similarly the Chronology of Hydrologic Events website[5] allows the public to submit historic evidence of flood events (Black and Law, 2004). These improvements would facilitate the characterisation of exposure, including the ability to differentiate between flood events with and without defences, and provide validation for modelled floodplain extents.

- Historic records on flood defences, including a time series of defence heights and condition. Obtaining information on defence crest heights at regular time intervals would improve the analysis of exposure. This would allow evaluation of exposure

[4]http://www.surgewatch.org/

[5]http://cbhe.hydrology.org.uk/

with defences over a longer time period (currently 50 years for Portsea), increasing understanding of how exposure has evolved historically. However obtaining historic defence data is difficult and these data are often lost with the retirement of experienced staff such as the city engineer. Digital databases containing flood defence data are sometimes overwritten and older data can be lost (Wadey, 2013). Older paper records can exist however these are not always easy to access. Data mining of historic data does take place although this is not consistently done. For parts of Kent and East Sussex such defence time series are being developed by Canterbury City Council as part of regional beach management plans. At the national level the UK Environment Agency is developing systems to consistently record information on flood defence structures. Best practice is evolving in UK FRM with new tools facilitating rapid data collection on the condition of flood defences (Canterbury City Council, 2015, personal communication). This will improve the availability of data for future studies.

- Evaluation of additional flood drivers. It would be useful to collect additional data to characterise the Wave driver. This is likely to improve estimation of the extreme floodplain in coastal areas where wave driven overtopping is the dominant flood mechanism. Similarly it is recommended that changes in land use are evaluated. These improvements are likely to increase the accuracy of the estimation of historic floodplain extents in some areas.

- Continued collection of land elevation data. The lack of land elevation data available for historic study highlights the importance of collecting regular datasets of land elevation. In the UK the Environment Agency currently collect LIDAR data for most locations every 1-2 years, and it is essential that this work continues so that changes in flood exposure due to land elevation can be calculated.

7.4 Wider Application of the Methodology

7.4.1 Application of the method to other sites in England and Wales

The methodology described in this thesis could be applied to any coastal site where adequate spatial datasets (land elevation, population size and location) and sea level data are available.

For a historical analysis users would need access to population data and indicative floodplain maps (or sea level data and an inundation model, as used in this work) at regular intervals. The population distribution method requires population data and mapping showing residential development. The availability of this data across England and Wales is as follows:

- *Census data.* This is available for all of England and Wales at 10 year time intervals from 1801-2011.
- *Historic maps.* These are available for all of England and Wales at an average 20 year time interval from 1870-current day.
- *Flood model/floodplain map.* The flood model used in this analysis was specific to the Solent case study (Wadey, 2013). Flood models exist for various UK locations however they are not consistently available. However the method is not flood model specific. Where no model exists coastal boundary conditions that exist for the whole UK can be used (McMillan et al., 2011), in conjunction with Digital Elevation Models which are available nationally from the UK Environment Agency.
- *Flood defence data.* This is specific to the case study location. Older defence data may not be stored digitally (and is often lost) or can be digitally overwritten as defences are modified (Wadey, 2013). However national data on flood defences is becoming more widely available, for instance the National Flood and Coastal Defence Database (NFCDD) used by (Hall et al., 2006), and the newer Asset Inspection Management System (AIMS).

7.4.2 Application of the exposure estimation method to the National Scale in the UK

To demonstrate the quantitative methods' (Chapter 5) applicability at a national scale, a low resolution analysis was performed for the whole of England and Wales (See Appendix C). A grid resolution of 200m grid cell was used, and population was not constrained to residential areas as it was in the thesis. The exposure of the population to the 200 year and 1000 year flood events between 1981 and 2011 was assessed using census population and the UK Environment Agency's indicative floodplain (IFM, Figure 7.3). The IFM includes flooding from both coastal and fluvial sources, which is a limitation for this application. The IFM does not include the effect of flood defences and hence is a measure of exposure *without defences*.
The analysis suggests that exposure to flooding in the UK has increased from 3,195,000 people in 1981 to 3,542,000 people in 2011 (1 in 200 year floodplain), and from 4,317,000 people in 1981 to 4,829,000 people in 2011 (1 in 1000 year floodplain). Changes could be due to the inaccuracies inherent in this analysis (population is not constrained), as the total population of England and Wales increased during this time.

The published estimate of the number of people exposed to flooding in England and Wales is 5.2 million (NFF, 2015); however it is not stated what return period event or which flood source this estimate refers to. It is also possible that this estimation was a misinterpretation of National Audit Office (2011) who estimate that there are 5.2 million *properties* at risk in England from coastal, fluvial and surface water sources. This

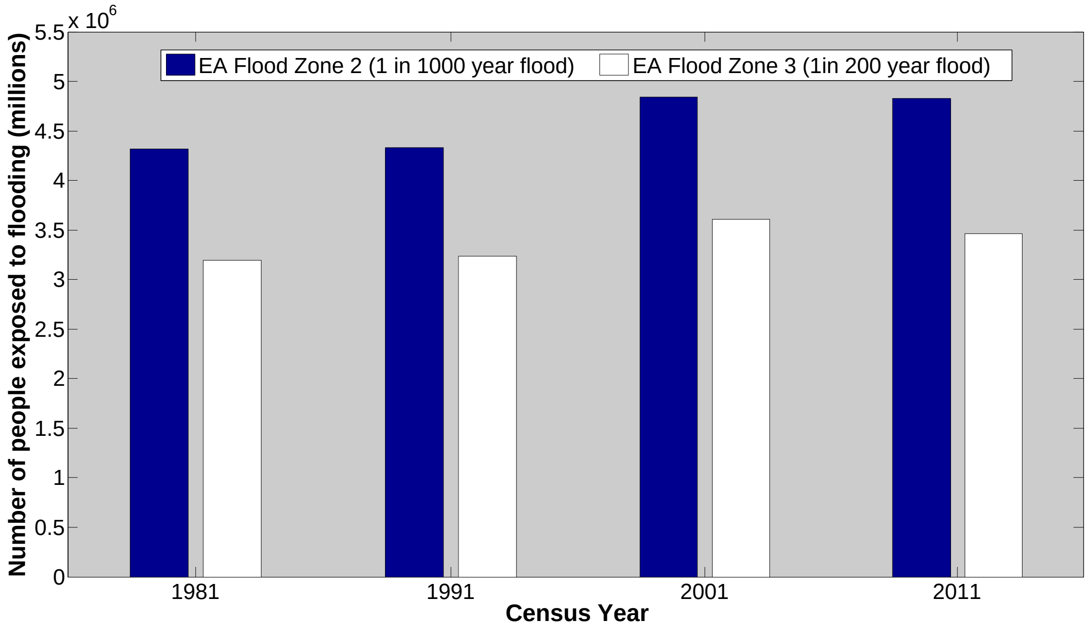

Figure 7.3: Estimated number of people exposed to coastal and fluvial flooding in England and Wales 1981-2011 for flood zones 2 (1 in 1000 year flood) and 3 (1 in 200 year flood)

uncertainty makes validation of the estimate in this work difficult.

However the results are of the same order of magnitude; the estimate of 5.2 million people shows good comparison (<10% difference) with the results from this analysis for the 1 in 1000 year floodplain in 2011 (4,829,000). The calculated exposure for the 1 in 200 year floodplain in 2011 (3,460,000) is 33.5% lower than the NFF exposure figure.

The lower resolution used in this national analysis (200m as opposed to 50m used earlier in the thesis) ignores small scale non-residential areas such as parks. Additionally, regional differences where exposure is overestimated or underestimated (due to inaccuracies in population distribution) will be averaged out.

This approach does not differentiate between coastal and fluvial floodplains, and population is not constrained to residential areas which are limitations of the analysis. However this analysis of exposure in England and Wales demonstrates that a low resolution national scale analysis is possible. It is recommended that the local scale method to quantify exposure described in Chapter 5 (areas at the city scale, 10-50km^2) should be repeated for all coastal areas (or at least at known hot spots such as Hull and Greater London) to give national coverage at a higher level of detail. Proposed future work is explored in Section 8.2 of the following chapter.

Chapter 8

Conclusions

This thesis has identified and filled a gap in our knowledge of the historic evolution and drivers of exposure to coastal flooding. The findings have implications for the current assessment of coastal flood exposure, and also for future planning decisions. This chapter contains an evaluation of how the thesis objectives were met (with reference to the limitations), suggestions of future work to expand on the work undertaken, and recommendations for the management of exposure in light of the thesis findings.

8.1 Achievement of Objectives

The thesis set out to answer the research question:

How can the temporal evolution of coastal flood exposure be characterised and quantified?

This question was evaluated using three objectives; to characterise and evaluate the historic evolution of flood events, to develop a framework to quantify the historic evolution of flood exposure, and to attribute the changes in flood exposure to the underlying drivers.

The definition of exposure used in this thesis characterises exposure explicitly in terms of the Source-Pathway-Receptor concept. This provides clarity on a term previously used inconsistently throughout literature. The quantitative methodology developed uses mostly nationally available datasets and provides a framework for quantifying the historic evolution of exposure in different areas, and hence comparing exposure between case studies. However the methodology has limitations as discussed in the previous chapter. In light of these it is believed that the method is best suited as a high level tool evaluating and comparing exposure between case studies; there are better methods available for an in depth analysis of an individual case study. The improvements discussed in the previous chapter would help to provide a more robust analysis, and future

work would help to further develop the method to provide a more detailed analysis (see Section 8.2). The analysis of exposure could be improved by analysing the current and historic probability of defence failure. Without this information risk cannot be calculated and this is acknowledged as a limitation of this work.
However, despite the limitations, exposure has been successfully characterised (using the SPR concept) and quantified (in terms of people exposure); and therefore on balance it is believed that the thesis question was satisfactorily answered.

In the following section the achievement of each individual objective is discussed.

8.1.1 Objective 1. Characterise and evaluate the historic evolution of flood events

The work produced a unique dataset of reported damaging flood events (i.e. flood events that impact society) in the UK over the last 128 years which was the basis for a published paper in the Hydrological Sciences journal (Stevens et al., 2016). It showed that the *reported* occurrence of damaging flooding in the UK has increased over the last 128 years. However the method has several limitations. Firstly the number of *reported* flood events and the actual number of events may be different. It is likely that there were improvements in the Met Office's reporting capabilities over the timescale of the analysis. Whilst damaging flooding is a good indicator of exposure (as it accounts for the magnitude of flood source, the presence of defences, and presence of receptors in the floodplain) these factors could not be unpicked from the national scale data source used. It was not possible to determine the magnitude of events, or the number of people exposed to each event, and often quantitative descriptions of the impacts were lacking.

Due to these limitations in the approach no conclusions on exposure can be drawn from this dataset; instead it illustrates the difficulty of evaluating exposure at the national scale and demonstrates the need for subsequent analysis. The dataset developed does give some context to exposure; even in light of potential changes in reporting capabilities over time, the vast quantity of reported events towards the end of the record gives confidence that the occurrence of damaging flood events has been increasing (the magnitude of changes is likely to be different to that recorded, however the qualitative conclusion that realised exposure is increasing is likely to be correct). Hence we conclude that this objective has been partially met; improvements to the method as discussed in Chapter 4 and Chapter 7 would improve the characterisation of the historic evolution of flood events.

8.1.2 Objective 2: Develop a framework to quantify the evolution of flood exposure

In Chapter 5 a framework was developed to quantify how exposure to flooding has evolved over time. This method formed the basis for a published work in a special issue of Natural Hazards and Earth System Sciences (NHESS) (Stevens et al., 2015). The method is unique in its study of how exposure evolves, rather than considering a single point in time as in previous work. The work demonstrated that:

- The evolution of exposure without defences can be estimated historically over a 210 year period in the UK
- We can estimate flood exposure with defences where defence crest data exists, a 50 year period for the Portsea case study

Application of the framework is independent of both the exact technical methods used (for example the raster based inundation model), and the region under consideration. It is believed therefore that the methodology can be applied generically where appropriate data exists, both in other coastal locations in the UK and elsewhere in the world. However there may be limitations in its use, for example for places where there is a lack of availability of defence data or validation data for the flood model. The length of quantitative data on flood defences is variable; 50 years of data may not be available elsewhere in the UK which will limit the evaluation of exposure. Likewise, whilst the UK has 210 years of census data available this is unlikely to exist in other countries. Therefore whilst applicable elsewhere, the length of study may not be replicable.

Overall the objective to quantify the evolution of flood exposure was successful achieved; and the highlighted limitations withstanding, the methodology produced may be applied nationally or even internationally for use as a flood exposure assessment tool.

8.1.3 Objective 3: Attribute the changes in flood exposure to the underlying drivers

In Chapter 6 a method was developed and applied for attributing the modelled change in flood exposure to the underlying drivers. The attribution of flood exposure to the underlying drivers has not been comprehensively studied before; the method for modelling each driver individually therefore represents a unique contribution to work in this field. As a result of the work we have the following knowledge:

- We can attribute flood exposure to the underlying drivers of change (Sea Level Rise, Population and Residential Development)

- Socio-economic drivers (Population, Residential Development) have had a bigger influence historically than physical drivers (Sea Level Rise) in Portsea and Hayling

However the approach is sensitive to the assumptions made. In particular the assumption that population is spread evenly over residential areas may, under certain circumstances, lead to the conclusion that changes in residential development reduced exposure when in reality no development was actually removed from the floodplain (see the discussion in Chapter 6). In the absence of spatial population data pre 1971 an assumption on population distribution had to be made; however this is fully acknowledged as a limitation of the attribution method.

Whilst other exposure drivers could not be quantified over the timescale of this analysis, it is still worth noting that they may lead to changes in the attribution results, as the relative exposure will be divided between a higher number of drivers. It is likely that the qualitative conclusion that socio-economic drivers of change have been more important would not change if more drivers were considered, since the magnitude of the exposure attributed to socio-economic drivers was significantly higher than for physical drivers. The three key drivers were selected, giving confidence that the exposure was successfully attributed to the **main** underlying drivers of change, thus achieving objective three.

8.2 Recommendations for further research

In the following section we summarise directions for further research that have emerged as a result of the work developed in this thesis. It is suggested that future research should be focused in two directions:

- Use the developed framework to quantify flood exposure at the national scale
- Expand on the analysis of exposure to evaluate the evolution of coastal flood *risk* at the local scale

8.2.1 Quantify flood exposure at the national scale

The local scale exposure evaluation method developed in this thesis could be applied to areas across the country to build a picture of how exposure to flooding has evolved nationally (Figure 8.1). The results from each local study can be compared to the lower resolution national results (Appendix C) as a way of cross-validating the results.

The method applied to the entire England and Wales could be done by a single researcher in about three years (with an additional three years if every location required a new validated flood model), which is an ambitious but achievable body of work. Wider application of the method could be improved by reducing the time taken to undertake

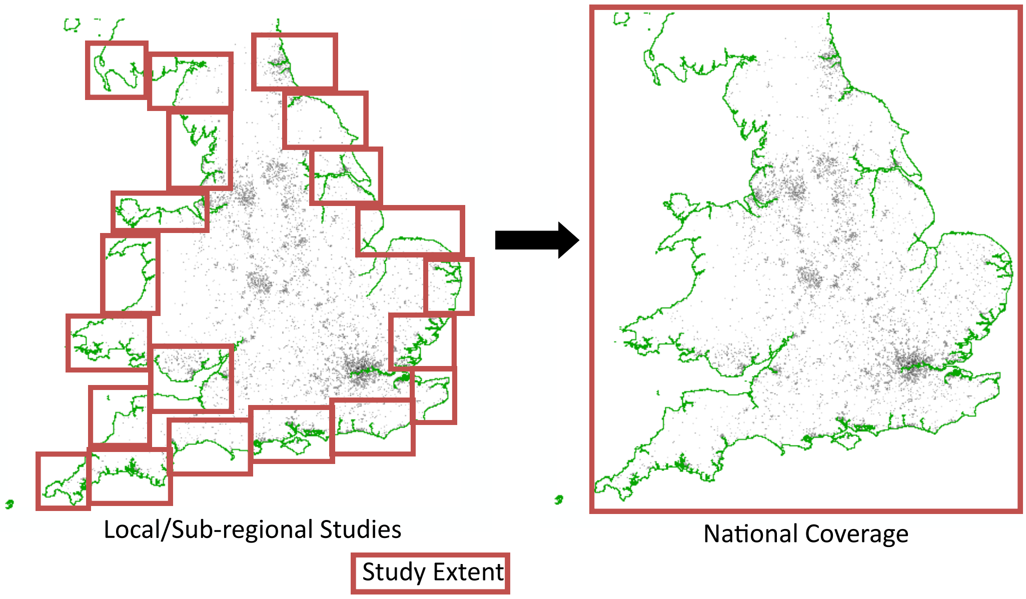

Figure 8.1: Evaluation of national exposure to coastal flooding using multiple local scale studies (size of local studies exaggerated for display reproduced from Chapter 3). Contains public sector information licenced under the Open Government Licence v3.0.

this framework. For instance applying the technique of automatic digitisation of OS maps (Visser, 2014) to the study could greatly decrease the time taken for this time consuming step in the methodology from days to minutes. This would allow the method to be applied to large spatial areas, which is not feasible through manual digitisation (Visser, 2014).

Reducing the map stage from an average of 3.5/1.75 days (urban/rural respectively) to half a day to perform and check an automated process would reduce the UK methodology significantly. This would still be a substantial body of work; however the output would be ground breaking and could inform policy and management at both local and national levels. An alternative approach is for each study to be undertaken locally, for example by the relevant local authority. This would have the benefit of local expert knowledge and easier access to defence records; however not all local authorities would have the capacity to undertake such a study.

The method is not unique to the UK and can be applied elsewhere where appropriate data exists. The method could therefore be repeated to look at other national or even continental case studies. For instance the CORINE land cover map of Europe (Buttner et al., 2002) and a 1k resolution DEM were used to evaluate exposure in 13 European countries (Lugeri et al., 2006). This could be used alongside global or national climate projections to study the evolution of flood exposure at the continental scale. For a country with a small coastline, such as the Netherlands, the method would be even quicker than the UK as fewer studies would be required. This demonstrates that replicating the methodology for an entire country is feasible.

The methods developed in this thesis offer a foundation for further analysis that could inform flood managers across the globe.

8.2.2 Evaluate the Evolution of Flood Risk

In Chapter 5 the 'AAD' of people (the number of people, on average, expected to be exposed to flooding in any given year) was assessed for Portsea and Hayling. For Portsea exposure both with and without defences were evaluated, and in Hayling (which contains few engineered defences) exposure without defences was evaluated. The annual average number of people exposed to flooding was defined as 'annual average people exposure' to avoid confusion with economic annual average damages (AAD). In the absence of data to quantify the failure probability of the defences in Portsea, people exposure for the with and without defences pathways were evaluated independently (Figure 8.2).

This analysis of 'annual average people exposure' (which evaluates exposure to a range of recurrence interval flood events) could form the basis of future work quantifying the historic evolution of risk to the coastal population. However, in order to fully evaluate risk additional datasets are required to fully characterise probability and vulnerability, as per the relationship Risk = f(Probability, Exposure, Vulnerability). The probability variable has traditionally been considered as simply the probability of an (extreme) storm occurring Sayers et al. (2015a), i.e. the probability related to the source term of the SPR, as considered in this analysis. However the probability related to the pathway term also needs to be evaluated (i.e. probability of defence failure). Probability can be more effectively characterised by these two components:

1. The probability related to flood source (i.e. extreme sea level)
2. The probability related to pathway (i.e. topography, defence performance)

The probability of extreme water levels has been well studied (Haigh et al., 2011; McMillan et al., 2011); in this work exposure to the 1 in 1, 10, 20, 50, 100, 200 and 1000 year recurrence intervals was evaluated. The reliability of defences (including natural topographical features) determines whether the defence will be effective or whether it will fail (i.e. the flood pathway); using the terminology in this work defence reliability determines whether the exposure with defences, or the exposure without defences will be realised. The reliability of coastal defences requires a huge quantity of data (Hall et al., 2006). It is difficult to quantify as it depends upon the complex interaction between surges, waves, defence shape, dimensions and material, and the bed material that the defence is founded on.

Previous work has defined 'fragility curves' to determine defence reliability which typically relate flood depth to the probability of defence failure (Simm et al., 2008). In

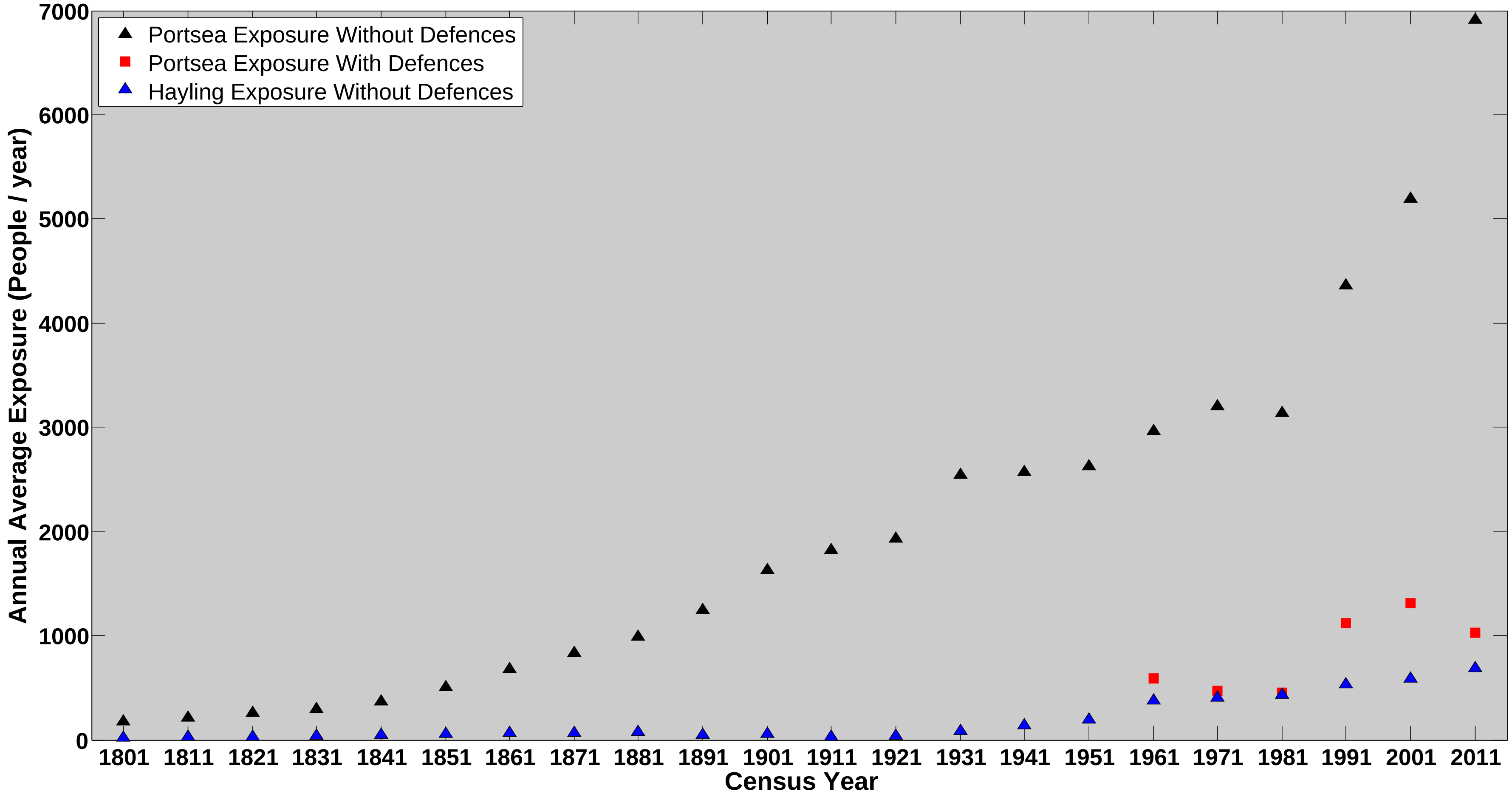

Figure 8.2: Annual average exposure of people to flooding in Portsea and Hayling, with and without defences, 1801-2011 (1.22 mm / yr sea level change rate applied)

project appraisal the approach is simplified further by assuming a set probability of defence breach by year x (for example, a 10% chance of defence failure by year 10). For this example the damages in year 10 (10 years after defence construction, or scheme funding for maintenance or beach management begins) will be calculated as exposure without defences x 10% + exposure with defences x 90%. Hence the quantified exposures calculated in this thesis could be used with local expert judgement to calculate a risk, expressed as the people expected to be affected by flooding per year.

However in order to fully quantify flood risk, exposure needs to be related to damages: vulnerability has to be evaluated. Vulnerability is a complex variable that is highly dynamic (and often uncertain) in time. Vulnerability can be characterised by two main components:

- The vulnerability of the receptors within the floodplain
- The vulnerability of defences (i.e. fragility curves, as discussed above)

Vulnerability of receptors is assessed using a depth-damage function which represents the vulnerability of the respective land-use type, as the increase of damage from 0 to 100% of the maximum damage figure with increasing inundation depth (Jongman et al., 2012b). Damages are typically evaluated as an economic value; however damage could also be injury or loss of life of a person (Penning-Rowsell et al., 2005a; Jonkman et al., 2008). In the UK there is an increasing drive to quantify intangible damages such as damage to habitat and people. This is aided by comprehensive guidance available in the form of the Flood and Coastal Erosion Risk Management: A Manual for Economic Appraisal Flood (Penning-Rowsell et al., 2013) and its predecessor the Multi Coloured Manuals (MCM). This guidance is the product of decades of research at the Flood Hazard Research Centre at Middlesex University. Whilst we have a handle on the vulnerability of receptors and defences for the modern day, for historic analysis vulnerability becomes more uncertain. As discussed in Chapter 2, vulnerability changes over time and defence time series is lacking. In this work a time series of defence crest elevations for Portsea Island was demonstrated back to 1990 (a 20 year period). Whilst defences were present before 1990, information is poorly recorded (See Section 7.3.6 for a discussion on the availability of defence data). This is likely to be typical across the UK and probably more widely, as until recently there has been little co-ordinated effort to record defence data (Canterbury City Council, 2015, personal communication).

At the national scale we can, however, evaluate policy decisions as these are well recorded. In Chapter 2 a history of policy decisions over the last 100 years in the UK was evaluated (see also Appendix B). Such studies can give an idea of when defences were constructed - for instance there was a drive to build sea defences of the East and South-East coasts of England following the 1953 North Sea Flood. Plausible defence

and management scenarios could be used to estimate historic defence levels. However, such analysis would be highly sensitive to the assumptions made and so would only give limited additional information on the historic evolution of exposure.
In this thesis the historic evolution of exposure has been characterised (Chapter 4) and quantified (Chapters 5 and 6). The relationship Risk = f(Probability, Exposure, Vulnerability) shows that additional information on probability and vulnerability are required to evaluate historic changes in risk. The lack of time series on defences and the dynamic nature of vulnerability make historic analysis of risk difficult and uncertain. However, with additional datasets and/or scenario analysis, the evaluation of exposure in this work could be expanded to evaluate historic changes in risk.

8.3 Recommendations for the Management of Exposure

This thesis has demonstrated the potential for evaluating exposure to flooding both with and without flood defences. The availability of development maps and population datasets at regular intervals is essential for evaluating exposure to flood risk. The work presented in this thesis used population datasets at 10 years intervals and residential development datasets at 20 year intervals. It is noted that the large time step used in this work (10 years) may miss shorter term population change dynamics and therefore future studies would benefit from smaller intervals between datasets to allow a smaller time step to be used in the analysis. The continued and regular collection of high quality data sets for characterising flood exposure is recommended, as listed in Table 8.1.

Data Required	Time step	Resolution/Requirements
Population Size and Location	1-5 years	50m
Development and Land Use Maps	1-5 years	Coverage of residential area
Flood Defence data	Per change	Crest height and geometry, condition, standard of protection
Flood event data	Per event	Number of people affected, source and extent, presence and behaviour of defences, recurrence interval

Table 8.1: Recommendations for the data required to quantity exposure

In their global assessment of coastal flood damage Hinkel et al. (2014) estimated 0.2-4.6% of the global population would be annually flooded by 2100 (assuming no adaptation, and 25-123cm of global sea level rise). Using socio-economic drivers alone Hallegatte et al. (2013) estimate that average global economic flood losses will increase almost ten-fold by 2050. Climate change and population growth are expected to further stress the flood risk situation in the USA (ASCE, 2014). It is estimated that the 100 year floodplain in contiguous states could expand by 45% by the end of the 21st century (ASCE, 2014). In Europe risks and associated damages from flooding are expected to rise substantially (Mokrech et al., 2014).

Coastal flood defences moderate exposure and hence risk, however they increase the risk of catastrophic consequences in the case of defence failure (Hinkel et al., 2014). Planners need adaptive strategies including landward or vertical retreat from the sea (Woodruff et al., 2013). In the context of rising seas and increased exposure, adaptation is essential. Bruin et al. (2014) make the case for what they call “climate robust spatial planning” - making decisions that are insensitive to climate related uncertainties (such as the probability of flooding, potential damage costs). The methodology presented in this thesis could be used to aid climate robust spatial planning. Adaptation has been shown in a model of the European Union to be highly cost effective (Rojas et al., 2013). Proactive adaptation to flooding therefore makes sense both on economic and societal terms.
In order to fully remove exposure of the coastal population two extreme options are;

1. Remove the flood hazard, using structural intervention to prevent all flooding, for example construction of unbreachable dykes (Ligtvoet et al., 2011). Such defences are prohibitively expensive, and require a huge spatial footprint which is not feasible in the UK context; the coastline is vast and development is often very close to the coast. There are further negative social effects (unsightliness of huge structural defences, lack of access to the coast) and environmental effects (loss of habitat through construction, exacerbation of wave attack on coastal habitat).

2. Remove receptors (e.g. population) from the floodplain, for example by managed retreat/realignment. This has been practised in some coastal areas (Tollesbury in Essex, Medbury in West Sussex), however at current the main goal of these schemes has been restoration/creation of coastal habitat, rather than large scale removal of population. Managed retreat has not yet been conducted in a highly developed and populated area, such as the Portsea case study or other large urban conurbation.

In reality exposure of the coastal population cannot be totally eliminated (Sayers et al., 2015a); future management must focus on pro-actively managing risks within the social, environmental and politic context in which they occur. Discouraging floodplain occupation, for example by removing flood insurance or placing the burden of flood management on those who occupy the floodplain, may reduce future exposure; however it is likely to have adverse consequences for those who financially deprived and already living in the floodplain (Penning-Rowsell and Pardoe, 2015). There is not a clear solution to the high degree of exposure already present within the coastal floodplain.

It is likely that a gradual investment in exposure reduction based on anticipated future changes to climate and population size and location will reduce future losses. In their review of UK flood insurance Harrabin (2015) called for more money to be spent on preventing damages rather than clearing up. This is illustrated by the 2007 summer floods throughout parts of England and Wales, which cost an estimated £3 billion (Chatterton et al., 2010), compared to an annual budget for Flood Risk Management of £500 million. This insight is not unique to the UK. For example the financial losses due to Hurricane Katrina were estimated at $125 billion (USA Today, 2005; About US Economy, 2011). In comparison, the entire US Army Corps of Engineers' (the federal provider of flood defences across the US) budget for construction during 2005 was only $1.8 billion (USACE, 2004). Better investment in flood defences and preparation may have reduced the overall expenditure. The case of 'Super Storm' Sandy in 2012 would appear to support this point. The storm warning system in New York greatly reduced loss of life (Chan et al., 2014). Yet the FRM budget in the USA is less than half of what it should be (ASCE, 2014).

It is clear that how we prepare for, respond to and recover from flooding can have huge implications in terms of human and financial losses. There is an identified need for future management to be conducted in a proactive manner and this can only be achieved with a strong scientific knowledge base. It is therefore paramount to further our understanding of flood exposure, risk, the underlying drivers of change, and how we manage flooding. A combination of novel methodologies such as those developed in this thesis, and continued collection of high quality datasets on floodplain geometry, sea level and population will contribute towards increased knowledge and understanding in this field. This will aid coastal managers in making financially and socially responsible choices about where to deploy a limited budget as they prepare to face the challenges of an uncertain future.

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Appendices

- Appendix A: National Flood Risk Management Approaches
- Appendix B: A History of Flood Risk Management in the UK
- Appendix C: National Scale Assessment of Exposure to Flooding
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Appendix A

National Flood Risk Management Approaches

For a given country or region, the resultant mix of policies and measures adopted is dependent on characteristics and consequences of flooding, the desired level of risk, available budget and cultural aspects (USACE et al., 2011). Case studies can teach us how national objectives can mould the FRM system in different countries. The case studies were chosen to represent countries with advanced flood risk management practices and differing flood conditions. Developing countries such as the Philippines, Thailand or Bangladesh have a high degree of flood risk (e.g. BBC, 2012a; GFDRR, 2009; GFDRR and The World Bank, 2012; Butzengeiger and Horstmann, 2004; Bangladesh Government and The World Bank, 2008). However the flood risk management systems are largely ad-hoc and lack a clear structure. Such case studies therefore offer limited insight into FRM. Dedicated research into conceptualising ad-hoc FRM in developing countries is recommended, however this is outside the scope of this thesis. The case studies represent developed countries with formal FRM structures: England and Wales, the Netherlands, and the USA.

England and Wales have a vast coastline and high population density which contribute towards a high risk of flooding. The FRM system is well advanced and complex making England and Wales a useful and important case study.

The Netherlands was chosen for its rich history of flooding and flood management - water management is said to have started around the 9th century (Khatibi, 2011). In fact the Dutch water boards are credited as being the first democratic institutions in the Netherlands (VanKoningsveld et al., 2008), with the first dikes constructed in 500BC (Butzengeiger and Horstmann, 2004). An estimated 50% of today's population live in flood endangered areas with an economic value of 130 billion Euros (Steenhuisen et al., 2007).

The USA represents a country with huge spatial scales and a strong emphasis on local governance. The case study focuses on the local arrangements in the state of Louisiana, which sits on the gulf of Mexico. Louisiana faces flood risk from both the heavily controlled Mississippi and tropical cyclones such as hurricane Katrina in 2005.

For each case study an extensive literature review was carried out to estimate how the Flood Risk Management system links together at different scales and to form a system diagram. Components of management were characterised as being either operational (denoted by an O on the diagrams) or strategic (denoted by an S on the diagrams). An 'operational' measure is one with a physical effect, for instance a structural intervention or an emergency response. A 'strategic' measure is a plan or a policy that affects FRM but does not involve a physical action (i.e. in itself, it will have no effect 'on the ground'). For each case study an attempt is made to track where the funding comes from. Only the main linkages are highlighted in order to avoid overly complex diagrams from which no understanding can be learned.

A.1 Flood Risk Management in England and Wales

The flood risk management system in England and Wales is affected by a complex array of stakeholders and interests (e.g. Tompkins et al., 2008; Johnson and Priest, 2008). For a single locality, the National Audit Office identified 19 different plans and strategies that would affect flood risk planning (National Audit Office, 2011).

Flood management in the UK can be traced back to the middle ages where institutions existed for repairing sea walls and maintaining drainage ditches (Purseglove, 1988). The 1600s saw large scale drainage operations in the fens of East Anglia in order to claim land for agriculture (Purseglove, 1988). Such operations continued through England and Wales's history with a strong emphasis on 'flood control', an attempt to constrain rivers and water levels through structural intervention. In recent years England and Wales has undergone a widely recognised shift from flood defence (or flood control) to flood risk management. (e.g. Butler and Pidgeon, 2011; Johnson and Priest, 2008; Tunstall et al., 2009; McFadden et al., 2009; Khatibi, 2008). This new era in flood management put flood defences as one part of a wider management strategy. Spatial planning - keeping development away from floodplains, flood warnings, and emergency planning (i.e. planning responses to potential flood events) were of increased importance to flood managers. By the mid 1990s flood England and Wales had advanced flood forecasting and warning systems compared to the rest of the UK, with around 50% of the countries covered(Parker and Fordham, 1996). Since 1996 a structures programme was implemented to raise public awareness of flooding, and the respective roles of the Environment Agency (the government agency with main responsibility for flooding) and the public in helping to manage flood risk (Borrows, 2007).

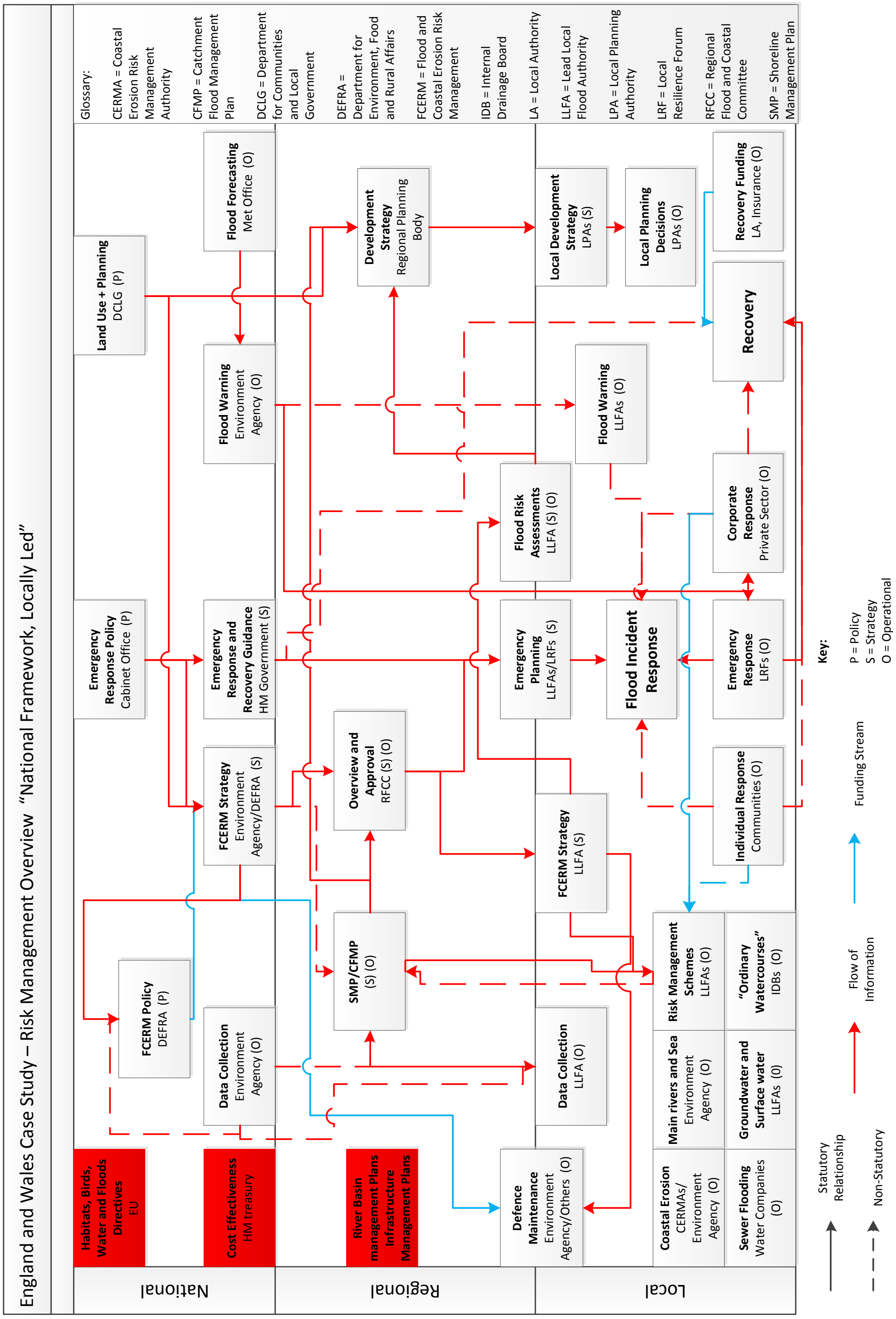


Figure A.1: The Flood Risk Management System in England and Wales. Key References: (EA and DEFRA, 2011; HM Government, 2010a; DCLG, 2009b, 2010; DEFRA, 2011; HM Government, 2010b; European Commission, 2011; HM Government, 2004; CCS, 2010; USACE et al., 2011)

England and Wales has a huge legacy of flood defence structures. There is an estimated £20 billion of sunk investment (Sayers and Saul, 2011) made up of over 25,400 miles of flood defences (EA, 2009a). As a result around £450 million is spent each year on maintenance and improvement (Sayers and Saul, 2011). By comparison £50 million per year is spent on remote sensing (for e.g. flood forecasting and coastal erosion mapping) (Hunt, 2002).

Compensation is mostly privatised by way of flood insurance - a way of 'risk pooling' where low risk homes effectively subsidise those at risk of flooding. Flood insurance began nationally in 1961 and until 2002 existed under government pressure as a 'gentleman's agreements' with the private flood insurance industry (Lamond and Proverbs, 2008). This agreement was formalised with the Statement of Principles (SoP) whereby insurers guarantee flood coverage to households in return for continued government investment in defences, reforms to land use planning and communication of flood risk to the public (ABI, 2005). This private insurance is widely available although a significant minority of households are refused flood cover (Lamond et al., 2009).
There are plans to reform flood insurance in England and Wales with a longer term solution to the "unsustainable" Statement of Principles (ABI, 2013). A schemed named Flood Re is proposed which introduces a cap to flood insurance premiums based upon council tax band (lower value homes have a smaller annual premium compared to more expensive homes). Flood Re is to be financed by a levy of 10.50 on all home insurance policies (ABI, 2013). The scheme provides a fund that is used to meet insurance pay outs in the case of large flood events.

In England around 12-16000 homes were built per year within high flood risk areas (defined by the UK environment Agency as being likely to flood once in 75 years) over the last decade (ASC, 2011). There are an estimated 6 million people (10%) at risk from river and coastal flooding and a similar amount from surface water flooding (Ramsbottom et al., 2012).

The system today is based upon a risk-based approach, with expected damage to be reduced by £5 for every £1 spent (EA, 2009a). An estimated 85% of potential damages (i.e. damages expected without defences or management) are prevented by existing management and defence systems (EA and DEFRA, 2011). The system has 3 main strands; flood and coastal erosion risk management, overseen by DEFRA (the UK government department for Environment, Food and Rural Affairs), emergency response and planning, overseen by the Cabinet Office, and land use planning, overseen by DCLG (the department for Communities and Local Government). The system is generally top-down, led by national policy and targets, with some feedback from local to a regional level by way of best practice guidelines (CCS, 2010). Other than flood forecasting, which is operated nationally, most FRM activities are undertaken operationally at the local level. Through policy documents and papers, the key components and linkages in the

FRM system have been highlighted (Figure A.1). The historical evolution of flood risk management in England and Wales is explored further within Appendix B.

The England and Wales system shows a high level of complexity (Figure 2.11). Flood risk management in England and Wales faces constraints at a national and international level from EU directives. Directives aimed at protecting habitat, water quality and preventing flooding affect all aspects of FRM and are therefore shown as unconnected red squares (Figure A.1). Additional constraints at a national level come from the treasury in its drive for cost effectiveness (i.e. HM Treasury, 2009).

Data collection at local level feeds up to influence Flood and Coastal Erosion Management (FCERM) policy nationally. FCERM policy then drives strategy at a national level. This feeds down through regional strategies in the form of Shoreline Management Plans (SMPs - coastal areas) and Catchment Flood Management Plans (CFMPs - inland areas). These strategies influence and are influenced by local risk management operation. Local management is the responsibility of several different agencies depending on the type of flooding; for instance FRM on main rivers is the responsibility of the Environment Agency, whereas groundwater and surface water flooding fall under local authority control.

Emergency response begins at a national level with policy underpinning national strategy. This is fed down to sub-regional emergency planning which determines flood incident response. Flood forecasting and warning are controlled nationally with warnings fed down to local level. Recovery is covered by national emergency response strategies and law and generally operated locally. There is some influence from (non-statutory) corporate response and the main funding stream comes from private insurance, although local authorities do also provide recovery funding in some cases.

Land use planning policy at a national level feeds into regional development strategies and through them local strategies. Operational decisions on land use are made at a local level under the guidance of these planning strategies.

A.2 Flood Risk Management in the Netherlands

The Dutch flood risk management system is characterised by a safety first approach (Steenhuisen et al., 2007; Gersonius et al., 2011). This comes as a direct result of the countries long history of living with the threat of flooding (VanKoningsveld et al., 2008). The approach adopted is not entirely surprising, given about a quarter of the country is below mean sea level, with around $\frac{2}{3}$ at risk from storm surges or river floods were defences not in place (Pilarczyk, 2007).

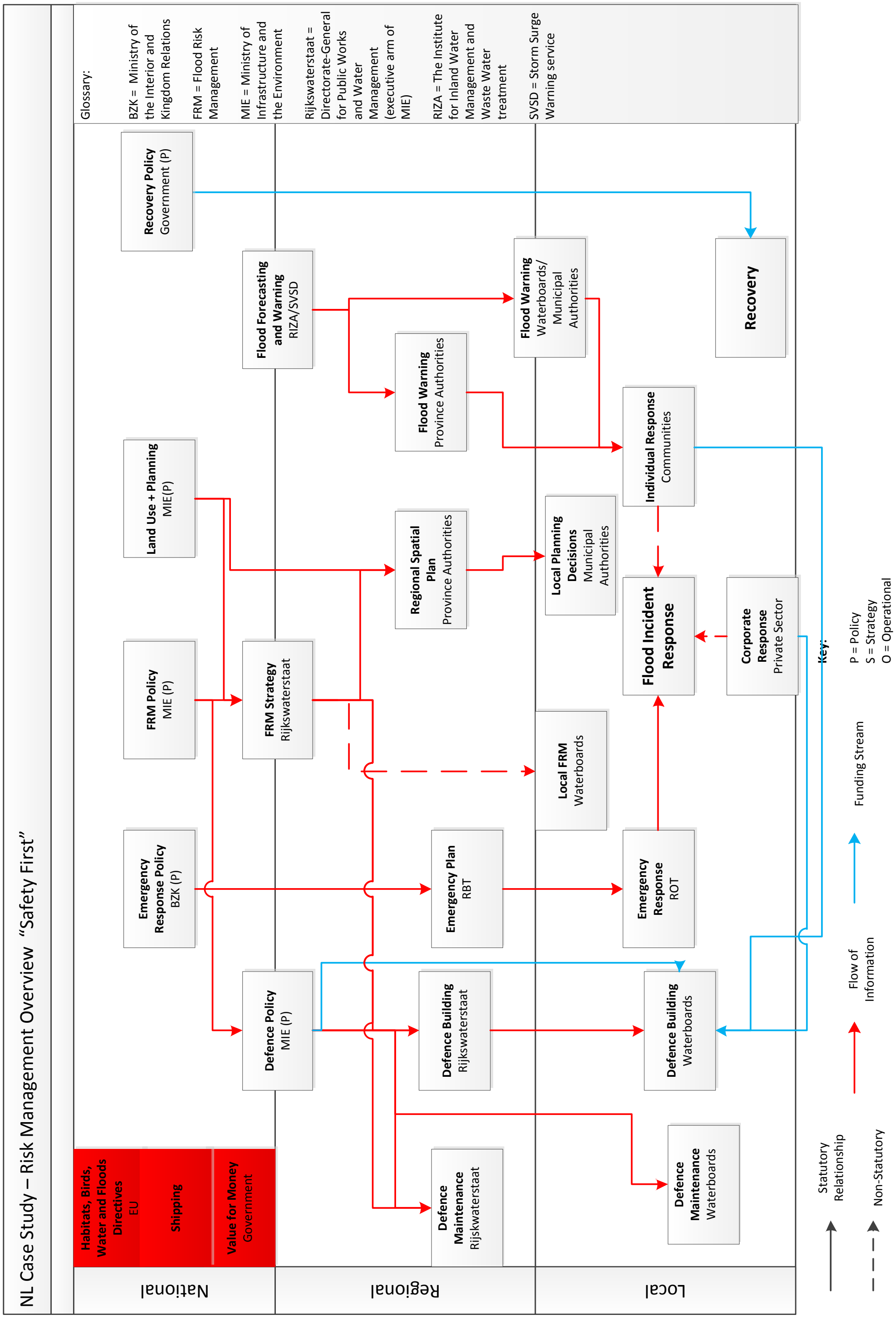


Figure A.2: The Flood Risk Management System in the Netherlands. Key References: (Van der Valk, 2002; Dutch Government, 2010; Parker and Fordham, 1996; Steenhuisen et al., 2007; Neuvel and van den Brink, 2009; Rijkswaterstaat, 2005)

The history of water management in the Netherlands started around the 9th century (Khatibi, 2011). Dutch society has always been receptive to new technologies and approaches in dealing with water challenges (VanKoningsveld et al., 2008). A study on behalf of OFWAT praised the Netherlands for its novel approaches to surface water management including roads acting as flood channels, water squares and floating homes (MWH, 2011). Laws dating to 1992 require members of the public to join 'dike armies' to assess and repair dike damages in the case of urgent danger (Parker and Fordham, 1996). The law also requires two infantry battalions to be on standby for dike repairs during flood season.

As with England and Wales, the Netherlands has seen a switch from flood control (attempting to stop all flooding) to risk based approaches (Broekhans and Correlje, 2008). However there is still a strong emphasis on structural intervention. Flooding is perceived not as a natural hazard but as an external safety risk which can be mitigated (Dutch Government, 2010). Perhaps as a result of this history of flood prevention, risk perception amongst the public is considered low (e.g. Botzen et al., 2009; Terpstra and Gutteling, 2008; Dutch Government, 2010).

In contrast to England and Wales private insurance system, the Dutch rely instead on government compensation and relief (Veraart et al., 2010). Between 1965 and 2001 flooding was considered an 'uninsurable risk' by insurance companies (i.e. companies would not provide flood cover to households) (Veraart et al., 2010).

The Dutch system today (Figure A.2) differs from that of England and Wales in that both FRM and land use policy are coordinated by the same government department (the Ministry of Infrastructure and the Environment). Flood forecasting is done at a sub-national level, and major defence building regionally, with smaller defences and measures being achieved locally.

The Dutch flood risk management system is relatively straightforward and segmented by its different functions of defences, emergency response, spatial planning and recovery (Figure A.2). As with England and Wales, the Dutch flood risk management system is bound by international and national constraints from EU directives on Habitats, Birds, Water and Floods. Further constraints come a from national focus on shipping: watercourses cannot simply be closed down to protect against flooding because they are required for international trade. Further constraints come from the need of government to ensure value for money in all spending.

Flood Risk Management policy drives national strategy which then influences both regionally development planning and regionally defence maintenance. Defence policy at a national level drives defence building and determines the funding at a local level.

Emergency planning starts with national policy when feeds through regional emergency plans into a local emergency response. Individual response can play a (non-statutory) part in flood incident response overall. Recovery is separate to emergency response with compensatory laws determining the level of funding received for recovery locally.

Land use planning national policy influences both national flood risk management policy and regionally planning strategies. Regional strategies influence decisions which are made at a local level.

A.3 Flood Risk Management in the USA

Floods are the most prevalent hazard in the USA (FEMA, 2001). In the USA governance varies at a local and regional level between the states. The state of Louisiana was chosen for a case study since it faces a high level of flood risk and has a rich history of active flood management (Rogers, 2008; McKenzie and Levendis, 2010; Burby, 2006). Whilst the spatial scale of the USA is greater than that for England and Wales or the Netherlands, there is some degree of national influence on FRM and therefore the same national-regional-local scale format can be maintained.

The large spatial scale of the USA is highlighted by the vast investment in flood management in the country. The country has a history of using levees to control large rivers which provide good protection up to design standards and are relatively cheap and easy to build (Tobin, 1995). The US Corp of Engineers estimate a cost of $2.2 trillion to maintain levees at a desirable standard (Sayers and Saul, 2011). Meanwhile £1500 million is spent each year on remote sensing for weather, flooding and coastal processes (Hunt, 2002).

Physical flood management systems have evolved over a long time scale. The flood protection system in New Orleans and its adjoining parishes is said to have evolved over a period of 280 years (Rogers, 2008). Pumps for removing water from low lying areas were built around the start of the 20th century (Rogers, 2008). From 1927 the US Army Corps of Engineers (USACE) assumed a leadership role in structural measures along the Mississippi (Rogers, 2008). However the corps built levees that were designed mostly to facilitate shipping, not to protect against frequent flooding (Harrison and Press, 1961)Following a series of lawsuits in the 60s and 70s USACE were forced to build concrete flood walls as part of flood protection works, however some elements of these new defences remained unfinished when hurricane Katrina hit in 2005 (Rogers, 2008).

The USA is unique in the three case studies in its approach to compensation. The countries national flood insurance programme (or NFIP) combines flood insurance, spatial planning and hazard mapping (FEMA, 2010). Designed as an alternative to disaster assistance, the voluntary NFIP provides flood hazard maps and government backed flood insurance in return for sound floodplain management. The NFIP has run since 1968 and

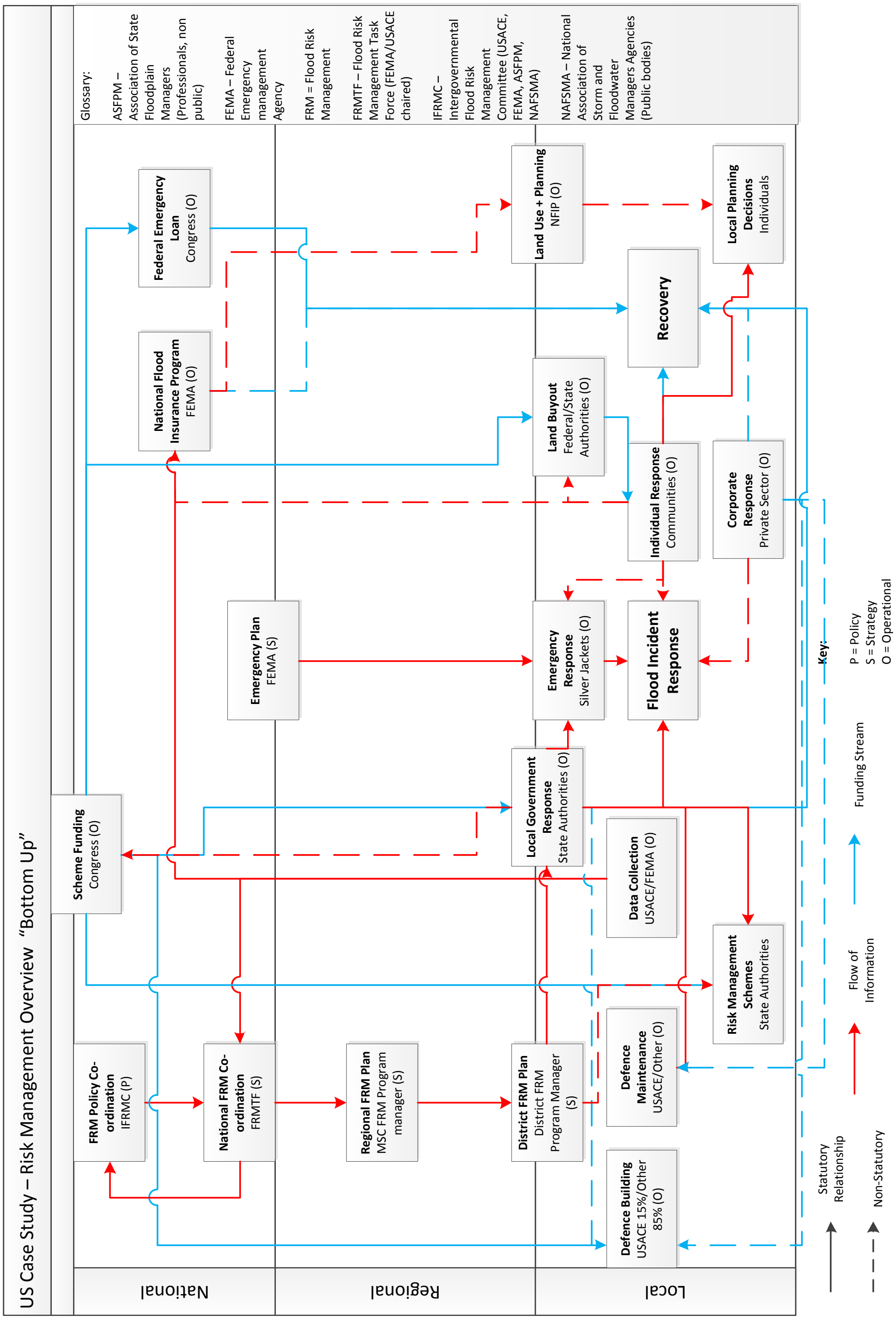


Figure A.3: The Flood Risk Management System in the USA. Key References: (USACE, 2009; USACE et al., 2011; Rabbon, 2008; FEMA, 2004, 2008; ASFPM and NAFSMA, 2007; Rogers, 2008) today covers $1.23 trillion of assets (Michel-Kerjan et al., 2012). Despite this programme however only 9% of residents in high risk (defined as a 25% chance or more of flooding over a 30 year period) and less than 1% in lower risk areas across the US mid-west have flood coverage (FEMA, 2008).

The system in the USA today is predominantly locally (sub state level) led, with limited national co-ordination (Figure A.3). The last attempt at national co-ordination occurred in the 1994 unified national program for floodplain management (ASCE, 2014). The USA has a less interventionist approach to governance than many European countries. This is reflected in their FRM, where a lack of national legislation, regulation or funding mechanisms has allowed innovation to flourish (MWH, 2011). The system is almost a polar opposite of the top down approach in England and Wales, relying on local initiatives to be fed up the system to get funding. Land use planning is a local issue, influenced but not controlled by national government via the National Flood Insurance Program (NFIP) (FEMA, 2008), which aims to remove houses from the flood plain by subsidising insurance for those who comply.

The American system is largely driven by the economy with the flow of funding determining management 2.13. Unlike it's European counterparts the American system does not face international or other external constraints.

FRM policy is coordinated nationally with national, regionally and sun-regional plans influencing risk management schemes locally. Funding for risk management and defence building schemes must be applied for locally with congress at a national level determining whether funding is granted.

Emergency response is coordinated nationally by emergency plans which determine the response at a local level. Local government, individual and corporate response also contribute largely towards flood incident response. Recovery funding comes from individuals with some compensation from local government via congress authorised funding.

Spatial planning decisions are made at a local level with virtually no national constraints or control. Development control is instead influenced by the national flood insurance program which provides recovery funding and insurance in return for development control in areas of high flood risk (FEMA, 2008; USACE, 2012).

A.4 National Scale Flood Risk Management Overview

The case studies presented share a common theme with the system split broadly into spatial planning, emergency response and planning, and the more physical flood risk management measures such as structural defences.The Dutch and British systems have an additional strand of flood forecasting warnings, which do not form such an integral part of the American system. Emergency response and planning, and flood forecasting and warning come under the umbrella term 'flood incident management' (e.g. Dawson et al., 2011b; EA, 2009b, 2006)). These components of the national level flood risk management systems are seen in Figure A.4.

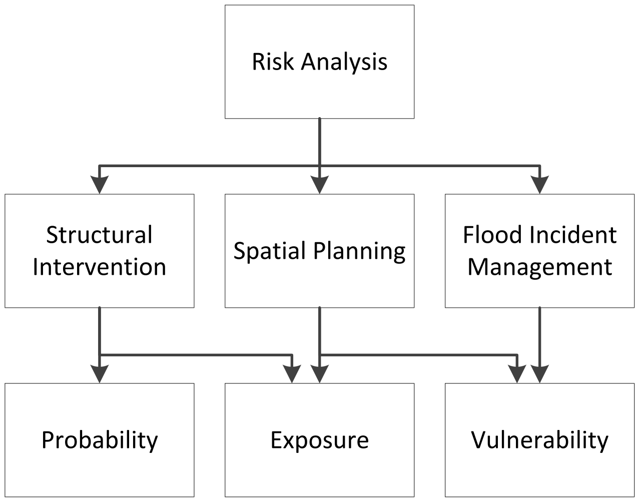


Figure A.4: Flood Risk Management components

All of the management systems follow the pattern of national strategy leading to regional and local actions, with measures carried out at all spatial scales from governmental at the national level to individual response at the local level. The British system is connected much more formally than the other two, with plans and strategies interdependent on each other. The Dutch system by contrast is more "top-down", with direct links from national policy to local action and fewer inter linkages. The American FRM system has less statutory links and is much more driven by the flow of funding, representing a more privatised management style.

The case studies show the complexity of flood risk management and the many activities and scales that encompass it. Further understanding of the FRM system can be achieved by evaluating these risk management activities.

Appendix B

A History of Flood Risk Management in the UK

In this chapter an in depth evaluation of how a national flood risk management (FRM) system has changed through time is presented. The FRM system in the UK is outlined from the beginning of the 20th century to present day. Diagrams are used to show changes to the management system at key points in its history.

B.1 Rationale and Motivation

In the literature review FRM was defined in terms of its components (Figure B.1). In this study the scale at which these components acted and the time at which they were adopted is reviewed. Historic FRM changes in the UK are organised into the following time periods: pre 1900-1930, 1931-1955, 1956-1975, 1976-1990, 1991-2005, and 2006-2011. These are chosen based upon the biggest changes to the FRM system in the UK.

B.2 Methodology

A literature review was conducted into FRM interventions in the UK from 1900 to 2011. An intervention in this context is defined as a national policy or strategy which affects FRM. For example the Land Drainage Act of 1930, or the more recent 'Making Space for Water' government strategy of 2005.

A system diagram is produced for a snapshot in time at the end of each of these periods. These diagrams are colour coded to differentiate between the type of measure or policy introduced; structural intervention (grey), spatial planning (orange), flood incident management (blue) and risk analysis (green). These measures are displayed in boxes

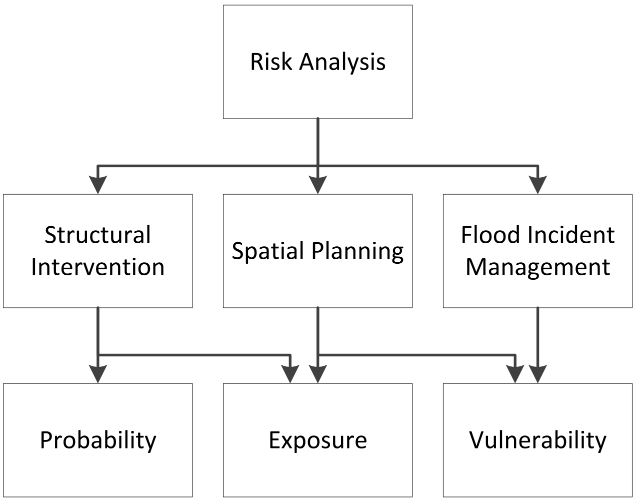


Figure B.1: The components of Flood Risk Management as defined through the literature review

whose position represents spatial scale - either national, regional or local. FRM measures are further categorised as being related to either policy (i.e. laws and legislation), strategy (i.e. planning, organisational) or operational (i.e. where a measure is physically carried out such as a local defence being constructed). These categories are represented in the diagrams with a letter in each box; P for policy, S for strategy and O for operational. The links between measures (for example how a national strategy interacts with local operation) are shown on the diagrams as arrows. A broken arrow represents a non-statutory (i.e. advisory, not required by law) relationship, and an unbroken arrow represents a statutory relationship.

National flood management policies in the UK fall broadly into two categories: water management policy (such as Land Drainage or Water Resources acts), and spatial planning (development and planning laws). Legislation dealing with Land Drainage has existed for at least 5 and a half centuries (ICE, 1996). National water policy is charted from its beginnings with the Land Drainage Act of 1930, the culmination of various preceding drainage acts (Trent River Authority Records, 1975).
FRM planning in England forms part of a wider spatial planning policy that governs all aspects of development and land use. The planning system today uses a series of Planning Policy Statements and accompanying guidance to "explain statutory provisions and provide guidance to local authorities and others on planning policy and the operation of

the planning system"[1]. Individual planning applications are traditionally the responsibility of local authorities, with a few exceptions for "nationally significant infrastructure projects", including nuclear power stations (Infrastructure Planning Commission, 2011).
The study has been divided into six key 'eras' chosen to reflect the biggest changes to the FRM system in England and Wales. The first of these eras is 1900-1930 which saw the start of national co-ordination of flood management practices - namely through the Land Drainage Act 1930 (ICE, 1996).
The second era is 1931-1955 which saw the start of national coastal management with the Coast Protection Act 1949 and the countries worst coastal flood event with the North sea floods of 1953. The floods sparked creation of the countries first nationally coordinated flood warning system (EDMED, 2000).
The next era covers 1956-1975 which saw the 'water revolution' of the 1973 Water Act. Existing regional institutions were subsumed under 10 regional water authorities (which evolved into modern day water companies) (Parker and Penning-Rowsell, 1980).
The fourth era covers 1976-1990, an era culminating in the birth of modern day flood risk management (as opposed to the previous paradigm of 'flood control'). This era saw the birth of the National Rivers Authority (NRA), a national body with wide ranging powers including flood risk management. The NRA is the direct descendant of the Environment Agency whom coordinate national flood risk management in the modern day.
The fifth era is 1991 - 2005 in which the new idea of flood risk management evolved into a fully integrated system encompassing flood defence, flood warnings and response (Butler and Pidgeon, 2011). Spatial planning was strengthened with several government circulars forming the basis of PPG25 - Development and Flood Risk, which introduced flood risk based land zoning into the planning system.
The final era runs from 2006-2011 which saw the countries first flood-specific legislation (previous laws had applied to water resources or planning in general with flood clauses) with the Flood Risk Regulations 2009. These were followed by the Water and Flood Management Act 2010 which together served to clarify government flood policy and incorporate European Union directives (DEFRA, 2011).

B.3 A Review of UK Flood Risk Management

The results of the literature review study are shown below. For each time period the key changes to FRM are described and a systems diagram of the FRM system displayed. Relevant international policies are described in Section B.3.8 of this appendix.

[1]See the Department for Communities and Local Government website at http://www.planningportal.gov.uk/planning/planningpolicyandlegislation/currentenglishpolicy/ppgpps

B.3.1 1900 - 1930: Implementation of National Co-ordination

Before the Land Drainage Act 1930, water management was "uncertain and fragmented" (ICE, 1996), and had been carried on an ad hoc basis at a local scale by varying authorities such as sewer boards, drainage boards and navigation authorities. Flood prevention on main rivers was the responsibility of local authorities, and there was no real national co-ordination.
The 1930 Land Drainage Act worked to consolidate preceding legislation and better define responsibilities. It was set up in part as a result of a Royal Commission, which suggested complete change in administration of land drainage, and also due to devastating floods in 1928 (BBC, 2003). In effect it marked the start of national FRM policy, creating a code of law relating to land drainage and made available increased financial resources to encourage the activities of drainage authorities (National Archives, 1997). The Act amalgamated the navigation authorities and drainage districts into sub-regional Catchment Boards, who had responsibility for main rivers, and also created Internal Drainage Boards (IDBs) responsible for water levels in local districts where drainage was a particular issue.
Some spatial planning acts did exist pre-1930, however they were focussed on provision of social housing (such as the Housing, Town Planning, &c. Act 1919), with no mention of development control. Development and planning was a local issue with no apparent national guidance, although some limitations were exercised through Public Health and local Acts[2]. However maps of early settlement in lowland Britain reveal a pattern of villages located just above areas periodically inundated (Purseglove, 1988). This suggests a sensible caution against living in flood prone areas, despite the lack of national planning legislation.

The FRM system in 1930 is seen in Figure B.2. Structural Intervention policy at a national scale has a statutory link to operation for main rivers at the sub-regional scale. Structural interventions for smaller rivers (termed 'ordinary watercourses') and land drainage are achieved operational at the local level with no strong statutory links to national policy. Spatial planning is achieve locally with no integration to national or the FRM system.

B.3.2 1931 - 1955: Concrete is King

The period of transition following the Land Drainage Act 1930 (LDA1930) lasted in some cases until 1941 (Trent River Authority Records, 1975). Despite the creation of catchment boards by the LDA1930 legislation, water resources planning by 1945 was still seen as a "highly localised activity with little co-ordination at either a regional or national level" (OFWAT and DEFRA, 2006), and "little was done for the coast"

[2]See http://www.planning-applications.co.uk/an%20introduction.htm for a brief history of the British spatial planning system

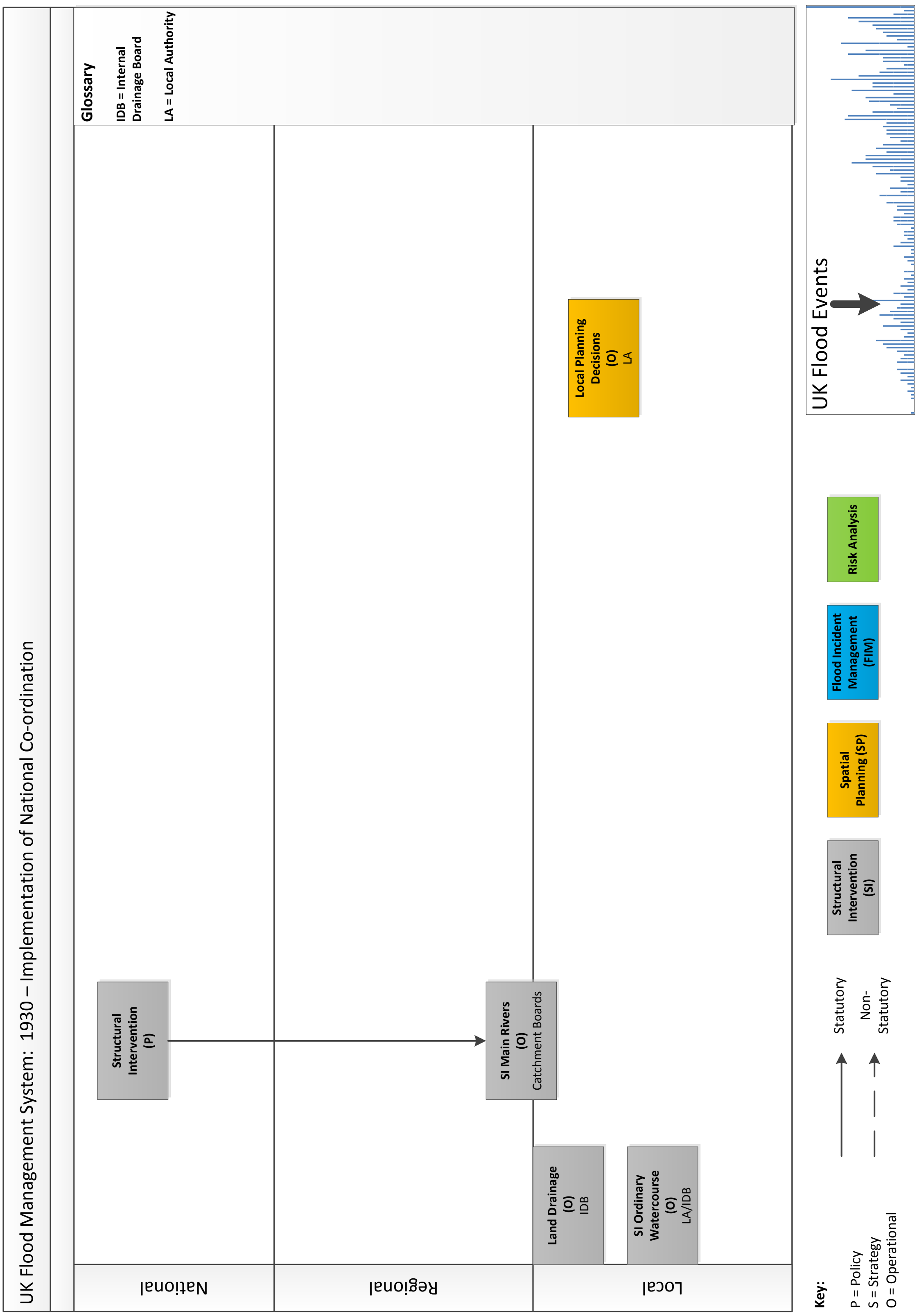


Figure B.2: The England and Wales Flood Management System in 1930

(BBC, 2003). It is in this context that the Catchment Boards were overhauled with the passing in 1948 of the River Boards Act. The new River Boards brought responsibility for drainage, fisheries and pollution under one single authority, known as River Boards (Trent River Authority Records, 1975). The same decade also saw the onset of national coastal protection policy, with local authorities (known for this purpose as Coastal Protection Authorities) given responsibility for defending their coastlines under the 1949 Coast Protection Act. Little change occurred until the North Sea Floods of 1953, which sparked creation of the first nationally coordinated flood warning programme, the Storm Tide Warning Service (EDMED, 2000). This service catered to the East Coast in an attempt to prevent the events of 1953 from happening again.
The sensible caution shown during the early 1900s in avoiding development within floodplains waned during the 1930s and 1940s, which saw unplanned urban growth spill onto the floodplains and low lying coastal areas (Werritty, 2006). Development and planning remained a purely local issue, with no major changes in this period. The birth of modern development control came with the 1947 Town and Country Planning Act, which introduced planning permission on a national scale. The act contained no specific flood related clause however.

The FRM system in 1955 is seen in Figure B.3. Structural interventions for smaller watercourses and land drainage remain an isolated local activity. Structural interventions for main rivers has evolved with regional strategies now informing more local operation. Coastal erosion management activities are informed by national policy and achieved locally, with a non-statutory link to the sub-regional level for local authorities who choose to work together. Spatial planning remains an isolated local activity. Flood Incident management has been introduced with flood forecasting at the regional level informing local flood warnings.

B.3.3 1956 - 1975: The 'Water Revolution'

There was little change to the FRM system during this period until the early 1960s, with the passing into law of the Water Resources Act 1963. This act replaced the River Boards with River Authorities, with increased powers for fisheries and pollution. It also introduced the Water Resources Board, a "go between" for government and the new authorities to offer advice, but with no executive powers of their own (OFWAT and DEFRA, 2006). In relation to FRM little changed over this period, with River Authorities simply replacing River Boards for the agency with FRM responsibility for main rivers. The major change came in the 1973 Water Act which amalgamating the existing River Authorities into 10 regional Water Authorities. The new Water Authorities had responsibility for all aspects of the hydrological cycle, representing a move to integrated water management. The act also created Regional Land Drainage Committees (RLDCs), which kept land drainage a separate entity from water resources, after

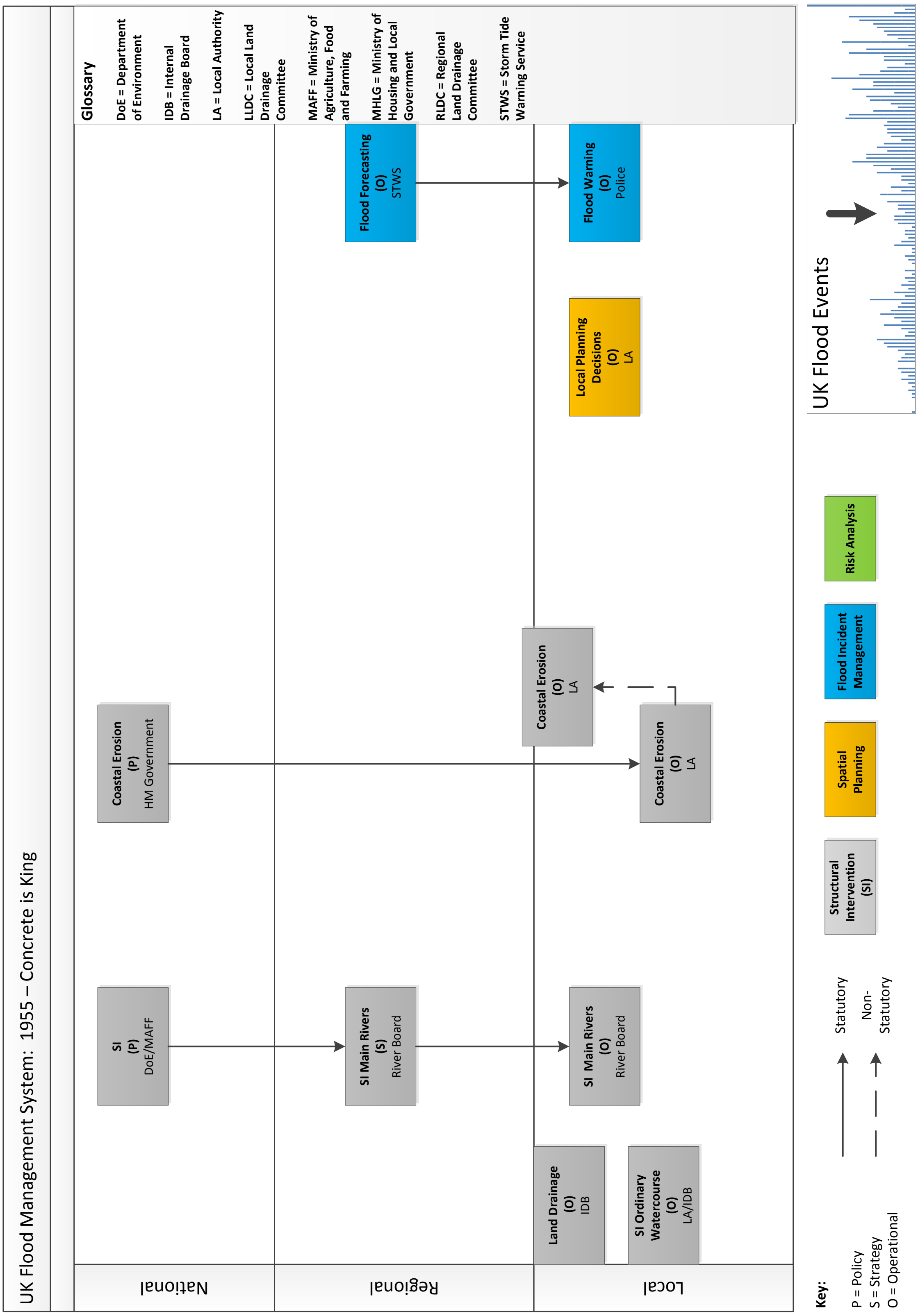


Figure B.3: The England and Wales Flood Management System in 1955

successful lobbying by the Ministry for Agriculture, Food and Fisheries (MAFF) and agricultural groups (Parker and Penning-Rowsell, 1980). In practice the committees delegated operational responsibility to Local Land Drainage Committees (LLDCs), retaining financial and strategic control (Parker and Penning-Rowsell, 1980). The act also introduced statutory data collection in the form of surveys by the Water Authorities which aimed to build a picture of national flood and land drainage problems (Parker and Penning-Rowsell, 1980). The short-lived Water Resources Board (WRB) was replaced with the Central Water Planning Policy Unit (CWPPU), who had more of a research and development role, and a National Water Council was introduced to fill the "go-between" role WRB had formally played (Parker and Penning-Rowsell, 1980).
Change to development during this period came in the form of the 1969 Ministry of Housing and Local Government Circular (94/69), which called for "rigorous investigation at the planning stage" into drainage from new development (ICE, 1996). In reality this circular has little effect on the system.

The FRM system in 1975 is seen in Figure B.4. There are several changes compared to the 1955 FRM system. Local land drainage operations are informed by statutory regional strategy, and statutory data collection (risk analysis) has been introduced to inform regional strategies for main rivers. Structural interventions on main rivers are further informed by national strategy, linked to policy at the national scale. Coastal erosion activities remain as they were in 1955, with local activities informed by national policy, and a non-statutory link to the sub-regional level for local authorities who work together. Spatial planning remains operational at the local level, with national strategy forming a non-statutory link (i.e. planning advice). Flood Incident Management remains as it was in the 1955 system, with regional forecasting informing local flood warnings.

B.3.4 1976 - 1990: Birth of Flood Risk Management

The 1976 Land Drainage Act introduced government funding to Water Authorities for any land drainage or flood alleviation work they had to carry out, provided as grant aid by MAFF (OFWAT and DEFRA, 2006). In 1978 a West Coast flood warning service was introduced following severe floods in 1976 and 1977 (Flather and Proctor, 1982). The next change came in 1983 with the abolition of the National Water Council with the Water Act 1983, as it was deemed ineffective (OFWAT and DEFRA, 2006). In addition the South coast was included in warning programmes (EDMED, 2000).
1989 saw the biggest change in a generation with the 1989 Water Act, which served to privatise the water industry, keeping flood management in government hands with creation of the National Rivers Authority (NRA). The NRA's work operational duties for main rivers were carried out via Regional Flood Defence Committees, which replaced Regional Land Drainage Committees. As with the land Drainage Committees, operational duties on a local scale were further devolved to local committees. During these

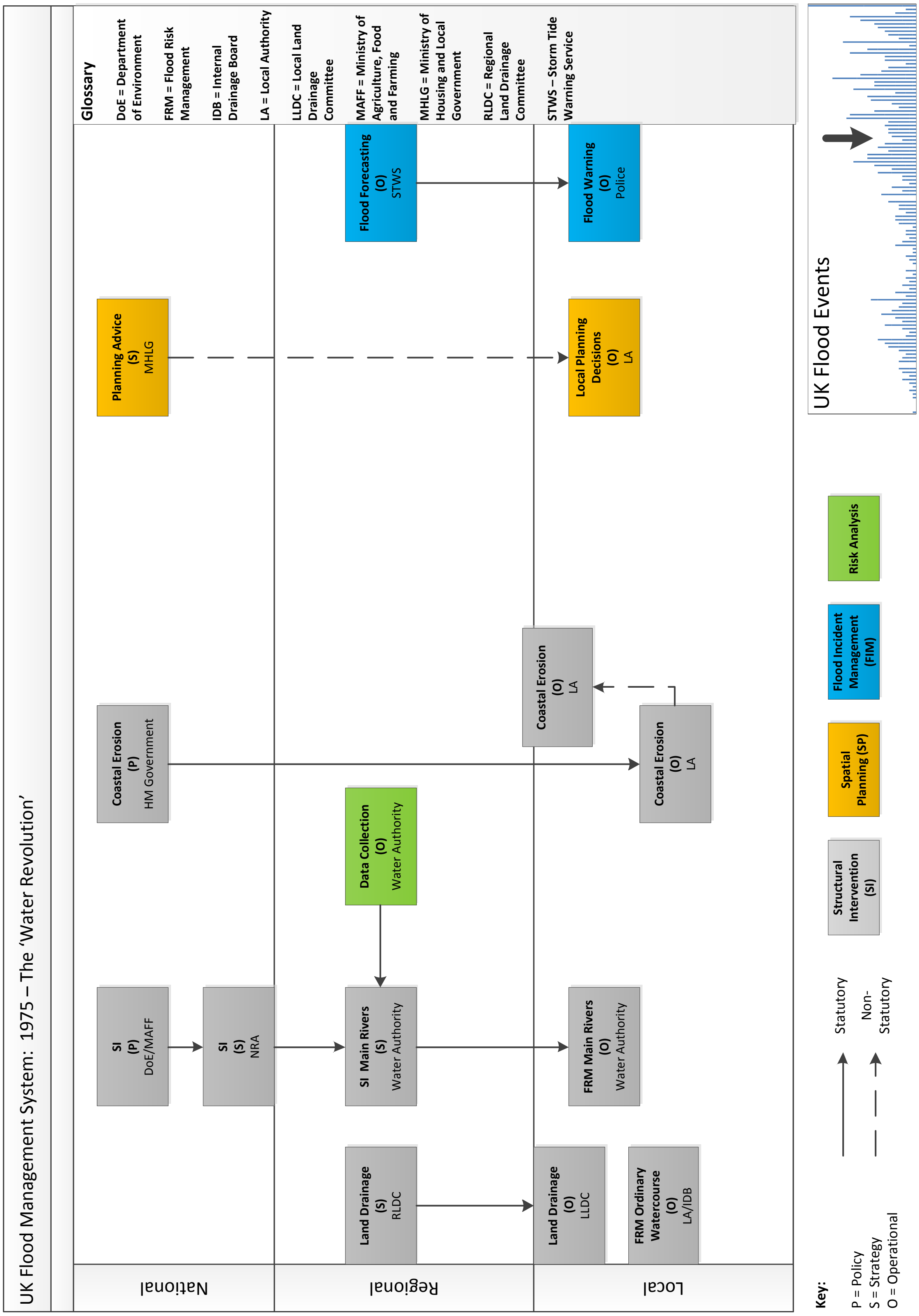


Figure B.4: The England and Wales Flood Management System in 1975

changes Internal Drainage Boards (IDBs) retained responsibility for their areas, and local authorities retained responsibility for ordinary watercourses in non-IDB areas.
A further circular in 1982 stated that where land drainage considerations arise, they should always be taken into consideration in planning (ICE, 1984). But again little change was noted with an inadequate amount of control exercised by planning authorities (ICE, 1984).

The FRM system in 1990 is seen in Figure B.5. In terms of its structure, the FRM system in 1990 is very similar to the system seen in 1975. The key change is the introduction of risk analysis activities at every spatial scale to underpin structural intervention strategy and operation (shown by the green shadows to the boxes). Structural intervention on smaller watercourses is linked to national strategy, with main rivers remaining operation locally, led by regional strategy and national strategy and policy. Coastal erosion remains structurally the same as for 1975, but with local and sub-regional operation underpinned by risk analysis activities. Spatial planning remains operational locally, with a non-statutory link to national strategy. Flood forecasting remains at the regional scale (although the spatial distribution is wider compared to that in 1975), linking to flood warnings locally.

B.3.5 1991 - 2005: Integrated Management

In this period FRM in England and Wales has involved a shift from flood defence into a more integrated flood risk management system (Butler and Pidgeon, 2011; Newman et al., 2011), encompassing flood defence, flood warnings and response. This shift can be seen on a governmental level by the merging of the Ministry of Agriculture, Fisheries and Food (MAFF) and the Department of the Environment (DoE) into the Department for Food and Rural Affairs (DEFRA) in 2001 bringing together most FRM activities under one government department (although spatial planning remains under another). At the strategic level the shift is seen in the Environment Agency(EA), whom were born out of the NRA in the Environment act 1995. The Environment Agency took responsibility for flood warnings (formerly the responsibility of the police) and together with DEFRA formed national strategy documents encompassing risk from both flooding and coastal erosion (EA and DEFRA, 2011). 2005 saw the publication of ‘Making Space for Water’ following a consultation exercise, which suggested a more holistic approach to FRM, thus better aligning with “sustainable development” aims of the government (DEFRA, 2005).
Perhaps most importantly, this period saw the start of nationally coordinated emergency response with specific guidance on flooding, which came about in the Civil Contingencies Act 2004. This act created Local Resilience Forums(LRFs), responsible for emergency planning and response for their areas (CCS, 2010), working to co-ordinate the emergency services and other responders.

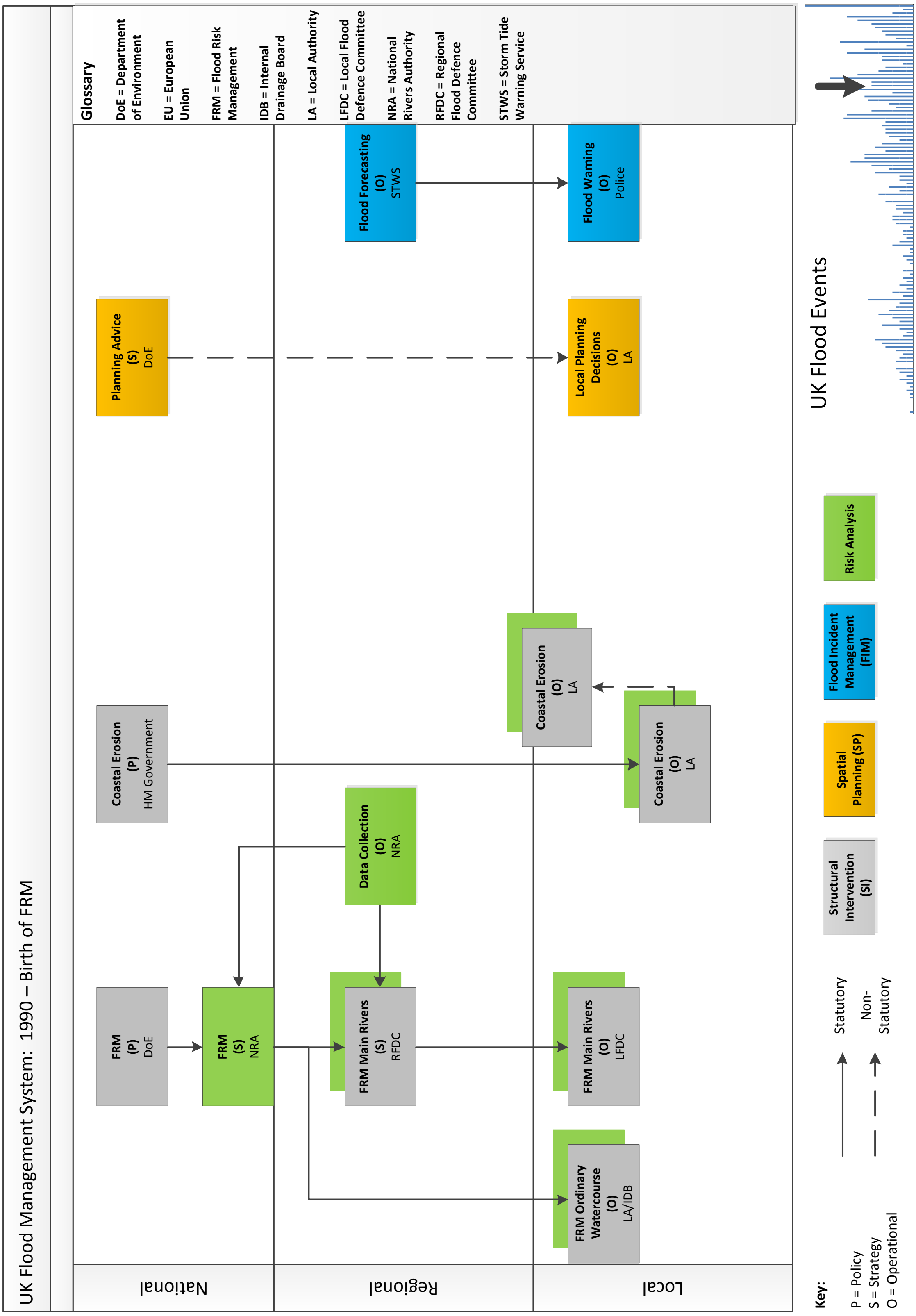


Figure B.5: The England and Wales Flood Management System in 1990

In 1992 the Department of the Environment released DoE Circular 30/92 (MAFF Circular FD1/92), which called for the National Rivers Authority to take an advisory role on developments where drainage/flood risk was a potential issue. This was effectively the precursor for PPG25, however remained non-statutory. 1992 also saw the publication of PPG20 Coastal Planning, which put restrictions on development in coastal areas (DoE, 1992). In 1995 the NRA's advisory role was put into statute in The Town and Country Planning (General Development Procedure) Order 1995. This was further strengthened in 2001 with the publication of PPG25 Development and Flood Risk, which introduced land zoning, in addition to an advisory role by the Environment Agency in development decisions involving flood risk.
The 1992 European Union Habitats Directive has a strong influence on structural interventions. Schemes must consider the likely impacts on local habitats, and any habitat destroyed to facilitate a structural scheme must be compensated for (see Appendix B.3.8).

The FRM system in 2005 is seen in Figure B.6. The system is influenced at a national scale by European Union Habitat Policy which requires environmental consideration in all FRM activities. Structural intervention policy at the national scale informs national strategy which informs regional strategies. Both regional and national strategies are informed by regional data collection. These strategies inform local structural interventions, underpinned by local risk analysis. Coastal erosion policy at the national scale informs local and non-statutory sub regional operation, both underpinned by risk analysis. The key change to the FRM system from 1990-2005 is introduction of emergency response as part of flood incident management. National policy informs sub regional strategies, which inform local responses. Spatial planning policy at the national scale has a statutory link to local decisions. Flood forecasting remains at the regional level, informing local flood warnings.

B.3.6 2006 - 2011: 'National Framework, Locally Led'

FRM continued to evolve over the period 2006-2011, with the first 'flood specific' policy entering into force with the 2009 Flood Risk Regulations and 2010 Water and Flood Management Act, which served to consolidate previous legislation, better define responsibilities, and incorporate new UE Directives such as the Floods Directive 2007 (DEFRA, 2011). Following the devastating floods of 2007, and corresponding Pitt Review (Pitt, 2008), an improved countrywide forecasting and warning service was created. The Flood Forecasting Centre was to be ran jointly by the EA and the Meteorological Office (Met Office, 2009).
Emergency planning and response was bolstered with publication of national strategy, giving guidance to LRF's to help them in their local planning (HM Government, 2010a).
In 2006 PPG25 was further strengthened with the publication of PPS25, with served to

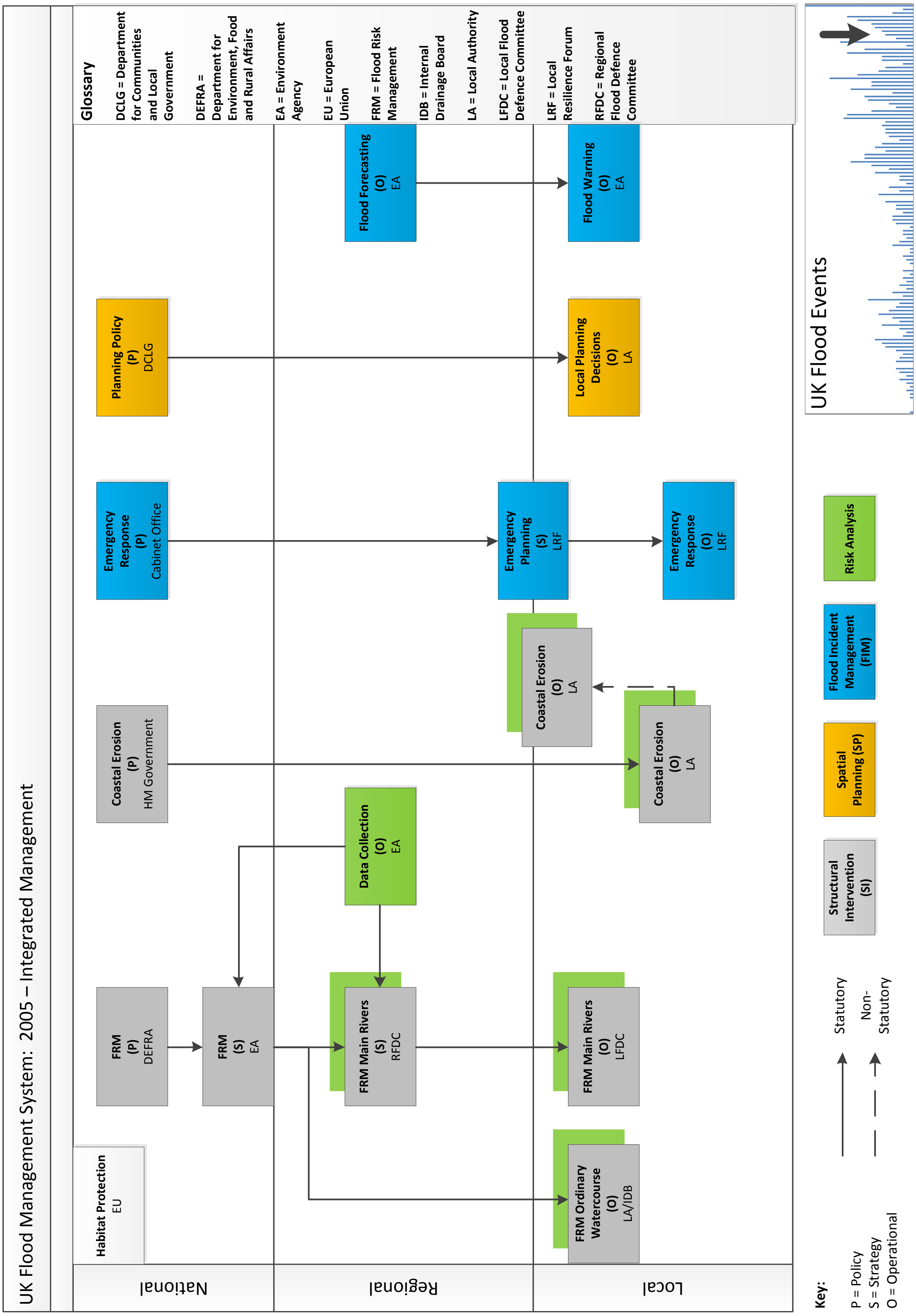


Figure B.6: The England and Wales Flood Management System in 2005

clarify PPG25 and leave it less open to interpretation (DCLG, 2006). PPS25 was further updated in 2010, with some changes to development restrictions following consultation with key stakeholders (DCLG, 2010).
The 2000 European Union water framework introduced river basin management plans, which influence all regional risk analysis strategies. The 2007 Flood directive introduces flood mapping as a statutory necessity, strengthening existing risk analysis activities. Government drive for cost effectiveness (e.g HM Treasury, 2009) influenced all aspects of FRM operation.

The FRM system in 2011 is seen in Figure B.7. The system shows a high level of complexity with links between different scales and FRM components (e.g. regional risk analysis plans inform spatial planning operation). Existing structural intervention policies seen in previous FRM systems are replaced by risk analysis national policy and strategy which inform regional risk analysis strategy and operation. These regional activities inform local structural interventions and also local spatial planning and flood incident management.
Flood incident management policy at the national scale informs national and sub-regional strategies which inform local responses. Individual and corporate responses at the local level have a non-statutory link to flood incident responses and recovery. Recovery funding comes mainly in the form of private flood insurance which operates locally (i.e. at the level of households). Flood forecasting and warnings operate nationally, informing local warnings to areas at risk.
Spatial planning policy informs regional and sub regional strategies which inform local operation.

B.3.7 2012 and beyond

It is widely noted that effective flood management should be proactive rather than reactive (e.g. Howe and White, 2004; DEFRA, 2005). A portfolio of response should be considered to evaluate and manage risk in an effective way (Sayers et al., 2015a). The continued emphasis on data collection and strategic planning in the FRM system in England and Wales supports this goal. However truly proactive management requires that the FRM system must be fully understood. Therefore for an effective proactive system, modelling of system behaviour is paramount.
In 2012 UK planning law was overhauled with the introduction of the planning policy framework. The policy replaced previous guidance (the Planning Policy Statements (PPS)) and notable introduces a "presumption in favour of sustainable development" (DCLG, 2012a). Guidance was condensed from over 1000 pages to just over 50. It is not yet clear how this policy will affect long term spatial planning, however at the time of consultation it was feared that the law could lead to an increase in flooding (NFF, 2011).

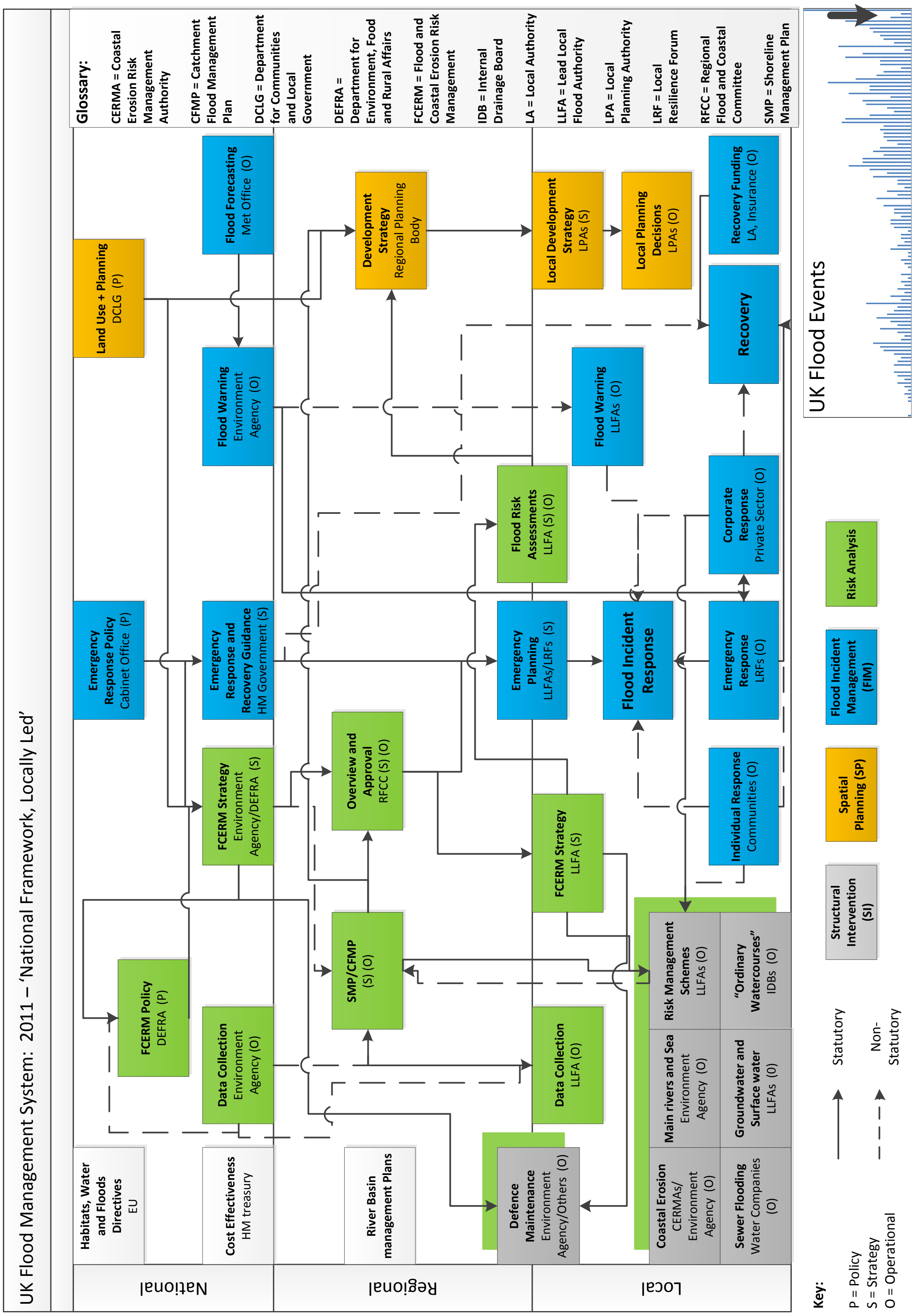


Figure B.7: The England and Wales Flood Management System in 2011

Environmental and social drivers of flood risk are expected to accelerate during the 21st century (Section 2.2.2). Sea levels are expected to rise and winter rainfall increase in intensity, increasing the probability of flooding. Further urbanisation and population rise are likely to increase flood exposure whilst population ageing will drive up the vulnerability of the population. The combination of these factors means future flood risk will increase, with severe implications for the way in which future flood risk is managed.

B.3.8 International Policy For UK FRM

International constraints affecting FRM in England and Wales come in the form of EU Directives. These directives "Lay down certain end results that must be achieved in every Member State" (European Commission, 2011), being implemented in domestic (national) law.
These directives relevant to FRM have been split into primary directives, those with a strong influence on FRM, and secondary directives, which have an indirect but still tangible influence.

Primary EU Directives

Directive (Year)	Relevance to FRM
Habitats (1992)	Aims to protect and/or restore habitats for wild flora and fauna.
Water Framework (2000)	Requires creation of River Basin Management Plans.
Floods (2007)	Member states must assess if all water courses and coast lines are at risk from flooding, to map the flood extent and assets and humans at risk in these areas and to take adequate and coordinated measures to reduce this flood risk. Also public right to access info and have a say.

Table B.1: EU Directives of primary relevance to FRM in England and Wales (based upon (OFWAT and DEFRA, 2006)).

The directives in table B.1 have a primary relevance to FRM in England and Wales. The first relates to protection of habitats, which is a major consideration in FRM schemes. Structural management schemes may require habitat to be destroyed to facilitate flood defence construction, which under the Habitats Directive will require compensatory action to be taken. Secondly, the directive gives protection to certain habitats, therefore this must be taken into account when assessing FRM schemes and the effect they will have on the environment.
The Water Framework and Floods Directives require creation of plans and maps relating to river basins and flood extents, thus enforcing data collection. Further, the public are given a right to information and input into discussions, thus requiring stakeholder engagement.

Secondary EU Directives

Directive (Year)	Relevance to FRM
Surface Water (1975) (repealed 2007)	Sets quality objectives for the surface water sources from which drinking water is taken.
Dangerous Substances (1976)	Prohibits the release of certain dangerous substances into the environment without prior authorisation.
Bathing Water (1976) (to be repealed 2014)	Sets standards aimed at protecting the health of bathers in surface waters and maintaining the aesthetic quality of these bathing waters.
Freshwater Fish (1978) (updated 2006)	Requires member states to protect designated surface waters from pollution that could be harmful to fish.
Shellfish Water (1979) (to be repealed 2013)	Sets maximum pollution levels for certain substances that can be toxic to shellfish.
Groundwater (1980) (to be repealed 2013)	Lists substances which should be prevented from entering, or prevented from polluting, groundwater. It requires a system of prior investigation, authorisation and requisite surveillance to be put in place.
Nitrates (1991)	Aims to reduce nitrate pollution in surface and ground water as a result of farming activities, and prevent it in future.
Urban Wastewater Treatment (1991)	Sets requirements for the provision of collecting systems and the treatment of sewage according to the size of the discharge and the sensitivity of the receiving surface water.
Drinking Water (1998)	Sets standards for drinking water to protect public health and maintain the aesthetic quality of drinking water supplies.

Table B.2: EU Directives of secondary relevance to FRM in England and Wales (based upon (OFWAT and DEFRA, 2006)).

The directives seen in table B.2 mainly relate to pollution control, which is a consideration of flood management due to the potential polluting effects of flood events, especially with regards to landfill site or industrial damage, or salt water intrusion into coastal aquifers used for drinking water.

B.4 Summary & Conclusions

Flood management in the UK has gone through two widely recognised shifts from land drainage in the early 20th century to flood defence around the 1970s-1980s (e.g. Johnson and Priest, 2008) and from flood defence to flood risk management around the 1990s-2000 (e.g. Johnson and Priest, 2008; Tunstall et al., 2009; Butler and Pidgeon, 2011; Khatibi, 2008; Newman et al., 2011).

This research has highlighted other periods of change. The evolution of Flood Risk

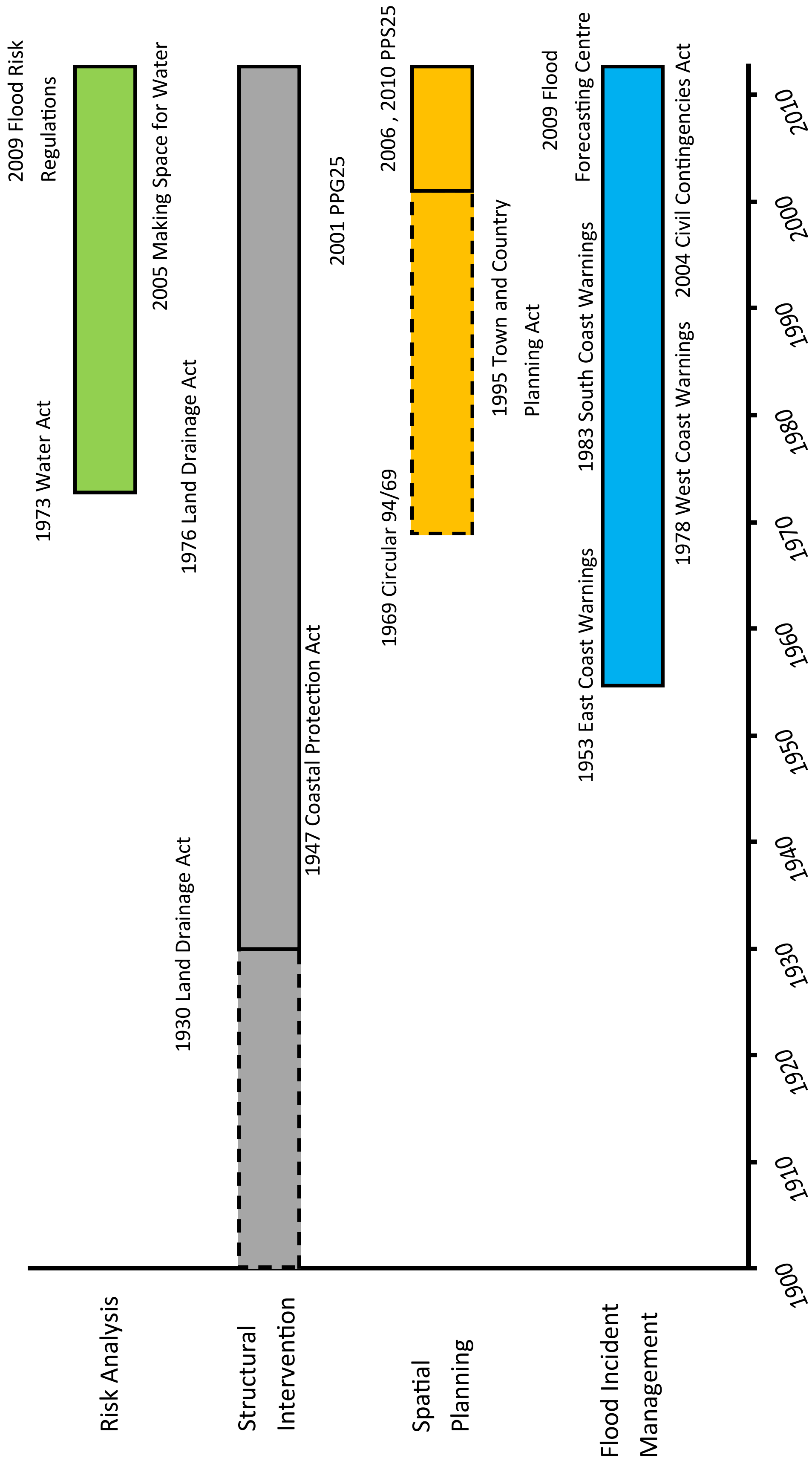


Figure B.8: A summary of the UK FRM system between 1900 and 2012

Management in the UK is summarised in Figure B.8. FRM has undergone several key 'shifts' between 1900 and 2012.

The first of these occurred in 1930 with the start of national scale management. In the period 1900-1930 devastating floods catalysed the beginning of national law relating to land drainage, with no regulation relating to development control. FRM at this time was predominantly structural as seen in Figure B.2.

In the period 1931-1955 creation of river boards marked a more centralised shift for water resources, and the nations first coastal protection legislation came into force. Spatial planning became a national issue however there was no regard for flooding in planning policy. In 1955 flood incident management is introduced by way of the first flood warning system for the north sea coast, following unprecedented flooding. Structural intervention policies still dominate with the introduction of coastal erosion policies with an emphasis on hard coastal defences (Figure B.3).

In the period 1956-1975 water resources underwent small changes until 1973 with creation of 10 regional water authorities. This separated water resources from flooding and sparked creation of regional and local land drainage committees responsible for draining land mainly for agricultural purposes. The 1975 FRM change did introduce a small degree of risk analysis into the management system, however it was mostly a legislative change with responsibility for FRM separated from other water resource concerns (Figure B.4).

In the period 1976-1990 flood warnings were expanded to other coastlines following a series of floods. The 1898 water act created the National Rivers Authority, a national body with responsibility for flood management. The 1990 FRM system change can be described as the birth of the Flood Risk Management paradigm. Risk analysis is introduced at every scale of management, underpinning structural intervention decisions (Figure B.5).

In the period 1991-2005 changes at the national scale reflected the shift from flood defence to flood risk management. The shift led to increased emphasis on spatial planning with flood specific national law, wider spatial distribution of flood warnings, and better organised emergency response. The key changes in 2005 are the introduction of statutory spatial planning to the FRM system and nationally coordinated flood incident management (Figure B.6).

In the period 2006-2011 the shift to flood risk management was finalised with strengthened spatial planning laws, better integrated national co-ordination and an improved nationwide flood forecasting and warning system. This final FRM system change strengthens all aspects of flood risk management. Structural interventions are re-organised and further underpinned by risk analysis, emergency response is strengthened, and spatial planning becomes better integrated into the FRM system (Figure B.7). A large degree of responsibility shifts to the local level, underpinned by national policies and regional strategies.

The period of time between the first two key changes (1930-1955) is 25 years. The next period between key FRM changes (1955-1975) is 20 years long. The following two transition periods (1975-1990, 1990-2005) last for 15 years each. The final change in the study (2011) occurs only 6 years after the previous key change (2005). These timings suggests that the rate of FRM change in the UK may be accelerating.

Appendix C

National Scale Assessment of Exposure to Flooding

A high level national analysis of flood exposure is possible using the approach developed in this thesis taking advantage of the modern day data collection systems available in many countries. As a validation exercise, a national analysis was carried out for the flood exposure in England and Wales from 1971-2011. We used the present day Environment Agency Indicative floodplain map for both river and coastal flooding plus Census data 1971-2011. This map does not include defences and so is a measure of exposure *without defences*. There are some limitations in this approach, for example the floodplain map includes both fluvial and marine flood extents, and we do not account for changes in the floodplain over time. However, sea level rise over the 40 years of analysis has been minimal. Further, the population is not constrained to residential areas, as in the quantitative analysis in Chapter 5.

The Environment Agency's flood zones 2 and 3 are used in the analysis. Flood Zone 2 comprises land assessed as having between a 1 in 100 and 1 in 1,000 annual probability of river flooding (1% - 0.1%), or between a 1 in 200 and 1 in 1,000 annual probability of sea flooding (0.5% - 0.1%) in any year. Flood zone 3 comprises land assessed as having a 1 in 100 or greater annual probability of river flooding (>1%), or a 1 in 200 or greater annual probability of flooding from the sea (>0.5%) in any year. This dataset is available nationally. The flood map is interchangeable in the methodology: an alternative map (perhaps from higher resolution modelling) could be used if available.
UK census populations are presented in Table C.1. For census years 1971-2011 population centroid data is available. A population density grid was created from census centroid data for census years 1971-2011 using the methodology presented in Chapter 5 (Figure C.1). For this national scale analysis population was not constrained using residential maps. The process of manual digitisation is possible, as discussed in Section 7.3.1, however the time required is beyond the scope of this thesis.

Year	Total Population	Source
1971	48,631,000	UK Census 1971 (Registrar General for England and Wales, 1971)
1981	48,506,000	UK Census 1981 (Office of Population Censuses and Surveys, 1981)
1991	48,129,000	UK Census 1991 (Office of Population Censuses and Surveys, 1991)
2001	52,042,000	UK Census 2001 (ONS, 2001)
2011	56,076,000	UK Census 2011 (ONS, 2011)

Table C.1: Population of England and Wales according to the UK census

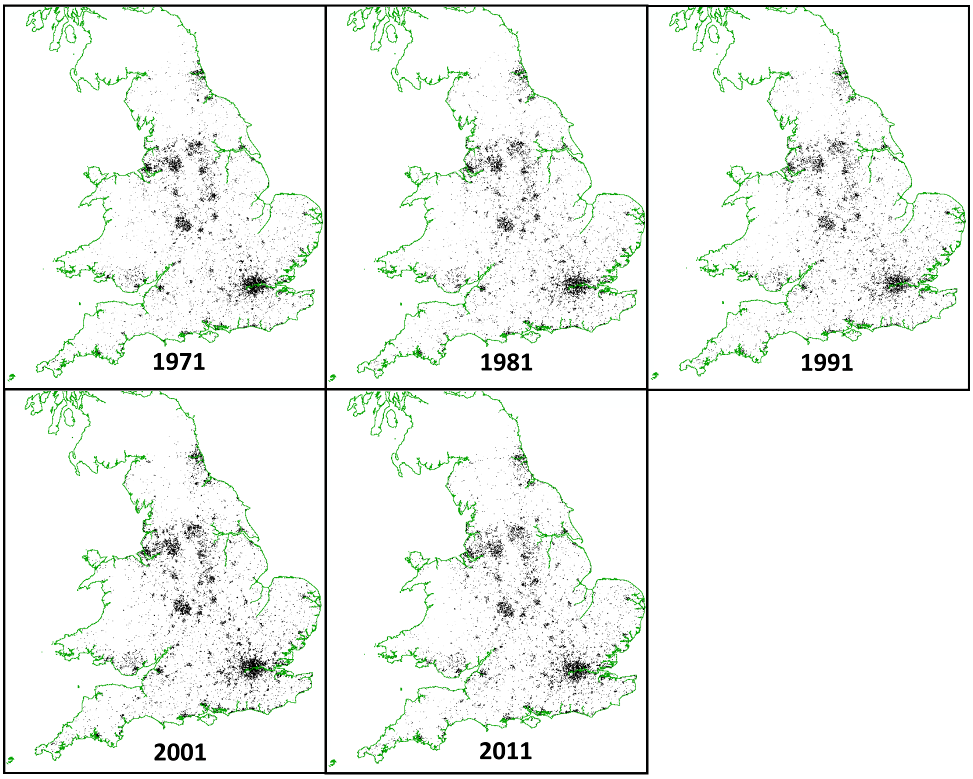


Figure C.1: Population grids for England and Wales for (from left) 1971, 1981, 1991, 2001 and 2011 (data from (Registrar General for England and Wales, 1971; Office of Population Censuses and Surveys, 1981, 1991; ONS, 2001, 2011)). Contains public sector information licenced under the Open Government Licence v3.0.

Analysis of the data shown in Figure C.1 showed that without masking the population to residential areas, the inaccuracy of census data in 1971 meant that the results for this year were not reliable. For the local case study where historic maps could be used to constrain population to developed areas, 1971 data could be used. However this initial national analysis does not constrain population. Therefore 1971 was excluded from this initial national analysis.

The algorithm took less than 1 hour to run. The number of people exposed to the 1 in 200 year floodplain (flood zone 3) has risen from 3,195,000 in 1981 to 3,542,000 in

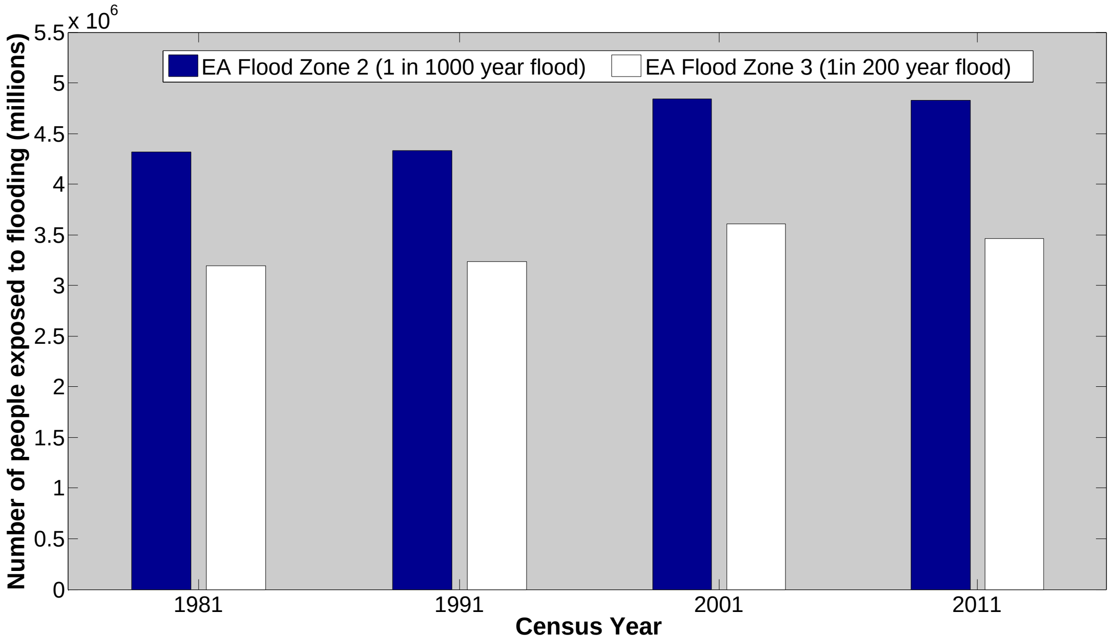


Figure C.2: Estimated number of people exposed to flooding in England and Wales 1981-2011 for flood zones 2 (1 in 1000 year flood) and 3 (1 in 200 year flood)

Year	Flood zone 2	flood zone 3
1981	4,317,000	3,195,000
1991	4,330,000	3,239,000
2001	4,841,000	3,606,000
2011	4,829,000	3,460,000

Table C.2: Estimated number of people exposed to flooding in England and Wales 1971-2011 for flood zones 2 (1 in 200 year flood) and 3 (1 in 1000 year flood)

2011 (Table C.2 and Figure C.2). The number of people exposed to the 1 in 1000 year floodplain (flood zone 2) has grown from 4,317,000 in 1981 to 4,829,000 in 2011. The calculated exposure to the 1 in 1000 year flood event (without sea defences) in 2011 of 4.8 million people is very close to the figure of 5.2 million quoted by the National Flood Forum (NFF, 2015).

This quick analysis gives credence to the methodology, however, for a full national scale analysis, a more detailed population data set and DEM model would be necessary (see Section 8.2).

Appendix D

A Comparison of Population Spreading Methodologies

In this appendix the population spreading method developed in this thesis is compared to other methodologies. In Chapter 5 three methods were described; a method using population centroids (A), a method using historic mapping to distribute population to residential areas (B) and a simpler method where population is uniformly distributed across the model (Figure D.1). The three methods are described in the following section, and then results using each methods are presented and discussed. The three population spreading methods are compared for a simple scenario where sea levels do not change, and the 1:200 year recurrence interval flood event is evaluated.

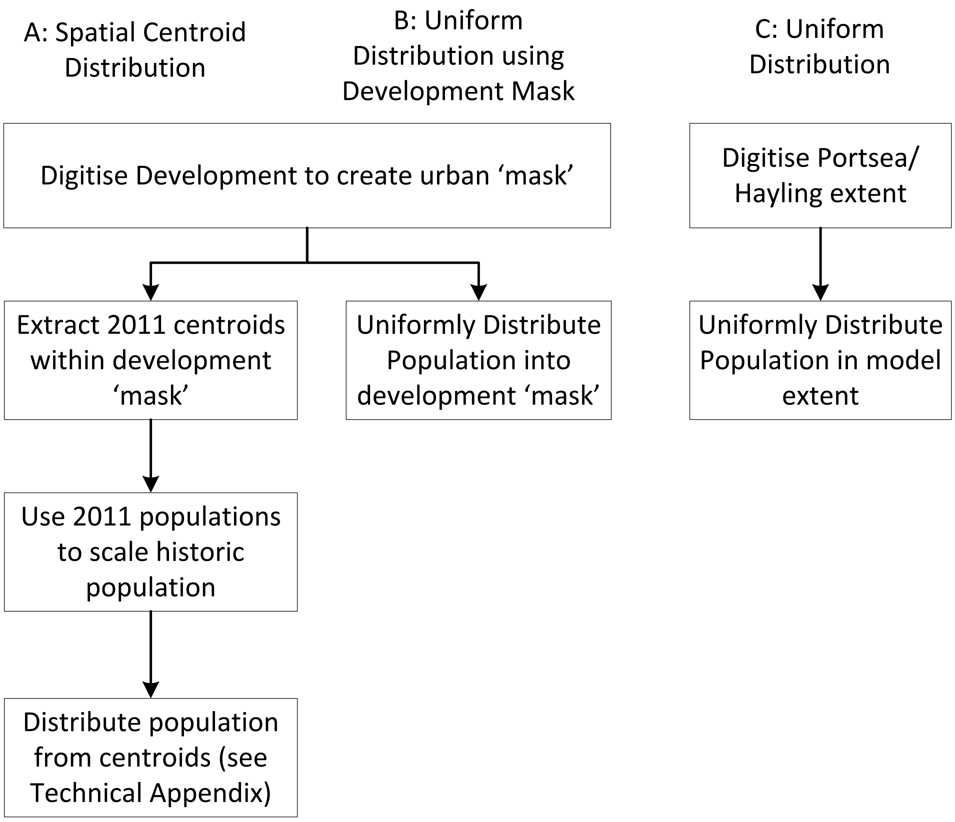


Figure D.1: Flowchart showing Population Spreading Methodologies

D.1 Population Spreading Methods

Method A (Figure D.2) uses a combination of spatial census data and historic maps to distribute population as realistically as census data allows. Population is distributed from census centroid points to nearby residential areas thus conserving the spatial population density of the underlying data. The population is distributed according to a distance-decay function as evaluated in SurfaceBuilder^{TM}, a surface population model widely used in studies using census data (Martin, 1989; Smith et al., 2014, 2015, e.g.). This raster based method has been demonstrated to be more reliable than other methods (Martin et al., 2002, 2011). However this method is only viable where spatial centroids exist (1971-2011).

Method B (Figure D.3) uses a more concise distribution in which population is constrained to the residential extent as per the historic maps. The population density is assumed to be spatially uniform within the residential areas.

Method C (Figure D.4) presents a 'crude' method of distribution where the population is evenly distributed across the model extent. This method assumes the population density is spatially uniform and allows population to be spread into non residential areas such as green space, industrial land or inland water bodies. It is intended as a baseline against which to judge the other methods.

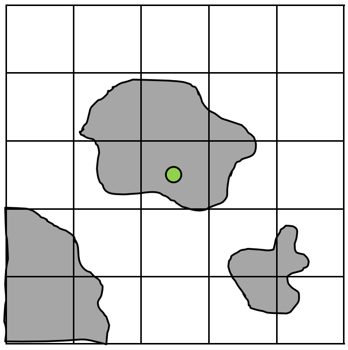
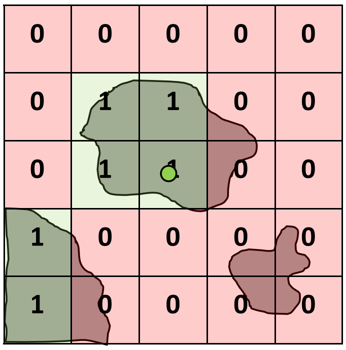
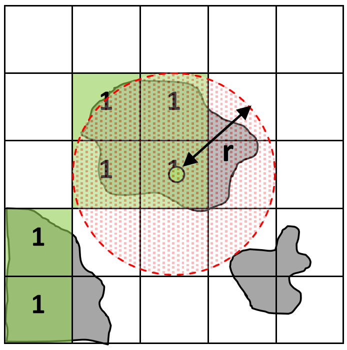
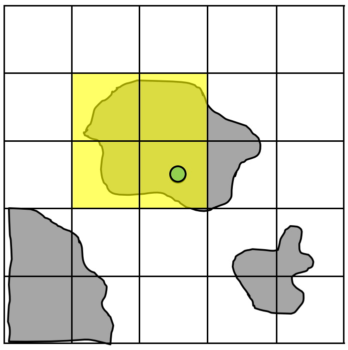
Method	Schematic
Residential areas are digitised within GIS software to create a residential layer. A raster grid (size 50m by 50m) is overlain onto the residential layer.	
Cells whose centres intercept the residential layer are allocated a value of 1 ('ON' shaded green) and cells whose centres do not intercept the residential layer are allocated a value of 0 ('OFF' shaded red). This creates a 'mask' layer which is used to constrain population to the residential area.	
The population is distributed to the underlying raster grid according to the Cressman function: $W = (r^2-d^2)/(r^2+d^2)$ Where: W = weighting, r = search radius (user defined, range used) and d = distance from centroid to cell centre	
A population layer is created with population constrained according to the residential 'mask' grid. In the case where no residential cells exist within a centroid's search radius, the centroid population is distributed entirely to the cell in which it is located.	
Key: Population centroid; Residential Area; Search area; Populated cell; 1 Population allowed; 0 Population blocked	

Figure D.2: Population spreading method A: Distributing population to a raster grid using population weighted centroid points and a residential 'mask'

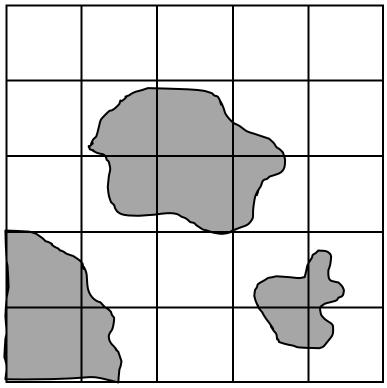
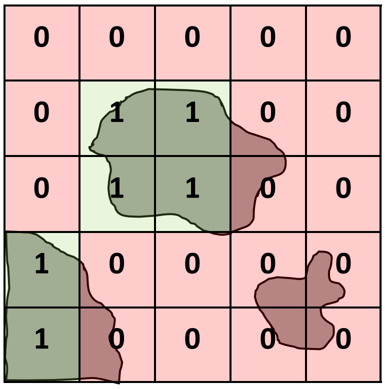
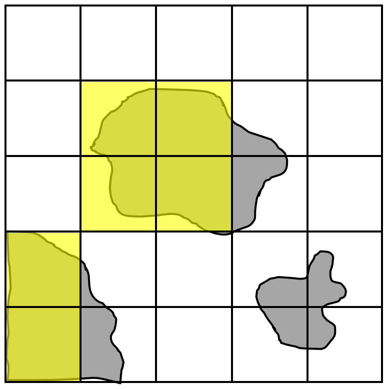
Method	Schematic
Residential areas are digitised using GIS to create a residential layer. A raster grid is overlain onto the residential layer.	
Cells whose centres intercept the residential layer are allocated a value of 1 ('ON') and cells whose centres do not intercept the residential layer are allocated a value of 0 ('OFF'). This creates a 'mask' layer which is used to constrain population to the residential area.	
Population is evenly distributed across the residential 'mask' area	
Key: Populated cell;  Residential Area	1 Population allowed; 0 Population blocked

Figure D.3: Population spreading method B: Residential Distribution. Population is evenly distributed to residential areas, as defined by the OS maps at different dates.

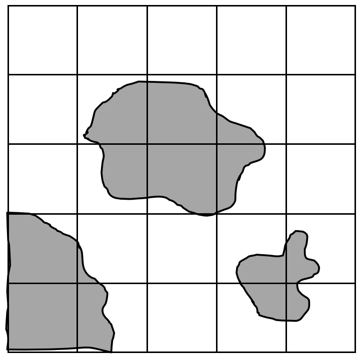
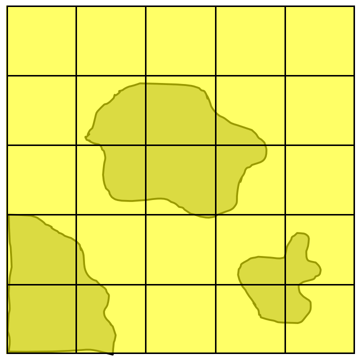
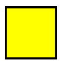
Method	Schematic
A raster grid is overlain onto the model domain.	
Population is uniformly distributed across the entire model domain. The uniform value is rounded to the nearest integer. This method is not appropriate for large spatial areas with small populations as this may result in a total population per grid cell of zero.	
Key:  Residential Area	 Populated cell

Figure D.4: Population spreading method C: Uniform Distribution. Population is assumed to be evenly distributed across all grid squares

D.1.1 Model Results: Exposure Without Defences with no Change in Sea Level

Variable	Value	Rationale
Sea level rise	0 mm / yr	baseline results for comparison
Recurrence interval	1 in 200 years	Comparable to existing studies, see Section 5.2.2 for results from a range of RI
Tidal cycles	1 cycle (12 hours inflow)	Used in previous study (Wadey et al., 2012; Wadey, 2013)
Population method	A(1-6) Centroid Method, B Residential Distribution, C Uniform Distribution	Comparison of results for three different methods. A1-6 represent different search radii, see Figure D.2
Defences	None (natural ground elevation used)	Evaluating exposure without defences

Table D.1: Model variables used for the Portsea and Hayling baseline model

In this section initial model results for a baseline scenario (no changes in historic sea level) are presented. A recurrence interval of 1 in 200 years is considered to be consistent with the Environment Agency's indicative flood map (IFM). The results from different population spreading techniques are given to compare the different methodologies.

Urban Case Study: Portsea

Exposure to flooding has increased over time in Portsea for all population spreading methods (Figure D.5). An upwards linear trend over time is apparent.

For the centroid method (A) there is only a small amount of variance in estimated exposure between the different search radii used. The most modern censuses (2001 and 2011) show no significant variation in exposure between different search radii used, which is likely due to the larger number of centroid points and therefore smaller spatial areas represented by each centroid (i.e. higher resolution data).

For the residential distribution method (B) there is an upwards trend between 1801 and 1941. There follows a period of decreasing exposure between 1941 and 1991. The exposed population then increases from 1991 to 2011.

The centroid and residential methods closely agree in 1991, 2001 and 2011. The differences are higher in 1971 and 1981 - these years have lower resolution centroid data and so we do not have the same confidence in the centroid method estimates for those years. This gives confidence that the residential distribution method is a good method for spreading population.

The uniform distribution method (C) gives a much higher estimate than the 'constrained' populations from the other methods, notably in the early 20th century time steps where the estimate is more than 60% higher compared to the residential distribution method. This gives the potential 'overestimate' from the uniform distribution method as being over 30,000 people for Portsea in 1931. On average the residential distribution method estimates an exposure 55% lower than the uniform distribution method. This shows that failing to account for the spatial distribution (both population density and spatial extent) of the population could lead to significantly overestimating the flood exposure in coastal areas.

Rural Case Study: Hayling

Exposure to flooding was very low in Hayling in the 19th century, and shows a steady increase over the 20th century (Figure D.6).

For the centroid method (A) there is a small amount of variation for different search radii used. There is an upwards trend between 1971 and 2011.

For the residential distribution method (B) the exposed population in Hayling is very low (<100) until the turn of the 20th century. In the 20th century exposure to flooding shows a linear increase which continues into the 21st century, reaching a maxima in 2011. The residential distribution method tends to overestimate compared to the centroid method. There is still much closer agreement between the centroid and residential methods, compared to the uniform distribution method.

The uniform distribution method (C) suggests no exposed population from 1801-1901. This is because the total population on Hayling is low enough that the integer value of people per grid cell is equal to zero - see Figure D.4. From 1921 to 2011 the method overestimates exposed population significantly. In some cases using the residential distribution method yields an exposed population estimate between 80% and 90% lower compared to uniform distribution, an absolute value of 1000-3000 people. On average the exposure estimate is 68.9% lower for the residential distribution method compared to the uniform distribution method. Realistically distributing the population is therefore very important for improving the estimate of population exposed.

The exposed population in Hayling is around an order of magnitude lower than that in Portsea, due to a much smaller population in Hayling compared to Portsea (i.e. see Figures 5.11 and 5.12).

Summary

The residential distribution method (B) predicts a much lower exposure compared to the cruder method of uniform distribution (C) - on average exposure is 55% and 69% lower for Portsea and Hayling respectively. The centroid method (A) predicts on average a 58% and 70% lower population exposed to flooding for Portsea and Hayling respectively. The change in estimate for methods which take account of both spatial extent and

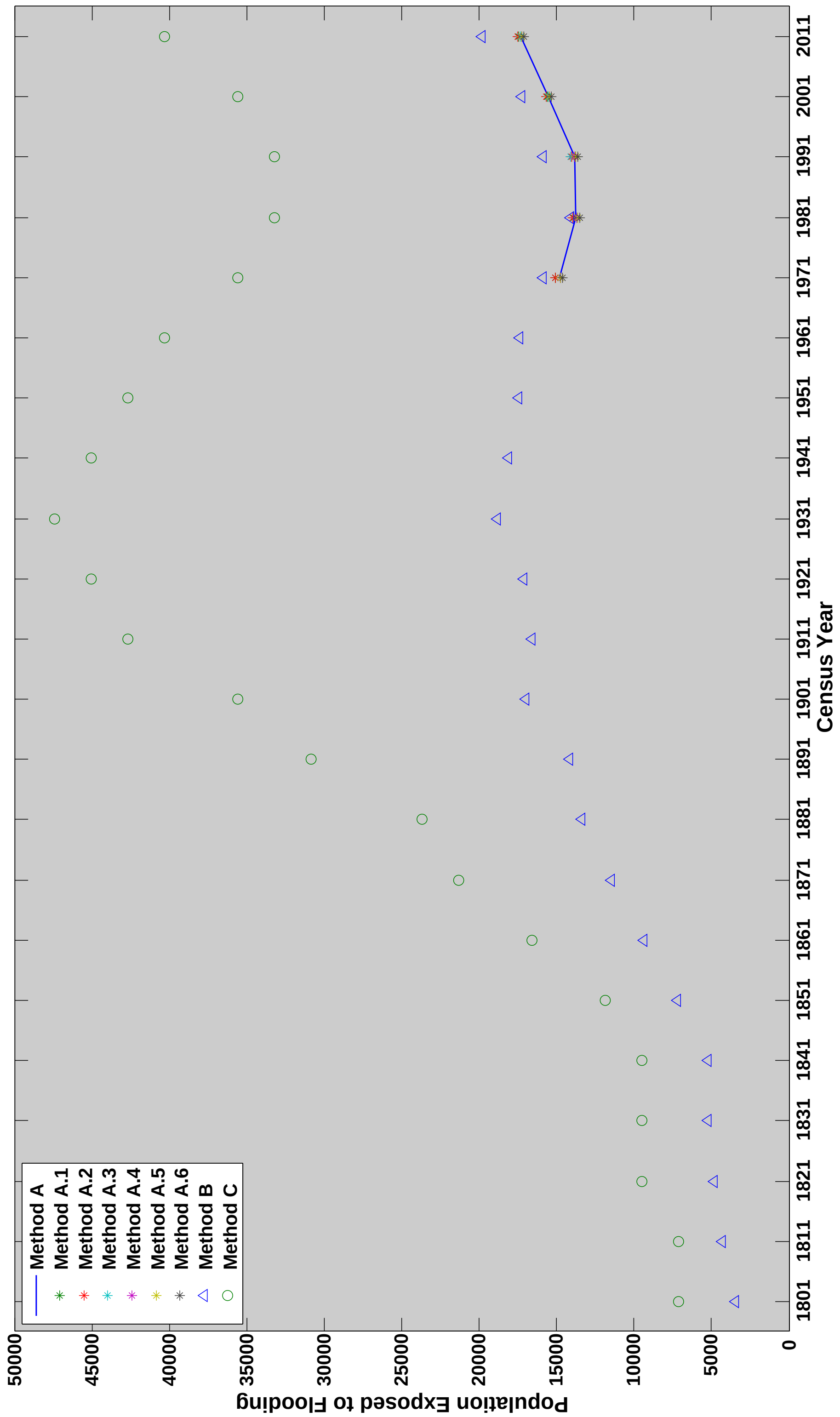


Figure D.5: Estimated number of people exposed to flooding in Portsea using different population spreading methods (1 in 200 year recurrence interval, no SLR, no defences)

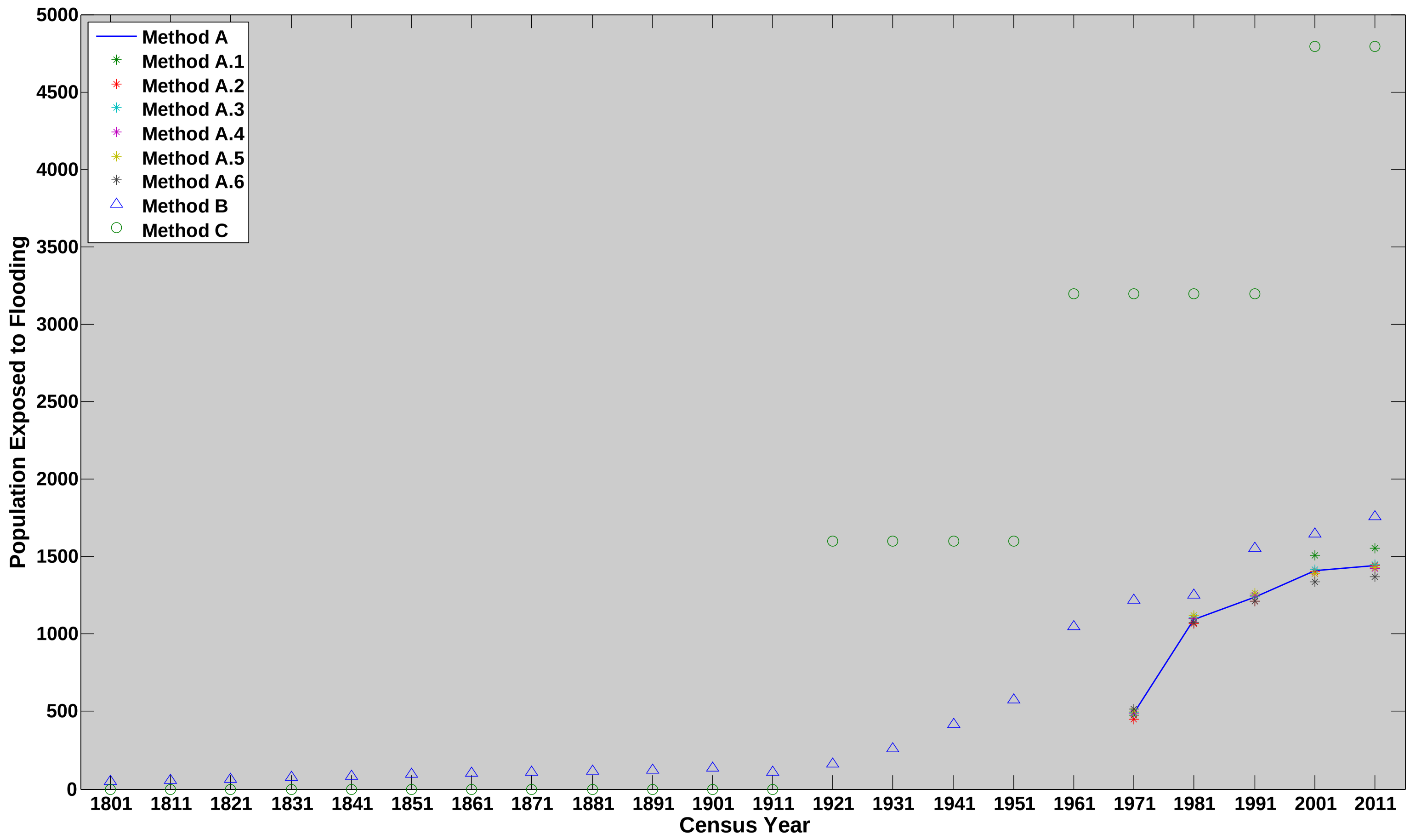


Figure D.6: Estimated number of people exposed to flooding in Hayling using different population spreading methods (1 in 200 year recurrence interval, no SLR, no defences) distribution of the population (A + B) are significant. There are unpopulated areas of coastline such as common land, green space, promenades and beach fronts. This is evidence that some land zoning has been successful as not all coastal areas are populated. Assuming that the population is uniformly distributed is an invalid assumption. This shows the importance of distributing population only to developed areas and therefore the strength of the methodology developed in this work.

Spreading methods that distribute population to developed areas (A + B) show similar results. This gives some cross-validation to the spreading methods and gives confidence that the residential distribution method (B) can be applied to historic study where spatial population data (e.g. centroids) does not exist.

Results presented in the thesis are based upon the residential distribution method (B), which offers reliable results (comparable to estimates from the highest resolution centroid method) whilst being applicable to historic study. Further, its low data requirements (e.g. only map and population count needed) make it widely applicable to other case studies and countries where higher resolution data are perhaps not available.

Appendix E

Sensitivity to Sea Level Change Estimates

In this appendix the rate of sea level used in the thesis (1.22mm/year which represents the average rate of historic change in the case study region (Haigh et al., 2011)) is compared to a scenario of no change in sea level (i.e. assuming that historic sea levels are equal to today's sea levels), and scenarios using the lower and upper sea level change estimates (0.98mm/year and 1.48mm/year respectively).

The different rates of sea level change are compared using a recurrence interval of 1:200 years.

E.1 Model Results: Exposure Without Defences for a Range of Historical Sea Level Changes

Variable	Value	Rationale
Sea level rise	0.94-1.48 mm / yr	A range of possible values (Haigh et al., 2011)
Recurrence interval	1 in 200 years	Comparable to existing studies, see Section 5.2.2 for results from a range of RI
Tidal cycles	1 cycle (12 hours inflow)	Used in previous study (Wadey et al., 2012; Wadey, 2013)
Population method	B - Residential Distribution	Best available method (see Appendix D)
Defences	None (natural ground elevation used)	Evaluation of exposure without defences

Table E.1: Model variables used for the Portsea and Hayling without defences model

The magnitude of change in sea level will affect the extent of the coastal floodplains and therefore estimates of the number of people exposed to flooding. A variety of sea level rates are applied based upon the uncertainty in sea level rise trend from Haigh et al. (2011) to extrapolate sea levels back to 1801. The sea level rates are applied to the flood model still water level boundary condition (Figure E.1). These sea level scenarios are compared against the baseline (no sea level change) where the known 2011 sea level is applied at every time-step.

Urban Case Study: Portsea

In Portsea the higher the sea level change rate applied to the model (hence the lower the historic water level), the lower the estimated exposed population (Figure E.2). This is expected as the higher the rate of sea level change applied, the lower the flood model's still water level boundary conditions for simulations of the historic floodplain (and thus likely a reduction in flood extent). The uncertainty as a result of sea level rate applied is less than that for the population spreading methods considered. However when we extrapolate back to 1801 the difference is still significant with a 40-65% reduction in exposed population reported once sea level changes are accounted for. This percentage change reduces over time to a value of 1% in 2001. The absolute variability is still in the order of magnitude of hundreds of people. The high sea level change rate estimates

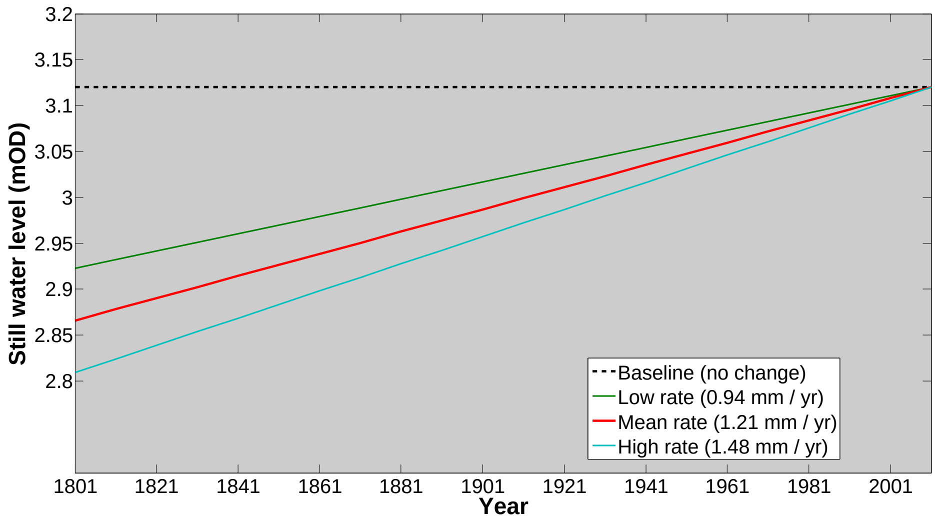


Figure E.1: Still water level boundary condition for each time-step

a population over 5000 less than the baseline for years 1881-1901.
For the mean rate of sea level rise, the best estimate, exposure rises from a value of 1,500 in 1801 to 19,800 in 2011.

Rural case Study: Hayling

The results for Hayling show a smaller level of variability in estimated exposure for different applied sea level change rates (Figure E.3). The percentage differences in estimated population exposed are lower than for Portsea. However when the sea level is extrapolated back to 1911 the results show a 15-24% reduction in estimates when sea level change is accounted for (the estimated exposure pre 1911 is zero). This is still a significant percentage change in exposure, although the small exposed population on Hayling means an absolute change of only 20-35 people for this time step. The largest absolute variability exists in 1961 where the high sea level change scenario predicts 117 less exposed population as compared to the baseline (no sea level rise).
For the mean sea level rate exposure rises from 40 in 1801 to 1,800 in 2011. Most of the exposure develops from 1931-1981, with residential development mostly outside of the floodplain until that time.

This work has shown that historic changes in sea level have a significant influence on the estimated population exposed to flooding. This is especially important for earlier time steps (e.g. 100-200 year time scales) where the absolute change in sea level is highest. However the sea level variable still has a noticeable (albeit lesser) effect over shorter time scales - notably on Portsea where estimates vary by up to 1000 people in 1981, and by several hundred in later time-steps.

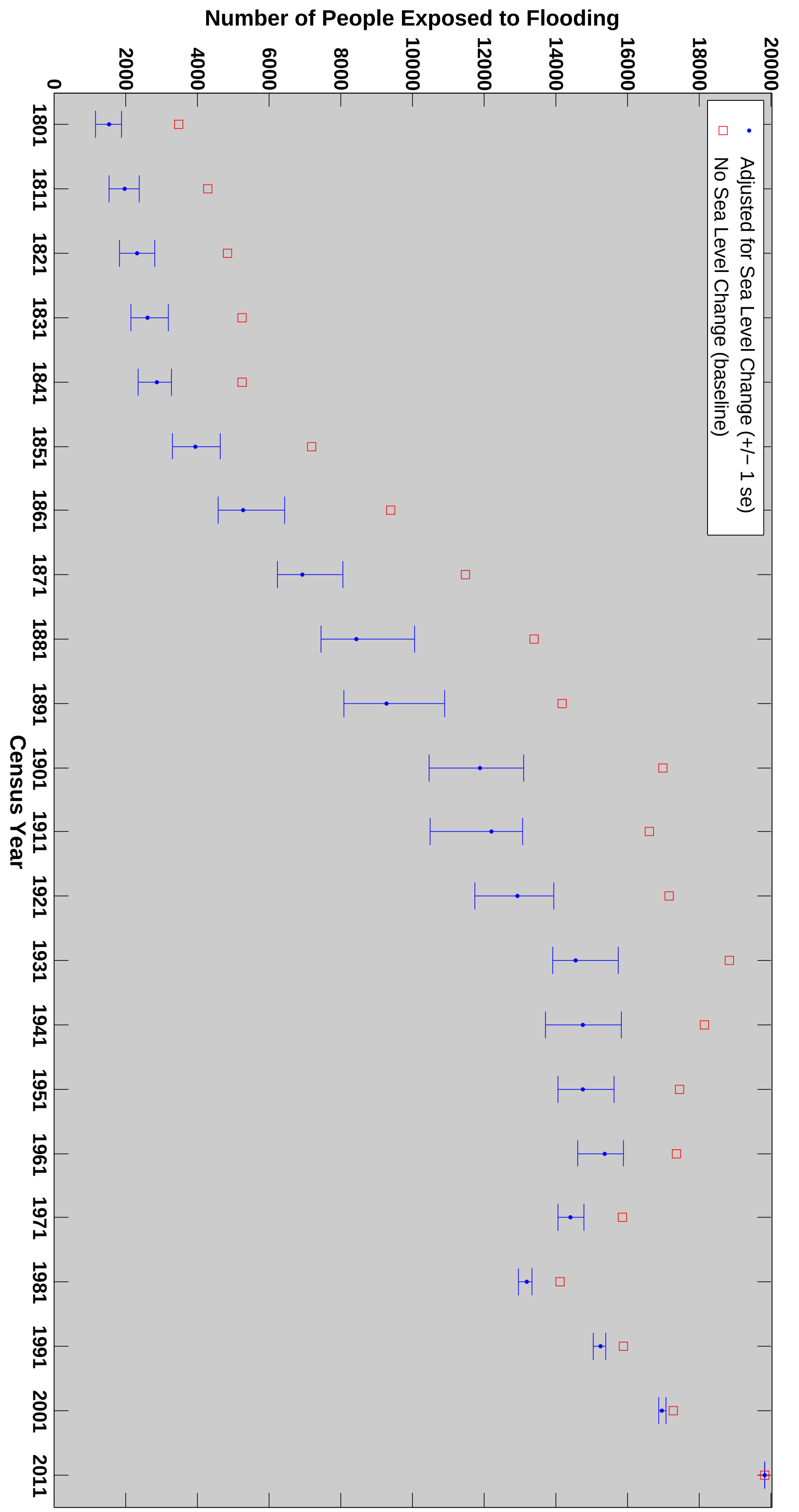


Figure E.2: Estimated number of people exposed to flooding in Portsea for different assumed rates of historic sea level change (1 in 200 year recurrence interval, no defences)

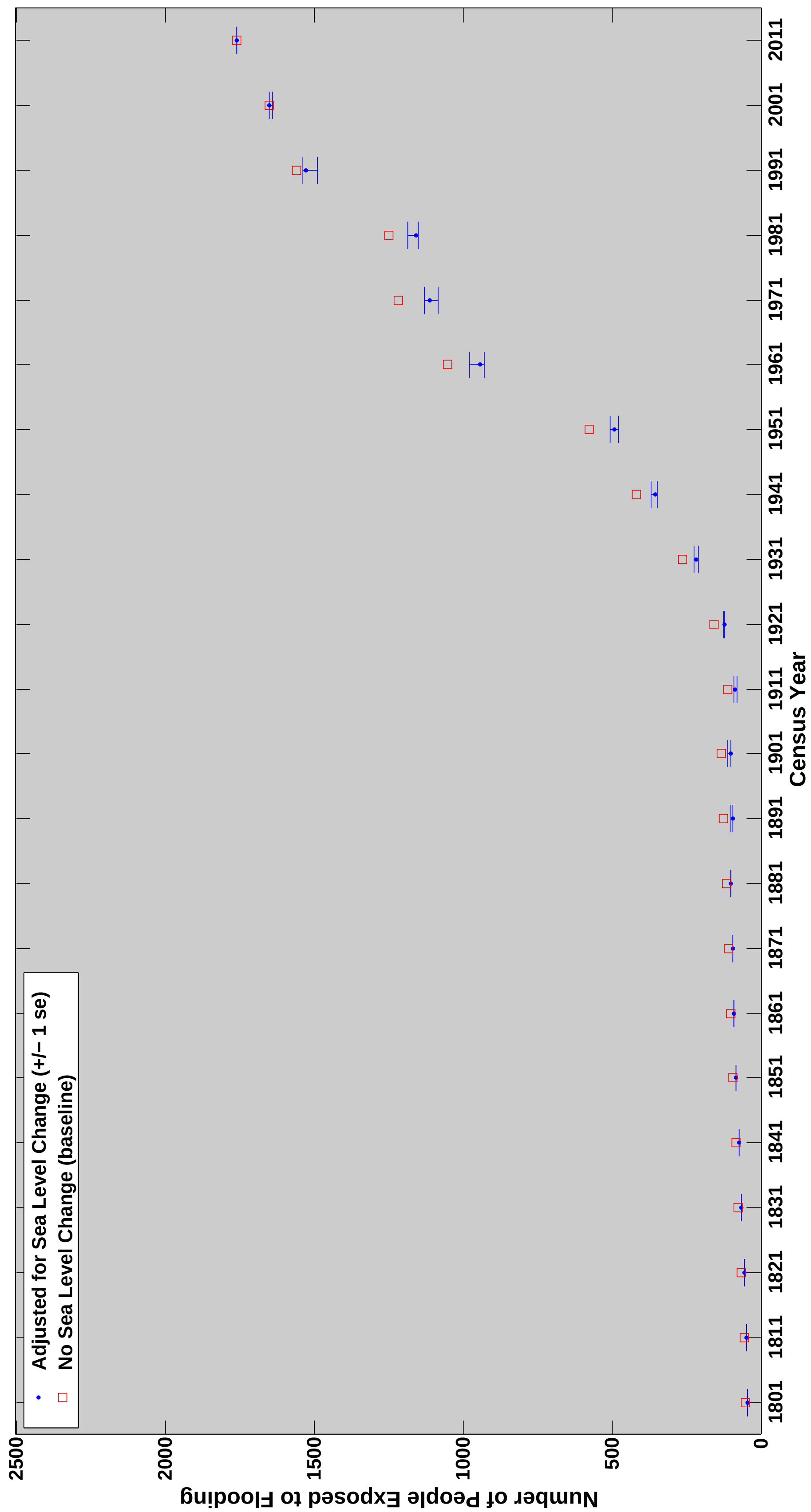


Figure E.3: Estimated number of people exposed to flooding in Hayling for different assumed rates of historic sea level change (1 in 200 year recurrence interval, no defences)

Appendix F

Quantification and Attribution of Exposure to the 1:200 Year Extreme Tidal Flood Event

In this appendix the model results for the 1 in 200 year extreme tidal flood event are presented and examined in more detail. Whilst the 1 in 200 year event alone gives less meaningful information than a wider analysis (as presented in this thesis), it does provide a useful context to flood risk managers familiar with this benchmark. Results for this recurrence interval are much more widely available than for the annual average approach used within the rest of this thesis, and hence results for this recurrence interval can be more easily compared to other studies.

Section 1 of this appendix presents the modelling results for exposure to the 1 in 200 year tidal flood event in Portsea, with and without defences (full results for the annual average people exposure from a range of recurrence intervals are in Chapter 5); Section 2 presents the results of attribution of the 1 in 200 year exposure to underlying drivers in both Portsea and Hayling (full results are presented in Chapter 6).

F.1 Exposure with and without defence: Results for the 1 in 200 year flood event

Variable	Value	Rationale
Sea level rise	1.21 mm / yr	Mean rate of sea level change (Haigh et al., 2011)
Recurrence interval	1 in 200 years	Comparable to existing studies, see Section 5.3.2 for results from a range of RI
Tidal cycles	1 cycle (12 hours inflow)	Used in previous study (Wadey et al., 2012; Wadey, 2013)
Population method	B - Residential Distribution	Best available method (see Appendix D)
Defences	None (without defences model), Observed Defence heights (Wadey et al., 2012; Easterling, 1991) (with defences model)	Comparison of exposure with and without defences

Table F.1: Model variables used for the Portsea model

The quantitative model from Chapter 5 was run for Portsea for two cases:

- No defences: natural ground elevations (Exposure without defences, as described in Section 5.2)
- With defences: using modelled defence levels (Exposure with defences, as described in Section 5.3)

The number of people exposed to flooding for the 1 in 200 year coastal floodplain under these two cases are shown in Figure F.1. The number of people exposed to flooding when defence heights are included are significantly lower than for the case without defences (natural ground levels).

The reduction in exposure due to defences between 1991-2011 is fairly static at around 65%, however it is estimated that in 1971 and 1981 the exposure reduction was higher at 75%, and 70% in 1961. This suggests that improvements in defences between 1991 and 2011 (Wadey, 2013) were effective in maintaining a constant standard of defence against

rising sea levels. The apparent drop in effectiveness of the defences between 1981 and 1991 is likely a product of the rise in population during this time; exposure with defences rose by 2,000 and exposure without defences rose by 2,500 which demonstrates that the majority of development was within the unprotected floodplain during this period.
The exposure without defences shows a downwards trend between 1961 and 1981 which reflects a reduction in overall population in Portsea. Between 1981 and 2011 the exposure without defences shows an upward trend, rising from a value of 13,200 people in 1991 to 19,800 people in 2011. When the flood defences are considered, there is a downwards trend in exposure between 1961 and 1981, a marked increase between 1981 and 1991 and then a gradual increase until 2011. The upwards trend from 1991-2001 can be explained by rising populations and sea levels as defences were modelled as static over this period. The exposure in 2011 corresponds to the modern day defence dataset which accounts for improvements in defences since 1991, however the overall population rise in Portsea appears to have offset these improvements leading to a modest increase in exposure 2001-2011 (approx. 800 people). Exposure with defences has risen from 4,600 people in 1961 to 6,900 in 2011, which shows that despite improvements to defences over this period, the combined effects of rising population, location of residential development within the floodplain and rising sea levels have driven a modest increase in the exposure with defences to coastal flooding in Portsea.

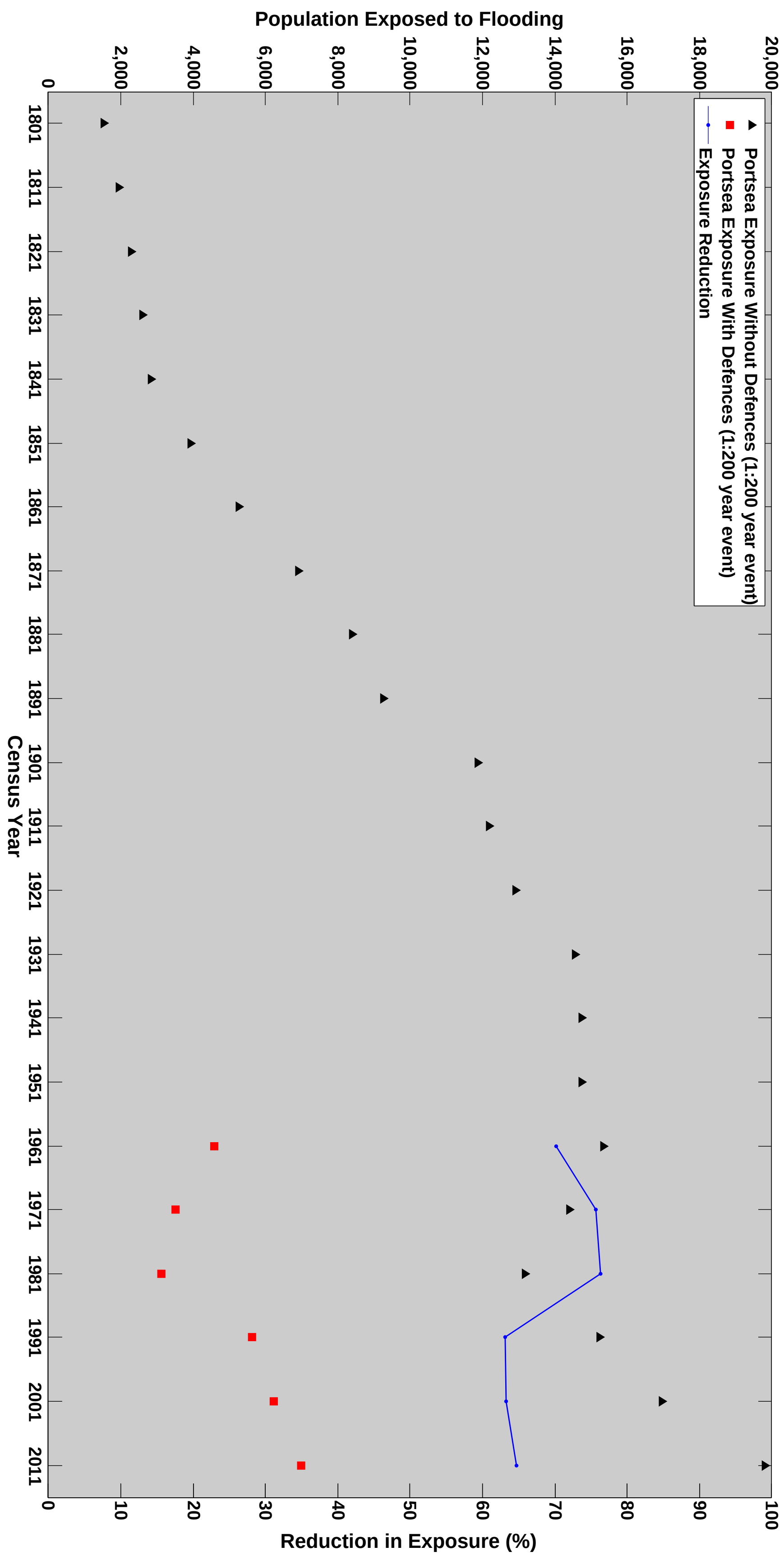


Figure F.1: Exposure with and without defences and population defended against the 1 in 200 year flood event in Portsea (using defence data 1961-2011)

F.2 Attribution of Flood Exposure: Results for the 1 in 200 year flood event

Urban Case Study: Portsea

The change in the number of people exposed to flooding for Portsea under the influence of each driver is shown in Figure F.2.
The change in exposure as a result of sea level rise in Portsea is highest between 1911 and 1931 (+1,600) and 1931-1961 (+1,700).The shorter 10 year time-step between 1961 and 1971 has a lower exposure change which is to be expected. Exposure due to sea level rise between 1971 and 2011 is linear; this is likely as Portsea was highly developed by this point in time and so as the coastal floodplain increases in size (due to higher sea levels) a linear number of people become exposed to potential flooding. The change in exposure due to population size has a high degree of variability as the population of Portsea is highly dynamic; whilst the long term trend is increasing their is decadal variability such as the reduction in population between 1931 and 1991. This is reflected in the calculated exposure. At the start of the record there is an increase in exposure between 1871-1891 (+3,000) and 1891-1911 (+3,700). There is a large decrease in exposure due to population in 1961 (-2,900) and a large increase in 2011 (+3,500). The negative changes are caused by a reduction in the total population of Portsea observed between 1931 and 1991. The change in exposure due to residential development is highly variable which is likely due to the piecemeal nature of housing construction. Large increases in development are reflected in large positive changes in exposure between 1931-1961 (+1,300) and 1971-1991 (+1,600). There are decreases in exposure as a result of the residential development driver between 1871-1891 (-2,000) and 1891-1911 (-3,200). The negative change seen here may be a result of the population spreading method rather than a suggestion that development was moved inland or abandoned; this is discussed within Chapter 6.

Fraction of Attributable Exposure
Sea level rise has been a relatively constant component of exposure over the last 100 years shown in the calculated FAE (Figure F.3). The average FAE due to sea level rise over the period 1871-2011 is 7%. The total population in Portsea has varied, with a decrease in the 1960s-1990s but has grown post 2,001 and this is reflected in the FAE. The highest FAE for population is in 1891 (32%) and 1911 (31%) where total population change was highest. Pre 1931 Portsmouth was expanding and most of the development was outside of the floodplain (negative bars - Figure F.3). Residential Development between 1911 and 1931 contributed towards increased exposure to flooding (FAE of 4%) and by 1961 Portsmouth was mostly covered in development and expansion onto the floodplain increased (+ bars, highest is between 1971 and 1991 at 10%). The large contribution of Population to exposure between 1961 and 1971 (white bar), compared with the much smaller contribution of Residential Development (green bar), shows that

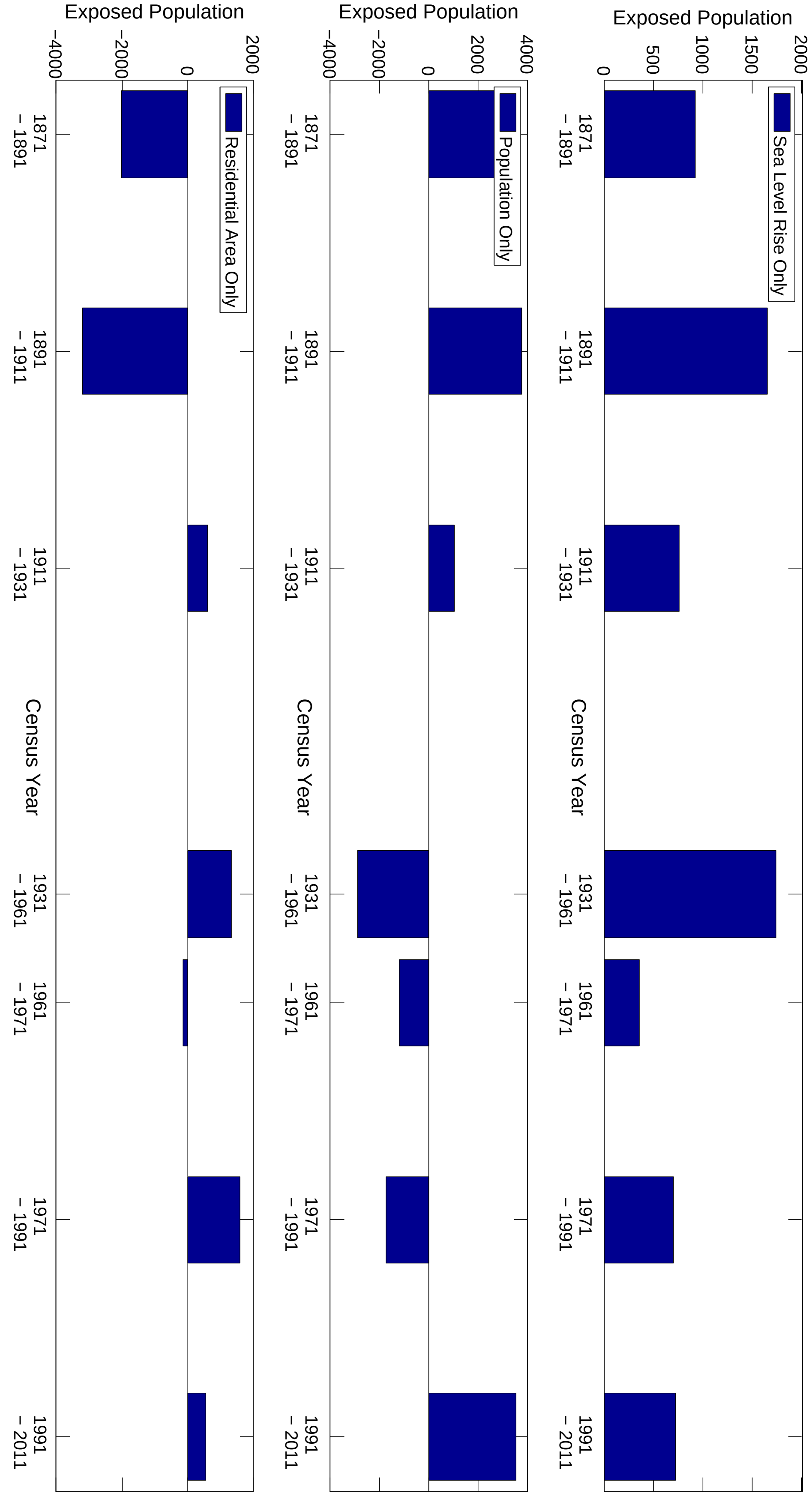


Figure F.2: The change in exposure due to sea level rise, population and residential development within the 1 in 200 year coastal floodplain in Portsea (note that the axis have different scales)

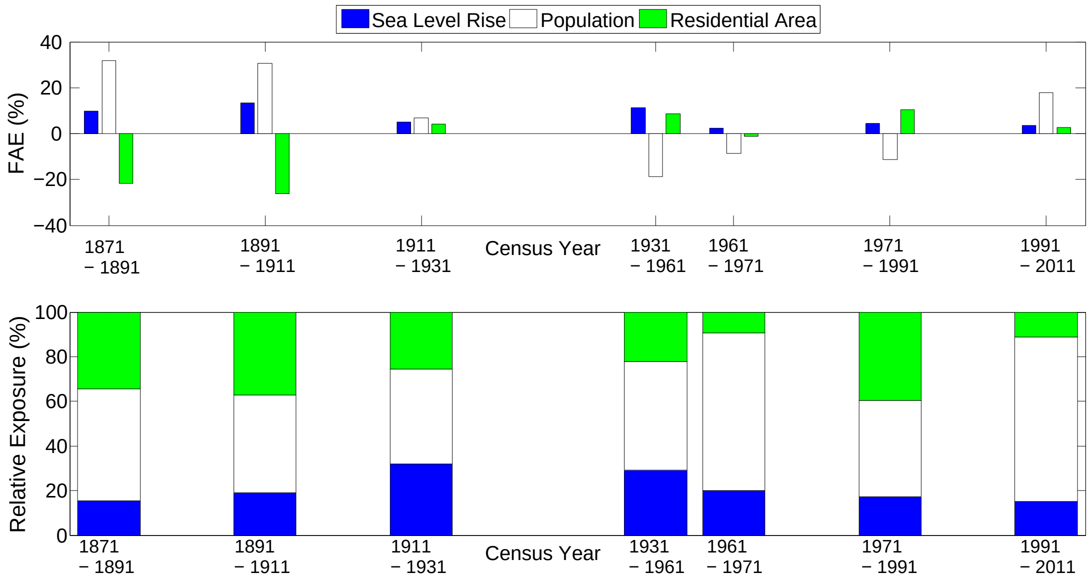


Figure F.3: The attribution of exposure due to sea level rise, population and residential development within the 1 in 200 year coastal floodplain in Portsea showing (a) the Fraction of Attributable Exposure and (b) the Relative Exposure

during this period the *area* within the floodplain that was developed did not change, however the population density did increase. The FAE for Residential Development towards the end of the record is low as the pace of additional development reduced following rapid expansion in the early 20th century.

Relative Exposure

Socio-economic drivers (population and residential development) have had a larger effect on flood exposure (either positively or negatively) than physical factors (sea level rise) in every time-step.

The relative exposure from sea level rise has been highest when the total change in population has been at its lowest (relative exposure of 32% in 1931). This is to be expected as a low change in population limits the effect this driver has on flood exposure. Conversely large changes in population lead to a higher relative effect from population size - as seen in 1891 (50%), 1961 (49%), 1971 (71%) and 2011 (74%). The relative exposure from the residential development driver was lowest in 1971 (9%) and 2011 (11%) due to small amounts of residential development change in the floodplain.

On average 53% of the change in exposure is a result of population size, 26.0% a result of residential development, and 21% a result of sea level rise. We can therefore attribute 79% of the changing exposure in Portsea to socio-economic (human) drivers of flood exposure, and 21% to environmental (climate) drivers over the period 1871-2011.

Rural Case Study: Hayling

Changes in exposure due to each driver for Hayling are presented in Figure F.4. The values are approximately an order of magnitude lower than those in Portsea, due to Hayling's smaller population. The changes in exposure due to sea level rise are negligible in the late 19th and early 20th centuries. This is due to early development being located away from the coastal floodplain and so the population was not susceptible to modest rises in sea level. The change in exposure from rising seas is more pronounced from 1961 onwards due to an increasingly developed coastline in Hayling. However throughout the record the sea level driver only increases exposure by less than 100 people between each time step (average 20 year time step). The change in exposure due to the population driver is small through the start of the record, reaching a peak in 1961 when the population grew significantly (approx. 600 people). The changes in consecutive decades are smaller in magnitude and relatively stable through time accounting for around 200 people each time-step. This demonstrates that population growth in Hayling has mostly been outside of the floodplain.
The change in exposure due to residential development are negative between 1971-1891 (-20), 1891-1911 (-70) and 1961-1971 (-70), suggesting that the majority of development was outside of the coastal floodplain. Between 1931-1961 the change in exposure is the highest in the record (+300) which suggests encroachment of residential areas into the floodplain during post war development. This correlates with the rise in exposure due to the population driver during 1931-1961. The change in exposure due to development post 1961 is variable and of a smaller magnitude which suggests only modest development within the coastal floodplain.

Fraction of Attributable Exposure
In Hayling sea level rise has been a relatively small and constant component of exposure (Figure F.5) with an average FAE of 3.5%. This highlights that modest rises in sea level between 1871 and 2011 did not have a big effect on Hayling's population. The FAE for the population driver is significantly higher. Between the late 1800s and the 1960s population became an increasingly important driver of exposure - accounting for over half of the changes in exposure 1931-1961 (64%). The magnitude reduces in later time-steps as the total population stabilises. The FAE from residential development is highly variable as a result of development both within and outside of the floodplain. The FAE for residential development is negative between 1871-1891 (-20%) and 1891-1911 (-80%) which suggests the majority of development was outside of the coastal floodplain during this period. Development has the largest positive effect on exposure in 1931 (28%) and 1961 (32%). During this time urban expansion on Hayling led development onto the coastal floodplain. Increases in population density on the island are evident from the large contribution of Population throughout the record.

Relative Exposure
The relative exposure from socio-economic (human) drivers at Hayling is high throughout the record and accounts for almost the entirety of the change in exposure observed.

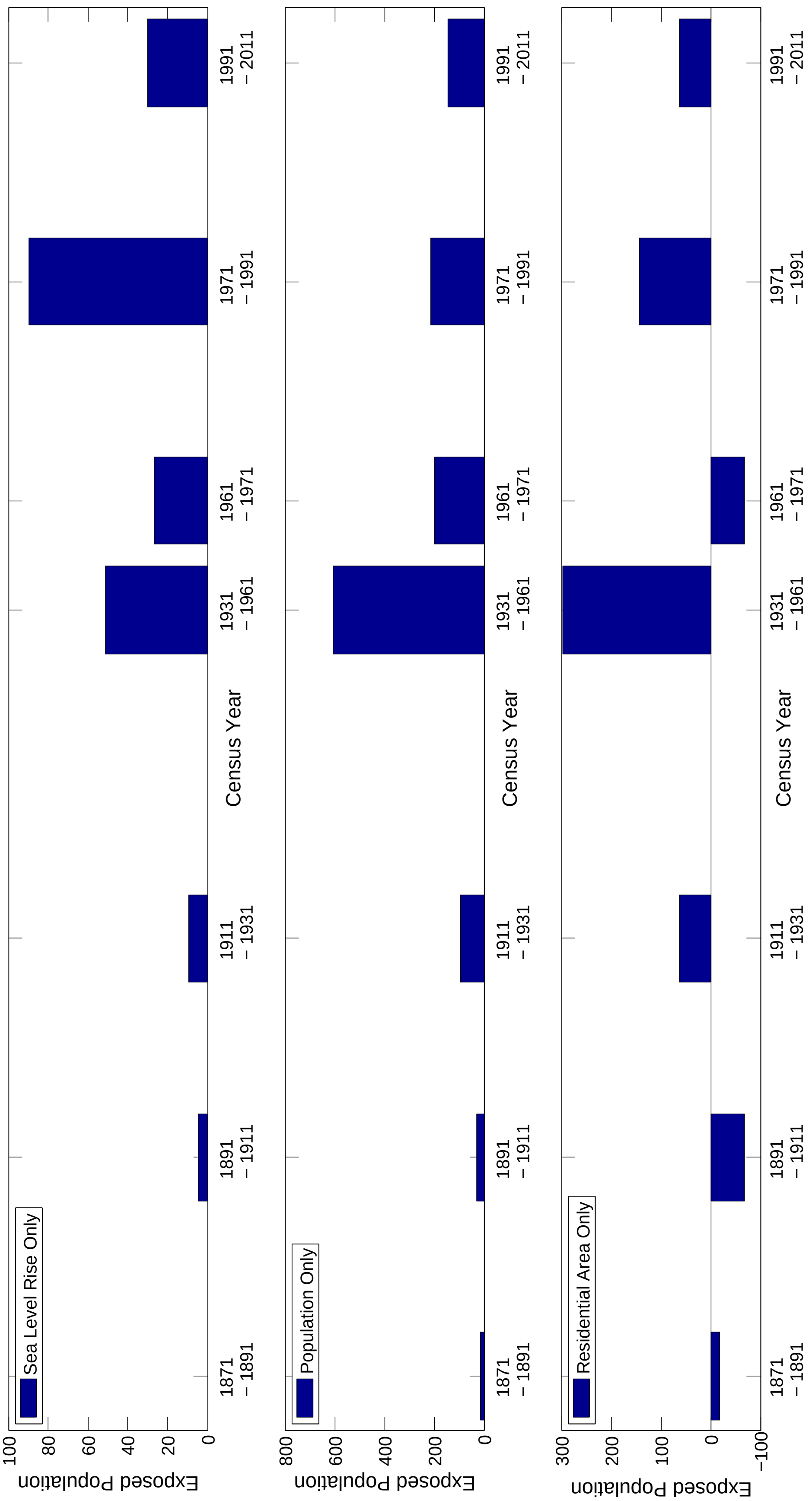


Figure F.4: The change in exposure due to sea level rise, population and residential development within the 1 in 200 year coastal floodplain in Hayling (note that the axis have different scales)

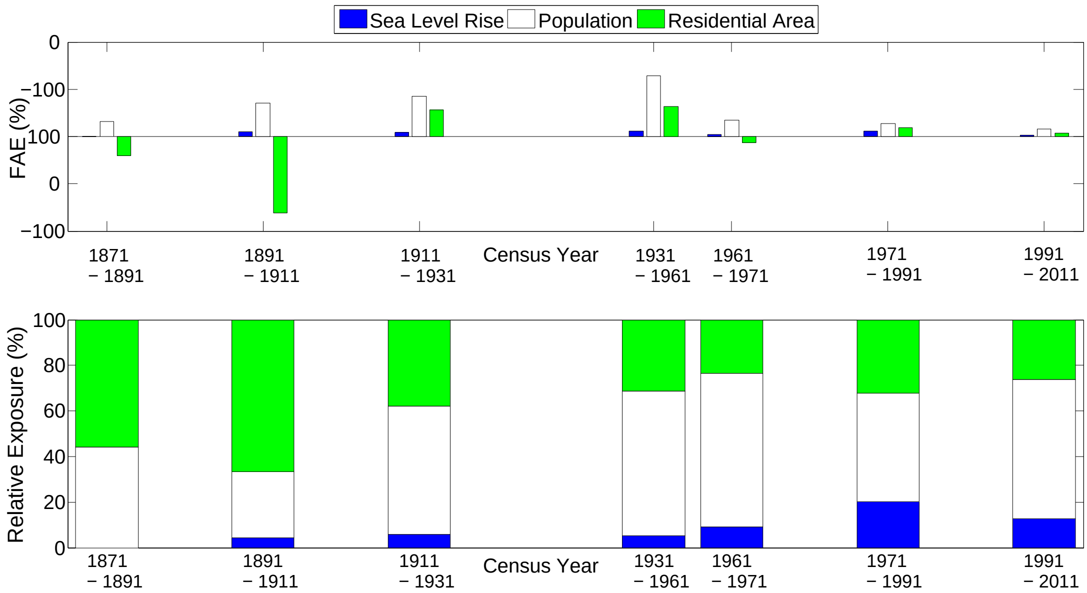


Figure F.5: The attribution of exposure due to sea level rise, population and residential development within the 1 in 200 year coastal floodplain in Hayling showing (a) the Fraction of Attributable Exposure and (b) the Relative Exposure

The effect of physical drivers (sea level rise) are almost negligible until the 1970s when the relative exposure increases. The relative exposure from sea level rise is highest in 1971-1991 (20%) and in 1991-2011 (13%). This is a combination of the reduced rate of population rise and development reducing the relative effect of human drivers, and an increasingly large coastal population driving the exposure from floodplain expansion due to sea level rise.

On average 53.0% of the change in exposure is a result of population size, 39% a result of residential area, and 8% a result of sea level rise. We can therefore attribute 92% of the changing exposure in Hayling to socio-economic (human) drivers of flood exposure, and 8% to physical (climate) drivers.

Summary

This analysis has shown that in Portsea the relative exposure as a result of socio-economic or human factors (i.e. population size and residential area) is higher compared to physical drivers (i.e. sea level rise). Socio-economic drivers have an almost 5-fold increase in exposure compared to physical drivers.

In Hayling the majority of exposure related to human drivers. On average the exposure due to socio-economic drivers are 13 fold higher than for environmental drivers. However the influence of sea level rise is increasing with time (especially as development encroaches closer to coastal flood risk areas) and so the risks posed by climate change cannot be ignored. These findings show that a holistic analysis of coastal adaptation must consider both environmental and socio-economic factors.

Appendix G

EGU 2013 Abstract and Poster

The following poster was presented at the General Assembly of the European Geosciences Union 2013 which was held in Vienna, Austria 7th - 12th April 2013.

Geophysical Research Abstracts
Vol. 15, EGU2013-3024-1, 2013
EGU General Assembly 2013

Reported flooding in the UK: 1884-2012

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Long term archives of reported flooding in the UK from 1884-2012 are used to build an indicator dataset of significant flooding at a national scale in England. The report describes the occurrence of significant flood events on a national scale based on the monthly UK Met Office weather reports and auxiliary sources. Unlike previous studies, which use flow gauging records, these data describe the occurrence of a flood event that affected people and property i.e. they are not flow station specific. The descriptions of reported flood events are classified in order of magnitude, extent and impact. Notable and significant reported flood events are analysed to determine long term temporal trends, changes in seasonality (summer/winter) and to detect any changes in spatial distribution and scale over the last 120 years.

The 19th century reports are less frequent, suggesting that flooding became much more common over the 20th century; however this may be due to an increase in rates of exposure to flood risk due to urban growth and as reporting technology became more sophisticated. The 20th century data shows a high variation with no clear trend of an increase in reported flooding over time. Reported events suggest that flooding occurs in clusters followed by periods of little or no flooding. This supports recent hypotheses regarding the flood-drought cycle of UK water resources. The data shows no tendency towards seasonal winter flooding, with an even distribution of flood events being reported in both summer and winter.

Reported Flooding in the UK: 1884-2012

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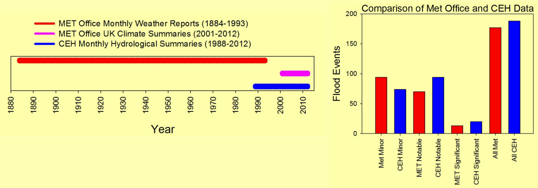
EPSRC Engineering and Physical Sciences Research Council

UNIVERSITY OF Southampton

1. Background

- Long records are required to ascertain reliable trends in flooding
- Hydrological floods (high river flows or sea levels) are not necessarily linked to damaging floods (those that affect life and property)
- This work presents an analysis of 130 years of monthly descriptive reports of damaging flood events in the UK.

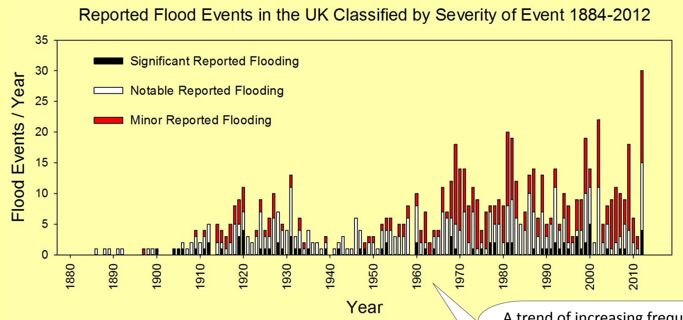


2. Flood Classification

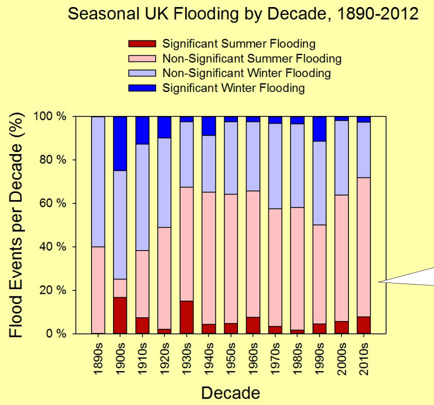
Classification	Description
Significant	Flood event(s) described in highly emotive language such as "disastrous", "unprecedented", "destructive", "devastating", "exceptional", "newsworthy", "significant"*, "major" "worst in 20+ years" etc. or where large damages (i.e. a value mentioned upwards of £1 million) or loss of life are noted. Loss of much livestock or serious physical damage (i.e. bridges/piers destroyed) or where 1000 or more people are evacuated.
Notable	Flood event(s) described as "heavy", "serious", "severe", "widespread", "extensive" etc., or events where local flooding is reported in 3 or more regions+ (i.e. widespread local flooding). Also where properties affected. * Exception for locally significant events (i.e. localised or very localised significant flooding noted), these are classified as notable national flood events). +Where "many places" mentioned this is assumed to mean 3 or more and thus deemed a notable flood month.
Minor	Flood event(s) in the record that are not classified as either notable or significant flood events. Either low impacts noted (for instance "a handful of properties affected") or no description of the event is given (typically "flooding in xx" or "localised flooding in yy".

Table 1 Classification of flood events according to severity

3. Results



- A trend of increasing frequency of reported flood events?
- Significant flood events show no trend of increase through time



- Large decadal variation in seasonal flooding
- Data from the 1890's to the present shows an increase in the proportion of summer flooding events

4. Discussion

Attribution to Drivers of Flood Risk

- Exposure is a key driver of number of reported floods and it has increased due to higher population and more development
- The flood defences constructed in the 20th Century have contributed to reducing the number of damaging floods
- When the data in Box 3 is de-trended for population growth, there is no apparent trend in the number of reported damaging floods
- Climatic variability between decades appears to be more important than long term trends caused in part by climatic change.

Implications for Risk Management

- Increased flood resilience required to reduce instances of flooding
- Adaptability of responses key to cope with future uncertainties

5. Conclusions

- Reported flooding datasets important in analysing flood trends
- Although exposure has increased, defences have kept number of damaging floods relatively constant
- Limited climate signals in the dataset for UK flooding

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Acknowledgements

Thanks go to the UK Meteorological Office for the Monthly Weather Reports and Climate Summaries and to the Centre for Ecology and Hydrology for the Monthly Hydrological Summaries.

Appendix H

YCSEC 2014 Abstract and Presentation

The following is the abstract for a talk presented at the Young Coastal Scientists and Engineers conference in Cardiff, UK April 14th-15th 2014.

Estimating the Evolution of Flood Risk to Coastal Populations

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Introduction

More than 200 million people are at risk of flooding from extreme sea levels caused by storms (Nicholls, 2010). Understanding how this exposure has evolved historically is a precursor to estimating future flood exposure and facilitating holistic, forward thinking flood risk management.

Methods

Historic maps and population data are used to estimate the spatial distribution of the coastal population through time, and extrapolated sea levels are used as a boundary condition in a hydrodynamic flood model to estimate the historic flood extent. The population exposed to flooding is then estimated for each time step. Uncertainty is addressed by comparing results for different population spreading techniques and rates of sea level change. The evolution of flood risk over a period of over 200 years (1801 to 2011) is assessed.

Results

The technique developed is applied to a case study of Portsmouth on the UK's south coast. Flood risk in the case study area is seen to have increased dramatically over the last 200 years, mostly as a result of population rise. Climatic changes have also increased exposure, with less population exposed to coastal flooding when changes in sea level are accounted for. This result shows that over the long term (100+ years) even modest changes in sea level can have significant impacts on the extent of the coastal floodplain.

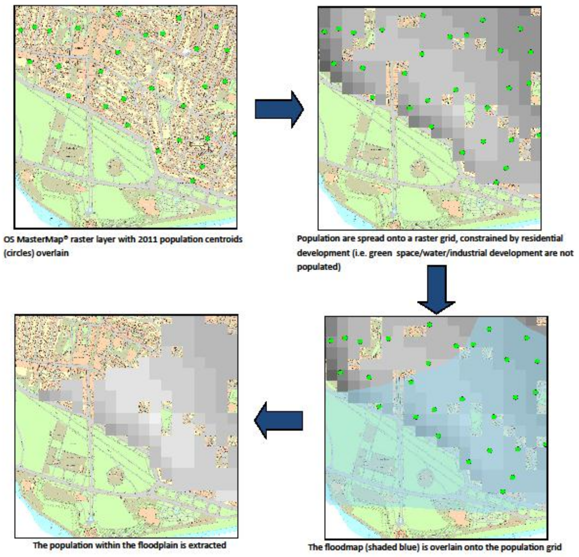

Figure 1 – Extracting population intersecting the floodplain

Discussion and conclusions

This work identifies a fundamental gap in (1) the assessment of exposure of coastal populations to flooding, and (2) the assessment of how this exposure can develop over time. This has implications for the current assessment of coastal flood events, and also for future planning decisions.

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Appendix I

EGU 2014 Abstract and Presentation

The following is the abstract for a talk was presented at the General Assembly of the European Geosciences Union 2014 which was held in Vienna, Austria April 28th - May 2nd 2014.

Geophysical Research Abstracts
Vol. 16, EGU2014-13348, 2014
EGU General Assembly 2014

Estimating the Evolution of Flood Risk to Coastal Populations

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The long term evolution of flood risk in a coastal area due to (a) Sea level rise and (b) Population rise is assessed. Historic maps and population data are used to estimate the spatial distribution of the coastal population through time, and extrapolated sea levels are used as a boundary condition in a hydrodynamic flood model to estimate the historic flood extent. The population exposed to flooding is then estimated for each time step. Uncertainty is addressed by comparing results for different population spreading techniques and rates of sea level change. The evolution of flood risk over a period of over 200 years (1801 to 2011) is assessed.

This work identifies a fundamental gap in (1) the assessment of exposure of coastal populations to flooding, and (2) the assessment of how this exposure can develop over time. This has implications for the current assessment of coastal flood events, and also for future planning decisions.

The technique developed is applied to a case study of Portsmouth on the UK's south coast. Flood risk in the case study area is seen to have increased dramatically over the last 200 years, mostly as a result of population rise. Climatic changes have also increased exposure, with significantly less population exposed to coastal flooding when changes in sea level are accounted for. This result shows that for long term (100+ year) studies even modest changes in sea level can have significant impacts on the extent of the coastal floodplain.

Appendix J

Journal Paper on UK Flood Trends

Hydrological Sciences Journal

ISSN: 0262-6667 (Print) 2150-3435 (Online) Journal homepage: http://www.tandfonline.com/loi/thsj20

Trends in reported flooding in the UK: 1884–2013

Andrew J. Stevens, Derek Clarke & Robert J. Nicholls

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Trends in reported flooding in the UK: 1884–2013

Andrew J. Stevens, Derek Clarke and Robert J. Nicholls

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ABSTRACT
A long-term dataset of reported flooding based on reports from the UK Met Office and the UK Centre for Ecology and Hydrology is described. This is possibly a unique dataset as the authors are unaware of any other 100+ year records of flood events and their consequences on a national scale. Flood events are classified by severity based upon qualitative descriptions. There is an increase in the number of reported flood events over time associated with an increased exposure to flooding as floodplain areas were developed. The data was de-trended for exposure, using population and dwelling house data. The adjusted record shows no trend in reported flooding over time, but there is significant decade to decade variability. This study opens a new approach to considering flood occurrence over a long time scale using reported information (and thus likely effects on society) rather than just considering trends in extreme hydrological conditions.

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KEYWORDS
Flooding; flood risk; detection; flood trends; UK

Introduction

Flooding has always been a feature in the British Isles and a number of major flood events in the 20th/21st century have caused significant damage and sometimes significant loss of life. They have also left an important legacy in how we manage flooding. The 1947, 1953, 1998/2000 and 2007 floods are examples, with the winter 2013/14 floods also likely to leave an important mark. Recently, the connection between flooding and climate change has been raised both in the UK (e.g. Wilby *et al.* 2008) and more widely (IPCC 2012, Jongman *et al.* 2012), and a linkage between climate change and flooding is often mentioned in the media. This raises questions about both historic trends and future prognosis of damaging floods. Growth in exposure to flooding is a major driver of flood risk (Evans *et al.* 2004, Merz *et al.* 2010, IPCC 2012) and hence increasing flood consequences may not be linked to just changes in hydrological regime. Detecting and understanding trends in flood consequences and all the relevant drivers is important, as this informs decision makers how best to allocate scarce resources for flood management (Pielke Jr 2000).

In this paper, we describe the historic trends in flooding in the UK by analysing a national dataset of over 125 years of reported flood events. This dataset is based on reporting systems that describe damaging terrestrial and tidal floods. National population and housing data are also considered to scale reported flooding by exposure. These datasets provide an unusual and possibly unique opportunity to evaluate any changes in the occurrence of damaging floods.

Flooding is often analysed using the Source-Pathway-Receptor-Consequence (SPRC) model (Thorne *et al.* 2007, FloodSite 2009, Narayan *et al.* 2014). Most historic studies focus on trends in flood sources, be it high river flows, extreme sea-level events and coastal storms (e.g. Robson *et al.* 1998, Haigh *et al.* 2010, Menéndez and Woodworth 2010, Marsh and Harvey 2012, Murphy *et al.* 2013, Wilby and Quinn 2013). Anticipated climate change suggests that in many areas of Europe summers are likely to be drier, but winters may be wetter, with a potential for a greater frequency of fluvial winter floods (Hulme *et al.* 2002, IPCC 2007). Coastal areas are likely to be more vulnerable than inland areas due to changes in sea level, wave heights and accelerated erosion (Zsamboky *et al.* 2011). However, an analysis in trends in consequences also needs to consider changes to the pathways and receptors. Changes in pathways may include degradation of natural protection, but they also include the provision of new and upgraded flood defences and other improvements in flood management over time. It is recognized that many flood defences have improved substantially over the last 100 years, as exemplified by London's flood defences, including the Thames Barrier.

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This has reduced flood consequences over time. In contrast, the number of receptors in the flood plain has increased significantly due to population growth and an increase in the number of buildings. This increases the potential consequences of a flood event (Evans *et al.* 2004, Hooijer *et al.* 2004).

Flood events have typically been evaluated using river flow data and the analysis of the frequency of peak flows (Robson *et al.* 1998, Robson 2002, Macdonald 2006, Petrow and Merz 2009, Delgado *et al.* 2010, Macdonald *et al.* 2010, Kjeldsen *et al.* 2012, Marsh and Harvey 2012). Long flow series are rare, with few records extending over 70 years (Macdonald and Black 2010). In the UK only the Thames and the Lee have flow records longer than 100 years (CEH 2013). There is much more data available for the last 50 years. For example, Petrow and Merz (2009) evaluated flow data for 145 sites in Germany between 1951 and 2002. Some studies have supplemented the hydrometric flow data with historical sources such as flood marks and descriptions (Macdonald 2006), documentary records (Macdonald and Black 2010), or palaeoflood hydrology such as geological records (Costa 1986). More local studies into the frequency and distribution of coastal flooding have used extreme sea-level data combined with local records (newspaper reports) to judge when tidal floods have occurred and consider their consequences (Ruocco *et al.* 2011).

Evaluations of trends in flood sources suggest there is variation spatially (IPCC 2007, 2013). Barredo (2009) assessed European flood losses in 31 countries between 1970 and 2006. The study shows no evidence of any trend in normalized flood losses. Delgado *et al.* (2010) found an increasing likelihood of extreme events in the Mekong River, whilst the probability of an "average flood" has decreased. Significant trends (both positive and negative) have been detected in a "considerable fraction" of basins in Germany (Petrow and Merz 2009). There is high year-to-year climate-led variation in the UK, with no significant long-term trends in flood frequency (Robson *et al.* 1998, Macdonald 2006, Marsh and Harvey 2012). There is evidence for a shorter-term (40–50 year) trend in the UK (Robson 2002) and significant trends were found in the UK in recent decades (Kjeldsen *et al.* 2012). Hannaford and Marsh (2008) found significant positive trends in the frequency and magnitude of flood events in 'relatively undisturbed' catchments in the UK in the last four decades of the 20th century. However, differing methodologies and the time scale of these studies make them difficult to compare with climate change scenarios that typically consider time scales of 30–100 years (Hulme *et al.* 2002, IPCC 2007, Ramsbottom *et al.* 2012).

Whilst historic sources can be used to extend records, these are not always consistent or reliable. Robson *et al.* (1998) state that long datasets are needed to identify trends, yet older data can be 'sketchy'. For instance, in European studies it was found that minor flood events were reported more widely in recent times (Barredo 2009). Journalistic evidence of flooding, however, may suffer from its ephemeral nature and potential lack of scientific rationale. It is clear that a trade-off exists between increasing the length of record with multiple data sources and maintaining consistency and quality of the record.

This paper develops and analyses a dataset of reported flood events covering the whole of the UK from 1884 to 2013, a period of 129 years. We are unaware of any other records longer than 100 years in the world that describe flood events for rivers and coasts on a national scale. The data record was used to explore trends in flooding over the 20th century. The effectiveness of the analysis framework used was evaluated to determine the ability to extract consistent knowledge in a changing social and physical world.

The reported datasets are described and critiqued, and limitations discussed. Validation of the dataset using independent flood impact data is then undertaken. The full time series is presented, and the data is de-trended for exposure and the implications of the findings are discussed.

Methodology

Datasets used for the long-term study of UK flood impacts

Macdonald and Black (2010) state "*the suitability and value of historical data in flood frequency analysis is determined by availability of records, their level of detail and their reliability*". There is a difference between a hydrological flood in terms of water level and a damaging flood which impacts on society. In this study only floods that have been reported as having an impact on society are considered. These are listed in the UK Meteorological Office (henceforth Met Office) *Monthly Weather Reports* (MET-WR; Met Office 2012a) and *UK Climate Summaries* (MET-CS; Met Office 2012b) (© Crown Copyright). These records span the period 1884 to present (Fig. 1) and are probably one of the longest regular sets of national reported flood consequences in the world.

The Met Office monthly weather summaries ended in 1993 and the *UK Climate Summaries* start in 2001. Hence, in this paper these reports are supplemented with the CEH (Centre for Ecology and Hydrology) monthly *Hydrological Summaries* (CEH-HS; CEH

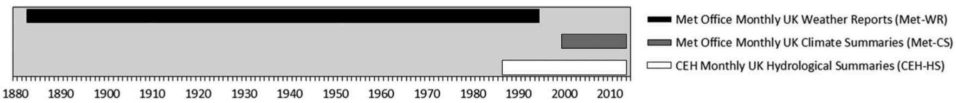


Figure 1. Lengths of the datasets used within this study.

2012) for 1988–2012 (© NERC – Centre for Ecology & Hydrology). These consider flood events (with limited descriptions of impacts), and they overlap with the Met Office reports for 18 years, allowing comparison.

The Met Office monthly weather summaries report on the meteorological 'highlights' for the UK each month (Fig. 2). Where flood impacts occur as a result of meteorological processes (such as rainfall, storm surges, high tides and gales), these are reported in the summaries as both terrestrial flooding (pluvial and fluvial) and tidal flooding.

This paper appraises the sources and methodology for producing a single unified record to provide an unbroken time series of reported flood events in the UK from 1884 to 2013.

Flood reporting terminology

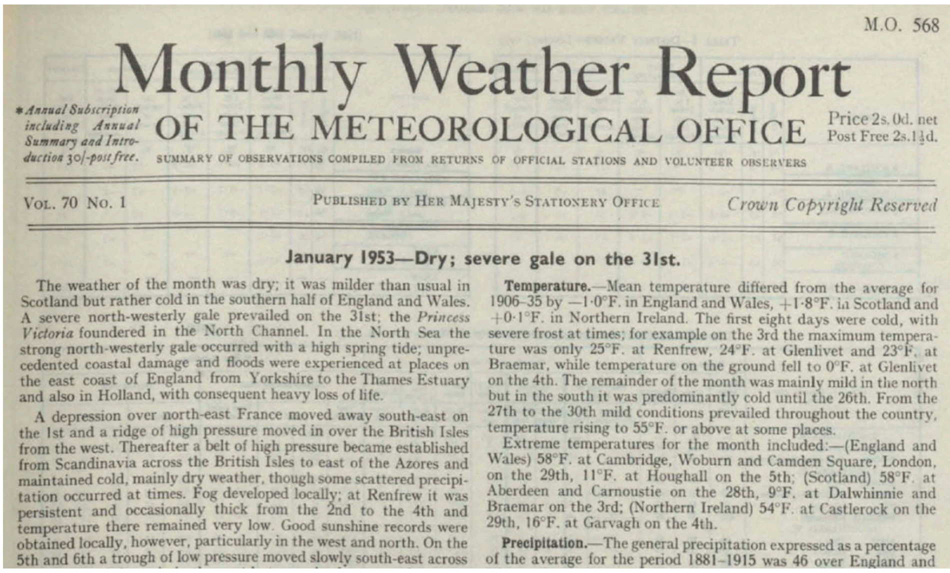
The *Monthly Weather Reports* provide the following information about flood events:

- Place(s) affected
- Description
- Cause (flood type)

The terminology used is often only descriptive; flow values or tide levels were rarely reported. Phrases used included 'Disastrous', 'Destructive' or 'Severe', which are difficult to quantify but nevertheless are useful indicators of the perceived scale of the event. The distribution of words used to describe flood events in the reports is shown in Table 1. The terms 'Widespread', 'Severe' and 'Extensive' have similar frequency of use in the two datasets, but CEH tends to use 'Significant' in place of a wider range of terms used by the Met Office.

Consistency of reporting terminology through time

The consistency of terminology through time is an important consideration. The use of the five most commonly used terms in the datasets ('Severe', 'Widespread', 'Serious', 'Extensive' and 'Considerable' – see Table 1) was analysed. Figure 3 shows that the majority of terms ('Severe', 'Serious', 'Extensive' and 'Considerable') are used continuously through time in the Met Office datasets and may be good indicators of the scale of event. The use of the term 'Widespread' is much more sporadic, first being used in the 1920s and with heightened use in the 1960s and 1980s. However, it is used more



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January 1953—Dry; severe gale on the 31st.

The weather of the month was dry; it was milder than usual in Scotland but rather cold in the southern half of England and Wales. A severe north-westerly gale prevailed on the 31st; the *Princess Victoria* foundered in the North Channel. In the North Sea the strong north-westerly gale occurred with a high spring tide; unprecedented coastal damage and floods were experienced at places on the east coast of England from Yorkshire to the Thames Estuary and also in Holland, with consequent heavy loss of life.

A depression over north-east France moved away south-east on the 1st and a ridge of high pressure moved in over the British Isles from the west. Thereafter a belt of high pressure became established from Scandinavia across the British Isles to east of the Azores and maintained cold, mainly dry weather, though some scattered precipitation occurred at times. Fog developed locally; at Renfrew it was persistent and occasionally thick from the 2nd to the 4th and temperature there remained very low. Good sunshine records were obtained locally, however, particularly in the west and north. On the 5th and 6th a trough of low pressure moved slowly south-east across

Temperature.—Mean temperature differed from the average for 1906–35 by —1·0°F. in England and Wales, +1·8°F. in Scotland and +0·1°F. in Northern Ireland. The first eight days were cold, with severe frost at times; for example on the 3rd the maximum temperature was only 25°F. at Renfrew, 24°F. at Glenlivet and 23°F. at Braemar, while temperature on the ground fell to 0°F. at Glenlivet on the 4th. The remainder of the month was mainly mild in the north but in the south it was predominantly cold until the 26th. From the 27th to the 30th mild conditions prevailed throughout the country, temperature rising to 55°F. or above at some places.

Extreme temperatures for the month included:—(England and Wales) 58°F. at Cambridge, Woburn and Camden Square, London, on the 29th, 11°F. at Houghall on the 5th; (Scotland) 58°F. at Aberdeen and Carnoustie on the 28th, 9°F. at Dalwhinnie and Braemar on the 3rd; (Northern Ireland) 54°F. at Castlerock on the 29th, 16°F. at Garvagh on the 4th.

Precipitation.—The general precipitation expressed as a percentage of the average for the period 1881–1915 was 46 over England and

Figure 2. Extract from the January 1953 *Monthly Weather Report*. This includes the extreme coastal flood event that caused over 2000 deaths in norhtwest Europe. (Source: Met Office *Monthly Weather Reports* © Crown Copyright. Contains public sector information licensed under the Open Government Licence v1.0).

Table 1. Number of times terminology used within the Met Office and CEH flood reports.

	Severe	Widespread	Serious	Extensive	Considerable	Significant	Disastrous	Destructive	Notable	Major	Substantial	Heavy	Protracted	Devastation	Great	Unprecedented
Met-WR	50	52	51	38	44	0	12	9	0	0	0	5	0	0	4	3
Met-CS	7	10	3	0	1	3	0	0	0	1	0	0	0	1	0	0
CEH-HS	48	23	2	14	1	26	0	0	8	5	5	0	5	3	0	1
Total	105	85	56	52	46	29	12	9	8	6	5	5	5	4	4	4

consistently toward the end of the record and so it may also be an indicator of scale. In the CEH dataset 'Serious' and 'Considerable' are used infrequently, however 'Widespread', 'Severe' and 'Extensive' are used continuously (the dataset starts in 1989 and so the 1980s data is only based upon one year and therefore is not comprehensive).

The evolution of use of the terms was explored for all of the datasets. The *Monthly Weather Reports* (Met-WR, Fig. 4(a) and (b)) used a wide array of descriptive terms, which evolved into a smaller number of terms in the *Climate Summaries* (Met-CS, Fig. 4(d)). The proportion of records using the terms 'Considerable' (6%), 'Severe' (9%) and 'Widespread' (9%) has remained relatively consistent throughout time. The term 'Serious' is used continuously throughout the record (to describe an average of 7% of flood events). The term 'Heavy' is seen at the start of the record only. 'Extensive' is used consistently throughout the Met-WR and also in the CEH-HS. 'Widespread' and 'Severe' appear throughout all the datasets.

Validation of descriptive terms

The descriptive terms used were compared to the Dartmouth Flood Observatory (DFO) records for the common period in the data (1985–2013). The DFO uses news, governmental, instrumental and remote sensing sources to compile a global database of large flood events (Brakenridge 2014). The dataset contains quantitative information such as number of fatalities, people displaced, estimated damage and area affected. These are used to assign a logarithmic flood magnitude score, similar to the Richter scale for earthquakes. Events with a flood magnitude score of 7, 8 or 9 can be reached for truly large events (Kundzewicz *et al.* 2013).

The flood events from the Met Office and CEH reports were compared to the DFO floods. Floods from each dataset were matched by consideration of start dates, places affected and flood type. 69% of the events in the Met Office record and 81% of the CEH events were reported in the DFO records. Flood events described in the Met Office and CEH reports that are not present in the DFO record were excluded from the validation exercise.

The magnitude of events from the DFO record was matched to the descriptive terms used in the Met Office and CEH records (Figs 5 and 6, respectively). Where several descriptive terms were used for a single flood event, each term was considered separately.

In the Met Office data (Fig. 5) the term 'Widespread' is used frequently to describe high-magnitude flood

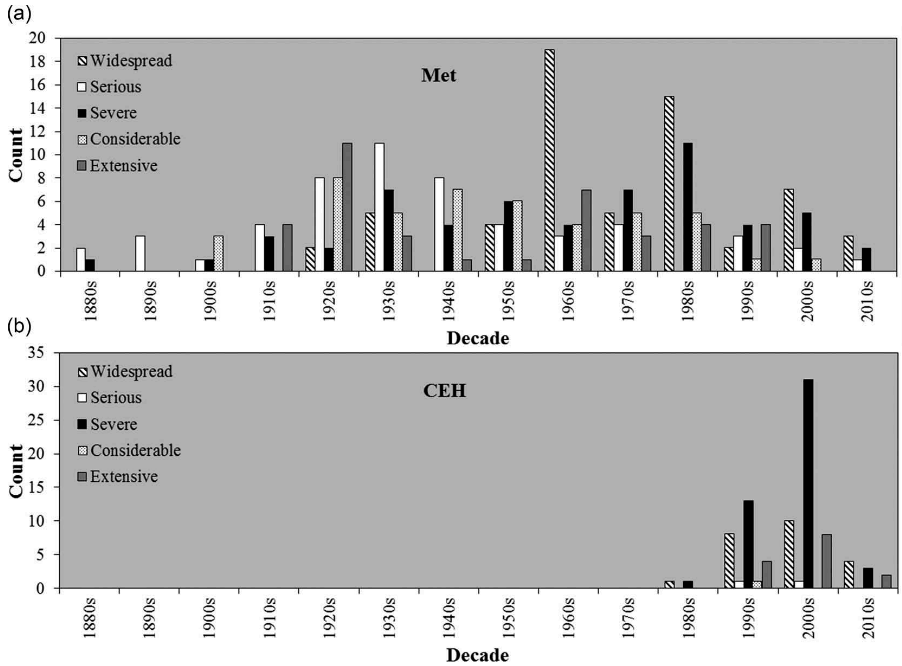

Figure 3. Frequency of commonly used terms over time in (a) the Met Office *Monthly Weather Reports* (1884–1993) and *UK Climate Summaries* (2001–2013) and (b) the CEH *Hydrological Summaries* (1988–2013).

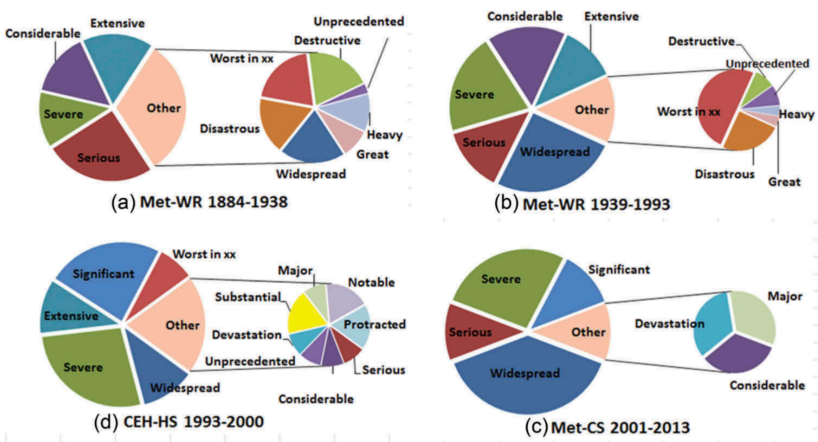

Figure 4. Descriptive terms in the Met Office *Monthly Weather Reports* (Met-WR) and *UK Climate Summaries* (Met-CS) and the CEH *Hydrological Summaries* (CEH-HS).

events. 'Serious', 'Extensive' or 'Disastrous' also describe high magnitude events from the DFO record, although the terms are used infrequently and therefore there is less certainty that they can be good indicators of scale. However, they still offer insight into the scale of the events they describe. Floods described as 'Severe', or that offer an estimated recurrence interval (or give assertions as to when the last flood of that magnitude was, e.g. "worst flooding seen in xx years"), are associated with mid-interval floods and are more frequently used in the dataset. The term 'Devastation' correlates to a low-magnitude event in the DFO (flood magnitude score 2.7); however, this refers to the locally significant event in Boscastle in 2004. This was a destructive event

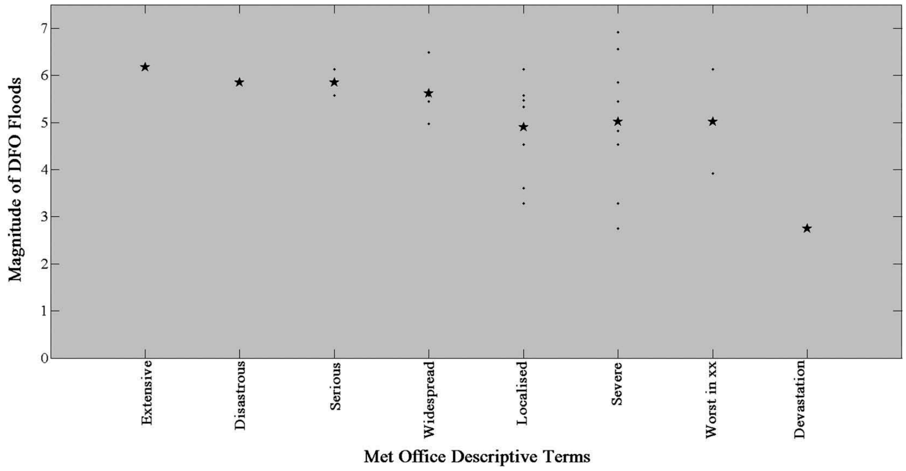

Figure 5. DFO magnitude *vs* descriptive terms used in the Met Office reports (star shows average magnitude, points show the spread).

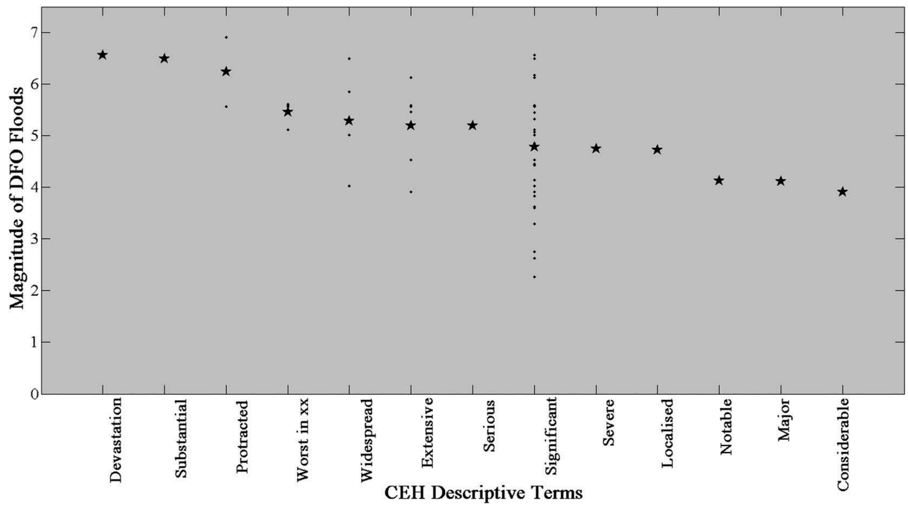

Figure 6. DFO magnitude *vs* descriptive terms used in the CEH reports (star shows average magnitude, points show the spread).

(Miller *et al.* 2013) that required a major airborne rescue operation to rescue victims (HR Wallingford *et al.* 2006). This is likely to have been underplayed in the global DFO dataset. Floods described in the Met Office reports as 'Localised' frequently correlated to intermediate to large floods from the DFO record. This highlights the limitation that locally significant events may be underplayed in the reports.

Some events described in the Met Office dataset that were considered to be 'Significant' on a UK scale have been missed in the global DFO data. For example the Met Office describes "significant" flooding in Aberystwyth on 9 June 2012 with hundreds of people rescued, costly damage to infrastructure and described as not seen in over 50 years (e.g. BBC 2012). This event is not present in the DFO, perhaps due to more severe flooding in the USA and Thailand occurring on the same date.

The CEH data (Fig. 6) uses 13 descriptive terms compared with the eight used by the Met Office. These tend to have a lower average DFO magnitude than Met Office data. Floods described as 'Devastating', 'Substantial' or 'Protracted' are associated with the highest magnitude DFO floods, and are used infrequently within the CEH data. However, the relationship is not strong because we are comparing reported issues of space, scale, rarity, duration and impact (DFO scoring system) with a single descriptive term that summarizes a flood event (CEH and Met Office). These terms are more difficult to quantify than information such as maximum water levels or peak flows. Nevertheless Figs 5 and 6 show that it is feasible to categorize these reports into classes, albeit not rank them in order of magnitude as for the DFO events. The comparison with the Dartmouth Flood Observatory dataset shows that descriptive terms used in the Met Office and CEH datasets can be related to an independent assessment of the magnitude of a flood event.

Reported impacts

Figure 7 shows the proportion of reports in which flood impacts were described either qualitatively (e.g. descriptively) or quantitatively (more substantially, such as spatial extent of flooding or specific impacts). The number of reports including information on impacts in the Met Office *Weather Reports* (Met-WR) varies through time; the number of quantitative records increased over the first part of the 20th century, falling towards the middle of the century before rising into the 1980s and 1990s. Between 20% and 40% of early reports record qualitative information on impacts; this proportion falls into the middle and end of the 20th century (being mostly replaced by quantitative descriptions). Of the total records, 21% provide quantitative information on flood impacts, with a further 8% providing qualitative descriptions. Only a small proportion (<10%) of Met Office *Climate Summaries* (Met-CS) provide information on flood impacts in the 2000s; however, the limited data for the 2010s shows almost half of the reports record quantitative information on flood impacts.

The CEH *Hydrological Summaries* (CEH-HS) provide limited quantitative information on flood impacts (only 10% of the total), with a further 10% of reports describing flood impacts qualitatively.

This assessment shows that the two datasets do not provide a comprehensive record on flood impacts;

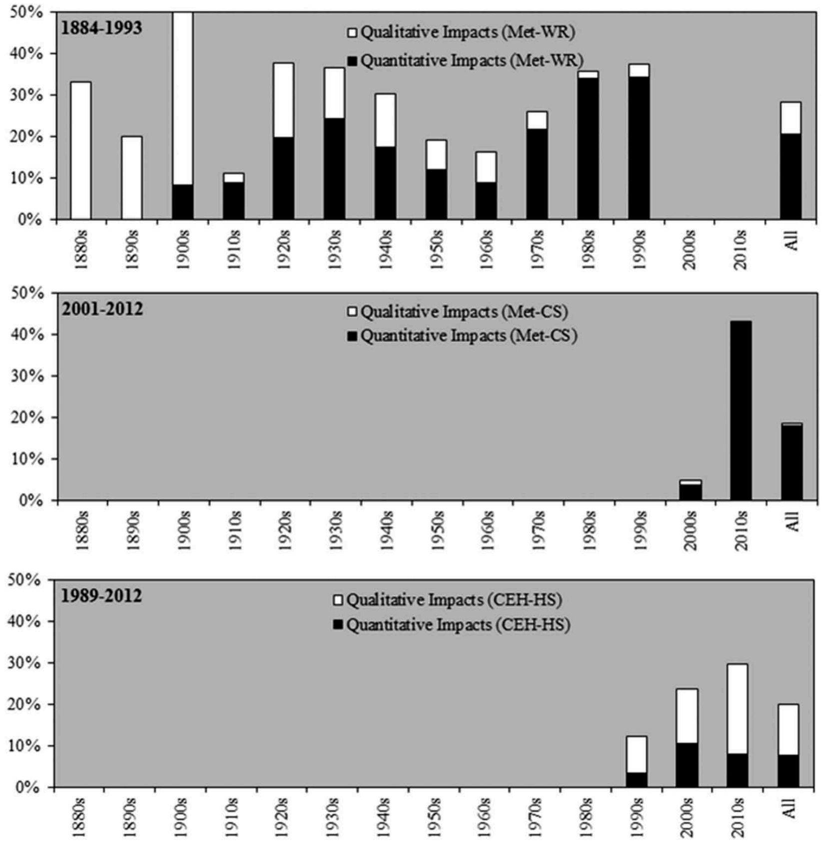

Figure 7. Percentage of flood records that described flood impacts (qualitative or quantitative).

however, we can still extract meaningful information from a significant proportion of reported floods.

Classification of flood event descriptors

The DFO validated descriptive phrases and information on flood impacts used in the CEH and Met Office reports were used to classify floods into groups that indicate the impact of the flood event. Three flood impact classes were created: Class 1 for low-magnitude events, Class 2 for intermediate-magnitude events, and Class 3 for high-magnitude events. Floods for which 'Localised', is the only description given were assigned to Class 1 (low magnitude of impact) because the use of 'Localised' as a descriptor was considered to be uncertain and inconsistent. Less than 10% of all floods described in the DFO dataset were 'Localised', so the effect of this assumption is minor.

The Met Office and CEH data were classified as shown in Table 2. Concurrent reports from the Met Office and CEH were available for 1989–1993 and 2001–2012 (Fig. 8). In these periods, 206 floods occur in the Met Office dataset and 204 in the CEH dataset. The CEH describes slightly more Class 2 (intermediate) floods and the Met Office describes slightly more Class 1 (smaller) and Class 3 (bigger) floods. The agreement between these datasets gives confidence in developing a consistent long-term reported flood event record.

Table 2. Classification of flood events according to estimated severity of event.

Classification	Description
Class 3	The most significant or damaging flooding as estimated from the reported record. For the Met record these are floods described as 'Widespread', 'Serious', 'Extensive' or 'Disastrous'. In the CEH record these are floods described as 'Devastating', 'Substantial' or 'Protracted'. Where quantifiable impacts are reported, a flood event involving loss of life, >1000 people evacuated or severe structural damage (such as hundreds of homes flooded, >£100 million in material damage).
Class 2	Floods events described in the Met reports as 'Severe' or 'Worst in xx' and in the CEH as 'Widespread', 'Serious', 'Severe', 'Considerable', 'Extensive', 'Significant', 'Disastrous', 'Worst in xx', 'Major' or 'Notable'. Quantified impacts less severe than Class 3, such as a handful (or unspecified number) of buildings destroyed, >£1 million material damage, some evacuations, substantial loss of livestock).
Class 1	Floods events either not described or with perceived low magnitude impacts: such as 'Localised'.

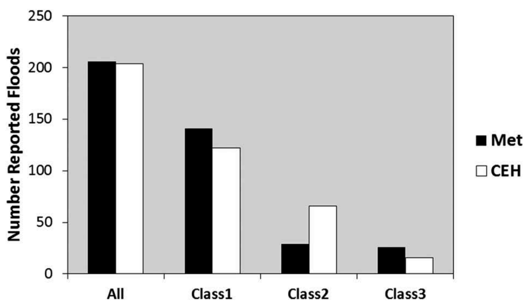

Figure 8. Comparison of reported flooding between Met Office and CEH data.

Creating a unified record

To create an unbroken record of records from 1884 to 2013 the datasets were combined. A total of 785 reported flood events were identified in the combined dataset. For the period 2001–2013, the Met Office *Climate Summaries* are used as they describe impacts more comprehensively than in the CEH reports. For the period 1993–2000 the CEH hydrological summaries are used, and the Met Office *Weather Reports* are used to extend the record from 1993 back to 1884. The combined dataset is shown in Fig. 9.

Well-known events, such as the floods of 1947, 1953, 2001, 2007, 2012, were readily identified. The causative mechanism (pluvial, fluvial) was rarely described and only 47 coastal flood events were identified from the records. The flood events were classified into 'Class 1', 'Class 2' and 'Class 3' floods using the definitions in Table 2. The annual totals of these events are shown in Fig. 9.

There is an upward trend in reported flooding over time and flood events appear more frequently towards the end of the 20th century. The start of the record is 'flood poor' but the number of events rose sharply through the 1910s and the 1920s. The number of reported events is lower between 1930 and the mid-1960s. This is most noted for 1939 and 1945 when there were government restrictions on reporting due to the Second World War. Reported events increased noticeably in the 1960s, with a peak in the early 1990s; 2012 was an exceptional year for floods in the UK, where annual rainfall was the second highest in over 100 years (Met Office 2013).

Estimating changes in exposure (receptors)

Over the 20th century, the UK population grew from 38.2 million to 59.1 million and the number of dwelling houses grew from 7.7 million to 24.8 million (Fig. 10). As a result there were more properties exposed to flooding and also more people to report flooding. A higher exposure to flooding will result in more reported flood events and larger potential consequential damage.

The reported flood events from the Met Office and CEH were normalized using the UK population and the number of dwellings. The population and dwelling counts were used as a proxy for exposure to flooding

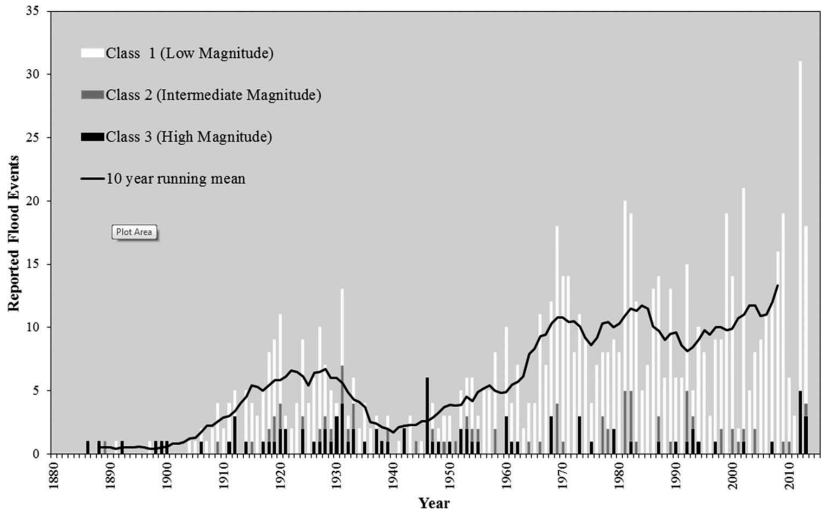

Figure 9. Instances of reported flooding in the UK each year 1884–2013 using combined Met Office/CEH data.

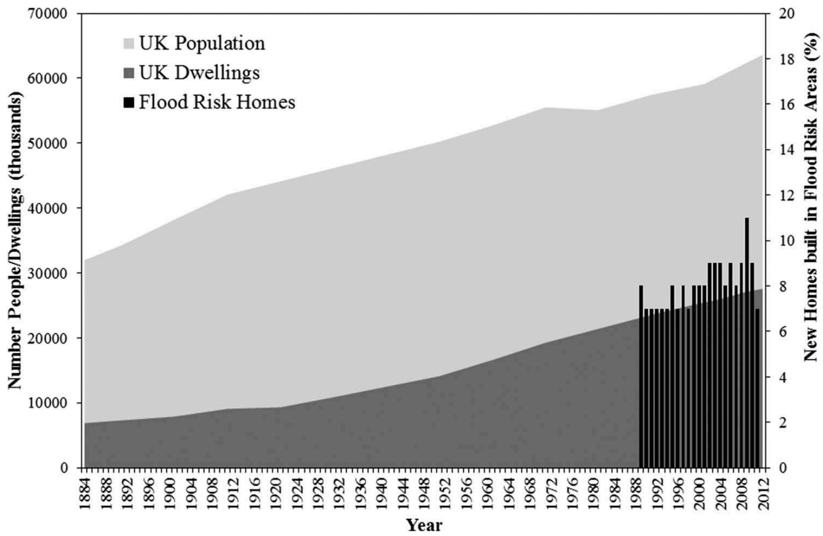

Figure 10. UK population counts (NISRA 2012, NRS 2012, ONS 2012a, 2012b), dwelling counts (DCLG 2013) and the proportion of new homes built in areas of flood risk (DCLG 2012).

assuming that the percentage of the population in floodplains is proportional to the total population. This is supported by data for the percentage of new households built on floodplains in England in 1989–2010 (DCLG 2012) (Fig. 10). The population and dwelling data were used to scale the aggregate yearly flood totals using

$$\mathrm{FSP_i} = (F_i/P_i) \quad (1)$$

$$\mathrm{FSD_i} = (F_i/D_i) \quad (2)$$

Where, for the year i, FSP_i is the flood count scaled for population; FSD_i is the flood count scaled for dwellings; F_i is the count of reported flood events; P_i is the UK population; and D_i is the UK dwellings count.

Estimating changes in defences (pathways)

There are no data available at a national scale that record changes in natural defences, artificial defences and other management. Natural defences are important and they may have declined, but data are poor (Jones *et al.* 2011). There have been significant upgrades to artificial defences, most notably following the 1947 Thames floods, with a sustained effort to improve conveyance of rivers, and the 1953 North Sea storm surge, which led to a major upgrade of flood defences on the East Coast, including the Thames Barrier and London's flood defences. Hence subsequent extreme sea-level events on the East Coast had much lower impacts even if the hydraulic conditions were similar—compare the major consequences of the 31 January/1 February 1953 event including more than 300 deaths (Steers 1953) with the 11 January 1978 event (Steers *et al.* 1979), and the recent 5/6 December 2013 event with similar or higher water levels and much smaller consequences. As well as defences, flood warnings have improved substantially and are now routine components of flood risk management (Horsburgh *et al.* 2008). The implications of these trends are considered later.

Trends in reported flooding – normalized for exposure

Reported flood impacts are normalized for exposure using population and number of dwelling houses in the UK (Fig. 11(a) and (b)). When scaled for exposure, the relative count of flood events shows a weaker trend and greater variability than the raw data shown in Fig. 9. The normalized data suggest that there is no

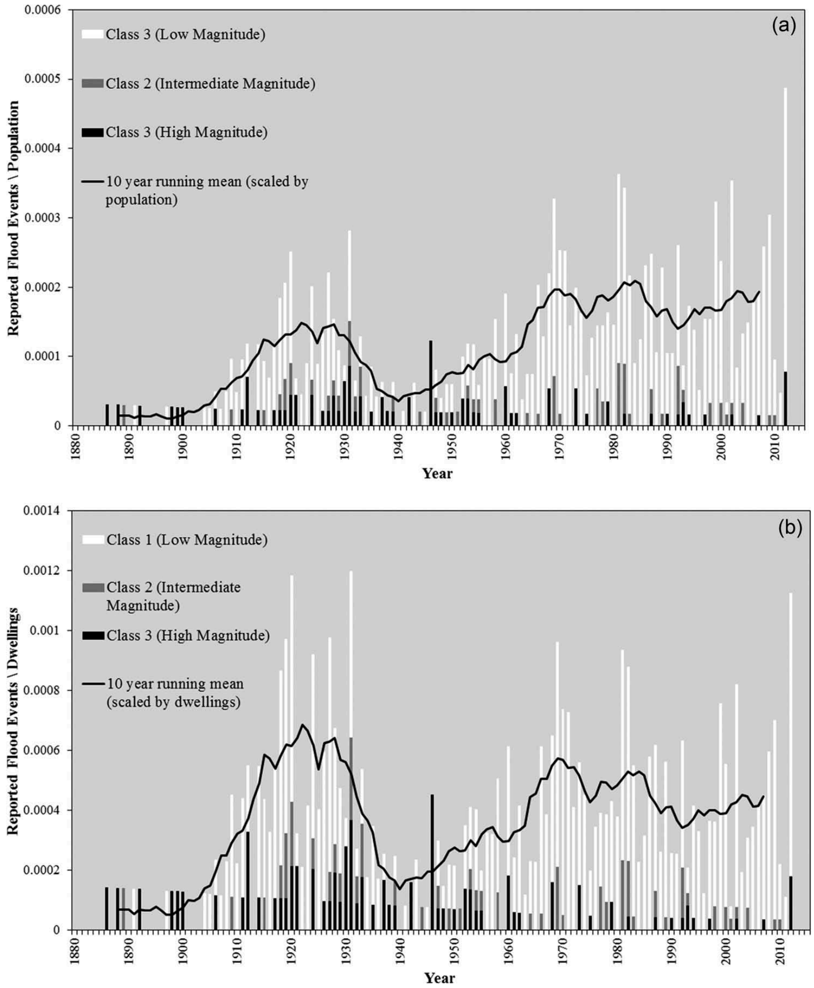

Figure 11. UK flooding normalized by (a) population and (b) number of dwellings (note: normalized data plotted to 2012 due to lack of 2013 normalization data).

consistent trend in the number of floods per head of population during the 20th century. There is significant decadal variability in both the raw data and normalized counts. Wilby and Quinn (2013) identified three hydrologically flood-rich episodes in river catchments since the 1870s, as follows: 1908–1934, 1977–1988 and from 1998 onwards. The first period is visible in Fig. 9, and the second and third periods are characterized by higher numbers of flood events (fluvial, pluvial and coastal) in the 1980s and post-1998. However, the reports also indicate a peak in the early 1970s which differs from the Wilby and Quinn (2013) analysis. Figure 11(b) shows that flood counts normalized by number of dwellings have not increased during the 20th century.

Clusters of 'Class 3' (high-magnitude) flooding (as defined in Table 2) appear in the 1920s, 1960s and the 1990s. 'Class 2' (intermediate) flood events appear more uniformly though time. The number of 'Class 1' (low-magnitude) events is highly variable. There is a fall in 'Class 1' floods between 1930 and 1960, but the frequency of 'Class 1' floods increases sharply after 1968. This may be associated with increased development on floodplains during the latter part of the 20th century (Parker 1995).

We cannot normalize for defences, but we note that the last peak of Wilby and Quinn (2013) is not apparent in Fig. 9. While it is speculative, this may represent the effect of improved defences reducing impacts and therefore 'reportable' flood events.

Discussion

Consequences are the combined results of high river flows, pluvial flooding and coastal flooding, the numbers of people and property exposed to flooding and the effects of flood defence construction and floodplain management policies. The increase in the total number of reported flood events in the 20th century in the UK appears to be a function of the gradual increase in exposure due to urban expansion and population growth. However, there is also greater capacity to report flood events. The number of reported 'Class 3' flooding events has remained static or decreased slightly over the 20th century. This is despite the UK population almost doubling and the number of dwelling houses tripling over the same time period.

There is no clear underlying trend in flood reports present in the UK flood data when they are normalized for exposure. Pielke and Landsea (1998) studied damage caused by hurricanes in the USA. They also found that normalizing damage reports to take account of exposure removed the upward trend of losses over time and only left a large decade-to-decade variation in losses. The lack of a systematic trend in the normalized UK total flood count mirrors these findings. It is also in agreement with studies of trends in river flows (Robson 2002). Land use change can affect the number of reported floods; e.g. Kjeldsen (2010) and Kjeldsen *et al.* (2012) suggested that increased urbanisation has a pronounced effect on flood hydrology. In this work, we used population and number of dwellings as a measure of exposure but not as a driver of increased hazard such as higher runoff. This demonstrates the complexity of separating hydrology from flood impacts.

These observations do not preclude concern about future flood impacts, especially in coastal areas where sea-level rise is being observed and faster rises are expected (Haigh *et al.* 2011), and areas potentially exposed to higher rainfall intensities (Hulme *et al.* 2002, Stern 2006). However, attributing periods of reduced flooding simply to the effects of improved management is difficult and must be done with care. Future flood risk may be very sensitive to changes in funding or management approaches and this has important implications for decision makers.

The reporting framework used by both the Met Office and CEH has been shown to be an effective resource for a national-scale study of reported flooding. The consistency of the data is a key asset, with the length of record giving useful insights into flood trends at a national level. Care must be taken with the use of multiple data sources and variations in the terminology used to describe floods. The reporting framework has some limitations—it is descriptive and rarely provides the opportunity for classification of flooding by mechanism (fluvial, pluvial, coastal etc.). It may also be biased towards urban areas where reporting of flooding is more likely. Further, the data are likely to under-represent localized events, which may have had implications for national policy. However, despite these drawbacks, the dataset opens the possibility of considering flood occurrence over a long time scale using reported information (and thus likely effects on society), rather than just changes in extreme hydrological events.

As a tool for reviewing the change in flood impacts through time, supplementary data are needed (such as local newspaper reports, *post-hoc* academic or professional reviews), as key events are typically mentioned, but underplayed in the data (e.g. the North Sea surge of 1953, which was condensed to "unprecedented coastal damage and floods", see Fig. 2). Additional data can be gathered for individual flood events, for example, the Environment Agency report on the costs of the summer 2007 flood events (Chatterton 2010), Met Office reviews of the 2005 and 2008 flooding (Met Office 2011, 2012c), and an appraisal of the 1947 fluvial event (RMS 2007).

The dataset presented here serves as a 'catalogue' of national level flood events in the UK over the last 125 years. A further study linking date of occurrence from this record with rainfall/river flow data could make assessment of flooding 'type' possible. The study could be complemented or extended further in time by using ancillary data sources, such as the Chronology of British Hydrological Events (Black and Law 2004). Analysis of the recurrence interval of events within the record could provide further validation. However, care must be taken due to the quality of reported impacts and the limitations of qualitative data sources, as discussed in this paper. This work highlights the need to maintain the reporting framework of flood events in order to provide continued information on long-term trends, such as the effects of climate change and sea-level rise.

Conclusions

This paper develops a 100+ year national dataset of 785 notable flood events in the UK. It is an unusual if not unique dataset. The dataset indicates an increase in reported flood events during the 20th/21st century and significant variation from decade to decade. However, normalizing the data by population and number of dwellings removes any long-term temporal trend and leaves a strong decadal variability. The effect of increasing and improving defences is unclear. It also shows the importance of drivers of flood events and losses, and the continuing benefits of monitoring changes in climate, exposure and impacts. Descriptive datasets of reported flooding can complement existing hydrological analysis, especially for combined descriptive/quantitative datasets such as the CEH *Hydrological Summary* of the UK.

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Disclosure statement

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Appendix K

Journal Paper on Historic Exposure

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Estimating the long-term historic evolution of exposure to flooding of coastal populations

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Abstract. Coastal managers face the task of assessing and managing flood risk. This requires knowledge of the area of land, the number of people, properties and other infrastructure potentially affected by floods. Such analyses are usually static; i.e. they only consider a snapshot of the current situation. This misses the opportunity to learn about the role of key drivers of historical changes in flood risk, such as development and population rise in the coastal flood plain, as well as sea-level rise.

In this paper, we develop and apply a method to analyse the temporal evolution of residential population exposure to coastal flooding. It uses readily available data in a GIS environment. We examine how population and sea-level change have modified exposure over two centuries in two neighbouring coastal sites: Portsea and Hayling Islands on the UK south coast. The analysis shows that flood exposure changes as a result of increases in population, changes in coastal population density and sea level rise. The results indicate that to date, population change is the dominant driver of the increase in exposure to flooding in the study sites, but climate change may outweigh this in the future. A full analysis of changing flood risk is not possible as data on historic defences and wider vulnerability are not available. Hence, the historic evolution of flood exposure is as close as we can get to a historic evolution of flood risk.

The method is applicable anywhere that suitable floodplain geometry, sea level and population data sets are available and could be widely applied, and will help inform coastal managers of the time evolution in coastal flood drivers.

1 Introduction

One tenth of the world's population live in the low elevation coastal zone (Lichter et al., 2011), or are exposed as temporary residents due to coastal tourism and industry (Kron, 2008). More than 200 million people are estimated to be at risk of flooding from extreme sea levels caused by storms (Nicholls, 2010). Hence there is an urgent need for coastal managers to understand coastal flood risk, the drivers of the risk and how the drivers change over time. Drivers of flood risk include population exposed to flooding, frequency of extreme events and the effectiveness of any flood defences and of any other adaptation. All of these drivers can change over time so a full analysis should include an evaluation of how these drivers evolve both historically and into the future (via scenario analysis). While there are many future analyses of flooding, historic analyses are less common, which misses important empirical insights on what has happened.

Flood risk can be assessed in a framework which considers the interacting elements of the SPRC (Source–Pathway–Receptor–Consequence) model (Holdgate, 1979) or more recently the “flood system” concept (Evans et al., 2004; Narayan et al., 2014; Sayers et al., 2002). Methods to assess exposure to coastal floods have focused on understanding the sources (e.g. extreme sea levels (Haigh et al., 2010; Batstone

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Table 1. Summary of required data and sources.

Data	Source
Population size and distribution	Census data (10 year time steps)
Urban/residential extent	Historic maps digitised in GIS (∼ 20 year time steps)
Flood extent	Inundation model (after Wadey et al., 2012)

et al., 2013) and waves (Wolf et al., 2011; Chini and Stansby, 2012)) or pathways (e.g. simulations of defence failure and inundation via event-based approaches (Wadey et al., 2012, 2013) and flood risk assessment (Gouldby et al., 2008; Dawson et al., 2009)). These studies can include the effects of anticipated sea level rise (SLR) which changes the probability of extreme events (Church et al., 2013; Wahl et al., 2013; Haigh et al., 2011). Coastal flood risk is bound to change in time because sea level is rising (IPCC, 2013) and more people are living closer to the sea (Nicholls, 1995; Small and Nicholls, 2003). However, previous studies have not looked at the detailed historic time evolution of this risk. Population assessments have only been considered in time-aggregated analyses such as Foresight (Evans et al., 2004).

Receptors and consequences have usually been incorporated into risk assessments by evaluations of economic consequences in the form of expected annual damages (Penning-Rowsell et al., 2005, 2013). Tools to model human responses and risk to life have been demonstrated via agent-based models (e.g. Dawson et al., 2011) and empirical methods (e.g. Jonkman et al., 2008; Wallingford et al., 2006).

In this paper, flood risk is considered as the interplay between the probability of a given event occurring, the people and property exposed to the flood event and the vulnerability of those at risk, as defined in earlier work (e.g. Samuels et al., 2009; Blaikie et al., 1994; Gwilliam et al., 2006; Kron, 2005; Fielding, 2007; UNDRO, 1982; United Nations and Birkmann, 2006; USACE et al., 2011).

Probability is included in the source component of the SPRC and it is commonly expressed as a return period (e.g. this work considers the 1 in 200 year flood event – an event that would be expected to occur, on average, once every 200 years, or more formally have a likelihood of occurrence of 0.5 per cent in a single year). This return period was chosen as it is a typical design standard for coastal defences and so is a critical threshold to assess. Exposure describes the area flooded (pathways of the SPRC) and the people/property within this area (receptors) (Narayan et al., 2014). Vulnerability links the receptors and consequence terms of the SPRC and determines the expected damages for given flood characteristics (e.g. in Fig. 1 a house with a raised floor level is less vulnerable, and thus expected damages would be reduced).

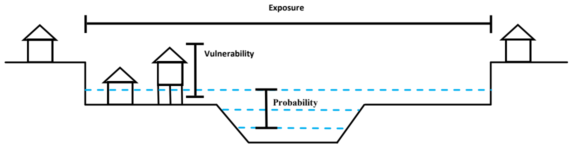

Figure 1. Cross section of a floodplain showing the components of risk.

In this paper, the change in the "exposure" component of flood risk is evaluated (i.e. we do not account for changes in vulnerability or attempt to evaluate the time-evolving cost of damage caused by flooding). We assume that no defences are present. This reflects that we do not have historic data on defences and beach state and these factors are probably not amenable to historic analysis.

In this paper we present a method for assessing the historic exposure of coastal residential populations, and how this has evolved over approximately 200 years (since 1800) for two UK case study sites. The analysis will enable us to determine the key drivers of changes in risk of flooding in the coastal environment. A study site is chosen that represents typical areas of the well-developed UK coast that have already undergone assessments of plausible changes in sea levels and inundation, and has good data sets on population density, coastal floodplain elevations and historic sea levels. Quantifying the number and spatial location of people in the floodplain is vital for effective flood risk management in relation to evacuation planning. It is important to note that the approach in this paper focuses on the population exposure rather than the financial cost of flooding.

The paper is structured into the following sections: Sect. 2, an introduction to the case study region; Sect. 3, methodology including Sect. 3.1, model outline and data sets used, Sect. 3.2, population distribution model, Sect. 3.3, flood inundation model and Sect. 3.4, exposure model (see Appendix A for modelling assumptions); Sect. 4, analysis/results of the exposed population calculations; Sect. 5, discussion and Sect. 6, conclusions and recommendations for future research.

2 Case study site

The study site (Fig. 2) is based in the densely populated region of the UK along the Solent estuary which includes the cities of Southampton and Portsmouth. The coastline spans approximately 55 km "as the crow flies" from Hurst Spit in the west to Selsey Bill in the east but it is heavily indented. The Solent region topography, population and land use is representative of many developed coastal areas, with approximately 25 000 properties on land exposed to a 1 in 200 year coastal flood (NFDC, 2010). Portsmouth has the UK's highest population density outside of London, and is a major site where properties are at risk of coastal flooding (RIBA

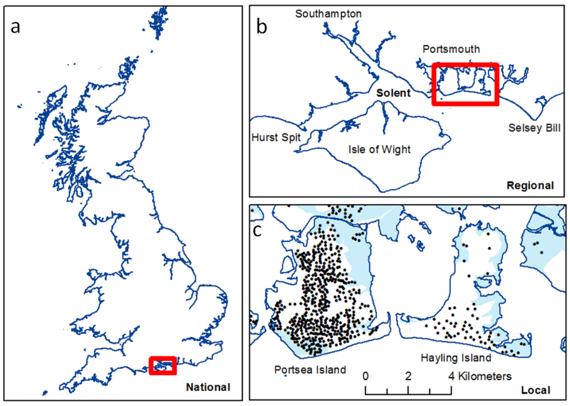

Figure 2. (a) and **(b)** Location of Portsea and Hayling Islands. **(c)** Centroid points for population data assigned to the 2011 UK national Census and the Environment Agency's 1 in 200 year indicative floodplain map (IFM, shaded blue) (Centroid points are Crown copyright/database right 2013. An Ordnance Survey/EDINA supplied service. IFM is ©Environment Agency copyright and database rights 2015.).

and ICE, 2008). The Solent region faces many of the typical global development pressures on the coast: high population density, a strategic trade location (road and sea transport routes) and tourist/environmental attractions (NFDC, 2010). Some parts of the coastline (notably Portsea Island) have hard engineered sea defences, whereas other sections use softer approaches such as beach nourishment (e.g. Hayling Island). These defences are managed whilst sea levels have been rising, increasing the probability of extreme sea level and flood events (Haigh et al., 2011; Wadey et al., 2013).

There is already a substantial flood history and present-day threat: a study assessing the history of extreme sea levels and media accounts of floods identified 40 flood events in Portsmouth between 1960 and 2005 (Ruocco et al., 2011). On 10 March 2008 a storm surge, high tide and waves in the English channel led to significant coastal flooding in the Solent area (Wadey et al., 2013). The storms and high tides of the 2013–2014 winter caused a number of coastal flood events (Wadey et al., 2015). The study area has been zoned for flood "risk" by the UK Environment Agency for a 1 : 200 year extreme event assuming that no flood defences are present (Fig. 2c). In this study we continue to use the worst case undefended scenario in consistency with current management practices.

This case study tests the developed concept that is transferable to other densely populated coastal regions with appropriate data.

3 Methodology

3.1 Outline and data sets

In this study we are evaluating the evolution of exposure (as a proxy for risk), measured as the number of people within the indicative undefended coastal floodplain, for a 1 in 200 year flood event, given population change, residential development and sea level rise. A detailed digital elevation model of the floodplain was developed by Wadey et al. (2012). Sea level data are available for the study area for 1960 to 2008 (Haigh et al., 2011). Population data are available from the UK Census for Portsea and Hayling from 1801–2011 at 10 year time steps. Historic maps are available at roughly 20 year time steps (1870s, 1890s, 1910s, 1930s, 1960s, 1970s, 1990s and 2010s). From 1870–1990 the maps are at a scale of 1 : 10 560. For the 2010s map a scale of 1 : 2000 is available. Data required and sources are summarised in Table 1.

The methodology used in this study is shown in Fig. 3, and details of how the population is located and the flood extent generated are presented in the following subsection. We use known population data from the UK Census, locate the population spatially using historic maps and then identify the number of people exposed to flood risk in the 1 in 200 year floodplain. This process is repeated every 10 years between 1801 and 2011. Exposure is evaluated in a time step of 10 years to match the time step of the census data. Data sets for the physical system (sea levels, tidal curve and land elevations) are combined in a floodplain extent model. This gives the extent of the floodplain at different stages of time (e.g. accounting for changes in sea level, and excluding defences). The changes in historic shoreline position are not accounted for as part of this study.

The socio-economic data sets (population, historic maps) are combined in a population distribution model. This gives the spatial distribution of the population at each time step. For simplicity the extent of the housing development is assumed to be constant between the historic map years, as interpolation of housing development between map dates is difficult and unlikely to provide additional knowledge or understanding.

3.2 Population distribution model

3.2.1 Population count

Demographic data from the UK Census were used to reconstruct the spatial population distribution at the study site since 1801 at 10 year intervals (Hampshire County Council, 2001; Registrar General for England and Wales, 1971; Office of Population Censuses and Surveys, 1981, 1991; ONS, 2001, 2011). These data were used within the model to identify the coastal population at risk of flooding (Fig. 3).

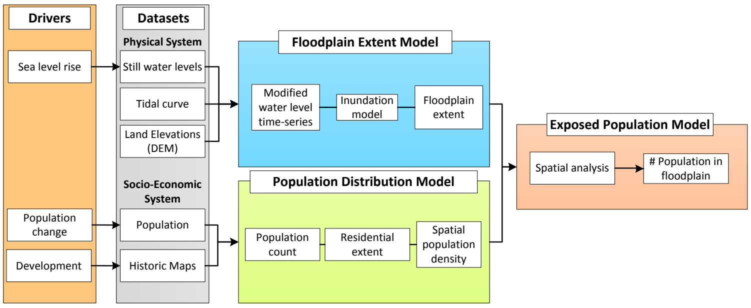

Figure 3. Methodology for evaluating changes to flood exposure.

Prior to 1971 the aggregate population for Portsea and Hayling Islands are used (shown as "non-spatial" data in Fig. 4), because the location of the population was not recorded. Some interpolation was necessary for the Hayling population (see Appendix A).

For census years 1971–2011 spatial census data are available as centroid points. Centroid points (Fig. 2c) represent the population within a census output area. Output areas (OAs) are the lowest geographical level at which census estimates are provided. The output areas are designed to have between 40–125 households, with a minimum population of 100. Census data from the 2001 and 2011 censuses at the output area level were used, (OAs 504 and 522 within Portsea Island, respectively). For 1971, 1981 and 1991, data were extracted at the enumeration district level (312, 314 and 303 EDs, respectively – these censuses pre-date output area levels). Enumeration districts are less well defined, containing between 45–940 people for the 1971 Portsea and Hayling data, for example.

3.2.2 Historic residential extent

Maps of Portsea and Hayling Islands between 1870 and 2012 were used to identify the level of development and which areas were populated. Urban areas were digitised to create a residential mask in ARC GIS (geographical information system) and these were used to distribute the population count from the census data into the populated areas and to constrain population to residential areas (see Appendix A).

The digitised residential areas are seen in Fig. 5. Development has increased on both islands between 1870 and 2012. On Portsea, early residential development (1870s) was centred near the dockyards area to the west of the island with small pockets of residential development elsewhere. The centre and east of the island began to be developed between the 1890s and 1910s and by 1930, the island was largely developed. Major developments since the 1930s include Anchorage park to the north-east of the island (seen in the 1990s map and expanded in the 2010s map), and developments in the Eastney area in the south-east corner of the island (seen from 1960 onwards). Hayling was sparsely developed from the 1870s through to the 1910s. In the 1930s development increased, mostly in the south of the island. As for Portsea, the pattern in the 1930s is similar to that of the modern day, although unlike Portsea, the population has grown more than 4 times larger. For instance, noticeable development did occur in the Eastoke peninsula (south-east corner of the island) seen in the 1960s through to the 2010s map. Portsea Island remains more developed than Hayling throughout the record.

3.2.3 Spatial population density

The Census data provided a population count and a centroid point to locate the population in each output area (OA) or enumeration district (ED) (see Fig. 2c). Surface Builder™ was used to distribute the population spatially (Martin, 1989). This model creates a raster grid with population density in each cell calculated as a function of the distance from each population centroid (see Fig. 6a, b and Appendix A). A raster grid is used as it offers ease of integration with other data sources (e.g. the raster flood maps) (Martin et al., 2011). Complications arose because census areas have changed over time (i.e. are different for each census) and the different geographies between censuses make longitudinal studies problematic (Langford, 2007; Martin et al., 2002). A solution is to use interpolation techniques to transform the population data to a common set of zones (Langford, 2007). For small spatial areas, such as output areas and enumeration districts, remodelling of the data to an underlying surface-based representation may prove the only alternative (Martin et al., 2002). In this study, the census population centroid data were aggregated to raster grid cells of size 50 m by 50 m using the SurfaceBuilder™ program. This grid-based method provides a consistent method of assessing the relationship between social vulnerability and exposure to flooding, as opposed to simpler methods based on census output areas (Martin, 1989; Thrush et al., 2005).

3.3 Floodplain extent model

As already noted, sea defences are excluded due to lack of data. An analysis of the effectiveness of coastal flood de-

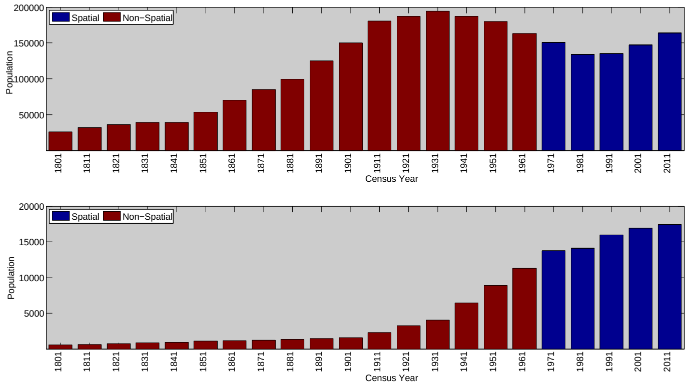

Figure 4. Population time series and source (spatial or non-spatial) for Portsea (above) and Hayling (below).

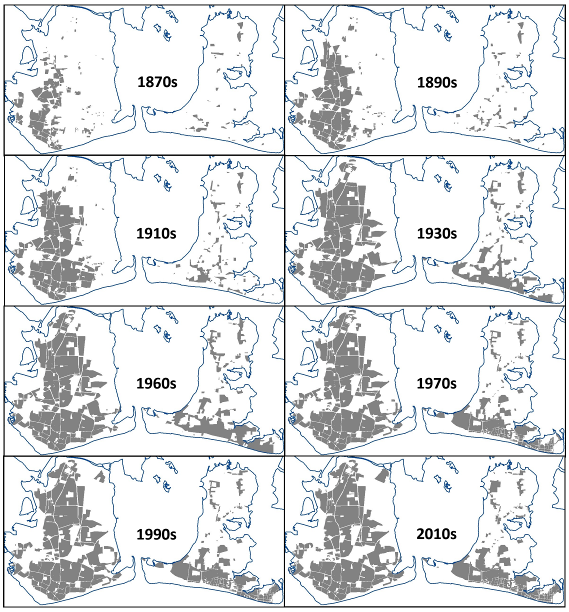

Figure 5. Digitised residential areas in Portsea Island (left island) and Hayling Island (right island). Maps sourced from Digimap® Crown Copyright and Landmark Information Group Limited (2014). All rights reserved. (See Appendix A for comprehensive list of maps used.)

fences is beyond the scope of this paper. The lack of historic data on flood defences makes a temporal study of risk evolution including defences time unfeasible. Our aim is to assess the worst case scenario.

To determine the floodplain extent, we used a combined hydraulic model (LISFLOOD FP) (Bates et al., 2010) and digital elevation model (DEM) (Wadey et al., 2012) for a range of flood simulations by return period assuming no sea defences. LISFLOOD FP is an inertial formulation of the shallow water equations (Bates et al., 2010). It has been used to simulate coastal flood events (Smith et al., 2012; Quinn et al., 2014), including within the Solent (Wadey et al., 2012) where the model has been validated (Wadey et al., 2013). Floodplain flows are treated using a "storage cell" approach and implemented for a raster grid to allow an approximation to a two-dimensional (2-D) movement of the flood wave. A continuity equation is solved linking flow into a cell and its change in volume, and a momentum equation for each direction where flow between cells is calculated. With good quality topographic data, this model can produce similar results to full 2-D formulations of the shallow water equations (for sub-critical gradually varied flows only). The model is run for a single tidal cycle.

This model has been shown to identify properties exposed to flooding in the Portsmouth case study with a vertical accuracy of approximately ± 10 cm. The model application by Wadey et al. (2012) was modified in this application for historic simulations of flooding by adjusting the still water level boundary condition. Sea level rise was based on the estimates of Haigh et al. (2011) at Portsmouth from 1960 to 2008 and extrapolated back to 1801 ($1.21\,\mathrm{mm\,yr^{-1}} \pm 1$ s.e.).

3.4 Exposure model (number of people at risk)

The population layer and flood extent layer are combined to determine the exposed population in the floodplain (Fig. 6). The exposed population in each grid cell is summed to give a total exposed population for that time step. The process was repeated for each census year to assess the evolution of exposure of the coastal population.

4 Results: changes in population exposed to flooding and its drivers

The temporal evolution of exposure in Portsea and Hayling are shown in Figs. 7 and 8. The error bars show the variabil-

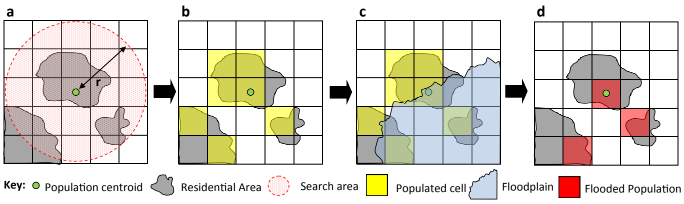

Figure 6. Method to calculate exposed population: **(a, b)** population is spread from centroid points to a raster grid according to specified search area (see Appendix A), **(c)** floodplain is overlain and **(d)** exposed population calculated.

ity in calculated exposure due to uncertainty in the estimates of sea level, population size and distribution (for a breakdown of the uncertainty, see "Sources of uncertainty" in the Appendix). Three rates of sea level rise were used; the mean value for the Portsmouth tide gauge of 1.22 mm yr^{-1} (Haigh et al., 2011), and ± one standard deviation of this value (0.94 and 1.48 mm yr^{-1}, respectively).

Between 1801 and 2011, the exposed population in Portsea has increased from approximately 1500 people in 1801 to 19 800 in 2011. This represents a greater than 10-fold increase in exposure. Figure 7 shows the temporal evolution; there is a slow rise 1800–1850, a faster rise 1850–1930. Exposure then levels off and falls slightly 1940–1970, followed by a further rise 1980–2011. The curve follows the same pattern as the island's total population (Fig. 4). In Hayling there was only a very small population (< 100 people) exposed to flooding prior to 1921 and this result is consistent across all sea level rates applied (Fig. 8). From 1921 to 2011 there is an almost 15-fold increase in population exposed to flooding over this period – rising from 120 in 1921 to 1759 in 2011. There are two periods with significant increases in exposure: 1951–1961 and 1971–1981.

To determine the relative importance of sea-level rise and population change as the drivers of flood risk, the exposed populations are re-calculated for two scenarios:

i. sea levels do not change from the extrapolated 1801 level, and population rises;

ii. population in 1801 remains static and sea level rises at the mean rate of 1.22 mm yr^{-1}.

The results are shown in Fig. 9. The differences between the two curves in each plot indicate the relative contribution to exposure caused by sea level rise and population change. For Portsea, sea level rise between 1801 and 2011 results in an increase in flood exposure to the 1801 population from 2200 to 4000 (i.e. +1800 people, 82 %), whereas population change over the same period with a static 1801 sea level accounts for +7600 people exposed to flooding (i.e. 2200–9800, 345 %). In Hayling, the equivalent figures are 50 to 50 (+0, i.e. no change in exposure due to sea level), but for population change the exposure rises from 50 people in 1801 to 1080 people in 2011 (i.e. +1030 people, 2060 %).

This demonstrates that population change has been a more important driver of flood risk than sea level rise in both Portsea and Hayling. Indeed at Portsea, population change is 5 times more important in changing flood risk over this period, which in Hayling, in relative terms, has been even more dominant, even though absolute figures are lower. This analysis was repeated for a range of return period water levels including 1 in 1, 1 in 5, 1 in 10, 1 in 50, 1 in 100 and 1 in 1000 year levels. All of the results show the same trend (albeit for Hayling; there is no exposure for the low return period storms): only the 1 in 200 year results were included in the paper to provide a succinct analysis.

This analysis used the mean change in estimated sea level; there is some uncertainty in the actual sea levels as shown in the error bars in Figs. 7 and 8. This uncertainty may account for a variation in calculated exposure of up to 1000 people in 1981. There is no easy way to assess the accuracy of the population data, but the data are the best available and it is a legal requirement for all UK residents to register in the Census.

5 Discussion: overview and applicability to other sites

This research builds upon that of Foresight (Evans et al., 2004) and Smith (2015) with its strength being in its transferability to other sites. The methodology described here could be applied to any coastal site where adequate spatial data sets (land use, elevations, population) and sea level data are available.

A national analysis of flood risk is possible using this approach, taking advantage of the modern day data collection systems available in many countries. To demonstrate this, a snapshot national analysis was carried out for the present day flood exposure in England and Wales. We used the present day Environment Agency Indicative floodplain map for both river and coastal flooding plus Census data for 2011. There are some limitations in this approach, for example the floodplain map includes both fluvial and marine flood extents. The algorithm took less than 1 h to run. The calculated exposure to the 1 in 200 year flood event (without sea defences) was 4.8 million people, which is within 10 % of the figure of 5.2 million quoted by the National Flood Forum (NFF, 2015). This quick analysis gives credence to the methodology, how-

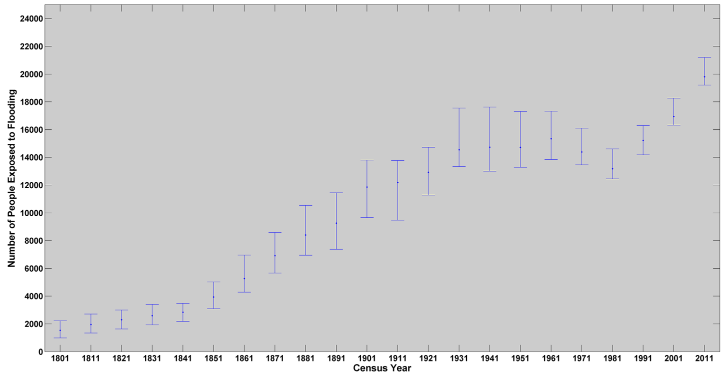

Figure 7. Estimated number of people exposed to flooding in Portsea (1 in 200 year recurrence interval, no defences). Error bars represent uncertainty in estimated rate of sea level change, population distribution and population size.

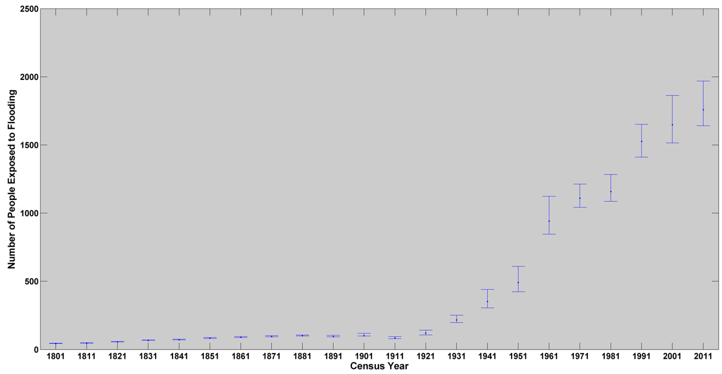

Figure 8. Estimated number of people exposed to flooding in Hayling (1 in 200 year recurrence interval, no defences). Error bars represent uncertainty in estimated rate of sea level change, population distribution and population size.

ever, for a full national scale analysis, a more detailed population data set and DEM model would be necessary. To reduce data processing times, analysis could be restricted to only those areas known to be at risk of flooding and it is estimated that a national scale study could be completed in a few months.

For an historical analysis users would need access to population data and indicative floodplain maps at regular intervals. The 10 year time step used in this study was chosen on the basis of the UK Census timings and some interpolation was necessary between the spatial data obtained from maps published at irregular time steps. However, the large time step (10 years) may hide changes in coastal population over shorter timescales because urban development can be rapid and significant areas of new coastal settlements can be constructed in less than 5 years This highlights the need for regular high quality data collection on both physical variables (land elevations, sea levels) and socio-economic variables (population size and density, residential extent). The methodology can be developed to look explicitly at attributing flood risk to the underlying drivers.

Applying the methodology to different case studies will test whether the attribution of flood risk is consistent across a nation or whether regional differences exist. Over the last 200 years, population has increased across the UK, leading to increased encroachment of development and a higher population density upon floodplains so we would expect a similar pattern to that seen in the present case study. Only in low-lying areas where development/population rise has remained static would observed sea level rise have played a more significant role than that of population change. We suggest that this is more likely to be the case in the future as cities such as Portsmouth reach "saturation point" in their development. The existence of exceptions could be tested by repeating the method across the whole country; we propose this as necessary future work.

The evolution of the effectiveness of flood defences is an area for further study as when combined with exposure, it allows estimate of changing flood risk. However this presents

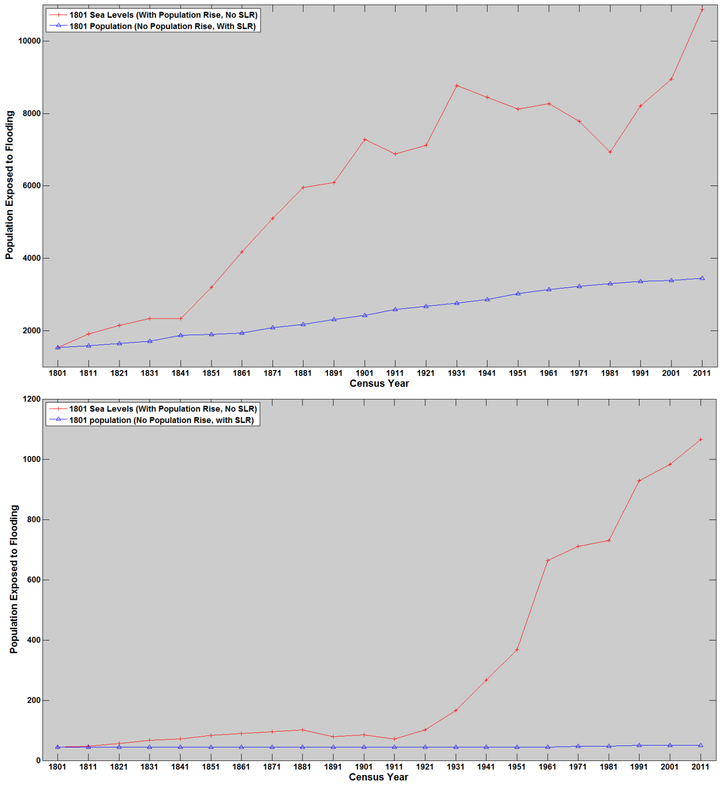

Figure 9. Estimated number of people exposed to flooding (1 in 200 year recurrence interval, no defences) in Portsea (above) and Hayling (below) for no change in sea levels since 1801 (red line) and no change in population since 1801 (blue line).

significant challenges for historical analyses, for example, we found that information on flood defences at Portsea before 1990 is poorly recorded. This is likely to be the general case and hence while we may estimate historic exposure back to 1800, we cannot similarly estimate flood risk. This emphasises the importance of documenting defences and vulnerability characteristics over time, such as seen in the UK's Strategic Regional Coastal Monitoring Programme (e.g. see http://www.channelcoast.org/).

6 Conclusions

This paper has identified and filled a gap in our knowledge of the drivers of risk of coastal flooding, and how this exposure has developed over time. This has implications for the current assessment of coastal flood events, and also for future planning decisions.

In the Solent case study, population change has been shown to be the most significant driver of flood exposure from 1801 to the present time. Observed sea-level rise has a lesser but still significant effect on flood exposure estimates, especially over long timescales (100+ years).The rate of sea level rise is expected to increase, and rising sea levels are likely to have a larger effect on exposure in the future. Furthermore, for small island communities, such as Portsea and Hayling, the area available for development may become a limiting factor in the future, causing a shift in drivers that increase the exposure of the population to flood risk towards sea level rise. The estimated exposure to flooding shows that large numbers of people are potentially at risk (18 000 in Portsea for a 1 : 200 event), but they are currently mostly protected by sea defences constructed to a present day 1 : 200 event, with a GBP 44 million defence improvement programme recently announced (Dredging Today, 2015). This paper further demonstrates that assuming a stationary system (for example, assuming the urban extent is static, that population does not change, or that sea levels do not change) is likely to lead to inaccurate estimates of flood exposure and thus flood risk.

A limitation of this work is the inherent unpredictability of future changes in population dynamics across the UK. Agent-based approaches have been used to predict development and population change (such as developed by Fontaine, 2010). Coupling the method presented in this paper with such approaches will develop insights on these processes.

The approach developed here agrees with an independent, national scale assessment of exposure. The methodology can be applied to other areas of the UK, or elsewhere, where population, urban extent and sea level data exists. Attribution of local flood exposure and risk will depend on relative sea level and morphology/hydrology and population dynamics. National studies have shown development in flood risk areas in the UK is increasing, in some cases at a higher rate than development outside of the floodplain (ASC, 2011). Hence, exposure to coastal flooding due to socio-economic drivers seems likely to continue, following the historic trends shown here.

A combination of novel methodologies such as those developed in this paper, and continued collection of high quality data sets on floodplain geometry, sea level and population will contribute towards increased knowledge and understanding in this field. This will aid coastal managers as they prepare to face the challenges of an uncertain future.

Appendix A: Technical appendix

A1 Modelling assumptions and considerations

The assumptions used in the methodology are summarised in Table A1. The temporal resolution of the available demographic data constrained the time step to 10 years. Whilst this time step may miss shorter term changes (i.e. seasonal/yearly variations in hydrology), it captures the longer term dynamics of population change and development, and sea level rise which occurs over a long time period. Further, the high spatial resolution and quality of the census data used gives the study greater reliability than if supplementary data (perhaps with a smaller time step) were used.

A2 Population scaling method

This data 1971–2011 exists in the form of population weighted centroid points. Each point represents a census output area and contains the total population of the output area.

For census data pre-1971 aggregate population counts for the city of Portsmouth (scaled to represent population within Portsea Island) and for Hayling Island were used. Scaling the total counts in this way deals with the problem of changing geographies through time (e.g. changing administrative boundaries). The populations were scaled using aggregate population counts for the city of Portsmouth for census years 1801–1961 and the modelled counts (spatial populations from centroid points) for census years 1971–2011 (Eq. A1).

$$\mathrm{Pop}_{\mathrm{scaled}_i} = \mathrm{Pop}_{\mathrm{total}_i} \times \frac{\sum_{n=1971}^{2011} \frac{n_{\mathrm{modelled}}}{n_{\mathrm{total}}}}{n_{\mathrm{years}}}, \qquad \text{(A1)}$$

where: $\mathrm{Pop}_{\mathrm{scaled}_i} =$ is the scaled population used within the model at time step i; $\mathrm{Pop}_{\mathrm{total}_i} =$ is the total population for Portsmouth from the census data at time step i; $n_{\mathrm{modelled}} =$ is the modelled population used in the spatial census study (1971–2011); $n_{\mathrm{total}} =$ the total population for Portsmouth from the census data (1971–2011); $n_{\mathrm{years}} =$ is the number of years where spatial data exists (which is $= 5$ for the case study).

Figure 4 summarises our reconstruction of the population in Portsea and Hayling; which for the former rose from 39 000 in 1841 to a peak of 194 000 in 1931. The population then falls to a low of 134 000 in 1981 before rising again to 164 000 in 2011. The modelled populations from 1801–1961 were from scaled population counts, and 1971–2011 from spatial census data. Historic census data for Hayling parish (which covers the spatial area of Hayling Island) extend to 1801. However, it is not complete due to changing administrative boundaries during the 19th and 20th centuries. Therefore the population counts for missing census years were interpolated. The population in Hayling rose steadily from just under 600 in 1801 to 4000 in 1941. Population continued to increase at a higher rate until the maximum of 17 400 in 2011. Modelled populations in 1801–1851, and 1881–1931 are formed from raw counts from census data, with values in 1861–1871 and 1941–1961 interpolated from these counts. Between 1971 and 2011 spatial census data for Hayling were used.

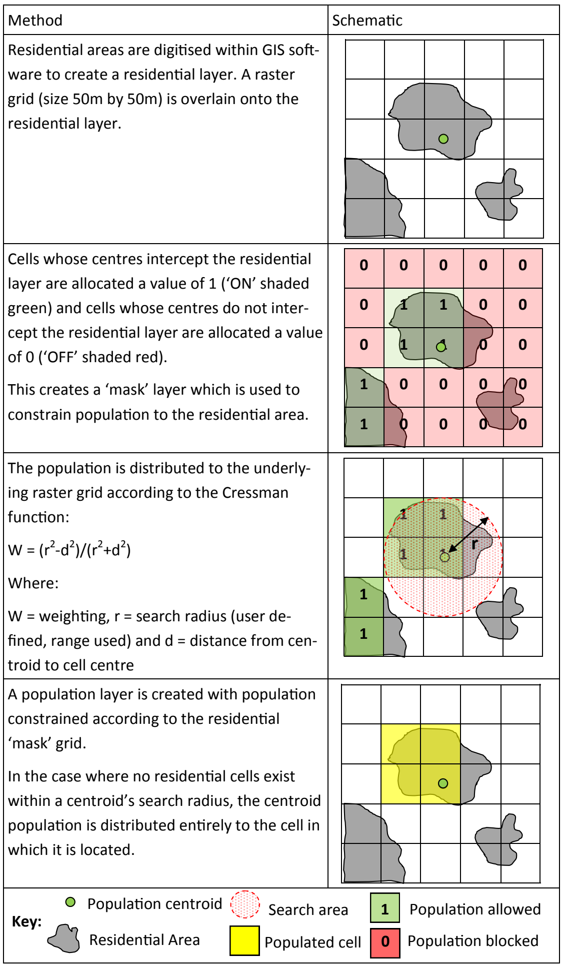

Figure A1. Population spreading method used in this study. See Martin (1989) and Bracken and Martin (1989) for further information on the centroid distribution method.

A3 Residential layer method

Maps (sourced from Digimap®, University of Edinburgh) for the 1870s, 1890s, 1910s, 1930s, 1960s, 1970s, 1990s and 2012 are summarised in Table A2. Developed areas were hand-digitised to create a residential layer of where population is situated. This allowed population to be spread more realistically. Non-residential features such as schools, hospitals and industrial units (e.g. the Portsmouth Dockyard) were removed from the residential layer in order to increase the accuracy of the population spreading. Use of a residential layer addresses the problem of differing census geographies by constraining population to the area developed for each time step.

The time between publication of the maps used averages 20 years between 1870–2011, which is typical of spatial planning timescales and so a reasonable assumption. Assuming static development over a 70 year time period (1801–1871) is more uncertain, however the low level of development seen in 1871 does limit the effect of this assumption. Analysis from 1801 is therefore included in the analysis but with the caveat that we are less certain of the results over this time frame.

The vector residential layer was converted to a 50 m raster mask for compatibility with Surface Builder™. A 50 m resolution includes adjacent roads in residential masks. However, the spatial resolution of census data makes higher resolution (e.g. 10 m grid cells) unrealistic. This layer was used as a mask within SurfaceBuilder™ which prevented the program placing population into areas that should not be populated.

A4 Population spreading method

The methodology used within SurfaceBuilder™ is shown in Fig. 8. A range of search radii were used in order to account for uncertainty due to this method. The search radii limits the distance from each centroid that the population can be distributed.

A5 Sources of uncertainty

There is uncertainty inherent in the estimated sea level, and the number and spatial location of the population. The uncertainty in rate of sea level applied was quantified by modelling for three different rates; the mean change from Haigh et al. (2011) and ± one standard deviation from this. Uncertainty in the population estimates are harder to quantify. The measured undercount in the 2001 census was calculated as 6 % (ONS, 2012a). There is a smaller potential for overcount which was estimated as 2 % for the 2011 Census (ONS, 2012b). These uncertainties are accounted for in census population counts, however for older censuses the adjustments may not have been performed and so as a conservative estimate we assume a potential uncertainty of +6 and −2 % in the population estimate (i.e. potential 6 % undercount, 2 % overcount). The spatial location of the population is sensitive to the search radii used when distributing the population from the centroid points. The uncertainty in population location was quantified by testing a variety of search radii. The relative contributions of these three sources of uncertainty are shown in Fig. A2.

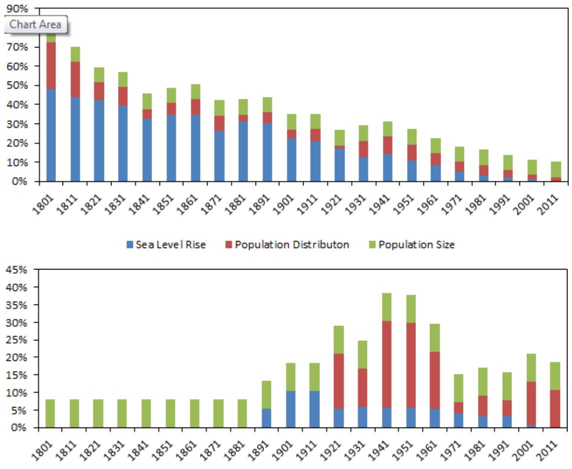

Figure A2. Quantification of the sources of uncertainty within the methodology for Portsea (above) and Hayling (below).

For Portsea, the uncertainty in sea level has a much bigger effect than Hayling as there is a much larger population density on the island, and so the floodplain size (a function of the sea level elevation) has a more pronounced effect on the estimated exposure. In Hayling there is a much smaller density of people and so the exposure is less sensitive to a slightly smaller/bigger floodplain.

In Portsea the distribution of the population has a moderate effect on exposure in the early 1800s, with an increasingly smaller effect for the more modern (better quality) census data. In Hayling there is no effect before 1920 as the low absolute exposure (less than 50 people exposed as the "best estimate") is not sensitive to changes in population distribution. As the population in Hayling started to encroach on the floodplain from 1920 onwards, the distribution has a larger relative effect.

The uncertainty as a result of population size is static through time for both Portsea and Hayling as this is assumed to be 6 % for undercount and 2 % for overcount (i.e. uncertainty in census data – see ONS, 2012a).

Table A1. Modelling Assumptions and justifications.

Component	Modelling assumption	Justification
Hydrodynamic model (LISFLOOD FP)	Simplified hydraulics compared to "full" 2-D models Sea level and extremes of still water level are dominant physical drivers (waves excluded) See Bates et al. (2010)	Better than "bathtub" methods (mass conservancy and hydraulic connectivity accounted for) Widely used flood model (e.g. Wadey et al., 2012; Dawson et al., 2009; Rojas et al., 2013) Use of full models expensive (cost and computationally) and without validation improved accuracy cannot be confirmed Represents realistic storm tide inflow Waves, although important to flood events, are contentious in an inundation modelling framework (hard to validate) but recommended for inclusion in future work Model proven for coastal use (Bates et al., 2005) and with a validated model for the case study region (Wadey et al., 2012).
Residential area	Developed residential area does not change between time steps (average 20 year time step – based on availability of historic maps)	20 years is typical of long-term spatial planning time horizon (Zevenbergen et al., 2008). Constraining population to residential area improves spreading over uniformly distributing population, so best available method
Population distribution	A centroid defines a location with above average population density and is a summary point for the local area A centroid's population is distributed in the surrounding area according to some distance decay function, which has finite extent Regions may exist in the population plane in which no population is present. Assumptions from Martin (1989)	Allows for high resolution population surfaces (Martin, 1989) Method offers stability through time and ease of integration with non-population data sources (Martin et al., 2011); both are essential parts of the methodology discussed in this paper
Population change over time	The dates chosen represent a trend in population change, rather than oscillations (which do not show correlation over time). The dates chosen are representative of population change	A period of 200 years was chosen to allow for a clear trend to propagate as opposed to variation which may occur over a smaller time span The dates correspond to census years, where it is possible to get high resolution spatial population and demography data. To use other years with less sufficient data would limit the reliability of the study

Table A2. Historic maps used to create residential masks for each census year. All maps sourced from Digimap® Crown Copyright and Landmark Information Group Limited (2014). All rights reserved.

Census year	Map used to create residential layer
1801–1871	County Series Edition 1 (1870s)
1881–1891	County Series Revision 1 (1890s)
1901–1911	County Series Revision 2 (1910s)
1921–1931	County Series Revision 3 (1930s)
1941–1961	National Grid Imperial Edition 1 (1960s)
1971	National Grid Metric Edition 1 (1970s)
1981–1991	Latest National Grid (1990s)
2001–2011	MasterMap® (2012)

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