An assessment of the unintended consequences of structural coastal flood protection

A Thesis Submitted for the Degree of Doctor of Philosophy

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Thesis Abstract

This thesis investigates the unintended socio-hydrological consequences of structural coastal flood protections (SCFPs) and assesses the implications for coastal flood risk management strategy in the UK. Climate change, and the continued urban development of flood exposed areas can exacerbate coastal flood risk, and thus flood risk management authorities often tend towards structural coastal flood protection measures to minimise losses. However, these structurally proactive measures can lead to infrastructural lock-ins, whereby the decrease in flood probability from the defence can lead to increased urban development and population, ultimately leading to higher losses due to an inundation event. This process has been referred to as the Safe Development Paradox (SDP), a cross-cutting science-practice-policy challenge that requires a systematic understanding in the context of increased uncertainty associated with climate change and the United Nations Sustainable Development Goals. However, literature of the phenomena is limited, compounded by a lack of consistent terminology, limited geographic distribution, and a skewed emphasis on fluvial flooding. Moreover, despite being an island nation, the UK, to date, has had very little research conducted into these unintended consequences of structural flood protection.

This thesis developed and applied a methodology that captures these coupled human-flood processes, by integrating well-established methods from other spheres of flood risk assessment in a novel way to explore the currently poorly understood phenomena in coastal settings. The study contributes to addressing this knowledge gap based on insights from three contrasting UK case studies: Portsmouth, Weston-super-Mare, and Southport. Differential analysis of historic LiDAR Digital Surface Models (DSMs) was used to identify temporal changes in the urban landscape to create a DSM of Difference (DoD), representing elevation change between two locations over time. Geostatistical testing, specifically *t*-tests, were then used to infer statistical significance of changes in urban development. The results reveal a consistent pattern: following completion or improvement of large-scale SCFPs, there is subsequent, and statistically significant, increases in coastal population and urban development within/near flood-exposed areas in all case studies, contrary to the limited flood-exposed development in neighbouring settlements, with no comparable defences constructed, or upgraded, during the same period. On average, new urban development occurs approximately 2 years after the completion of coastal flood defence projects. These data were then inputted into a newly developed agent-based model (ABM) that simulates futures changes under different climate scenarios. The results demonstrate that each SCFP project led to an initial decrease in Affected Population (AfP) following implementation, confirming the intended immediate benefits of flood risk reduction. However, long-term projections revealed significant unintended consequences under the scenarios where SCFPs were exceeded by Extreme Coastal Water Levels (ECWLs). For Southport and Weston-super-Mare, the ABM output shows a dramatic increase in AfP once ECWL surpassed the SCFP crest height, affecting a larger population than those initially protected, primarily due to the increased population growth behind the defences and the larger flood extent. Portsmouth, however, exhibited a more limited increase in AfP, attributed to its high urban density and limited room for further development behind the defences. This highlights how pre-existing land-use and population density can act as brakes on the unintended consequences of SCFPs.

The thesis concludes with a recommendation for future flood risk managers and policymakers to be aware of these unintended socio-hydrological consequences. SCFPs are crucial assets, and their construction and maintenance will continue to play an integral role in coastal adaptation to climate change, particularly in highly developed urban settlements. This thesis does not attempt to provide a comprehensive predictive modelling tool for planning, nor a detailed analysis of real estate markets, but instead focuses on socio-hydrological interactions of population change and SCFP. However, new SCFP design and implementation need to account for their long-term unintended consequences on communities and climate adaptation planning. In the short-term, flood risk communication provides a means of tackling these risks, improving flood memory, awareness, and preparedness. Furthermore, in the longer term a more holistic cost-benefit analysis and spatial planning strategy, internalising these factors should be utilised in order to create more sustainable and resilient coastal communities in the UK.

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List of Acronyms

Acronym	Expansion
ABM	Agent-based Modelling
AEP	Annual Exceedance Probability
AfP	Affected Population
BOS	Burnham-on-Sea
C/U	Constructed or majorly Upgraded / Construction or major Upgrade
CHANS	Coupled Human and Natural Systems
CP	Consequences × Probability (definition of Flood Risk)
CRS	Coordinate Reference System
CSWL	Coastal Still Water Level
DCLG	Department for Communities and Local Government
DEFRA	Department for Environment, Food & Rural Affairs
DEM	Digital Elevation Model
DoD	Digital Surface/ Terrain Model of Difference
DSM	Digital Surface Model
DTM	Digital Terrain Model
EA	Environment Agency
ECWL	Extreme Coastal Water Level
EiA	Proportion of population per OA that is Economically Inctive
FA	Floodable Area
FRM	Flood Risk Management
FZ	Flood hazard Zone
GIS	Geographic Information System
GLA	Greater London Authority
HEV	Hazard × Exposure × Vulnerability (definition of Flood Risk)
HMO	House of Multiple Occupation
HP	Hazard × Probability (definition of Flood Risk)
HV	Hazard × Vulnerability (definition of Flood Risk)
ICZM	Integrated Coastal Zone Management
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resources Management
LiDAR	Light Detection and Rangin
NPCS	North Portsea Coastal Scheme
OA	Census Output Area
ODN	Ordnance Datum Newlyn
ONS	Office for National Statistics
RCP	Representative Concentration Pathway
RTPI	Royal Town Planning Institute
SCFP	Structural Coastal Flood Protection
SDP	Safe Development Paradox
SLR	Sea-Level Rise
SMP	Shoreline Management Plan
SoP	Standard of Protection
SPR	Source-Pathway-Receptor
SS	Storm Surge
SWH	Significant Wave Height
UKCP	United Kingdom Climate Projections
WH	Wave Height
WRS	Water Resource Systems
WSM	Weston-super-Mare

Executive Summary

The interactions between increasing numbers of populations living in urban areas and rising sea levels will bring new challenges at the interface between these two domains, the coastline. Whilst knowledge of coastal flood risk, and management strategies thereof, have existed for many decades these have failed, in most part, to incorporate the unintended consequences of structural coastal flood protection (SCFP). Moreover, literature of these unintended phenomena is scarce, and where it does exist tends to focus on North American case studies. This combination at the science-engineering-policy nexus leaves the UK, an island nation, exposed and at risk to future climate-induced coastal hazards. This project sought to contribute to resolving this issue by firstly developing a comprehensive understanding of the unintended consequences of SCFPs in the UK, all in an effort to provide evidence-based advice to flood agencies and policymakers regarding these often unincorporated socio-hydrological phenomena. Internalising these future changes in coastal flood risk, due to a redistribution and increase of populations and assets, into a more holistic cost-benefit analysis and a more integrated spatial planning can lead to sustainable urban growth and more resilient coastal communities.

This thesis focuses exclusively on the socio-hydrological consequences of SCFPs in the UK, particularly the Safe Development Paradox (SDP), and associated coupled human-water mechanisms. It does not attempt to provide engineering standards, detailed predictive modelling for planning, or real estate market analyses; these would require specialised datasets and objectives that are beyond the remit of this study. Instead, the emphasis is on understanding population dynamics and the socio-spatial processes linked to SCFP implementation with the intended outlook of informing integrated flood risk management strategies.

The introductory chapter of this thesis provides a foundation for the topics covered by this project, focusing on the emergence and development of concepts and how and whether these have been utilised together in the past, and how they have been applied. Coastal flood risk is discussed first, from the historical evolution as a mainly economic measure, to modern definitions incorporating social elements. This document highlights the necessity of using a modern interpretation of coastal flood risk, as one that integrates hazard, exposure and vulnerability, in order to create resilient communities capable of withstanding climate change related effects. Spatial planning is also explored, evolving from early public health efforts to contemporary strategies aimed at sustainable development. Failures to integrate these two elements are also then discussed, and the unintended phenomena that they can create, referred to in the literature as the *Safe Development Paradox* or the *Levee Effect*.

Efforts to integrate and provide a holistic coastal management strategy have been attempted before, however, these often fail due to poor implementation, miscommunication, or a lack of political will. For example, Integrated Coastal Zone Management (ICZM) emerged as a coastal flood risk management strategy in the 1970s, aiming to provide oversight by integrating various policies and stakeholders from local and national levels. However, in the UK for example, ICZM initiatives are non-statutory and voluntary, with no real power to coordinate between central and local government, which undermines their effectiveness. Moreover, the scientific community itself has been lacklustre with ICZM operation and providing an understanding of the interactions between individual and community behaviour and hydrological processes, resulting in a fragmented approach to coastal flood risk management that often relies heavily on structurally engineered solutions without incorporating social or behavioural science insights. Effective ICZM, and coastal flood risk management in general, requires incorporating scientific knowledge and embracing a shared responsibility between authorities, both, local and national, and individuals and communities. Public education of issues that cause unintended consequences of SCFPs, such as residual risk, flood memory, and resilience measures, alongside stakeholder engagement is vital for a sustainable coastal flood risk management strategy in the 21st century.

The thesis then proceeds into the literature review, providing an overview of the evolution and significance of concepts associated with the unintended consequences of SCFPs. Definitions of coastal flood risk are firstly mapped, with a demonstration of how they vary widely across fields and time

periods, with the *hazard, exposure*, *vulnerability* definition becoming the most used in modern times. Therefore, it was this definition that was selected for use in this study to reflect coastal flood risk.

The literature review then proceeded to evaluate terms used to describe the emergent socio-hydrological phenomena as an unintended consequence of SCFPs and three key terms were identified: *Safe Development Paradox*, *Levee Effect*, and *Safety Dilemma*. The review revealed that when assessing the unintended consequences, in fluvial environments the *Levee Effect* was most often used, whereas in coastal environments the Safe Development Paradox was most often used. However, fluvial flooding accounted for the vast majority of papers, with 69% of the papers reviewed, compared to 17% in coastal flood hazard environments. Moreover, the majority of the case studies assessed by these papers were American, and a notable concentration on developed economies, and the need for more research in the Global South to understand emergent flood risk management strategies. However, the review also revealed that only two papers had referenced the UK, both of which were in fact a part of pan-European studies: there are presently no papers that specifically discuss this phenomena in the UK.

The review also identified several recommendations from the literature on how to break the infrastructural lock-in cycles associated with the unintended consequences of SCFPs. The majority of literature recommended that the scientific background should be expanded; a greater amount of case studies from a more diverse set would provide a more comprehensive understanding, and allow recommendations and resolution pathways to be tailored to an individual case. However, the second most argued for recommendation was planning control: using local authorities to coordinate better and more sustainable urban development to ensure that the placement of populations and infrastructure does not increase following the upgrade of SCFPs. Other suggestions included improved flood risk communication, improved flood modelling, and the development of flood insurance policies or relocation schemes. The review concludes by stressing the need for consistent terminology and integrated frameworks to bridge the gaps between science, policy, and practice in coastal flood risk management.

The thesis then describes and evaluates the methodology used within this project. This chapter emphasises the importance of addressing these unintended consequences through a multidisciplinary approach, incorporating various research methods investigating three case studies in an effort to comprehend, and determine ways to mitigate, the risk and feedback mechanisms associated with coastal flood protection. To facilitate this, the research, and associated methodology, was structured around five objectives. These objectives include analysing the development of coastal settlements from before a SCFP was constructed to after, quantifying changes in flood risk factors, both, through geospatial analysis and geostatistical testing, developing and applying ABM to simulate these socio-hydrological interactions, and then understanding these processes through the lens of public policy and identifying sustainable coastal flood risk management practices from there.

These three case studies include the high-density area of Portsmouth, an island city in Hampshire, a mid-density town, Southport in Merseyside, and Weston-super-Mare a low-density town in Somerset. When compared to their comparative sites these case studies can help to identify common patterns and factors that contribute to these unintended consequences, which are then used to refine the conceptual models and inform future strategies and produce actionable recommendations for flood risk management in the UK. The chapter states that this should involve an integration of the findings from the three case studies into a cohesive roadmap. The roadmap aims to address current shortcomings in UK flood preparedness and awareness, and suggest ways to overcome these issues through an integrated spatial planning system that includes FRM as a core component.

The Results chapter presents the output from the methods described in the previous chapter and their enactment on the case studies. The case studies revealed distinct socio-hydrological dynamics from the construction, or major upgrade, of the SCFP. In both Southport and Weston-super-Mare, significant increases in urban development, population, and housing occupancy were observed in areas adjacent to the SCFPs, which were not observed in other areas of the town or comparative sites. These changes were statistically significant and reflect the impact of SCFPs on urban development. In contrast, Portsmouth show more limited impacts: the SCFP did not lead to as great changes in population growth

nor urban development as pre-existing conditions inhibited these unintended consequences. The case studies demonstrated that whilst SCFPs initially reduced flood risk, it can also trigger medium-term socio-spatial changes, especially in lower-density areas with room for urban expansion.

The discussion chapter serves as a synthesis of the research findings, interpreting their significance and placing them within the broader academic and practical context and evaluating them at the science-engineering-policy nexus. It highlights the failure to integrate spatial planning with sustainable management of coastal flood risk, leading to a less resilient community at risk of the development of the unintended consequences of structural coastal flood protection.

The research concludes with the emphasis of the importance of an integrated spatial planning policy, and the usage of non-structural measures, to break the infrastructural cyclic lock-ins as an unintended consequence of SCFP. The conceptual model developed was intended to be accessible to all stakeholders, including residents at risk, policymakers, and flood risk managers, to foster more resilient communities. The discussion stresses that as sea level rises, the UK must adopt more adaptive measures to prevent these lock-in effects and address the increasing challenges of coastal flooding. Finally, the study calls for a collaborative approach, bringing users and scholars at the science-engineering-policy nexus to develop a truly integrated coastal flood risk management system.

1.0 Introduction

Almost three quarters of the surface of Earth is covered by oceans, with a collective mass of 1.37×10^{21} kg (Genda, 2016). As a primarily ocean planet, human history is closely linked to the sea; operating as a driving force behind migration to settle in new fertile areas when sea levels fall (Timmerman and Friedrich, 2016; Jakobsson *et al.*, 2017), facilitating trade and transportation (Bird *et al.*, 2019), as a food source (Jackson *et al.*, 2012), and creating mass exodus when sea levels rise both, historically and currently (Berchin *et al.*, 2017). Similarly, modern populations are also drawn to the coast for opportunities it provides.

Meanwhile, urbanisation has increased dramatically, from 700 million city dwellers in 1950, to 4.35 billion presently. The United Nations classifies a coastal city as one within 100km of the coast, and within these coastal cities lies 40% of the global population, with 42.5% of this living at 50m or less above sea level (Agardy *et al.*, 2005). A significant proportion of the population lives on an area covering just over 4% of the total land surface area of Earth (Brown *et al.*, 2006). Meanwhile, sea level has risen ~20cm since 1850, with the rate of change accelerating to 3.2mm/yr in the early 21st century (Siegert *et al.*, 2020). The growth of humanity, coupled with rising sea levels, without careful management (Burby, 2006), can result in tensions at the coastal zone, the interface between the two spheres: land and water. Yet, population growth and flood-exposed development continues (Hallegatte *et al.*, 2013).

Natural hazards, such as floods, cause severe disruption to daily life, often leading to significant socio-economic losses and environmental impacts worldwide (Sharples *et al.*, 2016; Natho and Thieken, 2018). Climate change and continued development in hazard-prone areas will exacerbate these risks (Gbadegesin *et al.*, 2011; Leichenko, 2011). Therefore, mitigation of these hazards is essential to protect communities and infrastructure from current and future risks. Numerous strategies are employed in practice for hazard mitigation: ranging from flood control channels for flash floods (Sanders and Grant, 2020) to levees for fluvial flooding (Vora *et al.*, 2018) and seawalls for coastal flooding (Betzold and Mohamed, 2016). Structural measures are often selected and are historically the preferred countermeasures in many parts of the world to combat flooding. However, these measures often lead to infrastructural lock-ins (path dependency) and may produce unintended consequences as increased safety can induce increased development, ultimately leading to higher losses in the event of failures of the structural safeguards in place (Kates *et al.*, 2007). This process has been diversely referred to as the *Safe Development Paradox* (Burby, 2006), *Levee Effect* (Di Baldassarre *et al.*, 2015), and *Safety Dilemma* (Di Baldassarre *et al.*, 2018). Even outside of flood risk, structural measures are often used in an effort to mitigate natural hazards with similar challenges in tackling the Safe Development Paradox (SDP): strengthening infrastructure in earthquake zones (Erdik and Durukal, 2007); larger dams for avalanches (Höller, 2007); stronger housing design in tornado zones (Ripberger *et al.*, 2018); and the fire paradox, whereby preventing forest fires against a steady increase in fire risk and subsequent wildfire damage (Arévalo and Naranjo-Cigala, 2018), to name a few.

Existing hazard mitigation infrastructure can be effective at reducing risk and minimising losses when operating within its design capacity. However, communities are increasingly vulnerable to hazard events larger than the planned capacity of the structure due to climate change, extreme events and a lack of knowledge on the limitations of defences and an increasing amount of assets placed behind the defence as time passes without a flood event (Burningham *et al.*, 2007; Collenteur *et al.*, 2014). Furthermore, urban layout may have changed since construction, placing infrastructure and populations at risk that did not exist when the initial design was drawn (Sanders and Grant, 2020). These mitigation structures can create a false sense of safety that leaves these *AfP*s unaware and underprepared to cope with potential disasters (Burningham *et al.*, 2007). Furthermore, as the climate changes, low-probability, high-consequence events may happen more frequently, placing an inexperienced population at risk (Van Aalst, 2006; Merz *et al.*, 2009).

A solution to combat changing natural hazards is to upgrade existing mitigation structures, however, this merely produces a new design capacity, albeit higher than previously (Hallegatte *et al.*, 2013). There

is a common belief in flood risk management programmes that the exposure of urban areas depends solely on socio-economic development and natural urban growth. However, numerous scholars, starting with White (1945), have shown that increasing levels of flood protection can result in unintended consequences: increases in flood exposure, and, in turn, vulnerability (Tobin, 1995; Burby, 2006; Kates *et al.*, 2006; Burton and Cutter, 2008; Montz and Tobin, 2008; Ludy and Kondolf, 2012; Di Baldassarre *et al.*, 2013a). If the growth of coastal urban areas were driven by population increases alone the spatial distribution of new settlements would be the same (Di Baldassarre *et al.*, 2013b). The cycle continues as greater populations and high-value assets are placed either within or in close proximity of at-risk areas, producing a need for even greater structural strengthening and/or heightening (or expansion) of existing structures. These structures also interact with natural processes (e.g., morphological evolution of river deltas) altering the physical characteristics of hazards and hence their likelihood (Welch *et al.*, 2017). This can ultimately lead to the lock-in effect of a cycle of continued and prohibitively expensive investments on maintenance and upgrades of defence. Whilst the defences may be built to a high-standard, such as the Dutch coastal policy of constructing flood defences with a 10,000 year return period (Winter *et al.*, 2012), inevitably disasters do happen. A term from economics, 'tail risk' is the chance of a loss occurring due to an extremely rare event. However, over a long enough period, nothing is unlikely, and it was this that led to the financial crisis in 2008 (Acharya *et al.*, 2010), and in the event of an unexpected defence failure, loss of human life and economic damages, as demonstrated by Hurricane Katrina and its impacts in New Orleans (Burby, 2006).

Of the many natural hazards, flooding presents some of the most frequent and with severe consequences: it impacts more people than any other natural hazards (Banks *et al.*, 2013). Approximately, three quarters of disasters due to natural hazard over recent decades were water related, of which flooding accounts for a third. More than half of the victims of natural hazards were as a result of a storm surge, a river flood, or a flash flood. Between 1985 and 2003 approximately 300,000 people lost their lives as a result of flooding. On average, the global death toll varies between 5000 and 15,000 casualties annually (Douben, 2006). Even those areas protected by flood protection measures are still vulnerable: floods in New Orleans (2005), Thailand (2011), France (2011), and Germany (2021) were characterised by a large number of breaches in flood defences. Overloading the protection system can lead to multiple failures, exacerbating the extent of the flooding and the damage (Jonkman and Schweckendiek, 2015). Overtopping of flood defences in New Orleans resulted in hundreds of deaths and billions of US dollars' worth of damage (Burby, 2006). The Thailand floods caused the national and global economy to be disrupted for several months and caused a significant drop in economic growth (Jonkman and Schweckendiek, 2015). The 2011 French coastal floods resulted in the deaths of 50 people (Lumbroso and Vinet, 2011). In both the New Orleans and France floods elderly people were the most vulnerable (Lumbroso and Vinet, 2011; Jonkman and Schweckendiek, 2015). Such disasters emerge when natural hazards meet vulnerable communities and infrastructure, with mitigation efforts often needed to keep destructive waters away from people or vice-versa or a combination of both

The hazard, exposure, and vulnerability definition enables a comprehensive understanding of flood risk and, when coupled with strong spatial planning, creates resilient communities able to withstand the changing climate. Failure to comprehend these two elements can result in unintended consequences, known as the SDP. However, literature in the field is scarce, especially with regard to coastal development. Understanding these exposed communities and populations, and their relations to these phenomena are essential; it our relationship with structural flood protection infrastructure and flooding that enables these emergent unintended processes. The project was guided by the overall aim, *to develop a comprehensive understanding of the unintended consequences of coastal flood defence construction, in order to provide evidence-based advice to flood agencies and policymakers regarding the often unincorporated changes in coastal flood hazard, exposure, and vulnerability. Creating more resilient communities, in a changing climate, as coastal flooding grows to become one of the largest modern challenges facing the UK, and many other coastal countries.* An assessment of the unintended consequences of structural coastal flood protection presents a cross-cutting science, policy, and practice challenge that requires a systematic understanding in the context of climate change and the United Nations Sustainable Development Goals (SDGs).

Understanding the socio-hydrological dynamics of these unintended consequences of structural coastal flood protection and comprehending them as a function of coastal flood risk and poor spatial planning is essential in the wake of climate change and induced sea level rise and increased storminess. Research of these unintended consequences in fluvial environments is increasing, but there remains a notable gap in the literature regarding the specific challenges and interactions that arise in coastal environments, and the socio-hydrological and socio-spatial interactions thereof (Breen *et al.*, 2022). From the literature review it was identified that the majority of published literature, almost 70%, regarding this topic was focused on flooding from rivers. In contrast, published literature investigating the unintended consequences of structural coastal flood protection, the *SDP* in a coastal zone, only accounted for 17% (**Appendix A**). Although the ratio between coastal and fluvial literature regarding these unintended consequences does not reflect changes in population, with coastal areas of the Global North seeing greater population increase than fluvial areas. Between 1970 and 2010, coastal areas at risk of flooding from the sea have seen an increase of 13.3%, whereas areas at risk of fluvial flooding saw a 0.5% decrease in population (Jongman *et al.*, 2012). However, these fluvial studies still have an important role, and lessons and knowledge acquired from them can be transferred to coastal studies, and provide an essential information source for this project.

Moreover, there is a large bias to North America in the literature, with the majority of published literature regarding the unintended consequences of structural flood protection analysing case studies in the USA (**Appendix A**). This is not surprising; the country has experienced large scale population growth and urban development over the previous century, and before, and as the literature review was limited to English language research this also reduced the potential breadth. However, this would not explain the lack of research into these unintended socio-hydrological consequences and the *SDP* in the UK, and other anglosphere countries, which had either two case studies (i.e. UK and Ireland) or none at all (e.g. Canada or Australia).

Therefore, information and data regarding the unintended consequences of SCFPs is limited, as well as a study of these socio-hydrological interactions in the UK. This project aims to fill this gap, and increase the amount of literature on the topic, and assess the infrastructural lock-ins and socio-hydrological processes in the UK, a relatively understudied nation in this regard. This lack of information about these processes in the UK is also crucial to rectify given the geographic location of the UK as an island nation, at the forefront of climate change and sea level rise. This research addresses this disparity by conducting comprehensive analyses of three coastal case studies: Southport, Weston-super-Mare, and Portsmouth. By examining the interactions between SCFP, population dynamics, and socio-economic factors, this project sheds light on the intrinsic pathways and feedback mechanisms within coastal flood risk management and structural protection thereof. Through this, it not only contributes to the broader understanding of coastal flood risk management but also provides valuable insights for policymakers and practitioners engaged in coastal resilience planning.

These socio-hydrological and associated socio-spatial processes were discerned using three case studies, and comparative sites to provide a local context and to act as a control. For the assessment of such phenomena, with little in previous research, new methodologies were created, and used in tandem with existing procedures, such as geostatistical testing and LiDAR differential analysis (**Appendix B**). These phenomena were then modelled using agent-based modelling, and whilst ABM has been used to model socio-hydrological processes and assessing expected damage, this was the first to model socio-spatial processes also, and to focus on the *AfP* element instead of assets and damage. Understanding these exposed communities and populations, and their relations to these phenomena are essential; it our relationship with structural flood protection infrastructure and flooding that enables these emergent unintended processes.

In order to resolve these issues and lack of information and data, three case studies were selected based on a proactive structural Flood Risk Management (FRM) strategy, obtained from Shoreline Management Plans (SMPs), and level of exposed infrastructure and populations. From this selection process, three case studies were identified in the UK: Portsmouth, a large island city in Hampshire; Southport, a medium density mid-sized town on the outskirts of Liverpool, in Merseyside; and Weston-super-Mare a lower density, but still substantial, town in Somerset. Attached to these case studies were

comparative sites, these were selected based on proximity, coastal location, similar population, and that there had been no SCFPs, or upgrades, constructed over the periods analysed. These comparative locations provided a control for the comparative analyses: identifying socio-hydrological processes that emerged and that could be linked to newly constructed or upgraded SCFP.

Using these locations, the thesis sought to comprehend the socio-hydrological consequences of SCFPs in the UK, with the particular emphasis on SDP and associated socio-spatial and human-water coupled feedback mechanisms. To achieve this, the study includes an analysis of population dynamics and the socio-spatial changes following SCFP construction or major upgrading, the application of geospatial and statistical methods to identify patterns of urban development and exposure, and the development of an ABM to explore possible socio-hydrological trajectories under different climate scenarios. It also includes the conceptualisation of these processes within a framework that can inform policy and practice at the science-engineering-policy nexus.Conversely, the research does not attempt does not attempt to provide engineering design standards or technical specifications for SCFP structures, nor does it include detailed predictive modelling for planning purposes: the ABM is exploratory rather than deterministic. Economic valuation and cost-benefit analyses of SCFPs are outside of the scope, as is real-estate market modelling or property price analysis, although, the implications of housing demand are acknowledged. This thesis also excludes fluvial and pluvial flooding, focusing exclusively on coastal environments. These remit boundaries ensure that the research remains targeted on assessing the socio-hydrological interactions and their implications for long-term costal flood risk management.

Hence, for this analysis, five objectives and associated methods were devised (**Table 1**). The first to be conducted, **Objective 1** was created to investigate the before and after changes of urban development, achieved using a LiDAR differential analysis and statistical testing. This Objective was derived to answer the question, Research Question 1, asking how urban development is affected by a SCFP. Published literature would suggest that urban development will tend towards the newly constructed, or upgraded, structural flood defence (e.g. Burby, 2006; Di Baldassarre *et al.*, 2018). This unintended phenomena paradoxically can increase flood risk in the medium- to long-term after the construction, or upgrade, of a SCFP (Di Baldassarre *et al.*, 2018). Therefore, if these unintended consequences of SCFP are in play in these case studies they will show similar socio-hydrological and socio-spatial processes in the data. Outputs and patterns obtained from such processes can fill in the knowledge gaps of these phenomena in a coastal environment and in the UK.

Following **Objective 1**, **Objective 2** was conducted. This second objective investigated the before and after changes in population dynamics, such as location, occupancy, vulnerability etc., comparing from before the construction, or major upgrade, of the SCFP to after. This was achieved through geospatial analysis, tracking the temporal and spatial changes, and through geostatistical testing, testing socio-spatial changes across time and space, comparing changes at the new (or upgraded) defence to those elsewhere in the town. **Objective 2** was created to streamline and coordinate the methodologies and procedures that were developed to answer Research Question 2, asking how exposure and vulnerability factors are affected by the constructed, or major upgrade, of a SCFP. The literature suggests that the construction, or major upgrade, of a structural flood defence will incite populations to the area (e.g. Husby *et al.*, 2014). Therefore, if these unintended socio-hydrological processes were existent in the case studies, similar changes in population socio-spatial dynamics would be expected to be seen. This would also demonstrate concordance with the literature.

In an effort to assess the unintended consequences of SCFP and construct the conceptual model, five research questions were developed to aid the completion of the objectives. These are displayed below in **Table 1**. These key questions and objectives reflect current issues in current FRM strategy and how they may be producing unintended consequences.

Table 1 List of the objectives and corresponding hypotheses in the project.

Research Question and Objective 1:

RQ1	How is urban development affected by the construction of SCFPs?
Obj1	Complete a comparative analysis of coastal settlement development following defence construction or upgrading

Research Question and Objective 2:

RQ2	How are exposure and vulnerability factors affected by the construction of SCFPs?
Obj2	Quantify changes and drivers in coastal flood risk temporally and spatially arising from defence construction

Research Question and Objective 3:

RQ3	How will socio-hydrological processes change in the future and under climatic scenarios?
Obj3	Develop and validate an agent-based model to simulate coastal socio-hydrological interactions, and project forwards based on behavioural scenarios and climate models

Research Question and Objective 4:

RQ4	How does government policy unintentionally influence coastal flood risk?
Obj4	Discover the impacts and consequences of defence construction and government intervention on coastal flood risk

Research Question and Objective 5:

RQ5	How can more resilient communities be built and unintended consequences reduced?
Obj5	Identify methods of achieving desirable flood risk outcomes and enable sustainable planning to create resilient communities

Once real-world data was collected and tested from **Objective 1** and **Objective 2**, an agent-based model (ABM) was developed. This model incorporated real-world elevation, sea level, and population spatial data, as well as projections for sea level rise, and changes in population distribution and socio-spatial processes associated with the construction or major upgrade (C/U) of the local SCFP. This was **Objective 3**, to create an ABM that successfully simulates coastal socio-hydrological interactions, that can be validated and can project these processes forwards based on climate scenarios. This Objective therefore answered the *third* Research Question, enquiring how socio-hydrological processes change

over time and under different future climatic scenarios. Published literature suggests that the ABM should show an increase in potentially *AfP* following the decision and enactment of a flood risk management authority to increase SCFP (e.g. Haer *et al.*, 2020). Therefore, if successful, the ABM should replicate these results, and would demonstrate that there are lock-in processes in coastal areas in the UK. Although, the scope of this research is limited to examining the unintended socio-hydrological consequences of SCFPs in the UK, it does not attempt to provide engineering design standards, nor a detailed economic and/or real-estate market analysis, which are beyond the remit of this study.

That being said, the presence of these unintended socio-hydrological phenomena in the UK presents a policy issue, one that should be resolved at the science-engineering-policy nexus. This leads into **Objective 4**, the creation of a conceptual model that encapsulates the data, information, and observed patterns from the previous three Objectives, and that can capture the impacts of the construction of SCFPs and a structurally proactive flood risk management authority on coastal flood risk. This conceptualisation was aimed to be simple and usable by multiple stakeholders and agents, and therefore must parsimoniously represent these emergent phenomena of the unintended consequences of SCFP. This conceptual model would work towards answering Research Question 4, investigating how a local flood risk management authority policy unintentionally influences coastal flood risk. Published literature on the topic suggests that the decreases in flood memory and comprehension of local residual flood risk, due to a proactive structural flood defence FRM policy, is one of the largest drivers that increases *AfP*, and drives the continuation of the unintended consequences of structural flood protection (e.g. Ridolfi *et al.*, 2021). Therefore, if this cyclicality of increasing Affected Population, Standard of Protection (SoP), and a consequent decreasing flood memory, is present in the conceptual model and apparent from the data then this will be a good reflection of these unintended consequences, and provide a resource for stakeholders, policymakers, and other agents to utilise to navigate these emergent phenomena.

The fifth Objective, **Objective 5**, sought to resolve the outward leaning area of the aim, and of this project, in order to provide evidence-based advice to flood agencies and policymakers. This would require a culmination of the evidence, data, information, and patterns observed obtained so far, and an application to the real world, to formulate advice. This is **Objective 5**, to identify methods of achieving desirable flood risk outcomes in order to enable sustainable spatial planning and in an effort to create more resilient communities. The outcome of this Objective would seek to answer Research Question 5, enquiring how more resilient communities can be built and the potential unintentional consequences of SCFP reduced. The output of this Objective should demonstrate why and how these socio-hydrological issues and emergent phenomena can be resolved at the science-engineering-policy nexus in order to create a truly integrated spatial planning system operated in tandem with sustainable FRM.

2.0 Literature Review

This chapter outlines findings of the critical literature review undertaken to better understand the emergence and development of the aforementioned concepts, how they relate, and the challenge in addressing the tensions identified in the context of coastal flood risk management. The study also highlights the key implications on three fronts: science (e.g., development of risk assessment methods), and policy (managing the nexus between spatial planning, infrastructure development, and environmental risks), and practice (e.g., stakeholder engagement and forming long-term partnership).

2.1 Emergence and Development

Throughout the past century the ideas of coastal flood risk, spatial planning, and the resulting SDP have emerged and developed, integrating themselves into modern science.

2.1.1 Coastal Flood Risk

An increasing frequency and severity of flood destruction exerted a strong pressure to provide protection against financial losses from flooding, manifesting in the American government creating the Federal Flood Insurance Act, approved in 1956 (Overman, 1957). This government-sanctioned insurance was based on risk-based premiums (Kousky and Kunreuther, 2010), whereby rates should be proportionate to the degree of risk as closely as possible (Grossman, 1958). Whilst risk was a known concept, the programme translated economic risk to physical risk for the first time: the concept of coastal flood risk emerged from insurance. A decade later, Benson (1967) considered how to incorporate probability into risk. He was one of the first to attempt to quantify this calculation and used the term 'extreme event' (Broska *et al.*, 2020). Yet the concept of economic loss remained, exemplified by the 'Cost of Preventing Thames Tidal Flood' (Schofield, 1970), not even considering social or environmental costs of a flooding disaster. However, Friedman (1972) was the first to recognise that coastal flood risk is composed of constituent elements: risk per individual structure and risk of a large number of simultaneous losses, the latter being deemed catastrophe potential. Indeed, unbeknownst to Friedman, the author described one of the modern definitions of risk, a product of hazard and probability. Progress towards a modern definition continued with Handmer and Smith (1983) noticing that social aspects were closely related to coastal flooding, and risk was not evenly distributed: males were more likely to become injured or die as a result of a flood hazard than females. Then in 1990, following discussion of how the physical environment may affect coastal flood risk, Garès offers that wave runup is one way of quantifying the risk of coastal flooding from overtopping. Garès (1990) determined that risk is the probability of wave runup along a beach profile, suggesting that geomorphology plays an integral part in risk, as the pathway that may facilitate a hazard to travel through.

'*Disaster preparedness and disaster mitigation are the goals of nations throughout the world during the 1990's'* reports Hays (1990), '*with the goal of the decade to keep such occurrences in the future from being disasters*'. Perhaps it is this leap to disaster mitigation that enabled Norfolk County Council to pursue preventing development within a specified distance of the coast and in high flood risk areas (Kay, 1991), whilst arguing that such a policy will only be effective if it becomes part of a coordinated national policy. An argument Glasby (1991) develops further, connecting the link between urban growth and flood risk, and suggests that sustainability must be incorporated into risk, to ensure mitigation at a national level. Fletcher (1992) continues that, to ensure coastal flood risk mitigation, *'hazard zones*' must be implemented to designate areas of planned retreat from the coast on a schedule dictated by natural events and processes, successfully linking risk and planning control. In the determination of risk, Reeve and Burgess (1993) develop a method for evaluating coastal flood risk, defining the area which becomes inundated by a storm of a particular severity, assuming that a sea defence fails, including its likelihood. The authors were the first to acknowledge that coastal flood risk depends on the defence itself, suggesting a recognition of the relationship between hazard and exposure. However, confusion within definitions remains, as Yim (1996) refers to high density urban and industrial areas as the most vulnerable, a term now associated with human vulnerability, not infrastructure.

Definitions of coastal flood risk evolved from a financial tool to one that influences the development of the urban landscape, however, difficulties remain in its definitions and intrinsic components. Adaptation to changing flood risk is necessary for a resilient community, and the mitigation of risk must consider multiple climatic, and socio-economic scenarios. Modern society faces more flood risk than the past century, propelled by an increase in hazard (e.g., sea-level rise), exposure (e.g., increasing coastal population), and vulnerability (e.g., changes in employment and industry) (Van Der Planck *et al.*, 2021). Policy and legislation have the tools to alter this, as well as manage development within the scope of flood risk under the remit of spatial planning.

2.1.2 Spatial Planning

'*What is this thing called spatial planning?*' announces Taylor in a 2010 publication, arguing that it is no different from those before it: Town and Country Planning (Keeble, 1952), Urban Land-use Planning (Chapin, 1965), Urban and Regional Planning (McLoughlin, 1969), Environmental Planning (Allison, 1975). Yet, strategic planning arose before then, from the 'Sanitary Movement' of 1840s England, planning public health across local areas (Moore, 1848), and the 'City Beautiful' movement. The movement pioneered American urban planning and operated until the 1920s aiming to incorporate social issues (Odum, 1945; Wilson, 1981). Urban planning continued to evolve, with city-wide strategic plans emerging from the publication of the CIAM's Athens Charter (Mumford, 2000). The Charter was the manual of post-war urban development in many countries and was the origin of the 'Functional City' (Gold, 1998; Kallis, 2021). The idea of the 'functional city' continued and in the 1960s and 1970s many Western countries moved to creating national development plans (Albrechts *et al.*, 2004). Progress was hindered by 1980s neoliberalism, whereby market forces overrode many of the nation-led Keynesian policies of the post-war period, and shifted to cost-effective projects, giving rise to random development, urban fragmentation, and environmental degradation (Albrechts, 2006). Specific areas were funded above others, creating imbalances within cities themselves due to gentrification (Smith and DeFilippis, 1999; Smith, 2002) and socio-spatial exclusion (Waterhout *et al.*, 2013). These issues demonstrated the need for a return to comprehensive strategies, the genesis for the modern form of urban design ─ spatial planning (Albrechts, 1999).

The UK Government defines spatial planning as *"going beyond traditional land-use planning to integrate policies... that influence both the nature and function of places*". Yet this definition is more a methodology, and does not address the incorporation of stakeholders, indeed the Royal Town Planning Institute (RTPI), a key proponent of spatial planning itself, notes that '*it is apparent that amongst key participants including planners, councillors, senior local authority and other public sector managers that there is little common understanding what this means in practice'*. In response the RTPI offers an alternative definition, presenting spatial planning from a more scientific perspective, as a '*critical thinking about space and place as the basis for action or intervention'* (RTPI, cited in Campbell, 2004). Thus, spatial planning should aim to coordinate spatial impacts to achieve maximum economic development with disregard to administrative and political boundary hurdles, whilst still being led by market forces (Jones, 2014).

Within the so-called '*Motherland of Planning'* (Kunzmann, 2009), it was the Planning and Compulsory Purchase Act 2004 that brought reform to the British planning system. The act created a three tier hierarchy of planning at national, regional, and local levels (Taylor, 2010). National planning was to be the most centralised, a direct responsibility of the Department for Communities and Local Government (DCLG) – what is now the Ministry of Housing, Communities and Local Government. The act created Regional Planning Bodies, whose primary function was to prepare and monitor the Regional Spatial Strategies (Allmendinger, 2003), and had the ability to identify key areas with disregard to local administrative boundaries. Local planning, organised by local planning authorities, formed the bottom tier, and set out the authority's policies relating to the development and use of land in their area. Notwithstanding the innovations, the Act remained controversial: Allmendinger and Haughton (2009) disagreed with its '*warm fuzzy feelings'* and labelled it a '*useful comfort blanket*' due to its flexible definition and use of 'buzzwords' such as '*collaboration'* and '*sustainable development'*.

For spatial planning to work it must have the facility to be delivered and implemented, therefore it is a simple matter-of-fact that it must have sufficient powers (Begg, 2018). Yet the actions of the New Labour government to forge partnerships and cross-boundary initiatives tended to exacerbate coordination difficulties (Cowell and Martin, 2003). Ultimately, contributing to confusion regarding the purpose of the partnership, accountability, and role of central government (Nadin, 2007). Regional Spatial Strategies were seen to be the incoming tide, but across the other side of the political spectrum they attracted contempt. Reform was promised and with a change of government, the rhetoric, '*getting the planners off our backs'* became law with the dissolution of Regional Planning Bodies, and the inception of the Localism Act 2011 (Lord and Tewdwr-Jones, 2018). The swift dissolution of Regional Bodies left the national planning framework '*a disintegrated mess'*, with power either centralised in a small, but intensely powerful, state, or residing within minute local authorities with limited power to wield (Lord and Tewdwr-Jones, 2012). Thus, the idea of spatial planning as a tool for public good, became overshadowed by projects of '*national significance*'*,* or diminished by local priorities that may only serve a handful of streets. Spatial planning may seem too broad and unviable in this national narrative, yet the inclusion of progressive social objectives, housing development, health inequalities, sustainability, and safe adaptation to climate change is possible (Lord and & Tewdwr-Jones, 2012). Indeed, many UK cities are already turning back to regional strategy, producing a new opportunity for spatial planning (Tomaney *et al.*, 2019).

2.1.3 The SDP and the Unintended Consequences of Flood Protection

Hurricane Katrina cost US$200 billion in economic losses (King, 2005), a disaster that may have been wholly avoidable and predictable (Burby, 2006). The fundamental idea behind safe development is that land, exposed to natural hazard, can be made profitable by the construction of defences leading to '*productive use'.* The paradox lies within the reasoning of planning authorities justifying a defence project, would lead to new urban development, infrastructure and populations that would have not been there if the levee system was not constructed, creating a feedback loop. Thus arises a paradox of poor spatial planning and misunderstanding of flood risk. Hence, the development of socio-hydrology.

'*Welcome to socio-hydrology, the new science of people and water'*

This was how Sivapalan *et al.* (2011) emphatically announced their '*new science',* aimed at '*understanding the dynamics and co-evolution of coupled human-water systems'*. Yet, these phenomena have been known since the mid-1940s: Human Adjustments to Floods was one of the earliest examples of an attempt to understand the coupled human-water system (White, 1945). However, it is only in recent times that knowledge and literature of these coupled human-flood interactions has grown.

Research into the integration of sociology and hydrology has occurred in four iterations: Water Resource Systems (1960s), Integrated Water Resources Management (1990s), Coupled Human-Nature Systems (2000s), and now Socio-Hydrology (2010s). Water Resource Systems (WRS) promoted thinking of hydrology as an open system where analysts should look beyond individual parts to see how other unforeseen elements may intersect and interact (Kasprzyk *et al.*, 2018). Nevertheless, the scope of it was limited to planning applications and was deemed too context-specific (Brown *et al.*, 2015). Integrated Water Resources Management (IWRM) followed in the 1990s, more pragmatic than sociology and hydrology, and less circumstantial than WRS' focussing on implementation and policy. IWRM sees water '*as an integral part of the ecosystem*' and a *'natural resource and a social and economic good* (Radif, 1999). IWRM aims to create integration across the water cycle, incorporate different stakeholders, and account for multiple spatial scales. Yet not all was positive, Liehr *et al.* (2018) critiques it as '*impractical and uncritically rehashes old ideas*' that makes it '*totally impractical to integrate all these issues'*. To improve IWRM, Dzwairo *et al.* (2010) suggest that it should adopt a systems approach, and aim to incorporate *'socio-economic dynamics, with a suggestion that the biophysical relationships like interactions in a basin between water, the human population and settlements should be analysed to the extent possible'*. This expanded IWRM echoes the development of other interdisciplinary frameworks exploring human and natural coupled systems, collectively referred to as CHANS. Research into CHANS aims to '*untangle complexities*' and understand

'*reciprocal effects and emergent properties*' (Liu *et al.*, 2007). Supporters believe that understanding these coupled systems can lead to novel scientific findings and is essential for developing effective, evidence-based policies to meet future '*unprecedented global challenges*' (Liu *et al.*, 2021). It is true that CHANS offers an opportunity for the integration of various disciplines, and some see it as the '*key to sustainability*' (Downing *et al.*, 2014), and as such CHANS may be seen as more of an umbrella term for socio-hydrology than a precursor. Indeed, Di Baldassarre *et al.* (2019) that socio-hydrology has a '*more explicit focus on water'* than CHANS, demonstrating links between the two.

Furthermore, there are continued efforts to bridge the gap between water research and the wider sustainability of the human-nature system, ignited by the United Nations Sustainable Development Goals (Biggs *et al.*, 2015). Mapping water, energy, and food as a nexus, aptly named the water-energy-food nexus (Cairns and Krzywoszynska, 2016), has been promoted as an emerging paradigm. At its core are targets to tackle natural resource scarcities under uncertain futures in climate and socio-economic conditions, and recognising that water, energy, and food are interlinked, where resource use and availability are codependent (Leck *et al.*, 2015).

2.2 Pre-Existing Applications, Integrations, and Policy Strategies

Since the emergence of coastal flood risk as a concept, and the institutionalisation of spatial planning, there have been numerous attempts to coordinate the two using varying frameworks and manage the coastal zone. Previous attempts have failed due to poor implementation, miscommunication, misunderstanding, or most often a lack of political will.

2.2.1 Coastal Flood Risk Management

'*One should not manage the flood, but the risk'* (Klijn *et al.*, 2008)

The 1953 East Coast floods provided the opportunity for great changes in public perception of flooding (Van Der Planck *et al.*, 2021), sea defences that were not fit-for-purpose were overtopped (Baxter, 2005). In the UK, 326 died, with 24,000 houses damaged, and an estimated 1600km^2 of land submerged, damage was calculated to cost approximately £50 million (Ho Choi *et al.*, 2018). The event led to significant investment in flood risk mitigation, and the creation of a nationwide flood warning system (Lumbroso and Vinet, 2011).

Due to the amount of investment placed on coastlines there is often a tendency to improve structural flood defences, and to increase protection level after a major hazard event. For instance, following the devastation of Hurricane Katrina, the Hurricane and Storm Damage Risk Reduction System was commissioned to protect New Orleans. The project consists of 133 miles of levees, floodwalls, gates, barriers, pump stations, and approximately 70 miles of '*interior risk reduction structures*' (Gotham, 2016). The vocabulary of this project reinforces the belief that the residents of New Orleans are safe from the hazard, with terms such as 'risk reduction' and physical structures placed within the city that can be seen in the day-to-day lives of the residents. Gotham *et al.* (2018) identified that post-disaster the risk perception of New Orleans residents was still low: residents who were male, on a higher income, and not flooded previously, were found to have little perception of the risk that they were still under. However, such lands are still vulnerable to flooding due to exceeding the design capacity of the levees; they are still affected by residual risk (Ludy and Kondolf, 2012). Increasing risk, failing federal structural defences, and an unprepared proportion of the population led to the last disaster to hit New Orleans. With hurricane frequency and magnitude rising, it is imperative elements of socio-hydrology and an understanding of the SDP are incorporated into future strategies for coastal flood risk management.

There is a common belief in flood risk management programmes that the exposure of urban areas depends solely on socio-economic development and natural urban growth. Yet, the presence of structural flood protection tends to create incentives to build closer to the coast; as Di Baldassarre *et al.* (2018) states '*socio-economic trends determine the amount of urbanisation increase, while the presence*

of structural flood protection influences the spatial location of new settlements'. Thus, as hazard decreases, an increase of exposure and vulnerability causes overall risk to increase in the medium- to long-term (Moel *et al.*, 2011), generating the SDP as its defences are strengthened again to protect the exposed assets (Kind, 2014).

As was with the case of the 'risk reduction' structures in New Orleans, physical structures can generate a sense of complacency amongst a population. Tobin (1995) found that complacency can reduce flood awareness and preparedness, increasing vulnerability. De Marchi *et al.* (2007) found that exposed residents tended to underestimate and discount hydrological risk, often induced by the presence of '*impressive structural works'* and large civic buildings constructed in hazardous areas. They note that the general attitude of the residents was that the symbolic messages of bricks and stone are more powerful than the verbal messages conveyed by information campaigns. Indeed, the report states that the most vulnerable groups during a hazard are those that have faith in local authorities; the competency of an authority promotes trust that the institution will not fail, however, this has the unintended side effect of increasing vulnerability. Furthermore, modelling done by Haer *et al.* (2020) demonstrates that a proactive (or competent, the term used by De Marchi *et al.*, 2007) government can lead to a decrease in building flood-proofing; whilst a proactive government increasing protection standards can lead to significant decreases in flood risk, this often unintentionally transpires to a decrease in the protective efforts made by households, and consequently an increase in the impact of extreme events. Successful coastal risk management should tailor communication to individual communities, respective of past experiences and vulnerabilities, and embrace the idea of shared responsibility between the authority and the individual. Shared responsibility and the incorporation of stakeholders in coastal flood risk management is being driven by the growth of joined up coastal strategies ─ the integrated coastal zone.

2.2.2 Integrated Coastal Zone Management

The coastal zone is a varied place, yet requires holistic oversight for successful management. Integrated coastal zone management (ICZM) attempts to join up different policies and bring together stakeholders from local to national levels to inform, support, and then implement these policies.

ICZM first appeared in the 1970s, out of growing concern for the quality of coastal environments. First appearing in the American 'Coastal Zone Management Act, 1972' and the European 'Resolution on the Protection of the Coastline, 1973', succeeded by the 'European Coastal Charter' in 1981 (Zile, 1974; Pierret, 1982). Then, in the 1980s, there was a growth in ICZM programmes in LEDCs, guided by the World Bank, United Nations Environment Programme, and the Food & Agriculture Organisation to allow for sustainable growth, in vulnerable nations reliant on the coastal zone (Ngoile and Linden, 1997).

In England, DEFRA and English Nature (now Natural England) took the lead with ICZM implementation (Tyldesley, 2005). As organisations focussed primarily on environmentalism, not housing development or economic growth, protecting social assets took a backseat. Shoreline management and coastal defence was externalised to other authorities, betraying the integrated element of ICZM (Ballinger *et al.*, 2010). Similar to spatial planning advances, ICZM initiatives in England were largely non-statutory and relied on voluntary participation by government, private, and civil stakeholders, operating under the titles of 'Partnerships', 'Networks', or 'Fora' (Stojanovic and Ballinger, 2009). Indeed, the voluntary model of ICZM has been described as an inherent weakness which hinders the uptake of the strategy as long as it is a 'voluntary, powerless, under-funded and non-sustainable project' (McKenna and Cooper, 2006).

Furthermore, one of the key principles of ICZM is integration, and the concepts of power sharing between central and local governments, and coordination of local planning, budgeting, development, and environmental management. Sorenson (1997) and Olsen (2003) both note that the lack of coordination between all levels of government and the integration of stakeholders has been a limiting factor in the growth of ICZM; there is a lack of a transparent, effective, and democratically accountable framework, as such policy has limited power, public support and awareness. Furthermore, McFadden

(2007) offers that the scientific community has failed to be incorporated into ICZM, leaving coastal management with a '*20th century legacy… that can be characterised to a large degree by fragmentation, the use of heavy engineering approaches to coastal protection and a lack of scientific tools'*. Indeed, as already raised within this paper, there is a lack of incorporation of the SDP within the coastal science literature. Thus, applying scientific knowledge to achieve tangible outcomes is still a major challenge within ICZM. Understanding integrated processes is a primary foundation of coastal zone management, currently employed methods do not attempt to integrate sociological processes with physical drivers, and the literature and current policy do not reflect the behavioural environment of the coast (McFadden, 2007). Socio-hydrologists must grasp this opportunity to reinvigorate ICZM with aspects of coupled science, and fill gaps within the legislative and scientific structure, towards a forward-looking sustainable management of 21st century coastal zones.

2.2.3 Incorporation of these Unintended Consequences

Eriksen *et al.* (2021) reviews the outcomes of interventions geared towards vulnerability reduction and adaptation, and highlights how they may in fact inadvertently reinforce, redistribute, or create new sources of vulnerability. Magnan *et al.* (2016) concurs, reviewing vulnerability reduction projects, and notes two examples of the SDP in Bangladesh and the Maldives. Here coastal infrastructure has been upgraded to protect against flooding, which in turn encouraged people to remain in high-risk areas. Case studies illustrate what may happen when policymakers are focussed on avoiding near-term disruption at the cost of reducing future risk; there is a preference for incremental adaptation that preserves existing behaviours over '*transformative adaptation'* that will disrupt embedded societal norms (Erikson *et al.*, 2021). A lack of incorporation can lead to extreme, low probability flooding, with devastating consequences that are not evenly distributed spatially or socially: pre-existing socio-economic conditions can play a key role in the ability (or inability) of certain social groups to respond to a disaster well and cope with flooding, as was the case in New Orleans (Masozera *et al.*, 2007).

The lack of understanding also presents itself within the literature: the 2014 book, 'Coastal Risk Management in a Changing Climate' authored by Losada *et al*. The authors, an '*international group of experts'*, suggest the book provides '*innovative, multidisciplinary best practices for mitigating the effects of climate change on coastal structures'* yet contains no reference to White (1945) or the seminal efforts with human adjustments to floods, Burby (2006) or work with regard to the SDP, or Sivapalan *et al.* (2011) or work with regard to socio-hydrology. Furthermore, whilst some papers discuss the increasing role of civil input and socio-economics into coastal risk management such as an increase in stakeholder engagement co-delivery (Nye *et al.*, 2011), or availability of hazard mapping to citizens (Percival *et al.*, 2020), or the introduction of flood warning systems (Priest *et al.*, 2011), they are all one-directional viewpoints of a cyclical system: very few papers discuss the flow backwards of hydrological development on society, focussing overtly on societal impacts on hydrology.

Yet, whilst institutionalisation of the SDP remains limited, Johnson *et al.* (2005) identifies that a flood disaster can accelerate incorporation of new flood science into policy, however, it cannot change policy if there is no willing already there, thus the impact is highly contextualised to the individual area. The authors suggest that '*environmental drivers'*, magnitude of the flood disaster and its impact; '*technological drivers'*, availability of technology, knowledge and information at the time of the flood; '*socio-political drivers'*, the socio-economic, political, and governance structures in place; and '*behavioural drivers'*, the dominant attitudes, beliefs, and values of society toward the hazard, all influence policy, legislation, and science after a major flood, but require '*key actors'* to be involved and start the mechanism, suggesting that flood disasters can change the public's perspective of a government. However, the authors continue to suggest that geo-political factors are also an influence; after all, floods are a natural geographical process, and the geomorphology of a country will influence legislation and the values of the public. For example, in the Netherlands the economic heartland is predominantly in an area that is more prone to flooding, and the westernmost urbanised area, the Randstad, lies below sea level. This knowledge would be constantly present within the minds of the Dutch public and government, as such flood disasters in the Netherlands led to the construction of large-scale flood defences, seeking to settle the basic human need for security (Kruizinga and Lewis, 2018).

Furthermore, public pressure limits the growth of new ideas within coastal risk management; operating with a mindset that only structural defences will do. Hence, governments seeking re-election champion structural defence, and when increased funding for risk management was announced by DEFRA in 2007, it was depicted by the UK government as a funding increase for flood defence, rather than money for impact reduction (Harries and Penning-Rowsell, 2011). Harries (2008) argues that humans feel comforted when 'protected' from nature. The framing of the human-nature dynamic is not easily changed, thus only repeated, and severe, events prompt change in representations and associated behaviours (Kates, 1971). Furthermore, recent government initiatives have tended towards an increase in community consultation in public sector decision-making, and whilst the democratisation of environmental policy is admirable, it tends to attract the involvement of those most directly and personally affected by the environmental issue at hand. Such is the issue that one of the flood risk managers for the Water Management Agency stated that, "*The people who came were the same ones who always come when there is a public discussion somewhere. The mass population were not interested. They only come when water is already in their cellar and then only to complain*". Thus, policymakers perceive this group as 'the public' and their opinions as representative of the population, leaving flood management policies skewed towards a small number of victims who insist on the elimination of risk in their own localities (Harries and Penning-Rowsell, 2011). Increasing public education of the SDP will allow the inclusion of non-structural and other resilience measures into coastal risk management.

2.2 Coastal Flood Risk

There are different definitions of flood risk, varying across time, and fields, therefore it is essential that these definitions, and consequent components are mapped. This will ensure that the right components are selected for the field and time period. For the review, 1367 journal articles were reviewed from the advanced search, 290 were deemed relevant enough and their definitions catalogued. Irrelevancy was defined as not being directly related to the coastline, discussions of fluvial or pluvial flooding, and not clearly stating the components of the authors' definition of risk. Indeed, many articles discussed coastal flood risk without describing constituent components, often this was due to the paper not being primarily focussed on flood risk, but perhaps insurance, or house prices (e.g. Votsis and Perrells, 2016; Beltrán *et al.*, 2018).

Flood risk has been described as having an almost philosophical element: if a large-scale flood occurs in an uninhabited region with no human property, is that a disaster? Therefore, should risk not be examined as a function of event consequences, not simply the event itself (Kron, 2009). Similarly, in European papers many follow the EU Floods Directive definition of risk, the product of hazard and vulnerability (Apel *et al.*, 2009), whereby this definition describes hazard, as the '*physical and statistical aspects of flooding*', and vulnerability as the '*exposure of people and assets to floods and the susceptibility of the elements at risk to suffer from flood damage'* (Merz and Thieken, 2004; Hadipour *et al.*, 2020). Although other authors have offered an alternative: risk is the product of hazard and probability, rather than vulnerability (e.g. Zheng *et al.*, 2015). Others suggest that risk is the product of consequences and probability (e.g. Klijn *et al.*, 2015), the definition used by the Rijkswaterstaat, the Netherlands flood management agency. This definition, however, facilitates the idea of *'acceptable risk*' and '*adaptive risk'* leaving communities still vulnerable, and often unaware (Roth and Warner, 2007). Consequently, it has been argued that when coupling risk and probability, important aspects may be unintentionally disregarded; no matter the low probability, there are dangers nonetheless (Aven, 2010). Consequently, some have suggested that flood probability is not as relevant as exposure, the link between vulnerability and hazard (Aven, 2012). In other words, a community is at risk when the hazard (deemed '*risk source'* by the author) can interact with the vulnerability of a population, facilitated by the exposure of the system. This is echoed by Mostert and Junier (2009) and Klijn *et al.* (2008), who expand on the definition offered by Kron (2009) and divide consequences into exposure and vulnerability.

These five definitions of coastal flood risk are explored in **Figure 1**. At the turn of the century, coastal flood risk as the product of consequences and probability (*CP*) was the leading definition, and still

remains one the most widely used. The definition is often used when describing the Netherlands, such as Jonkman *et al.* (2008) and their assessment of coastal flood risk in South Holland. It is interesting to note, however, that definitions using vulnerability (*HV*, hazard × vulnerability) and (*HEV*, hazard × exposure × vulnerability) became the dominant definitions following Hurricane Katrina in 2006, which brought socio-economic disparities to the forefront of coastal flood risk. Kleinosky *et al.* (2007), for example, identified that flooding still presents a significant hazard, especially for vulnerable people, and planning *should steer development away from low-lying coastal and near-coastal zones*, an epitaph to New Orleans perhaps. Yet, despite differences between definitions, literature regarding coastal flood risk has increased dramatically since 2000, influenced by an increase in the magnitude and frequency of storms in a changing climate.

Extreme flooding is inherently destructive (Rougier *et al.*, 2013) to which coastal areas are particularly susceptible (Chang *et al.*, 2015). These coastal areas are socially, economically, and environmentally important, attracting economic activity, driving urbanisation, and infrastructure developments. However, they tend to rely on local ecosystems, transient tourists, and exposed infrastructure, leading to higher hazard vulnerability. Therefore, at this cross-sectoral zone there are many areas where coastal flood risk may present itself, depicted in **Figure 2**. To create this chart, papers were divided into categories depending on the context of which definition of coastal flood risk was applied. Papers that discussed how coastal flood risk may affect house prices were limited, and whilst the most popular definition was hazard and probability (*HP*), this was only by two papers (Filatova *et al.*, 2009; Votsis and Perrels, 2016), compared to one for the others and so differences remain negligible. Whereas impact analysis featured papers that discussed the impacts of coastal flooding (Lumbroso and Vinet, 2011), or the impact that a definition may have (Montgomery and Chakraborty, 2015), *HEV* was the primary definition for these papers, as it was for those reviewing insurance (Bin *et al.*, 2008), GIS and modelling (Toimil *et al.*, 2017), policy evaluations (López-Martínez, 2020), and risk analysis. Analysis was the most frequent use of coastal flood risk, and whilst the majority did indeed use *HEV* (Adelekan, 2010), many also used *CP* (Lamb *et al.*, 2010), particularly earlier on in the century. Those requiring a greater human element were more likely to use vulnerability as a distinct component: risk analysis, management (Yeo, 2003), and perceptions (Horney *et al.*, 2010). Whilst *CP* is more used than *HV* in all three, due to the downward trend in *CP* use, and the increase in use of *HV*, this may change, and the literature will need to be constantly reviewed progressing forward, to remain up-to-date.

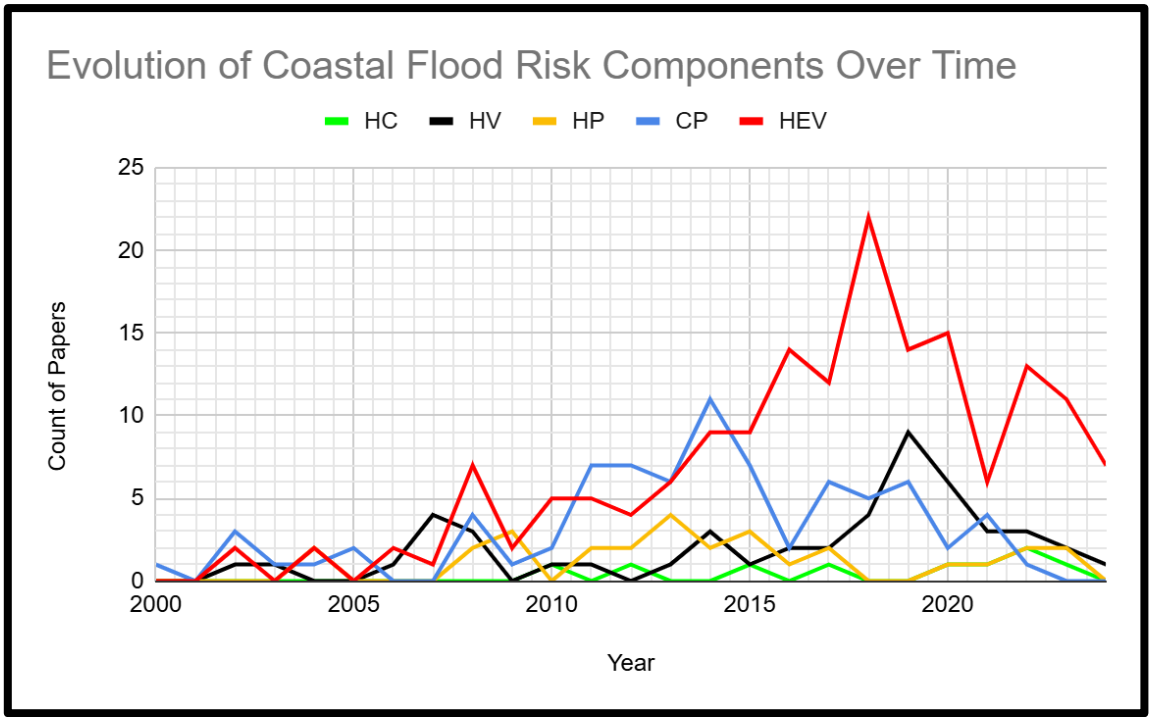


Figure 1 Line graph of changes in use of each risk definition over time in the coastal flood risk literature during the years 2000 to 2024.

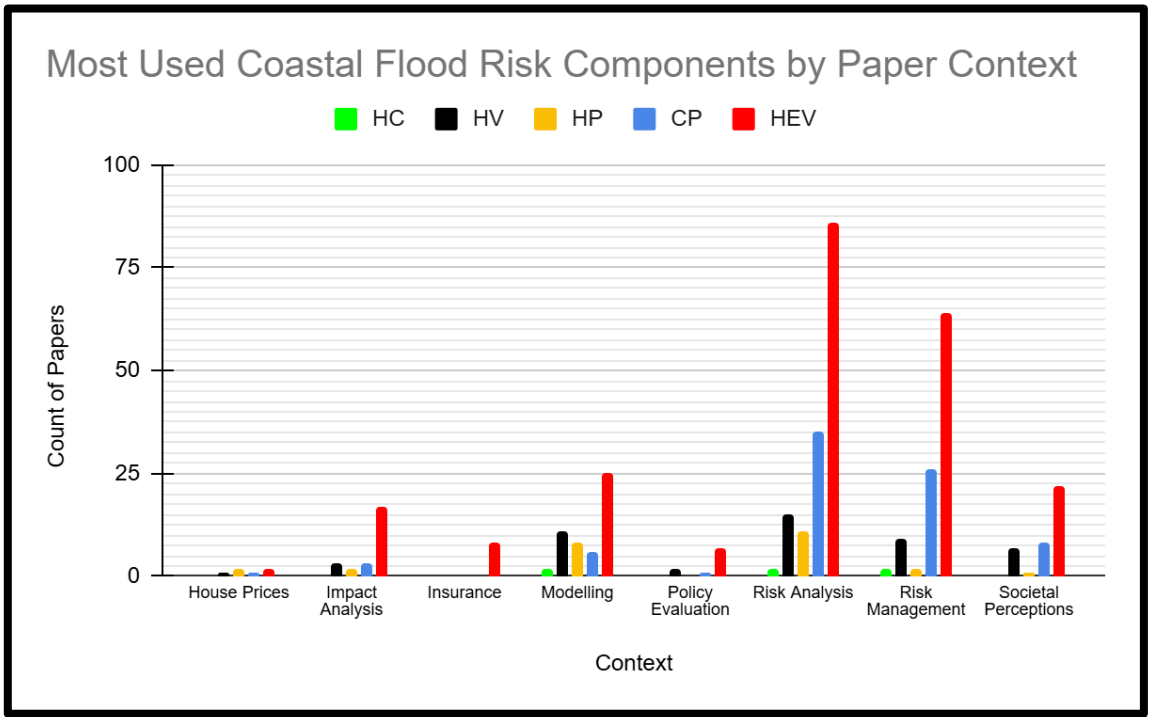


Figure 2 Bar plot displaying most used risk definitions by paper context in the coastal flood risk literature.

Hazard refers to an event that may have an adverse impact on a community (Percival and Teeuw, 2019). Rumson *et al.* (2020) lists climate change, storm surges, and frequency of previous events as drivers. The paper uses an SPR model, consequently some relevant metrics are listed as pathways: urban topography, beach profiles, local bathymetry, coastline length. Pathways represent what may propagate a hazard to reach a receptor, and whilst SPR models are increasingly being used in flood risk management (King, 2005; Narayan *et al.*, 2014), it is difficult to map its metrics directly onto a hazard-exposure-vulnerability model, and so literature must guide choices to ensure relevancy. Topography,

bathymetry, and beach profiles are often used in mapping flood hazard as they occur in tandem with the event, and so may need to be considered in hazard assessment (Hrăniciuc *et al.*, 2017; Moftakhari *et al.*, 2019). As is coastline length, often used in inundation modelling (Lewis *et al.*, 2011; Dhiman *et al.*, 2019). Therefore, when mapping hazards numerous elements should be considered: event frequency, sea-level rise, storm magnitude changes, storm surge depth, urban topography, beach profiles, nearshore bathymetry, and coastline length.

According to Ayala-Carcedo (2004), a strong link exists between inundation effects and urban layout; spatial planning directly affects the flood risk of an area. Hence, it is imperative that flood risk analysis includes urban layout, which some authors deem '*physical vulnerability'* (Başaran-Uysal *et al.*, 2014; Percival and Teeuw, 2019). Whereas in this paper it is referred to as '*exposure*', in accordance with the IPCC, the elements of urban fabric that may affect inundation (Cardona *et al.*, 2012). These may be drivers such as population or housing density (Cai *et al.*, 2018), or infrastructure in hazard zones: commercial buildings (Abenayake *et al.*, 2018b), council-owned buildings and public services (Meoni *et al.*, 2012), industry (Papathoma-Köhle *et al.*, 2010), transportation (Burton, 2015), telecommunications (Cutter *et al.*, 2014; Salazar-Briones *et al.*, 2020), utility assets (DasGupta and Shaw, 2015), and land cover or surface permeability (Abenayake *et al.*, 2018a).

Thus, risk is inherently human-necessitated and requires a human element ─ vulnerability. Definitions are often broad and 'fuzzy': Nakamura and Llasat (2017) suggest that vulnerability is '*a characteristic of a community that increases hazard damage, is affected by mitigation, preparedness, and response*'. The terms '*community*' and '*mitigation, preparedness, and response*' map well onto drivers provided by Kreibich *et al.* (2017): flood awareness, flood preparedness, and emergency management. The authors describe flood awareness as experience, information campaigns, or precautionary measures; flood preparedness as early warning systems, lead times, risk communication during events, private emergency measures; and organisational management as the performance of governmental crisis management, civil protection, emergency plans, evacuation, etc.

Nonetheless, vulnerability is highly contextual. Brooks *et al.* (2005) argue that factors that may make a small coastal settlement in semi-arid Africa vulnerable, will be very different to those that make residents in Southend-on-Sea vulnerable. The authors suggest poverty, health, economic inequality, local government structure, number of storm shelters locally, regulation of building strength, as drivers. In contrast, Percival and Teeuw (2019) offer age, household structure, illness or disability, English proficiency, economic activity, providers of unpaid care, occupation, communal establishment residents, and home population. A combination of metrics from both papers will ensure a holistic view of socio-economics. Furthermore, incorporating the elements from the Kreibich *et al.* (2017) paper, will ensure broader topics such as socio-political pressures, hazard memory, levels of government communication, and public service capacity are accounted for.

2.3 Unintended Consequences of Structural Flood Protection

A total of fifty-seven articles were assessed (forty-two when **Appendix A** was created), regarding the SDP in the context of flood risk management. Articles were assessed within five themes: year of publication, terminology, types of hydrological hazard, geographic distribution, and their recommendations for addressing the SDP.

2.3.1 Literature Frequency

The amount of literature increased throughout the research period, with the greatest sustained increase beginning 2013, with the exception of the 2016-2017 lull (**Figure 3**). Meanwhile other closely related concepts emerged: Integrated Water Resource Management (IWRM) developing in 2006, from a UN and Global Water Partnership taskforce (Petit, 2016); Coupled Human and Natural Systems (CHANS) emerging in academia in 2007 (Liu *et al.*, 2007); and then Socio-hydrology in 2011 (Sivapalan *et al.*, 2011). Literature peaked and troughed as these closely related concepts emerged. However, following the emergence of Socio-hydrology, paper publications followed a steady increase, with many following publications being completed in that context (e.g. Di Baldassarre *et al.*, 2013a). The increase in publications is also coupled with a general increase in flood risk literature (**Figure 3**), rising steadily since the turn of the century.

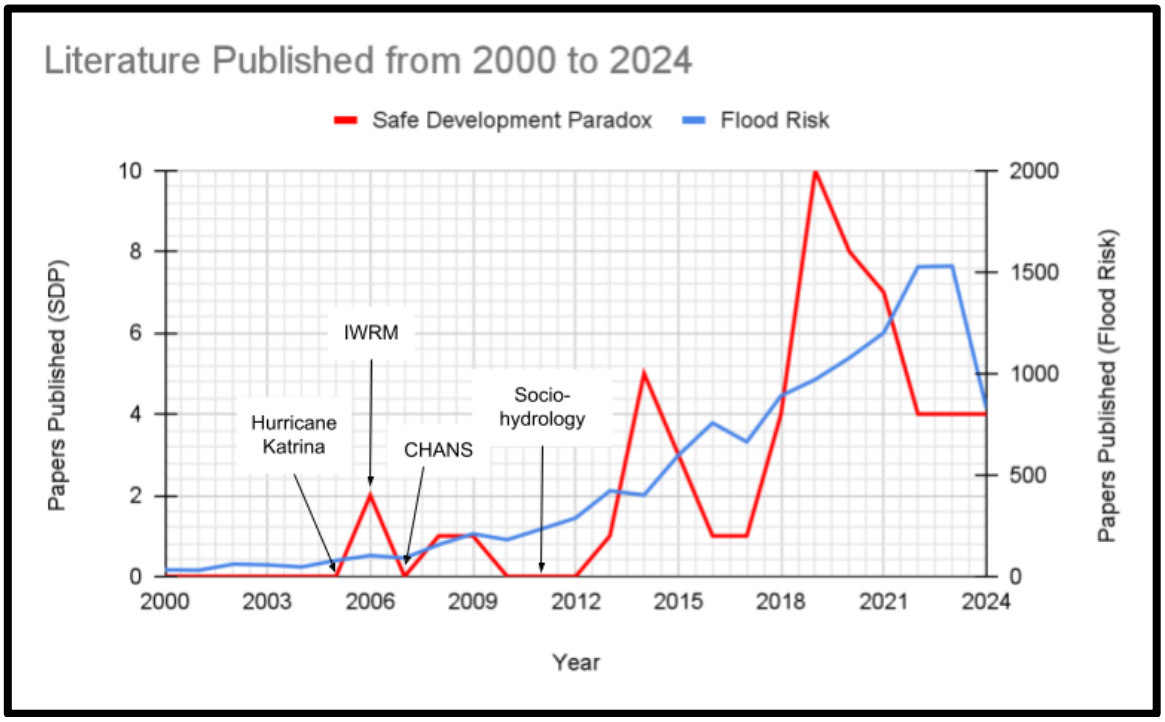


Figure 3 Distribution of SDP/ Levee Effect/ Safety Dilemma articles and general flood risk articles over the review period (2000 to 2024), with Hurricane Katrina and emergence of new related concepts are annotated.

2.3.2 Terminology Usage

In the literature, three terms are used to refer to the same process of unintended consequences of hard flood defence: *SDP* (Burby, 2006), *Levee Effect* (Di Baldassarre *et al.*, 2015), and *Safety Dilemma* (Di Baldassarre *et al.*, 2018). When reviewing the graphs it should be noted that some articles use the terms interchangeably within the same article (e.g. Di Baldassarre *et al.*, 2018). Originally, the *SDP* was used, and it continued to be used steadily throughout the 2010s (**Figure 4**). However, the term was superseded by the *Levee Effect*, a term often used by authors approaching the lock-in cyclical process from a socio-hydrological perspective (e.g. Sivapalan *et al.*, 2015). In fact, authors who use the term *SDP* often discuss a real-world case study and recommend better planning control to solve the lock-in effects (e.g.

Stevens *et al.*, 2009). Whereas authors that use the *Levee Effect* focus on recommending further developing the scientific knowledge and engage more in modelling and theory (e.g. Angelo *et al.*, 2020). These connections are discussed in greater detail in later sections.

At present, the *Levee Effect* is the most used term for this process (**Figure 4**), and partly reflects the growth of socio-hydrology, as well as flood risk literature in general. However, the *Levee Effect* has the chance of being misused, when discussing how a levee may affect the studied topic, such as Saito and Fukuoka (2011) discussing the effects of natural levees. Likewise, use of the *Safety Dilemma* was broad, and at present, there is only one paper in which the *Safety Dilemma* was used in the context of the SDP for this paper (i.e. Di Baldassarre *et al.*, 2018). In contrast, once grey literature has been discarded, the *SDP* was used in the correct context in each paper that mentioned it.

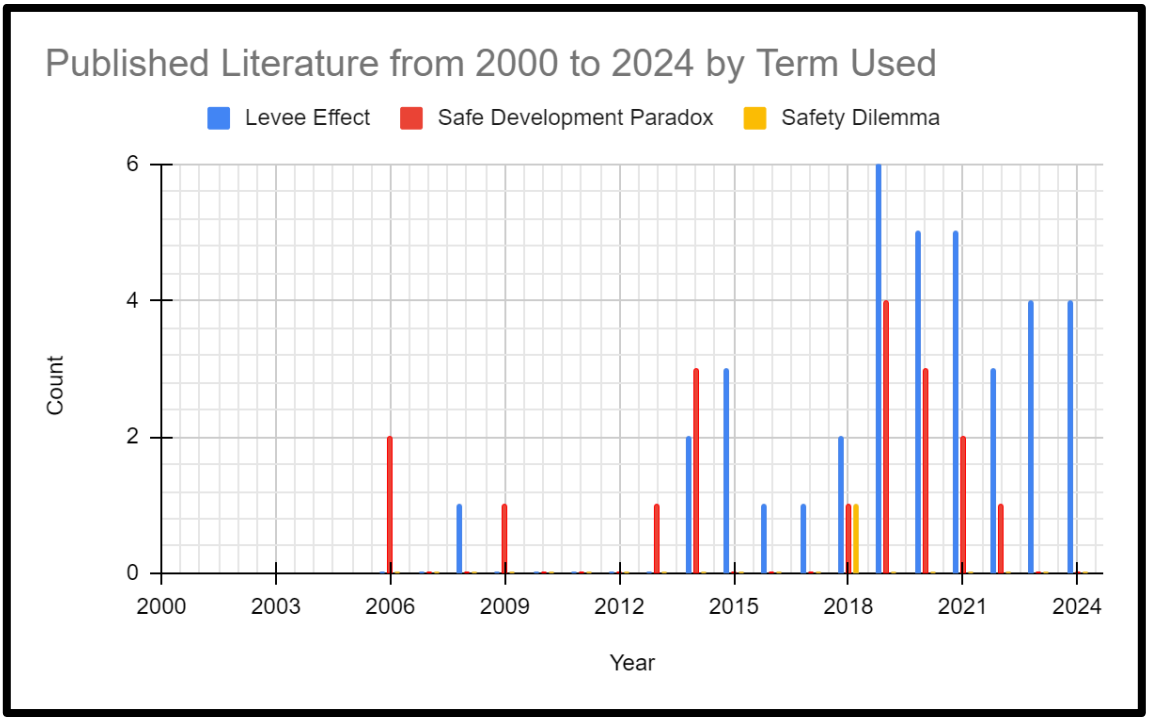


Figure 4 Distribution of published literature regarding the lock-in cyclical process, referred to in this article as the *SDP* over the review period (2000 to 2024). Articles have been divided by the terminology used.

2.3.3 Hydrological Hazard Investigated

The majority of the literature focuses on fluvial flooding and the unintended lock-in consequences thereof: fluvial flooding consists of **72.2%** of analysed literature, coastal flooding is **14.8%**, and papers studying both account for **13.0%** (**Figure 5**). Of the fifteen papers that discuss coastal flooding, eight specifically focus on coastal flooding; the other seven discuss both, fluvial and coastal flooding. These papers were often review papers or compared between case studies (e.g. Tyler *et al.*, 2019). Consequently, disregarding papers that discuss both, as mentioned previously, for every paper that investigates the SDP in a coastal setting, there are four in a fluvial setting. The majority of purely coastal flooding papers used the term *SDP*; only one used the term *Levee Effect*. Moreover, all articles that specifically focus on coastal flooding study case studies in Western countries: nine studying an American case study, and one studying a European case study. Ultimately, research attempting to understand the interplay between coastal flooding and the SDP is lacking.

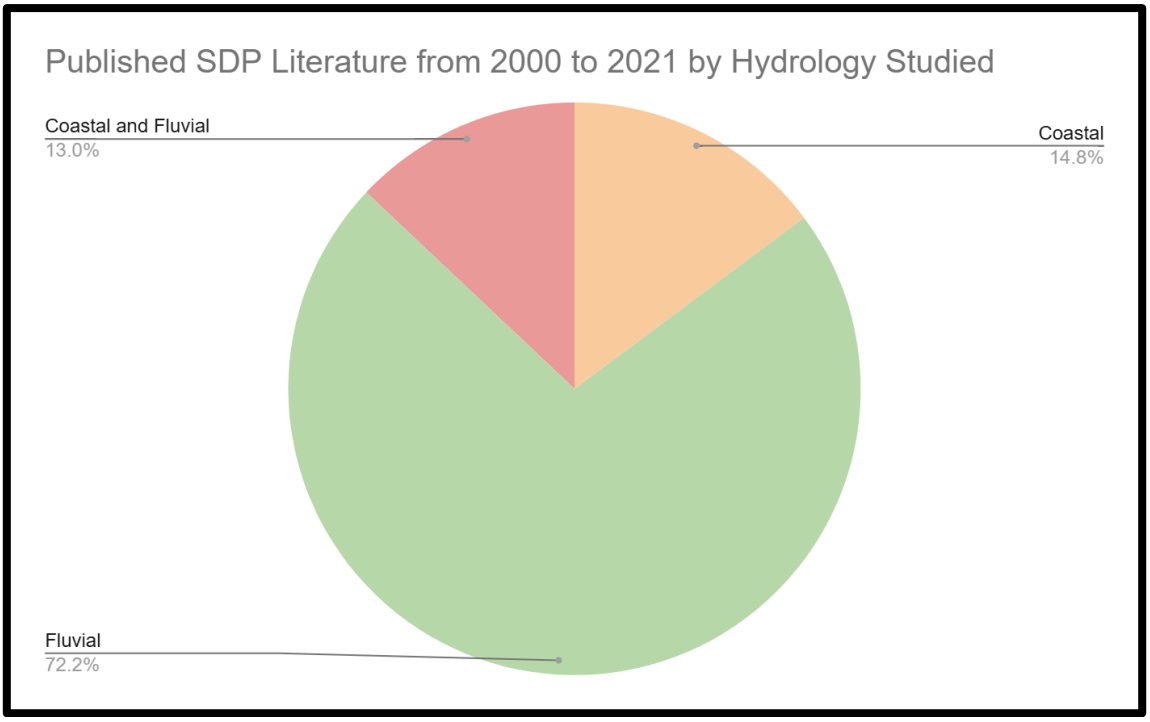


Figure 5 Published literature, divided by the hydrological hazard studied (coastal or fluvial) over the review period (2000 to 2024).

Between 1970 and 2010, populations in North America have observed a 13.3% population increase in coastal flood risk areas, compared to a 0.5% population decrease in fluvial flood risk areas (Jongman *et al.*, 2012). Similar changes occurred across continents of the Global North during the same period: in Europe, a 6% increase in populations at risk of coastal flooding compared to a 0.3% decrease in those at risk of fluvial flooding; and in Australasia, a 2.5% increase in populations at risk of coastal flooding, compared to a 0.7% decrease in those at risk of fluvial flooding (Jongman *et al.*, 2012). New populations moving to the coast lead to increased communities, assets, and infrastructure placed on the coastline than would have been there previously. In coastal areas locked into the cycle of the SDP, additional populations can further drive this process.

2.3.4 Geographic Distribution of Literature

The majority of published articles focus on cases in the USA (28), followed by Italy (11), Bangladesh (6), Germany (5), Austria (4) and China (4). Then France and the Netherlands (3 each) and Denmark, Ireland, Australia, Croatia, Greece, India, Portugal, Spain, and the UK (2 each). All other countries highlighted in the map below have one paper each (**Figure 6**). Use of the term *SDP* was more predominant in papers from the USA, with **65%** of papers using the term researching cases in the country. In contrast, use of the term *Levee Effect* was more predominant in European case studies. Europe and the USA were the predominant locations studied in the literature. These locations of the Global North are often more economically developed than others in the Global South (Lees, 2020), and represent a greater proportion of the literature (**Figure 6**). This may be due to the SDP not being a present issue in many places in the Global South where major structural flood defences are limited, with an opportunity for lessons from the Global North for avoiding the development of similar infrastructural lock-in conditions (Scussolini *et al.*, 2016). Furthermore, a focus on English-language articles may have contributed to this skew.

Developed economies may have already fallen into the infrastructural lock-in effects of the *SDP*, and may already be trapped in a cycle of an ever-increasing need for defences (Di Baldassarre *et al.*, 2015). Lock-in conditions can lead to high levels of flood protections and highly urbanised floodplains (Di Baldassarre *et al.*, 2018). In contrast, as emerging countries develop, the effects of the SDP have begun to take hold. In Bangladesh, for example, it has been identified in areas where flood protection has been

structurally developed, population density has increased greatly over the past decades as well as the number of assets exposed to flooding (Ferdous *et al.*, 2020). Flood mortality rates associated with the 2017 flooding in Bangladesh were lower in the areas with a lower protection level (Ferdous *et al.*, 2020). As countries continue to develop, more research regarding the Global South will provide a better understanding of emerging flood risk management approaches and the challenge/opportunities for safe and sustainable development in hazard-prone areas.

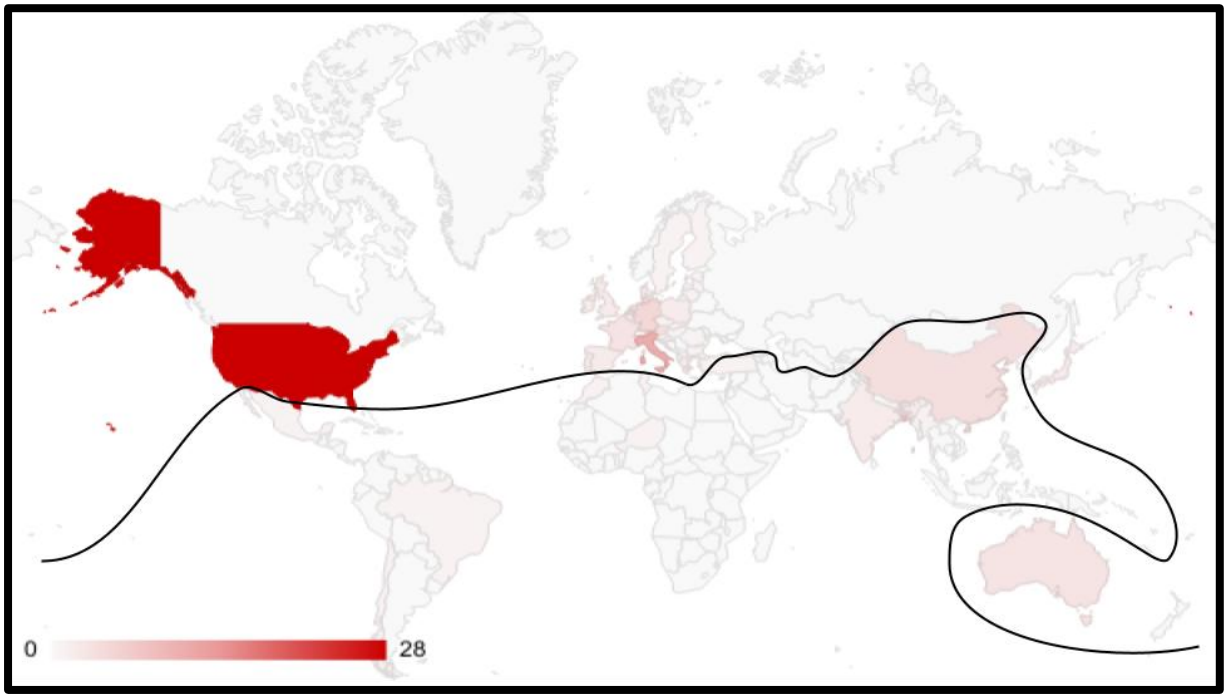


Figure 6 Geographic distribution of locations studied in literature by country (2000 to 2024). The map features the Brandt line, delineating the Global North and Global South (Lees, 2020). Colour scale represents the paper count.

2.3.5 Literature Recommendations

The majority of analysed literature recommends *Improved Science* when discussing how to break the lock-in cycle of the SDP (**Figure 7**). Proponents for improving knowledge and bettering the science surrounding the process come from a range of backgrounds: the *Levee Effect* (e.g. Michaelis *et al.*, 2020) and the *SDP* (Armstrong and Lazarus, 2019) terms are used in papers recommending it, both in fluvial and coastal settings, and from a variety of locations around the world. With the majority of papers being produced focussing on the Global North, increasing SDP knowledge may be produced from studying a greater number of case studies, especially those from developing nations in the understudied Global South.

In total, sixteen articles suggested stronger *Planning Control* as a way to alleviate the SDP, with two-thirds of these articles focussed on case studies in the USA. Better *Planning Control* would require the use of governing bodies to coordinate urban development to ensure that the placement of populations and infrastructure did not increase following the upgrade of a flood defence (Hutton *et al.*, 2019; Richert *et al.*, 2019). Other papers suggested *Improved Communication* of flood risk would break the SDP (e.g. Fox-Rogers *et al.*, 2016), some suggested *Improved Modelling* to understand risk and the impacts of new development better (e.g. Barendrecht *et al.*, 2017), others proposed using flood *Insurance* policies to provide an incentive for building more sustainably (e.g. Haer *et al.*, 2020). In some papers, *Relocation*, as part of a mixed package, was the best suggested way to ultimately combat the SDP and the effects of climate change (e.g. Ferdous *et al.*, 2019). One paper suggested that better *House Defences* were the most appropriate measure in order to reduce the cost of flood defences and at-risk houses should have flood doors and windows (Ventimiglia *et al.*, 2020). However, not all papers offered a recommendation.

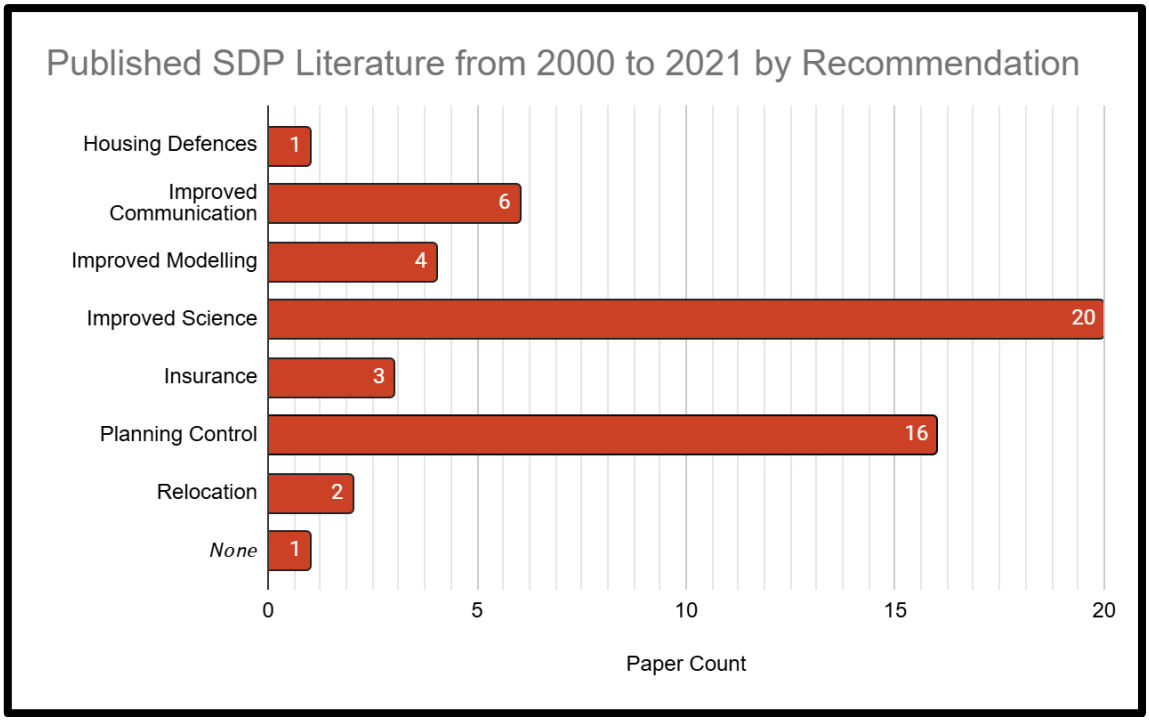


Figure 7 Published analysed literature divided by the key recommendation provided by the authors in the papers published throughout the review period (2000 to 2024).

2.4 Strategies and Implications

Previous attempts at an integrated framework have achieved limited success. Integration requires effective collaboration amongst a variety of institutions and stakeholders that have the power to both inhibit and facilitate policy coordination. Future attempts at forging partnerships between agencies must build on the previous scientific, social, and legislative landscape. These must challenge current paradigms, offer sustainable alternatives, produce resilient communities, and break the SDP.

2.4.1 Integrated Spatial Planning

Insufficient powers, limited resources and accountability, and a lack of true integration between urban, environmental, and economic planning led to the destruction of the system of spatial planning in the UK. Followed by the failures of the 'Localism Act (2011)', requiring local authorities to coordinate in the production of strategic 'Local Plans', yet ultimately many chose not to coordinate to create effective strategic plans (Gallent *et al.*, 2013). The spatial planning system can influence development across multiple spatial scales from the local level to international strategy and is often granted more powers than flood risk agencies (White and Richards, 2007), despite previous work highlighting how flood protection measures can influence property markets (i.e. Filatova *et al.*, 2009; Votsis & Perrels, 2016), an area beyond the scope of this study, but relevant for future work.

Perhaps it is no coincidence that the review of Localism Act 2011 occurred in tandem with British regional devolution and the creation of Metro Mayors, with strategic planning oversight (Gains, 2015). Bailey and Wood (2017) suggest that these Metro city-regions are puppets of British 'meta-governance', yet a coerced return to a more effective approach to spatial strategy is not necessarily negative. Meanwhile, the desire to devolve power to mid-tier bodies marks a clear departure from the early 2010s coalition government and presents an opportunity for an integrated spatial planning that must be guided in the right direction. In this context, Portman *et al.* (2015) propose that ICZM should be revisited, and become a more pragmatic and malleable concept, one that acknowledges that achieving full economic development whilst generating comprehensive environmental protections is not always attainable. McShane *et al.* (2011) echo the proposal, arguing that the blind following of the 'right' approach to

conservation can obscure important considerations, leading to unresolved conflict, and can limit the success of policy implementation. Thus, the future of ICZM is not to abandon the concept, but to integrate it with other management approaches such as spatial planning and climate change adaptations, meanwhile supporting community-level dynamics with awareness programmes (Portman *et al.*, 2015). Likewise, spatial planning should embrace a wider definition whether that be on land, coastal, or marine environments. There has already been growth in the idea of marine spatial planning (Jones *et al.*, 2016), consequently, the next logical step should be to spatial plan the coastal zone. Here, at the land-sea interface, numerous elements have a spatial component: urban growth, nature conservation, coastal defence, shoreline management, regulation of minerals, and fisheries (Taussik, 2007). With the current emphasis on sustainable development and spatial planning, combined with the requirement for public inclusion, there are clear parallels between the ways ICZM and spatial planning operate, therefore in the new embodiment of spatial planning, lessons should be learnt from ICZM to increase the legitimacy of related policy.

Shoreline Management Plans (SMPs) establish the strategy for coastal risk and define coastlines on the basis of physical process characteristics. The first tranche of SMPs was produced in the late 1990s, yet Cooper *et al.* (2002) identified that these documents contained little stakeholder participation, with limited public awareness, poor links to the spatial planning system, and were non-statutory, thus encountering problems engaging institutions with already well-established methods. Furthermore, Taussik (2007) identified that few development plans made reference to the SMPs, with some local authorities still permitting infrastructure and communities to be built on areas at risk. The strategic nature of SMPs means their contribution to integrated spatial planning is invaluable, enabling an understanding of where future development may be economically feasible, creating a better spatial policy with coastal risk management at its core. Furthermore, spatial planning can lend itself to ICZM and SMPs by including the statutory requirements for public involvement and consultation, providing an opportunity for a debate regarding risk, creating a better informed and aware public, and a community that is considerably less vulnerable. Integrated spatial planning therefore will carry a considerable status; it will have survived public examination, contributed to safer development, whilst safeguarding the local environment. Providing 'good growth', growth that is socially and economically inclusive, and environmentally sustainable, moving away from approaches that promote growth at any cost. Placing coastal risk management at the core of planning enables the SDP to be broken, as socio-economic growth and non-structural coastal defence, often treated as antitheses, can be brought together and considered in parallel. Yet most importantly, the stakeholder engagement created by integrated spatial planning should provide public awareness of coastal areas not likely to be protected from coastal risk, particularly important in view of the expected future impact of global climate change and isostatic readjustment (Taussik, 2007). Indeed, the Independent Assessment of UK Climate Risk report released this year states that '*the UK is not prepared for unprecedented extreme weather events that could occur now'* and *'lack of adaptation over the past five years has also led to lock-in, irreversible changes and higher future costs for the Government*' (King *et al.*, 2021). Action must be taken to prevent further lock-in effects and an exacerbation of the current flooding issues. Issues must be resolved at the science-engineering-policy nexus, creating a truly integrated spatial planning system.

2.4.2 Implementation

To ensure sustainable futures for our coastal urban areas, there is an urgent need in incorporating socio-hydrological processes into spatial planning, which itself must be at the forefront of local politics. Yet, as **Figure 5** demonstrates, literature regarding coastal socio-hydrology is limited, highlighting the need to increase not only scientific understanding, but ensure that it is incorporated into legislative frameworks. As a community, socio-hydrology must seek to inform new and evolving local political dynamics as well as raise awareness of the unintended consequences of coastal flood defences, including the residual risk that many residents experience daily, yet are frequently unaware.

2.3.2.1 Geospatial Strategy

Integration between institutions starts with a shared goal and collective knowledge (Oliver, 1990). It requires technologies and connections to support smooth communication and the transmission of vital knowledge between actors (Evans-Cowley and Hollander, 2010). Geospatial technologies (e.g. GIS) can provide a potential facilitator, whilst the true integration of institutions and a reorganisation of the planning hierarchy may take decades. GIS provides a medium for flood risk and spatial planning to operate on the same plane. Ran and Nedovic-Budic (2016) suggest that GIS has already demonstrated its worth both with its use in spatial planning and flood risk management. In spatial planning, GIS is often used in site selection (Chang *et al.*, 2008), assessing spatial distributions (Oh and Jeong, 2007), spatial modelling (Barredo *et al.*, 2003), public participation (McCall and Dunn, 2012), and plotting development sustainability (Vukicevic and Nedovic-Budic, 2012). Whereas, in flood risk contexts GIS has been used to model the extent of flooding (Rahmati *et al.*, 2016), determine flood risk (Rincón *et al.*, 2018), evaluate impacts of floodplain urban development (Nedovic-Budic *et al.*, 2006), and determine the effects of land-use changes on hydrology (Bahremand *et al.*, 2007).

Despite the widespread use of GIS, the absence of shared geospatial strategy is one of the factors impeding the integration of flood risk and spatial planning agencies (Ran and Nedovic-Budic, 2016). Furthermore, GIS provides the opportunity to integrate geographic data across different sectors and simulate events, providing a useful tool for flood risk reduction and sustainable development (Kuznetsova *et al.*, 2018). In the United Kingdom, for example, the Geospatial Commission has been created to provide geospatial integration between departments and agencies. One of the remits of the Commission is to work with key stakeholders to deliver a national land-use framework, working with the Food, Farming and Countryside Commission, DEFRA, Ministry of Housing, Communities and Local Governments, Department for Business, Energy & Industrial Strategy and the devolved administrations. The framework could provide a basis for a better-integrated and long-term strategy for land-use, as currently there is no single national dataset that tracks land-use change, and are held across multiple organisations that are difficult to bring together (Geospatial Commission, 2020). The processes of deriving a national land-use framework may be applied to spatial planning and flood risk, and demonstrate a possible path for integration between agencies, and a method to break the SDP. Yet, whilst GIS enables an understanding of complex phenomena, it cannot replace true institutional integration and the benefit of a shared perspective.

2.3.2.2 Institutional Strategy

Technology has its limits, and GIS strategies would still be bound by politics and man-made boundaries. For example, in the UK a lack of formalised municipal governance outside of the Greater London Authority (GLA) and the Metro city-regions makes it difficult to consider broader strategic growth beyond already willing partners. Therefore, in the longer term Peters (2019) offers that municipal governments can adopt approaches that can consider areas as a whole, instead of individual local authorities, whilst still providing a local enough resolution than regional authorities (RPBs), and so can still direct growth to the most sustainable places. Peters (2019) continues with a case study of the GLA, stating that it is '*abundantly clear that spatial planning at a city-wide level is absolutely fundamental to the delivery of good growth'* and that without the London-wide view that current metropolitan governance there provides, it would be impossible for London to grow sustainably. The author argues that spatial planning needs to learn from previous iterations to address neglected current issues, and future challenges and priorities, as effectively as possible. Therefore, as Riddell (2019) suggests, future spatial planning agencies should take a 'boundary-blind' approach as '*looking at a map without local authority boundaries changes the view, exposing new opportunities and, consequently, new potential solutions'*. Local community level planning is failing due to authorities' reluctance to give up decision-making, thus without an overarching authority to take wider scale decisions, it can significantly delay the time needed to prepare and implement plans if all authorities are not aligned in their views (Riddell, 2019). Coastal urban areas should be viewed as integrated systems, rather than a series of separate issue and vulnerabilities should be addressed without the constraints of administrative boundaries, by a collective authority. It must have the resolution to resolve issues across a coastal zone, yet larger than

local authorities, they should be given the scope to address municipal issues. Integrated spatial planning should form the foundation of the authorities, being directed, not guided, by coastal risk management, and new scientific advances. The new authorities are needed to ensure ICZM and SMP has the power to control planning and development, and will create a presence within coastal communities, reminding residents of risk, and decreasing vulnerability. The incorporation of spatial planning and flood risk as one composite process will break the SDP and ensure 'good growth', that is sustainable, accountable, and backed by legislation.

2.4.3 Constructing a Framework

Conceptual frameworks allow for complex issues to be mapped easily, facilitating the understanding of emergent phenomena. From this systems perspective, problems relating to real-world or hypothetical processes can be visualised and resolved, bringing together information in a logical manner. The Source-Pathway-Receptor model (SPR), for the description of coastal flood risk, is a popular concept, envisaged by Holdgate (1979). The framework has its origins in hydro- and geochemistry to describe the flow of environmental pollutants from source to receptor, via pathways. Subsequently, it was adopted for the mapping of coastal flooding by the Environment Agency (HR Wallingford, 2002), whilst suffixing the framework with a consequence element to capture the full spread of impacts. The framework also allows for specific descriptions of the state of coastal flood defence pathways (Evans *et al.*, 2004).

2.4.3.1 Linear SPR/C

Holdgate (1979) was instrumental in the development of an integrated framework, considering all aspects: not just the origins and the sinks, but the linkages in between. The author states that 'the concept of a pathway is fundamental in considering pollution', before continuing that 'within the environment, pollutants generally follow diverging pathways as they spread and are diluted. The rate of dispersion, and the distance a substance travels depends on its properties and those of the medium to which it is discharged'. Substituting a coastal flood for the pollutant, it is easy to see how SPR/C has been applied to coastal flood risk, mapping how a coastal flood may propagate through a coastal settlement.

The Source-Pathway-Receptor-Consequence model is a commonly adopted conceptual tool to represent a process that leads to a particular consequence. Sayers *et al.* (2003) offer the example that for a risk to arise there must be a source, or an 'initiator event' such as high rainfall, a receptor, such as cliff-top properties, and a pathway linking the source and the receptor, such as flood routes or a landslide. This process is depicted in **Figure 8**. However, a hazard does not always lead to a harmful outcome and so not all hazards are sources, but it does mean that there is a possibility of the hazard becoming a source (Sayers *et al.* 2003). Furthermore, there are likely to be multiple sources, pathways, and receptors forming a web of processes.

A strength of the SPR/C framework is its wide ranging applicability; it can be used on a variety of spatial and temporal scales, with the range of detail included varying as necessary. Monbaliu *et al.* (2014) used the SPR/C framework to provide an overview of estuarine case studies in western Europe: the Gironde estuary, France; the Dendermonde region in the Scheldt estuary, Belgium; and in the Elbe estuary in Hamburg, Germany. The framework cut out the noise created by differences in culture, hydrology, education, stakeholder involvement and provided a clear overview of flood events. SPR/C is transparent and easy to understand, hiding the complex statistics and analyses that determine the relationships, behind graphics so that the reader does not need to be a flood risk expert to understand the dynamics of the system.

However, flood risk conceptualisation requires data and inputs from different elements that are often spatially distributed across a wide area. Streamlining these processes into a linear one-dimensional representation may be inadequate for large and complex systems. After all, it would be impractical to try to fit cyclical phenomena, such as the SDP into a one-way, linear framework. Therefore, SPR/C has been extended into a two-dimensional model to provide a more comprehensive picture of flood systems

and constituent elements. 2-Dimensional SPR/C provides better flexibility, and can display multiple scales simultaneously, or model numerous flood sources and pathways (Monbaliu *et al.*, 2014).

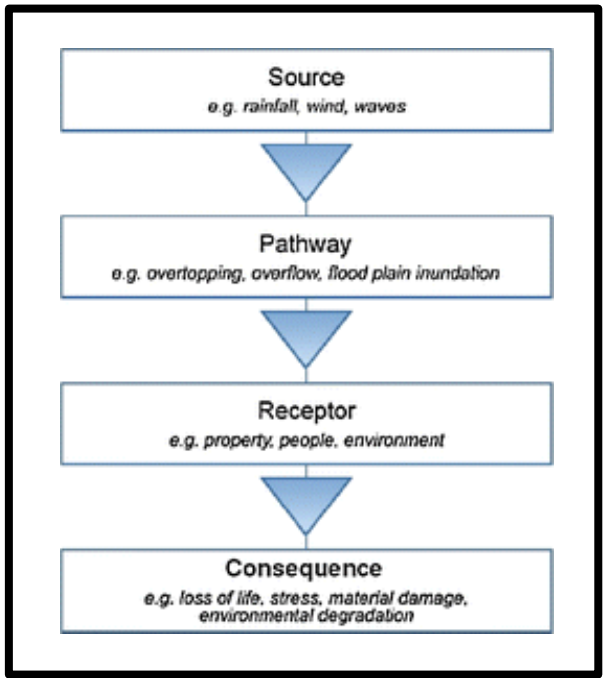


Figure 8 SPR/C conceptual framework (Sayers *et al.*, 2003).

2.4.3.2 Two-Dimensional SPR/C

The traditional linear SPR/C approach is a well-understood and a widely used approach in coastal flood risk analysis, and has been used in several flood risk assessments since Evans *et al.* (2004), promoted by the Foresight Future Flooding project in the UK (Bernard *et al.*, 2004). However, this one-dimensional consecutive framework may not capture all of the elements in cyclical emergent phenomena hence the development of two-dimensional SPR/C. Narayan *et al.* (2012) first developed the framework in an effort to combine flood risk processes with ecological health, however, the authors also suggest that the framework may also be used for the integration of coastal flood risk with coastal erosion. The conceptual framework provides a descriptive yet flexible platform to integrate coupled processes, such as hydrological and societal. The framework forces a systems approach to coastal flooding being built iteratively from the aggregation of linear SPR/C models, highlighting spatial connectivity and interlinks between system elements.

Monbaliu *et al.* (2014) suggests that the conceptualisations can be constructed manually using Microsoft Publisher, but also automated in GIS. An example of a basic model can be seen in **Figure 9**. The conceptual diagram constructed by the authors was based on the exposure of floodplain elements, and the items were spatially distributed according to real-world distance from the source. Elements that were one or two items away from the source were deemed to be exposed. The choice of the arbitrary exposure limit was based on the reasoning that in most coastal settlements, the first element to be exposed to the source would be the coastal flood defence.

The construction of the conceptual model is flexible in terms of data required and how the elements are represented, although it is suggested that a degree of spatial representation be kept so that links are clear and explicit to readers (Narayan *et al.*, 2012). GIS can also be integrated into the development of the conceptualisation, evidenced by **Figure 10**. Furthermore, Ran and Nedovic-Budic (2016) propose that GIS can support the conceptual integration between flood risk and societal change. The framework can capitalise on demonstrating land-use, spatial distributions, and key linkages. The authors suggest that the use of GIS in a new conceptual framework can help societies to prepare for flood disasters, evaluate development scenarios, and combine urban flood management with urban planning.

A systematic representation of the conceptual model created using GIS (**Figure 10**), is presented as **Figure 11**. The graphic facilitates an immediate recognition of the spatial relationships between datasets and demonstrates how the framework can provide an effective platform for integrating diverse information. In the case of **Figure 11**, the 2D SPR/C diagram combines flood extent information with the vulnerability of a vegetation community. Narayan *et al.* (2012) report that the framework helps to structure and streamline the inclusion of alternative characteristics with flood models and capture essential and relevant information for flood risk assessments. The framework captures dynamics that would not be possible in a linear one-dimensional conceptualisation. Creating one conceptualisation capturing all aspects, instead of a chain of linear processes, allows the conceptual model to reflect the entire dynamics of the system. Additionally, as all of the information is in one location it can be updated quickly to reflect changes in the relationship within the coastal flood system, such as a change in government policy towards FRM. Hence, the conceptual model must capture all aspects, and relationships defined from the data and analyses.

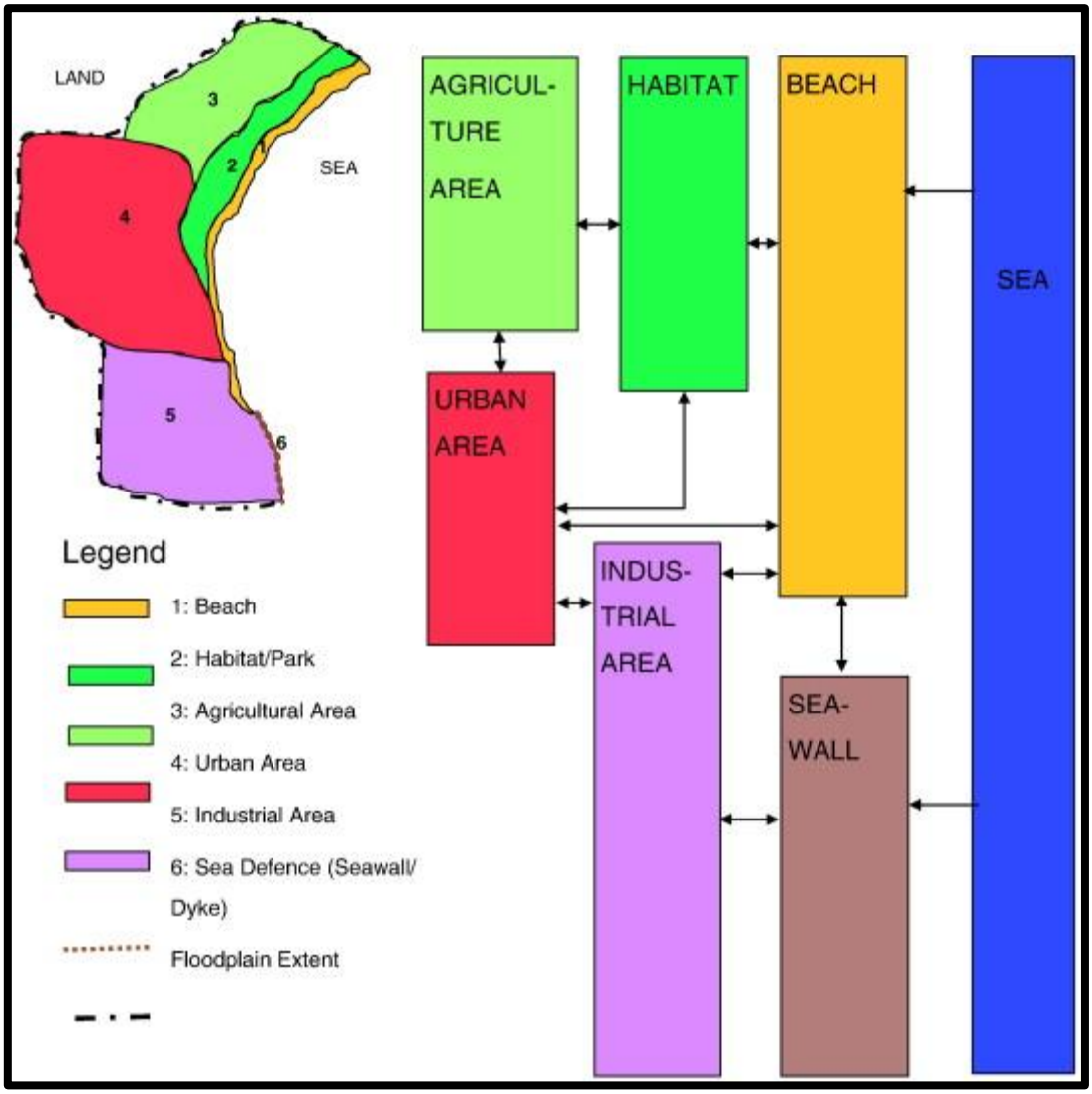


Figure 9 Example of a 2D SPR/C systems conceptualisation of a coastal settlement (Narayan *et al.*, 2014).

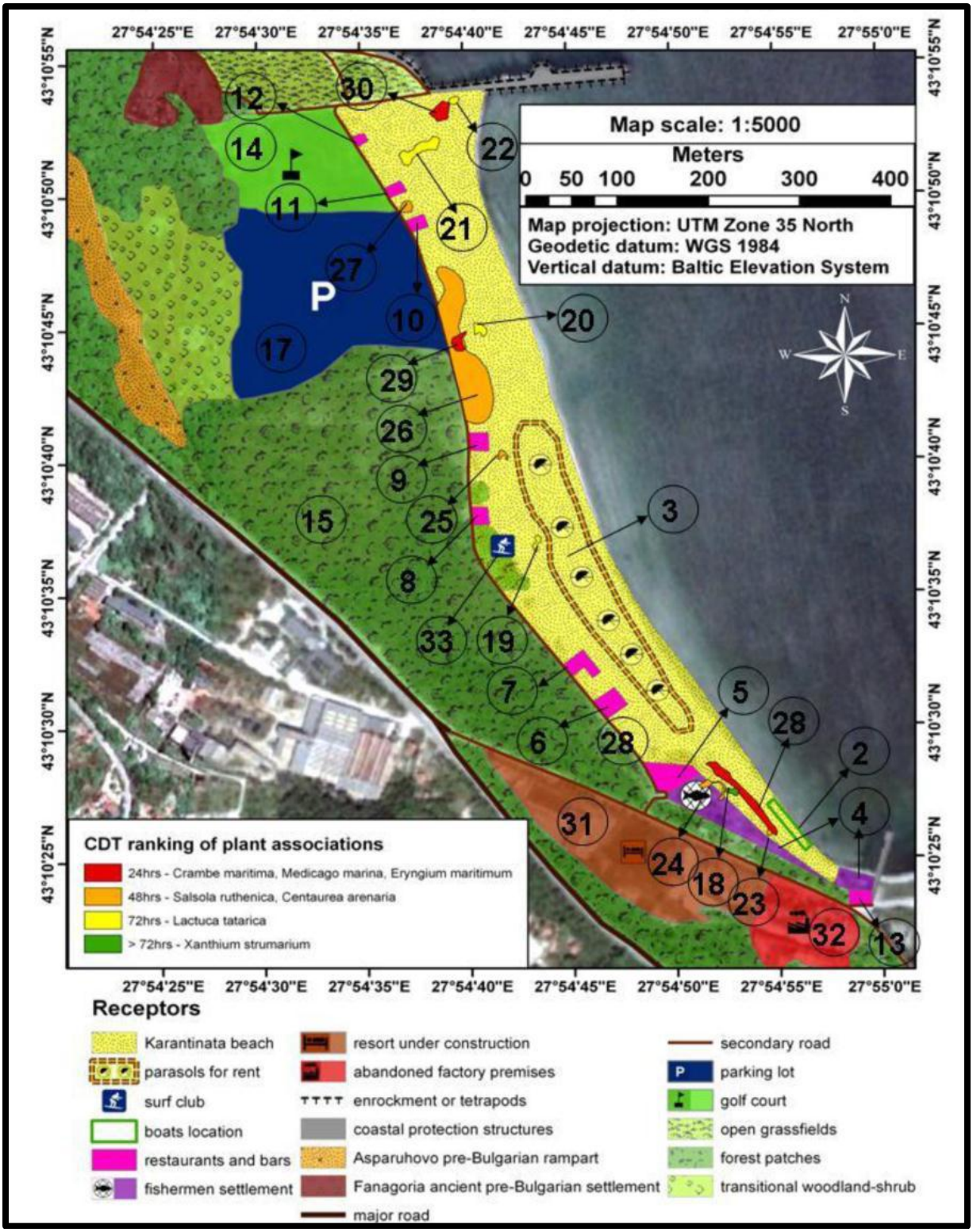


Figure 10 2D SPR/C conceptualisation using GIS for Karantinata Beach, Bulgaria for a 1% AEP flood (Narayan *et al.*, 2012).

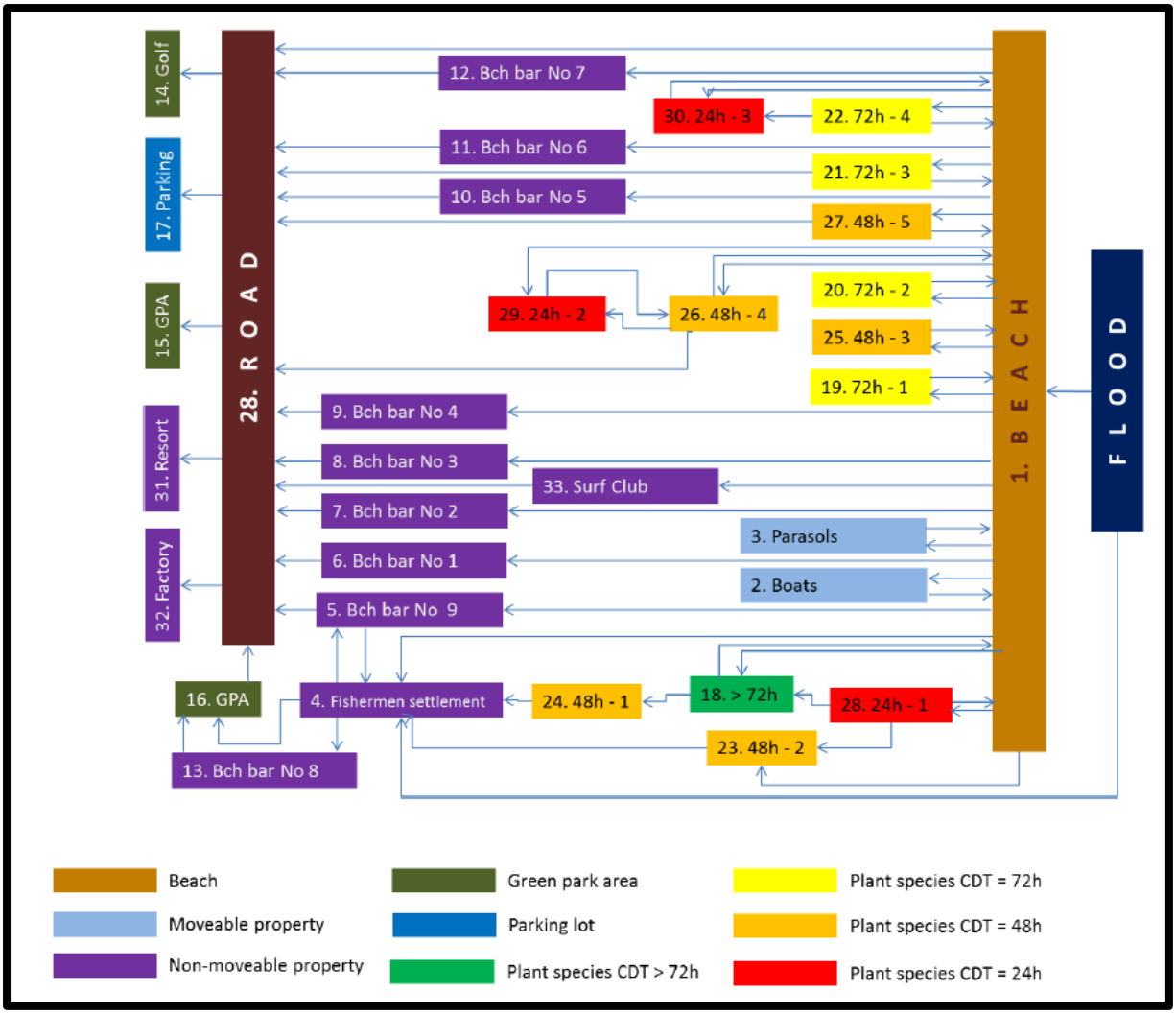


Figure 11 2D SPR/C systematic conceptualisation for Karantinata Beach, Bulgaria in a 1-in-100-year flood (Narayan *et al.*, 2012).

2.5 Concluding Remarks

The climate is changing and sea levels globally are rising as a result. Meanwhile, the human population has dramatically risen, and with decreasing availability of land, there is an increasing pressure on being placed on a dwindling space: the coastal zone. Populations are drawn to the coastal zone for the economic, recreational, and environmental opportunities it provides. Yet, current levels of flood risk management are insufficient, and new approaches are required to resolve the issues presented by an increasingly changing world.

Some concepts of socio-hydrology have already been incorporated into national policy: Integrated Coastal Zone Management provides a base to work towards a coastal zone that integrates both, flood risk management and spatial planning. Using the UK as a case study, aside from limited case studies, success has been limited as difficulties remain in coordinating budgeting, housing development, and environmental strategy between local authorities, failing the 2011 Localism Act, leaving the full potential of ICZM to be unattainable. For a truly integrated coastal zone, power must be given to a new body, ignoring man-made boundaries and operating within geographically and hydrologically defined regions. At the level of the coastal zone, the incorporation of flood risk and spatial planning can truly occur; it is at this level that the processes of socio-hydrology become apparent, and can provide a scientific framework to build legislation and increase public awareness. Integrated spatial planning can reduce exposure to a hazard when correctly applied, and the new bodies will need to be democratically

accountable, creating a focal point for risk communication and public involvement, reducing vulnerability, opposed to the piecemeal approach applied currently. With an aware and involved public, and a broader scope for 'good growth', only then can the SDP be broken, and a more sustainable coastal zone be achieved.

Developments within practice and policy can only occur with a strong scientific foundation. Definitions of risk remain haphazard, and literature with regard to the SDP in a coastal context is minimal. Risk is a complicated concept, however, with many authors describing it using various definitions. Most common within the literature, coastal flood risk was chosen to be defined as hazard, an event that has an adverse impact on a community, whether that be loss of life or earnings, or damage to infrastructure and ecosystems; exposure, the elements of infrastructure that are needed for a coastal society to function that may affect, or be affected by, an inundation event; and vulnerability, the characteristics of a community that increases its susceptibility to a hazard.

Ultimately, literature with regard to the SDP in coastal flood risk management is limited and needs to be expanded and made consistent. Numerous terms have been used for the same process: '*levee effect*', '*safety dilemma*', and the '*safe development paradox'*. To ensure successful integration at the scientific-practice-policy nexus, and reduce confusion, one term must be used within the literature. Perhaps, overlaps of this field with several others add to the confusion, with knowledge from engineering, risk management, hydrology, and sociology being combined. Yet there is limited crossover between these fields, hence 'socio-hydrology' by Sivapalan *et al.*, an attempt to comprehend interactions between society and water, and in this context describes literature within the overlap between flood risk management and spatial planning. In practice, however, literature is unbalanced, with greater research within the scope of rivers. However, some lessons from fluvial literature can be applied to coastal flood risk management, and indeed they should; it provides a solid foundation for growth in coastal science and should not be disregarded.

Science guides policy, which guides practice, therefore coastal flood risk management must not be left with 20th century ideals which translate into 20th century practice. Future researchers must build on these data, incorporate social elements into coastal hydrology, and break the SDP.

3.0 Data and Methodology

An assessment of the unintended consequences of SCFP present a cross-cutting issue, and requiring multidisciplinary investigation, including sociology, environmental and civil engineering, GIS and geography, using three case studies across the UK, each with different social, governance, and economic environments (**Table 2**).

Table 2 Case studies selected for this project.

Built Environment	Local Governance	Location
High Density	Metropolitan	Portsmouth
Low Density	Metropolitan	Southport
Low Density	Provincial	Weston-super-Mare

A broad collection of case studies, across different technical and political environments helps to identify potential or actual occurrences and developments of the unintended effects of SCFP and find common patterns and factors that produce these effects (Di Baldassarre *et al.*, 2018). Common patterns and factors reflecting these emergent phenomena were conceptualised in a conceptual model which provides a general framework of how these processes interact and affect risk calculation. Emerging and current methods used within prominent papers in socio-hydrology, modelling, statistical and geospatial analysis, and conceptual frameworks were evaluated for suitability. The most applicable methods were then used in order to complete the objectives and resolve the research questions. The flowchart below, **Figure 12**, summarises the objectives, dataflow and assessment approaches implemented. An overview of how each objective will be achieved is provided below also, **Table 3**.

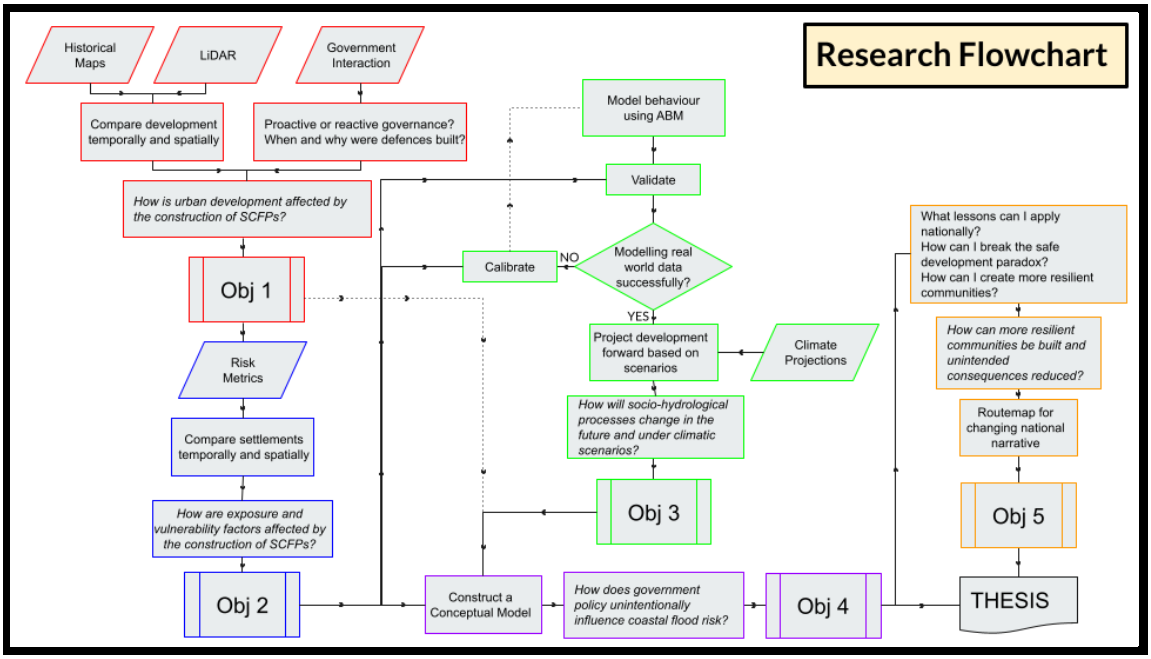


Figure 12 A flowchart showing the research objectives, dataflow and associated assessment methods and protocols implemented.

Table 3 An overview of the methods that will be used to achieve each Objective.

Objective		Method
1	*Complete a comparative analysis of coastal settlement development following defence construction or upgrading*	Geospatial Analysis
2	*Quantify changes and drivers in coastal flood risk temporally and spatially arising from defence construction*	Geospatial Analysis
3	*Develop and validate an agent-based model to simulate coastal socio-hydrological interactions, and project forwards based on behavioural scenarios and climate models*	ABM
4	*Discover the impacts and consequences of defence construction and government intervention on coastal flood risk*	2D SPR/C
5	*Identify methods of achieving desirable flood risk outcomes and enable sustainable planning to create resilient communities*	Literature Review

3.1 Case Study Selection Process

In April 2018, the UK Government established the Geospatial Commission to ensure that the nation was able to capitalise on the opportunities presented by emerging industries that use geospatial data and technologies. Geospatial data describes the location of a data element and arises in many industries: transports, oil and gas, water and electricity, communications, crime management, disaster planning, military, delivery services, wildlife conservation etc. (Jozefowicz *et al.*, 2020). Whilst historically geospatial data was often associated with maps, the technology has evolved into GIS, remote sensing, navigation systems, earth observation, and better levels of simulation and modelling, to name a few (Gray and Laurence, 2019). Geospatial data can facilitate analysis of comparative or historical changes in an urban environment, and will provide an essential component of analysis.

Differential analysis, intrinsically, has a time dimension that can be exploited to compare geospatial data to show changes in local SCFPs. Therefore, this type of longitudinal analysis can show changes in urban development, both, before and after defences. Changes in urban development, however, must be considered in tandem with local, national, and global economics. Utilising a case study approach, widely used in geography and engineering to consider all elements of the local system, can work towards unpicking whether the local FRM strategy had an impact on urban layout, especially in those study sites where this was not precedented nor encouraged. Case studies allow for longitudinal study, whilst also providing a clear and easy way to compare between study sites, facilitating cross-sectional comparative analysis. Furthermore, they are a useful way of reviewing real-world information and data. Our theoretical understanding of structural FRM must be incomplete for these emergent coupled human-water feedbacks to occur, and be *unintended*. Therefore, operating a bottom-up approach by deriving theory from real-world data provided by case studies can produce a generalised model, one that encapsulates these emergent unintended consequences across case studies parsimoniously.

In addition, the case study approach can be further elevated by not only comparing between study sites, but adjacent settlements across the same timescale: regional and subnational economics and processes are just as important as global to study sites. Therefore, cross-sectional comparative differential analysis and case study comparisons were conducted that consisted of two levels, secondary (**Figure 13**) and primary (**Figure 14**). Secondary comparison compares regional settlements of similar population and location where the local coastal flood defence had not been C/U during this period. This level compares urban growth across the same timescale, reviewing if it was a regional housing bubble for example, or whether it may have been linked to the defence. Primary comparison compares between study sites and

observes if these effects have been identified in all, and significantly increases the likelihood of causality, and whether the issue is widespread across multiple sites.

For example, if there has been demonstrable increase in growth adjacent to a structural flood defence after improvements have been made to that defence, that could suggest a link between the two, but it may be a simple correlation. If this same process has not been observed in a neighbouring coastal settlement (of similar population) across the same timeframe, then this would suggest some causality. If this same process repeats across case studies, then it would definitely imply causality. The significance of this link was tested using inferential statistics.

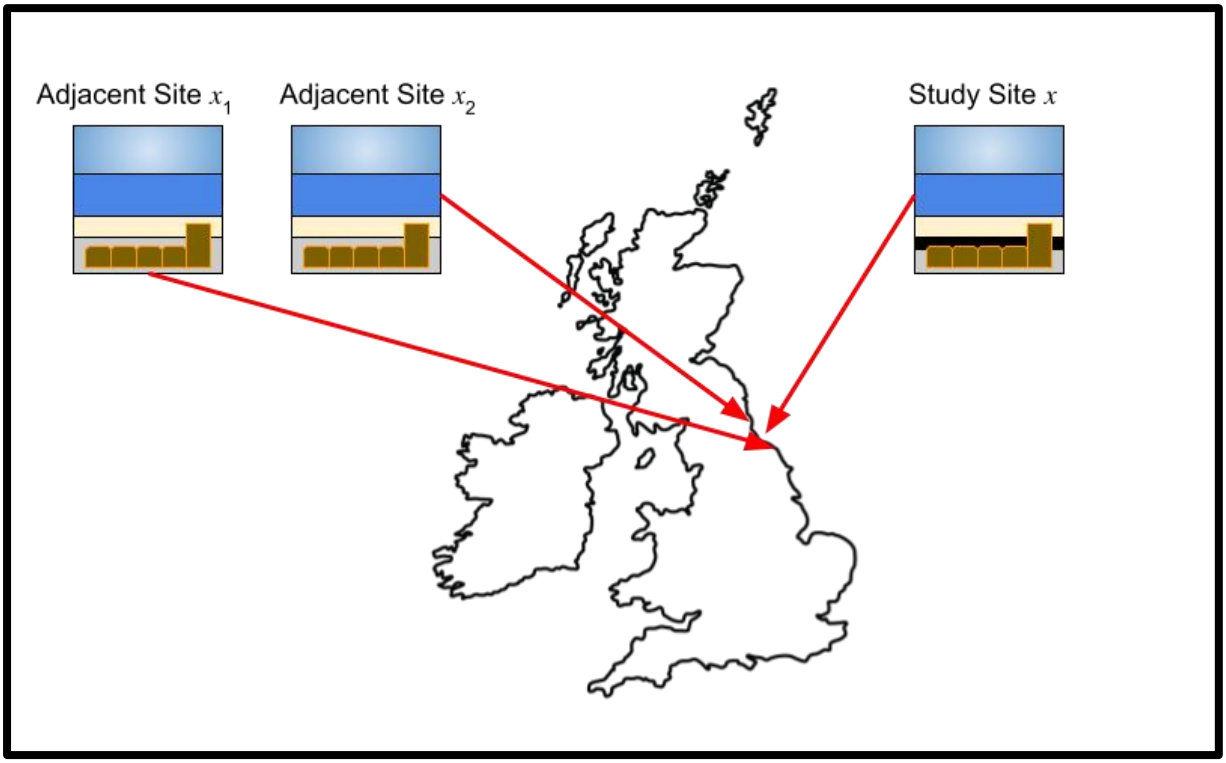


Figure 13 Secondary comparison between a study site (Study Site x) and its adjacent settlements that have no had coastal flood improvements over the timeframe.

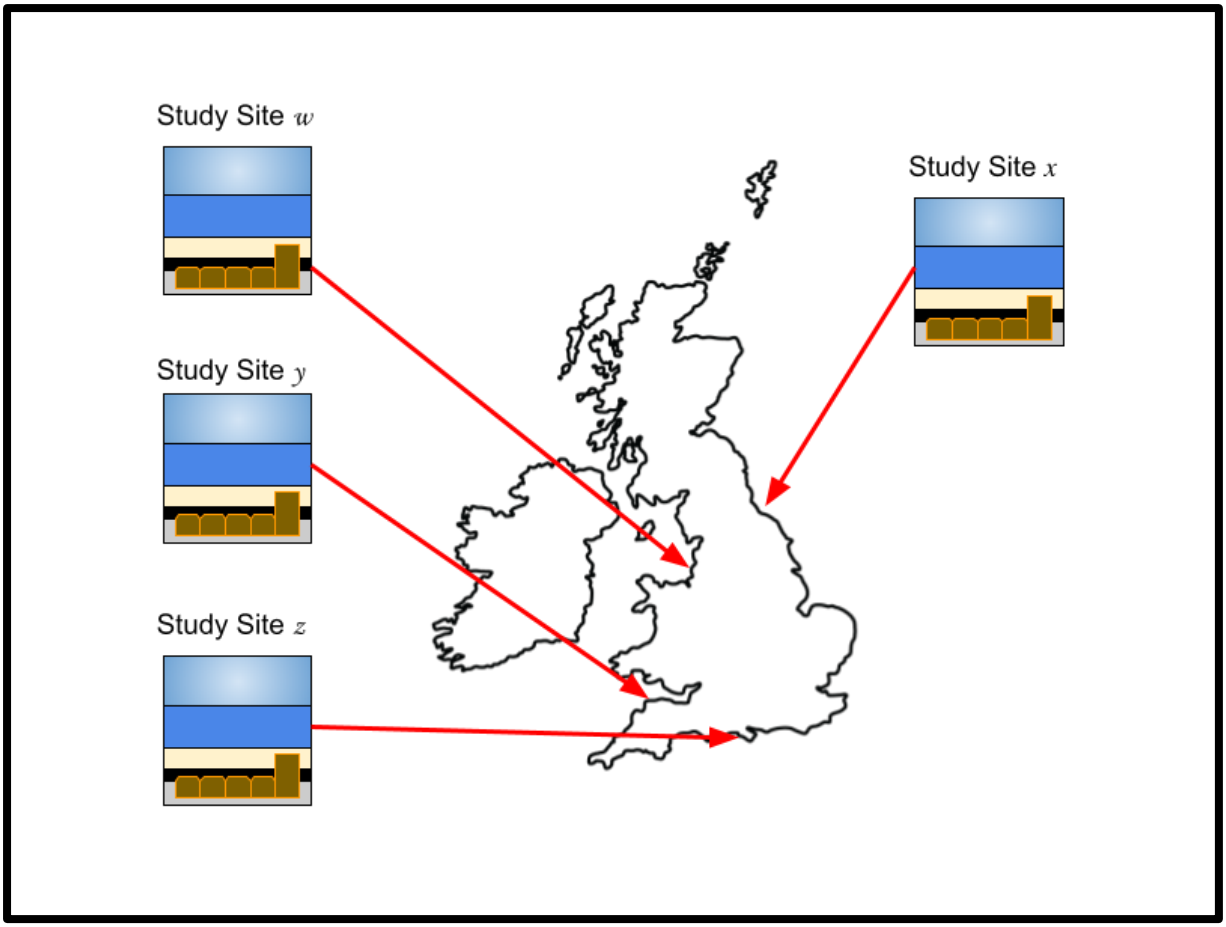


Figure 14 Primary comparison between the study sites.

3.1.1 Geographic and FRM Strategy Filtering

The availability of data is a necessary element of site selection for primary comparison; Rumson *et al.* (2020) selected their study site based on data availability, and the ubiquitous nature of UK geospatial data and its geography as an island nation, allows it to be a prime location for spatial analysis. Whereas Percival and Teeuw (2019) selected their site (Portsmouth) based on its coastal location and relative exposure, conversely, Vries *et al.* (2011) chose their site based on the presence of FRM challenges, and the level of social, economic, and ecological vulnerability to climate change.

Ultimately, a chosen settlement must have suitable geography (i.e. located on the coast) and must have had a SCFP scheme implemented since at least 1996, the earliest year with available Digital Surface Model (DSM) data, and also have a plan to increase the strength of SCFP in the long-term epoch of its Shoreline Management Plan (SMP).

Towns and cities in the UK were therefore filtered, as part of the first round (**Figure 15**), by the following key criteria:

- Location: Is the settlement on the coast? (as in Percival and Teeuw, 2019)
- Recent SCFP: Has a SCFP been constructed or majorly upgraded since 1996? (as in Vries *et al.*, 2011)
- Future SCFP: Is there any intention to hold the line and structurally upgrade the SCFP in the future? (as in Vries *et al.*, 2011)

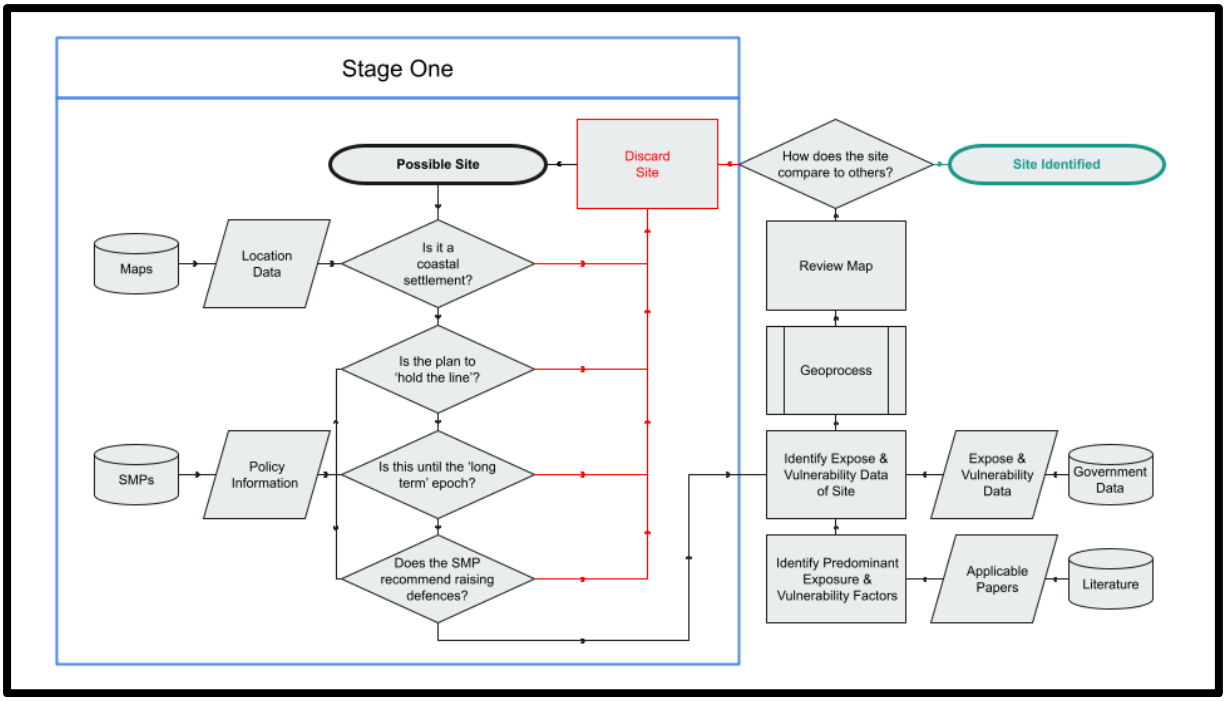


Figure 15 The process of site selection, with the first stage sectioned.

3.1.2 Exposure and Vulnerability Filtering

From the literature review it is evident that the *HEV* (hazard, exposure, and vulnerability) definition of coastal flood risk is predominant. Therefore, when determining a site for study it should experience a function of these elements. Hazard refers to an event that may have an adverse impact on a community (Percival and Teeuw, 2019). For the process of the site selection, government flood risk geospatial data (e.g., via the DEFRA data services platform) was used to identify the extent of a flooded area and evaluated using GIS software. Both, Flood Zone 2 (FZ2) and Flood Zone 3 (FZ3) data, which cover the maximum flooding extent from rivers or the sea with disregard to defences in place, were used. FZ2 and FZ3 have a 1 in 1000 (0.1%) or 1 in 200 (0.5%) chance of flooding each year, respectively. The use of maximum coastal flood extent, disregarding current defences provides an absolute overview of inundation ignoring socio-economics or level of government intervention, and a clear image of local coastal flood hazard consistent across study sites.

However, the Zones delineated are based on modelled data and are therefore indicative rather than specific. These data consisted of both, fluvial and coastal flood risk, and they were edited within GIS to extract the coastal data used in this study. The data were then overlaid with Census Output Areas (OAs), which were clipped to match FZ2 boundaries. These areas provide the smallest element of Census output and provide local specific data. Only OAs within the flood risk areas were studied, with the FZs used as a proxy for *hazard* (following the approach used by Rumson *et al.* 2020).

An ideal site would have a larger coastline, to ensure a wider range of areas are exposed and the data is varied. Furthermore, coastline length is a vital component of inundation modelling (Lewis *et al.*, 2011; Dhiman *et al.*, 2019). As identified in the literature review, population and housing density, shops, local government buildings, essential transportation, telecommunications, and utility assets, all render an area exposed when placed in a hazard zone. Therefore, an ideal location for study must have a greater number of these elements exposed than other candidate sites. Without a high exposure, the vulnerability elements of a population may not be truly represented. Hence, a second stage is required.

Stage two, shown in **Figure 16**, is the process of selecting the three prime sites for this study, based on the initial pool filtered in the first stage. Exposure data is gathered from Ordnance Survey maps,

identifying elements in flood hazard zones (FZs). The greater the number of exposure elements in a hazard zone, the more the population is at risk, and the stronger the capability of the site for research.

Furthermore, critical infrastructure such as police, fire, and ambulance stations, hospitals, council buildings, supermarkets, and key transport hubs were identified from online sources (constabulary websites, county councils etc.) and mapped onto the site selection database. In addition to the physical infrastructure exposure elements, population density was also added to represent the spatial distribution of the local population. Population density within each OA was extracted from the Census 2011 data. This was then georeferenced using the 'Join' tool in GIS and plotted in the form of people per hectare; only retaining the population density within FZs. These combined elements provided a good overview of candidate sites, ensuring selection of representative sites.

Therefore, the first round of filtering removed candidate sites based on inadequate geography and FRM policy, both, historic and future. Locations that satisfied these criteria were then passed to secondary analysis, an investigation of the exposure and vulnerability factors of the locations themselves:

- Coastline Length: Which sites have the largest urbanised coastline? (as in Karamouz and Zahmatkesh, 2016)
- Population Density: Which sites have the greatest population density in FZs? (as in Cai *et al*., 2018)
- Essential Services: Which sites have the greatest quantity of police, fire, medical centres, local governance centres in FZs? (as in Cutter and Derakhshan, 2018)
- Supermarkets: Which sites have the greatest quantity of supermarkets in FZs? (as in Cutter and Derakhshan, 2018)
- Transportation: Which sites have the greatest quantity of key routes in FZs? (as in Van Dongeron *et al*., 2018)

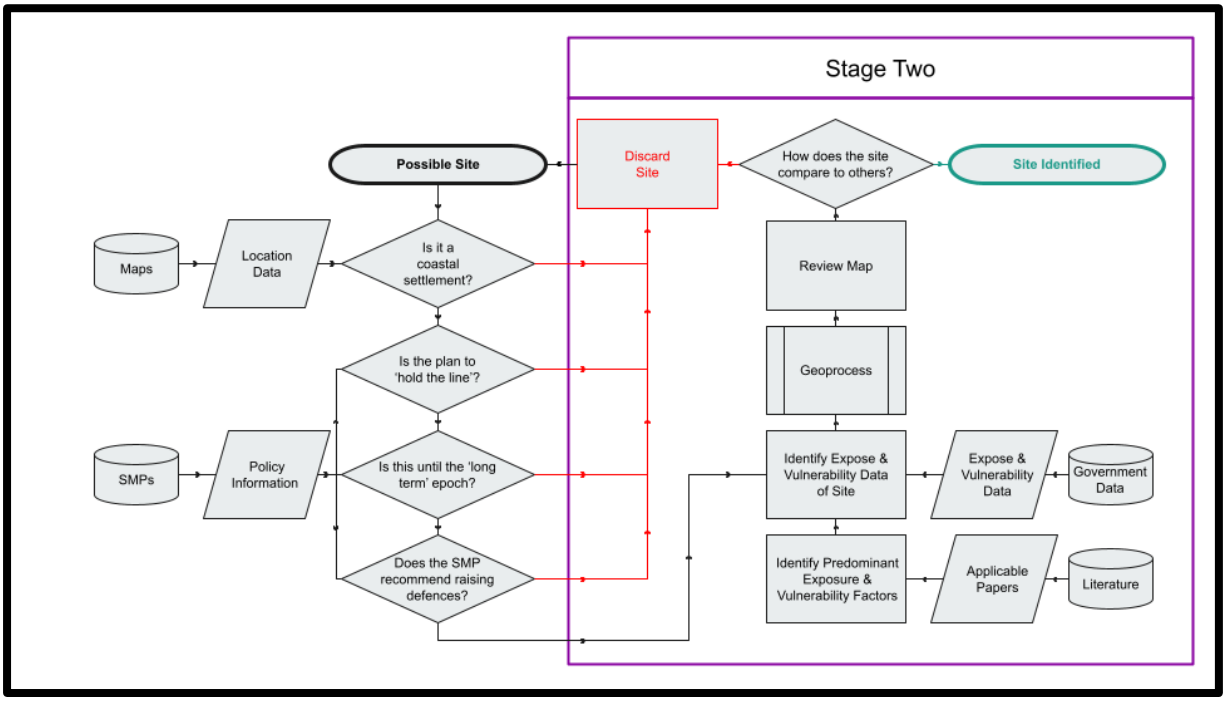


Figure 16 The process of site selection, with the second stage sectioned.

3.1.3 Study Site Elimination

After the location filtering, the three sites were selected as the primary case study sites: Southport (**Figure 17**), Weston-super-Mare (**Figure 18**), and Portsmouth (**Figure 19**). These sites have a greater density of population and essential services in the FZ. Southport has the most significant amount of exposed infrastructure out of the study sites, with a significant amount of the retail placed on the coastline. Furthermore, whilst the area has two essential services and one supermarket exposed, leaving food supply chains vulnerable (MacMahon *et al.*, 2015). Weston-super-Mare had the largest area exposed of the sites, with the flat North Somerset Levels providing a large low-level hinterland for coastal flood water to proceed into. Furthermore, all essential services are in the exposed area, causing issues in the ability of services to act in the event of a flooding emergency. Portsmouth has a high population density in the exposed area, especially towards the southern tip of Portsea Island. Towards the northeast of the island, there is heavy industry placed in the FZ, with potential risk to the local economy. Furthermore, Portsmouth is an island city and relies heavily on the Portsmouth Direct Line/ A2030 and M275/ A3 corridors for traffic in and out of the island. These access routes pass through the FZ, and are vulnerable to coastal flooding, endangering those on the heavily populated island.

Poole (**Figure 20**) has been provided as an exemplar site that was rejected by the exposure and vulnerability filtering. Whilst the location had some of the greatest population density of the settlements reviewed, only a very limited area of the city was exposed to coastal flooding. Moreover, in comparison to the other sites, Poole had the least number of essential services in the FZ, with just one police station. Whilst Southport only had one more, with two healthcare facilities, it had a greater amount of population, both, count and density, and a larger extent of trunk roads in the FZ than Poole. Similarly, Weston-super-Mare had a greater population within the FZ than Poole, and Portsmouth had the greater amount of dense population, and therefore, Poole was rejected. However, future research should consider the town, and others around the UK, in order to extend this analysis. However, three case studies were deemed to be suitable for this analysis.

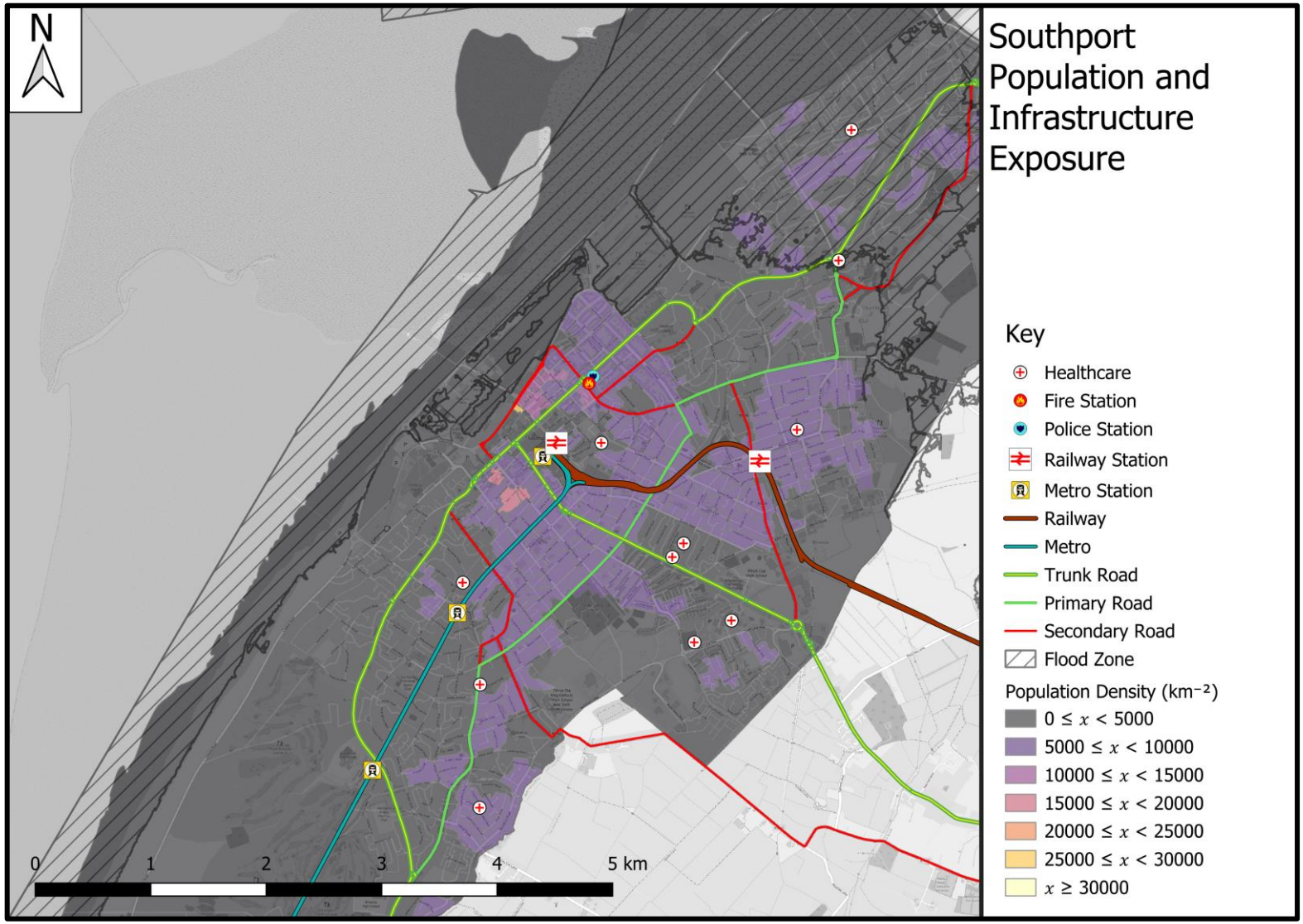


Figure 17 Map of Southport with hazard details and exposure elements plotted.

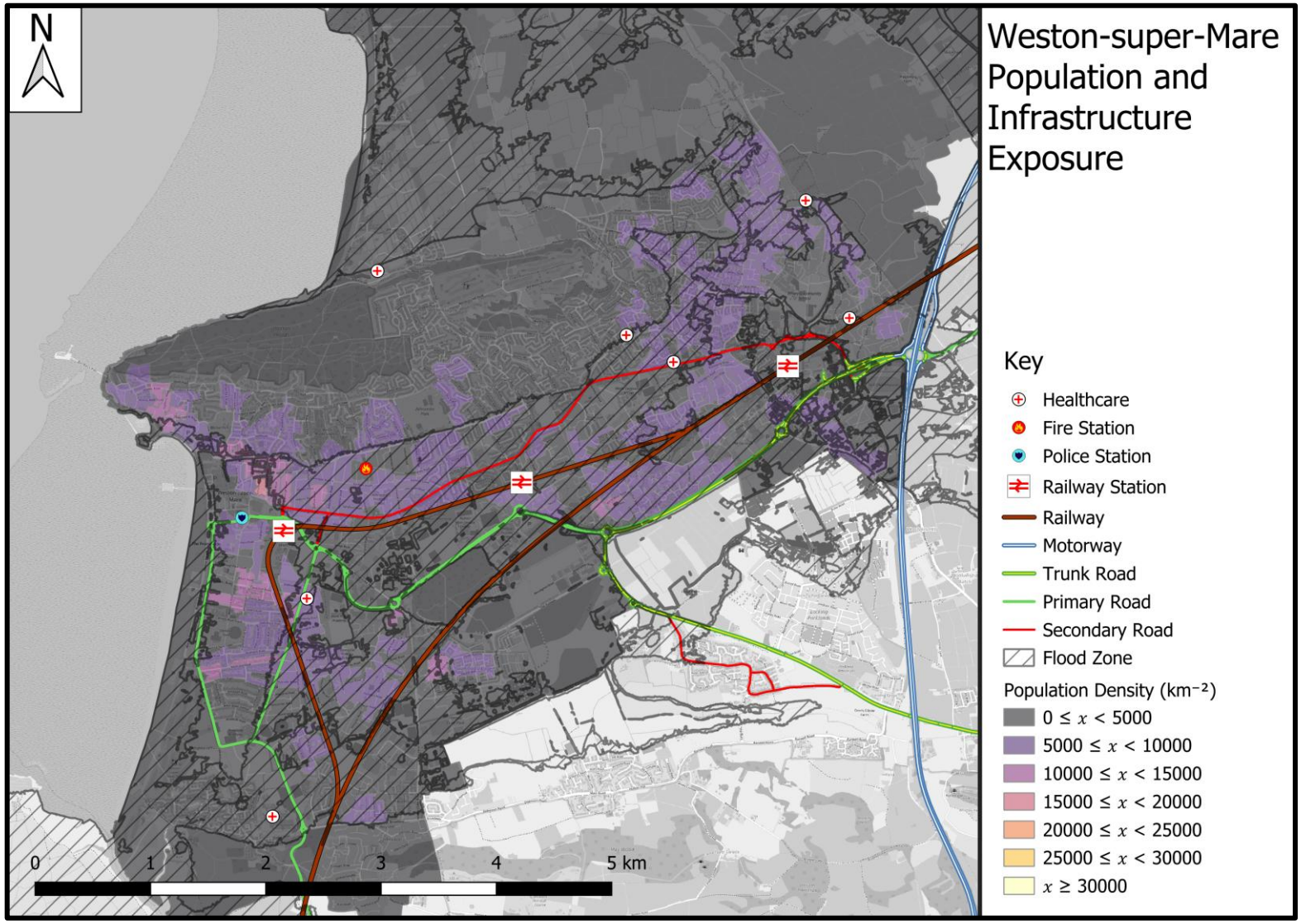


Figure 18 Map of Weston-super-Mare with hazard details and exposure elements plotted.

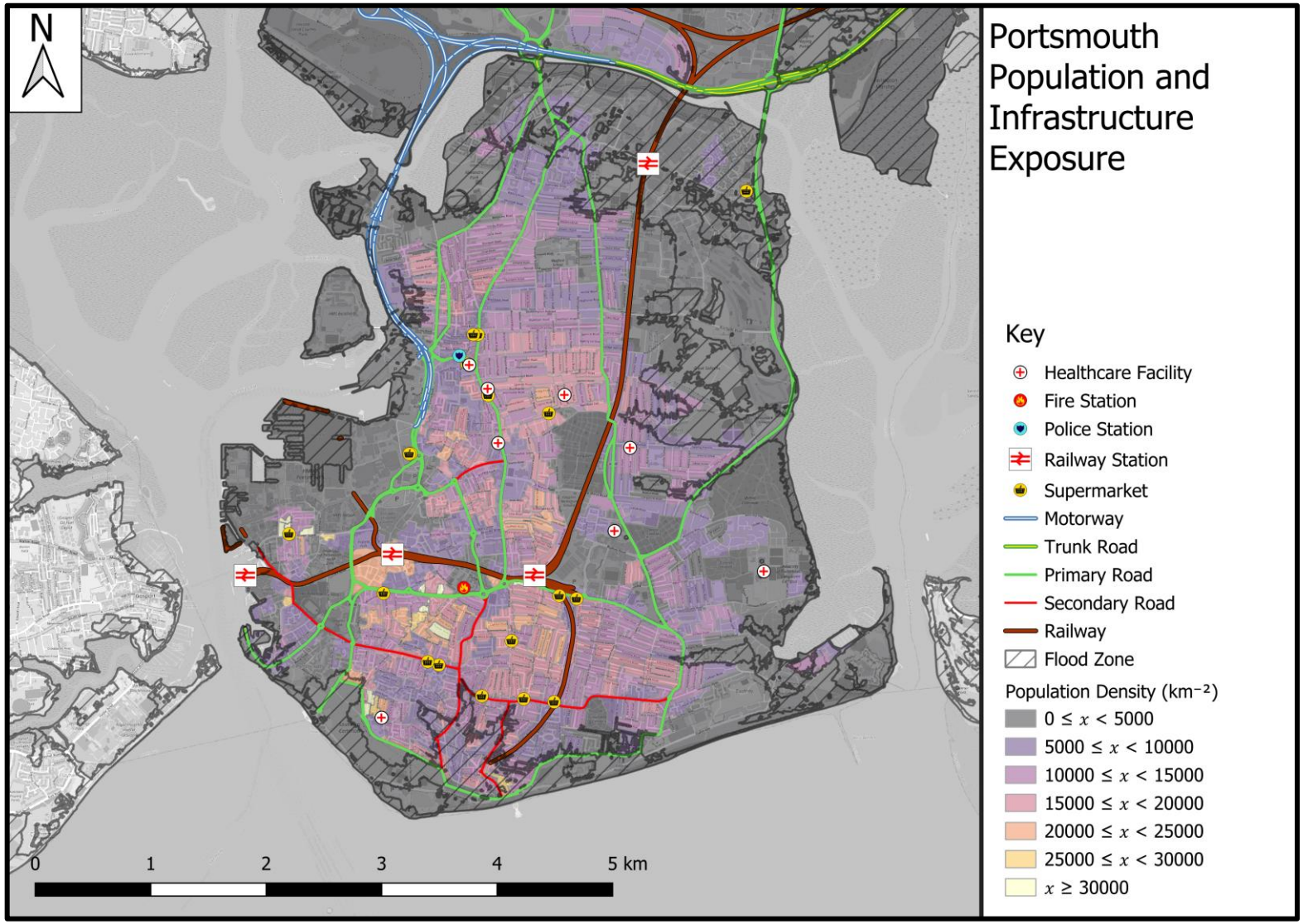


Figure 19 Map of Portsmouth with hazard details and exposure elements plotted.

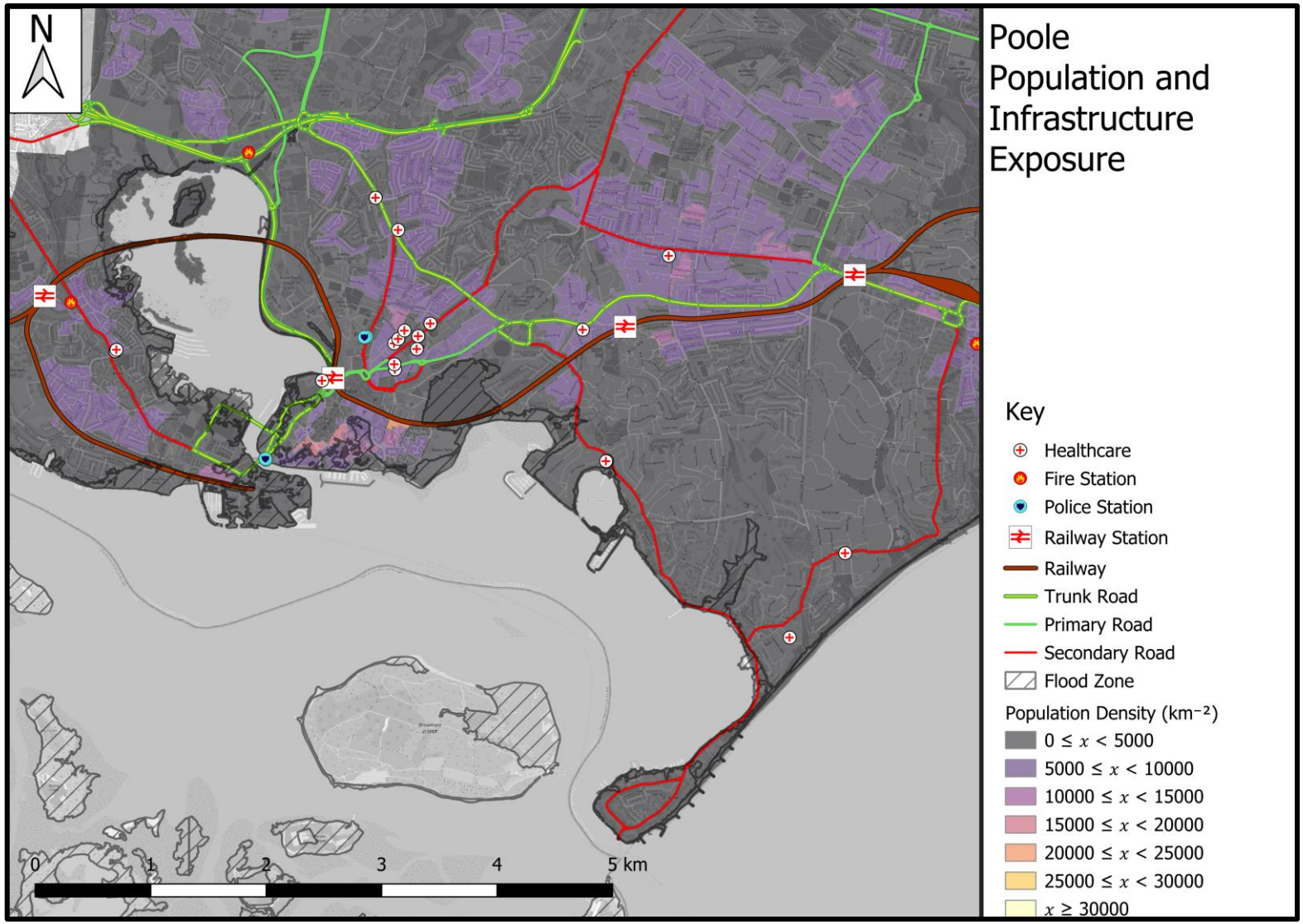


Figure 20 Map of Poole with hazard details and exposure elements plotted.

3.2 Case Study Site Description

This section explores the physical geography and local economy of three selected case study sites: Southport (Merseyside), Weston-super-Mare (Somerset), and Portsmouth (Hampshire). The information for these provide context for the further analyses by facilitating the investigation through the presentation of the locations through a geographical lens, both human and physical.

3.2.1 Case Study A ─ Southport

Construction of a new coastal flood defence, competed in 2003 (**Figure 21**). Located at (53.6531N, -3.01462E).

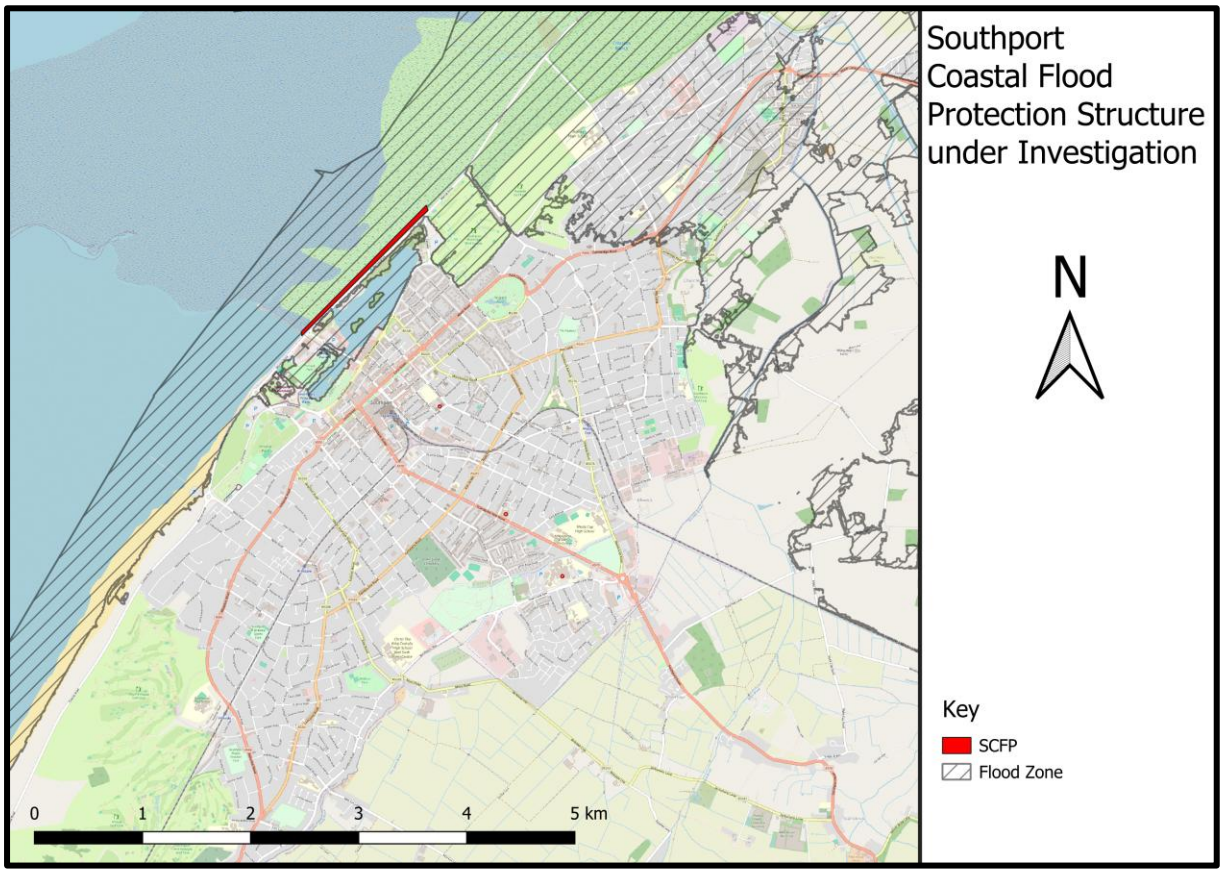


Figure 21 Map of Southport with FZ and the SCFP being investigated displayed**.**

3.2.1.1 Physical Geography

Like much of north Merseyside and south Lancashire, the town lies on a bedrock of mudstone. As a sedimentary rock, the bedrock was most likely formed as an ancient valley from the River Ribble into the lowland that is now the Irish Sea, formed during the Neogene period. Much of the town is constructed on ancient sand dunes, an area once dominated by aeolian processes since halted by human activity. However , the town centre was built on tidal flat clay and salt marsh obtained through reclamation, so this area is under severe flood risk.

At the southern end of the town, where urbanisation subsides, a dune system has formed, However, moving further north through the town, as the coastline protrudes landwards and urbanisation increases the wide sandy beaches become progressively siltier. North of the pier the foreshore has been colonised by saltmarsh and wide intertidal flats, which aid the dissipation of wave energy. Liverpool Bay has the second largest tidal range in the UK, rising up to 10m twice a day, with enough energy to power two thirds of metropolitan Liverpool (Becker *et al.*, 2017) ─ the largest after the Bristol Channel.

The beach at Southport is affected by sediment influx from offshore sources and the steady, continuous erosion of Formby Point. Longshore drift transports sediment across the beach and into the Ribble Estuary, providing an ideal medium for saltmarsh growth. The saltmarsh has been significantly affected by changes within the Ribble Estuary, including degrading, the construction of training walls, and land reclamation. Efforts have been made to limit the saltmarsh, through herbicide and the physical removal of surface sediment up to depth of 1m (Metropolitan Borough of Sefton Council, 2012). This, however, would increase the flood hazard to the town. Therefore, the town has two options: removal and treatment of marshland, yet increased tourist revenue, at the cost of increased flood risk; or leave the beach alone as a protective feature instead of an amenity, with decreased tourism.

3.2.1.2 Local Economy

Southport is a moderately large town at the northern extent of Merseyside, the Liverpool metropolitan region. Southport receives direct railway service to Manchester and Wigan and metro services from the Merseyrail Northern Line which links it directly to Liverpool city centre and south towards Liverpool John Lennon Airport. There are 3 metro stops operating on a north-south corridor, which runs through the town, providing service to the Hillside and Birkdale areas of the town. Other areas include Marshside, Crossens, Blowick, Pool Hey, Brown Edge, and Meols Cop, which has its own railway station. Due to the many connections of the town, many residents commute to large settlements, however the town still retains many features of its own independent economy.

Tourism is the greatest wealth generator in the town; the beaches, the second-longest pier in the UK, and other tourist amenities in the town provide a strong pull factor which dominates the Northwest south of the River Ribble. The town features many accommodation options, hotels, guesthouses, bed and breakfast, which also provide employment for the local population, and those in surrounding areas, albeit seasonal.

The other tertiary sector contributor, retail and services, are an important industry in Southport, complimenting the tourism economy, and providing economical continuity throughout the low-season, with many residing on reclaimed land on the seafront. The town centre features a mix of national and independent retailers, scoring middling on a Clone Town survey. Furthermore, a growing digital sector has taken root in the town, taking advantage of the rail and road connectivity the town offers to Liverpool and Manchester.

However, the town does not rely entirely on its tertiary sector, having strong secondary and primary sectors, which provide economic sustainability. Avon, a global beauty and personal care products company, has a manufacturing base in the town. As does Nidec, an electric motor company, and Eco Executive Travel, an electric and hybrid vehicle manufacturer. Traditional primary sector employment also still contributes to the local economy with many fishing vessels still operating out of Southport, selling at local markets.

3.2.2 Case Study B – Weston-super-Mare

Upgrading a coastal flood defence from 1-in-50 year SoP, to 1-in-200 (**Figure 22**). Located at (51.3477N, -2.9816E).

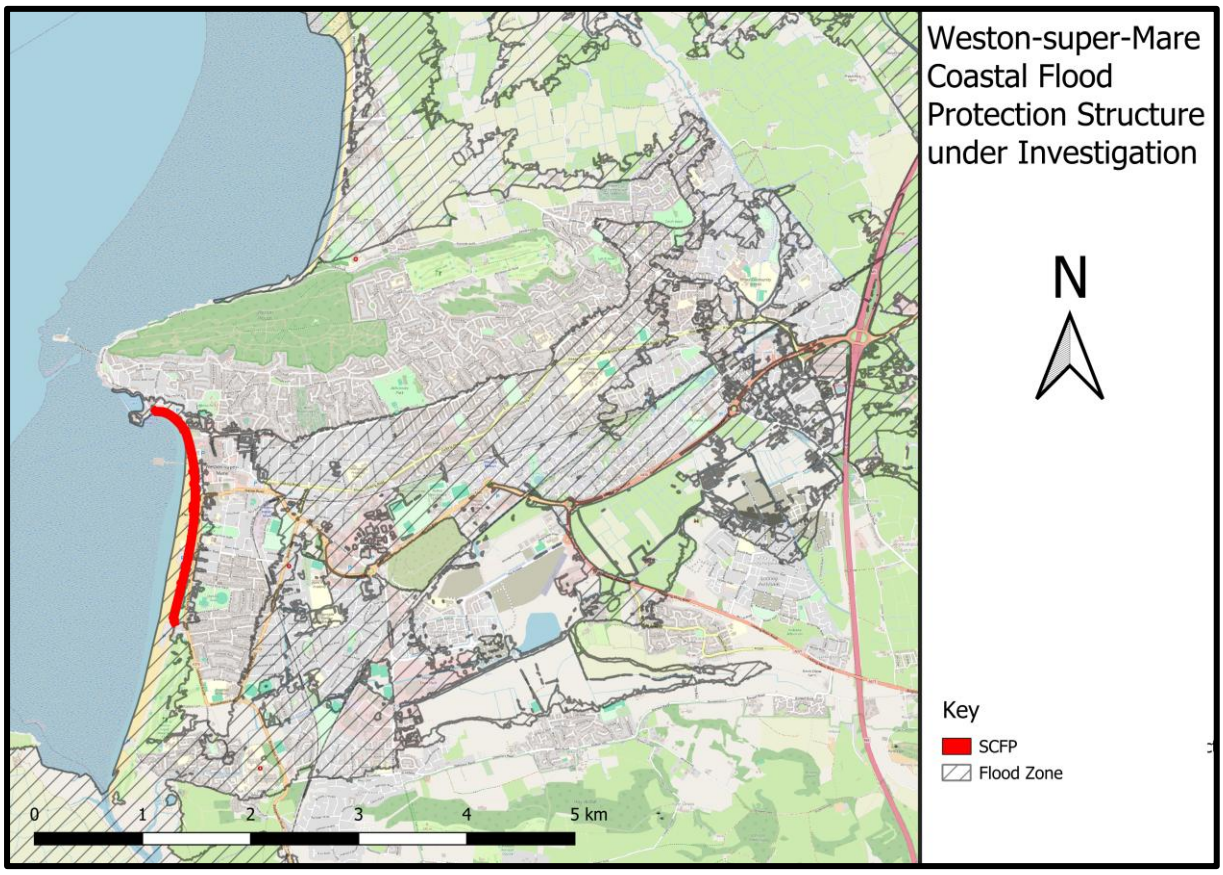


Figure 22 Map of Weston-super-Mare with FZ and the SCFP being investigated displayed**.**

3.2.2.1 Physical Geography

Weston-super-Mare is a coastal town on the Bristol Channel, on the west coast of England. The town precedes the North Somerset Levels, a coastal plain that spreads across north Somerset towards Bristol, drained to produce arable land and scarcely above sea level. To the north, the town is enclosed by Worlebury Hill standing at 109m, and to the south is Bleadon Hill at 134m tall. The primarily wealthy areas of the town lie around the base of Worlebury Hill on locations often greater than 20m higher. However, the majority of the town lies only a few metres above sea level, defended only by the sea wall and the slight inclination of the coastal sections of the town, which are between 3-4m higher than the streets behind.

Further south of the town protrudes a limestone peninsula, Brean Down, which extends 3km into the Bristol Channel. This provides Weston-super-Mare with a protected bay, Weston Bay. The peninsula traps outflowing water from the Severn Estuary, and due to the decreases in velocity, it deposits sediment. This forms the seaward section of Weston Bay, a large mudflat extending 2km, exposed at low tide due to the exceptionally large tidal range of the Bristol Channel, the second highest in the world (Natural Resources Wales, 2015). The landward section of the beach is dominated by aeolian processes, historically these would have created sand dunes, that the town has now constructed over, and so just the eastern section of the beach is sand.

As with a majority of the UK, the prevailing wind at Weston-super-Mare is between the West and the South, driven by the Atlantic winds, primarily west-southwest at the town. However, wave fetch is limited by the prominence of the southwestern peninsula, rendering it to around 40km. Furthermore,

due to the extent of the Brean Down peninsula it is likely that the impacts of wave fetch are limited, which may indicate that estuarine and tidal processes are the dominant hydrological forces on the town.

3.2.2.2 Local Economy

Over the latter half of the 20th century, Weston-super-Mare declined as a holiday destination, a trend encountered by many coastal towns as package holidays and international travel became commonplace. The construction of the M5 motorway further redeveloped the town as a satellite town of Bristol. However, in recent years tourism in the town has regrown: in 1995, 4 million visitors went to Weston-super-Mare, and in 2005 this had risen to 5.3 million. The majority of tourists are from the West Midlands and tend to either be elderly or young families. Numerous tourist amenities lie on the coastline, and provide a draw to the area, with visitors often spending money on accommodation, dining, entertainment, and other services.

As a result, the town relies heavily on the tertiary sector, and associated tourist-driven sub sectors: hospitality, food and beverage, and entertainment. The town, and hinterland of north Somerset, contains many hotels, guesthouses, and holiday parks, and a recent trend towards the development of luxury accommodation along the seafront. In addition, a growth in new visitors to the town has fuelled an increase in the number of restaurants and bars.

The entertainment subsector is also a significant contributor to the economy in Weston-super-Mare, with a range of attractions and activities catering to visitors. The town is home to a number of popular attractions, including the Grand Pier, which features amusement park rides, arcade games, and a range of other activities. Other attractions in the town include the SeaQuarium aquarium, the Weston-super-Mare Museum, and a range of cultural events and festivals throughout the year.

Despite the strong tourism industry in Weston-super-Mare, the town faces a number of challenges in maintaining and growing its economy. One of the key challenges is the seasonal nature of the tourism industry, which can lead to fluctuations in demand and employment opportunities throughout the year. Many businesses in the town rely heavily on the summer season to generate revenue, and may struggle to stay afloat during quieter periods.

Infrastructure is also a challenge for the economy in Weston-super-Mare, with some residents and businesses calling for improvements to roads, public transportation, and other essential services to better connect the town to the wider north Somerset area and Bristol. Whilst the town has seen some investment in recent years, further investment and improvements are necessary to ensure that the local economy can continue to develop and sustain.

3.2.3 Case Study C ─ Portsmouth

Multiple upgraded and new coastal flood defences around Portsea Island (**Figure 19**). As of the production of this report, NPCS Phases 4 & 5 and the Southsea Coastal Scheme have not yet been completed. Located at (50.8045N, -1.0745E).

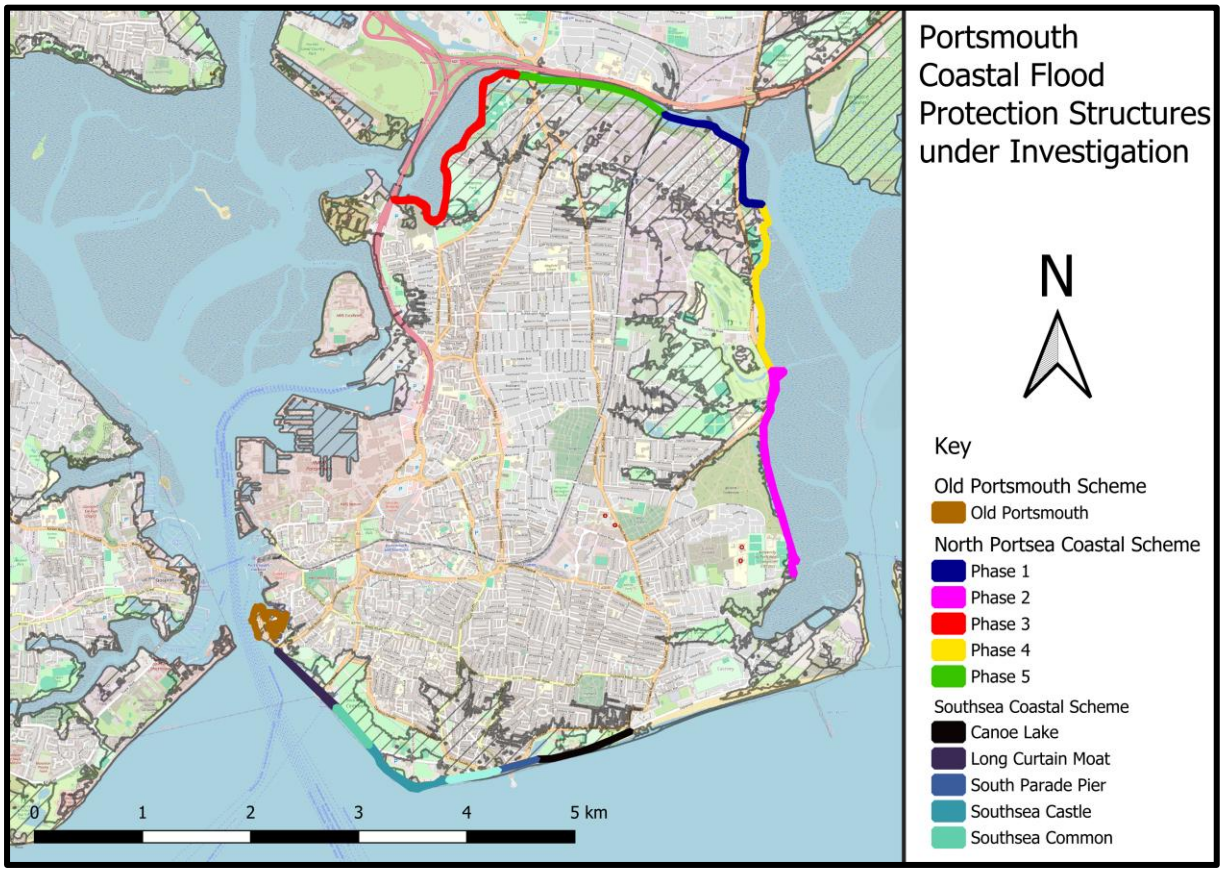


Figure 23 Map of Portsmouth with FZ and the multiple SCFP being investigated displayed.

3.2.3.1 Physical Geography

Portsmouth is a city situated on the south coast of England. The majority of the settlement is on Portsea Island, geographically isolated from the British mainland by Portbridge Creek, 10m across at its narrowest point. The waterway is liable to sedimentation and vegetation, so much so that in the mid-19th century it was possible to walk across. Therefore, essential works were carried out to widen the creek to allow for the passage of gunboats, and dams and floodgates were built at either end to maintain water levels despite the tide.

The city and island are a part of the Hampshire Basin, a low-lying area filled with sands and clays, surrounded by chalk hills. As a drainage basin, it has no single dominant river, however historically this would have been the Solent, which grew to become a strait after the last ice age rose sea levels, separating the Isle of Wight and Portsea Island from the mainland. Today, the western section of the basin drains into Poole Harbour via the Frome and Piddle, the central drains into the Solent via Southampton Water, and the eastern part by many small streams draining the Weald.

The Solent feeds into Portsbridge Creek via Portsmouth Harbour, a large natural harbour bounded by Gosport Peninsula to the west and Portsea Island to the east. The harbour has a series of natural lakes, a feature capitalised upon by the city as a natural advantage for trading and as a military base. On the other side of Portsea Island is Langstone Harbour, another large tidal inlet, bounded to the east by Hayling Island. The far north of Portsea Island and across the creek on the mainland has a bedrock of chalk, from the late Cretaceous. Chalk, due to its porous structure, is highly resistant to erosion, which

would have led to a headland around the chalk stub at the north of Portsea Island. Rising sea levels would have reduced the velocity of the River Solent, producing a lower energy area and ideal conditions for the deposition of larger particles such as sand, then silt, and eventually clay as energy decreased. This process is ongoing with the beaches at the south of the island being shingle. Others are either saltmarsh or have been constructed over.

3.2.3.2 Local Economy

Portsmouth, mostly located on Portsea Island, the third most heavily populated island in the British Isles, after Great Britain and Ireland, and the island with the highest population density in the entire archipelago. In fact, the population density of Portsmouth is so great that the city is the most densely populated, outside of London. The city is a part of the South Hampshire conurbation, in combination with Southampton, Gosport, Fareham, Havant, Eastleigh, with a combined population of over 1.5 million.

The city is a major naval base and home to the Royal Navy command. Portsmouth has a long maritime warfare history and during the British Empire it was heavily fortified to provide a safe and secure port for the fleet. Following the downfall of *Pax Britannica*, and then the rise in multi-polarity and globalisation, the historic military port land has been converted to commercial use, leading Portsmouth to become a global port and centre for shipbuilding and repair. Due to the amount of shipbuilding and military industry, many manufacturing companies reside in Portsmouth, providing shipping materials for repair, aerospace technology, and electronics. In total, the secondary sector provides employment for 20% of the local workforce.

Although, outside of the shipyards, Portsmouth's economy is mainly driven by the tertiary industry, which accounts for 70% of employment in the city. Portsmouth is a major tourist destination, with attractions such as the Mary Rose Museum, the HMS Victory, and the Spinnaker Tower. Retail also provides a pull factor for the city, counterbalancing nearby Southampton and drawing in people from across the South Hampshire conurbation and surrounding metropolitan area. Outside of retail and tourism, Portsmouth also has a large number of residents working in the financial industry, most likely as a result of the high amount of international trade passing through.

The economy of Portsmouth grew by 2.5% in 2019, falling to 0.8% in 2020. The Covid-19 pandemic weakened global trade leaving many in Portsmouth without long-term work. The wider economic effects of the pandemic on Portsmouth are not yet fully known. As a city intrinsically tied to the global market, the future for the local economy of Portsmouth relies on much wider scale factors than any other case study. Predicting global markets, especially during periods of economic uncertainty, would be difficult.

3.3 Climate and Biophysical Data

The following subsections provide context for the various climate and biophysical data used in this research, in terms of what the data is, where it came from, and how it was used.

3.3.1 Geomorphology and the Built Environment

In more recent years LiDAR has developed to provide an accurate representation of urban development without the need to digitise existing mapping. Starting in January 2017 the UK Government undertook the National LiDAR Programme, by which England was divided into 302 survey blocks, which were subsequently captured during the winter months (approximately November to April each year) up to February 2023. Surveys are published through the DEFRA Data Services Portal. LiDAR data has been provided by the Environment Agency in England and Wales since the mid-1990s, however this was with a resolution of 2m (Crutchley, 2006). Whilst this is adequate for large-scale modelling, such as for flooding, it is not as useful for analysing an urban landscape, therefore 1m resolution LiDAR was selected where possible (**Table 4**).

Table 4 Data used describing the local landscape and buildings.

Data	Use
LiDAR DSM 1m	Differential analysis, Geospatial statistics
LiDAR DSM 2m	Differential analysis, Geospatial statistics
LiDAR DTM 1m	Land morphology/topography for ABM
LiDAR DTM 2m	Land morphology/topography for ABM
OpenStreetMap	Building and infrastructure layout for ABM

Aerial photogrammetry has numerous benefits over LiDAR: it accurately portrays colours and textures, has significant cost-efficiency, and has a high horizontal accuracy (Salach *et al.*, 2018; Rogers *et al.*, 2020). However, LiDAR can penetrate through vegetation and produce DTMs, otherwise known as a 'bare earth model', and with its multiple returns can produce a DSM. It is, however, much more difficult to produce a DTM from aerial photogrammetry due to the inability of the camera sensor to penetrate through canopy (Rogers *et al.*, 2020). Although, due to the multiple returns provided by a LiDAR DSM, this is also affected by canopy vegetation. So, depending on use, aerial photogrammetry, once processed, can produce comparable DSMs to those derived from LiDAR, albeit with a lower accuracy yet at a lower cost to produce (Wallace *et al.*, 2016; Khanal *et al.*, 2020). However, as the Environment Agency has already undertaken LiDAR data collection via the National LiDAR Programme, concerns over cost-efficiency are unnecessary, and seeking higher accuracy should be the primary driving factor.

A geospatial raster, in its simplest form, is a gridded dataset composed of individual pixels associated with a specific geographic location (see **Figure 24**). These pixels can be continuous, such as those used in elevation, or categorical, land-use for example. A DEM therefore is a matrix of numbers with geographic metadata, which when aligned with other rasters of the same location, cell size, and extent can have mathematical operations performed on it. Consequently, due to the large size of the DEMs, containing thousands of observations, it can be safely assumed that the matrices follow the normal distribution and the central limit theorem applies (Zhang *et al*., 2018). Therefore, parametric inferential statistical analyses can be conducted increasing the strength of the conclusions drawn. This was termed a geostatistical analysis, and the use of which was novel in this context (**Appendix B**).

The DSM of Difference (DoD) creation procedure, estimating elevation change (as detailed in **Eq. 1**, where R1 is the oldest DSM and R2 is the most recent DSM), has been described as DSM differencing or differential analysis. Such approach is widely used in physical geography, e.g., assessing the evolution of drainage basins (Brasington *et al.*, 2003), detection and estimation of landslides (Tsutsui *et al.*, 2007), and estimating the change in sediment budgets (Wheaton *et al.*, 2009).

$$DoD = \Delta DSM = R_2 - R_1 \qquad \text{(Eq. 1)}$$

While the use of DSMs has long been established in studying human settlements (e.g. Priestnall *et al.*, 2000; Yan *et al.*, 2015), the simulation of DoDs to identify flood exposure and urban environment change is a novel approach. Coupled with the large amount of research already using DSM differencing in physical geography, the analysis reported here also demonstrates knowledge transfer of the method to human geography.

The simulated DoD of settlement shows direct change in the urban landscape across time, providing an accurate method of longitudinal urban analysis, with the accuracy of the output directly linked to the spatial resolution of the DSM input. A conceptual schematic of the process is shown in **Figure 25**. If the blue line represents an earlier DSM, say for example from 2010, and the red line represents a later

DSM of the same location, for example 2020. Following **Eq. 1**, urban change over the decade can be represented as shown in **Figure 26**. Hence, the new high-rise building constructed between the DSMs will be the only difference, and theoretically all else will be zero. However, in reality, this is unlikely. Natural elements of the landscape can also change, resulting in an increasing effect the larger the period between the DSMs is, producing natural noise: trees grow, foliage grows, beach morphology changes, and even tides can affect the DoD. Nevertheless, natural noise and LiDAR artefacts can be reduced, or often eliminated due to their scale: with disregard to large tidal ranges, most natural growth/changes will be on the scale of centimetres (Sharma *et al.*, 2010). Artificial structural changes would be primarily constructed for human habitation or use, providing a lower limit on identifying new development. Due to the nature of the study, analysing buildings, it is unlikely that such structures have a footprint less than $4m^2$ (Heris *et al.*, 2020) and therefore this combination of resolutions was considered sufficient.

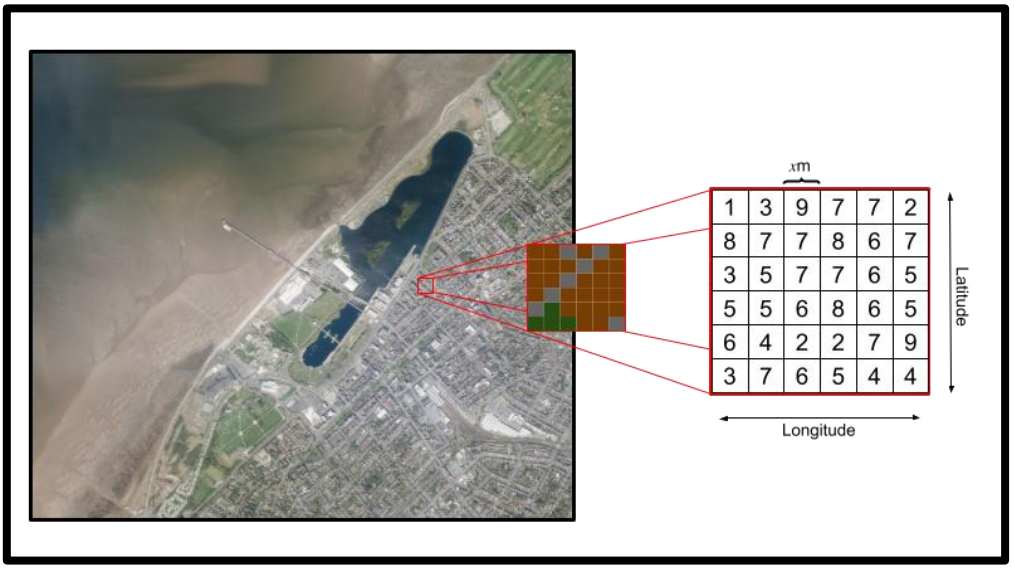


Figure 24 Demonstration of the components of a geospatial raster. Elevation values are contained within the two-dimensional cell, size dependent on the resolution of the raster.

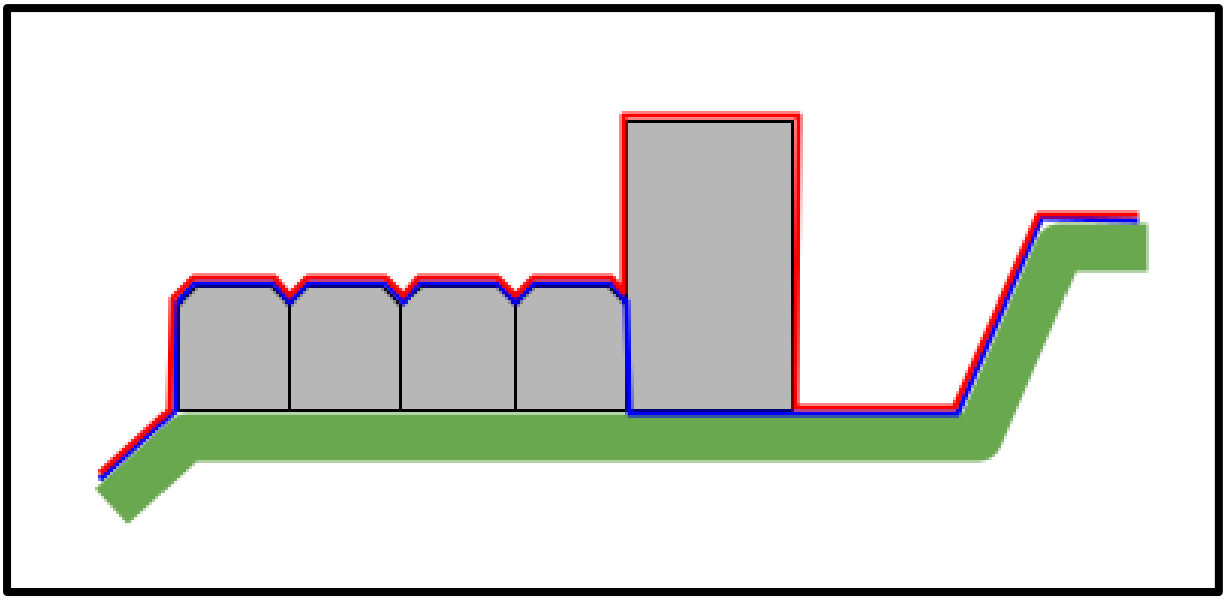


Figure 25 Two DSMs overlaid. The blue line represents the older DSM and the red line represents the newer DSM.

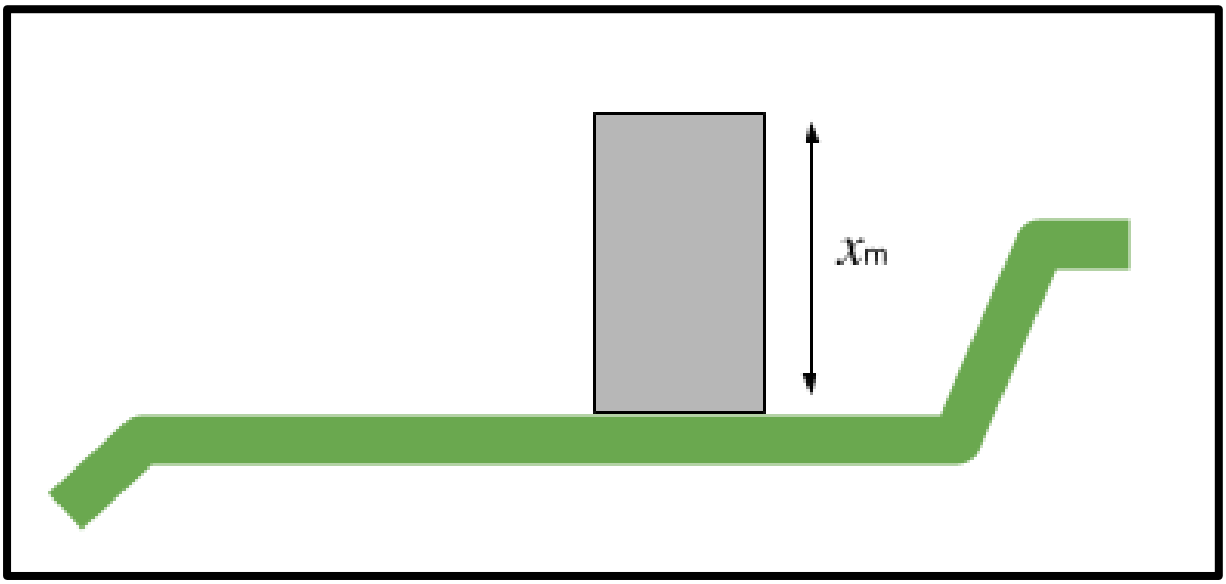


Figure 26 The resulting DoD from the differential analysis of **Figure 25**, using **Eq. 1**.

DEM differential analysis, intrinsically, has a time dimension that can be exploited to compare DoDs to changes in local coastal structural flood defence. Therefore, this type of longitudinal analysis can show changes in urban development, both before and after defences. Changes in urban development, however, must be considered in tandem with local, national, and global economics.

Due to the large size of the DSMs, containing thousands of observations, the central limit theorem and the law of large numbers apply, enabling parametric inferential statistical analyses (Lumley *et al.,* 2002; Mascha and Vetter, 2018). However, to minimise the computational demand associated with the length or direction of some coastlines, a threshold limit is considered for the sampling. Iterative optimisation of several sample sizes, ranging from 0.1km^2 to 1km^2 grid, equivalent to 10,000 and 100,000 samples in a 1m raster, revealed that a 500m by 500m square (0.25km^2, eq. 25,000 samples) was best for all resolutions, and enabled compatibility with smaller resolutions whilst also ensuring the stability of the program (as in Reuter *et al*., 2006).

Samples were collected randomly using a transect along the urban coastline from DSMs that were captured an equal amount of time preceding the construction of the defence to afterwards, based on data availability. Maintaining time period consistency when conducting the neighbourhood analysis was essential for comparability and minimisation of external influences. Once the samples were collected, the statistical testing began, with the sampled DSMs being put through a t-test. Whilst a z-test should be used for large samples ($n > 30$), it relies on the use of the population mean (Abebe, 2020), which in the geostatistical testing, was unknown: a raster is limited by its resolution and cannot account for every possible elevation within its cells, and therefore obtaining the population mean would not be possible. However, at the large sample sizes provided by raster matrices, t-scores tend toward z-score (**Eq. 4, Figure 27**). The power of the t-test in extremely large samples as a parametric test in statistical inference shows its ability in raster analysis and geostatistics. It is therefore perhaps unsurprising that is has been used by others in geospatial analysis: assessing the ability to compress LiDAR data (Anderson *et al.*, 2006), the strength of a DEM in capturing morphometric ratios of a drainage basin (Sahoo and Jain, 2018), and comparing between flood modelling and observed data (Stephens *et al.*, 2012).

For this investigation, the t-test compared each pixel of the raster to the exact same point at the chosen later point in time, where L_{R1} represents the selected pixel of R_1, L_{R2} the selected pixel of R_2 (**Eq. 2**). The paired two sample raster t-test (**Eq. 3**) then produced a t-statistic which was compared to the significance level (α=0.05). If the t-statistic was less than 0.05, then there had been a statistically significant change over the timeframe. At study sites, this timeframe was taken over SCFP improvement/ construction. If the t-statistic suggested a statistically significant change there, then this could be due to the SCFP. However, to ensure that this was not as a result of wider social or economic development, tests were also conducted in neighbouring settlements (**Figure 14**). Using the case study approach, wider economic and social changes on the national or global level have also been considered as potential causes. Each study site, however, was improved over different timeframes, therefore reducing the likelihood that potential increased development changes were due to external social or economic factors to structural FRM improvements if there is statistical significance in all.

This method provides a fast and robust direct comparison of how urban development has changed, by which degree, and if this can be considered statistically significant. Geostatistical testing can facilitate the integration of this kind of analysis, assessing these unintended consequences of SCFP into policy, and enable flood risk managers to quickly ascertain significant growth, and the potentiality of the paradox in action (Breen *et al.*, 2024).

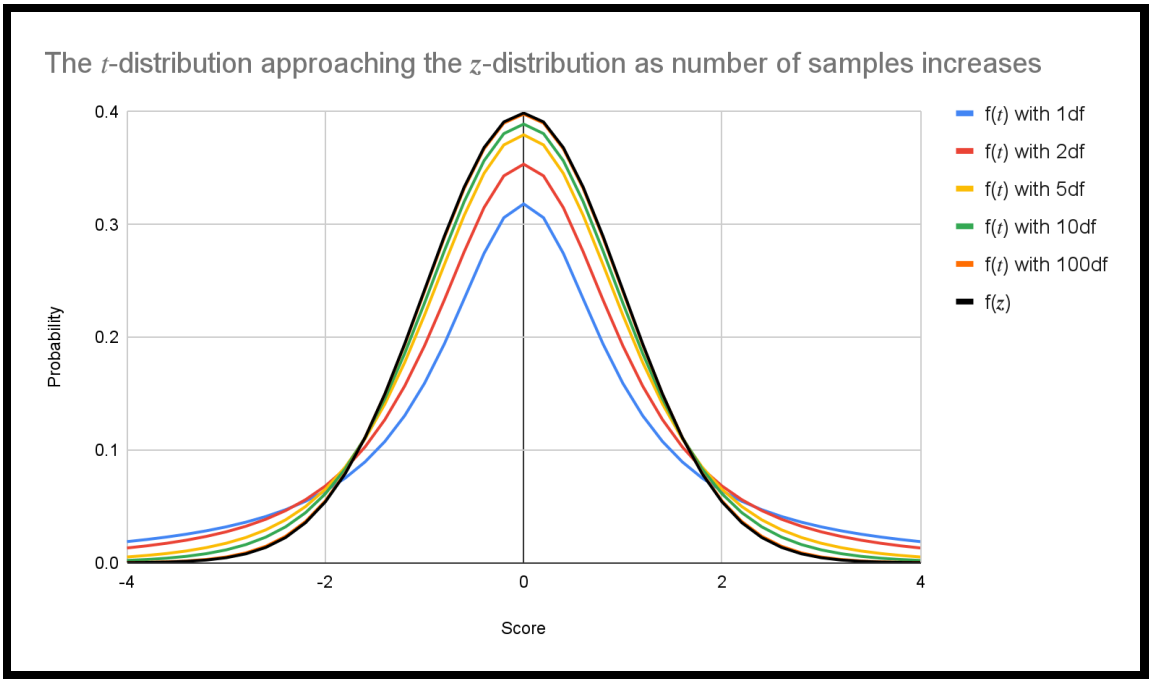


Figure 27 The t-distribution approaching the normal distribution as (n → ∞), where the degree of freedom, df, is n-1.

$$L_{R1} = (x, y) \in R_1 \quad \text{(Eq. 2a)}$$

$$L_{R2} = (x, y) \in R_2 \quad \text{(Eq. 2b)}$$

$$t = \frac{\Sigma\,(L_{R2} - L_{R1})}{\sqrt{\frac{n(\,\Sigma(L_{R2} - L_{R1})^2) - \Sigma\,(L_{R2} - L_{R1})^{\,2}}{n-1}}} \quad \text{(Eq. 3)}$$

$$\lim_{n\to\infty} \frac{\Sigma\,(L_{R2} - L_{R1})}{\sqrt{\frac{n(\,\Sigma(L_{R2} - L_{R1})^2) - \Sigma\,(L_{R2} - L_{R1})^{\,2}}{n-1}}} = Z \quad \text{(Eq. 4)}$$

3.3.2 Hydrometry and Sea Level Rise

Tidal data, sea level rise, and storm surge data were obtained as a shapefile from the Met Office UKCP User Interface. These data are the standard for UK government hydrological projections for the British Isles. Datapoints are spaced every 2km around the UK coastline, using estimates of current extreme sea levels at all open-coast Coastal Flood Boundary point locations, provided by the Environment Agency and projections of 21st Century time-mean sea level change prepared at the Met Office. Tidal data, Sea-Level Rise (*SLR*), storm surge, and wave height data were used for modelling Extreme Coastal Water Levels (ECWL) used as input to the ABMs (**Table 5**).

Table 5 Data used describing the local sea level, wave conditions, and future SLR.

Data	**Use**
Tidal Data	ABM Simulation and Projection
Sea Level Rise	ABM Simulation and Projection
Storm Surge	ABM Simulation and Projection
Wave Height	ABM Simulation and Projection

Projected extreme sea level values are described for 16 different annual probabilities of exceedance (AEP), ranging from 1:1 (100%) to 1:10,000 (0.0001%), identified in the shapefile as 't1' to 't10000'. Confidence levels relating to the 5% and 95% lower and upper bounds of confidence are included, identified in the shapefile with the prefix 'c1_' and 'c3_' respectively, as well as the 70% confidence level identified in the shapefile with the prefix 'c2_'. The data covers the period from 2020 to 2100 and is available for each decade (i.e., 2020, 2030... 2100), and was extracted using GIS.

However, these data from the Met Office are coastal still water sea levels (*CSWL*), including only the effects of storm surge (*SS*) and astronomical tides (*T*), but do not account for localised increases in sea level from wave action, topography (**Eq. 5**), or whilst not mentioned explicitly, it can be assumed that localised air pressure differences are also not accounted for. Two additional effects are of note and can be significant in certain circumstances. Wave set-up is an increase in water level due to on shore wave action (wave set-down is the opposite). Wind set-up is where the local wind shear stress pushes the water level up at the shore (and again set-down is the opposite). Depending on the circumstances these may or may not be well accounted for in the extreme sea level estimates. Tide gauges can be exposed to these effects or sheltered from it.

$$CSWL = SLR + SS + T \qquad \text{(Eq. 5)}$$

Projected future CSWL, are not technically above the Ordnance Datum Newlyn (ODN) as projections include relative mean sea level change, whereas ODN is an absolute datum. At those coastal sites that experience low variability in sea level extremes, with a shallow return level curve, projected CSWL return levels for 2100 may be outside the envelope of present day return levels (Howard *et al.*, 2019). For example, the 2100 projection for Lerwick under the RCP8.5 scenario is a level that would not be expected to occur there under sustained present day CSWL even with a 0.0001% AEP. Similarly, at coastal sites with high CSWL variability, projected return levels for 2100 may be inside the envelope of present day return levels. For example, the 2100 projected 100% AEP CSWL for Avonmouth, under RCP8.5, is a level that would be anticipated to occur with a 2.5% AEP today. This is because of the steep return curve at Avonmouth, formed by the large variability in sea level at Avonmouth, as a result of the action of the Bristol Channel and it having the second largest tidal range in the world, due to the Channel being close to the resonance with the moon, with a time period of 12 hours and 25 minutes. This reveals a caveat in the projections: they do not include possible changes in tidal characteristics with increased water depth (Palmer *et al*, 2018). Although, projections of change in tidal range, particularly

for the Bristol Channel, can be model dependent and can range by up to 10% at some locations. However, these are a secondary effect, with the change in sea level over the coming decades being the dominant driver (Howard *et al.*, 2019).

The following graphs present CSWL, derived using **Eq. 5**, for each case study: Weston-super-Mare, shown in red; Southport, shown in blue; and Portsmouth, shown in green. The lighter shades represent a 2%AEP flood event, the core colour represents a 0.5%AEP flood event, and finally the darkest shades represent a 0.1%AEP event, the most extreme considered within this analysis. Three climate scenarios are also used to project into the future, using a 2018 baseline. As an example, RCP8.5 (**Figure 28**), RCP2.6 and RCP4.5 are provided in **Appendix C**.

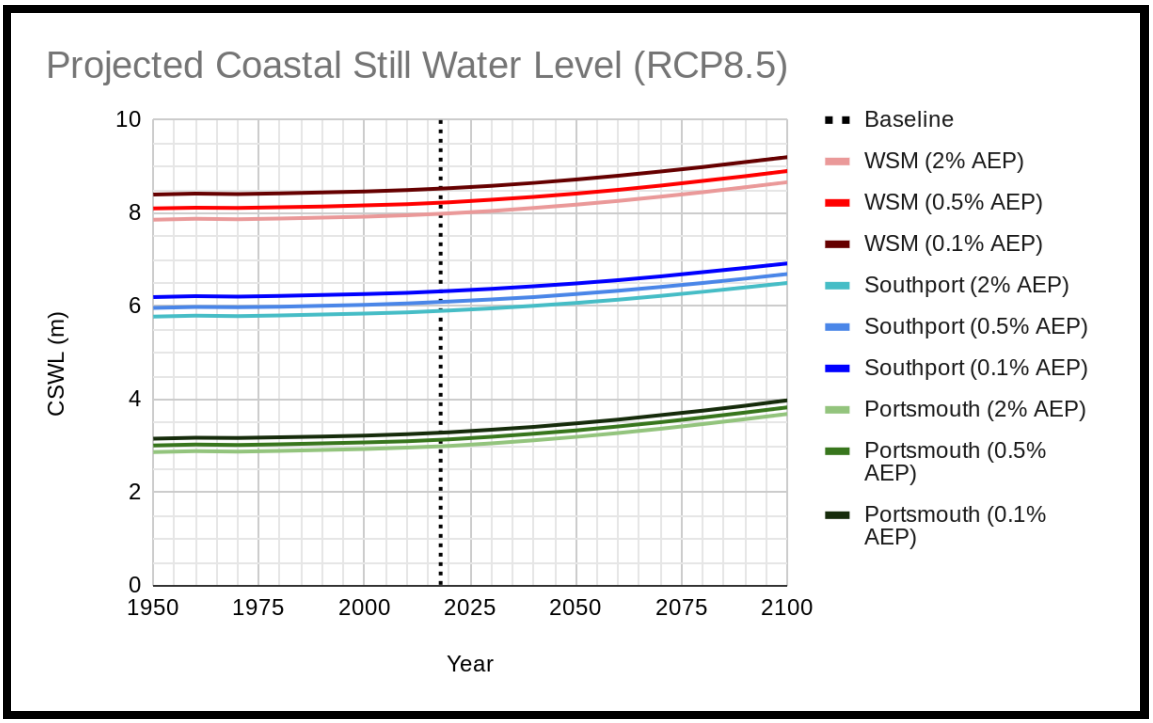


Figure 28 The historic and projected (1950-2100) coastal still water level at locations around the UK under the RCP8.5 scenario, calculated using Eq. 5.

However, climate projections of wave height across the 21st century are inherently uncertain, with varying reports of sign and/or magnitude across literature (Lowe *et al.*, 2019). Each individual study has its own set of atmospheric climate models that are used to create a set of wave models. These varying models give rise to structural uncertainty because of the different ways are solved within each model and how parameterisation differs. Moreover, different emissions scenarios give rise to different wave projections, particularly towards the end of the 21st century. For example, RCP8.5 is expected to produce the largest changes in wave height in general. This would mainly be attributed to the effects of climate change on atmospheric circulation, which then would have an effect on the wave climate. Whereas RCP2.6 would, theoretically, result in the least change in the wave climate relative to the present, as there would be less external climate forcing changing atmospheric conditions, and ultimately, wave climate (IPCC, 2014).

The IPCC Fifth Assessment Report concludes:
'There is low confidence in wave model projections because of uncertainties regarding future wind states, particularly storm geography, the limited number of model simulations used in ensemble averages, and the different methodologies used to downscale climate model results to regional scales'

Adding greater uncertainty to wave projections is the experimental method used in obtaining local-scale results from downscaling the output of General Circulation Models (GCMs). These methodological

differences will lead to different projections of the local wave climate. Downscaling from GCMs to regional, and then local modelling, may not incorporate internal wave variability, and the difference between locally driven waves and swell waves. Areas that are less exposed around the UK, such as the Irish Sea, between Great Britain and Ireland, and the east coast of Great Britain at the North Sea. When wind blows across the sea surface, wind waves are formed. Over time, waves formed in remote regions may travel long distances until they reach a location. These waves are self-sustaining and are not formed by the local winds. These are known as 'swell waves'. These unexposed areas are less influenced by swell waves that originate from farther afield than they are locally generated waves from storm systems (IPCC, 2014). Therefore, it can be difficult to extract a robust climate change signal due to the high variability associated with the generation of wind waves from storm systems. When only one GCM is used, the results from future wave projections depend on emissions scenarios (Wang *et al.* 2004, Reeve *et al.* 2011). However, when a group of GCMs were considered together, across multiplied emissions scenarios, the studies agreed that modelling uncertainty was greater than RCP scenario uncertainty (Howard *et al.*, 2019).

Therefore, any change in the offshore wave climate due to climate change does not have as great an impact as the increased water depths due to sea level rise, which allow a bigger wave to reach the flood defences. Waves are depth limited in the UK shallow water coastline and any changes to offshore wave height, without a great increase in water depth, are unlikely to be transformed to the defence. Wave height and period are critical features for consideration in coastal defence, and with increasing wave height and breaking later, it is likely that flood water volumes will increase in the FZs. This has great implications for the infrastructure vulnerability on the coast in the UK. Future changes in waves therefore, may be negligible, and at the very least highly unpredictable. It is for this reason that modern Significant Wave Height (SWH, also referred to as WH herein as ECWL suggests significance), has been used in flood modelling and analysis. Therefore, building on **Eq. 5** is **Eq. 6**, which incorporates Wave Height (*WH*) to consider the impacts of storms and strong winds and associated waves that can reach to the coastal flood defences.

$$ECWL = SLR + SS + T + WH \quad \text{(Eq. 6)}$$

The following graphs present ECWL, derived using **Eq. 6**, for each case study: Weston-super-Mare, shown in red; Southport, shown in blue; and Portsmouth, shown in green. The lighter shades represent a 2%AEP flood event, the core colour represents a 0.5%AEP flood event, and finally the darkest shades represent a 0.1%AEP event, the most extreme considered within this analysis. Three climate scenarios are also used to project into the future, using a 2018 baseline: RCP2.6 (**Figure 29**), RCP4.5 (**Figure 30**), and RCP8.5 (**Figure 31**).

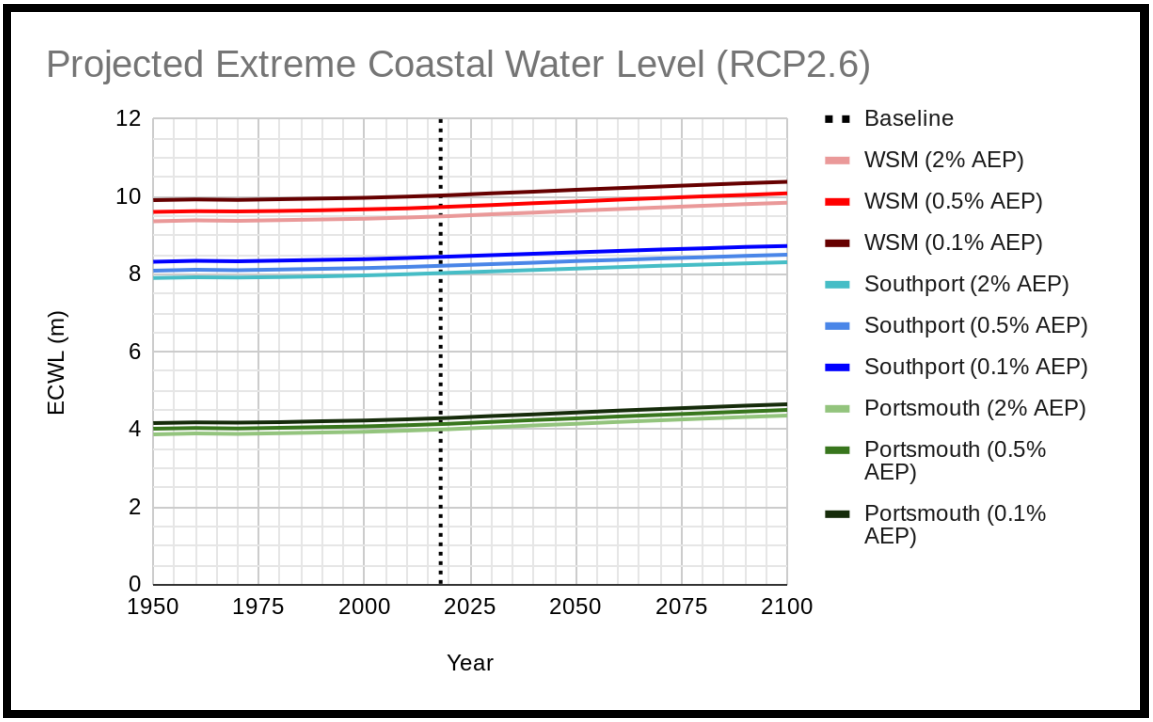


Figure 29 The historic and projected (1950-2100) extreme coastal water level at the case studies under the RCP2.6 scenario, calculated using Eq. 6.

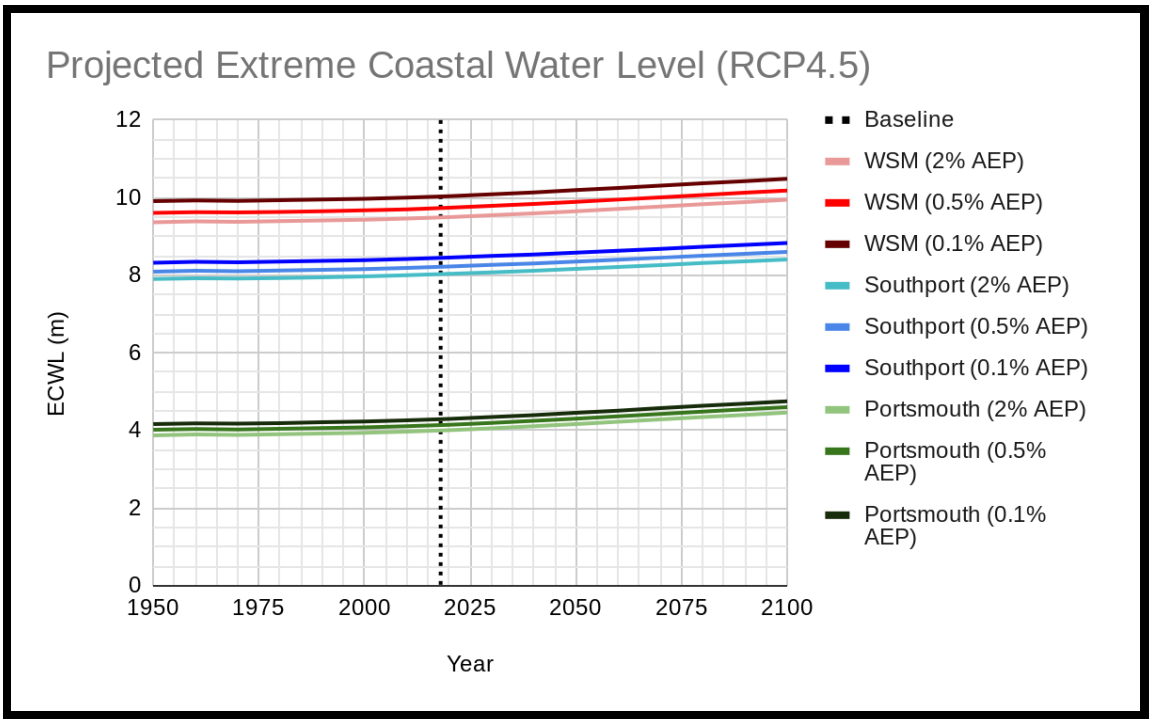


Figure 30 The historic and projected (1950-2100) extreme coastal water level at the case studies under the RCP4.5 scenario, calculated using Eq. 6.

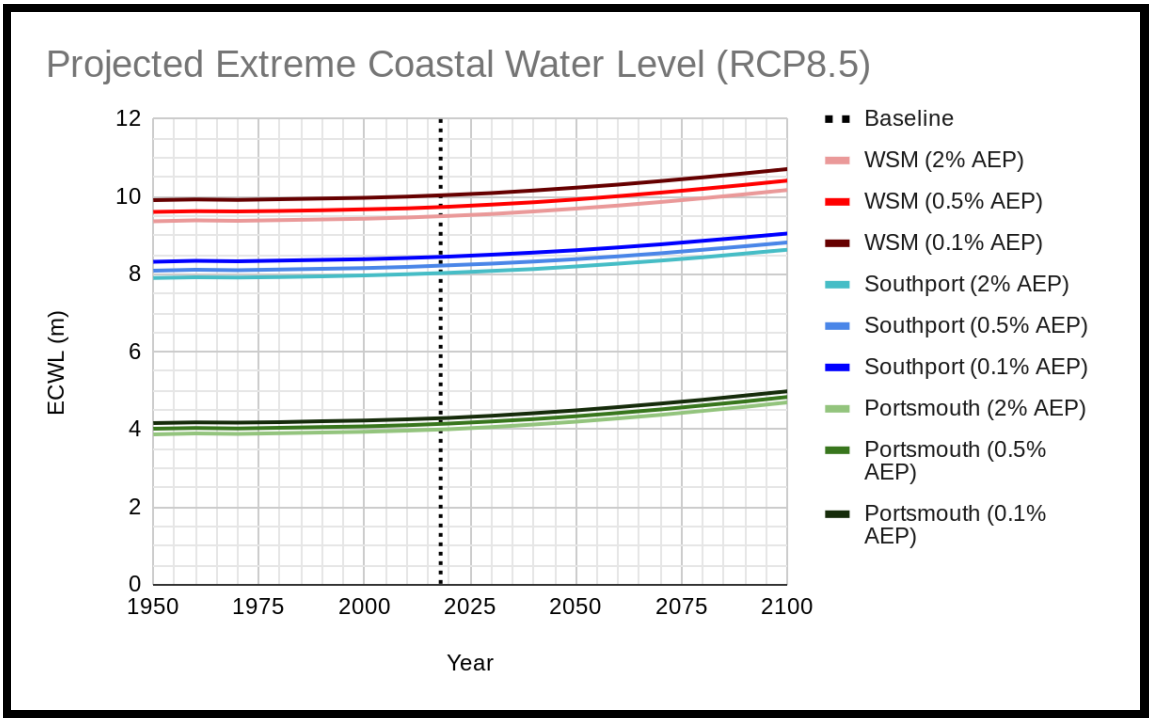


Figure 31 The historic and projected (1950-2100) extreme coastal water level at the case studies under the RCP8.5 scenario, calculated using Eq. 6.

3.3.3 Environment Agency Flood Zones

FZ2 and FZ3 have a 1 in 1000 (0.1%) or 1 in 200 (0.5%) chance of flooding each year, respectively, are designations created by the Environment Agency (EA) to identify areas that are at a greater risk of flooding from the sea or rivers, and are used within this analysis for delineating exposed areas and determining populations at risk (**Table 6**). Although, flood risk arising from fluvial sources was omitted for this project. Therefore, areas not represented by FZs in mapping may also be at risk from other sources of flooding, such as high groundwater levels, Hortonian flow, or the failure of infrastructure such as sewers and storm drains.

Table 6 Data used to identify areas that are exposed to flooding.

Data	**Use**
FZ 2 Shapefile	Delineating at-risk areas
FZ 3 Shapefile	Delineating at-risk areas

FZ2 also known as the medium probability zone, represents areas with a medium risk of flooding from rivers or the sea. This means that there is a higher chance of flooding occurring in these areas compared to areas outside the zone. FZ3 on the other hand, is the high probability zone, indicating areas with a significant risk of flooding. These areas have a higher likelihood of experiencing flooding than both, FZ2 and the areas outside the designated zones. These data are the best estimate of at-risk areas when the presence of flood defences are ignored. The FZ2 dataset also includes areas defined by FZ3.

However, these zones indicate flood risk to areas of land, and do not have a sufficient resolution nor detail to identify danger to individual households, and properties may not also face the same amount of flooding as those immediately surrounding them. This is due to the fact that the EA does not hold information on properties or their floor levels. This, and the fact that the zones ignore the impacts of flood defences, means that these data provide a worst-case scenario for identifying those who are exposed and/or vulnerable. However, in FRM it is preferred to overestimate and to not *tempt fate*.

As the go-to exposure identification tool in British FRM, the EA must ensure that the zoning is as accurate as possible. River and coastal monitoring provides real-time data for the agency on water levels, flow rates, and wave conditions. Combined with meteorological, topographic and historic flood data, these data can be used to develop hydraulic and hydrological models, identifying flood extent, depth, and velocity. This information is crucial for land-use planning, insurance, and the development of FRM strategies, as well as identifying primary stakeholders for informed decision making and emergency planning.

The methodology to determine these zones, working with a variety of factors and data sources, however, is not publicly available, lacks transparency, and has not been exposed to independent peer review (Bates *et al*., 2023). However, the use of the Environment Agency FZs remains widely used, not just within public institutions, but also in the scientific literature: assessing links between flood vulnerability and funding allocation (Gooden *et al.,* 2024), identifying differences between modelled and actual flood impacts (Penning-Rowsell, 2020), quantifying links between the location of new homes being built in FZs and the socio-economics of the area (Rözer and Surminski, 2021), locating legacy waste sites that are at risk of releasing contaminants (Riley *et al*., 2022), and examining how coastal change policies have been implemented in the UK (Kirby *et al*., 2021), to name a few. The proliferation of the FZ mapping provided by the EA in the literature is testament to its utility, and despite the lack of transparency in its creation, it provides a widely-used and consistent national dataset.

3.4 Socio-spatial and Socio-economic Data

These data provided the human element to this analysis and form the core of the conclusions. There would be no risk to consider if there were no coastal inhabitants in these areas; it is human activity that drives and exacerbates these coupled human-water cycles. The following subsections provide context for the data: what the data is, where it came from, and how it was used.

3.4.1 Population Change

Census data was used in this analysis in population dynamic mapping, identifying where populations live and their proximity and socio-hydrological relations to the associated SCFP (**Table 7**). These dynamics then were fed into the ABM to project these patterns forwards and identify emergent trends and phenomena.

Table 7 Data used to model and analyse population change, both, historic and future.

Data	**Use**
1991 Census	ABM Simulation, Future Projection, Exposure Calculation and Mapping
2001 Census	ABM Simulation, Future Projection, Exposure Calculation and Mapping
2011 Census	ABM Simulation, Future Projection, Exposure Calculation and Mapping
2021 Census	ABM Simulation, Future Projection, Exposure Calculation and Mapping
ONS Projections	ABM Simulation, Future Projection, Exposure Calculation and Mapping

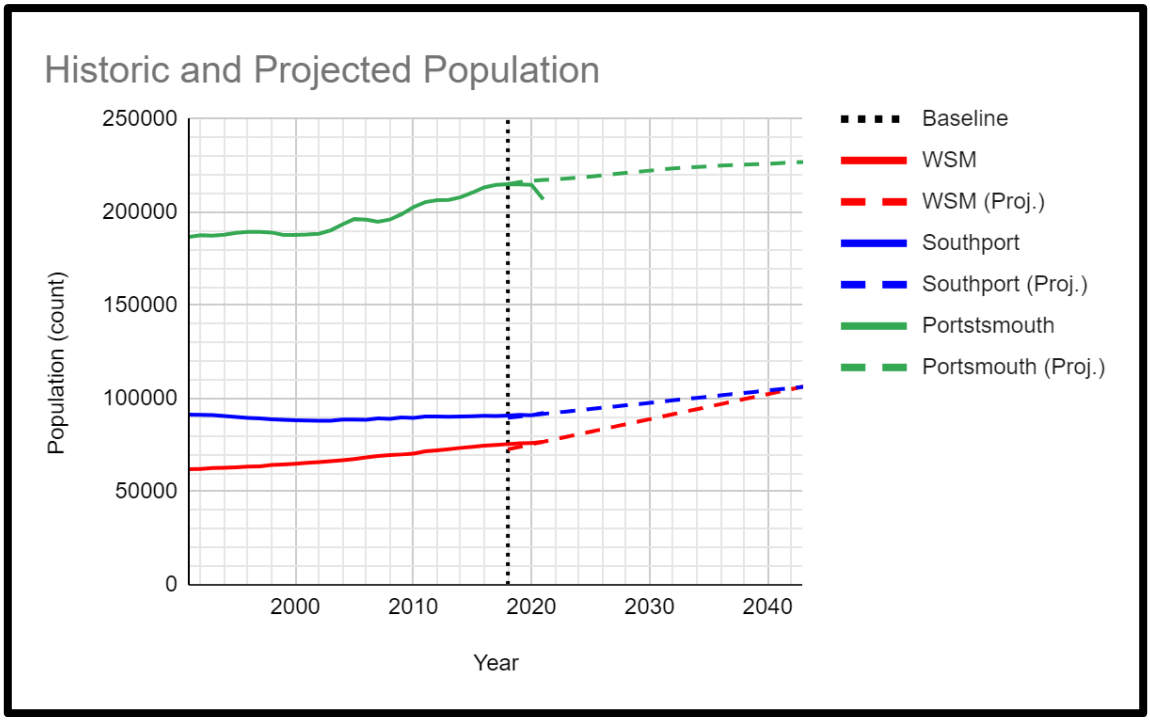


Figure 32 The historic and ONS projected (1991-2043) population at each case study site. The misalignment is due to the ONS projections using a baseline of 2018, and not yet taking into account the 2021 census.

The Office for National Statistics (ONS) is the body that plans, conducts, and analyses the census across England and Wales. The data used in this investigation was collected from four censuses conducted by the ONS: 1991, 2001, 2011, and 2021, the latest. Moreover, in between censuses, the ONS provides population estimates yearly at the local authority level, both, for historic data and future projections, these have been represented for each case study in **Figure 32**: Weston-super-Mare in red, Southport in Blue, and Portsmouth in green. However, as the projection data is created from a 2018 baseline, by the ONS, it does not take into account the most recent census, hence the misalignment between projection and actual census data.

Estimates are based on decadal censuses, updated to account for population change in the period between Census Day (21st March) and the mid-year point (30th June). Mid-year points have the benefit of taking into account the excess winter deaths in one count, instead of dividing them over calendar years. As a statistical procedure, interpolating between two data points a decade apart, this type of estimation has inherent limitations. These are reduced by using certain known factors: ageing, births, deaths, and internal and external migration.

However, in this analysis, it is critical to state that the population socio-economic changes within military bases was not included in this analysis. Firstly, military bases typically operate under distinct jurisdictional framework and command structures, falling under national government oversight. This autonomy may lead to variations in data availability, reporting mechanisms, and infrastructure management practices, making it difficult to seamlessly integrate these areas into wider flood risk and socio-economic analyses. Secondly, the population dynamics and socio-economic characteristics of military bases are not often linked to, or reliant on, surrounding areas, creating isolated pockets that may diverge from the socio-hydrological processes within the civilian population. Moreover, these military bases often house transient populations, and residents may have had little choice of locations, including active-duty personnel and their families. These populations would therefore be isolated from the demographics of nearby civilian populations making inclusion difficult.

3.4.2 Population Distribution

Whilst examining the overall changes in population at the macro level provides valuable insights into demographic trends, analysing, comparing, and contrasting the spatial distribution of these populations is equally crucial, particularly in the context of flood risk analysis, determining socio-economic and population dynamics, and identifying the intrinsic socio-hydrological processes at these locations.

Understanding population distribution across the case studies allows for a higher resolution assessment of exposure and vulnerability to flood hazards. Populations situated in low-lying coastal regions, in exposed areas, are inherently more susceptible to the impacts of flooding: property damage, displacement, and loss of life. By tracking the changes in population distribution over time, trends and demographic patterns emerge that may exacerbate, or even mitigate, flood risk within the case studies. Moreover, if the population distribution has changed at the SCFP, then this would imply a linkage between the two.

Therefore, a statistical *t*-test was performed on the changes in population distribution, comparing population distribution change at the new SCFP to those elsewhere in the settlement. This statistical test would identify the significance of this disparity, if there was one at all, and therefore ultimately identify whether there was a statistically significant change in population distribution at the SCFP.

Here, being at the SCFP was defined as being within two Output Areas (OAs) distance away. Whilst there would be merit in using the FZ as a determiner for being *at the defence*, in locations such as Weston-super-Mare the inundation created by coastal flooding proceeds far into the town and would affect a great majority of the population. The distance of up to two OAs is similar to the 500m buffer used in an analysis of the impact of perceived flood risk exposure on flood risk perception, investigating the role of flood risk communication in the flood awareness of residents (O'Neill *et al.*, 2016). Having these flood risk uncertainty zones around FZs has been found to be important; FZs may underestimate the extent to some areas and suggest that residents in those areas are outside the FZ (Percival *et al.*, 2020). Buffer areas around FZs improves the flood awareness and preparedness of those who may not think that they are at risk (Brandt *et al.*, 2021).

$$t = \frac{\frac{\Sigma\left(\frac{C_2 - C_1}{C_1}\right)}{n} - \frac{\Sigma\left(\frac{T_2 - T_1}{T_1}\right)}{n}}{\sqrt{\frac{\sqrt{\frac{\Sigma\left(\frac{C_2 - C_1}{C_1} - \frac{\Sigma\left(\frac{C_2 - C_1}{C_1}\right)}{n}\right)^2}{n-1}}}{n}^2 - \frac{\sqrt{\frac{\Sigma\left(\frac{T_2 - T_1}{T_1} - \frac{\Sigma\left(\frac{T_2 - T_1}{T_1}\right)}{n}\right)^2}{n-1}}}{n}^2}}$$

(Eq. 10)

The *t*-test compares the change in population distribution of OAs over time between areas, those at the new defence and those randomly selected elsewhere in the town. The sample size (*n)* was equal between the two samples. The statistical test (**Eq. 10**) uses the *Population Distribution* at the new defence from before the SCFP was completed (C_1) and afterwards (C_2), and the *Population Distribution* across the same timeframe in other non-coastal areas of the town, from before (T_1) and afterwards (T_2). Samples were assessed against a 0.05 significance level. These statistical data aid with assessing significance in population distribution change from the defence, and help with determining the strength of the population distribution projections conducted by the ABM: if there was a statistically significant change in the population distribution at a new SCFP then it gives weight to the proportion of residents at this area continuing to increase at a similar annual rate to previous years.

These population distribution data were essential for the ABM, to spatially distribute the population accordingly and to provide a facsimile to real-world population locations. However, the boundaries

provided by the ONS do not map exactly onto the DTM rasters used in the ABM, and therefore applying these data to the ABM cells was not directly possible due to the different geospatial data types: a raster, a geospatial matrix, and a vector, a continuous database stored as points, lines, or polygons. Whilst in modelling it would be possible to overlay the population distribution data over the cells and command the cells to take the value this would lead to a potential overestimation of *Affected Population* (AfP) as the raster cells are smaller than the OA polygons. Although, as raster cells must be uniform, this overestimation was reduced and the population distribution polygon was therefore rasterised within the ABM (**Eq. 11**).

$$P_S = \frac{P}{\Sigma P} \times \frac{A_R}{A_V} \qquad \text{(Eq. 11)}$$

The equation (**Eq. 11**) produces *Population Share* (P_s), a vector that contains the OA boundaries, with each OA having a value that represents the proportion of the *Total Population* (ΣP) that the specific OA contains. Taking a single hypothetical OA, the *Population Share* value is obtained by firstly identifying the proportion of the population that the OA has within it, which is the ratio of the *Population* (P) of the OA compared to the *Total Population* of all OAs. This is then multiplied by the ratio of the size of the raster cells within the ABM (A_R), which should be uniform, and the area of that specific OA (A_V). The product (in **Eq. 11**) calculates the *Population Share* to apply to the ABM cells that exist within it, and therefore reduces overestimation by optimising the *Population Share* spatially and comparing the specific OA size to its constituent raster cells. The vector is then applied as an input to the ABM for the modelled *Population Distribution*, an intermediate value within the ABM.

3.4.3 Economic Inactivity

The Economically Inactive (EiA) population, the proportion of people who are neither working nor looking for work, for example, full-time students, those with long-term sickness or disability, carers, retirees, and those who are currently unable to work, for example those with very limited English ability. This population group has risen sharply since the start of the Covid-19 pandemic, a trend observed across all G7 countries after lockdown restrictions were introduced. However, this has largely reversed in all countries except the UK, where it has continued to rise (Kirk-Wade and Harker, 2023). These data were used in the vulnerability mapping, counted as the P_{Vun} population (**Table 8**). ONS data for these populations in the primary sites are presented in **Figure 33**, which shows the general trend in EiA population across the settlements. Portsmouth saw a decrease of EiA population, troughing in the mid-2000s before increasing again. This would suggest that the EiA population was already increasing across Portsmouth before the Covid-19 pandemic. In contrast, in Southport, EiA population was relatively stable until a decrease across the 2000s, before rising again across the 2010s. This was similar to Weston-super-Mare, which saw a steady decline of EiA population, before a sharp rise across the 2010s (**Figure 33**).

Table 8 Data used to map and analyse economic inactivity.

Data	Use
1991 Census	Vulnerability Calculation and Mapping
2001 Census	Vulnerability Calculation and Mapping
2011 Census	Vulnerability Calculation and Mapping
2021 Census	Vulnerability Calculation and Mapping

EiA populations often have little accessible capital, unable to move quickly and respond to dangers, and have limited flood awareness and preparedness (Burningham *et al.*, 2007). Moreover, many are often isolated from their communities, and therefore have limited sense of place ─ these factors all contribute to the higher vulnerability of this population. Assessing these EiA populations is therefore crucial to the understanding socio-economics as a potential driver, and/or impact of, the unintended consequences of SCFP.

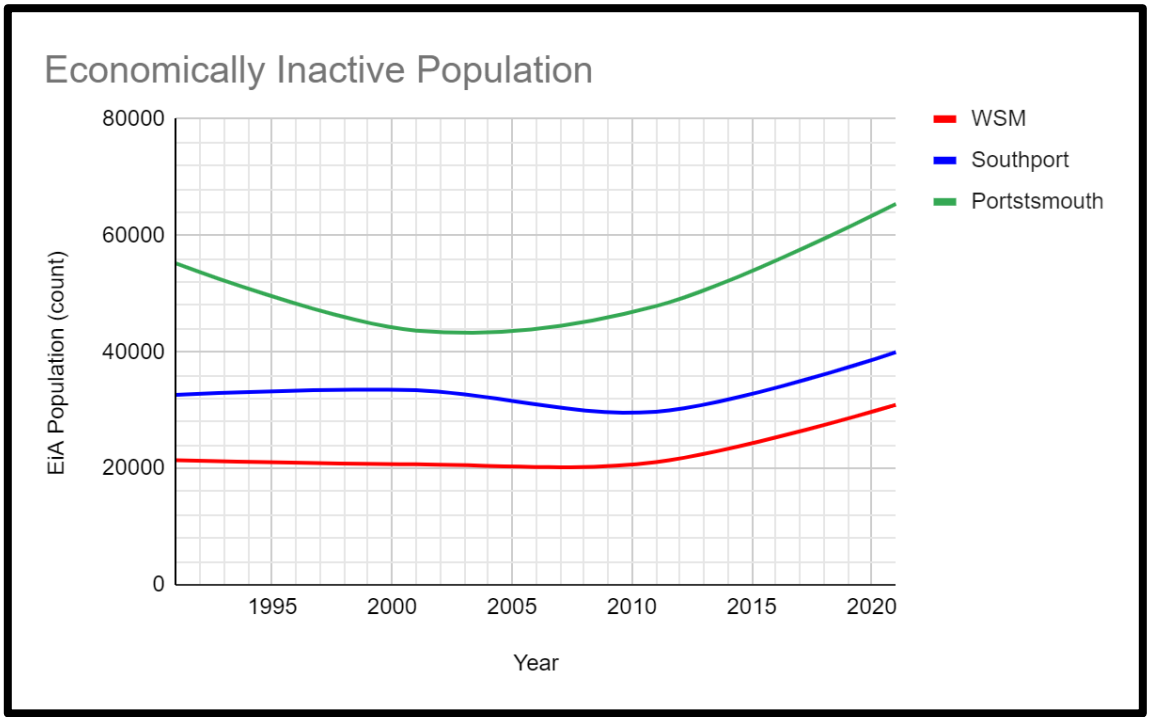


Figure 33 The number of economically inactive population at each case study site over the 1991 to 2021 period.

3.4.4 Households and Occupancy

Household and household occupancy data, the number of people living within each household, were used within this analysis in the exposure mapping, investigating how and where people are living and how these population dynamics are affected, or not, by the potential socio-hydrological processes present at SCFPs (**Table 9**). Both housing occupancy rate (e.g. Talent, 2016) and household size (Salcedo *et al.,* 2012) have used in the literature to refer to the same value: the number of people living in one residential property. This document and project shall refer to this value as household occupancy to avoid confusion with the physical properties of a house, and instead reflects better the number of occupants in the property, and aligns with terms used by local authorities, e.g. Houses of Multiple Occupation (HMOs). Identifying the areas with increasing housing occupancy is crucial; spatial concentrations of unrelated, multi-person households often accompanies high population transience, overstretched community assets and public management, and weak community cohesion, leading to increased socio-spatial segregation and the restructuring of social relations and housing markets (Smith, 2012), which can exacerbate flood vulnerability in already at-risk populations and communities (Greene *et al*., 2015; Castro, 2023).

Table 9 Data used to map and analyse households and occupancy.

Data	Use
1991 Census	Exposure Calculation and Mapping
2001 Census	Exposure Calculation and Mapping
2011 Census	Exposure Calculation and Mapping
2021 Census	Exposure Calculation and Mapping

In the case studies, over the 1991 to 2021 period there was a steady increase in households in Weston-super-Mare, Southport, and Portsmouth, weakening over the 2010s in Portsmouth and Southport (**Figure 34**). This increase in households led to an overall decrease in the average household occupancy in all three case studies across the 1990s (**Figure 35**). In Portsmouth, there was a slight increase in average housing occupancy from 2001 but this remained stable over the 2010s, in contrast to Southport which saw an increase across this period, suggesting the population is increasing greater than the housing stock can support, leading more people to cohabit than previously. However, with the exception of the 2000s stabilisation, Weston-super-Mare saw a continuous decrease in housing occupancy across the 1991 to 2021 period (**Figure 35**).

Increases in housing occupancy would suggest that more people are living together and there is a push factor towards cohabitation. Alternatively, as the intensity and frequency of storms increase, urban development can be hindered, which may stagnate or even decline the number of households in the area as the expenses of repair and reconstruction increase (Karanci *et al*., 2017). A decrease in the amount of housing stock, would lead to a decrease in households, and if population is maintained, an increase in housing occupancy, as more and more people cohabit.

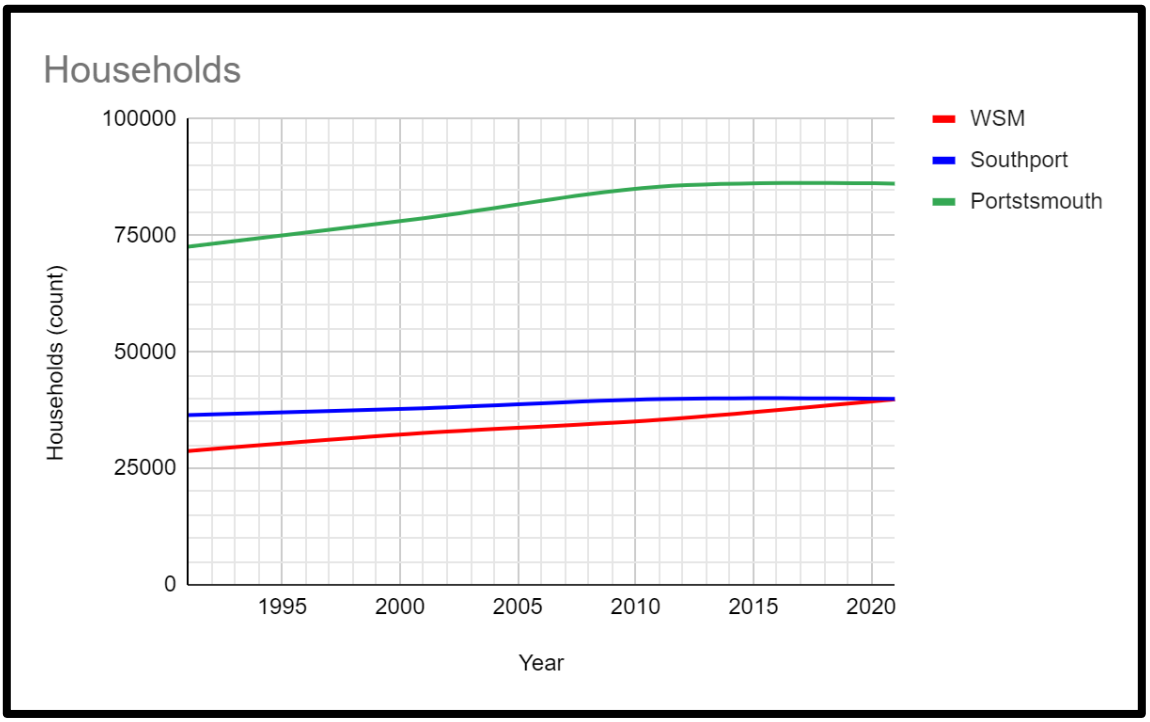


Figure 34 The number of households at each case study site over the 1991 to 2021 period.

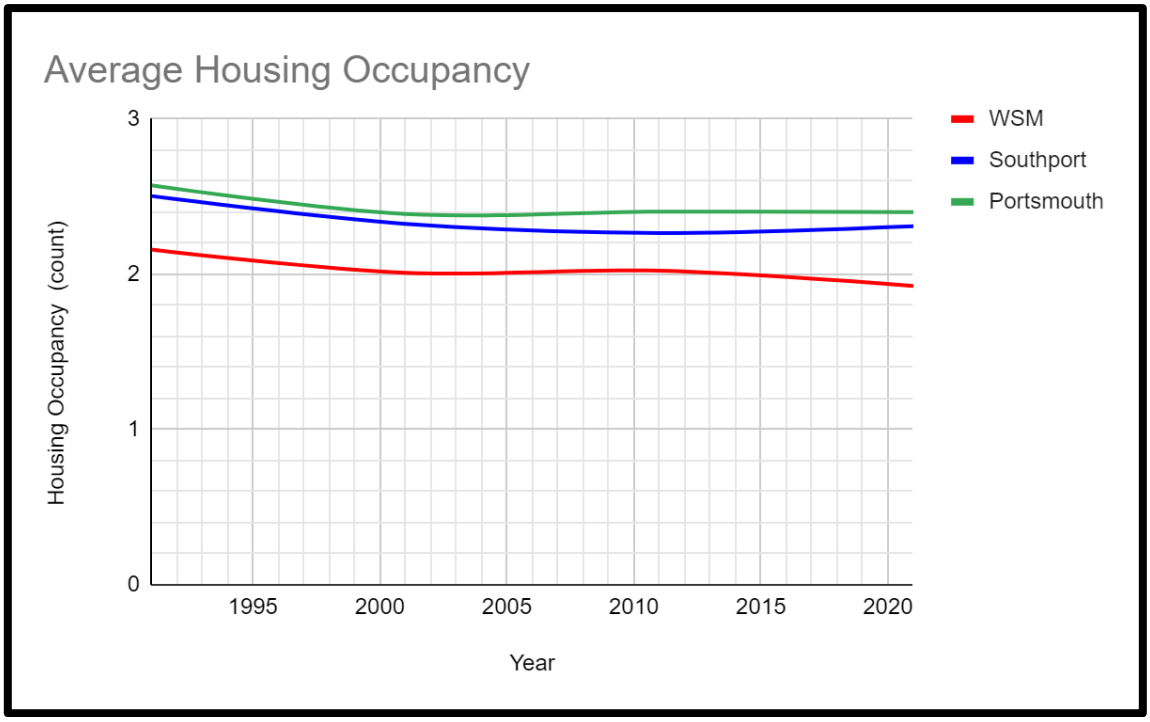


Figure 35 The average housing occupancy of each case study site over the 1991 to 2021 period.

3.5 Impact Assessment Approaches

The approaches detailed within this sub-section provide the means of capturing these unintended and emergent phenomena allowing investigating their medium- to long-term impacts.

3.5.1 Agent-based Modelling

The ABM developed for this analysis used several inputs to produce the intended outputs (**Table 10**). There was the LiDAR DTM, obtained from the Environment Agency, used for topographic modelling, the ECWL equations, used for modelling local coastal water level, population distributions, spatially modelling the population, and the population equations, producing the total population output to be model by the distribution data.

Published in 1987, Empirical Model-Building and Response Surfaces, provide an important and innovative discussion of the construction of empirical models and the fitting of surfaces to data still studied more than 30 years later (Box and Draper, 1987). On page 424 of the book, the authors discuss the usefulness of models in relation to reality:

> *'Essentially, all models are wrong, but some are useful. However, the approximate nature of the model must always be borne in mind.'*

This is paraphrased to form the often quoted aphorism, 'all models are wrong, but some are useful', as in the pursuit of parsimony, models may sacrifice precision for realism or generality, opting to explore overarching quantitative relationships over mathematical precision and form. In turn, to maintain precision, realism may be sacrificed to produce a more generalised model, applicable in a wider range of case studies, yet losing its tangibility. Whereas, sometimes generality is lost to focus on accurate predictions for specific case studies (Troy *et al.*, 2015). These trade-offs are demonstrated in **Figure 36**, and represent the decisions that must be made in order to replicate reality in some form. Truly, all of these models will be both 'right' and 'wrong'; seemingly incompatible models may make predictions about the same phenomenon that are mutually inconsistent, yet both accurate.

Table 10 Data used to build the Agent-based Model (ABM).

Data	**Origin**
Topography	LiDAR DTM
ECWL (Historic)	Hydrometry Measurements
ECWL (Proj.)	Hydrometry Measurements and IPCC/ Met Office Projections
Population Distribution (Historic)	*Derived from* Previous Censuses
Population Distribution (Proj.)	*Derived from* Previous Censuses
Population (Historic)	Previous Censuses
Population (Proj.)	ONS Projections

Assessing how human behaviour and society responds to a flood event is an important aspect in determining the interlinked processes of human-flood interactions, and the consequences of these that may either reduce or exacerbate flood risk (Loucks, 2015). In the context of this study, it is the feedback mechanisms and emergent phenomena operating in the coastal zone that is of concern, namely the unintended consequences of SCFP.

Opposed to the purely mathematical approach of differential equations, agent-based modelling operates by prescribing rules to 'agents' representing how individuals interact. The integration of agent-based modelling with spatial data has been widely recognised as a powerful approach for exploring complex coupled sociological dynamics. For instance, Gimblett (2002), provides a foundational perspective on combining GIS with ABM to simulate interaction between human and environmental systems. Decisions are made on an individual level and therefore have a higher precision than other methods as behaviours are not generalised. Individual decision-making is key when replicating a highly heterogeneous society, with varying vulnerabilities. The losses of lives in New Orleans show that populations are not equal and the spatial distribution of risk is unfair, and that society is a mix of varying vulnerabilities and views. Haer *et al.* (2020) aims to capture the system outcomes of the SDP resulting from decisions made in a population. ABMs allow simulation of heterogeneous behaviour through a range of different behavioural rules, producing a complex societal system, with emergent trends. Citizen agents interact with government agents differently based on their risk situation and initial level of protection, leading the government agents to operate their FRM strategies 'proactively' or 'reactively'. Government agents may also influence citizen agents by creating building codes or policies that force households (and citizen agents) to act more rationally. These studies emphasise the ability of ABM to capture emergent behaviour arising from individual decision-making processes within spatially explicit landscapes, a feature particularly relevant to socio-hydrology, where feedbacks between human settlement and flood protection infrastructure are critical.

The use of ABMs in flood risk analysis and management is growing. Sobiech (2013) developed an ABM of coastal flooding in Germany with the aim of simulating the dynamics of vulnerability. The study focussed on the social context and preconceptions in which decisions, when a flood event occurs, are taken. Whereas McNamara and Keeler (2013) link sociological and physical models in their ABM, simulating the impact on the housing market of sea-level rise and an increase in storminess on the American East Coast. Similarly, Chandra-Putra *et al.* (2015) developed an ABM to simulate the effect of sea-level rise and insurance programmes on where people choose to live. Agents of the ABM respond to flood events, alternative insurance policies, implications of government action, and the provision of flood risk information. Du *et al.* (2017), conversely, developed an ABM to investigate the coupled

dynamics of public opinion and flood evacuation. The paper identified that flood evacuation behaviour is not solely influenced by warning, but also impacted by social media and the actions of others nearby.

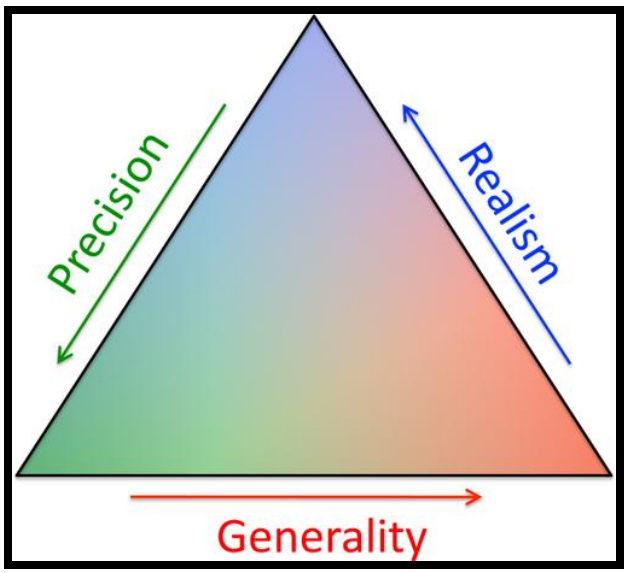


Figure 36 Trade-offs in model construction between precision, realism, and generality (Troy *et al.*, 2015).

ABMs provide a method of replicating individual decisions and the emergent behavioural patterns they can generate. However, ABMs should be interpreted as exploratory, rather than predictive: demonstrating possible socio-hydrological trajectories under different scenarios rather than forecasting exact outcomes. With this in mind, simplified models are often more effective for explanation than for prediction, particularly when they aim to reveal emergent system behaviours rather than replicate detailed processes (Murray, 2007)

In contrast, in pursuit of realism, ABMs often require many parameters, inevitably becoming more complex and moving away from comprehensibility and transparency (Dubbelboer et al., 2017), and may not be as generalisable (Janssen and Ostrom, 2006). Excessive complexity can hinder the explanatory power of a model, reducing robustness and transparency (Murray, 2003). Observing how flood risk changes over time can provide key quantitative insights into the relationships between metrics. Yet one of the key drawbacks of ABMs is their lack of transparency, often producing complex patterns that originate from the interactions between several parameters. Therefore, in an effort to provide an open and transparent platform, each rule that describes how agents interact is described in detail so others may reproduce the ABM and critique the parameters and relationships directly, rather than inferring from the outputs of the model.

3.5.1.1 Model Construction and Operation

The ABM interface used for this project was the NetLogo development platform, with code written in the native NetLogo language. The program has been used for modelling flood risk analysis before and so has a proven record in this context. Dawson *et al.* (2011) used the software to analyse the risks of flooding to people and support emergency planning. The authors developed a multi-agent ABM, coupled by a hydrological model, to estimate the risk of flooding to residents in the coastal town of Towyn under different conditions: storm surges, overtopping, flood warning times, and evacuation strategies. The study demonstrates the utility of NetLogo to develop ABMs and interact with geospatial data.

The NetLogo ABMs used in this analysis were developed using an approximation of the socio-hydrological processes, which were then validated, and calibrated where necessary, using the real-world data collected as part of **Objective 1** and **Objective 2**. Further validation was performed using policy documentation: those that discuss the benefits of the scheme, and the people and properties and/or how much worth of infrastructure assets were designed to protect ─ see Model Validation. The process of

calibration and validation was repeated until the ABM accurately models the dynamics of the system of study parsimoniously, justifying each relationship and action conceptualised by using real-world data.

The ABM developed in this study has five inputs (**Figures 37**): population data, historic and projections (from the ONS); the LiDAR DTM data (from the EA); extreme coastal water levels, historic and projections (from the Met Office); Population Share boundaries, data, and projections; and SCFP projects, construction date and height obtained from government/council documentation. These inputs are processed by the ABM to produce two key outputs: 1, *AfP* (the amount of population living in floodable areas) and 2, the Floodable Area, the *FA* (the ratio of dry land to flooded land at each iteration).

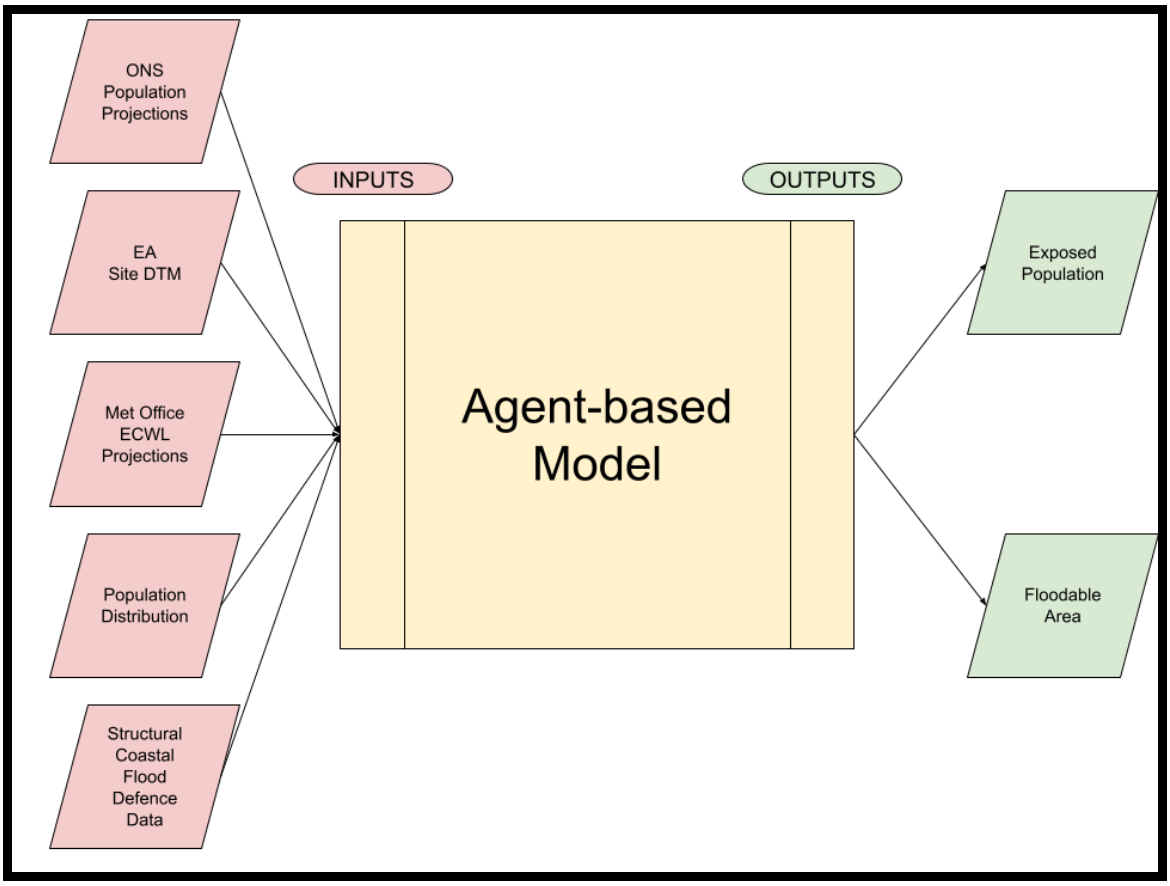


Figure 37 ABM inputs (red) and outputs (green).

The backdrop of the ABM is a DTM of the location, with a resolution of 100m × 100m, colour-coordinated code on a green scale for land, and just blue for water. Cells were assigned three-dimensional values, x as longitude, y as latitude, and z as elevation. To increase processing speed and reduce unnecessary information, the ABM used polynomial equations to represent input population data. These polynomials were developed using ONS population projections. Treating population count as the y-axis, time as the x-axis, and historic population and population projections as points along the polynomial, an equation was derived. This equation was verified using R-squared: if the polynomial estimated the data with a high enough R-squared then it could be used to represent the data ($R^2 \geq 0.995$, when $1991 \leq x \leq 2043$). Beyond 2043, towards 2100, the accuracy of the ABM decreases due to the ABM now running on the polynomial and without ONS projections. Past 2043, the polynomial follows the trend from the last vertex within the ONS population data, and carries that trend onto 2100. This output of this equation each year forms the *Total Population.*

As well as the three-dimensional values, a secondary value was added to the ABM, *Population Share*, obtained from the *Population Share* vector created by **Eq.11**. This ABM cell value is determined from a geospatial analysis, linking the cell layout of the ABM with real-world census boundaries and census data obtained from the ONS, and refers to the share of the total population that a specific individual cell

has. The *Population Share* of the cells is then multiplied by the *Total Population*, dividing it up accordingly and instilling it on the cells. The product of the *Total Population* and the *Population Share* of the cells produces the *Population Distribution* for that year. However, after 2021 there is no population spatial distribution data or high resolution population data as the censuses have not been taken yet. To resolve this a *Population Share Change Rate* was calculated.

This value, *Population Share Change Rate*, was determined by spatially linking and numerically comparing the 2011 and 2021 *Population Share* vectors (**Figure 38**) and obtaining a change rate that reflects the change in share over time. The *Population Share Rate Change* vectors were supported by the geostatistical testing conducted on the boundaries with real-world Population and comparing the difference across time between those OAs at the coastline and those elsewhere in the town. A statistically significant difference would give strength to the *Population Share Rate Change* as it would suggest that the patterns and trends observed from the rate change at the coastline compared to those landward of the defence are valuable and should be continued (as in Schoppa *et al*., 2024).

Then, to calculate *Population Share* following the 2021 census, the *Population Share Rate Change* is multiplied by the current year of the ABM subtracted by 2021, to give years elapsed. These changes are then also multiplied by the 2021 *Population Share* vector to give how the *Population Share Rate Change* has changed over time, and thus the *Population Share* for that year (**Figure 39**). Consequently, the product of the *Population Share* and *Total Population* of a given year post-2021 gives the modelled *Population Distribution*. This *Population Distribution* is then applied to the ABM and the model is run.

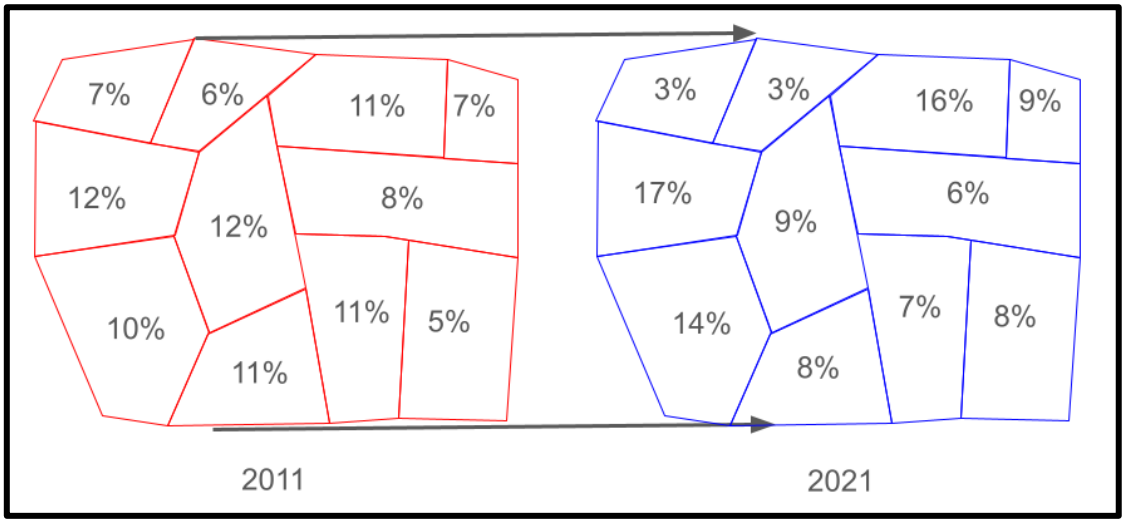


Figure 38 The *Population Share* of a hypothetical settlement and the comparison of it across time, from the 2011 census compared to the 2021 census.

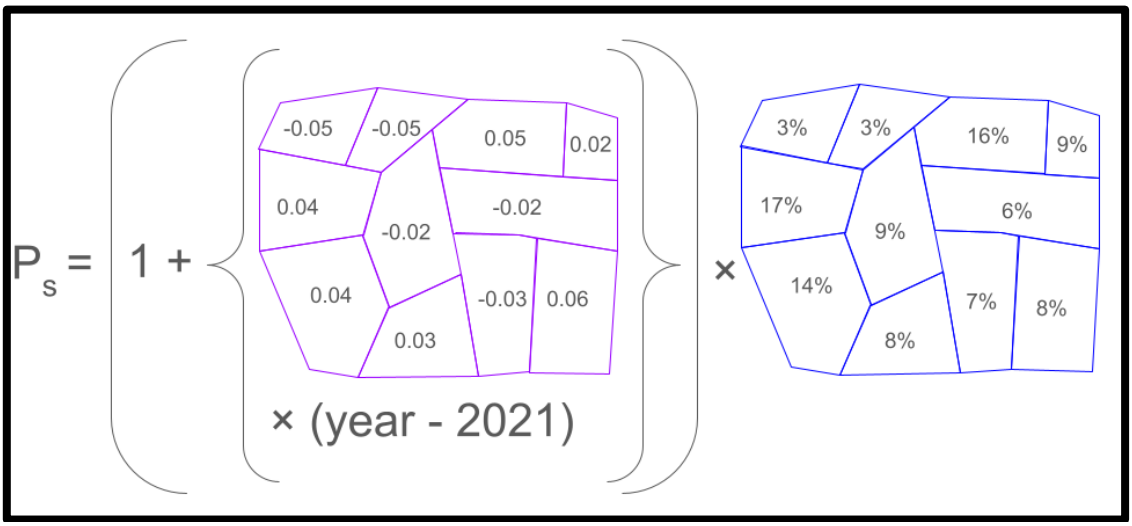


Figure 39 A modelled equation to produce *Population Share* (P_S) following 2021. The purple shapes are the *Population Share Rate Change* vector. The blue shapes are the 2021 *Population Share* from Figure 38. This is represented mathematically in Eq. 12.

Once a cell comes into contact with the floodwater it is marked as *flooded*, and the *AfP* is summated. At the end of each year the land area is reset and the *flooded* cells returned to their normal state for the next iteration. Each year the sea rises following the ECWL scenarios. In a similar manner to population approximation, annual ECWL changes were interpolated using a polynomial and the Met Office decadal predictions as datapoints. This ensured that ECWL was a continuous data and not a jagged decadal jump. The SCFP is represented using real-world dimensions and location in the ABM. Once the ECWL is higher than the SCFP the land around it is assumed that areas are flooded, this happens cell by cell until the floodwater cannot go any further due to the elevation of the land surrounding it (**Figure 40**).

To summarise the *AfP* data within the ABM an equation has been formulated to represent the process (**Eq. 12**). Up to, and including, 2021 ($t \leq 2021$), the ABM uses the *Population Share* (P_S) derived from each decadal census, and so these are derived from the 1991 census, the 2001 census, the 2011 census, and then finally the 2021 census. These *Population Share* vectors are multiplied by the overall Total Population (P_Σ). This generates *Population Distribution* for the year, the subset of *Population Distribution* affected by flooding (E), is the *AfP* output for the year.

Following the 2021 census ($t > 2021$) there is no further spatial population data and so the ABM relies on 2021 boundaries but projects how the *Population Share* will change based on a *Population Share Change Rate* (ΔP_S). This rate, when multiplied by the time elapsed since 2021 ($t_x - 2021$) and the *Population Share* from 2021, gives the *Population Share* for any given year after this period (**Eq. 12**). Then the process is the same as the calculations performed in the years prior to 2022: the *Population Share* is multiplied by the Total Population (P_Σ) to produce the *Population Distribution*. Again, the subset of the *Population Distribution* affected by flooding (E), is the *AfP* output for the year.

$$\mathrm{AfP} = \begin{cases} (t \leq 2021) \Longrightarrow [(P_\Sigma \times P_S) \in E] \\ (t > 2021) \Longrightarrow [(P_\Sigma (P_{S2}(1 + (\Delta P_S \times (t - 2021))))) \in E] \end{cases} \quad \text{(Eq. 12)}$$

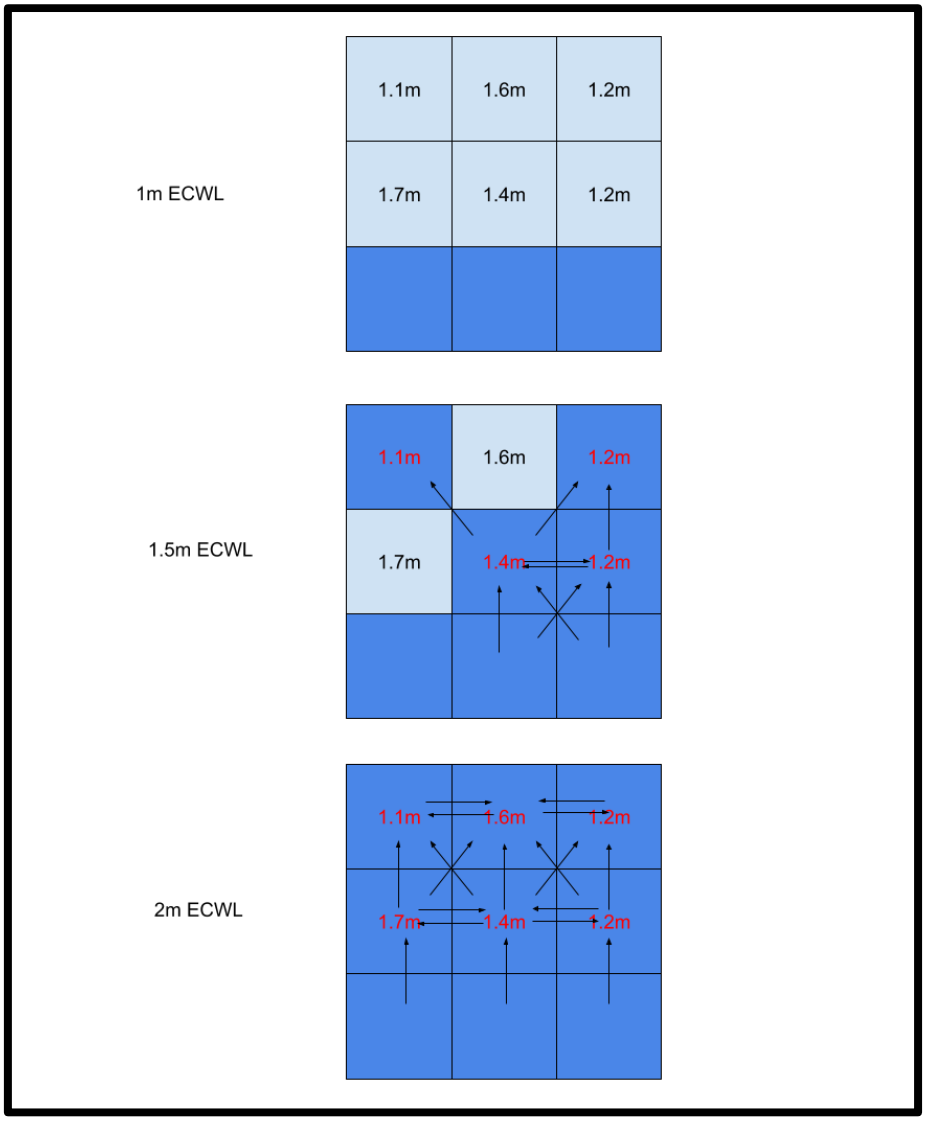


Figure 40 The processes by which cells become flooded by the sea, if there were no SCFP. This can occur in all eight directions.

3.5.1.2 Model Code

The agent-based socio-hydrological model can be split into five main stages (**Figure 41**): Set-up, Populate, FRM, Flood, and Export. The full output of the ABM is displayed in **Appendix D** and the full code in **Appendix E**.

Set-up (setup), firstly clears the ABM of anything from previous iterations (clear-all) and resets the time elapsed to zero (reset-ticks). It then loads the GIS libraries and imports the geospatial data (setup-gis): the raster DTM, the dimensions of the raster DTM, and the several population distribution shapefiles. Then it calls the creation of the boundary (setup-boundary), this boundary shapefile ensures that at the end of every iteration the land returns to being land and the sea returns to being the sea. Whilst this subroutine does nothing directly, it provides a failsafe should the flood coding fail or an error to be produced and ensures that the data is accurate. Finally, the set-up process applies the elevation values from the DTM to the cells (ask patches [set patch-elevation (gis:raster-sample elevation self)), anything below ECWL values and outside of the land boundary is then classed as the sea and coloured blue, with land coloured green. The ABM is now ready and is currently in t=0, once the ABM is allowed to run it becomes 1991 and the population is applied.

Populate (populate?) is the second stage and is activated as soon as the ABM is allowed to run. Firstly, the process calls for the creation of the anti-boundary, a shapefile that covers the sea, this is to ensure errors are not produced within the ABM: the population distribution shapefile only covers the land, as that is where people live, however, during rasterisation this creates an error as rasters must be a quadrilateral. The anti-boundary handles this by instructing the ABM that cells within the sea have a population distribution of zero. Next the ABM checks if a decade has passed yet, if it has it applies the new population share boundaries from that year (gis:apply-coverage census2001-dataset "DISTRO" patch-distro). If the ABM gets to 2021, the process applies the 2021 population share but also gives cells a new value, patch-distrorate. The ABM then either applies this rate change and multiplies by the population, or uses the population share and then multiplies by the population as determined by whether it is before 2021 or after, this the ABM interpretation of **Eq. 12**.

FRM (defend?) is the third process involved in the running of the ABM. This process is relatively simple in its operation. Firstly, the process checks whether enough time has passed and if the defence should be built yet. If it has, the process calls the SCFP shapefile, a digitisation of the real-world defence. The process then adds the defence to the ABM, and instructs the underlying cells within its boundaries to change their elevation based on the real-world height of the defence (ask patches gis:intersecting seawall [set patch-elevation defence height]).

On the other hand, the Flood (flood?) process is the most complex; using bathtub flood modelling whilst also ensuring flood cell connectivity. The process asks sea cells if they have any land neighbours with an elevation less than the ECWL (ifelse any? patches with [(pcolor = blue) AND (any? neighbors with [patch-elevation < sea-level-flood AND pcolor = lime])]). Whilst this condition is TRUE, the subroutine repeats, with sea cells asking neighbouring land cells if their elevation is lower than the ECWL, if it is marking it *flooded*, and temporarily making it part of the sea. This repeats until there are no more land squares that can be flooded. Then once this subroutine cannot go any further, the ABM counts the squares that have been flooded and summates their populations (set output (sum [patch-population] of land with [pcolor = blue])), as determined by the population share shapefile and the Total Population equation. The ABM then checks if the operator has asked for an image of the maximum flooded extent of that year (export-images?), outputs one if so, and then progresses a year (tick).

Export (export?) forms the final stage of the ABM. This process ends the ABM once it reaches the year 2100, and exports the *AfP* and *FA* data collected from the ABM run as a .csv file, which can then be loaded into a spreadsheet and analysed. This research advances our understanding of the SDP by illustrating how SCFP can increase flood risk over long-term by influencing socio-spatial distribution over the medium-term, and a dedicated paper to the topic is presented in **Appendix F**.

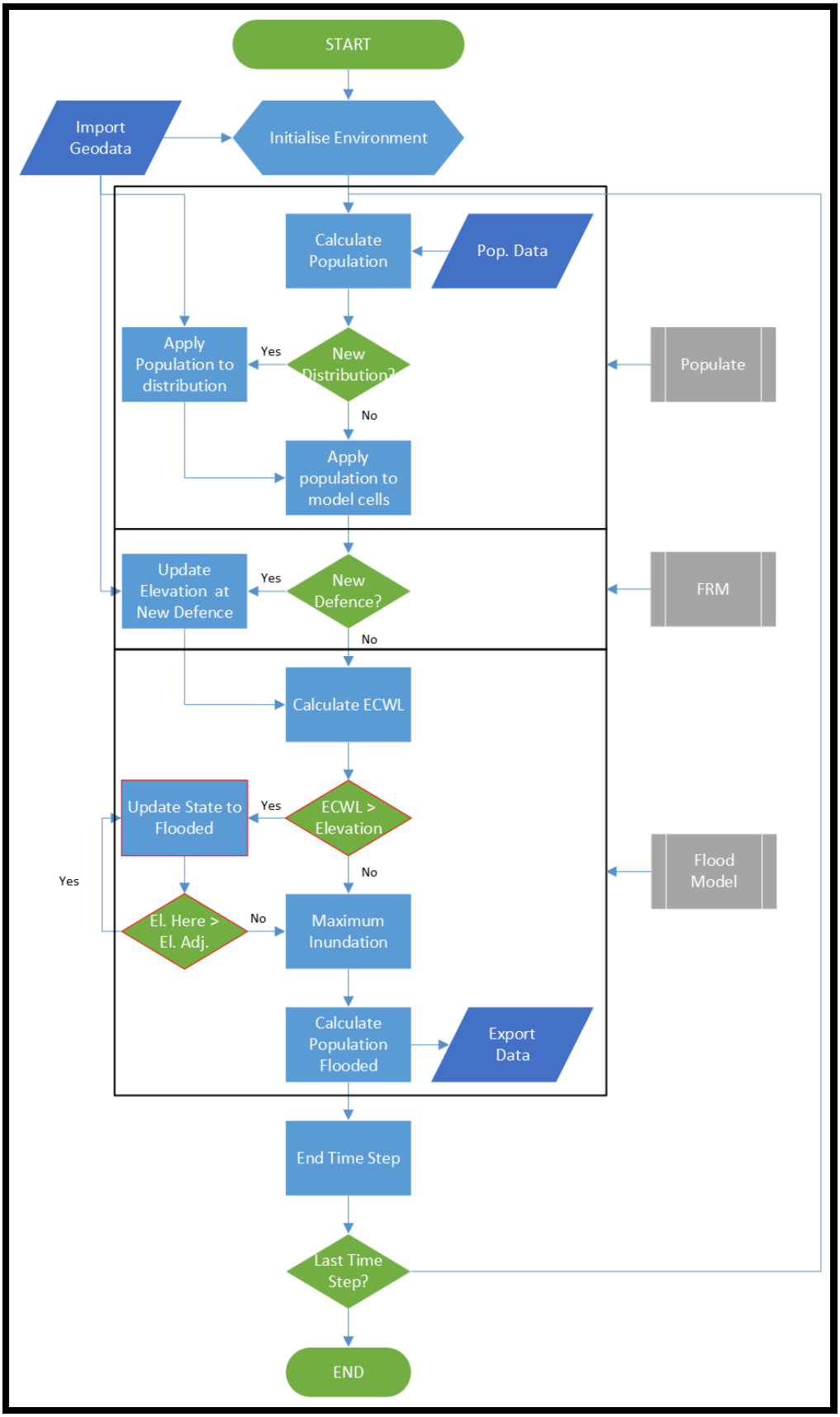


Figure 41 Flowchart of the ABM processes. Starting from *t=0* to *t=109 years*, 1991 to 2100.

3.5.1.3 Model Validation

The validation of models is critical, to test performance, accuracy, and reliability, especially when utilising complex computational tools such as agent-based models (ABMs). These models simulate the behaviour of individual agents within a system to comprehend and untangle emergent phenomena and, in this case, can assess their potential impacts on communities, infrastructure and the environment. However, before relying on these models for deriving information, patterns, and data it is essential to validate their accuracy and reliability.

The validation process involves comparing the output of the ABM against real-world data and observations to assess how closely the ABM reflects the actual behaviour of the socio-hydrological system. In the context of this analysis this translates as verifying whether the ABM accurately reproduces the dynamics of flooding, population dynamics, and *AfP*. Validation will provide confidence in the ability of the ABM to generate meaningful insights and predictions that can inform not only this project, but FRM strategies and future adaptation measures.

A polynomial equation determines the *Total Population* of the model. This equation was formulated using ONS data, and so therefore should match the actual real-world data and official predictions well. Using Portsmouth as an example, and plotting the output of the *Total Population* equation against the official ONS data for the city, shows a strong link between the two, with a coefficient of determination (R^2) of 0.992, indicating that the ABM is a very strong fit to the ONS data (**Figure 42**). The very high coefficient of determination indicates that the polynomial equation to model *Total Population* works very well and can therefore be used within the model.

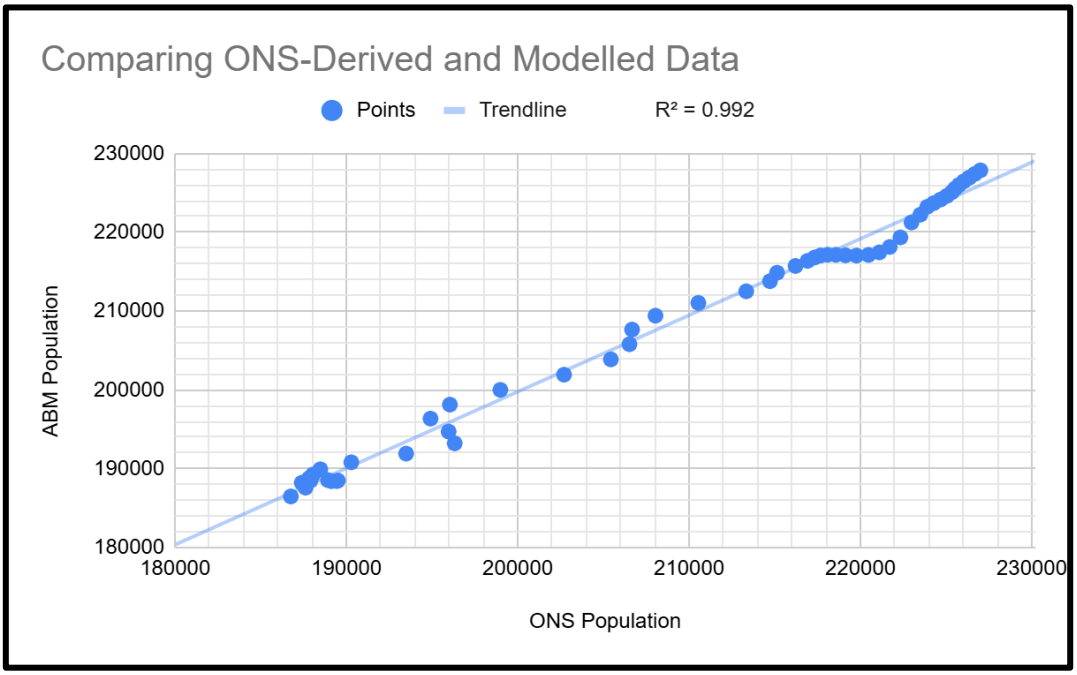


Figure 42 Population growth validation plot for the years 1991-2043, with the R-squared value of the two of 0.992 displayed.

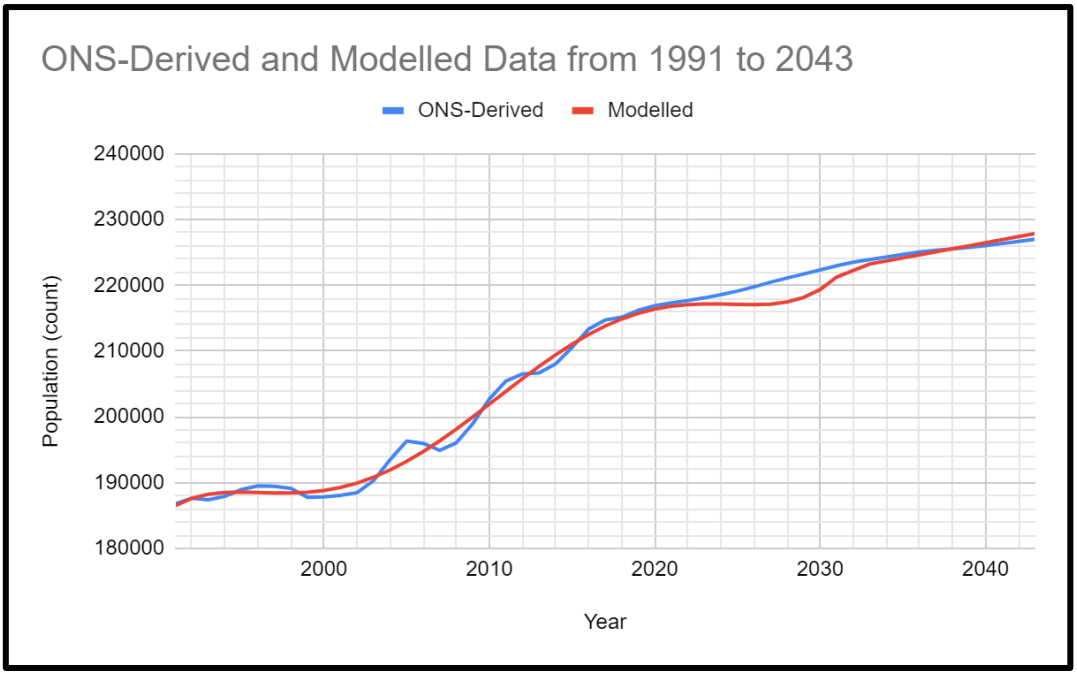


Figure 43 A comparative line graph comparing the ONS historic and projected population data for Portsmouth, and the output of the polynomial modelling equation used within the Portsmouth ABM.

However, the polynomial modelled equation does not reflect natural variations in Portsmouth well, with the small-scale peaks and troughs averaged out, and are therefore not represented by the ABM (**Figure 43**). Although, whilst the polynomial model of *Total Population* underestimates in many places, such as over the 1990s, it also overestimates a similar amount. Whilst this is not perfect, it still provides a year-on-year generatable approximation of *Total Population*, and provided the increase and decreases are not strictly limited to coastal areas at the new structural coastal flood areas, but instead dispersed across the city, then it would be reasonable to use the modelling equation. In fact, this is the exact case in Portsmouth, with the census population distribution analyses revealing that the changes in coastal population at these areas does not reflect the size of the natural variation within the ONS data. Therefore, these natural variations are not limited to these defences, but spread across the city, confirming that the ABM projects population well, and is validated in this regard.

With the modelling of *Total Population* validated, it is important to validate the spatial distribution of the population and the success of the flood modelling, this would entail comparing the *AfP* output of the model.

In 2020, Gamma, a geospatial data collection company, released a report assessing long-term climate impacts on housing stock in the UK. The company used UKCP09 projections, DTM and DSM rasters, land-use mapping and building geodata. The output produced has a resolution of 5m with a vertical accuracy of ±0.15m in areas, and is regularly validated against actual flood events in the UK.

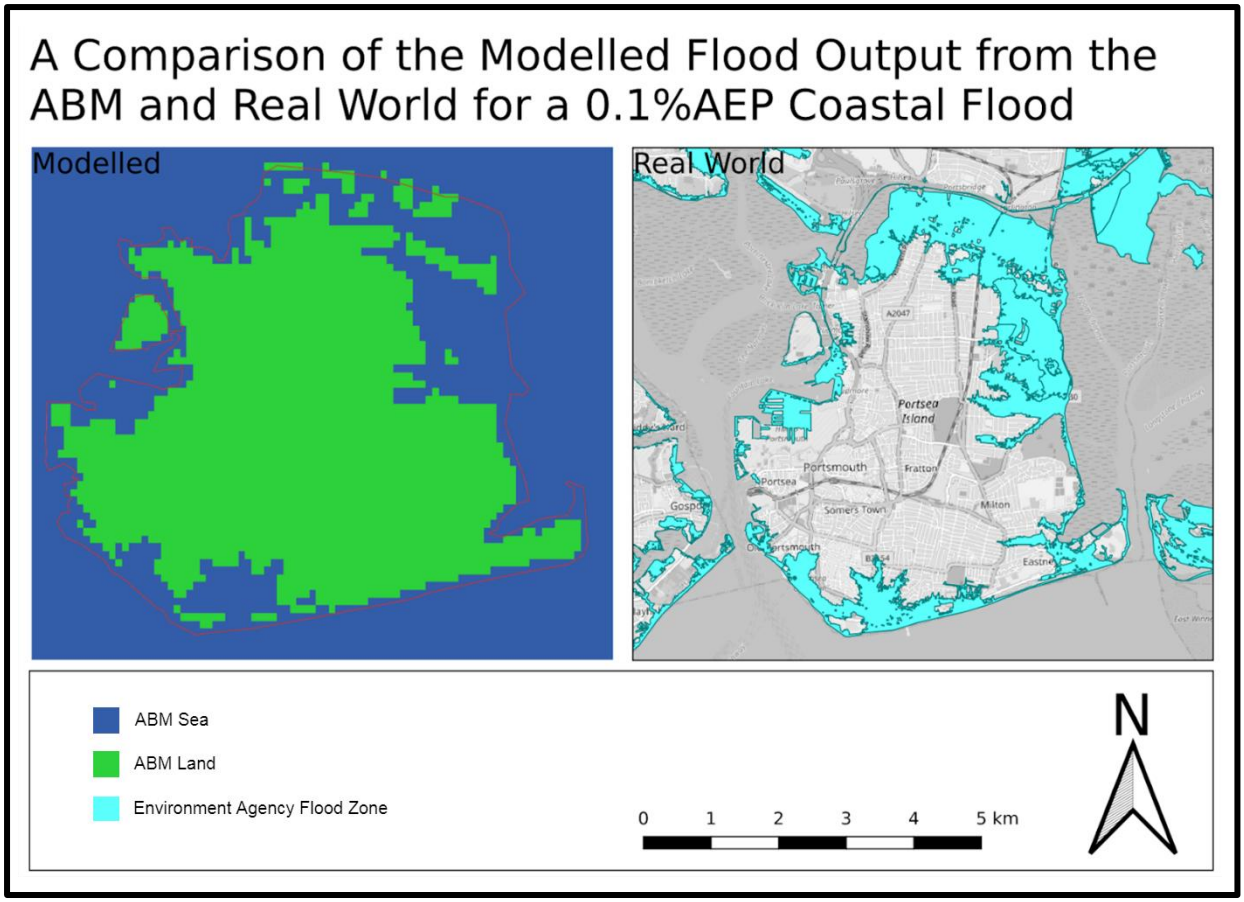


Figure 44 Comparing the flood extent of a 0.1%AEP coastal flood output from the ABM to the exposed area determined by the EA for Portsmouth.

The flood model used by Gamma, indicated that there are 4,630 properties at risk of 1%AEP flooding in Portsmouth at the baseline period, 2017 (Cantwell, 2020). Using the 2.5 people per household assumption often used in Local Flood Risk Management Strategy modelling (Metropolitan Borough of Sefton Council, 2014), this number of houses affected translates to 11,575 people. The Portsmouth ABM simulation, when running on a 1%AEP event, produces an output of 11,234 people who are exposed in 2017. Comparing the *AfP* output from the Gamma flood model to the one produced by the Portsmouth ABM gives the Portsmouth ABM an accuracy of 97% for 2017, confirming that the ABM simulates *AfP* well, and is validated in this regard.

One of the main drivers of *AfP*, determining whether a person will be flooded or not, is the coastal flood extent. To run the flood model, the ABM relies on an accurate DTM, a bare earth model of elevation derived from the Environment Agency, and accurate ECWL equations, derived using data from the Met Office. To flood, the ABM relies on a bathtub approach, flooding by simply comparing the elevation of a flooded cell to its eight adjacent cells, and if any of those cells are lower than those cells also become flooded. The bathtub approach tends to overestimate flooding due to a lack of connectivity (Kasmalkar *et al.*, 2023), and whilst the ABM does consider connectivity it will also slightly overestimate as it does not account for many of the relevant underlying hydrodynamic processes.

Nevertheless, the ABM flood extent maps well onto that of the Environment Agency and provides a good facsimile of flood extent into Portsmouth. This is evidenced by both, the comparative map (**Figure 44**) and the similarity of the *AfP* output to that produced by the Gamma flood model, confirming that *the ABM simulates coastal flood extent well, and is validated in this regard*.

3.5.2 Conceptualisation of Socio-Hydrological Processes

Conceptual frameworks can capture and visualise complex socio-hydrological phenomena. This systems perspective is particularly important in inter-disciplinary fields, such as coastal flood risk management, where multiple variables such as hydrological dynamics, societal impacts, and environmental factors interact in complex ways. The framework developed by this methodology aims to capture and represents these interactions in a structured and generalisable format, with the hope to facilitate better decision-making and planning for flood risk managers.

Designing this generalisable framework is built on an adaptation of the SPR/C model, as described in **Section 2.4.3**. This framework allows the model, to not only depict the sources of risk, but also the chain of interactions that lead to the consequences, providing a highly structured, systematic understanding of coastal flooding and associated socio-spatial dynamics, to understand not just and plan for not just the immediate risks, but also the long-term vulnerabilities created by changes in human behaviour and settlement patterns around SCFP. One-dimensional SPR/C models are sequential in nature, representing coastal flooding as a process that follows a straightforward path from source to consequence. Whilst this type of representation works well for basic analyses, it fails to fully capture the emergent phenomena and cyclical feedback loops that characterise the unintended consequences of SCFP. The two-dimensional SPR/C framework extends the linear model into a more interconnected system that allows multiple source, pathways, and receptors to interact simultaneously. This broader representation provides a more holistic view of the risks and consequences of coastal flooding, where interactions can compound and lead to unintended consequences. This framework is more suited for cyclical processes and allows for the representation of feedback loops.

The generalisable framework allowed for the identification of points of reducing the unintended consequences and move towards greater flood resilience, allowing for a better understanding of how communities might recover from flood events and adapt over time. The conceptual framework also provides a platform for exploring future risk scenarios, where urban development interacts with coastal flooding and the impacts of climate change, the framework can be a powerful tool for adaptive flood management, helping planners to anticipate and mitigate the long-term unintended consequences of SCFP.

The generalisable conceptual framework was developed using a five-step process.

1. **Pattern Identification**
   Observing changes and identifying patterns in socio-spatial and built environment geodata, across time, in response to SCFP.
2. **Mapping Linkages**
   Plotting the relationships between the components and mapping how these processes allow for the progression of the cycle across time
3. **Model Development**
   Building the conceptual model by constructing linear SPR/C framework to fit real-world data and connecting them together to form a larger cycle
4. **Scenario Testing**
   Testing the conceptual framework on historic flood events to see if the processes and outcomes match the events
5. **Implementation**
   Using the conceptual model to identify points in the cycle to mitigate the unintended consequences of SCFP and suggest methods to tackle these complex phenomena

This approach provides a flexible and comprehensive tool for flood risk management: by creating a multidimensional framework, this methodology captures both the immediate risks of coastal flooding and the long-term socio-hydrological consequences, ensuring that communities are not only protected but also resilient to future changes in climate and human development.

The immediate risk originating from more frequent and unpredictable hazards, leading to more severe consequences, demonstrates the need for alternative FRM strategies, such as building resilience

(McClymont *et al.*, 2020). Resilience first originated in ecology, used by Holling (1973) before growing into uses in the social sciences, psychology, and disaster management. At its core, resilience relates to the ability of a system to resume functionality after a disastrous event (McClymont *et al.*, 2020). Percival and Teeuw (2019) argue that in the context of flooding, resilience is the ability of a community to alter itself so that the damage of floods is mitigated and minimised. A resilient community should therefore maintain a significant amount of processes, functioning and structure (Adger, 2006). Therefore, when building the resilience of a community, practices must be found that keep the functioning and structure of the system running, and allow the community to persevere. This will assist in the completion of **Objective 5**: *Identify methods of achieving desirable flood risk outcomes and enable sustainable planning to create resilient communities*. Building resilient communities must seek to undo the unintended consequences brought on by the construction of SCFPs. These consequences will have been defined via the completion of Objectives 1 to 4, and it is these emergent processes that must be overcome in order to build resilience at the science-engineering-policy nexus.

Lessons are drawn from the data and a new approach for FRM in the UK is proposed. This is aided by the literature review, assessing innovations in FRM, stakeholder engagement, geospatial technologies, and socio-hydrology. A roadmap will be produced as the culmination of this report, suggesting a way to change the national narrative on FRM, in an effort to break the SDP. A changing climate is inevitable and the UK may be ill-prepared: the Independent Assessment of UK Climate Risk report states that '*the UK is not prepared for unprecedented extreme weather events that could occur now'* and *'lack of adaptation over the past five years has also led to lock-in, irreversible changes and higher future costs for the Government*' (King *et al.*, 2021). Action must be taken to prevent further lock-in effects and an exacerbation of the current flooding issues, which need to be resolved at the science-engineering-policy nexus, creating a truly integrated spatial planning system with FRM.

4.0 Results

This chapter presents the findings from the detailed analysis of the three contrasting coastal case studies and their associated comparative sites located across the UK (**Figure 45**): Southport, with Blackpool and Crosby; Weston-super-Mare, with Burnham-on-Sea and Clevedon; and Portsmouth, with Gosport.

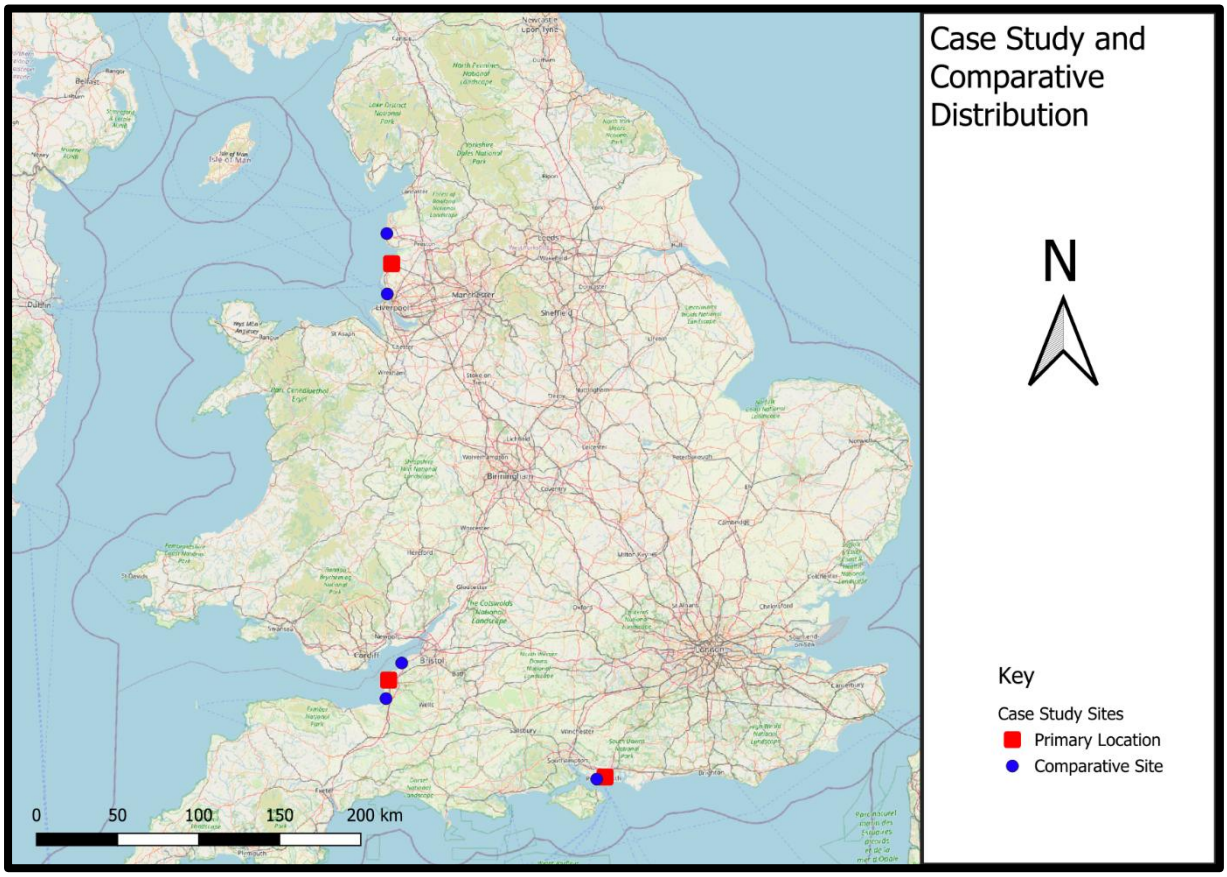


Figure 45 Location of the three contrasting primary sites (red block) and adjacent comparative secondary sites (blue circles) distributed across the UK.

4.1 Longitudinal Analysis

From an analysis of the changes in population distribution, economic activity, housing occupancy, and urban development this section highlights the influence of SCFP on demographic changes and settlement patterns. Both, socio-spatial and economic shifts are critical for understanding how SCFP impacts demographic trends, urban expansion, and the evolution of community resilience in flood-prone areas. Pre-defence is defined as the time prior to the construction, or major upgrade of the SCFP. Post-defence is defined as the time afterwards.

4.1.1 Case Study A

This case study focused on the construction of a new coastal flood defence in Southport (Merseyside). The new SCFP has a SoP of 1-in-150. Towns selected for comparative analysis were Blackpool (Lancashire) to the north and Crosby (Merseyside) to the south (**Figure 46**). Blackpool has an independent economy, whereas Crosby is also part of the Merseyside economic area.

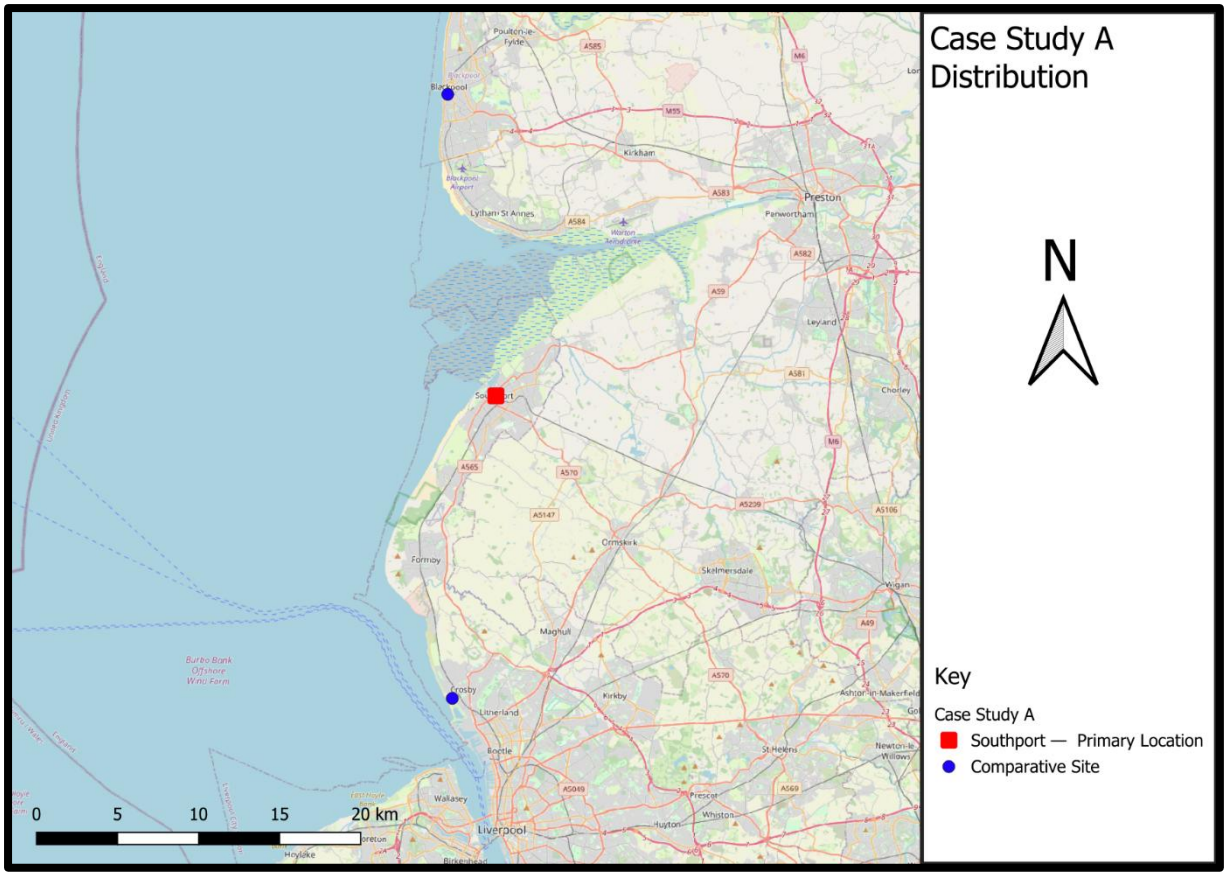


Figure 46 The distribution of sites, primary and comparative, used for Case Study A.

4.1.1.1 Southport

Located at (53.6531N, -3.01462E).

In 2001, prior to the construction of the coastal flood defence, the population of Southport was reported to be 82,170. In 2001, the majority of the population lived along the A570 and A565 corridor. The A570 (E-W) connects to the M58, the northern Merseyside and Greater Manchester connector route, whereas the A565 (N-S) parallels the coastline and metro service, and progresses south into Liverpool city centre. Population density varies across the town, with higher concentrations observed in the urban areas closer to the town centre, whereas the suburban areas exhibited lower population densities, suggesting a more dispersed settlement pattern. The town centre consisted of a majority of apartment blocks and terraced houses, catering to the needs of tourists and urban residents. Moving landward, away from the town centre, detached and semi-detached housing become more prevalent.

The age distribution of the population of Southport in 2001 indicated a predominantly older population compared to the national average. This is likely due to the popularity of the town as a retirement destination, with many older populations moving to the area from elsewhere in Merseyside and across Lancashire. Coastal areas had a higher concentration of retirement homes and are those with a higher proportion of older adults. Southport has historically been known as an affluent town, attracting residents of higher socio-economic status. In 2001, the town exhibited signs of socio-economic disparity. The coastal areas and central regions tended to have higher levels of affluence, whereas those just behind the coastal areas and some suburban areas showed signs of lower income and higher deprivation. Areas in the north of the town, in the Marshside area, areas also in Flood Risk Zone had a higher concentration of economically inactive (EiA) populations.

The coastal flood defence was constructed in 2003, the census following was in 2011. Therefore, there is a decade gap between analyses. As reported by the 2011 census, the population of the town was 90,381, up 8,211 people at an annual percentage growth rate of 0.99% per year, greater than the increase

in *AfP* (0.49%/yr) (**Table 11**). Areas in the FZ, such as those in Marshside, in the northern to northeastern area of the town, saw a decrease in population from before the construction of the coastal flood defence to afterwards. However, areas such as Blowick and some OAs in the town centre saw a population increase, as did several OAs to the immediate southwest of the newly constructed defence. However, these were not in the FZ, but were adjacent to it (**Figure 47**). *Therefore, following the construction of the defence in Southport, overall populations in the FZ decreased, but population near to the flood defence increased, although this was also part of the increased population growth across the town centre.*

Across the decade, from pre- to post-defence, the proportion of EiA residents of each Output Area (OA) generally decreased. The largest drop was the OA that the new SCFP runs through, contributing to the slight decrease in the *Exposed & Vulnerable* population as well as two smaller OAs to the far north of Southport (**Table 11**). In contrast, many neighbouring OAs in the FZ in Marshside increased, as well as one to the east (**Figure 48**), although generally, most OAs decreased in the proportion of EiA residents, especially those by the defence and other central areas. Historically, Merseyside was not an affluent area with many residents unemployed and EiA. However, in 2008 Liverpool became European City of Culture, multiple large-scale regeneration projects took place, and a strong local economy developed. These impacts trickled down to Southport residents over the decade. It would be difficult to draw a conclusion from this and suggest whether decreases in the EiA population were from the construction of the defence, the strengthening of the local economy, or whether it was from the economic dominance from Liverpool. *Ultimately though, the proportion of EiA people by the defence per OA decreased from the time before the SCFP was constructed to afterwards*.

Overall, comparing the pre- and post-defence period, housing occupancy increased in the town, by an average of 0.854% in each OA (**Table 12**). During this period, 2001 to 2011, the number of people per household per OA decreased in the outer edges of the town, even in areas within the FZ and in the more EiA areas of the town: presence in the FZ appears to have negligible impact on occupancy (**Figure 49**). However, the OA that is bisected by the SCFP saw an increase in housing occupancy, as did the majority of neighbouring OAs also. *There was an increase in the number of people per household in the OAs at and neighbouring the new SCFP, while other OAs saw a stabilisation or a decrease in housing occupancy across this period*.

In addition to population change, physical change is also apparent in the town during the pre- and post-defence period due to the construction of new buildings over this period. One development, to the southeast of the pier and adjacent to the railway, was also constructed in this period, out of the FZ, replacing a 3m to 10m structure. Whereas, at the southwestern end of the new flood defence, three large buildings were constructed, each ranging from 3m to 20m and exist entirely within the FZ (**Figure 50**). Other significant development occurred in areas just outside this area of the FZ where the new large-scale development has occurred, such as a new small square building 3m to 20m tall to the southwest, a new 10m to 20m tall tower and a >20m tall one next to it, as well as a new square of housing to the east. In fact the majority of the new urban development across this period was significantly weighted towards the coastline, this is reflected by the statistically significant growth in urban development from pre- to post-defence period (**Table 13**). *The study highlights that a new large-scale, and statistically significant, urban development has occurred in Southport post-defence, with the vast majority of that development being within the FZ, or in areas immediately adjacent*.

In summary, the key changes observed in Southport post-defence include:

- Population at the central section of the defence increased, however, population also increased across the town;
- The proportion of EiA residents decreased at the defence, this was also apparent generally across the town;
- Housing occupancy at the newly constructed defence increased, whereas other areas of the town saw a decrease or a stabilisation;
- There was significant urban growth at the defence, but limited urban growth in the majority of other areas of the town.

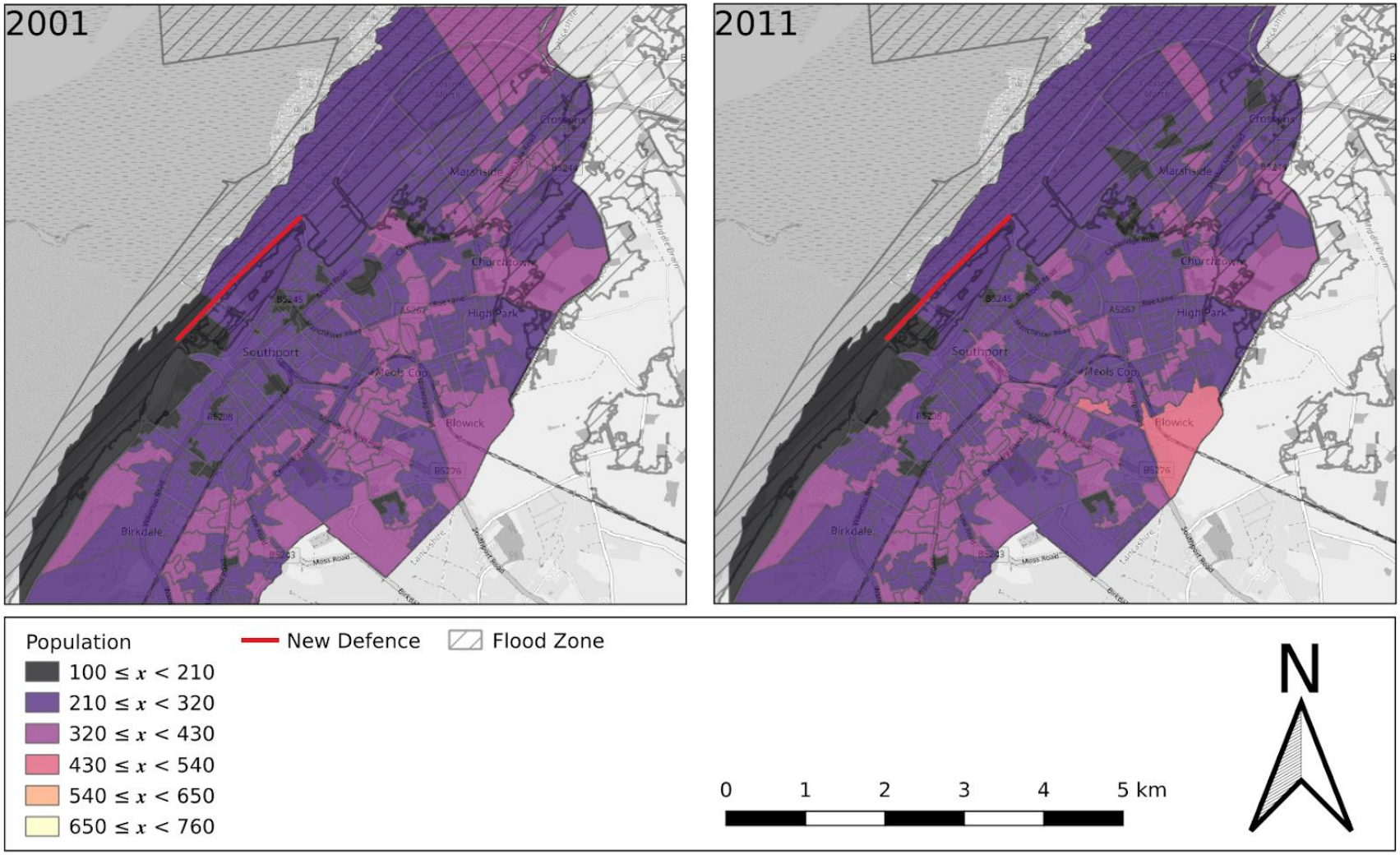


Figure 47 A comparison of the population of Southport grouped by census Output Area in 2001 (pre-) and 2011 (post-defence).

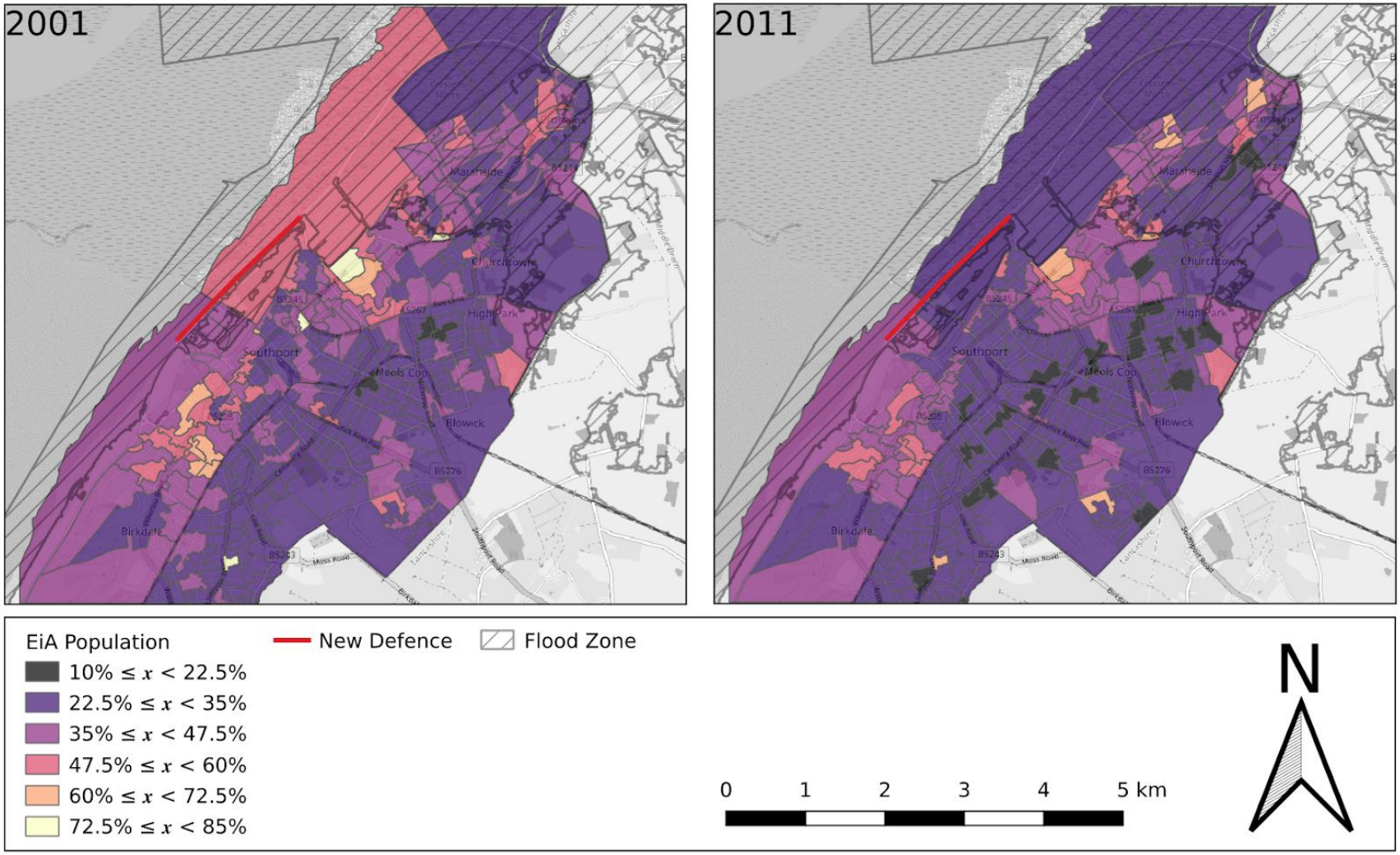


Figure 48 A comparison of the economically inactive (EiA) population of Southport grouped by census Output Area in 2001 (pre-) and 2011 (post-defence).

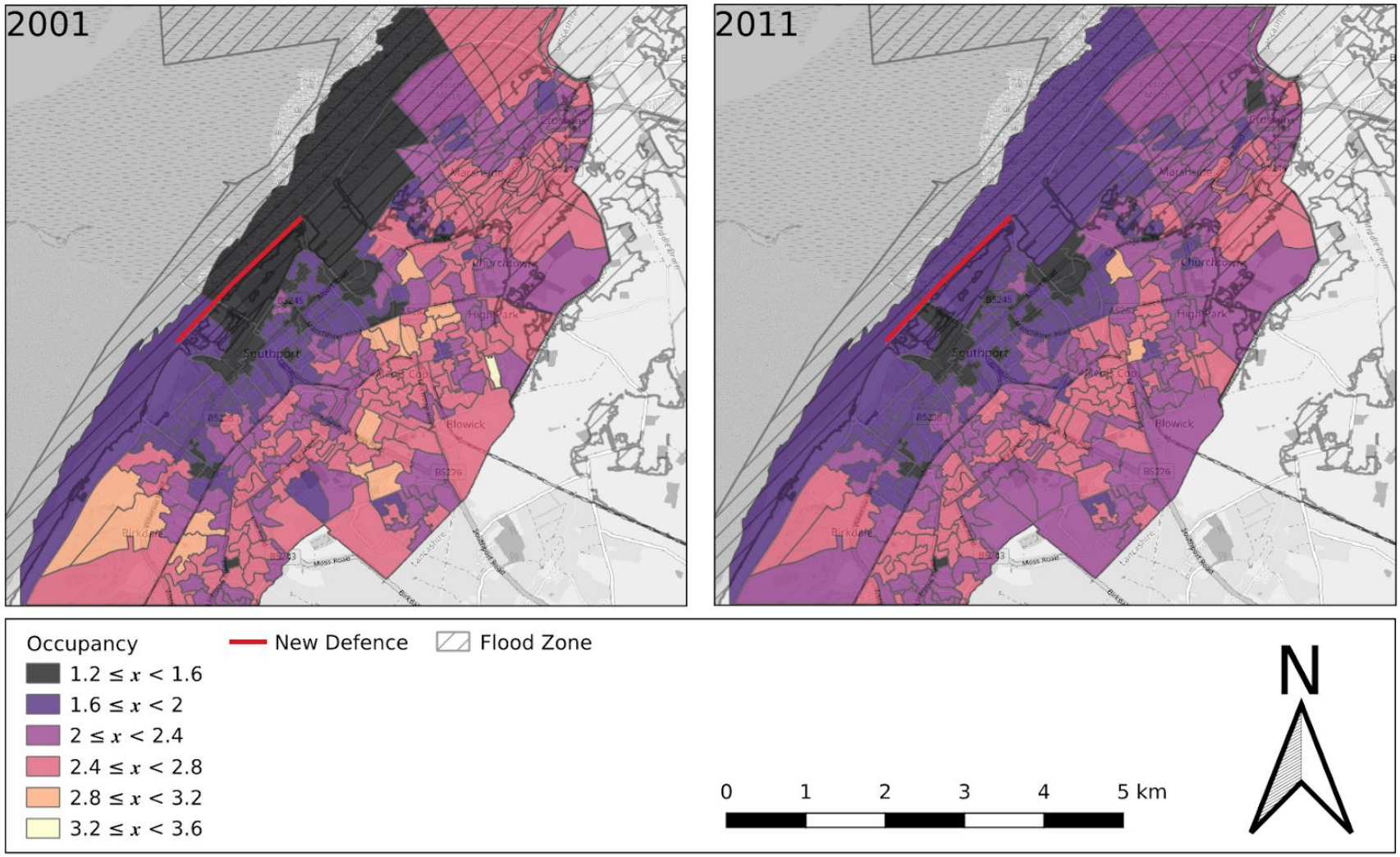


Figure 49 A comparison of population per household of Southport grouped by census Output Area in 2001 (pre-) and 2011 (post-defence).

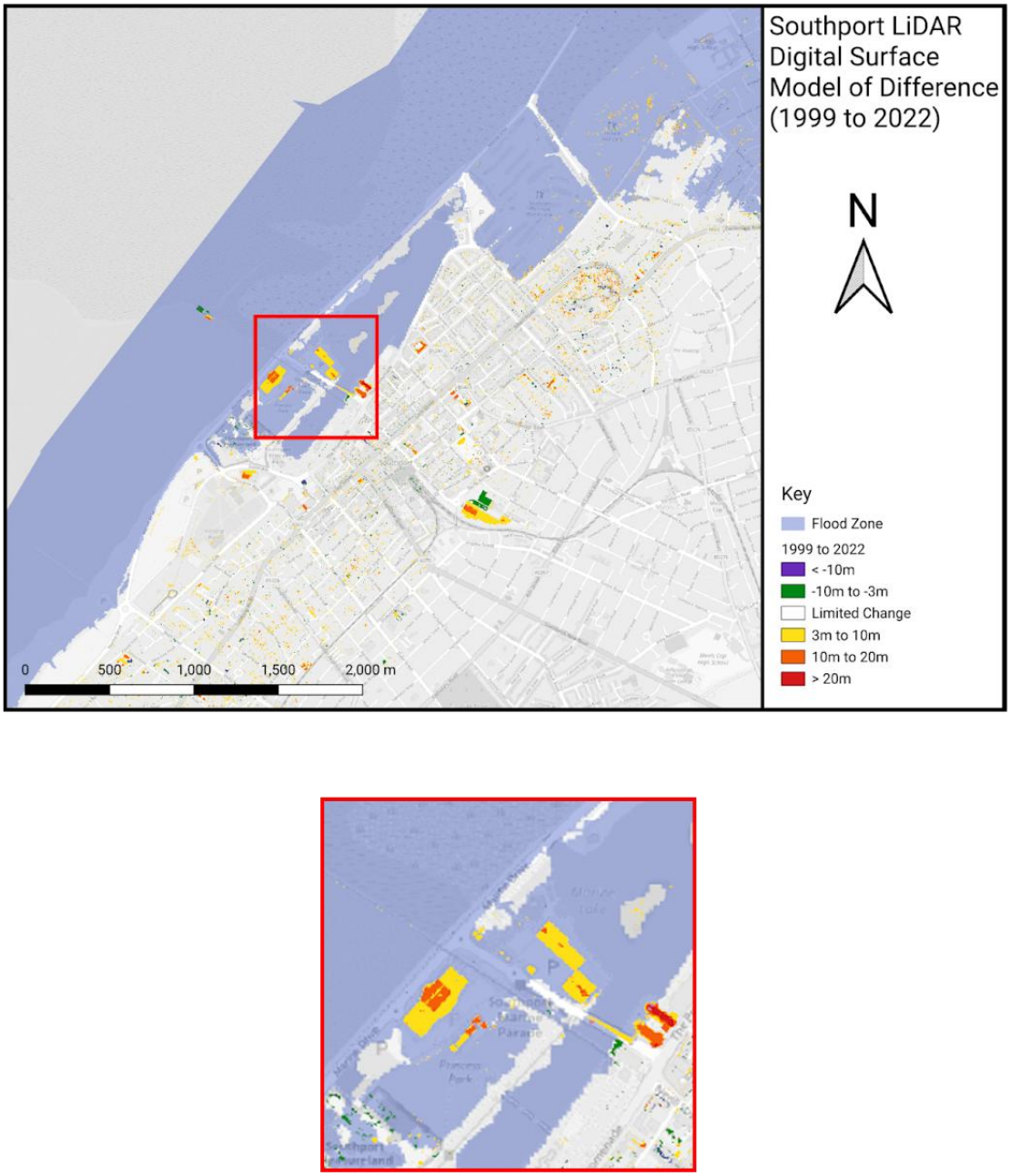


Figure 50 Southport 1999 and 2022 LiDAR DSM comparison. Central-west Southport is inset.

Table 11 Population changes from the census before (2001) and afterwards (2011) in Southport.

Risk Category	**Time Period**	**Population**	**Annual Growth Rate**
Total Population	Before	82,170	0.99%
	After	*90,381*	
Exposed Population	Before	17,170	0.46%
	After	*17,793*	
Exposed & Vulnerable Population	Before	4,544	-0.18%
	After	*4,461*	

Table 12 Occupancy rate changes between censuses in Southport.

Average Occupancy		**Percentage Change (%)**		
Before	*After*	Average	Standard Deviation	Maximum
2.20	2.22	0.854	21.740	75.183

Table 13 The results of the geostatistical test of Southport urban changes before defence construction and afterwards.

Result	**Lower Bound**	**Upper Bound**	***p*-Value**
2.548	1.783	3.312	≤0.05

4.1.1.2 Blackpool

Blackpool lies approximately 18.8km north of Southport. Located at (53.81914N, -3.05603E).

Until the 18th century Blackpool was a small coastal village, however, following construction of a new link road in 1781 the area grew in popularity and population. The town had a population of 500 in 1801, growing to over 2500 by 1851. The construction of the railways connected the town to the major industrialised cities of north England, which brought in an influx of settlers. By 1881, the town had grown to 14,000, and 47,000 by 1901, and 147,000 by 1951; over this time the seafront was developed to include piers, entertainment, and a tram network. Blackpool, and surrounding areas grew, becoming one contiguous urban area along the Fylde peninsula incorporating the towns of Fleetwood, Cleveleys, Thornton, Poulton-le-Fylde and Lytham St Annes. In the 2001 census, before the defence at Southport was completed, the population of Blackpool was 129,071. The most populated areas at this time were those on the eastern edge of the town and the densely populated South Shore. Those areas in the South Shore on the coast also had the greatest amount of EiA population, compared to wealthier areas towards the eastern edge of the town.

Presently, Blackpool is a sizeable town, one of the largest in Lancashire, especially when including its metropolitan area. The town has the longest surviving tramway in the UK, five railway stations on two railway lines within its official boundary and an international airport ─ albeit yet to reopen since the Covid-19 pandemic. The southern line provides a direct service to Preston, whereas the northern line provides wider intercity services out of Lancashire to York, Liverpool, Manchester, and London. Blackpool proper has several distinct areas and is split into 3 districts: North Shore (including Bispham), Central Shore, and South Shore (including Marton). North Shore is the quieter end of Blackpool, with significantly less tourist activity and comprising mostly residential buildings, light industry and business parks.

In contrast, Central Shore is where the majority of the nightlife and evening entertainment exists, the location of the main commercial area, many pubs, and major transport links. However, landward behind this area is one the oldest residential areas of Blackpool, formed of tightly packed Victorian terraced housing. Similar is the South Shore, featuring the theme park and southernmost pier, smaller shops and hospitality venues. The residential buildings of this area are mostly post-war expansionist: large semi-detached housing, large gardens, and large amounts of social housing, linked to the centre via the tram network. Linking to South Shore is the main route out of Blackpool, the A5073, which connects to the M55, the main E-W link across the Fylde peninsula and access to the major northern industrial cities via the M6 at Preston.

As reported by the 2001 census, the population of Blackpool at this time was 129,071, which grew to 142,065 by 2011 ─ a percentage growth rate of 1.00% per annum (**Table 14**). OAs that grew the most were often on the edge of the town and followed key infrastructure, such as railways or primary roads, suggesting that they may be intercity commuters. Between the coast and the outskirts, the town centre itself and Central Shore saw a drop in population between this period. Similarly, at the coastline almost all OAs saw a population decrease, and whilst none were within the FZ, all were bounded by it to the west (**Figure 51**). *Therefore, from the time before the SCFP was constructed in Southport to afterwards, coastal population in Blackpool decreased. This coastal population decrease also occurred in Southport, with the notable exception, however, of OAs bordering the newly constructed defence*.

Generally, across Blackpool there was a decrease in the EiA population from before the SCFP was built at Southport (2001) to afterwards (2011). Coastal OAs in the southern part of the town, around South Shore saw a large decrease in the proportion of EiA residents, whereas many to the east and south remained stable, as well as slightly north in the town centre (**Figure 52**). The largest decreases were the OAs in the northeast. Between these two periods there appears to be negligible connection between coastal locations and impacts on the proportion of EiA residents. *Therefore, the proportion of EiA residents in each OA was not related to proximity to the coastline and changes were not apparent from before the defence was constructed in Southport to afterwards, but there was a decrease in the proportion of EiA residents in some coastal OAs*.

However, housing occupancy from before the construction of the Southport SCFP to afterwards were noticeable. Some coastal OAs encountered a fall in housing occupancy over the decade, whereas other sporadic OAs increased, most notably the large OA at the central eastern edge of the town (**Figure 53**). The stabilisation of many areas across the period, but a drop in some coastal OAs led to a decrease in the average people living in each house per OA (**Table 15**). The coastal areas that saw decreases in housing occupancy were those around the railway station and near to the coastal attraction the Pleasure Beach. *Comparing Blackpool from before the defence at Southport was constructed to afterwards, housing occupancy decreased in some coastal areas. This is in contrast to Southport, which saw a decrease or stabilisation in occupancy in much of the town, at the coastal flood defence there was an increase in housing occupancy*.

Decreases in housing occupancy in these areas can be accounted for by new high-density residential, and commercial development, which may have the effect of lower housing occupancy by providing more accommodation leading to a higher population density. New development in this area was revealed in the LiDAR change map, highlighting development change across the decade (**Figure 54**), in addition to the construction of the new stadium in the South Shore. The geostatistical testing output gave a large range, with a t-score of 0.042 and a resulting p-value of 0.872, consequently, the change in Blackpool urban development from before the SCFP at Southport was not statistically significant at the 0.05 α-level (**Table 16**). *In summary, Blackpool did not have statistically significant coastal urban development in this period, but there was in Southport*.

Consequently, comparing from before the Southport defence, to afterwards, in Blackpool:

- Coastal population and the proportion of EiA residents in coastal areas decreased;
- Housing Occupancy in most coastal OAs decreased;
- There was not a statistically significant change in coastal urban development.

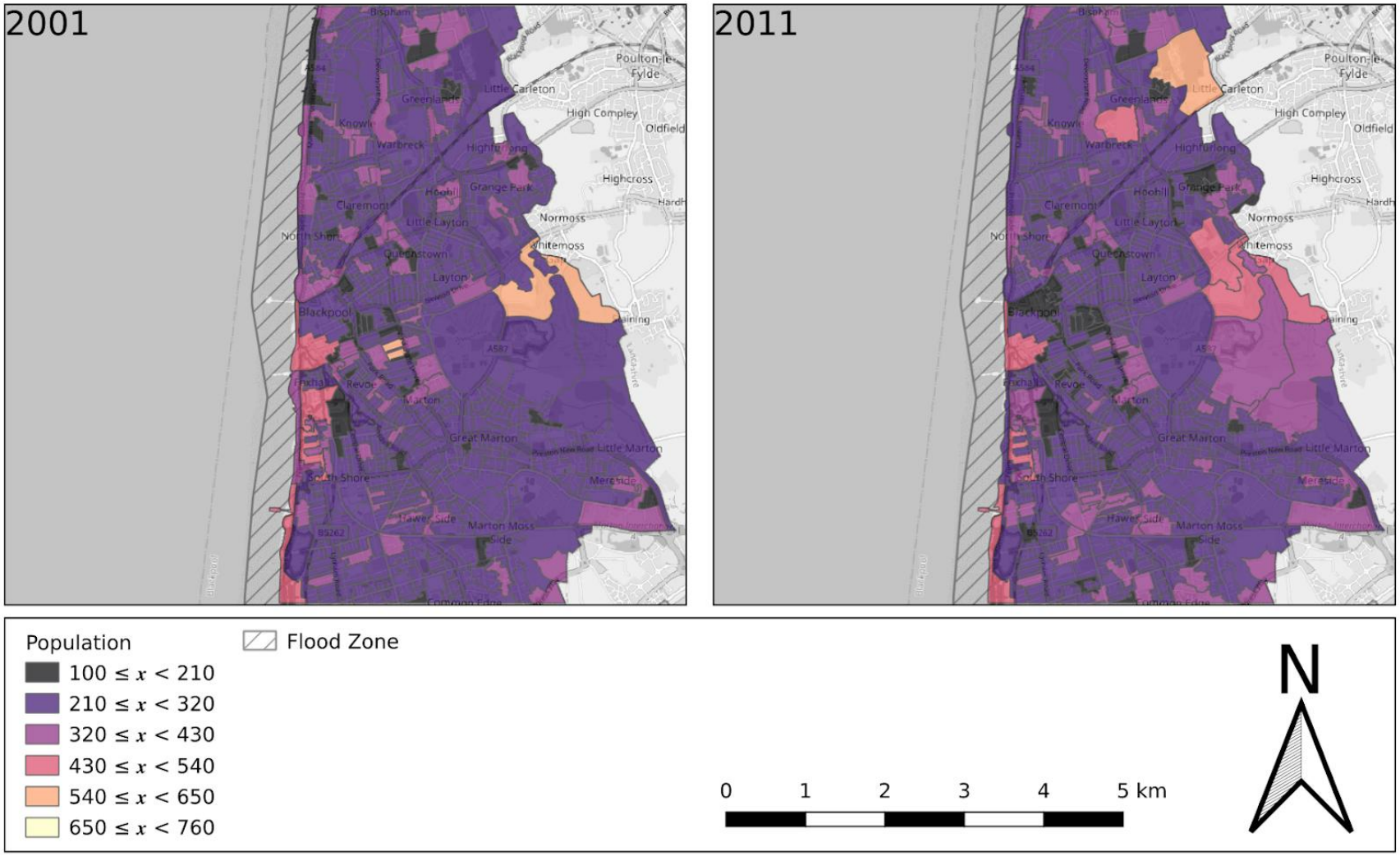


Figure 51 A comparison of the population of Blackpool grouped by census Output Area in 2001 (pre-) and 2011 (post-defence).

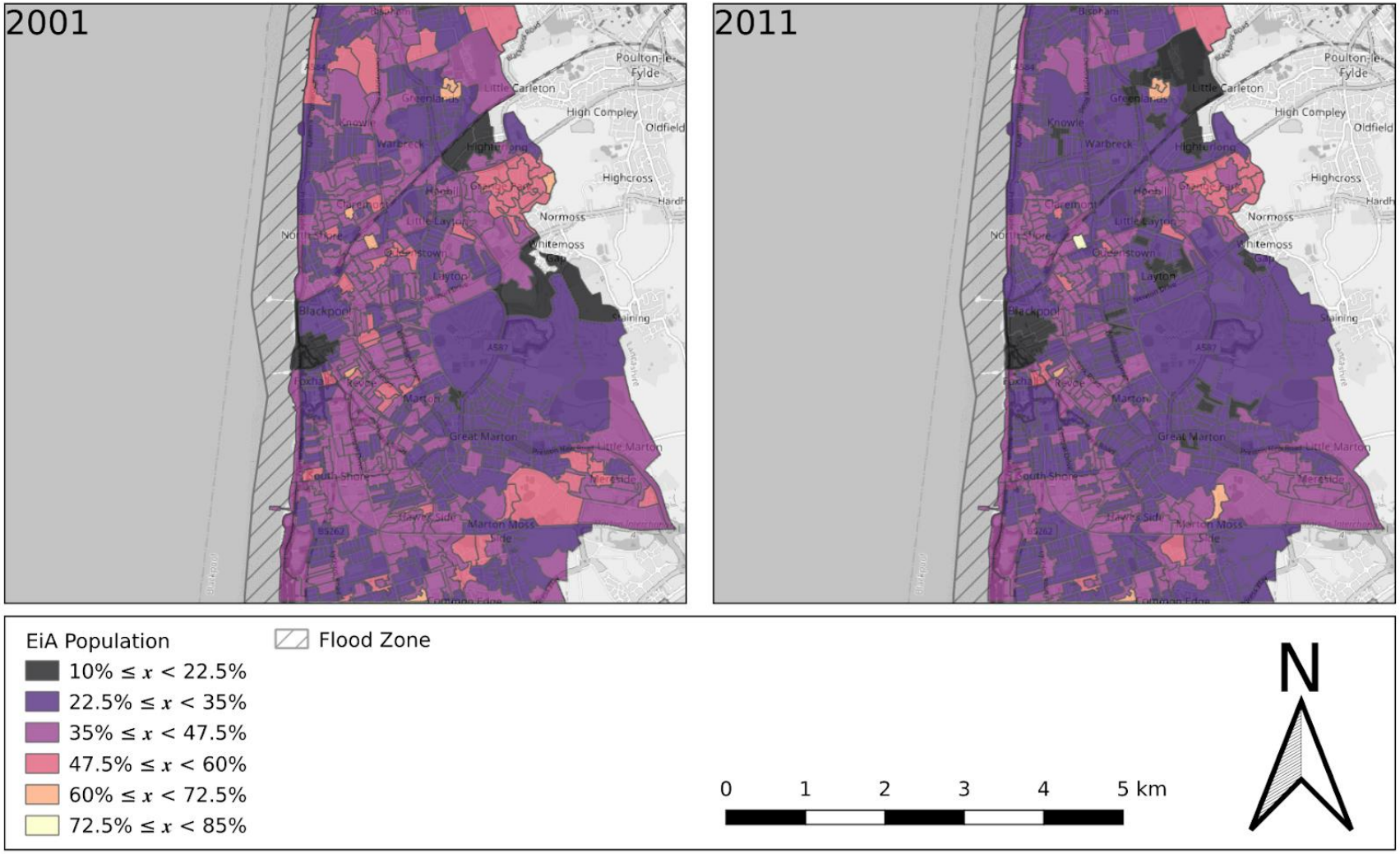


Figure 52 A comparison of the economically inactive (EiA) population of Blackpool grouped by census Output Area in 2001 (pre-) and 2011 (post-defence).



Figure 53 A comparison of population per household of Blackpool grouped by census Output Area in 2001 (pre-) and 2011 (post-defence).

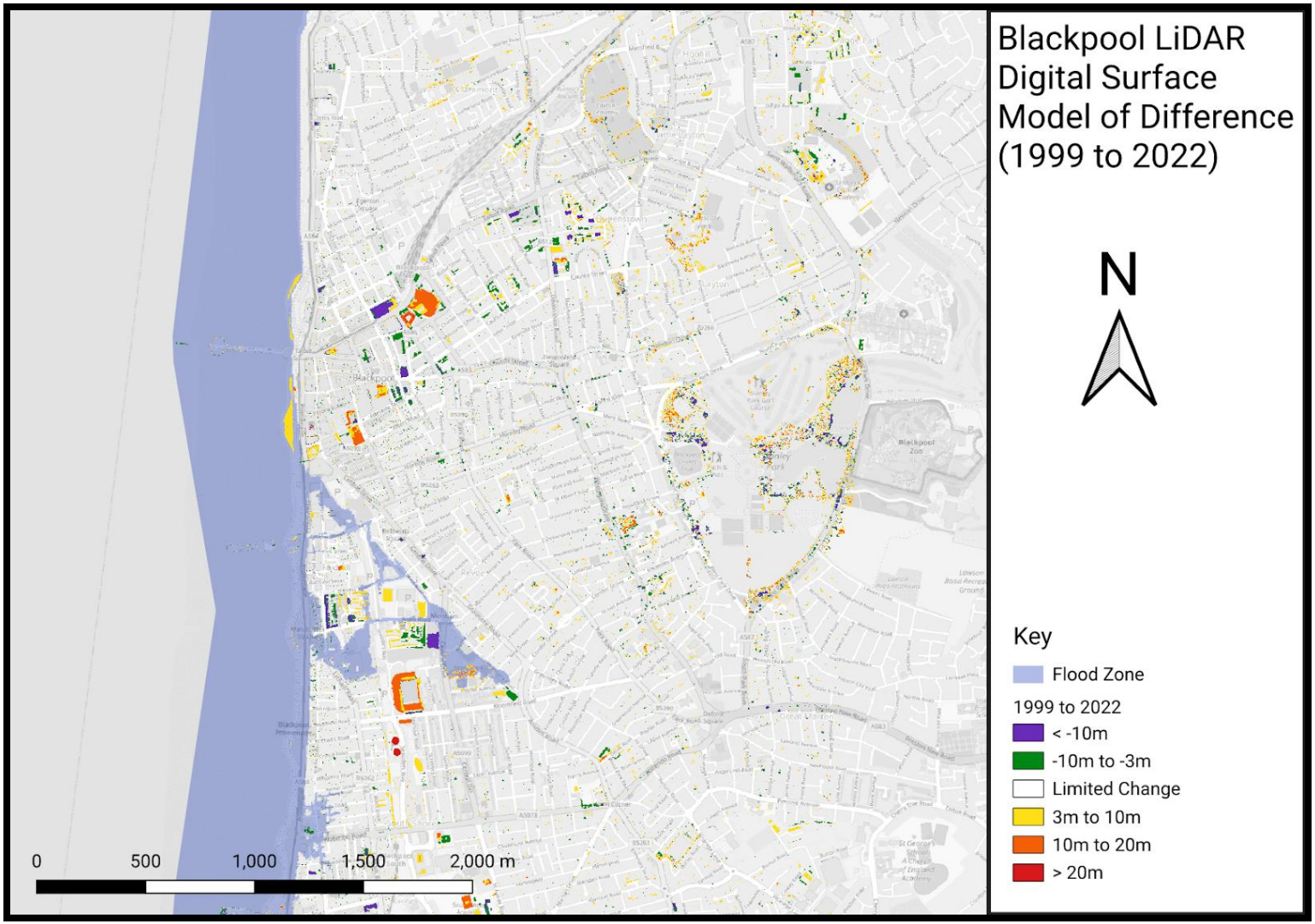


Figure 54 Blackpool 1999 (pre-) and 2022 (post-defence) LiDAR DSM comparison.

Table 14 Population changes from the census before (2001) and afterwards (2011) in Blackpool.

Risk Category	Time Period	Population	Annual Growth Rate
Total Population	Before	129,071	1.00%
	After	*142,065*	
Exposed Population	Before	18,649	1.03%
	After	*20,571*	
Exposed & Vulnerable Population	Before	5,296	0.28%
	After	*5,443*	

Table 15 Occupancy rate changes between censuses in Blackpool.

Average Occupancy		Percentage Change (%)		
Before	*After*	Average	Standard Deviation	Maximum
2.15	2.14	1.900	22.734	96.970

Table 16 The results of the geostatistical test of Blackpool urban changes before the Southport defence construction and afterwards.

Result	Lower Bound	Upper Bound	p-Value
0.043	-0.476	0.561	0.872

4.1.1.3 Crosby

Crosby lies approximately 18.9km south of Southport. Located at (53.48426N, -3.04845E).

Crosby was originally settled by the Vikings, although evidence of human occupation suggests the area has been settled for over 8,500 years. The population of the area remained stable until the opening of the Liverpool, Crosby, and Southport Railway in 1848. The railway encouraged growth along the Mersey and Liverpool Bay, and led to Crosby being incorporated as an urban district in 1937, and then as an official part of Merseyside in 1974. In 1977 the Merseyrail project was completed, converting old Victorian railways and enabling through-running of metro trains from Southport, along the Irish Sea, Liverpool Bay, and River Mersey via the city centre, creating a comprehensive and linked metropolitan area.

Rapid growth led Crosby to become an amalgamation of many surrounding settlements: Crosby, Great Crosby, Little Crosby, Blundellsands, Waterloo, Brighton-le-Sands, and Thornton. Little Crosby and Thornton are relatively rural settlements on the edge of the area, mainly comprising larger detached and semi-detached. Great Crosby acts as the commercial hub for the area, despite being a distance away from the metro line. The Northern Line runs north-south through the area following the coastline, with stops at Waterloo, Brighton-le-sands, Blundellsands, and Crosby. Running parallel is the A565, which provides a direct connection to Liverpool city centre and to the Mersey tunnels linking to the Wirral, Chester, and North Wales. At the landward extremity of the Crosby area is the A5758 that connects to Switch Island, the major junction between the A59 (Liverpool - Preston), M57 (Liverpool Outer Ring Road), M58 (North Liverpool - North Manchester), and the A5036 (main route to Liverpool Docks).

Before the construction of the Southport coastal flood defence, Crosby had a population of 42,079, with the majority of the population living in Great Crosby and along the A565 road, and small pockets around Merseyrail stations. Over the decade, the population of the town grew by 0.42% annually, to 43,876 in 2011. Crosby, and many nearby areas, are part of the more affluent areas of Liverpool, and this is highlighted by the economic inactivity of the local population, which is low overall.

Before the SCFP was built in Southport, Crosby had a population of 42,079, with the majority of the population living in Great Crosby and along the A565 road, and small pockets around the Merseyrail stations. A decade later, after the SCFP at Southport was complete, the population of the town grew by 0.42% annually, to 43,876 in 2011, in contrast to the 0.15% annual growth in *AfP*, from 3,762 to 3,820 (**Table 17**). Population growth tended to increase mostly in the south of the town, towards Waterloo and Seaforth. At the coast however, the population stayed the same or decreased in two OAs to the north of the town. Inland, population growth was mainly focused around the A565 and metro stations towards the south of the town (**Figure 55**), this corridor-focused population growths were the main driving force behind increases in Crosby population, not proximity to the coastline. *Therefore, when comparing the time from before the Southport SCFP to afterwards, the coastal population and Crosby mostly remained stable. This is in contrast to the coastal population at Southport that primarily decreased, with the exception of OAs adjacent to the defence*.

Generally, there were fewer residents of Crosby who were EiA in the time after the defence at Southport was completed. Although there was an increase of 18 people who were EiA and lived in an exposed area, this is far too small to be significant (**Table 17**). Despite the FZ not passing too deeply into Crosby, it does pass through some OAs, only two of which saw an increase in the proportion of EiA population. Although most of these exposed, and other coastal OAs, saw a decrease in the proportion of EiA. The inland of south Crosby saw the largest decreases in EiA, around the Litherland area, and similar to population the largest changes were around main transport corridors (**Figure 56**). These areas saw an increase in population, but a decrease in the proportion of EiA residents, suggesting that during the time period more people moved to the area who were economically active, or residents who were already there became more economically active. Regardless, the area became less vulnerable as a result. *Therefore, the proportion of EiA residents living in coastal Crosby decreased from before the defence was constructed in Southport, to afterwards. This occurred similarly in Southport, both, at the defence and in the general coastal population*.

Occupancy, the measure of people per household, decreased generally across Crosby from 2001 to 2011, including in coastal areas whereby the occupancy of most OAs decreased (**Figure 57**). Housing occupancy in the north of the town remained stable whereas proceeding further south more and more OAs saw a decrease. The largest decreases were near metro stations in Seaforth and Litherland, and on key roads, suggesting the importance of transport corridors in the area. On average, the housing occupancy of each OA fell from 2.41 to 2.23 people per household (**Table 18**). *Therefore, in Crosby housing occupancy decreased in coastal OAs from the time before the Southport defence was completed, to afterwards. This is in contrast to the area around the defence at Southport that saw an increase in housing occupancy*.

Further, this is combined with a lack of new construction over this decade also: there was negligible new residential or commercial development, with the exception of a new leisure centre built on the seafront (**Figure 58**). This resulted in a t-score of -0.137, with a range of -0.352 between 0.078, and a p-value of 0.212, reflecting the low growth over this period (**Table 19**). *Consequently, there was not statistically significant growth in Crosby from before the SCFP was built at Southport, to afterwards*.

Consequently, comparing from before the Southport defence, to afterwards in Crosby:

- Coastal population remained stable, whereas coastal EiA population decreased;
- Housing Occupancy did not increase at the coastline;
- There was not a statistically significant change in urban development.



Figure 55 A comparison of the population of Crosby grouped by census Output Area in 2001 (pre-) and 2011 (post-defence).



Figure 56 A comparison of the economically inactive (EiA) population of Crosby grouped by census Output Area in 2001 (pre-) and 2011 (post-defence).



Figure 57 A comparison of population per household of Crosby grouped by census Output Area in 2001 (pre-) and 2011 (post-defence).



Figure 58 Crosby 2002 (pre-) and 2022 (post-defence) LiDAR DSM comparison.

Table 17 Population changes from the census before (2001) and afterwards (2011) in Crosby.

Risk Category	**Time Period**	**Population**	**Annual Growth Rate**
Total Population	Before	42,079	0.42%
	After	*43,876*	
Exposed Population	Before	3,762	0.15%
	After	*3,820*	
Exposed & Vulnerable Population	Before	976	0.18%
	After	*994*	

Table 18 Occupancy rate changes between censuses in Crosby.

Average Occupancy		**Percentage Change (%)**		
Before	*After*	Average	Standard Deviation	Maximum
2.41	2.23	-3.027	7.754	48

Table 19 The results of the geostatistical test of Crosby urban changes before the Southport defence construction and afterwards.

Result	**Lower Bound**	**Upper Bound**	***p*-Value**
-0.137	-0.352	0.078	0.212

4.1.1.4 Synthesis of Case Study A

The construction of a SCFP in Southport led to noticeable socio-economic and infrastructural changes in the area surrounding the newly constructed defence. The population adjacent to the defence increased, suggesting that the structure may have provided a sense of security and protection, attracting new residents to the area. This occurred whilst many other coastal areas of Southport saw a decrease in population (**Table 20**). Additionally, Blackpool, one of the comparative settlements for the study, saw a decrease in coastal population, while Crosby, the other comparative settlement, saw a stabilisation in coastal population.

Table 20 A summary table of the studied factors and locations in Case Study A and how they change from the time before the new Southport coastal flood defence (blue font) to after: upwards arrow and green cell indicate positive change, dynamic equilibrium arrow and orange cell indicate stabilisation, downward arrow and red cell indicate a negative change.

	Southport		**Comparative**	
	Defence	Elsewhere	Blackpool	Crosby
Coastal Population	⇧	⇩	⇩	⇌
Coastal EiA	⇩	⇩	⇩	⇩
Coastal Occupancy	⇧	⇩	⇩	⇩
Coastal Development	✓		×	×

At the newly constructed SCFP in Southport, there was an increase in the population distribution in census OAs adjacent to the defence from before the construction to afterwards (**Table 21**). This increase (~15.3%) was statistically significant compared to the population distribution change elsewhere in Southport which saw an average change of -1.8%. However, in the comparative sites there was not a statistically significant change in population distribution between coastal OAs and those within the town (**Table 21**). Blackpool saw a similar change in population distribution at the defence and in the sample of OAs elsewhere in the town, but not statistically significant at the 0.05 α-level. Likewise, there was a similar decrease in the population distribution change between the coastal area and the town sample, which was also not statistically significant. Therefore, in Southport, the increase in population distribution of adjacent areas to the newly constructed defence, whilst the other areas of the town did not change at a similar rate, was not replicated in other comparative sites: the defence altered the population distribution of the town with a 97.6% certainty that it was not induced purely by chance.

Table 21 A table containing the output of the average change in population distribution in the area adjacent to the newly constructed/ upgraded SCFP in Southport, or seafront in Blackpool and Crosby. The table also contains the p-value output from a t-test comparing the two locations within each site at the 0.05 α-level.

	Coastal/Defence	**Elsewhere**	**p-Value**
Southport	15.265%	-1.796%	0.024
Blackpool	4.072%	3.090%	0.345
Crosby	-2.268%	-5.586%	0.144

However, regarding socio-economic factors, the proportion of EiA people decreased near to the newly constructed SCFP in Southport, as they did generally across other coastal areas in the town. Similar patterns were also seen in Blackpool and Crosby (**Table 20**). This could be attributed to several factors, including increased job opportunities associated with the construction and maintenance of the defence, as well as potential improvements in the local economy due to increased tourism or business development.

In contrast, the housing occupancy increased near to the newly constructed SCFP in Southport, but this was not observed in coastal areas in Blackpool or Crosby (**Table 20**). This increase could be driven by a combination of factors such as increased safety perception and potential economic opportunities. Whereas, the housing occupancy decrease in coastal areas of Blackpool and Crosby, suggests a decline in demand for housing in those areas.

Moreover, the construction of the SCFP in Southport resulted in statistically significant urban growth in the area adjacent to the defence. This significant growth was not observed in Blackpool or in Crosby. This growth could be attributed to the perceived benefits of the defence, such as increased security, potential economic opportunities, and improved quality of life. However, these improvements can lead to infrastructural lock-ins and the socio-economic and urban changes observed in Southport. These outcomes are consistent with research by Burby (2006), showing that structural flood protection measures tend to shift population socio-spatial dynamics. Moreover, the statistically significant urban development adjacent to the SCFP also parallels trends observed by Harries (2012), where structural flood defences and flooding experience serve as catalysts for increased urbanisation. *Therefore, to summarise, the construction of the new SCFP at Southport led to socio-economic and urban changes in adjacent coastal areas. These were not replicated in comparative sites*.

4.1.2 Case Study B

This case study focused on the upgrading of a coastal flood defence in Weston-super-Mare (Somerset), from a 1-in-50 SoP, to a 1-in-200. Towns selected for comparative analysis were Burnham-on-Sea (Somerset) to the south and Clevedon (Somerset) to the north (**Figure 59**). Burnham-on-Sea is more likely to have an independent economy, whereas Clevedon is on the periphery of Bristol.

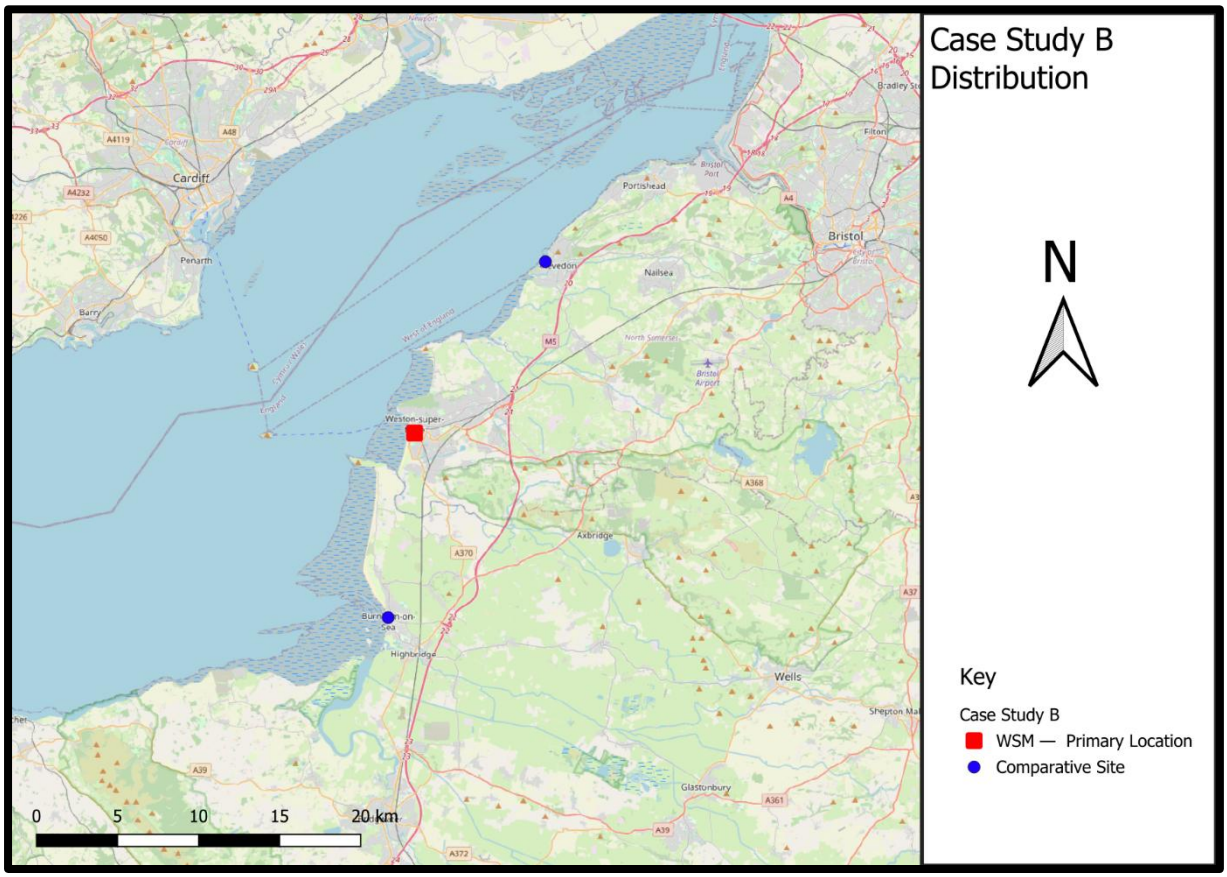


Figure 59 The distribution of sites, primary and comparative, used for Case Study B.

4.1.2.1 Weston-super-Mare

Located at (51.3477N, -2.9816E).

In 2001, the population of Weston-super-Mare was 65,489, rising to 76,703 in 2021 with an annual percentage growth rate of 0.86%. In the early 19th century, the town emerged as a Victorian coastal resort. However, once the Bristol and Exeter Railway opened, connecting the town to the wider country, the population rose dramatically, and established Weston-super-Mare as the primary settlement in North Somerset. The town has numerous suburbs: St. Georges, West Wick, and Worle in the far east adjacent to the M5 motorway; Milton and Ashcombe just east of the town centre; Worlebury in the north; Uphill in the southwest; and the new urban village of Haywood in the southeast of the town, on the former Weston airfield.

In 2001, the areas with the highest population were those adjacent to the town centre and in the St. Georges area of the town, most likely owing to its proximity to the M5 motorway that provides direct connections to Bristol. In 2001, the areas to the east of the town centre, St. Georges, West Wick, and Worle, had the lowest economic inactivity. All of the areas with populations with the highest economic inactivity were at risk of flooding.

The SCFP upgrade in Weston-super-Mare was completed in 2011. From before the project was complete, to afterwards, population in the town had increased by 11,000, increasing at a rate of 0.86% per year (**Table 22**). The majority of the population of the town are exposed, due to the extent of coastal

flooding and the degree to which the FZ extends into the town. The eastern edge of the town borders the M5 motorway, linking Birmingham and the South West via Bristol. The motorway links to the Weston-super-Mare seafront through the A370, which bisects the town centrally on an E-W axis. These OAs bordering the M5 motorway saw some of the greatest increases in population during the pre- and post-defence upgrade period, despite lying within the FZ. In fact, the greatest increase of any OA is that of one lying in the FZ, which also contains the M5-A370 junction (**Figure 60**), suggesting a large commuter population in this area. In addition, another large increase was the development of the Haywood estate towards the centre of the town, 2.1km away from the coastline. Historically an airfield, the development started in 2013 and created a new large-scale housing estate, a large proportion of which is in the FZ. The extreme inundation potential of Weston-super-Mare leads to many relying on the SCFP, despite being kilometres away: in fact the FZ proceeds further into the North Somerset Levels, a large coastal plain of 79.5km^2. At the coastline, at the far western end of the town where the newly upgraded flood defence exists, OAs which the defence runs through remain stable with regards to population. However, there were increases in OAs adjacent to the defence. *From the period before defence upgrading, to afterwards, population increased in areas adjacent to the newly upgraded defence, as well as in other areas of the town*.

Two decades later, economic inactivity had worsened across the town, most likely as a result of economic stagnation arising from the Covid-19 pandemic: EiA residents in exposed areas had increased by 3.13%/yr, much greater than the increase in overall and *AfP*, despite being a function of the latter (**Table 22**). The largest increase in the proportion of EiA residents occurred at the largest OA that the newly upgraded defence passes through. This increase was also seen in other OAs adjacent to the newly upgraded defence, but to a lesser degree (**Figure 61**). Moving eastwards, the pocket of moderately high proportion of EiA residents surrounding the town centre decreased, although some OAs to the south of this area increased. Further east, in the new estate, the proportion of EiA residents is low, as well as in those areas adjacent to the M5 motorway, yet again suggesting a high population of commuters. *Therefore, whilst many areas of Weston-super-Mare saw an increase of the EiA population the largest concentration of increases were those on or adjacent to the newly upgraded SCFP*.

The changes in population and the proportion of EiA people per OA were echoed in the differences in the housing occupancy from before the SCFP was upgraded to afterward. Across the town, occupancy rates were already relatively high for the region, and the housing occupancy of each OA increased on average by 0.05 people per household (**Table 23**). The largest decreases were in the east of the town, in those OAs adjacent to the M5 motorway (**Figure 62**). However, the largest increases were in those OAs on the seafront, adjacent to the newly upgraded SCFP, with every OA seeing a large increase. This increase means that more people at the defence are living more densely and reflects desirability of the area. Other OAs in the town remained relatively stable, with the exception of the Haywood estate, but a new large-scale housing estate being created would be expected to have an impact on the OA it resides in. The FZ appears to have limited effect on housing occupancy because as many occupancy changes happen inside it, as outside (**Figure 62**). *Therefore, from before the SCFP was constructed to afterwards, the housing occupancy of OAs adjacent to the newly upgraded defence had the largest increases, whereas changes in occupancy in other OAs of the town was mixed*.

The increase in the housing occupancy of the coastal area was not reflected in the LiDAR differential mapping, comparing from before the upgrade of the SCFP to afterwards: there was little change in the area (**Figure 63**). This would suggest internal construction, with the conversion of properties to 'Houses in Multiple Occupation' (HMOs). Further north, still parallel to the newly upgraded defence, there was a large change from before the SCFP was upgraded to afterwards: large-scale medium density development was constructed, the majority of which lies within, or adjacent to, the FZ. This new development was completed over the 2013 to 2014 period, only two to three years after the newly upgraded defence was completed. This area had the greatest amount of new development, not only the largest buildings, but also the highest concentration. Other areas of Weston-super-Mare also saw some low-level growth in a roughly N-S line in the centre of the town, almost entirely within FZ 2 (**Figure 63**). The urban growth at the coastline in Weston-super-Mare was statistically significant (**Table 24**), and demonstrates that there had been significant change at the coastline across the period of the defence

upgrade project. *From before the SCFP was upgraded in Weston-super-Mare to afterwards there was statistically significant growth in the area adjacent to the defence*.

Therefore, to summarise the changes in Weston-super-Mare that occurred from before the SCFP to afterwards:

- Population at the coastal flood defence increased, but population also increased across the town of Weston-super-Mare generally;
- EiA population increased the most at the coastal flood defence, EiA population also increased across the town, but not as significantly;
- Housing occupancy increased at the coastline, but changes in housing occupancy were mixed in the rest of the town;
- There was a statistically significant change in urban development at the coastline, with a new group of large-scale medium density urban development, the scale of which not seen elsewhere in the town.



Figure 60 A comparison of the population of Weston-super-Mare (WSM) grouped by census Output Area in 2001 (pre-) and 2021 (post-defence).

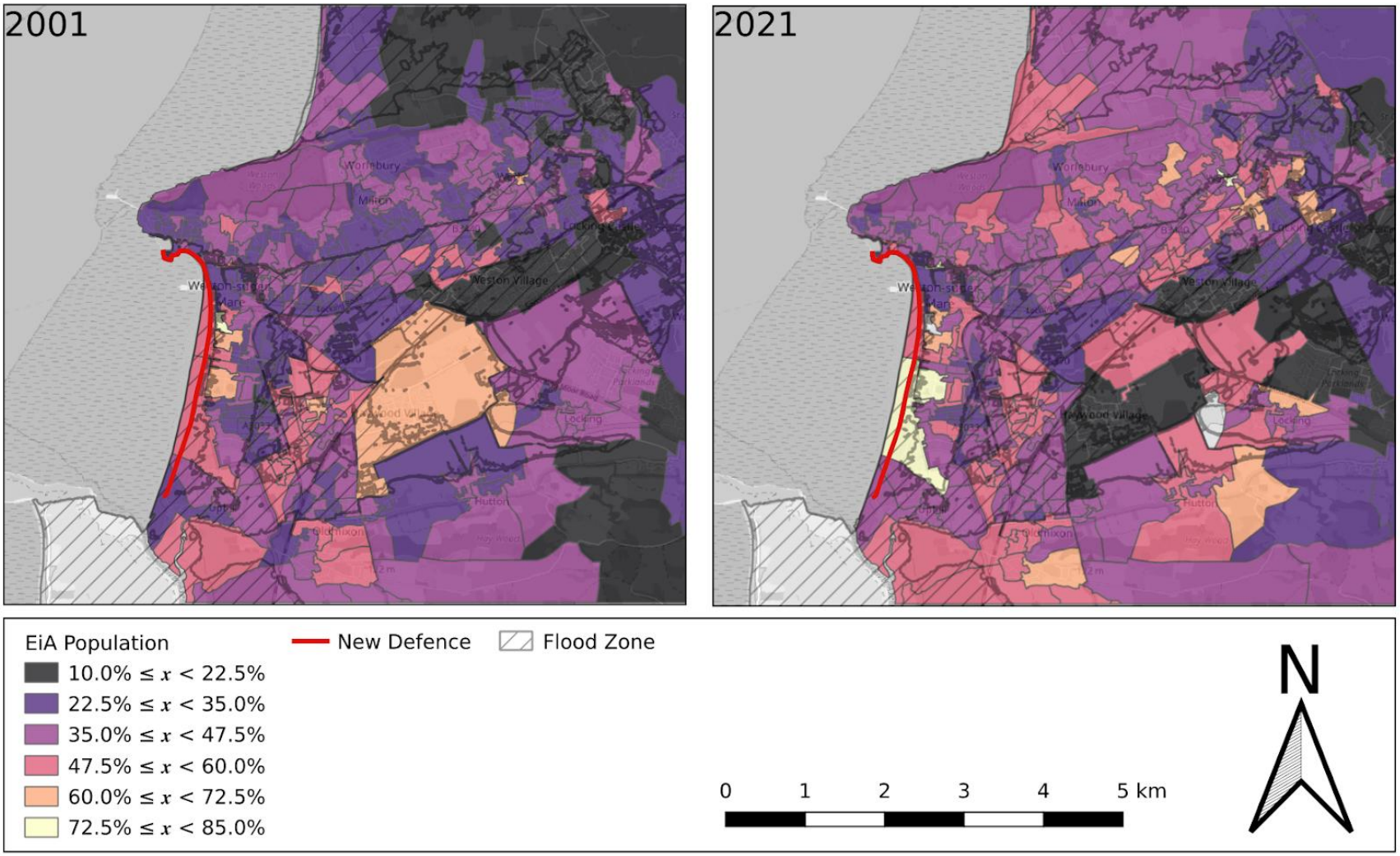


Figure 61 A comparison of the economically inactive (EiA) population of WSM grouped by census Output Area in 2001 (pre-) and 2021 (post-defence).

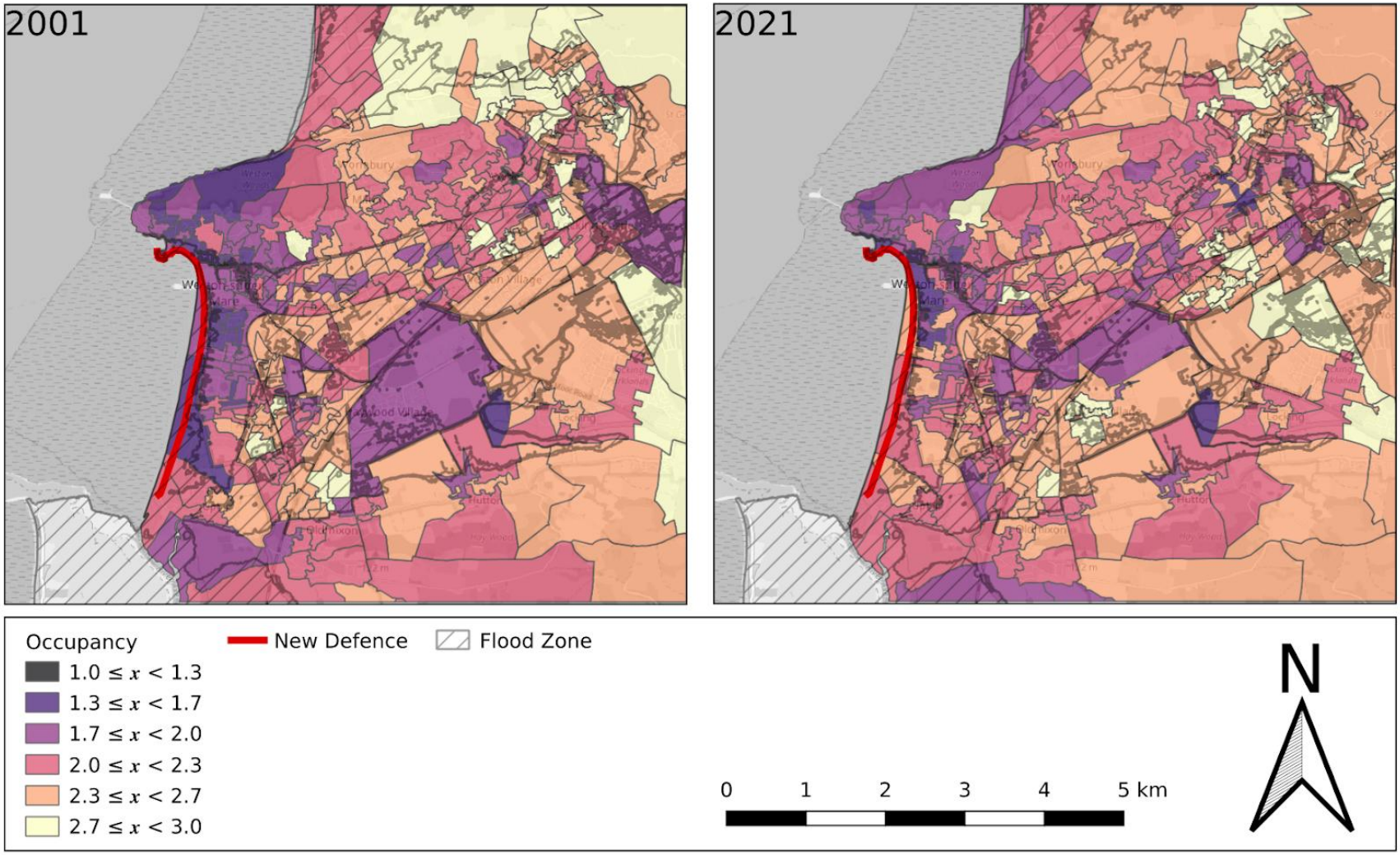


Figure 62 A comparison of population per household of WSM grouped by census Output Area in 2001 (pre-) and 2021 (post-defence).

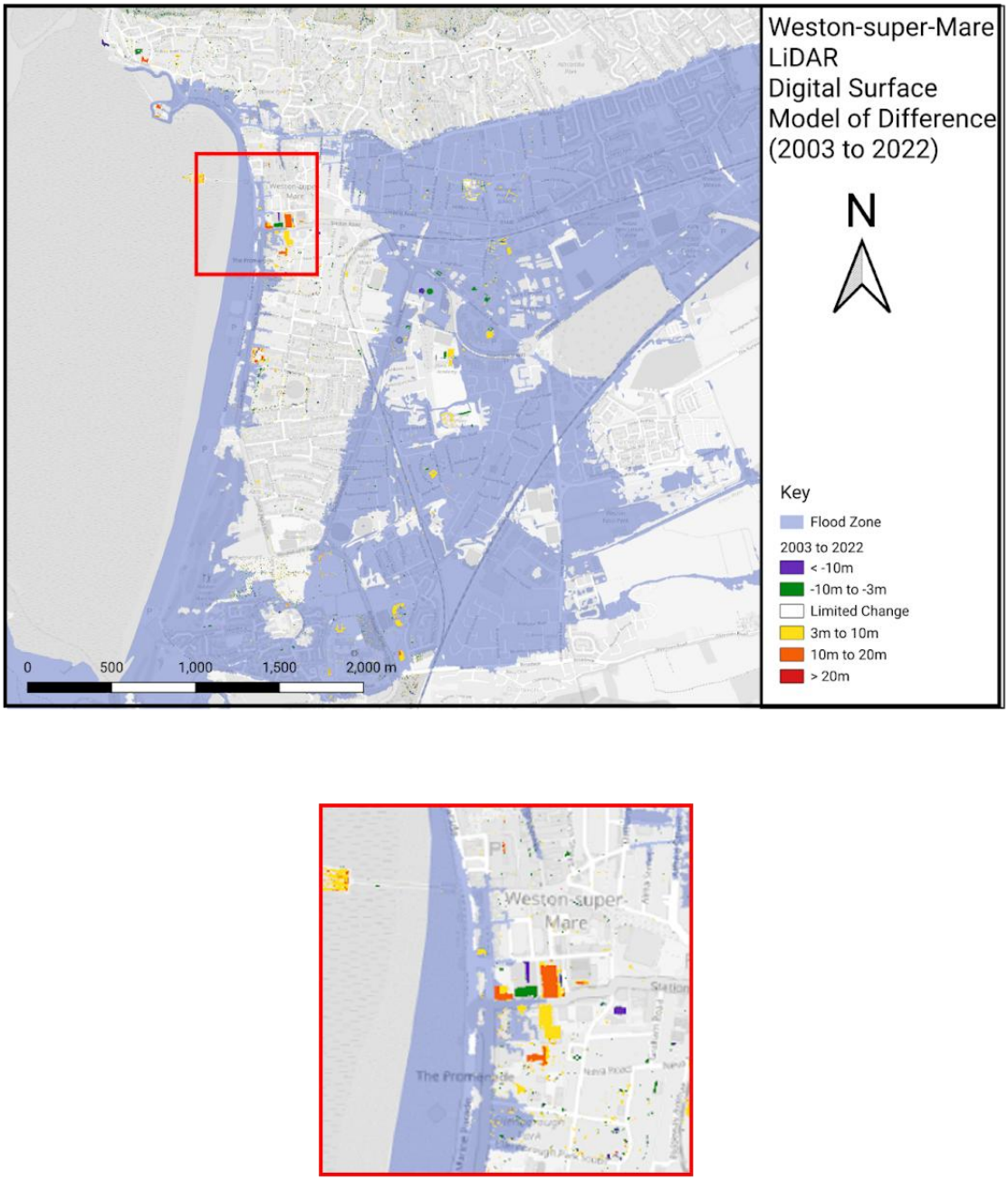


Figure 63 Weston-super-Mare 2003 and 2022 LiDAR DSM comparison. Northwest Weston-super-Mare is inset.

Table 22 Population changes from the census before (2001) and afterwards (2021) in Weston-super-Mare.

Risk Category	Time Period	Population	Annual Growth Rate
Total Population	Before	65,489	0.86%
	After	*76,703*	
Exposed Population	Before	55,844	0.48%
	After	*61,191*	
Exposed & Vulnerable Population	Before	12,858	3.13%
	After	*20,918*	

Table 23 Occupancy rate changes between censuses in Weston-super-Mare.

Average Occupancy		Percentage Change (%)		
Before	*After*	Average	Standard Deviation	Maximum
2.149	2.200	0.960	11.468	52.950

Table 24 The results of the geostatistical test of Weston-super-Mare urban changes before defence construction and afterwards.

Result	Lower Bound	Upper Bound	*p*-Value
0.622	0.548	0.695	≤0.05

4.1.2.2 Burnham-on-Sea

Burnham-on-Sea lies approximately 12.5km south of Weston-super-Mare. Located at (51.23424N, -2.99950E).

Over a 20-year period, from 2001 to 2021, the population of Burnham-on-Sea grew by 2.17% annually, rising from 11,537 to 16,553 people. Due to the flat nature of the Somerset Levels, all residents of Burnham-on-Sea are potentially exposed to flooding. In 2001, the majority of residents lived on the coastline in the northwest of the town or along the River Brue/ B3139 corridor, linking the centre of the town with the M5 via Highbridge. In 2001, the areas with the lowest economic activity were those in coastal areas in the northwest of the town, and those alongside the River Brue. However, those EiA areas in the northwest of the town were also adjacent to areas with the least EiA population, suggesting a large wealth disparity in that vicinity.

Compared from before the SCFP was upgraded in Weston-super-Mare to afterwards, population at the coast in Burnham-on-Sea remained predominantly stable (**Figure 64**). Population had changed to the north of the town in Berrow, with the one OA for the town increasing, but the other decreasing, leading to a net stabilisation for the area. East of the town centre and coastline, OAs bounding the M5 motorway and the Bristol Temple Meads - Exeter St David's railway, which has a station in Highbridge (southeast of Burnham-on-Sea), saw an increase in population (**Figure 64**), leading to Burnham-on-Sea having an annual percentage growth rate of 2.17%/yr, increasing by ~5000 people in the two decades (**Table 25**), a greater growth than Weston-super-Mare, but less absolute (**Table 22**). This would suggest that similar to the extremities of Weston-super-Mare, this area houses many commuters, most likely commuting north to Bristol. However, these OAs are much larger than those in the town centre and reflect a lower population density for the area. These populations are all within the FZ, which extends throughout the town and into the Somerset Levels behind. *Therefore, in Burnham-on-Sea, the population remained stable at the coastline from before the upgrading of the SCFP at Weston-super-Mare to afterwards. However, population increased in areas to the far east of the town. This is in contrast to Weston-super-Mare that saw an increase in coastal population*.

From before the SCFP was upgraded in Weston-super-Mare to afterwards, the proportion of EiA population increased in the majority of Burnham-on-Sea. At the coastline, those in the very centre of the town remained stable, with some decreasing, likewise with Berrow to the north. However, those in-between increased a category from 35% - 47.5% to 47.5% to 60% (**Figure 65**). In fact, the increase in EiA residents in exposed areas (the majority of the town) was the largest of the three sets at 2.94%/yr (**Table 25**). Even areas traditionally held out by commuters saw an increase in a proportion of EiA residents. *To summarise, the proportion of EiA residents increased in coastal OAs outside of town centres, and those elsewhere in the town. This is similar to Weston-super-Mare, with the EiA proportion increasing across the town. Although, unlike Weston-super-Mare, this did not occur in coastal central areas*.

However, in contrast to the increases in the proportion of EiA residents in Burnham-on-Sea, changes in housing occupancy in the area were mixed (**Figure 66**). At the coastline in central Burnham-on-Sea housing occupancy some OAs remained stable, but many decreased. Whereas, in the Highbridge area, the OAs surrounding the railway station were a mix of increases and decreases with limited recognisable pattern. The more rural areas sounding the town saw decreases in housing occupancy, and then further out some remained stable (**Figure 72**). Across the entire town, the average occupancy per OA fell from 2.22 people per household to 2.11 (**Table 26**). *Some coastal OAs saw a stabilisation in occupancy, but the majority saw a decrease, with a similar pattern observed across the town. This is in contrast to Weston-super-Mare that saw large increases in housing occupancy in areas adjacent to the newly upgraded SCFP*.

Across this timeframe, there was not statistically significant growth in coastal development (**Figure 67, Table 27**). In fact, the geostatistical t-test revealed a slight decrease of -0.052 in the LiDAR models from 2003 to 2022, although the range of the output also went into positive, highlighting that there was minimal change, if not marginally negative. This had a corresponding p-value of 0.065, which would

make in fact make it significant at the 0.1 α-level, but not at the 0.05 α-level used within this test. This small decrease was most likely driven by vegetation management, which was not excluded by the filtering due to the large time period. New development across the town during the period was limited, with the exception of a new housing estate in Highbridge, near to the railway station in the southeast of the map (**Figure 67**). This new housing estate precipitated a local increase in population (**Figure 64**) and a decrease in housing occupancy in the area (**Figure 66**). However, this new housing estate is 1.6km away from the coastline and therefore was not included in the geostatistical coastal analysis. *Therefore, to summarise, from the time before the SCFP was upgraded at Weston-super-Mare to afterwards there was not statistically significant growth in coastal development in Burnham-on-Sea. This is in contrast to Weston-super-Mare that saw significant growth in areas adjacent to the newly upgraded defence*.

Consequently, comparing from before the SCFP was upgraded at Weston-super-Mare, to afterwards in Burnham-on-Sea:

- Coastal population remained stable;
- The proportion of EiA people at the coastline per OA increased;
- Housing occupancy did not increase in coastal areas;
- There was not statistically significant urban coastal growth in Burnham-on-Sea.



Figure 64 A comparison of the population of Burnham-on-Sea (BOS) grouped by census Output Area in 2001 (pre-) and 2021 (post-defence).

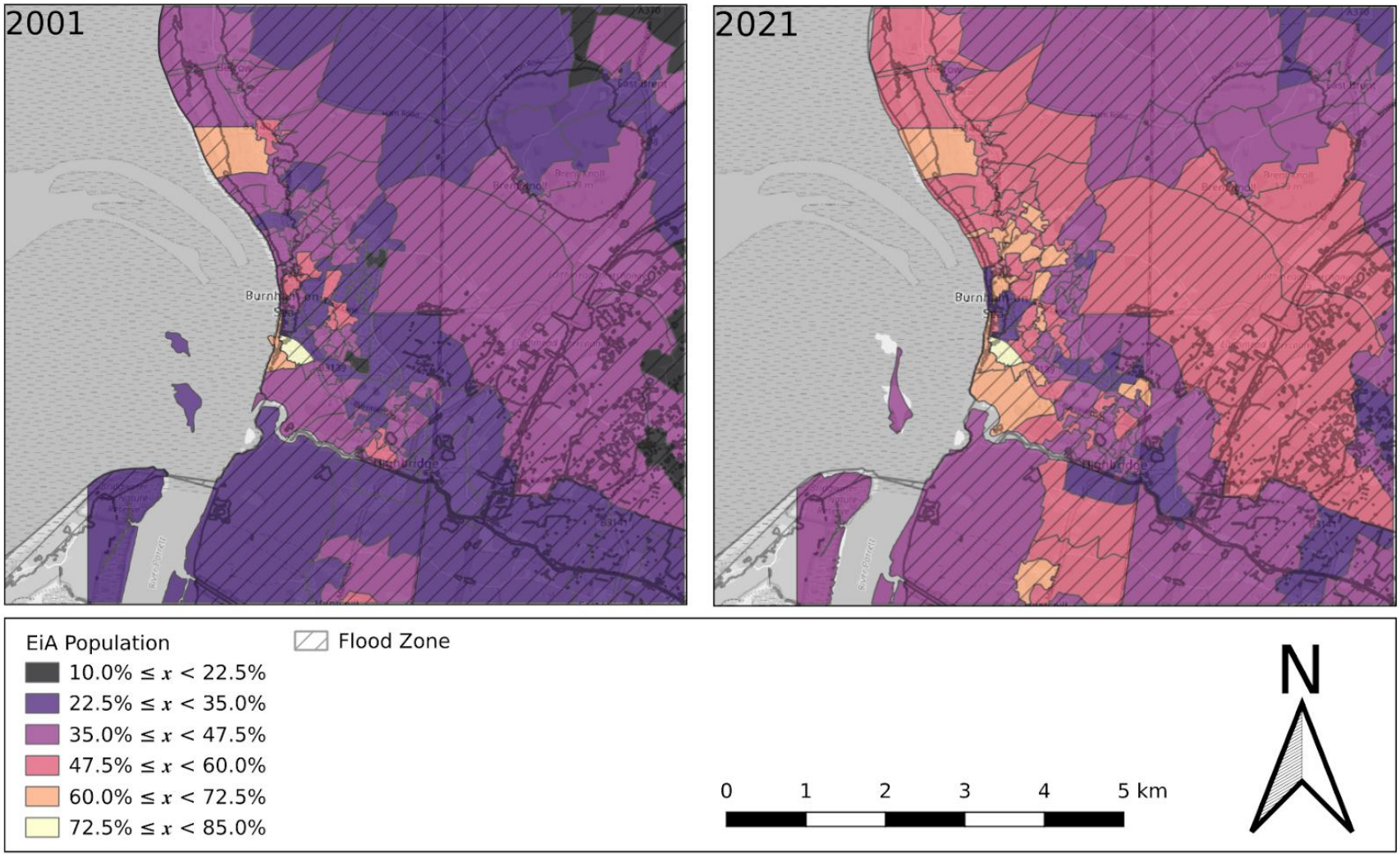


Figure 65 A comparison of the economically inactive (EiA) population of BOS grouped by census Output Area in 2001 (pre-) and 2021 (post-defence).

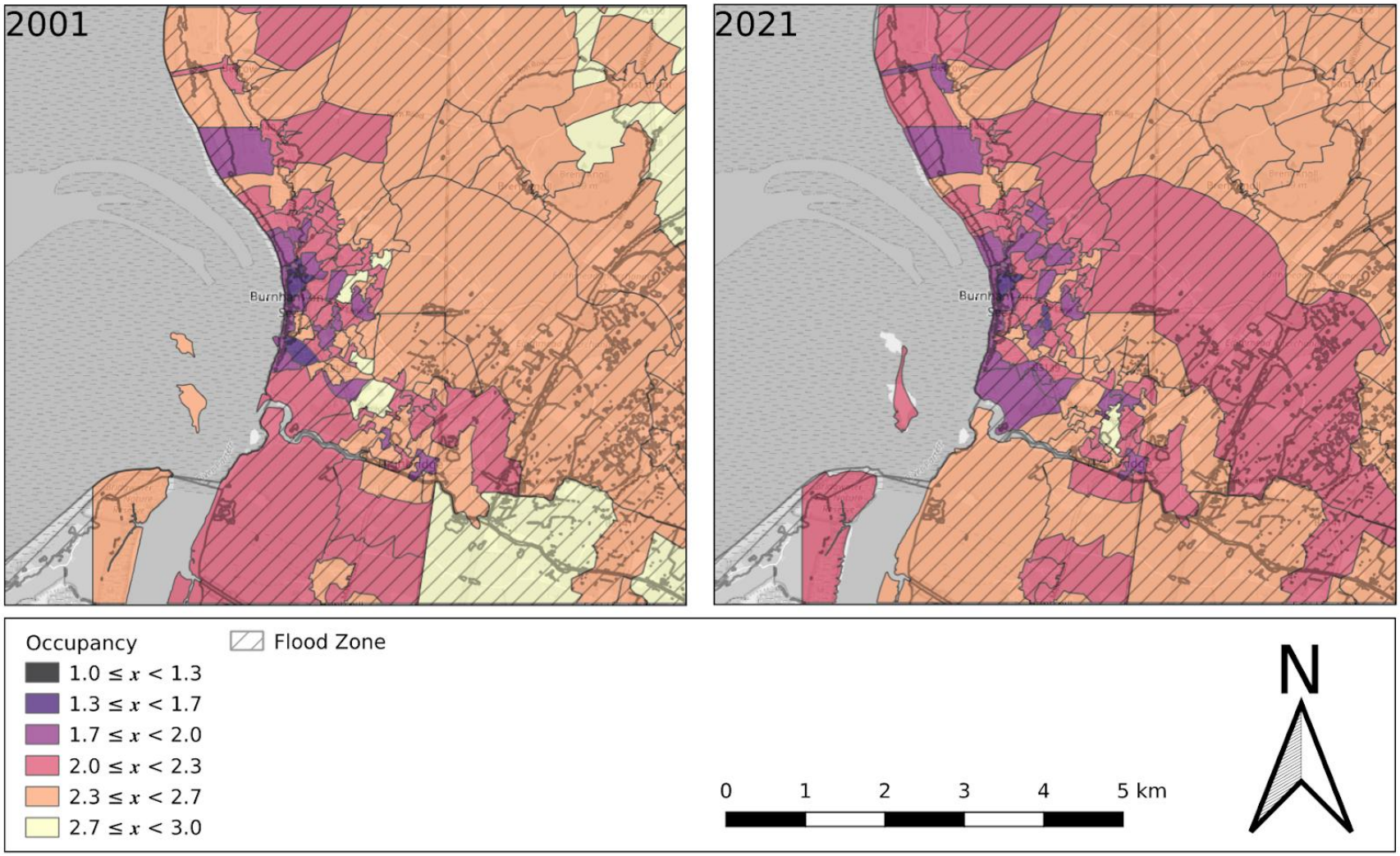


Figure 66 A comparison of population per household of BOS grouped by census Output Area in 2001 (pre-) and 2021 (post-defence).

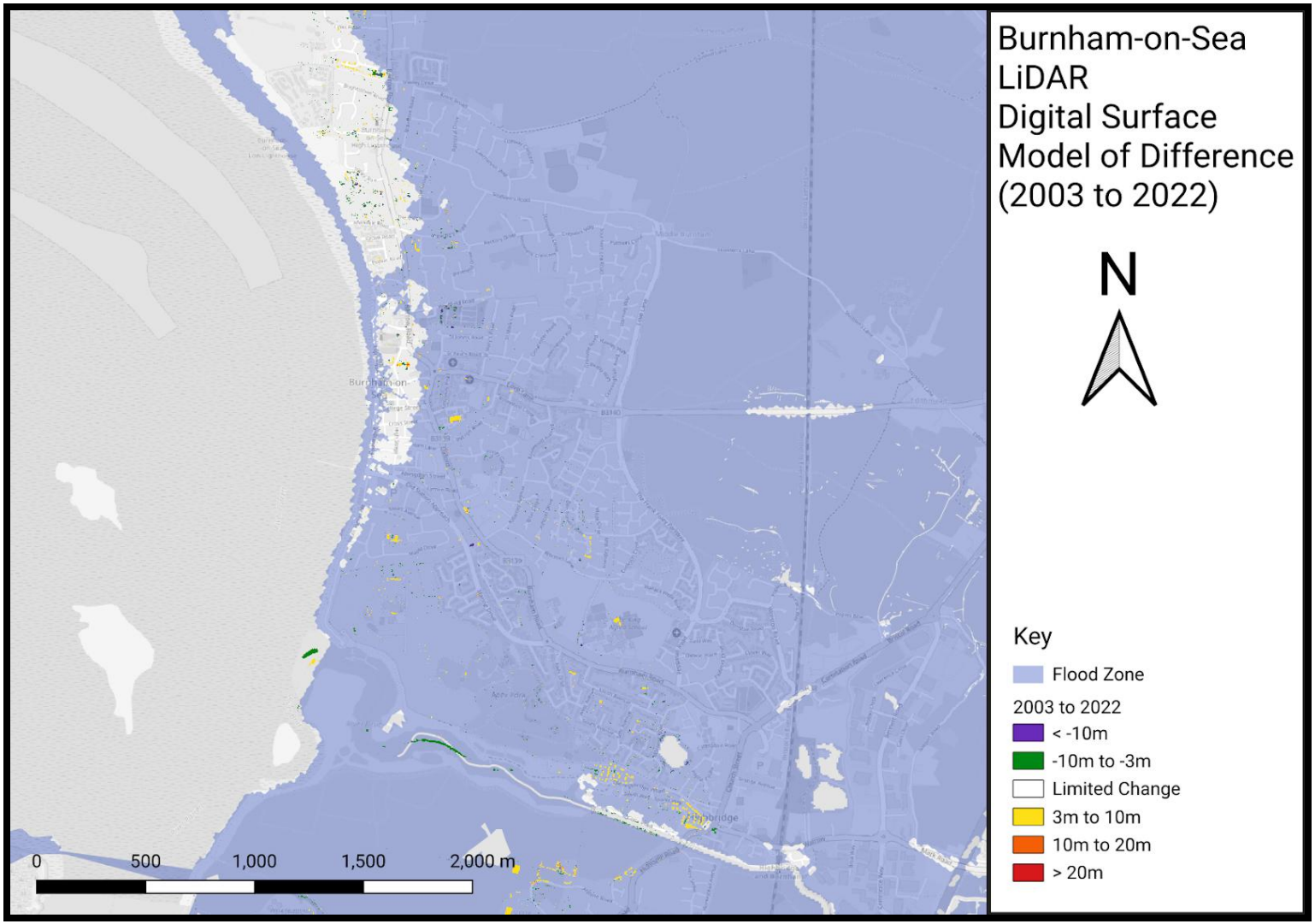


Figure 67 Burnham-on-Sea 2003 (pre-) and 2022 (post-defence) LiDAR DSM comparison.

Table 25 Population changes from the census before (2001) and afterwards (2021) in Burnham-on-Sea.

Risk Category	Time Period	Population	Annual Growth Rate
Total Population	Before	11,537	2.17%
	After	*16,553*	
Exposed Population	Before	11,537	2.17%
	After	*16,553*	
Exposed & Vulnerable Population	Before	4,280	2.94%
	After	*6,796*	

Table 26 Occupancy rate changes between censuses in Burnham-on-Sea.

Average Occupancy		Percentage Change (%)		
Before	*After*	Average	Standard Deviation	Maximum
2.220	2.110	-2.551	15.301	35

Table 27 The results of the geostatistical test of Burnham-on-Sea urban changes before the Weston-super-Mare defence construction and afterwards.

Result	Lower Bound	Upper Bound	p-Value
-0.052	-0.107	0.003	0.0654

4.1.2.3 Clevedon

Clevedon lies approximately 13.5km northeast of Weston-super-Mare. Located at (51.44289N, -2.86155E).

In 2001, areas on the outskirts of the town had a lower population density, compared to those within the town. Much of the town is within FZ 2, propagating from across the North Somerset Levels. Proximity to the sea appears to have little impact on the population of each area, with some heavily populated, some mildly, and others with very little population. In Clevedon, however, proximity to the motorway appears to have a greater effect on local population. This direct effect suggests Clevedon to be a commuter town, also owing to its proximity to Bristol. Hence, it is likely that the town is in the Bristol economic area, it is unclear, however, as to how much of an effect this has on the town, and whether local driving forces may override the regional economics.

To commute to the most likely better-paid jobs available in Bristol, commuters need the initial capital to buy a car, maintain it, and buy petrol, especially in locations such as Clevedon without a railway station and have infrequent and time-consuming bus connections. This is reflected in the areas close to the motorway having a lower incidence of economic inactivity; people there are more likely to be able to work, have a regular job, and have the ability to commute. These populations also live in FZ 2. In contrast to many other study sites, the areas with the highest economic inactivity incidence lie outside of the FZ. These places, in the north of the town, are mainly bungalows and residential care homes, with some detached housing. It is unlikely that these populations are EiA due to loss of work or income, but are on long-term health leave, or have simply retired.

Following the upgrading of the SCFP at Weston-super-Mare, population across Clevedon generally remained stable, with some sporadic increases and decreases in the more rural OAs. At the centre of the town at the coastline most OAs remained stable, with only one increasing, rising a category from 180-260 people to 260-340 people. Further northeast of the town centre, along the coastline, there were population increases, again by one level upwards, but further northeast along the coastline after this there is a population decrease (**Figure 68**). Unlike Burnham-on-Sea and Weston-super-Mare, only half of Clevedon lies within the FZ. To the south of the town there are large OAs, reflecting a low population density and a more rural location. These OAs saw an increase in population, and lie within the FZ. But these increases were predominantly away from the coastline, likewise the population increase in the southeast of the town centre (**Figure 68**). This area is a small secondary urban centre, focused on the B3133-B3130 junction and is the primary route out of Clevedon to the M5 motorway. The annual percentage growth rate of the population of the town was 0.4%/yr, double that of the *AfP* annual increase of 0.23%/yr, which would suggest the population is predominantly increasing in the areas outside of the FZ (**Table 28**). This ratio between total population and *AfP* annual growth is similar to Weston-super-Mare, but a far higher proportion of Weston-super-Mare lies within the FZ than Clevedon and so the population sample outside of the FZ is far lower. *Therefore, to summarise the changes in population in Clevedon from before the SCFP was upgraded in Weston-super-Mare to afterwards, there was a stabilisation of coastal population. This is in contrast to Weston-super-Mare, which saw an increase in coastal population at the newly upgraded defence*.

Across the coastline in Clevedon, the proportion of EiA people per OA increased, with each Output Area increasing by a level. The increase of the proportion of EiA people was universal across the town, with the vast majority of the OAs seeing an increase. The impact of the FZ was not noticeable, with increases both inside and out, and stabilisations likewise (**Figure 69**). *The proportion of EiA people per OA increased at the coastline, and across the town. This also occurred in Weston-super-Mare*.

Comparing the situation from before the SCFP in Weston-super-Mare was constructed to afterwards, changes in housing occupancy in each OA in Clevedon were mixed. In the centre, at the coast, the majority of OAs remained stable, with one increase and one decrease also (**Figure 70**). Further north of the town, the OA in the far north that experienced a population decrease (**Figure 68**) also saw a decrease in housing occupancy (**Figure 70**), suggesting a link between the two in that local area. There appeared to be similar decreases and stabilisations, both, in the FZ and outside indicating that the

delineation had limited-no impact on housing occupancy. The average occupancy per OA was 2.23 people per household in the 2001 census, falling to 2.14 people per household twenty years later at an average of -5.7% per Output Area (**Table 29**). *To summarise, housing occupancy in coastal areas in Clevedon mostly stabilised from the time before the SCFP was upgraded in Weston-super-Mare to afterwards. This is in contrast to Weston-super-Mare, which saw an increase in housing occupancy at the coastline at the newly upgraded defence*.

The LiDAR DSM differential analysis, comparing 2003 to 2022 shows a large development in the southwest of Clevedon. However, this housing estate was in fact constructed in the 1980s and the inverted U-shaped building to the slight northwest of this development was constructed in 1994. However, in reality, these *new developments* were a vertical displacement error, most likely between 3m and 10m (**Figure 71**). Excluding this area, urban development was minimal across the town, with limited/no urban development on the coastline during the 2003 to 2022 timeframe, comparing from before the SCFP was upgraded in Weston-super-Mare to the time afterwards. This is reflected by the output of the geostatistical t-test, which gave a t-score of 0.005 with ±0.086 bounds and a p-value of 0.908, far greater than the 0.05 α-level (**Table 30**). However, there was development in the south of Clevedon during this period, inside the FZ also, a new retirement village for over 70s, completed in 2022, although it is 1.6km away from the coastline and therefore was not included in the geospatial analysis. *Therefore, when comparing urban development in Clevedon from before the SCFP was upgraded in Weston-super-Mare it is apparent there were limited changes in coastal areas across this period. This is in contrast to Weston-super-Mare, which saw statistically significant urban growth in coastal areas adjacent to the new SCFP*.

Consequently, comparing from before the SCFP was upgraded at Weston-super-Mare, to afterwards in Clevedon:

- Population remained stable in most areas adjacent to the coastline;
- Vulnerable Population increased in most of the coastal areas;
- Housing occupancy remained stable in most coastal areas;
- There was not statistically significant urban development.

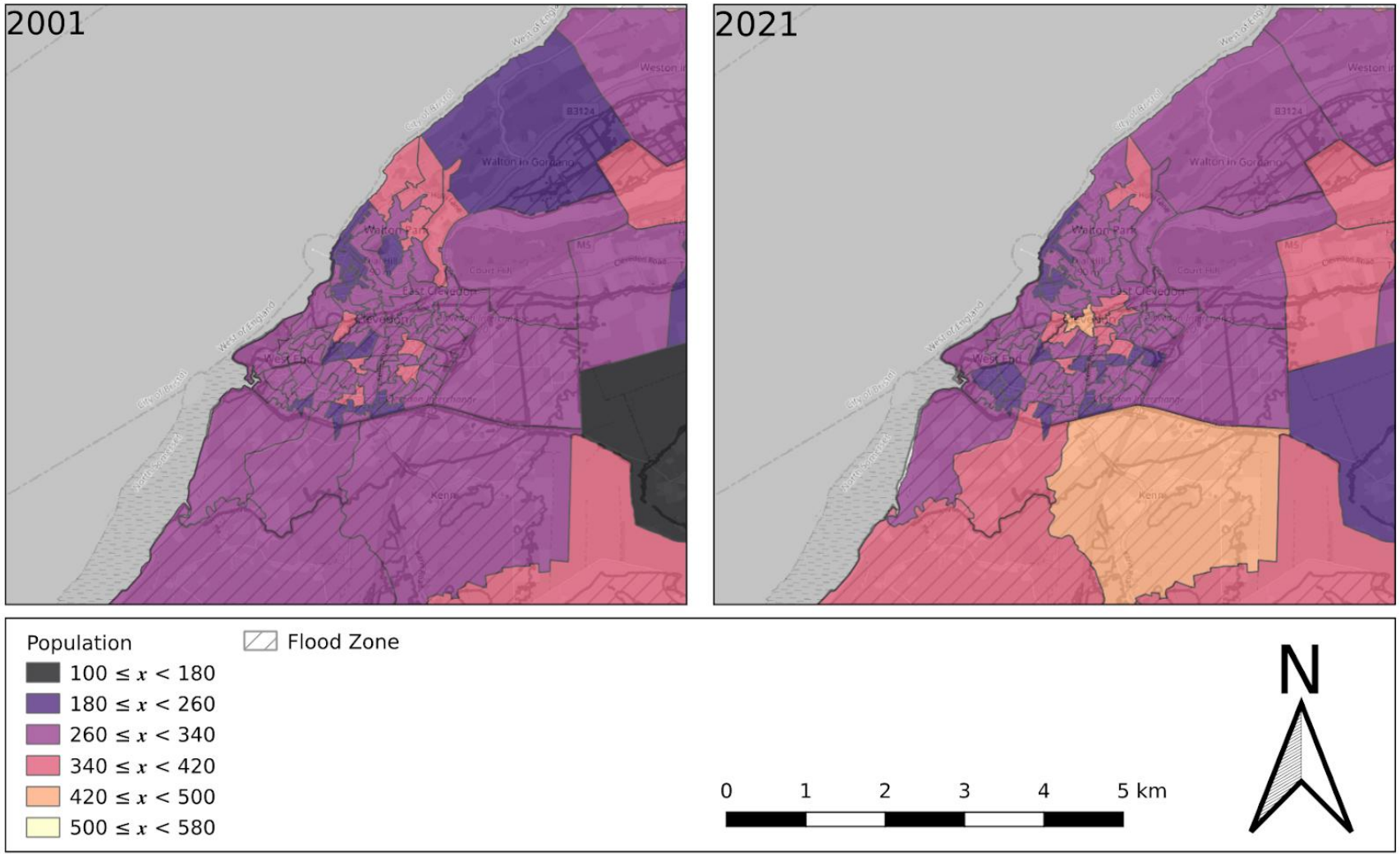


Figure 68 A comparison of the population of Clevedon grouped by census Output Area in 2001 (pre-) and 2021 (post-defence).



Figure 69 A comparison of the economically inactive (EiA) population of Clevedon grouped by census Output Area in 2001 (pre-) and 2021 (post-defence).

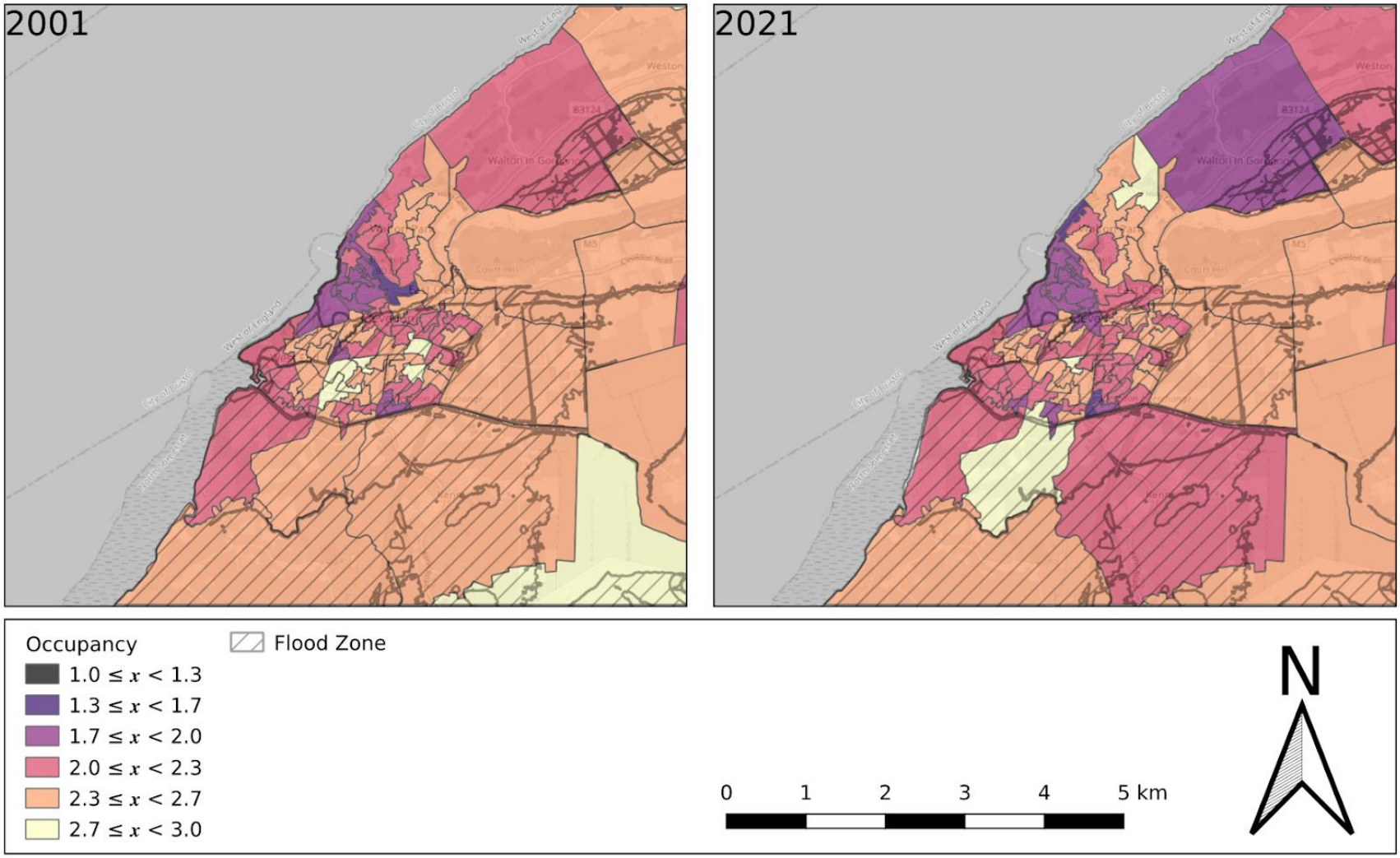


Figure 70 A comparison of population per household of Clevedon grouped by census Output Area in 2001 (pre-) and 2021 (post-defence).

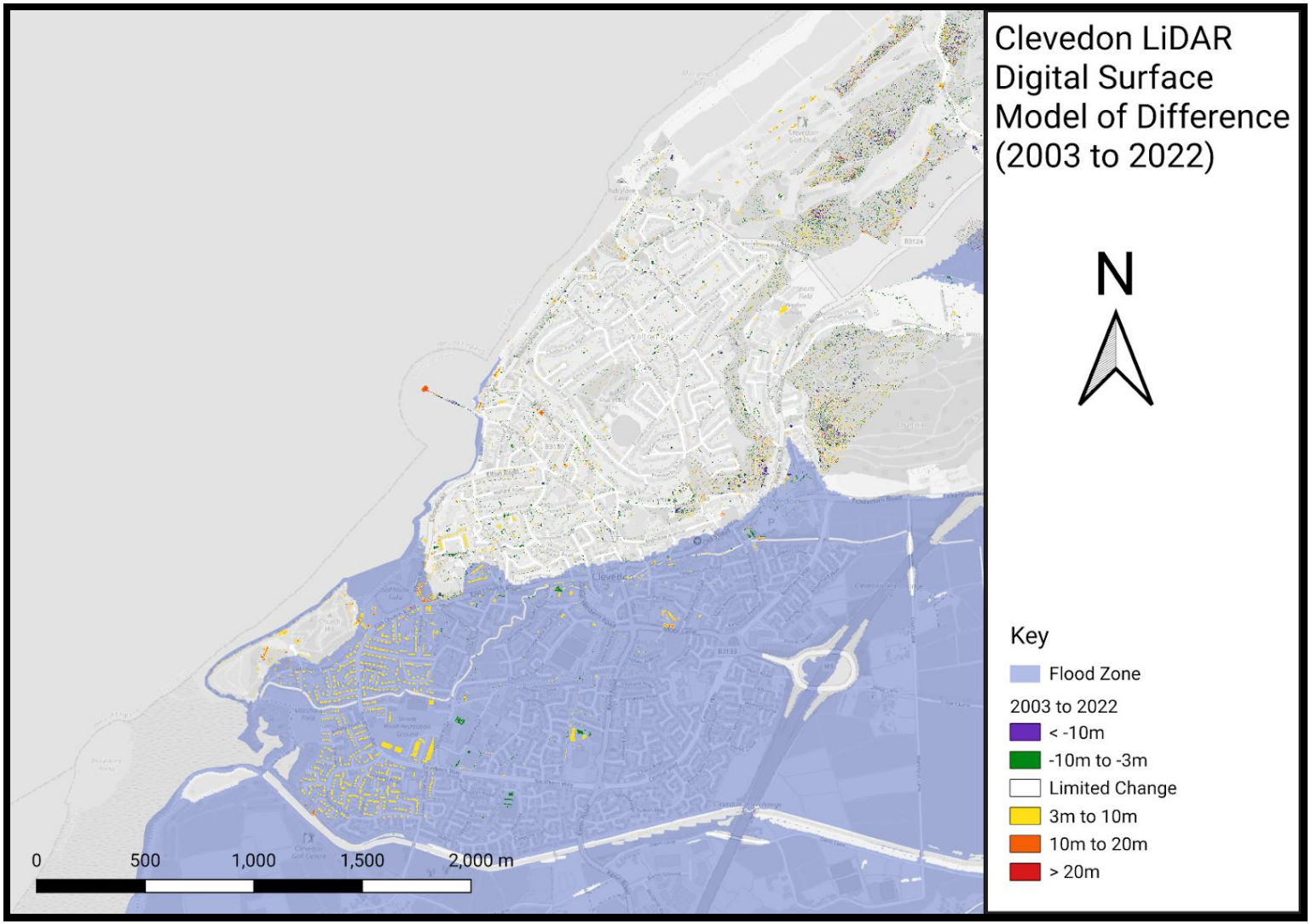


Figure 71 Clevedon 2003 (pre-) and 2022 (post-defence) LiDAR DSM comparison.

Table 28 Population changes from the census before (2001) and afterwards (2021) in Clevedon.

Risk Category	Time Period	Population	Annual Growth Rate
Total Population	Before	19,825	0.40%
	After	*21,404*	
Exposed Population	Before	15,582	0.23%
	After	*16,296*	
Exposed & Vulnerable Population	Before	2,836	4.16%
	After	*5,195*	

Table 29 Occupancy rate changes between censuses in Clevedon.

Average Occupancy		Percentage Change (%)		
Before	*After*	Average	Standard Deviation	Maximum
2.234	2.137	-5.712	15.411	28

Table 30 The results of the geostatistical test of Clevedon urban changes before the Weston-super-Mare defence construction and afterwards.

Result	Lower Bound	Upper Bound	p-Value
0.005	-0.080	0.091	0.908

4.1.2.4 Synthesis of Case Study B

The upgrade of the SCFP in Weston-super-Mare led to an increase in population, the proportion of EiA residents, people per household, and urban development in the coastal area adjacent to the newly upgraded defence. However, coastal population and EiA population increased elsewhere along the coastline in the town, but the same did not occur with housing occupancy, which stabilised from the period before the SCFP to afterwards (**Table 31**). The comparative sites, Burnham-on-Sea and Clevedon, did not see increases in all factors. For example, there was a stabilisation, not an increase, in coastal population in both towns (**Table 31**).

Table 31 A summary table of the studied factors and locations in Case Study B and how they change from the time before the new Weston-super-Mare coastal flood defence (blue font) to after: upwards arrow and green cell indicate positive change, dynamic equilibrium arrow and orange cell indicate stabilisation, downward arrow and red cell indicate a negative change.

	Weston-super-Mare		**Comparative**	
	Defence	Elsewhere	Burnham-o-S	Clevedon
Coastal Population	⇧	⇧	⇌	⇌
Coastal EiA	⇧	⇧	⇧	⇧
Coastal Occupancy	⇧	⇌	⇩	⇌
Coastal Development	✓		×	×

In all three locations, Weston-super-Mare as the primary site, and Burnham-on-Sea and Clevedon as the comparative sites, there was a decrease in the population distribution change from the time before the SCFP was upgraded in Weston-super-Mare to afterwards (**Table 32**). The average change of population distribution by the newly upgraded SCFP (~-13.1%) was statistically significant compared to the population distribution change in the sample of other locations in Weston-super-Mare (~-27.6%) with a p-value of 0.012. Population distribution change led to a decrease in many areas of Weston-super-Mare due to the development of the Haywood estate, which saw a vast area of underutilised land turned into a large residential area, albeit 2.1km away from the coastline (**Figure 66**). However, these data would also suggest that the SCFP too affected the distribution of population: only Weston-super-Mare had this statistically significant change in population distribution change across this timeframe. Burnham-on-Sea saw a lower change (~-9.3%) on the coastline than elsewhere in the town (~-10.7%), with a p-value much greater than the 0.05 α-level (**Table 32**). In contrast Clevedon saw a greater average decrease in population distribution on the coastline (~-6.1%) than elsewhere in the town (~-2.4%), but this was not a statistically significant change. Moreover, whilst there was a larger ratio in Clevedon between the change in population distribution between those on the coastline and those elsewhere in the town, Weston-super-Mare had a greater absolute change and was the only that was statistically significant at the 0.05 α-level. It is evident from these data that the upgrades of the SCFP in Weston-super-Mare had an impact on the change in population distribution from before to after the upgrade.

Table 32 A table containing the output of the average change in population distribution in the area adjacent to the newly constructed/ upgraded SCFP in Weston-super-Mare, or seafront in Burnham-on-Sea and Clevedon. The table also contains the *p*-value output from a *t*-test comparing the two locations within each site.

	Coastal/Defence	**Elsewhere**	***p*-Value**
Weston-super-Mare	-13.071%	-27.546%	0.012
Burnham-on-Sea	-9.315%	-10.681%	0.367
Clevedon	-6.132%	-2.352%	0.207

The proportion of EiA people per OA increased in all study sites from before the SCFP was upgraded in Weston-super-Mare to after (**Table 31**). Although Weston-super-Mare saw the greatest increase in EiA population in coastal areas, more so than Burnham-on-Sea and Clevedon. Moreover, in Burnham-on-Sea the increases in the proportion of EiA population per OA did not occur in coastal areas in the town centre. The impact of the Covid-19 pandemic would have driven a lot of this leading to greater unemployment as the national and local economic situation worsened. Especially in coastal areas which rely on seasonal holiday income which would have decreased during the Covid-19 pandemic lockdown.

In contrast, in Weston-super-Mare at the newly upgraded SCFP there was an increase in housing occupancy, and unlike the proportion of EiA residents per OA, this was not replicated in other areas of Weston-super-Mare, nor in Burnham-on-Sea or Clevedon (**Table 31**). In Burnham-on-Sea, whilst some OAs saw a stabilisation of housing occupancy, a majority of coastal OAs saw a decrease across the period analysed. Whereas in Clevedon, there was a stabilisation of housing occupancy along the coastline. Therefore, this would indicate that the upgrading of the SCFP had an impact on the amount of housing occupancy in Weston-super-Mare.

Similarly, only Weston-super-Mare had statistically significant growth on the coastline (**Table 24**). Whereas, comparing the LiDAR DSMs at the sites did not suggest that there was statistically growth at the comparative sites: Burnham-on-Sea, with a *p*-value of 0.07 (**Table 27**) and Clevedon, with a *p*-value of 0.908 (**Table 30**). Therefore, this would indicate that the newly upgraded SCFP created an incentive that led to new urban development on the coastline. This finding is aligned with previous research, such as Di Baldassarre *et al.* (2013b), which explored how structural flood protections often lead to increased urbanisation in protected areas. *Therefore, to summarise, the upgrade of the SCFP at Weston-super-Mare led to socio-economic and urban changes in adjacent coastal areas. Only increases in the proportion of EiA population per OA of coastal areas were replicated across all sites, both, in Weston-super-Mare and the comparative sites. The increases in coastal population, housing occupancy, and urban development were not replicated in other sites, however, while the increase in coastal population also occurred in areas not adjacent to the newly upgraded defence in Weston-super-Mare*.

4.1.3 Case Study C

This case study focused on the multiple coastal flood defence upgrades across Portsea Island from 2005 to present. Therefore, as Portsmouth (Hampshire) experienced multiple coastal flood defence upgrades, each subsection has been split into multiple decades. The town selected for comparative analysis was Gosport (Hampshire) to the west (**Figure 72**). The Old Portsmouth scheme led to a 1-in-200 year SoP for the Old Portsmouth area. NPCS hopes to lead to a 1-in-500 year SoP, and the Southsea Coastal Scheme hopes to lead to a 1-in-200 year SoP.



Figure 72 The distribution of sites, primary and comparative, used for Case Study C.

4.1.3.1 Portsmouth

Located at (50.80849N, -1.07359E).

In 2005, the coastal flood defences around the Old Portsmouth area of Portsea Island, an area containing many historic buildings with local urban development, were upgraded. This area includes many residential and commercial properties, historic military fortifications and maritime industries, such as the Isle of Wight ferry terminal and the only fishing quay within Portsmouth Harbour. The 2005 coastal defence scheme at Old Portsmouth included placing rock armour and sea wall improvements, providing a 1-in-200 year SoP, up from a 1-in-50 year SoP.

In the 2001 census, the densest area of Portsmouth was the area surrounding the Guildhall and the main railway station, Portsmouth & Southsea. In contrast, Southsea, on the southern end of Portsea Island, were some of least populated places on the whole island. The most populated areas were inland and on the mainland. However, this is with the exception of the naval base of Whale Island and surrounding areas which had a greater than the average population per km^2.

As an island city with the second highest population density in the country, Portsmouth has seen several SCFP schemes over the 21st century, with some such as the Southsea Coastal Scheme and the North

Portsea Coastal Scheme still ongoing, continuing into the 2020s. The Old Portsmouth SCFP occurred during the 2001 to 2011 census period, and the first four phases of the North Portsea Coastal Scheme (NPCS) occurred during the 2011 to 2021 census period.

When comparing from before the Old Portsea SCFP scheme was constructed to afterwards, there were several notable changes in population across the city. There was a population decrease on Tipner West peninsula and Whale Island, areas in the northwest of the island (**Figure 73**). However, Whale Island, and the area directly south across Portsmouth Harbour on the island, are a naval base and therefore population change, and that of any other socio-economic factors were not be considered by this analysis. Population increases, on the other hand, occurred in many locations around the city. Two OAs in the north of the island, lying within the FZ saw a population increase, as did those on the southeast near to the hospital. This also occurred in the Southsea area of the island, in areas adjacent to the FZ. The largest change was the increase in population in the area surrounding the main railway station, Portsmouth & Southsea station. Population in this area had increased by such a level to warrant being split into another OA (**Figure 73**). Population also rose in surrounding areas, such as one to the northeast of the newly constructed SCFP in Old Portsmouth. However, the population at the new defence itself did not change over this period. Although, nor did the coastal population around much of Portsea island, with the exception of decreases and an increase in the northwest area. *Therefore, from before the SCFP was constructed at Old Portsmouth to afterwards, population at the new defence did not change by a noticeable degree, although overall nor did the coastal population around much of Portsea Island across the 2001 to 2011 period*.

The NPCS covers much of the north and east of Portsea Island with new or major upgrades to structural coastal defence split in five phases, the first four of which are covered by the 2011 to 2021 census. The largest increase occurred in the west of the island, in the area surrounding the naval base, to the north of the Old Portsmouth SCFP constructed during the previous period (**Figure 74**). Population increases inside the base are not considered by the analysis, but OAs increase in the peripheral, with many increasing across the period. In the far south and east of the island, along the coast, there was a decrease in population, although this was counterbalanced by increases further inland (**Figure 74**). Moreover, one of the largest increases occurred on the mainland, directly across Portsbridge Creek from NPCS Phase 1. Nearby, another increase, and the only one in the FZ, occurred to the west. Although, near to all of the defences built over this period there was no/limited increases in population, whilst there was in other areas of the city. This may imply local population saturation in these areas, especially with the exceptionally high population density of Portsmouth already. This is reflected in the low population growth across this period (**Table 33**): in the 2001 to 2011 census total population and *AfP* increased by 0.98%/yr and 0.81%/yr respectively, yet these decreased to 0.14%/yr and -0.19%/yr. Even looking at the absolute figures, the population of Portsmouth increased by 18,355 people from 2001 (186,701) to 2011 (205,056), but only by 2,960 from 2011 to 2021 (208,016) (**Table 33**). This limited population growth translated to limited population growth at the new SCFPs. *Consequently, when comparing from before implementation of the first four phases of the NPCS to after, there was no notable change in population at the new defences, although there were increases in other areas of the city*.

Portsmouth is quite a divided city socio-economically, with OAs with the greatest proportion of the constituent population who are EiA more likely to be in the southwest of the city, closer to the historic and contemporary portlands. During the 2001 to 2011 census period, when the Old Portsmouth coastal flood protection scheme was completed, the proportion of EiA population decreased in OAs immediately adjacent to the new defence (**Figure 75**). Around the coastline, in Southsea there were also several decreases, all within the FZ. This was also replicated in the north of Portsea Island. In fact, overall, there were only two coastal OAs which saw an increase, the rest either saw a decrease or a stabilisation. This is reflected by the very small increase in exposed and EiA population (**Table 33**). *Comparing from before the SCFP was built in Old Portsmouth to afterwards, both areas at the new defence and other coastal areas in Portsmouth saw a decrease in the proportion of EiA residents across the 2001 to 2011 period*.

However, the decrease in the EiA population per OA did not continue into the 2011 to 2021 period, which saw the greatest annual increase of all factors with an annual increase of 4.01%/yr (**Table 33**).

The proportion of EiA residents per OA increased across the town. The OAs surrounding the railway station contained the highest proportions. Those around the Old Portsmouth flood defence project also saw an increase (**Figure 76**). Many OAs on the south coast, in the Southsea area, and within the FZ had an increase by one category, from 20%-35% to 35%-50%. All OAs adjacent to the newly constructed NPCS defence also increased. The largest increase, however, was the land adjacent to the NPCS Phase 1, which jumped two categories, from 5%-20% to 35%-50% (**Figure 76**). This level of increase, however, was not seen in the other phases of the North Portsea Coastal Scheme. Although, many of these other phases pass through parkland or industrial areas. *Therefore, to summarise, the proportion of EiA residents increased across Portsmouth's coastal areas from before the NPCS to afterwards. This also occurred in areas by the new defences. Although the largest increase was the residential area adjacent to NPCS Phase 1*.

Unlike population and economic inactivity, housing occupancy did not appear to follow a general pattern across Portsmouth from before the completion of the Old Portsmouth scheme to afterwards. The vast majority of OAs in the north of Portsea Island, also in the FZ, did not see much change in housing occupancy, with many remaining the same from the time before to afterwards: only one had a decrease (**Figure 77**). Whereas, in Southsea, at the other end of the island and also in the FZ, there was an increase in housing occupancy across OAs, but decreases or stabilisations in others. Similarly, OAs around the naval base saw an increase in occupancy in some, and decreases in others. This paints a mixed picture around the coastline, with increases in some OAs, decreases in others, and half saw no change at all (**Figure 77**). *To summarise the changes in housing occupancy originating from before construction of the Old Portsmouth defence to after, there was a mix in the change in housing occupancy in coastal areas, leading to a net zero change overall. However, there was an increase in housing occupancy in areas surrounding the newly constructed Old Portsmouth defence*.

In contrast to the increases in housing occupancy in Southsea from the previous period, comparing the time before (2011) to after (2021) phases 1 to 4 of the NPCS were completed, the area saw a decrease in housing occupancy. Whereas the other area of the island that is dominated by the FZ, in the north, there were more mixed changes between the maps (**Figure 78**). Starting from the northwest, in the area bounded by NPCS Phase 3, most OAs remained stable although there was one that decreased. This decreasing OA was also bounded by two other OAs that also decreased, these were in the unprotected section of the area, awaiting the construction of NPCS Phase 5, to cap the top. NPCS Phase 1 saw a stabilisation in housing occupancy between the maps, similarly to the majority of Phase 2 and Phase 4. However, there was a decrease in the OA that contains the intersection of NPCS Phase 1 and Phase 4 (**Figure 78**). In contrast, in central Portsmouth, the OAs that surround the main railway station saw the largest increase, rising by multiple levels, an increase of 150% (**Table 34**). These OAs were the same that also contained the largest proportion of EiA residents across this period (**Figure 76**), this would suggest an increased concentration of more vulnerable populations in this area. Though with the exception of the naval base, the majority of coastal OAs, not bounded by the new defences, saw a decrease in housing occupancy (**Figure 78**). *Therefore, across this period, from before the construction of the NPCS Phase 1 to 4, to afterwards, there was an overall stabilisation of housing occupancy in the OAs. However, this was not replicated in other coastal OAs which saw a decrease in housing occupancy*.

Using LiDAR vertical change as a proxy for the construction of new buildings identified some urban development near to the first coastal defence upgrades in Portsmouth (**Figure 79**): a new medium-density residential development. Elsewhere during this period, there was Admiralty Tower to the north of the new defence, but out of the FZ, and the new industrial estate in the northeast of the island (**Figure 79**). Elsewhere on the island, there was a new industrial park built on the northeast of the island, slightly outside of the FZ. Moreover, there were also demolitions, with numerous buildings demolished in the north of the city, all within the FZ, but no other construction within it other than that by the new defence (**Figure 79**). The coastal development around the Old Portsmouth defence led to a statistically significant results under the geostatistical LiDAR analysis (0.05 α-level), with a t-score of 0.329 (**Table 35**). *Therefore, since the construction of the Old Portsmouth SCFP there has been a statistically*

significant change in the urban development of the area. Moreover, urban development did not occur in any other FZ locations over this period.

Then, during the NPCS, mostly dominating the northern and eastern side of Portsea Island, more new buildings were constructed (**Figure 80**). There were new industrial estates built in the FZ in the northeast of the island, in areas near to NPCS Phase 1 (**Figure 80**). The estate is entirely within the FZ and opened in 2018, two years after the flood defence scheme for that area of the island was constructed. This industrial estate, the largest industrial development in the city, brings 0.026km^2 of brownfield land back into use. The first phase of the North Portsea Coastal Scheme was designed to reduce the risk of flooding from the sea to 4,200 homes, 500 businesses and critical infrastructure over the next 100 years. The construction and upgrading of coastal flood defence structures can induce development within exposed areas greater than would otherwise be the case if the scheme was not conducted (Haer *et al.*, 2020). Although, both, NPCS Phase 2 and Phase 3 saw little development within the FZ boundary, yet both run alongside primarily outdoor recreation areas, limiting the ability to develop in these areas. Then, in southwest Portsmouth, a large new commercial centre was built on the seafront at Old Portsmouth constructed 10 years after the original flood protection scheme was constructed. The difference between building type and elevation is apparent when comparing the same location in Old Portsmouth from 2012 (**Figure 81**) to 2019 (**Figure 82**). Moreover, other new medium-scale development was constructed in the area, completed in 2019 as part of the upgrades to the WightLink ferry terminal. All within the FZ (**Figure 80**). The large changes in urban development in Portsmouth from before the NPCS to after are apparent with the statistical testing revealing that growth is statistically significant, with a t-score of 0.972 (**Table 35**). Whilst over this period, urban growth was not limited to the FZ, the majority of development still occurred within it, and it occurred in locations adjacent to defences built during this period (NPCS Phase 1) and prior (Old Portsmouth). *To summarise this period, since the construction of Phase 1 to 4 of the NPCS there has been a statistically significant change in coastal urban development. Moreover, whilst the majority of urban development occurred inside the FZ, some occurred outside, but most occurred in areas adjacent to recently and newly built defences*.

The protection of Portsea Island continues with the coastal flood protection schemes at Ports Creek (2024-2025) and Southsea (2020-2028). The scheme at Southsea, providing protection for a majority of south Portsea Island will fundamentally change the area. Future research should be carried out using the 2031 census to assess these changes, and analyse them in the wider context of data presented here from the 2001, 2011, and 2021 censuses, and the potential effects of the SCFPs built over these periods.

Therefore, to summarise the changes in Portsmouth that occurred from before the Old Portsmouth SCFP to afterwards:

- Coastal population remained stable at the defence, but coastal population also remained stable across the city generally;
- EiA population decreased at the coastal flood defence, but the EiA population also decreased in coastal OAs across the city also;
- Housing occupancy increased at the coastline, but changes in housing occupancy were mixed in the rest of the city;
- There was a statistically significant change in urban development at the coastline, development in the FZ did not occur elsewhere in the city.

Then, to summarise the changes in Portsmouth that occurred from before Phase 1 to 4 of the NPCS to afterwards:

- Again coastal population remained stable at the defence, but increased elsewhere in other coastal areas of Portsmouth;
- EiA population increased at the coastal flood defences, but EiA population also increased elsewhere in other coastal areas;
- Housing occupancy remained stable at the coastline at the new defences, but decreased in the rest of the city;
- There was a statistically significant change in urban development at the coastline, and whilst development did occur elsewhere in the city, the majority occurred at current and recently built SCFPs.

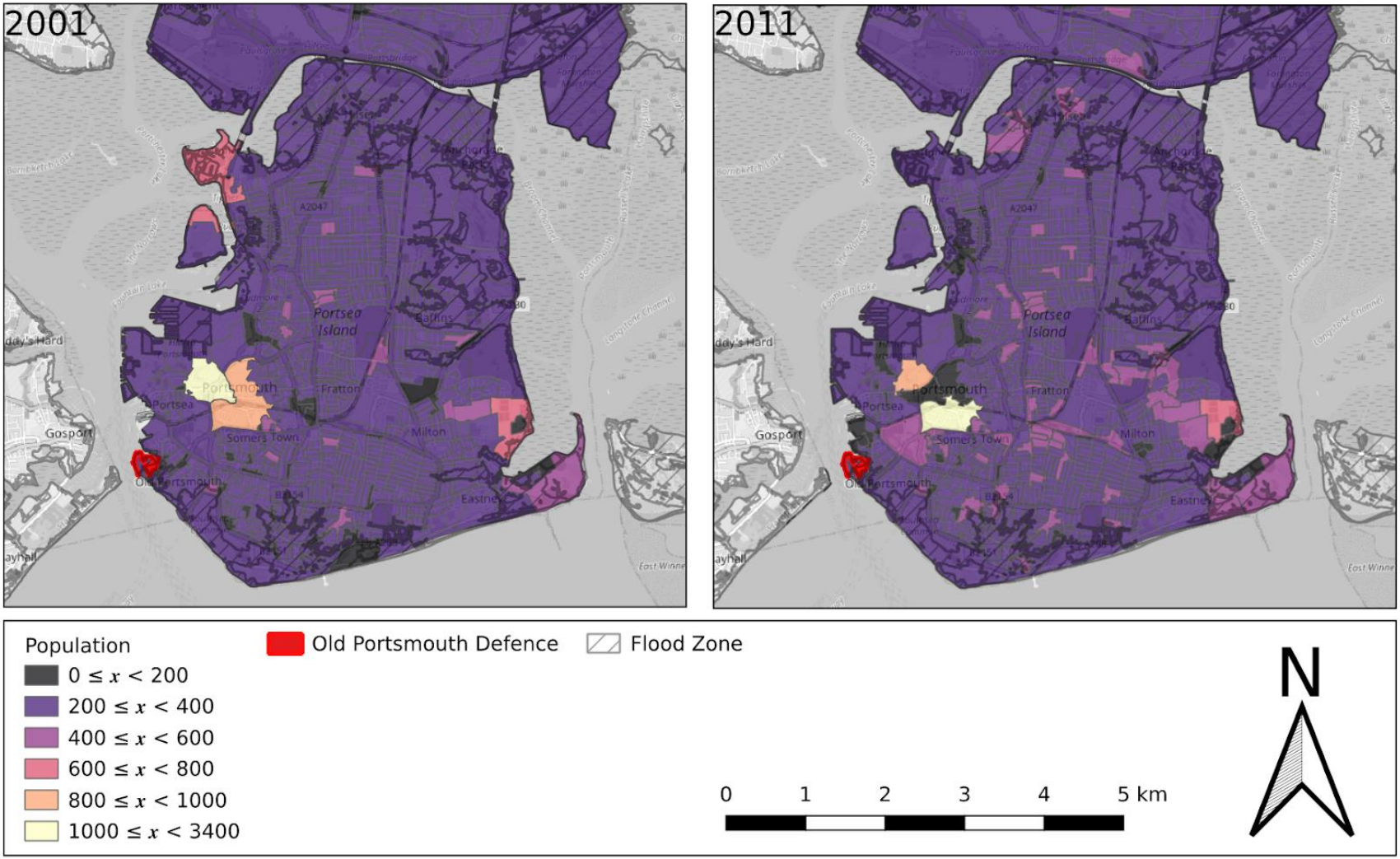


Figure 73 A comparison of the population of Portsmouth grouped by census Output Area in 2001 (pre-) and 2011 (post-Old Portsmouth).

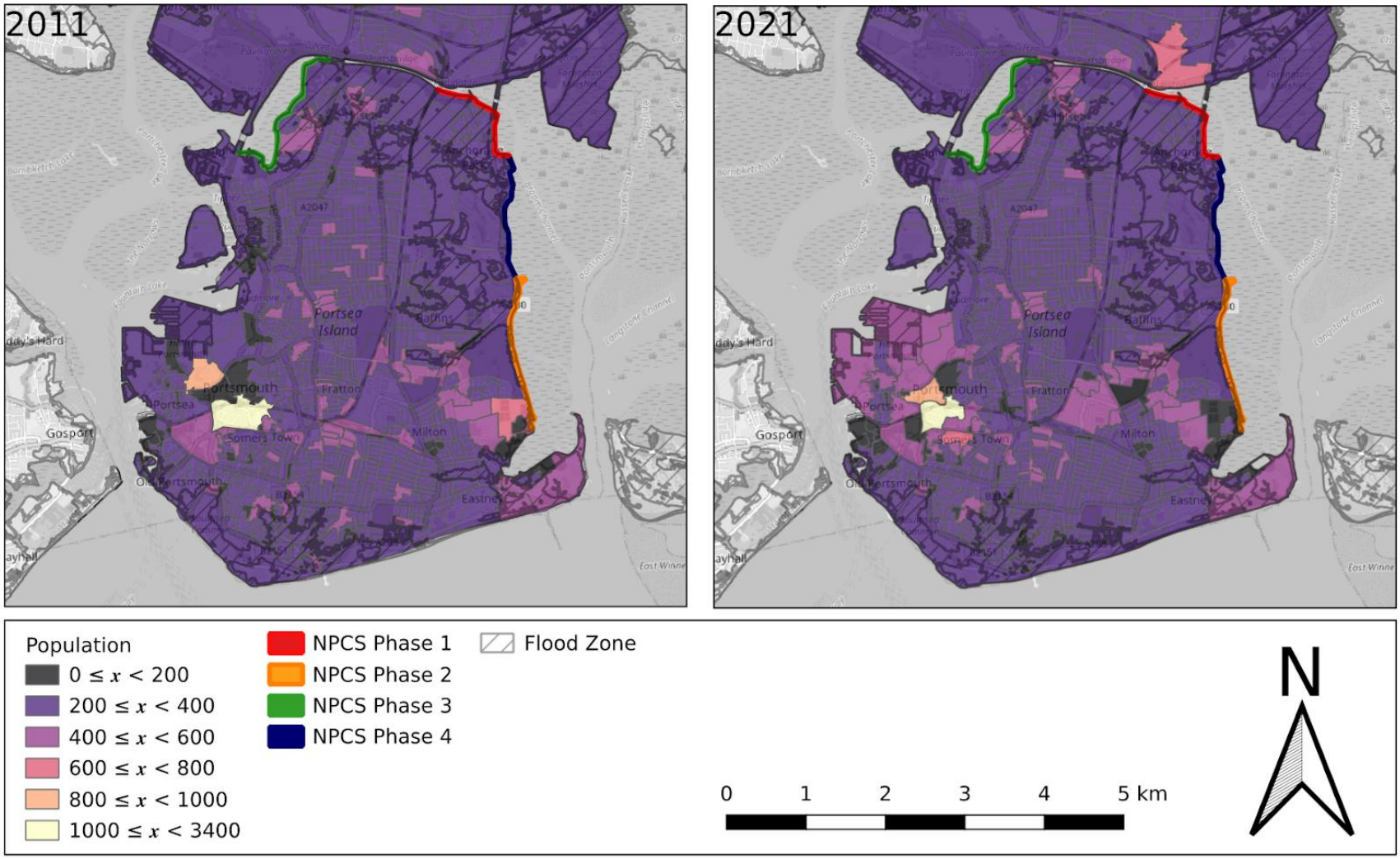


Figure 74 A comparison of the population of Portsmouth grouped by census Output Area in 2011 (pre-) and 2021 (post-NPCS).

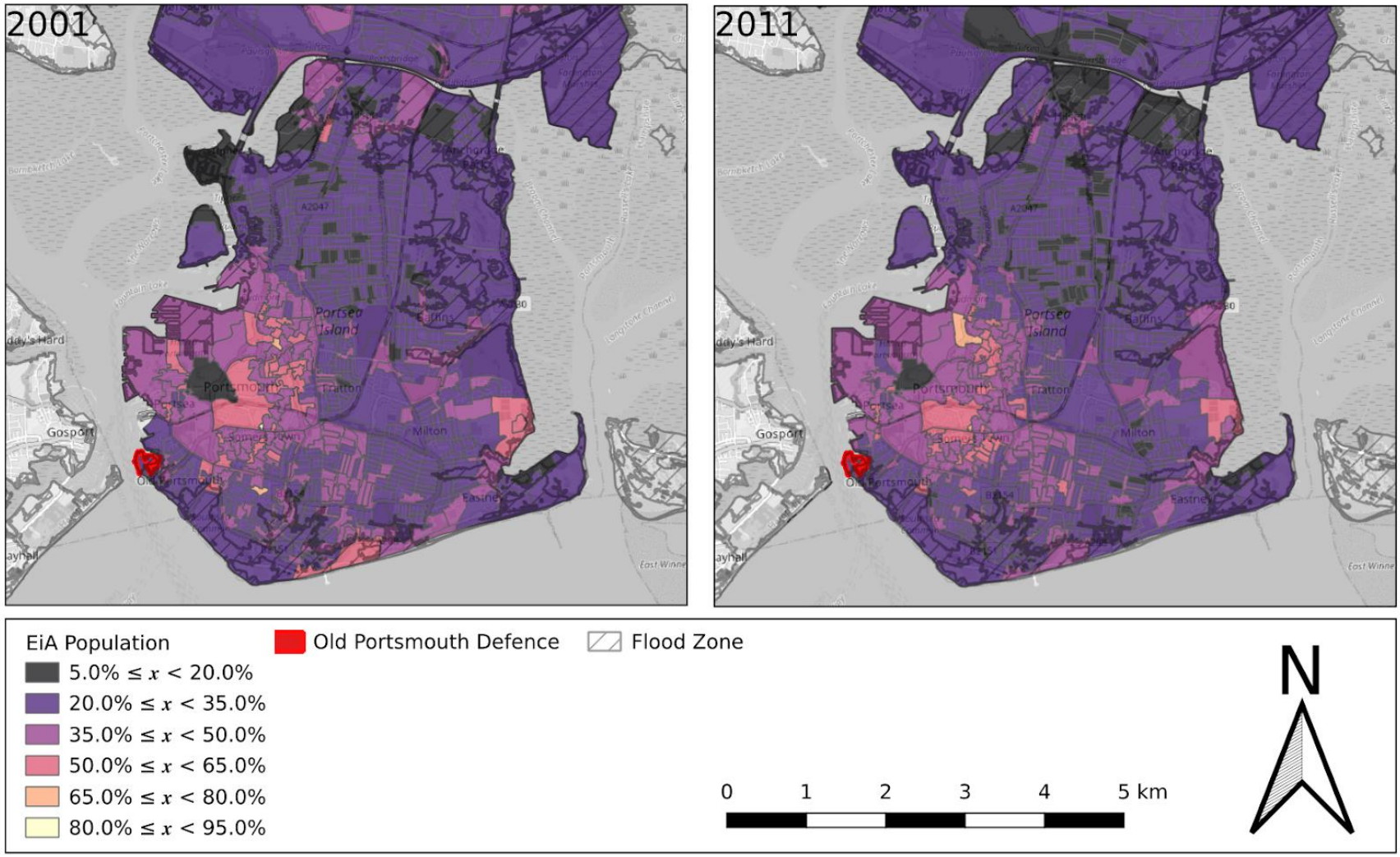


Figure 75 A comparison of the economically inactive (EiA) population of Portsmouth by census OA in 2001 (pre-) and 2011 (post-Old Portsmouth).

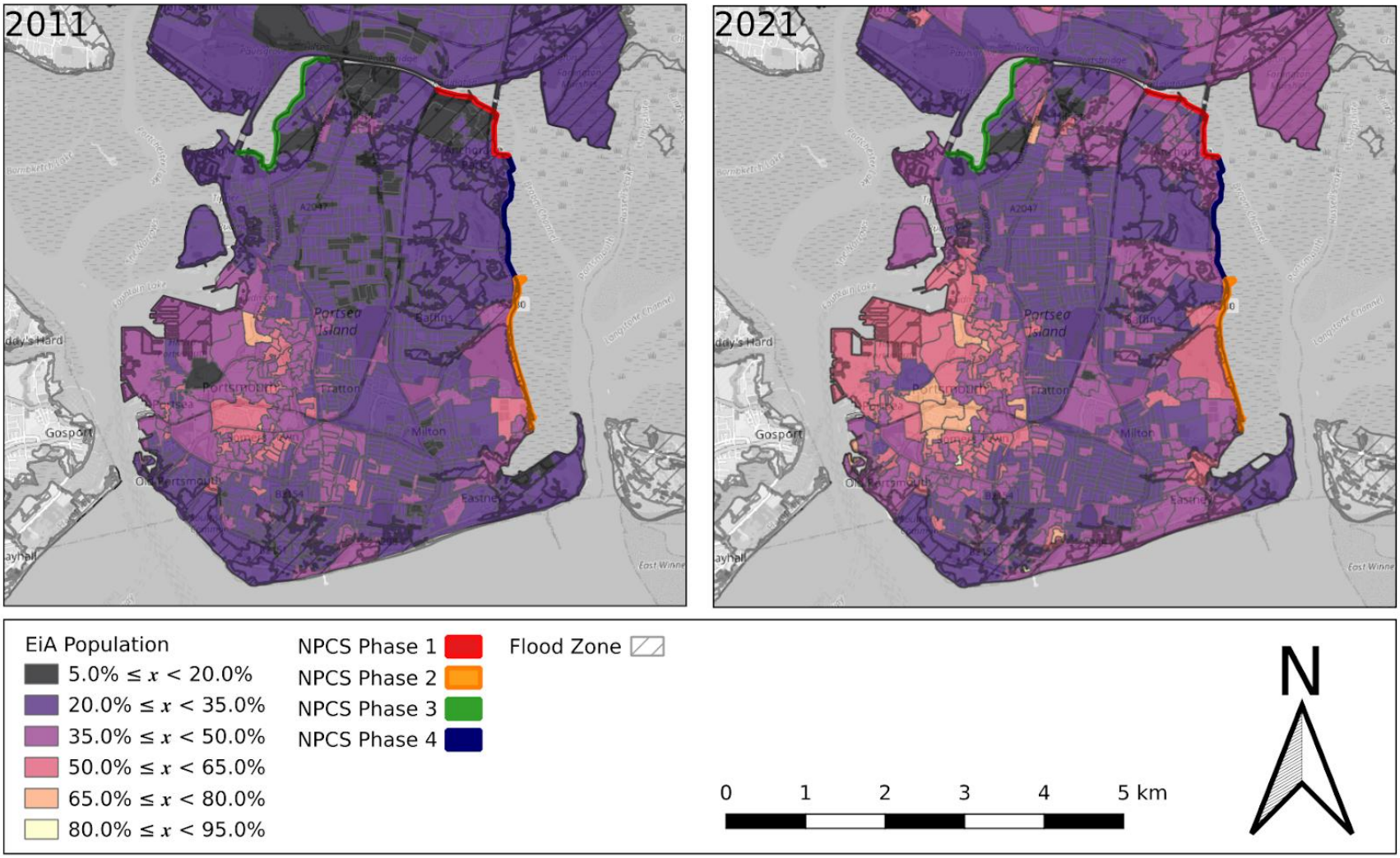


Figure 76 A comparison of the economically inactive (EiA) population of Portsmouth by census OA in 2011 (pre-) and 2021 (post-NPCS).

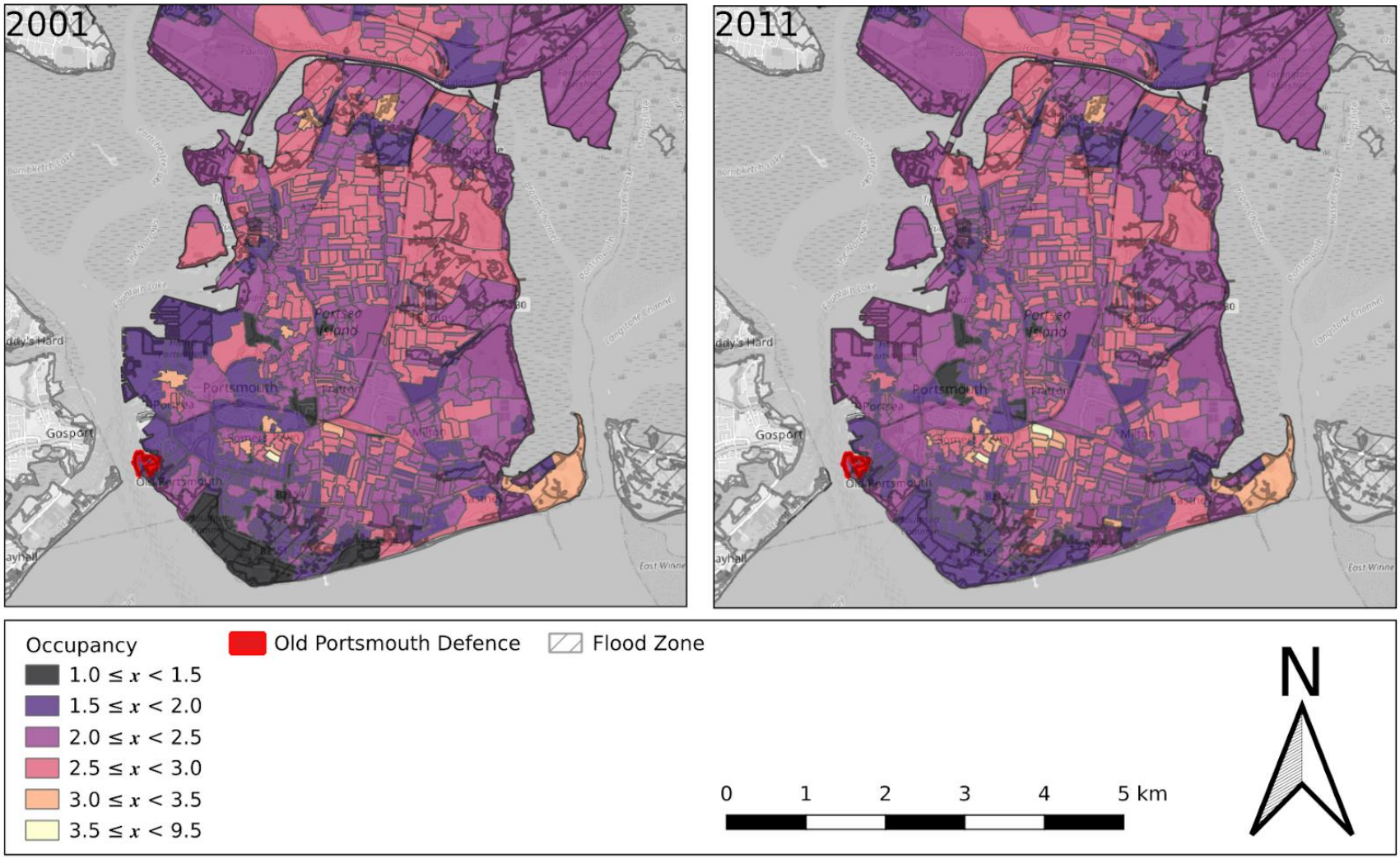


Figure 77 A comparison of population per household of Portsmouth grouped by census OA in 2001 (pre-) and 2011 (post-Old Portsmouth).

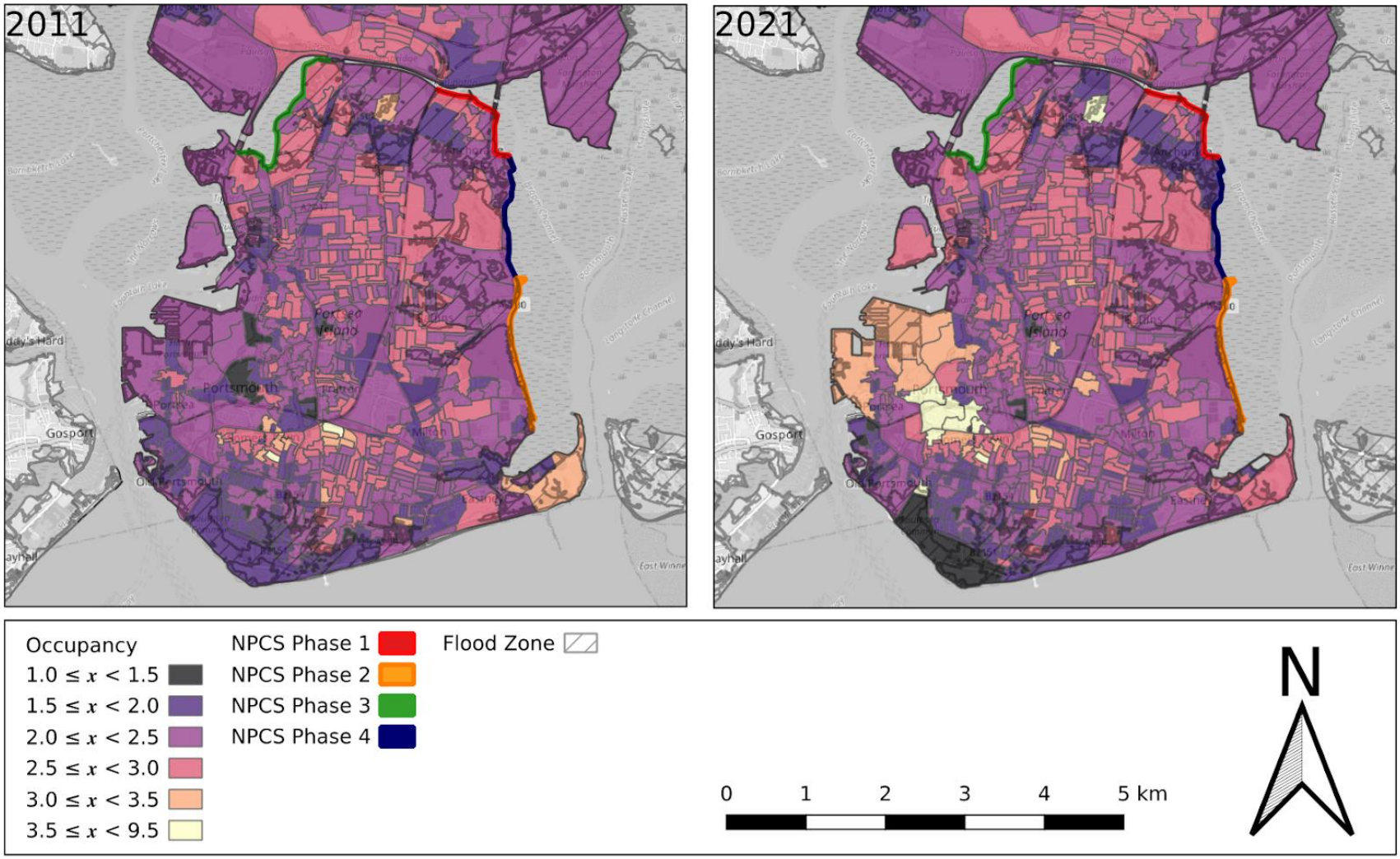


Figure 78 A comparison of population per household of Portsmouth grouped by census OA in 2011 (pre-) and 2021 (post-NPCS).

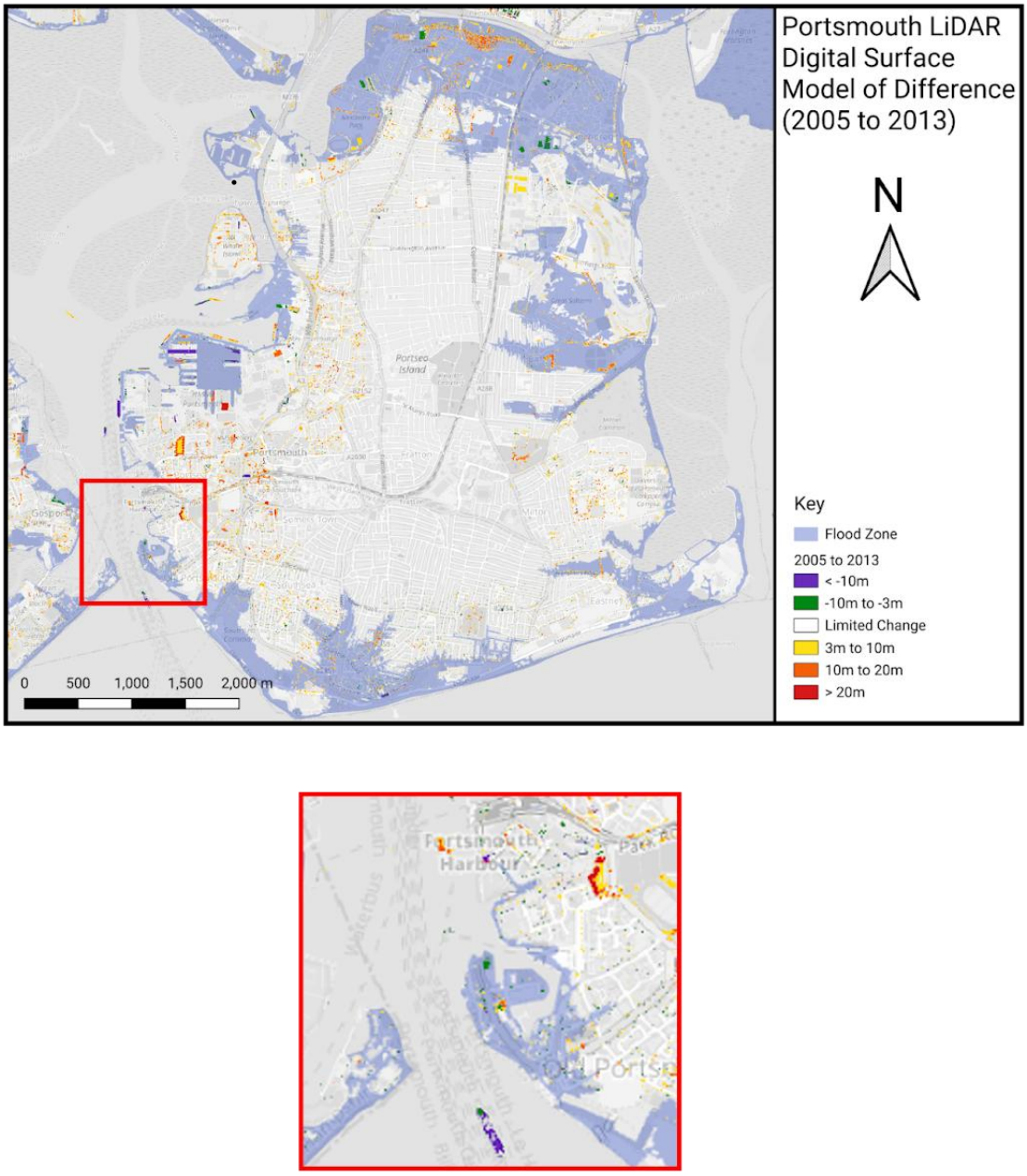


Figure 79 Portsmouth 2005 and 2013 LiDAR DSM comparison. Southwest Portsmouth extract is inset.

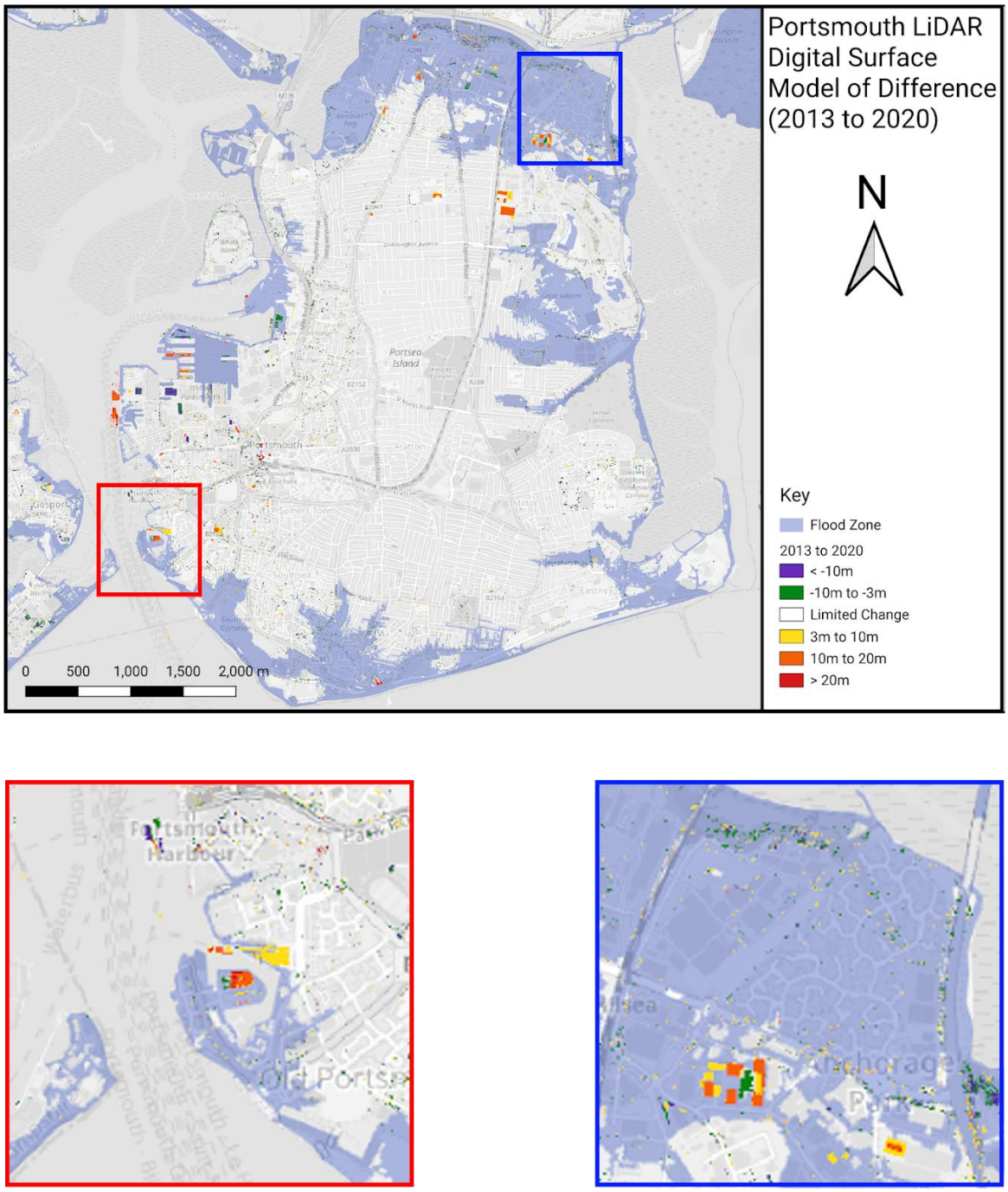


Figure 80 Portsmouth 2013 and 2020 LiDAR DSM comparison. Southwest and northwest Portsmouth extracts are inset.



Figure 81 (50.79185N, -1.10761E) in Old Portsmouth in 2012 (Google Street View, 2024).



Figure 82 (50.79185N, -1.10761E) in Old Portsmouth in 2019 (Google Street View, 2024).

Table 33 Population changes from and between each decadal census in Portsmouth.

Risk Category	Time Period	Population	Annual Growth Rate
Total Population	2001	186,701	-
	2011	205,056	0.98%
	2021	208,016	0.14%
Exposed Population	2001	50,165	-
	2011	54,236	0.81%
	2021	53,201	-0.19%
Exposed & Vulnerable Population	2001	11,552	-
	2011	11,578	0.02%
	2021	16,224	4.01%

Table 34 Occupancy rate changes between censuses in Portsmouth.

Year	Average Occupancy	Percentage Change (%)		
		Average	Standard Deviation	Maximum
2001	2.299	-	-	-
2011	2.337	2.973	8.799	43
2021	2.478	1.677	16.831	150

Table 35 The results of the geostatistical test of Portsmouth urban changes per decade.

Raster	Result	Lower Bound	Upper Bound	p-Value
2005 to 2013	0.329	0.273	0.385	≤0.05
2013 to 2020	0.972	0.818	1.126	≤0.05

4.1.3.2 Gosport

Gosport is approximately 0.6km west of Portsmouth. Located at (50.79489N, -1.11846E).

The georeferenced 2001 census reveals that Gosport has a highly varied population distribution: some areas have relatively low population, whereas some are quite high. The central areas of Gosport are the most populated, as expected. However, in other locations to the west, there is a lower than average population density, this is due to local geography, and these areas covering inhospitable environments unconducive for house building and development. Such as the large lesser populated area on the northeast of the town, this is a large salt marshland, in essence an extension of Portsmouth Harbour, than physical land. The only buildable land in this area is covered by the Ministry of Defence owned DM Gosport, providing weapons and munitions for the naval base at Portsmouth. Whereas the large empty space in the centre-west of the town, whilst it would be expected that an area this large so central would be populated, this area is floodplain and marshland for the River Alver, which would be difficult to construct on.

Gosport town centre is focused on the extreme eastern point of the Gosport peninsula, across the narrow strait connecting the Solent and Portsmouth Harbour, 570m from Portsea Island. The most populated area within the town is Elson, to the immediate northwest of the town centre, and the area bordering the River Alver, on the centre of the peninsula. Both of these areas are connected to the B3334, the main route out of the peninsula to the M27, which then connects to Southampton and Portsmouth. Perhaps explaining the lack of population in Gosport town centre; it would be very difficult to get to work, cross the peninsula daily, unless the person worked in Gosport itself, especially with the lack of a fixed link to Portsea Island.

The town of Gosport lies across Portsmouth Harbour from Portsea Island and Portsmouth. When comparing population in Gosport from before the SCFP at Old Portsmouth was completed to after, the population maps reveal some change. The largest change was the decrease in population in Haslar, the peninsula in the southeast of the town. Population here decreased so substantially that it led to a drop of three levels, from 800-1000 people down to 200-400 people (**Figure 83**). To the north of Haslar, across Haslar Lake, lies the town centre of Gosport, here there was a slight increase in population, although neighbouring OAs also saw a decrease. Other OAs to the north of the town centre did not see any change, and therefore only saw a stabilisation. However, to the south of the town there was an increase, in both a coastal OA and a neighbouring one. These OAs that increased lie within the FZ, which extends northwards through the Alver Valley (**Figure 83**). This population increase, whilst not on the coastline, results in an increase in *AfP* (**Table 36**). However, whilst most OAs along the coast did not see much population change, with population stabilising, the large decrease of the Haslar OA dominates coastal population change in Gosport over this period. *Consequently, when comparing from before the Old Portsmouth SCFP to afterwards coastal population in Gosport decreased, whereas, in Portsmouth there was a stabilisation of coastal population at the defence across this period*.

Whilst the NPCS was underway across Portsmouth Harbour on Portsea Island, Gosport also went under some population change during this period (**Figure 84**). Comparing from before Phase 1 to 4 of the scheme to afterwards, population increased in Haslar, but only enough to increase by one level, from 200-400 people to 400-600 people. Whereas, north from the area, in the town centre, there was a population decrease, both in those living on the coastline and more internally. To the west of the town there was a population increase to the highest seen in Gosport during this period, but yet again only by one level (**Figure 84**). In fact, across this period, the total population decreased by 0.08%/yr and the *AfP* increased by 0.34%/yr. However, the majority of coastal OAs remained stable, and those that did change were equally likely to have increased by one level as decreased. *Therefore, whilst Phases 1 to 4 of the NPCS were undertaken in Portsmouth, coastal population remained relatively stable across this period. This is similar to the population at the new defences in Portsmouth*.

Similar to Portsmouth, Gosport has socio-economic divisions with OAs with the greatest proportion of the OA population who are EiA were more likely to be in the south and west of the town. However, from the time before the Old Portsmouth coastal flood defence project was completed to afterwards,

Gosport as a whole saw a general decrease in EiA population (**Figure 85**). The OAs on the northern and eastern coastline saw a mix of decrease and increase in the proportion of EiA residents both by one level. The large internal OA containing the Alver Valley saw a decrease in the proportion of EiA residents, despite an increase in population, suggesting less vulnerable populations had moved into the area. An adjacent coastal OA saw a decrease in the proportion of its EiA population, and lies primarily within the FZ. With the uneven mix of increases and decreases in OAs on the coastline, there is likely a net neutral change across the decade taking the EiA of coastal OAs in Gosport as a whole. *Therefore, when comparing the EiA of the population from before the Old Portsmouth defence was completed to afterwards, there was limited/no net change in coastal populations. Whereas, in Portsmouth there was a decrease in the proportion of EiA people living by the defence*.

However, during the 2011 to 2021 period, the proportion of EiA residents out of the total population per OA increased in most areas of Gosport. Most coastal OAs saw an increase in the proportion of EiA population, the largest increase occurring on the southern coast, which saw some OAs increase from the 20%-35% level to 50%-65% level (**Figure 86**). Haslar, in the southeast of the town, was the only coastal OA to see a decrease in EiA population. In contrast, coastal OAs to the north, in the town centre all saw an increase in EiA population. Further north, many of the coastal OAs remained stable, but half also increased. The domination of the increasing proportion of EiA residents per OA is difficult to miss in coastal areas, and indeed across the town generally. *From before the first four phases of the NPCS to afterwards the proportion of EiA people within coastal OAs increased in Gosport,whereas in Portsmouth during the same period there was a net stabilisation with many remaining not seeing enough change to alter category*.

In Gosport, comparing the maps from the time before the Old Portsmouth site was constructed in Portsmouth to afterwards, there was notable internal change, but limited on the coastline. Starting at the far north of the town there were two decreases in housing occupancy, but also two stayed the same (**Figure 87**). Further round clockwise there were more decreases, but those in the town centre remained stable. Across Haslar Lake onto the Haslar peninsula the OA remained stable, although adjacent ones decreased. Farther west there were many stabilisations across the decade, although there were some decreases in the far west. Internally, there was a large increase in many OAs bordering the Alver Valley (**Figure 87**). Across the period, coastal OAs either decreased or were stable, whereas many elsewhere in the town increased, or remained stable also. The large amount of coastal, and internal, OAs decrease in housing occupancy is reflected in the decrease in average housing occupancy across this period, with each OA decreasing on average by -2.086% (**Table 37**). *From the period before the Old Portsmouth SCFP was constructed to afterwards, housing occupancy decreased in the majority of coastal OAs in Gosport, whereas in Portsmouth across this period, housing occupancy increased*.

During the period of the implementation of the first four phases of the NPCS (2011 to 2021) Haslar saw a large growth in housing occupancy, rising from 1.5-2 people per household to 3.5-9.5 (**Figure 88**), this large increase drove the greatest change of 43% of housing occupancy (**Table 37**). Other OAs along the southern coastline of Gosport also saw an increase of housing occupancy, with one increasing by two categories. On the north coast there was an increase in the majority of OAs, although it did decrease, with a corresponding increase in a neighbouring OA. Though OAs on the coastline in the town centre saw a stabilisation across this period. Internally there was some change: OAs to the east of the Alvar Valley saw an increase in housing occupancy, and so did one OA to the west of it. In fact, there was a general increase in hoisting occupancy across this period**.** *Therefore, in coastal areas of Gosport, housing occupancy increased during the period of the NPCS implementation. Constrastingly, in Portsmouth across this period, housing occupancy remained stable in areas adjacent to coastal flood defences*.

During the period in which the Old Portsmouth SCFP was being built in Gosport there was some urban growth, as detected by the LiDAR analysis. Namely the Flag Staff Green estate built in the late 2000s. Moreover, a large proportion of this development lies within the FZ, despite there being no new SCFP projects being undertaken in the area. This area is apparent in the LiDAR imagery to the north of the town centre, on the eastern coastline (**Figure 89**). Whereas, in the town centre, across this period, there was a decrease in urban development, most likely driven by the demolition of a building. However, the

change in Gosport from the construction of the Flag Staff green estate was large enough to warrant statistical significance, albeit with a lower *t*-score compared to Portsmouth, 0.053 (**Table 38**) and 0.329 (**Table 35**), respectively. These data reflect the changes that occurred in both locations, high-density development occurred in Portsmouth, and low-density in Gosport, however, this is more a reflection of the locations themselves: Portsmouth is already a city with a larger population, constrained by Portsea Island, whereas Gosport is relatively less populated. This 2005 to 2013 LiDAR comparison (**Figure 89**) is the only comparative site that obtained statistically significant results after undergoing the statistical test. *Therefore, during the period the Old Portsmouth SCFP was being constructed, comparing from before to after, there was statistically significant growth in Gosport. This was also replicated in Portsmouth, albeit with a larger output*.

However, during the second geostatistical analysis for the area, comparing the 2013 to 2020 DSM rasters, across the period that the first four phases of the NPCS were implemented, Gosport did not see statistically significant growth (**Table 38**). Across this period there was only development within the Defence Munitions Gosport bases in the north of the town (**Figure 90**). Excluding this construction, as military bases are not included in this analysis, there was limited urban development. Likewise, the construction of several large cylinders in the east of the town should, despite being close to the coast, should not be considered as they are owned by the military, forming a part of the Oil and Pipelines Agency. In contrast, there was some demolitions in Haslar (**Figure 90**), despite the increase in housing occupancy for the area (**Figure 68**) which would suggest internal modifications. *Therefore, across this period, from before the NPCS SCFPs, to afterwards, there was no statistically significant urban growth in coastal areas, unlike Portsmouth*.

Therefore, to summarise the changes in Gosport that occurred from before the Old Portsmouth SCFP to afterwards:

- Coastal population decreased;
- There was overall a net zero / limited change in EiA population in coastal areas;
- Housing occupancy decreased in coastal OAs;
- There was a statistically significant change in urban development at the coastline.

Then, to summarise the changes in Gosport that occurred from before Phase 1 to 4 of the NPCS to afterwards:

- Overall there was little change in coastal population;
- There was an increase in EiA population in coastal areas;
- Housing occupancy increased in coastal OAs;
- There was not statistically significant change in urban development at the coastline.

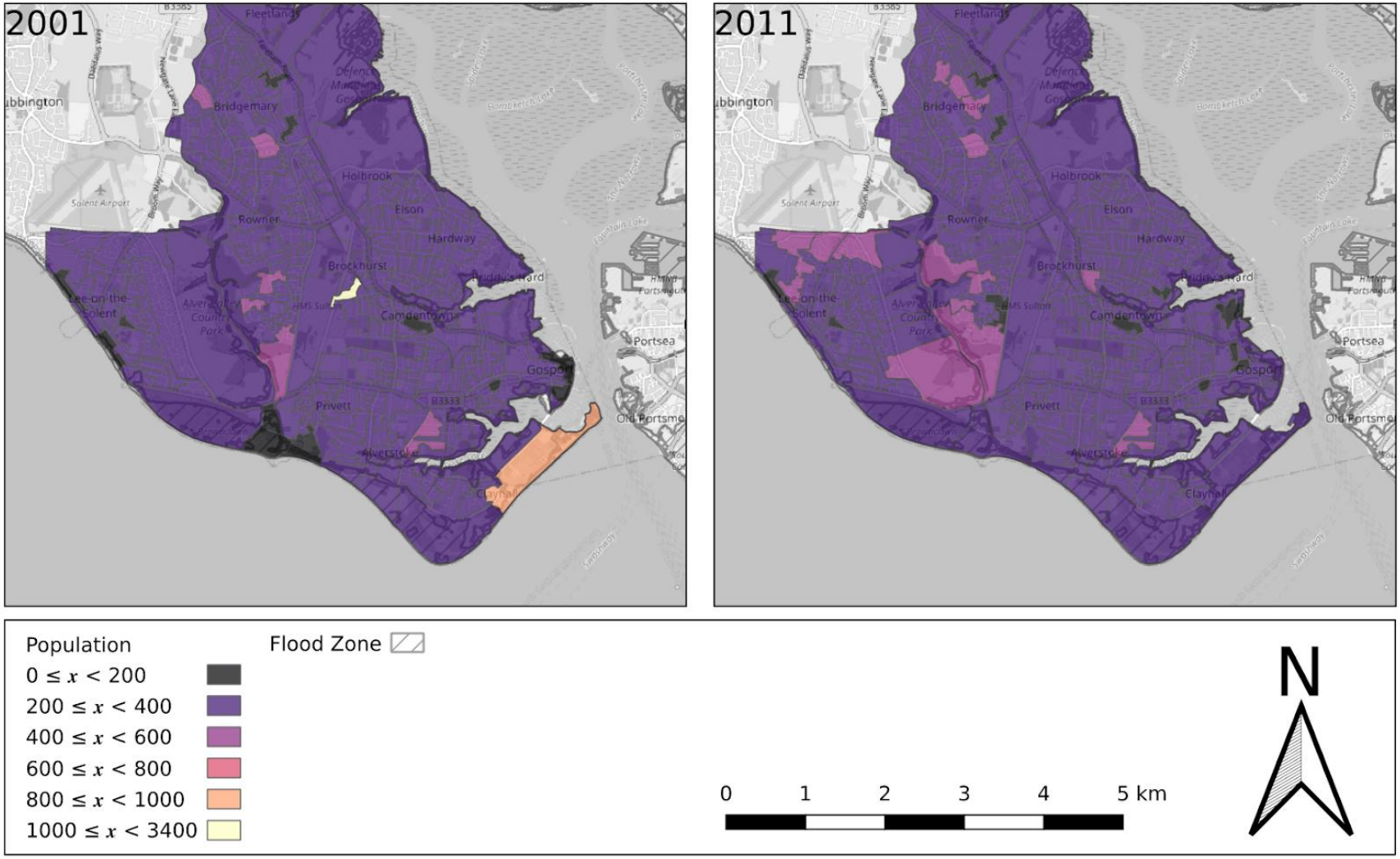


Figure 83 A comparison of the population of Gosport grouped by census Output Area in 2001 (pre-) and 2011 (post-Old Portsmouth).

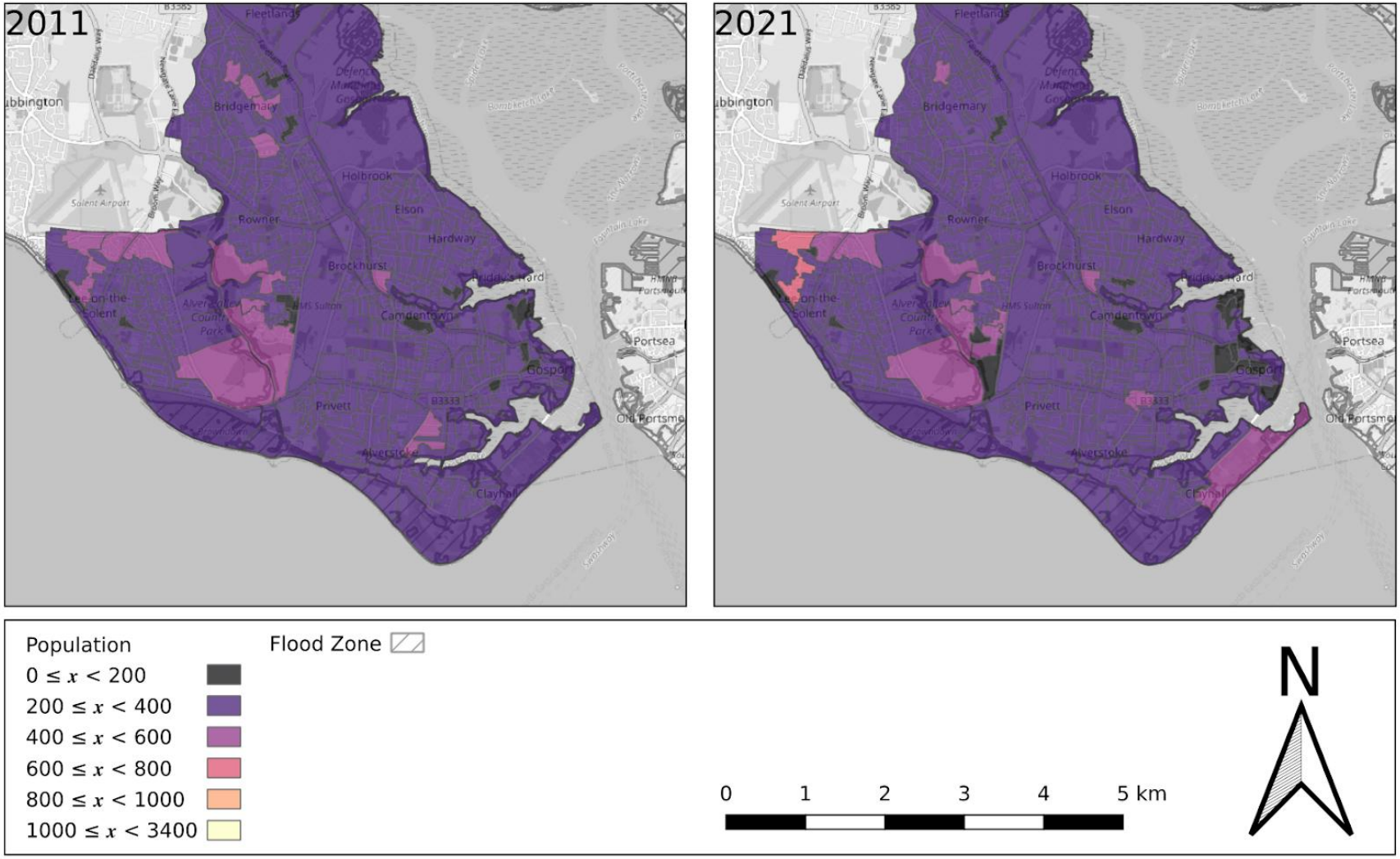


Figure 84 A comparison of the population of Gosport grouped by census Output Area in 2011 (pre-) and 2021 (post-NPCS).

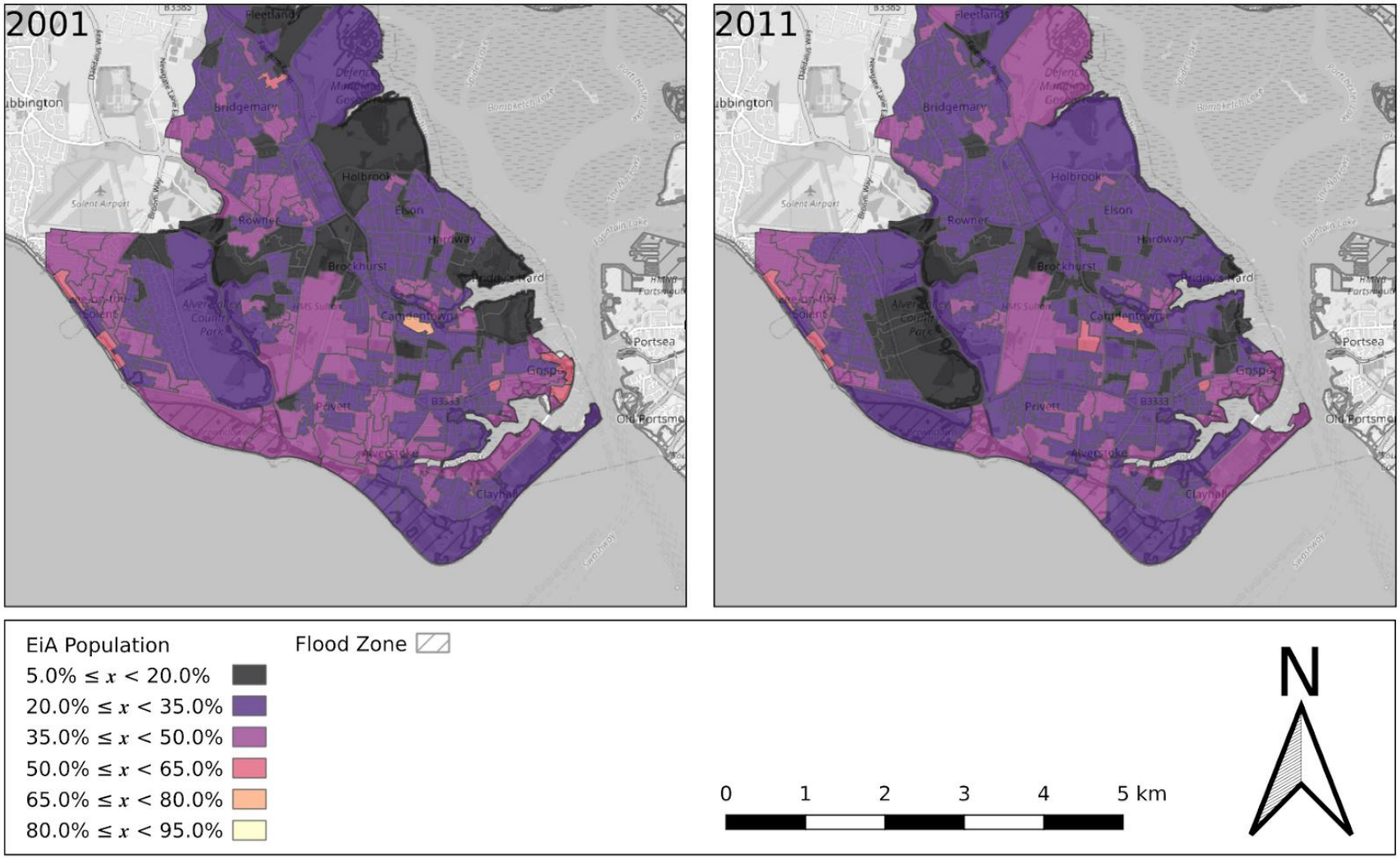


Figure 85 A comparison of the economically inactive (EiA) population of Gosport by census OA in 2001 (pre-) and 2011 (post-Old Portsmouth).

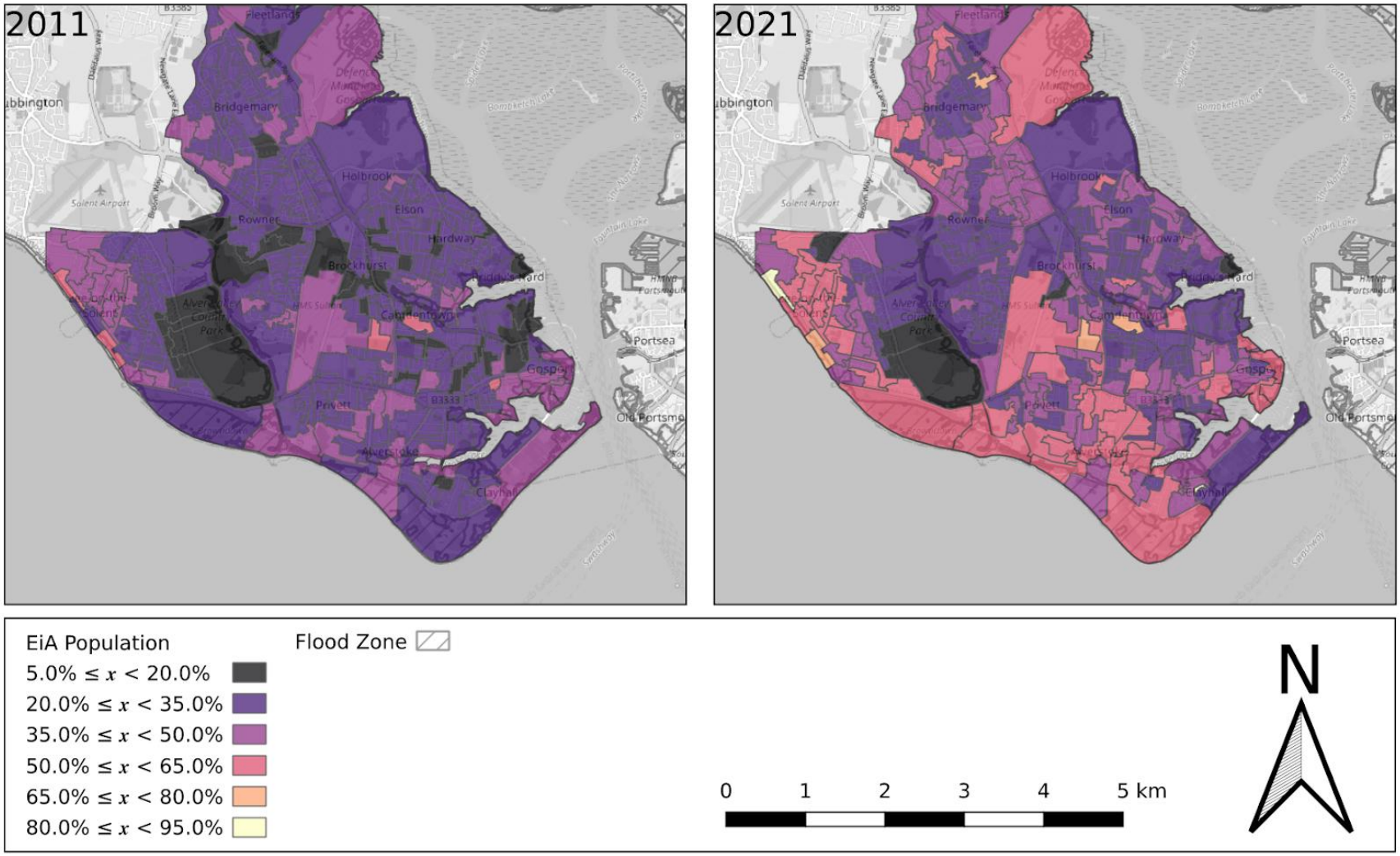


Figure 86 A comparison of the economically inactive (EiA) population of Gosport by census OA in 2011 (pre-) and 2021 (post-NPCS).

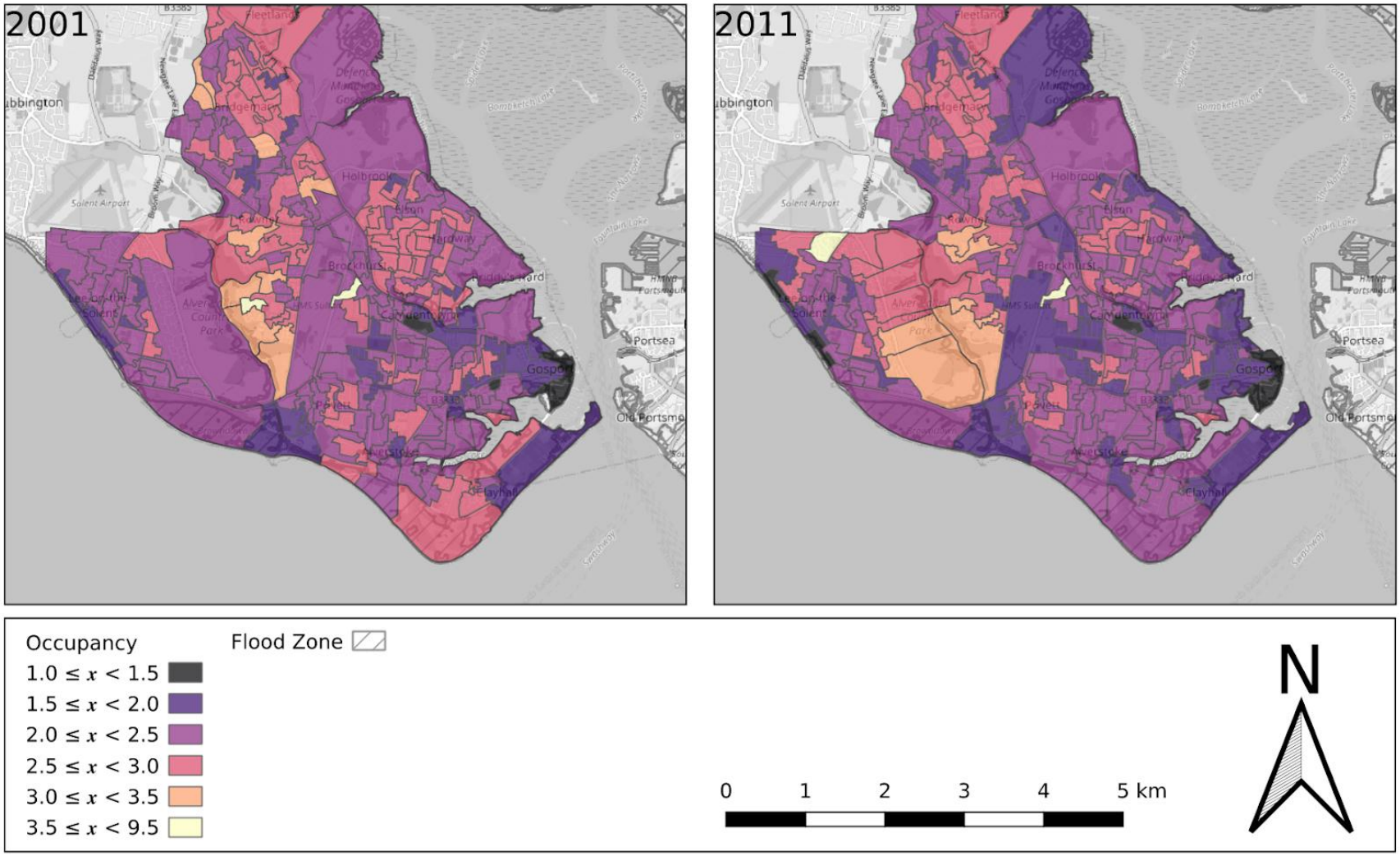


Figure 87 A comparison of population per household of Gosport grouped by census OA in 2001 (pre-) and 2011 (post-Old Portsmouth).

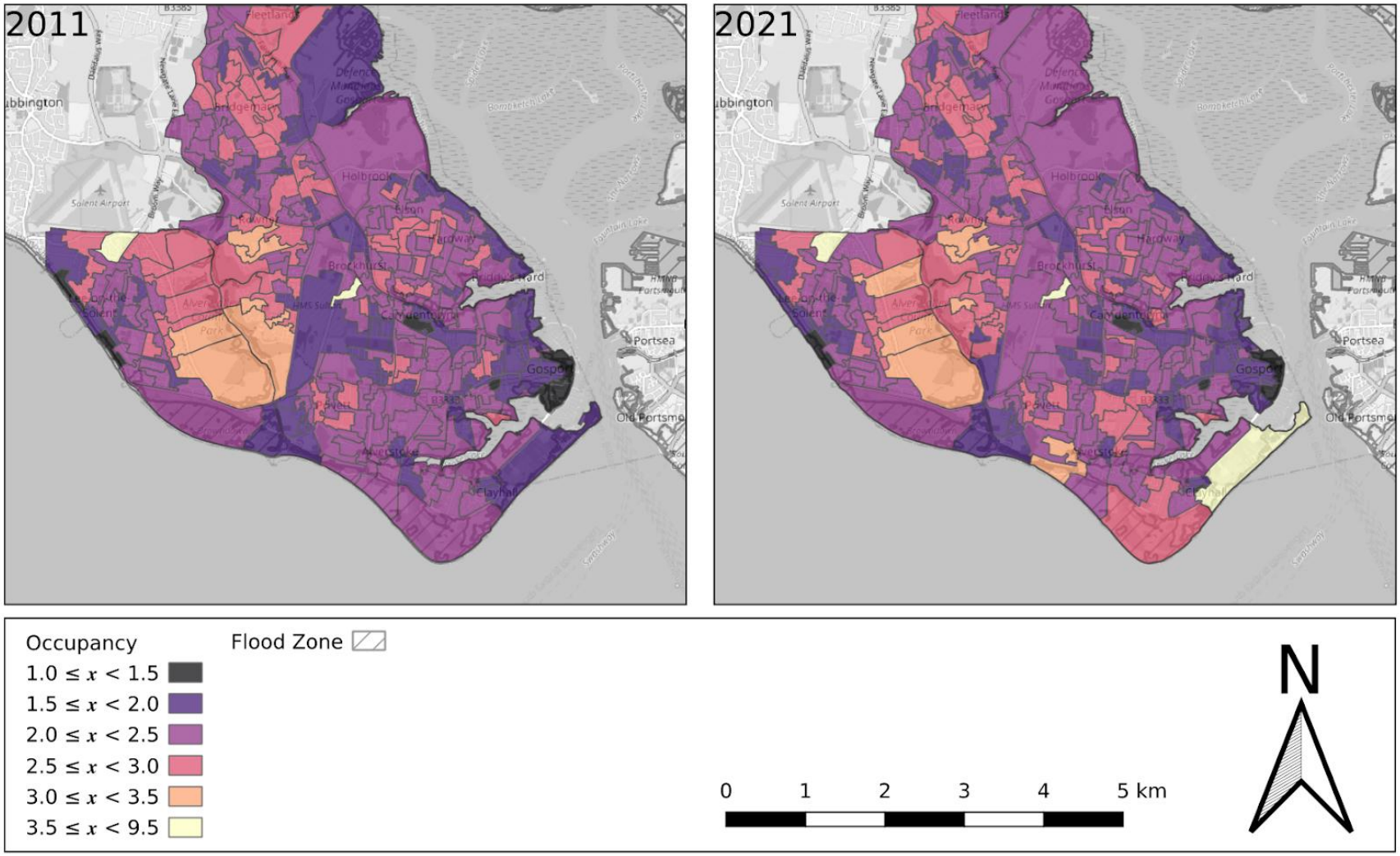


Figure 88 A comparison of population per household of Gosport grouped by census OA in 2011 (pre-) and 2021 (post-NPCS).

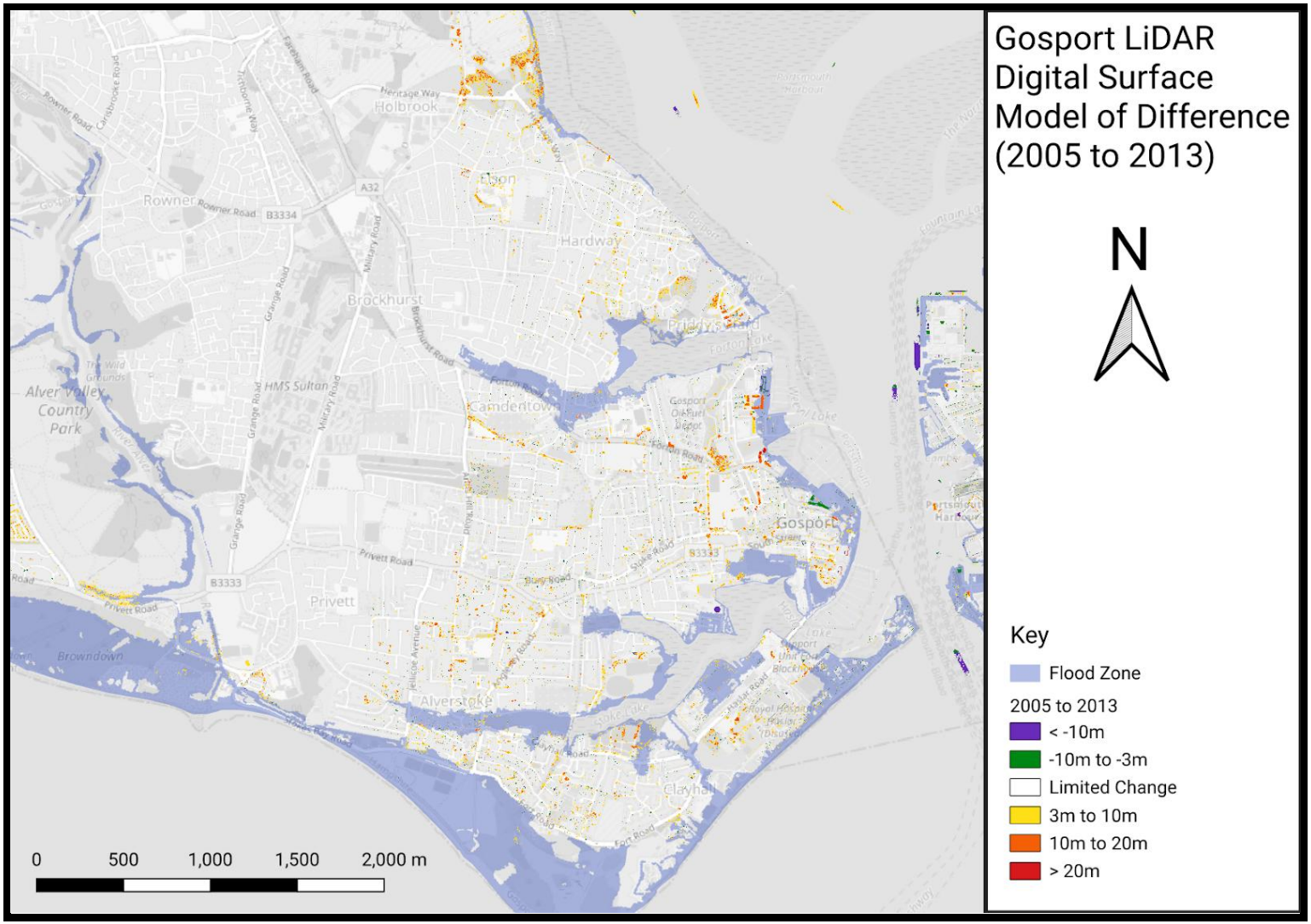


Figure 89 Gosport 2005 (pre-) and 2013 (post-Old Portsmouth) LiDAR DSM comparison.

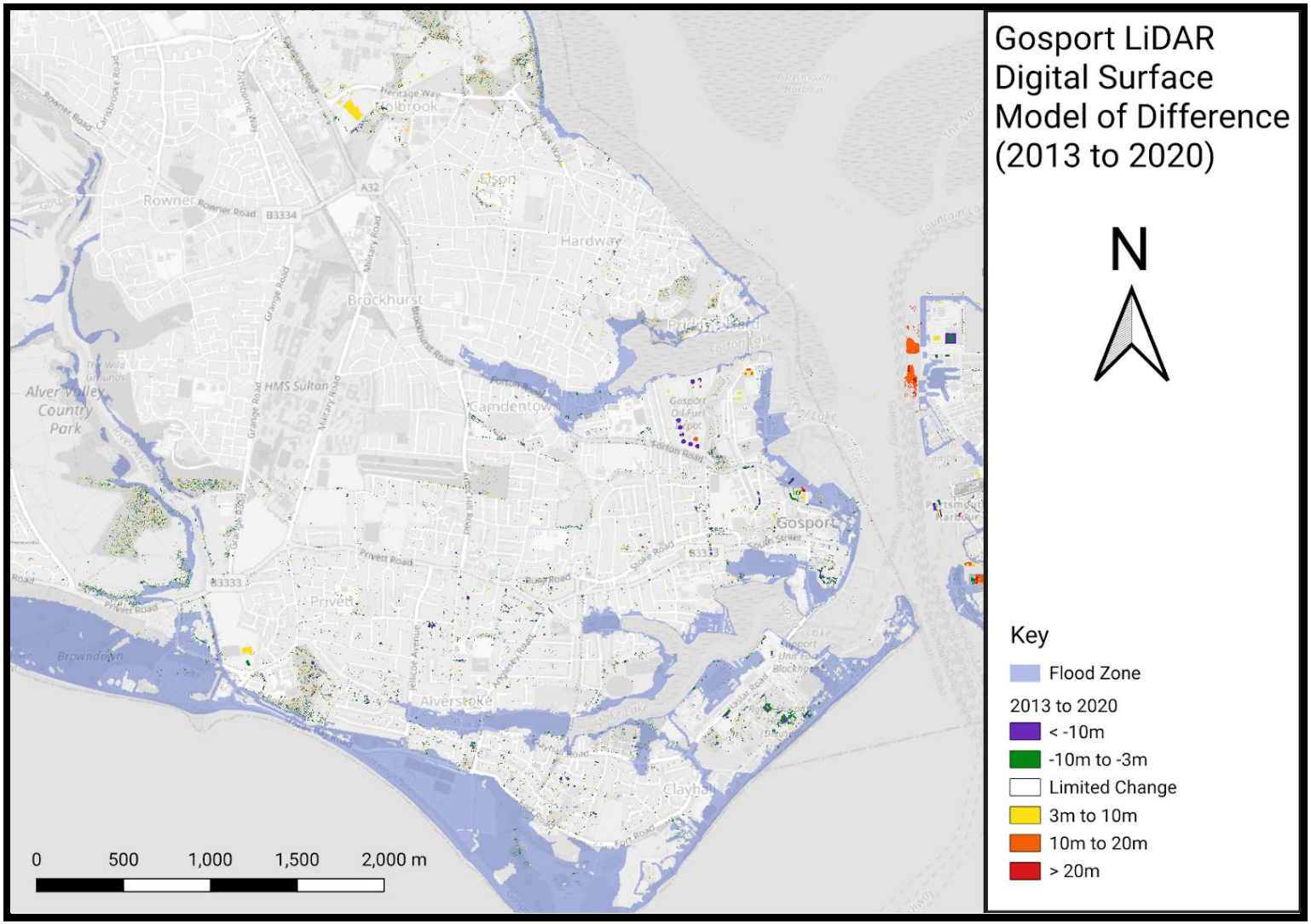


Figure 90 Gosport 2013 (pre NPCS) and 2020 (post Phases 1-4) LiDAR DSM comparison.

Table 36 Population changes from and between each decadal census in Gosport.

Risk Category	Time Period	Population	Annual Growth Rate
Total Population	2001	76,415	-
	2011	82,622	0.81%
	2021	81,956	-0.08%
Exposed Population	2001	20,140	-
	2011	23,473	1.65%
	2021	24,268	0.34%
Exposed & Vulnerable Population	2001	4,442	-
	2011	4,883	0.99%
	2021	8,298	6.99%

Table 37 Occupancy rate changes between censuses in Gosport.

Year	Average Occupancy	Percentage Change (%)		
		Average	Standard Deviation	Maximum
2001	2.347	-	-	-
2011	2.313	-2.086	6.235	17.318
2021	2.355	0.917	8.560	43.098

Table 38 The results of the geostatistical test of Gosport urban changes per decade.

Raster	Result	Lower Bound	Upper Bound	p-Value
2002 to 2013	0.053	-0.069	0.175	≤0.05
2013 to 2020	0.080	0.016	0.171	0.102

4.1.3.3 Synthesis of Case Study C

Since the turn of the millennium, two main SCFP projects have been implemented in Portsmouth, the Old Portsmouth development constructed during the 2001 to 2011 census period, and the North Portsea Coastal Scheme (NPCS), the first four phases of which have been completed and coincide with the 2011 to 2021 census period. The construction of the Old Portsmouth SCFP, in the west of Portsea Island led to not enough change in the representation of the coastal population at the newly constructed defence, and therefore a stabilisation across this period (**Table 39**). Likewise, the coastal population in other areas of the town also saw a stabilisation. This was not replicated in Gosport, however, which saw a decrease in coastal population across this period.

Across the 2010s, the decade of the first four phases of the NPCS, coastal population at the newly constructed structural flood defences also stabilised, whereas elsewhere in the town, in other coastal areas the coastal population increased (**Table 39**), although there was also a stabilisation of population in Gosport in coastal areas.

Table 39 A summary table of the studied factors and locations in Case Study C and how they change from the time before the new Portsmouth SCFP (blue font) to after: upwards arrow and green cell indicate positive change, dynamic equilibrium arrow and orange cell indicate stabilisation, downward arrow and red cell indicate a negative change.

	Old Portsmouth		**NPCS**		**Comparative**	
	Defence	Elsewhere	Defence	Elsewhere	Old Portsmouth	NPCS
Coastal Pop.	⇌	⇌	⇌	⇧	⇩	⇌
Coastal EiA	⇩	⇩	⇧	⇧	⇌	⇧
Coastal Occ.	⇧	⇌	⇌	⇩	⇩	⇧
Coastal Dev.	✓		✓		✓	×

Despite a stabilisation in coastal population in Portsmouth during the 2001 to 2011 census period, covering the construction of the Old Portsmouth SCFP, there was a statistically significant change in population distribution of ~-0.8% compared to OAs internally in Portsmouth, away from the coastline which saw an average change of ~-12%, the difference in population distribution change between these two samples was statistically significant with a p-value of 0.004, far lower than the 0.05 α-level (**Table 40**). Population distribution change in Gosport across this period, the 2001 to 2011 census period, had an average population distribution change of ~-2.8% in coastal areas, compared to ~-7.2% internally elsewhere in the town. These two population samples were not statistically significant at the 0.05 α-level with a resulting p-value of 0.255 (**Table 40**). This mirrors findings in similar studies, such as by Hinkel *et al.* (2014), which highlight how SCFPs alter population dynamics and development patterns.

However, during the 2011 to 2021 census period, covering the construction of the first four phases of the NPCS there was no statistically significant change in Portsmouth nor Gosport. Portsmouth saw an average change in population distribution of ~-8.8% across this period in coastal areas, and an average of ~-4.9% in internal OAs from elsewhere in the city. These two samples were significant at the 0.1 α-level, but not at the 0.05 α-level used in this analysis, with a p-value of 0.079 (**Table 40**). Similarly, in Gosport there was no statistically significant change in population distribution between coastal populations and those more internal. During the 2011 to 2021 census period, there was an average change of ~-0.2% in Gosport in coastal areas, compared to the ~-3.6% average internally in the town. These samples gave a p-value of 0.144 and were therefore not statistically significant.

Portsmouth, during the 2011 to 2021 census period, was the only primary site not to see statistically significant population change at the new SCFP. As Portsmouth is far larger than the other two primary

sites, this may suggest that there is an upper limit to the induction of population distribution change as an urban area becomes more densely populated up to the point that no new development in the area is possible.

Table 40 A table containing the output of the average change in population distribution in the area adjacent to the newly constructed/ upgraded SCFP in Portsmouth, or seafront in Gosport. The table also contains the p-value output from a t-test comparing the two locations within each site.

		Coastal/Defence	Elsewhere	p-Value
Portsmouth	2001 to 2011	-0.808%	-12.809%	0.004
	2011 to 2021	-8.815%	-4.941%	0.079
Gosport	2001 to 2011	-2.844%	-7.265%	0.255
	2011 to 2021	-0.200%	-3.351%	0.144

Comparing from before Old Portsmouth SCFP to after, the proportion of EiA residents living in each OA decreased in coastal areas at the defence and other coastal areas in the city, whereas there was a stabilisation in Gosport (**Table 39**). Although, during the 2011 to 2021 period, when the first four phases of the NPCS were constructed, the proportion of EiA residents per OA increased at the new defences, other coastlines in Portsmouth, and in Gosport also. Although this was also seen in Weston-super-Mare and the comparative sites there, Burnham-on-Sea and Clevedon, and is therefore likely to be derived from the Covid-19 pandemic and its impacts on the local, regional, and national economy, placing more people out of work.

In contrast, in Portsmouth, at the newly constructed Old Portsmouth SCFP there was an increase in housing occupancy that was not replicated in other coastal areas of Portsmouth or in Gosport, which saw a stabilisation and a decrease in housing occupancy respectively (**Table 39**). Although, during the period of which the NPCS Phases 1 to 4 were constructed, the reverse was true: there was an increase in housing occupancy in coastal areas in Gosport but not in Portsmouth which had a stabilisation of housing occupancy at the newly built defences and a decrease in housing occupancy elsewhere on the coastline. From this information it would be difficult to draw conclusions about the connections between the SCFPs and impacts on housing occupancy. Although, the NPCS Phase 1 to 4 mainly followed parkland or industrial land, with only Phase 1 directly protecting a residential area.

There were also mixed outcomes from the geostatistical test on LiDAR change in both, Portsmouth and Gosport. Both, the Portsmouth raster changes, comparing between 2005 and 2013 for the Old Portsmouth scheme, and 2013 and 2020 for the NPCS, had statistically significant coastal development. The two rasters covering the Old Portsmouth defence construction were significant with a p-value lower than 0.05, likewise for those covering the NPCS (**Table 35**). This follows trends identified by Mandarino *et al.* (2023), who emphasised the role that SCFP have in encouraging urban development in its proximity.

Although whilst this was not the case for the analysis of the 2013 to 2020 Gosport rasters, which did not produce a statistically significant output with a p-value of 0.102, it was for the 2005 to 2013 rasters (**Table 38**), albeit with a lower t-score compared to Portsmouth, 0.053 and 0.329, respectively. *Therefore, to summarise, the construction of the SCFPs in Portsmouth may have led to socio-economic and urban changes in Portsmouth. Changes were either replicated in either other coastal areas of the city or in Gosport or were not repeated during the second round of upgrades, the North Portsea Coastal Scheme. Although this scheme mainly protected parkland or industrial areas, which may limit analysis. These outcomes and conclusions make Portsmouth unique as a case study, as these were not replicated in the other two: Southport and Weston-super-Mare*.

4.1.4 Socio-economic and Urban Development Analysis Synthesis

The construction of the SCFP in Southport coincided with population increases in nearby OAs, which was not apparent in other coastal areas in the town, nor in the comparative sites. There was also an increase in coastal population in Weston-super-Mare at the newly upgraded SCFP, but also in other coastal areas (**Table 41**). But this was not replicated in coastal areas of its comparative towns. This was not replicated in Portsmouth, however, as there was no significant change in coastal population at the new defences after either project, and whilst there was never an increase in Gosport coastal population, there was an increase in coastal population away from the new NPCS defences (**Table 41**). It is the inclusion of Portsmouth as a case study that pushes the summary of population change in other coastal areas into a positive figure, +0.25 (**Table 42**). However, there is still a strong signal that there is a link between a new SCFP and an increase in coastal population at it, with a +0.5 average of population change at the defence. This is much greater than the -0.33 average of the comparative sites, and a -0.1 non-defence average produced from the combination of comparatives sites and non-defence primary site outcomes (**Table 42**). Although due to the inclusion of Portsmouth, this non-defence average is only slightly below the threshold and into negative figures. This would suggest that something about Portsmouth would make it unique to other case studies, the most obvious factors being its size, density, and local economy compared to the other two, which are mid-sized towns. Moreover, this would indicate that there may be an upper limit to the impact of new SCFP impacts on coastal population via two conceivable pathways:

A. Population Driven
The already very high population density limits population increases, either due to the economics of supply and demand in the area, or physically limits the number of people that can live in the area.

B. Economy Driven
The economy of the city is powerful enough to overcome the unintended impacts of the SCFP on its population and that is the primary driving force.

These pathways may be independent or a function of both.

In contrast to the coastal population changes at the newly constructed SCFP, which had a strong signal of a link emerging through the data, connections between these structural interventions and the proportion of EiA residents were limited. EiA residents decreased at the defence in Southport, but this population also decreased elsewhere in Southport in other coastal areas. This decrease was also replicated in the comparative sites for Case Study A, Blackpool and Crosby (**Table 41**). Whereas, in Weston-super-Mare, following the upgrade of the SCFP, there was an increase of EiA population in the areas adjacent to the new structural intervention. However, there was also an increase in EiA population in other coastal areas of Weston-super-Mare, as well as coastal areas in the comparative sites, Burnham-on-Sea and Clevedon (**Table 41**).

Table 41 A summary table of the studied factors, primary locations and comparative sites, and how they change from the time before the newly constructed or upgraded coastal flood defence (blue font) to after: upward arrow and green cell indicate positive change, dynamic equilibrium arrow and orange cell indicate stabilisation, downward arrow and red cell indicate a negative change. Gosport 1, Portsmouth 1, and Defence 1 refers to the 2001 to 2011 period, while with '2' refers to the 2011 to 2021 period. BoS: Burnham-on-Sea; WSM: Weston-super-Mare.

Sites		**Coastal Pop.**	**Coastal EiA**	**Coastal Occ**
A	Blackpool	⇩	⇩	⇩
	Crosby	⇌	⇩	⇩
	Southport	⇩	⇩	⇩
	Defence	⇧	⇩	⇧
B	BoS	⇌	⇧	⇩
	Clevedon	⇌	⇧	⇌
	WSM	⇧	⇧	⇌
	Defence	⇧	⇧	⇧
C	Gosport 1	⇩	⇌	⇩
	Portsmouth 1	⇌	⇩	⇌
	Defence 1	⇌	⇩	⇧
	Gosport 2	⇌	⇧	⇧
	Portsmouth 2	⇧	⇧	⇩
	Defence 2	⇌	⇧	⇌

Table 42 A summary table displaying the output of the table above converted to numbers with a decrease becoming -1, dynamic equilibrium becoming 0, and an increase becoming +1. These data have been grouped into the area at the defence and non-defence: coastal areas not at the defence (Elsewhere), the comparative sites, and those data combined.

Outcome Summary	**Primary Site**		**Comparative Sites**	**Non-Defence Combined**
	Defence	**Elsewhere**		
Coastal Population	+0.5	+0.25	-0.33	-0.1
Coastal EiA	0	0	+0.16	+0.1
Coastal Occupancy	+0.75	-0.5	-0.5	-0.5

There was also a mix of outcomes in Case Study C when comparing EiA proportion from before structural interventions to afterwards. For example, following the Old Portsmouth structural coastal flood scheme, there was a decrease in EiA proportion in the immediate area of the new defence. Whilst this decrease in EiA proportion was replicated in other coastal areas of Portsmouth, it was not observed in Gosport, which saw a stabilisation of the EiA proportion in coastal areas (**Table 41**). Although, this was not observed again in the next decade during the construction and completion of the first four phases of the NPCS: during this period EiA proportion increased in OAs adjacent to the new defences, but also in other coastal areas of Portsmouth and in Gosport also (**Table 41**).

Averaging the outcomes of the changes in EiA adjacent to the new or majorly upgraded SCFPs gives a neutral score of ±0 (**Table 42**). This was also the score for other coastal areas in primary sites. On the other hand, the outcome for comparative sites showed an increase of +0.16 (**Table 42**). The outcome score of the comparative sites would have also been ±0 if it were not for the lack of change in Gosport during the period when the Old Portsmouth SCFP scheme was implemented. From these data it would be difficult to ascertain any links between construction of new, or major upgrades of existing, SCFP projects and changes in the proportion of EiA people per OA nearby. Either there are no links or they are weak enough to become overpowered by local and national events. For instance, there was major redevelopment of Merseyside as part of the European City of Culture project in the late 2000s, which brought a lot of wealth, regeneration, and investment into the city, and its associated county. Then, on a broader scale, the proliferation of increases in EiA proportion over the 2010s, with increases in all study sites, both primary and comparative, that used the 2021 census, would have been drastically impacted by the Covid-19 pandemic which saw large increases in unemployment and ill-health. A future longer longitudinal study may help to investigate this further and look at trends over time to see past these externally driven impacts.

Whilst there was no strong signal emerging from the summary outcome scores for changes in EiA proportion, there was for housing occupancy, the average number of people per household, which saw the largest changes overall. In Case Study A, there was an increase in housing occupancy in OAs adjacent to the newly constructed SCFP in Southport. This increase was not seen in other coastal areas of Southport, nor was it observed in coastal areas of Blackpool or Crosby (**Table 41**). This was similar to changes in housing occupancy observed in Case Study B: at the newly upgraded SCFP in Weston-super-Mare there was an increase in housing occupancy that was not replicated in other coastal areas of the town, nor in the comparative sites of Burnham-on-Sea and Clevedon. Albeit there was a net no change in housing occupancy in the other coastal areas of Weston-super-Mare and of Clevedon. But there was an overall decrease in housing occupancy of coastal OAs in Burnham-on-Sea (**Table 41**).

The increase in housing occupancy in areas adjacent to the newly constructed or majorly upgraded SCFPs was also apparent following the construction of the Old Portsmouth defence. However, this was not seen in other coastal areas of Portsmouth, which saw limited overall change in housing occupancy, or in coastal areas of Gosport, the comparative site for Case Study C, which had a decrease in housing occupancy (**Table 41**). However, this was not replicated during the 2011 to 2021 period of the NPCS, which saw an overall net no change in housing occupancy in OAs adjacent to the new defences. In contrast, there was an increase in the housing occupancy in coastal areas of Gosport, and an overall decrease in other coastal areas of Portsmouth (**Table 41**). Yet again, the NPCS period of the Portsmouth case study yields different outcomes to the others. The reasoning behind this may be that three out of the four NPCS phases constructed over this period were primarily adjacent to industrial estates or parkland and so would not have been able to influence socio-economic changes in these areas.

Regardless, outcome summary scores reveal a definitive link between housing occupancy in neighbouring OAs and the construction, or major upgrade, of SCFPs. The outcome score for areas adjacent to the defence was +0.75, far higher than the -0.5 outcome score for other coastal locations of the primary sites and for the comparative sites (**Table 42**). This would suggest that there is a strong link, especially as this was replicated across the case studies and different temporal periods, albeit with the notable exception of the NPCS.

Table 43 A summary table of the statistical outputs of the geostatistical test assessing significance of urban change using LiDAR DSM data and georeferenced population distribution change. Both were samples from before the SCFP scheme was constructed/ upgraded.

Sites		Significant Change?	
		Urban Development	**Population Distribution**
A	Blackpool	✗	✗
	Crosby	✗	✗
	Southport	✓	✓
B	BoS	✗	✗
	Clevedon	✗	✗
	WSM	✓	✓
C	Gosport 1	✓	✗
	Portsmouth 1	✓	✓
	Gosport 2	✗	✗
	Portsmouth 2	✓	✗

Table 44 A summary table displaying the output of the table above converted to numbers with a decrease becoming -1, dynamic equilibrium becoming 0, and an increase becoming +1. These data have been grouped into the primary site (Southport, Weston-super-Mare, and Portsmouth) and the corresponding comparative sites.

Outcome Summary	**Primary Site**	**Comparative Sites**
Urban Development	+1	-0.66
Pop. Distribution	+0.5	-1

The LiDAR geostatistics approach was used to conduct a t-test on two DSM rasters from different periods. The alpha value used for this analysis was 0.05, giving a 5% chance of obtaining a false positive of a statistically significant correlation. For Case Study A, Southport, the primary site obtained a statistically significant result, with a p-value less than 0.05, and therefore there was statistically significant urban growth in the coastal area by the new defence, from before the construction of it to afterwards. This statistically significant change across time was not observed in coastal areas of Blackpool nor Crosby (**Table 43**). Likewise, for Case Study B, Weston-super-Mare, the primary site, saw statistically significant urban growth on its coastline in an area adjacent to the newly upgraded SCFP. This statistically significant change in urban development was not apparent in the comparative sites, Burnham-on-Sea and Clevedon (**Table 43**).

In contrast to the other sites, however, across the 2005 to 2013 period, covering the time of which the Old Portsmouth SCFP was constructed, there was statistically significant coastal urban growth in both Gosport and Portsmouth (**Table 43**), albeit with a significantly lower t-score in Gosport than that of

Portsmouth. Whereas, in the 2013 to 2020 period, only Portsmouth had statistically significant change in urban development in coastal areas adjacent to the newly constructed structural flood defences of the NPCS (**Table 43**).

The link between structural coastal flood interventions and adjacent urban coastal development is the strongest out of all analyses, with an outcome score of +1. This outcome score for the primary sites is far greater than that of the comparative sites, which had an outcome score of -0.66 (**Table 44**). This score would be -1 if it were not for the statistically significant growth in Gosport during the 2005 to 2013 period. Although, this statistically significant growth did not translate to a large increase in coastal population (**Table 41**), which would imply either the urban development was for a limited population, or that many moved to the area after the 2011 census had been conducted.

Statistical testing was also performed on the change of population distribution using samples from before the local SCFP was constructed/ upgraded at the primary sites to afterwards. A statistically significant difference in population distribution change rate between those at the newly constructed/ upgraded defence and those internally in the town would imply that there was a definitive connection between these defences and impacts on population distribution; if positive it would imply that the defence creates a pull factor to the area.

In Southport, the primary site of Case Study A, there was a statistically significant difference in the population distribution change rate between the OAs at the newly constructed SCFP, and those in the town. Although, this was not seen in the comparative sites for the location, Blackpool and Crosby, which did not see statistical significance at the 0.05 α-level (**Table 43**). Likewise Weston-super-Mare, the primary site for Case Study B, had a statistically significant difference in the population distribution change rate between OAs at the newly upgraded SCFP, and those from internally in Weston-super-Mare. This statistical significance was not apparent in the comparative sites of Burnham-on-Sea and Clevedon, which failed to see a large enough difference in the population distribution change rate to meet the 0.05 α-level (**Table 43**).

At the Old Portsmouth site, between the 2001 and 2011 census there was a statistically significant difference in population distribution change rate between those OAs at the new defence and those internally. This was not apparent in Gosport over this period (**Table 43**). The failure to meet the significance level, over this period in Gosport, aligns with the idea that despite the construction of the statistically significant urban development, many residents did not move in until after the 2011 census, which would explain why Gosport had a coastal population increase between the 2011 and 2021 censuses (**Table 41**). However, the population increase in coastal areas was not apparent in Portsmouth, at the new NPCS SCFPs or in other coastal areas. This lack of coastal population increase drove the failure of the population distribution change rate in Portsmouth to meet the significance threshold across the NPCS 2011 to 2021 era. This failure to reach the significance level was most likely driven by the fact that three out of the four NPCS phases ran adjacent to parkland and industrial areas, with only one passing by a residential estate. This would suggest that it is the land-use of adjacent sites that affects the impacts and unintended consequences of SCFP: coastal parkland has no change, coastal industrial areas see new development, and coastal residential areas see increases in urban development, housing occupancy, and population. The greatest limit to the unintended consequences of SCFP, though, is the size of the settlement, either through pre-existing local population density or economic strength, or a function of the two.

Information obtained from this synthesis, and individual case studies, will provide inputs and context to the ABMs simulations detailed below.

4.2 Agent-based Modelling Output

This section presents the ABM simulation outputs for the three primary case study sites: Southport, Weston-super-Mare, and Portsmouth, investigating the future potential effects of the unintended consequences of structural coastal flood protection, and their relation to the effects of climate change on local extreme coastal water levels. Results are provided for the RCP 8.5-0.1%AEP scenario, the other scenarios are displayed in **Appendix D**.

4.2.1 Case Study A

The new defence at Southport was finished in 2002 and provides a 150-year SoP. This would provide protection against a 0.66%AEP (Annual Exceedance Probability) event in 2002.

The Extreme Coastal Water Levels (ECWLs) considered are presented in **Figure 31**. The most extreme event for each scenario and wave inclusion is represented by a dashed line. As exposure is a function of ECWL and its interaction with the topography of the landscape (**Figure 91**), the variable *FA*, defined as the ratio between *Dry Land* and *Wet Land* and expressed as a percentage, was also obtained to capture this.

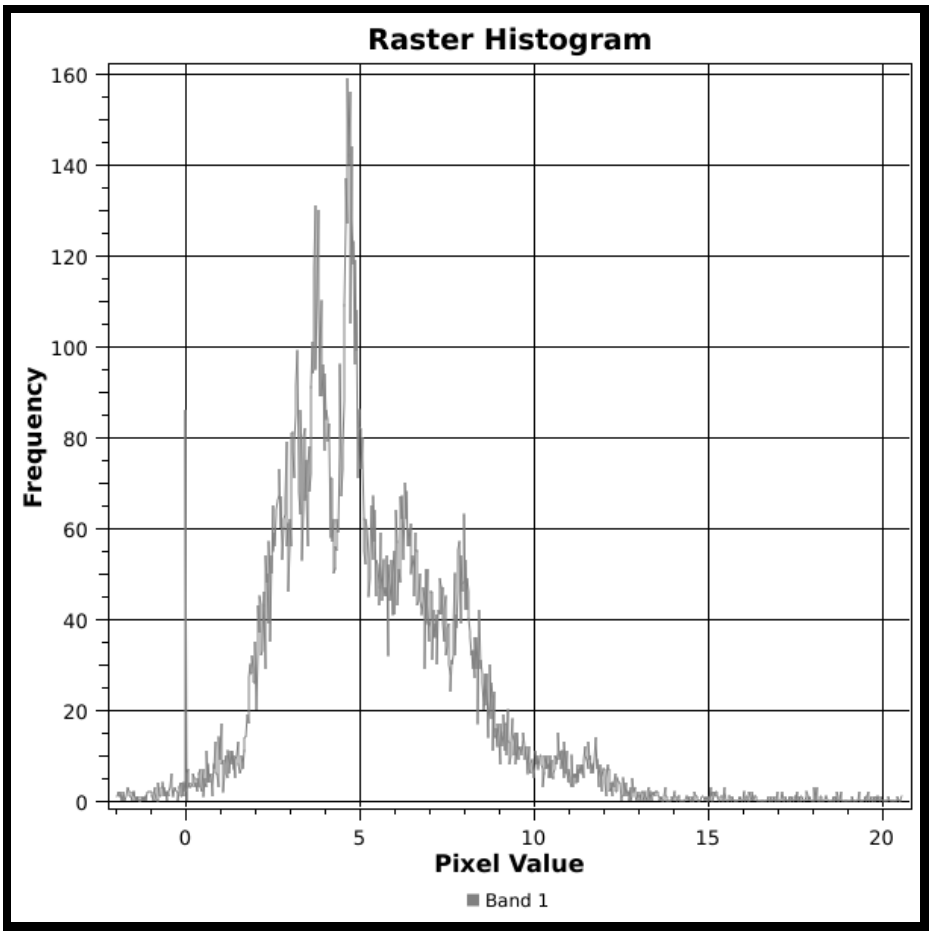


Figure 91 Raster histogram based on the DTM data used in the Southport ABM.

The ABM output used to represent the Southport analysis is the RCP8.5 - 0.1%AEP scenario, which was the only output that exceeded the new SCFP before 2100. Before the construction of the new structural defence, ECWL was increasing (**Figure 92**), the *FA* was remaining stable (**Figure 93**), and the *AfP* in Southport was decreasing (**Figure 94**).

The construction of the SCFP in 2003 led to a sharp decrease in *FA* (**Figure 93**) and *AfP* (**Figure 94**) and, the severity of this decrease is represented by the steep decrease in *d*AfP/*d*t (**Figure 95**). The

negative derivative output demonstrates a decreasing gradient in *AfP*, that quickly reverts to zero in the following year: it is clear that the construction of the new SCFP had an impact on *AfP*, as would be expected.

After the construction of the new SCFP, population at the new SCFP increased (**Figure 47**). Moreover, this led to a statistically significant increase in the population distribution of the area: the share of the population that this area adjacent to the new defence had of the total population increased by 15%, a statistically significant amount (**Table 13**). This increase in population share would later lead to the large sharp increase in *AfP* towards the end of the RCP8.5 and 0.1%AEP scenario model once the defence is exceeded.

Following this period, in spite of increasing ECWL (**Figure 92**), growth in the *FA* of Southport slows down and eventually stabilises in the 2050s (**Figure 93**). The elevation of Southport is predominantly lower than 5m above sea level (**Figure 91**), and this land is mostly flooded even after the construction of the new SCFP, with *FA* decreasing to its lowest of 60% after the defence, and its highest 78% in 2100 (**Figure 93**). However, over this period there was a steady increase in the *AfP* of Southport, with *AfP* returning to pre-defence amounts by 2045. Then *AfP* mirrors the growth in Total Population until around 2086 (**Figure 94**), at which point the growth rate stabilises (**Figure 95**). This is an example of diminishing returns: the higher elevated places are more likely to be more difficult to flood, and so would require much higher ECWL, hence the slowdown in *AfP* around this period (**Figure 94**, **Figure 95**).

In 2085 the newly constructed coastal flood defence in Southport will be exceeded (unless upgraded), flooding the area previously defended by it and a large increase in *FA* (**Figure 93**). Meanwhile, *AfP* increases dramatically as some locations become floodable, whilst they were not before, this leads to an increase far greater than the growth of Total Population (**Figure 94**). The sudden high-level growth is also represented as a large increase in the derivative of *AfP* (**Figure 95**), jumping to over 33,033 people per year, far greater than the 15,585 people per year saved generated by the construction of the new SCFP. In essence, the defence being exceeded led to an extra 17,448 people now exposed. These populations protected by the defence would not have been flooded during the 2003 to 2085 period and would therefore have no flood memory, decreasing flood awareness and preparedness, putting them at a high level of risk. It is unlikely that new urban development would have been sanctioned in the area where new buildings were built in Southport following the new SCFP construction, and that these new populations would have moved there, had it not been built. Moreover, due to the increase in ECWL between the 2003 and 2085 period (**Figure 92**), when the defence is exceeded, areas that had not been flooded previously would now be floodable, without flood risk communication, these populations would not be prepared for such an event. *Therefore, the short-term savings provided by the construction of the new SCFP in Southport would be greatly overshadowed by the long-term losses, highlighting the importance of considering these unintended consequences in future coastal FRM and spatial planning*.

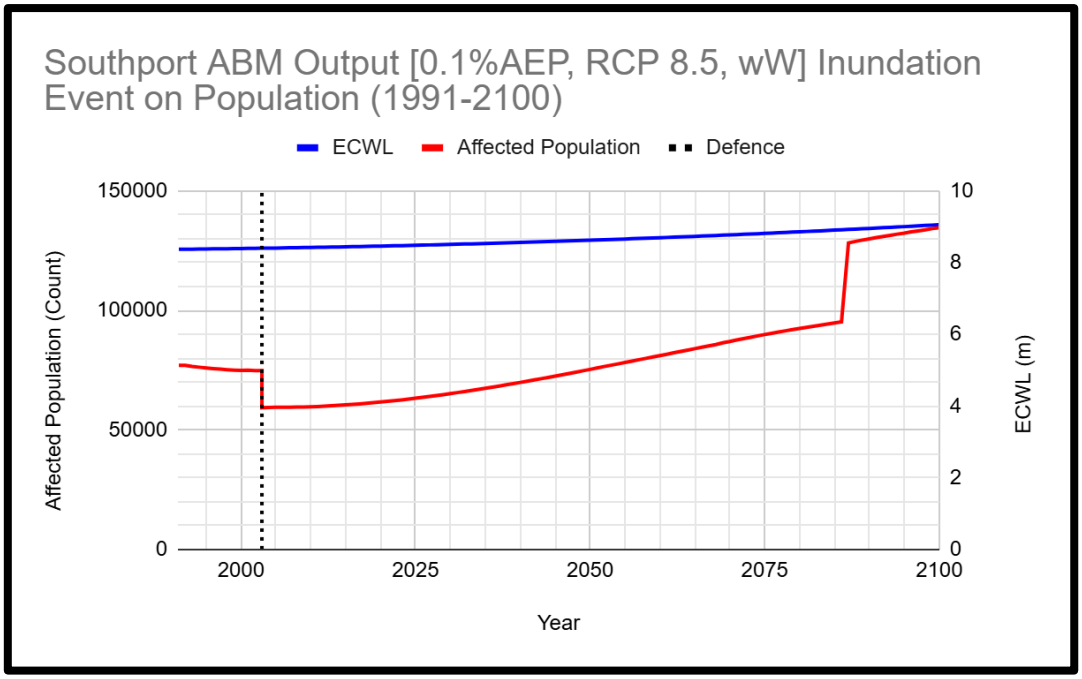


Figure 92 ECWL and population exposed to flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

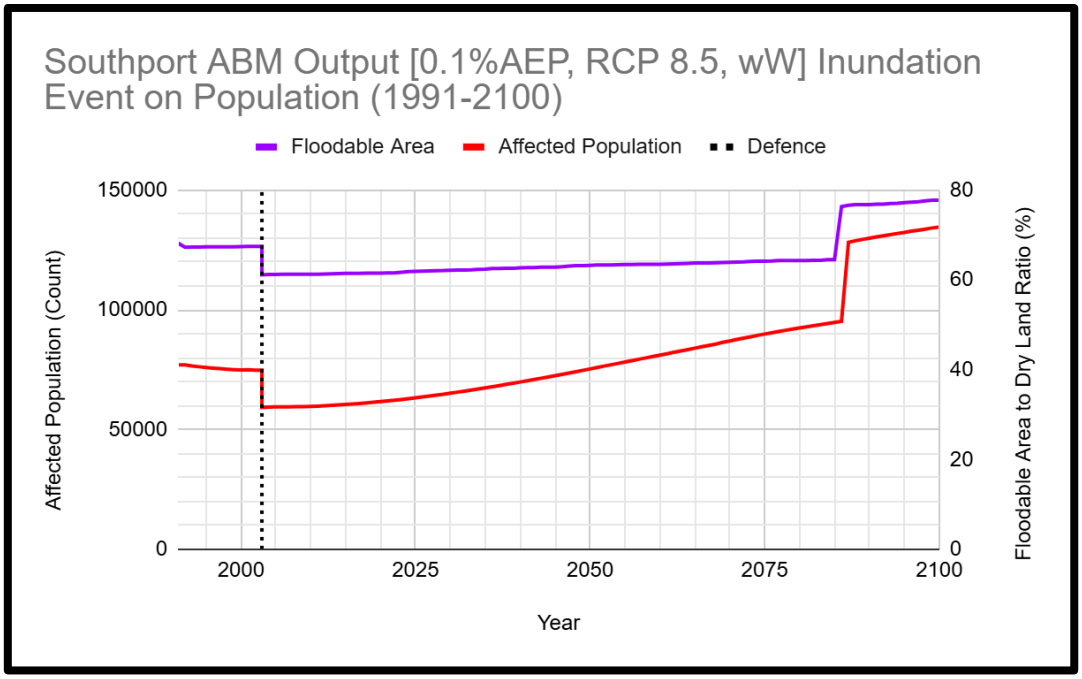


Figure 93 The ratio of dry land to wet land (*FA*) and population exposed to flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

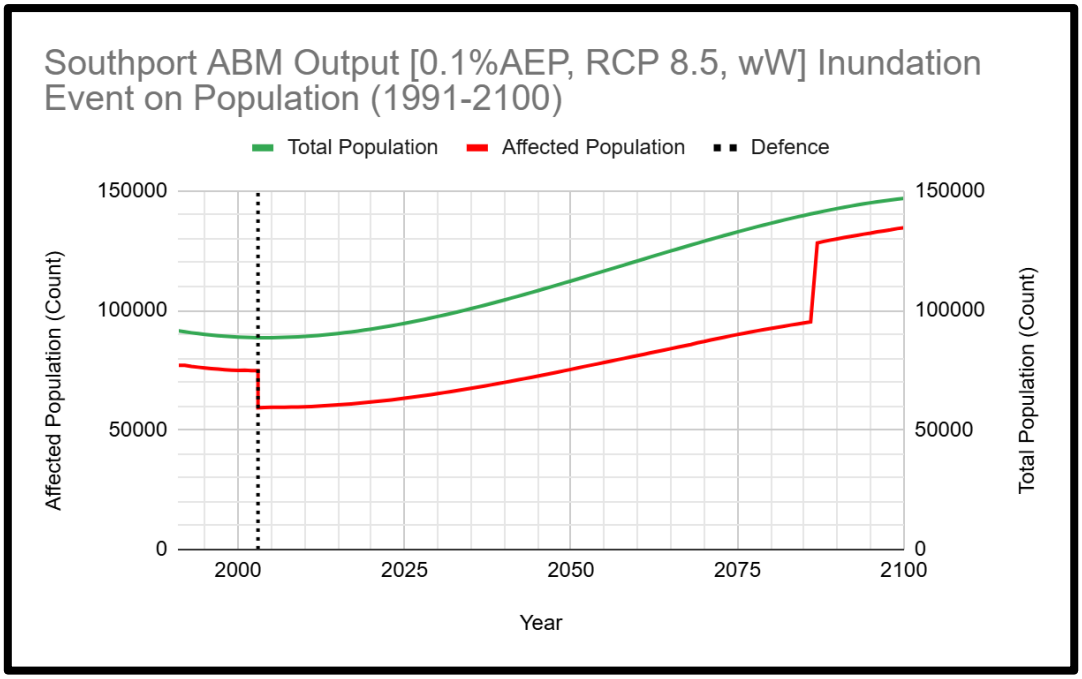


Figure 94 Total population and population exposed to flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

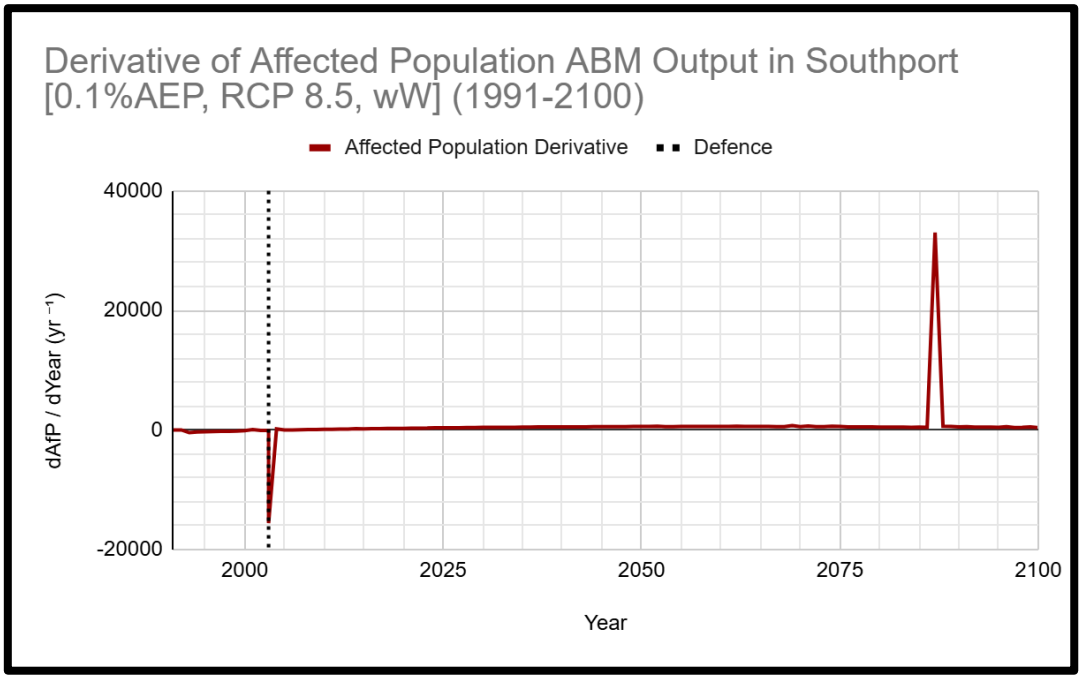


Figure 95 The derivation (dAfP/dYear) of the population exposed to flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

4.2.2 Case Study B

The new defence at Weston-super-Mare was finished in 2011 and provides a 200-year SoP. This would provide protection against a 0.5%AEP event in 2011.

The ECWLs considered are presented in **Figure 31**. As exposure is a function of ECWL and its interaction with the topography of the landscape (**Figure 103**), the variable *FA*, defined as the ratio between *Dry Land* and *Wet Land* and expressed as a percentage, was also obtained as an output to capture this.

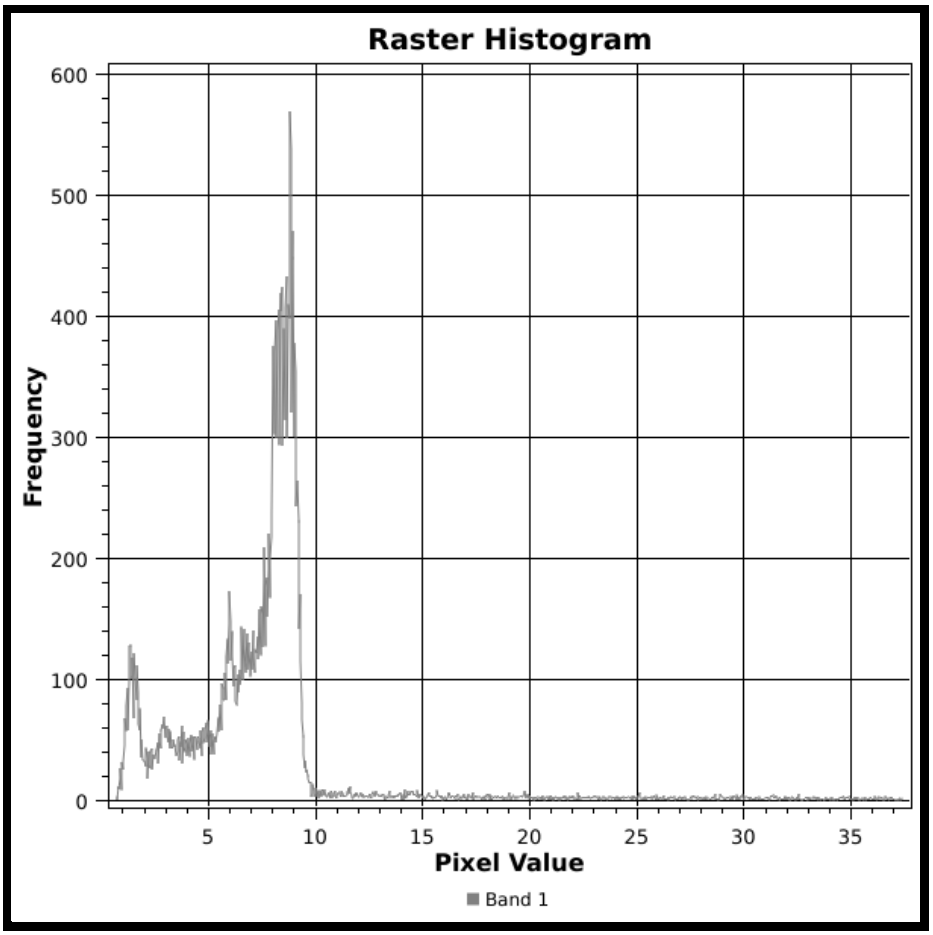


Figure 96 Raster histogram based on the DTM data used in the Weston-super-Mare ABM.

The ABM output chosen to represent Weston-super-Mare is based on the RCP8.5 - 0.1%AEP scenario. This output represents a worst-case scenario for the town, under the most extreme climate scenario (RCP8.5) and the greatest inundation events (0.1%AEP) considered by this study. Only the RCP4.5 - 0.1%AEP, RCP8.5 - 0.5%AEP, and the RCP8.5 - 0.1%AEP scenarios led the newly upgraded SCFP being exceeded.

Before the upgrading of the new defence in Weston-super-Mare, ECWL was steadily increasing (**Figure 97**), the *FA* remained stable (**Figure 98**), and *AfP* was steadily increasing by 3 people per year (**Figure 99**). The upgrading of the SCFP in Weston-super-Mare led to a decrease in *FA* by 0.8% (**Figure 98**), in *AfP* by 78 people (**Figure 99**), and *d*AfP/*d*t (**Figure 100**). The decrease in *AfP* per year is too few to be apparent in the graphs due to the large scale *AfP* increase when the flood occurs, due to the ECWL becoming higher than the crest height of the SCFP. This is due to the fact that Weston-super-Mare already had a mostly effective SCFP, protecting not only itself but also the North Somerset Levels behind, and the structure was an upgrade to a 1-in-200 year SoP. If there was no other SCFP present, then the decrease in *AfP* would likely be much greater.

Following the upgrading of the SCFP in Weston-super-Mare, the interaction between the ECWL and the underlying DTM raster data, which has several smaller frequency peaks between 0m and 5m (**Figure 96**), translate to the slight increases in *FA* across this period (**Figure 98**). Likewise, *d*AfP/*d*t quickly returns to around 2pp/yr steadily increasing to 6pp/yr before the defence is exceeded in 2054 (**Figure 100**); although, there are several smaller peaks in the run up to it being exceeded: a temporary increase to 18pp/yr in 2026, 12pp/yr in 2046, and 25pp/yr in 2048.

Changes in population distribution attributed to the SCFP upgrades may have led to increases, and decreases, in both, *AfP* and its derivative. In Weston-super-Mare coastal population increased in areas adjacent to the newly upgraded coastal flood defence (**Figure 60**). Although, in this area there was an average 13% decrease in population share from before the SCFP was upgraded to afterwards, yet this was still a statistically significant change from the rest of the town (**Table 24**). This decrease in population share was created by the construction of the large-scale Haywood estate further into town, which led to an average 27% decrease in population share elsewhere in Weston-super-Mare (**Table 24**).

The new SCFP leads to a decrease in *FA* from 5.0% to 4.1% the year after (**Figure 98**). However, once the defence is exceeded, the *FA* increases from 4.3% to 54.2% in a single year, rising to 56.5% by 2100 (**Figure 98**). The newly upgraded flood defence in Weston-super-Mare is exceeded in 2054 under the ECWL scenario explored, flooding the area previously defended by it, and new land that had never been flooded before due to higher ECWLs than had hitherto never been experienced: *FA* (**Figure 98**) and *AfP* (**Figure 99**) and increases drastically. This sudden increase in *AfP* translates to a large increase in its derivative (**Figure 100**), jumping to 26,008pp/yr, far greater than the 78pp/yr protected when the defence was initially upgraded. The upgraded SCFP in Weston-super-Mare being exceeded leads to an extra 25,930 people being exposed than before the defence was upgraded. These populations would have no flood memory, and this would likely impair flood awareness, preparedness, and consequently responsiveness. This highlights the importance of flood risk communication, so that when large-scale inundation events do occur, the population is ready and capable. *Therefore, the short-term savings provided by the upgrading of the SCFP in Weston-super-Mare would be greatly overshadowed by the long-term losses, highlighting the importance of considering these unintended consequences in future coastal FRM and spatial planning*.

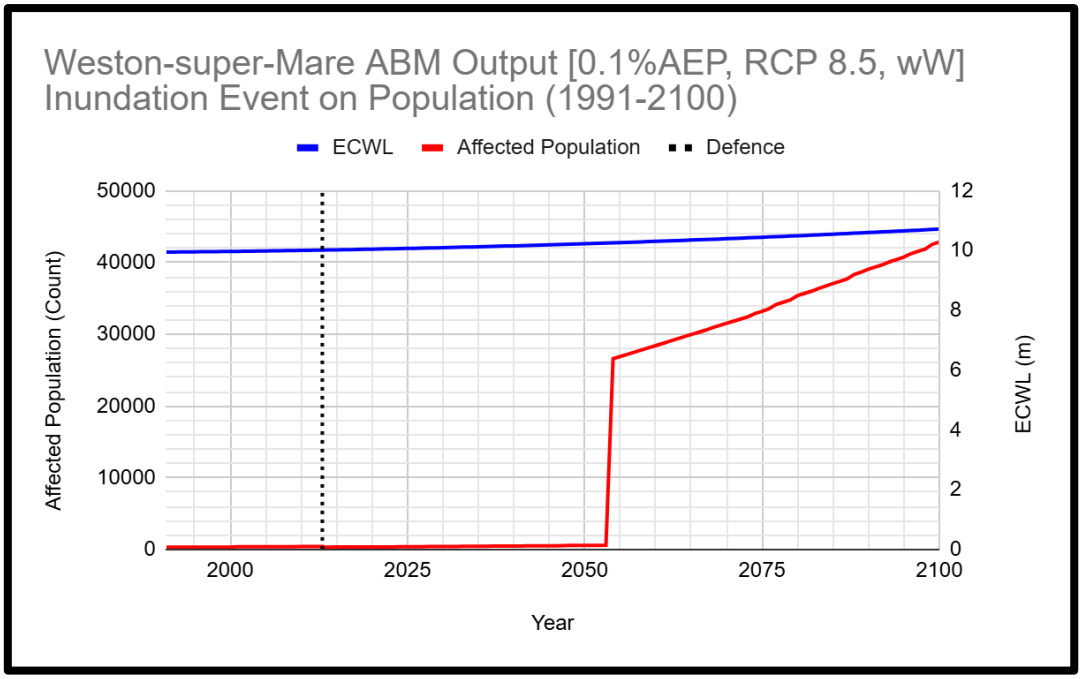


Figure 97 ECWL and population exposed to coastal flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

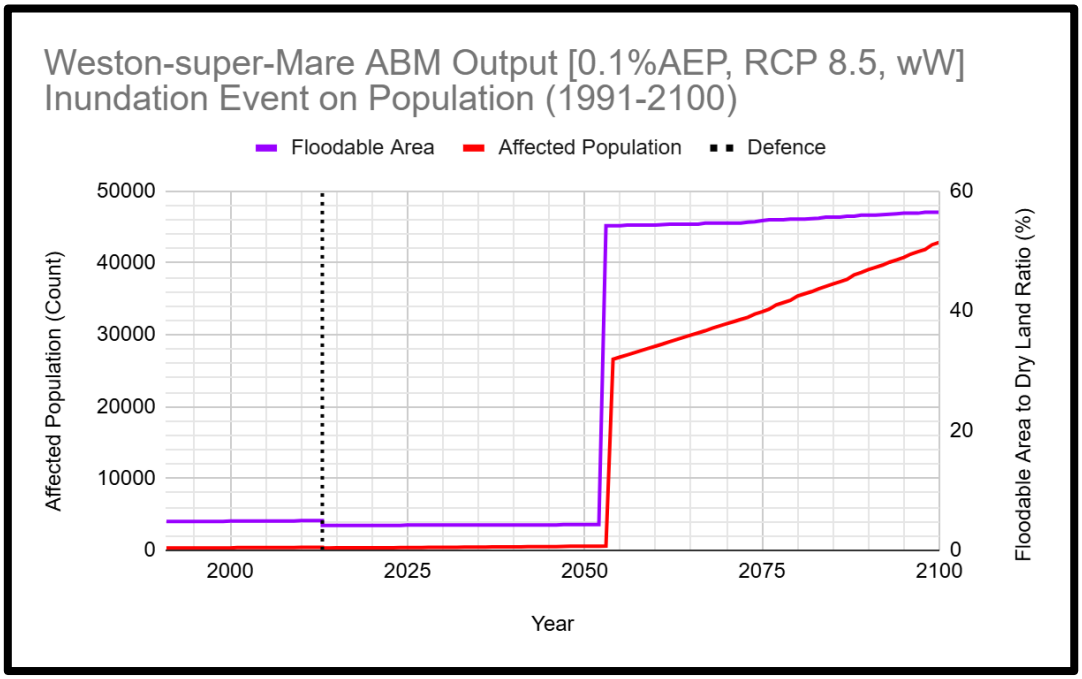


Figure 98 The ratio of dry land to wet land (*FA*) and population exposed to coastal flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

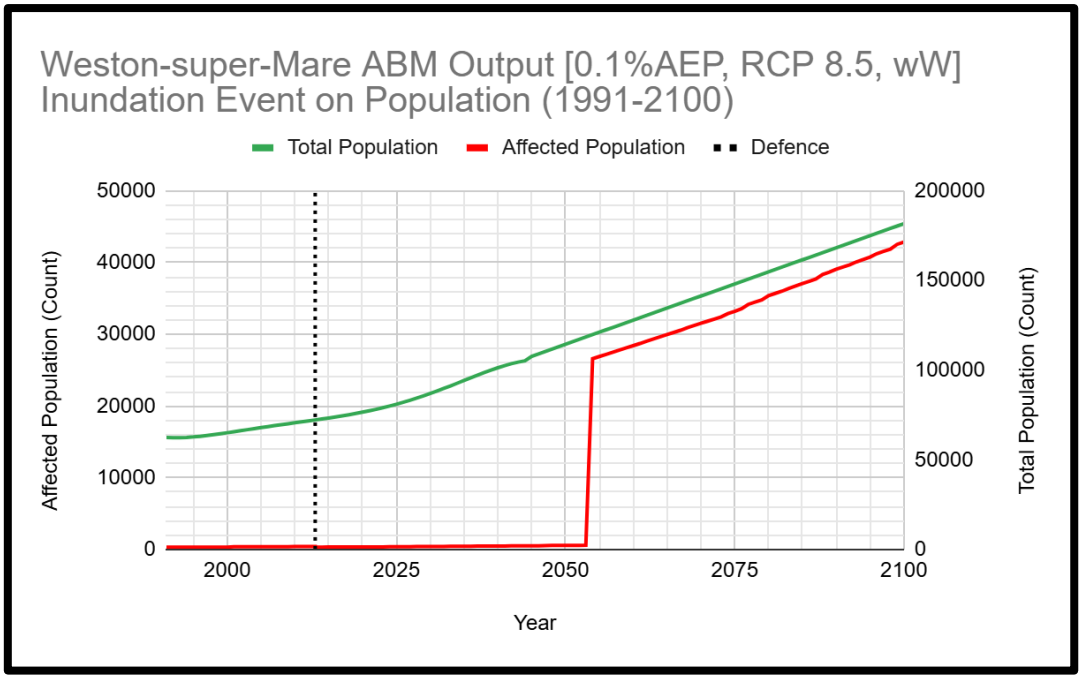


Figure 99 Total population and population exposed to coastal flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

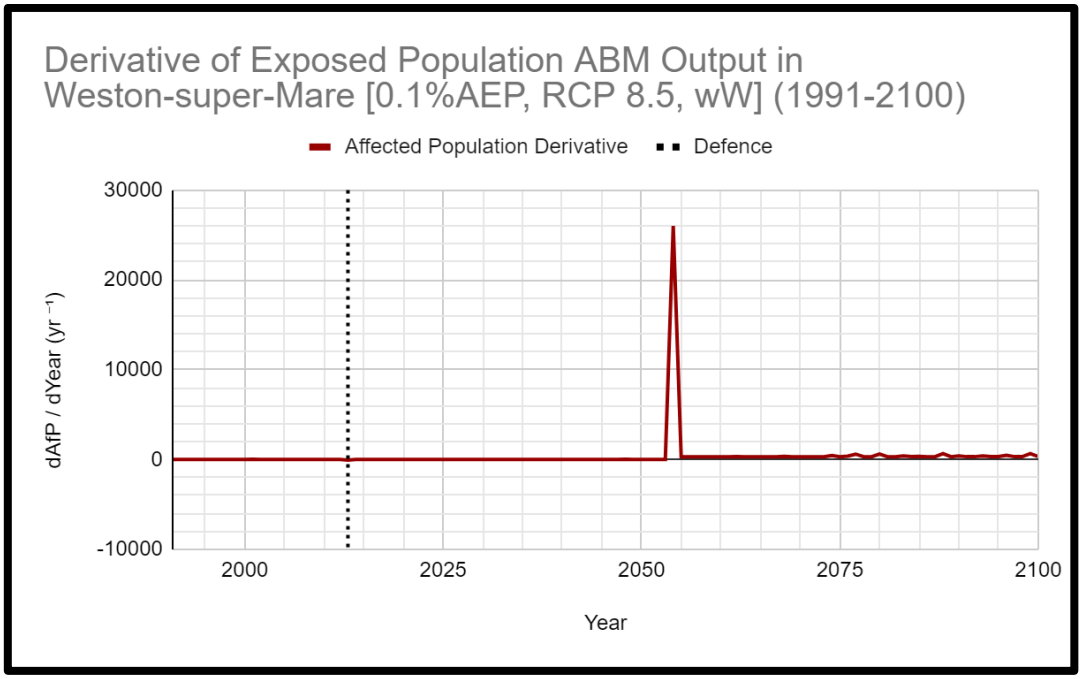


Figure 100 The derivation (dAfP/dYear) of population exposed to coastal flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

4.2.3 Case Study C

The defences at Portsmouth were constructed or upgraded multiple times over the decades: Old Portsmouth site in 2005, NPCS Phase 1 in 2015, NPCS Phase 2 in 2016, NPCS Phase 3 in 2019, as well as the ongoing Southsea scheme starting in 2022 and finishing in 2029. Some defences were yet to be built, and information from these came from planning documentation, these include NPCS Phase 4 (2024), NPCS Phase 5 (2026), and subsections of the Southsea scheme. The six sub-projects of the Southsea projected have not been represented in the charts below for better visualisation, but are represented by the final Southsea line graph (2029) which connects the project together.

The ECWLs considered are presented in **Figure 31**. The most extreme event for each scenario and wave inclusion is represented by a dashed line. As exposure is a function of ECWL and its interaction with the topography of the landscape (**Figure 101**), the variable *FA*, defined as the ratio between *Dry Land* and *Wet Land* and expressed as a percentage, was also obtained as an output to capture this.

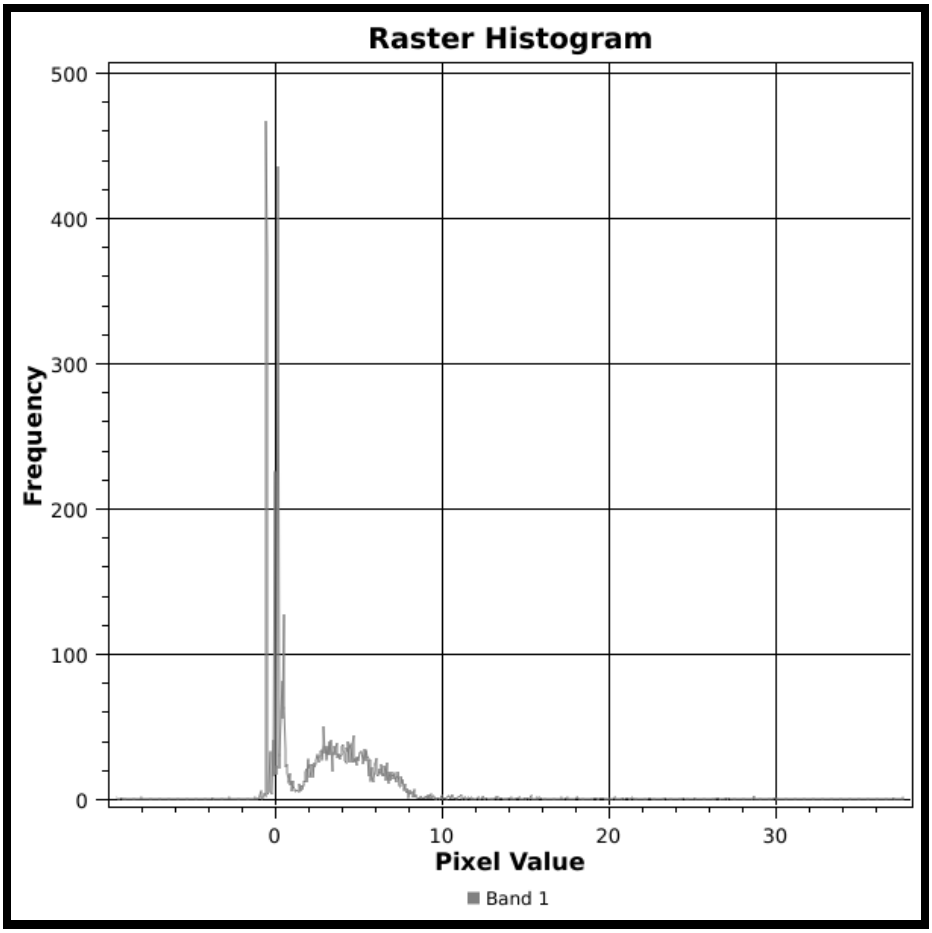


Figure 101 Raster histogram based on the DTM data used in the Portsmouth ABM.

The ABM output chosen to represent Portsmouth is based on the RCP8.5 - 0.1% scenario. This output represents the worst-case scenario for the city, under the most extreme climate scenario of all of the climate pathways considered within this analysis (RCP8.5), in combination with the greatest inundation event included by this study (0.1%AEP). This scenario produced the only output from Case Study C to feature a discontinuous increase, representing greater chance of defences being exceeded.

Before the Old Portsmouth SCFP project was implemented the *FA* increased steadily (**Figure 103**). Likewise, *AfP* in Portsmouth was initially flat, but increased exponentially year on year up to the new defence (**Figure 104**). This increase in *AfP* was greater than the increase in the citywide Total Population. During this period, the ECWL input increased steadily also, but much less than the extent towards the latter half of the century (**Figure 102**).

Following the completion of the Old Portsmouth SCFP in 2009, *FA* (**Figure 103**), *AfP* (**Figure 104**), and the derivative of *AfP* (**Figure 105**) all showed decreases. This decrease amounted to a fall of 421 people per year, a direct impact of the new SCFP. However, following this period there was a continuous rise in citywide *FA* after the initial decrease (**Figure 103**). Hence *AfP* also increased again to that of before the Old Portsmouth SCFP, due to coastal flooding in other unprotected areas of the city (**Figure 104**)

During the period following the construction of the Old Portsmouth SCFP and the first phase of the North Portsea Coastal Scheme (NPCS) *FA* did increase, but the rise was steady (**Figure 103**), unlike the increase in *AfP* (**Figure 104**): increasing exponentially with the derivative of the *AfP* not only remaining positive, but increasing (**Figure 105**). Equally however, the citywide Total Population rose at its greatest rate (**Figure 104**) and was therefore the most likely primary driver of *AfP* growth over this period. Then as the phases of the NPCS began to be implemented *AfP* remained relatively stable oscillating between positive and negative growth, with Phase 3 leading to the biggest decrease in *AfP* with 341 people protected (**Figure 105**). This phase directly protected the northwest of Portsea Island and did not see a population decrease over this period (**Figure 74**), therefore, the large decrease must originate from the SCFP being implemented. The NPCS phases were designed to operate at their best capacity in conjunction with one another, and therefore linking with already implemented phases would also provide greater flood protection and impact reduction.

Projecting into the future, using trends obtained from population distribution data (**Figure 74**) and change rates (**Table 40**), the completion of the NPCS Phase 5 led to the greatest decrease in *FA*, decreasing by 11.4%, from 26.7% to 15.3%, compared to a decrease of 3% from the Southsea SCFP scheme (**Figure 103**). However, the same could not be said for the *AfP* **(Figure 104)**; the NPCS Phase 5 SCFP led to a decrease of 7200 people per year (**Figure 105**). Then, once the Southsea structural coastal flood scheme had been completed, there was an even greater decrease of 8807 people per year (**Figure 105**), to the minimum *AfP* amount of the RCP8.5 and 0.1%AEP scenario of 1813 people. This would suggest that Southsea is a much more populated area than north Portsmouth, where the NPCS protects. Moreover, this is concordant with the idea that the area protected by the NPCS is primarily industrial with limited residential population and that the unintended consequences of structural coastal protection primarily are determined by land-use.

Following the large decrease in *FA* and *AfP* due to the SCFPs in Portsmouth, both factors remain comparatively low, with minimal growth rate: *AfP* growth remains around 4 people per year (**Figure 105**). This continues up until 2067 at which point *AfP* increases by 137 people per year, and is the last spike before the significant increase later towards the end of the century (**Figure 105**). These increases begin as the ECWL gets to such a high level exceeding the defences (**Figure 102**) and inundating areas with higher and higher elevations, these greater elevation levels are less frequent than those around the 4m mark (**Figure 101**). The defences are first exceeded significantly in 2083, and despite the *FA* only increasing by 0.4% (**Figure 103**), there is a 2581 increase in *AfP* (**Figure 105**), suggesting a densely populated area had become flooded, the city centre, as the Old Portsmouth defence being exceeded.

As time progresses such instances become more common with the next, the major one following a SCFP becoming exceeded in 2083, is in 2091 an increase of 0.3% in *FA* (**Figure 103**). After this, there was an increase of 1533 people who were exposed, and a corresponding increase of 0.9% in the *FA*. This matching increase in *FA* was triple the 2091 increase, despite having double the population; this reflects the sizable variance within the underlying DTM in Portsmouth (**Figure 101**). The final large increase in *AfP* occurred not too long after in 2097 when the ABM projected an increase of 652 people in the *AfP* output (**Figure 105**) and a corresponding 0.2% increase in *FA* (**Figure 104**).

FA (**Figure 103**) and *AfP* (**Figure 104**) outputs never recovered to their levels from the time before Old Portsmouth. Moreover, the decreases in *AfP* caused by the construction of the NPCS Phase 5 and Southsea SCFPs were much greater than any of the increases in $d\text{AfP}/dt$ generated by the ECWL rising to higher than the crest height of any of the SCFPs (**Figure 105**). Although if the ABM were to run for longer, this may become apparent. Exploratory ECWL scenarios beyond 2100 are available, but they are of less statistical certainty than those used up to the end of the twenty-first century. Portsmouth is

the second most densely populated city in the UK, after London, and therefore has the corresponding levels of SCFPs, with some of the highest SoPs per defence in the UK. The NPCS protected the northern part of Portsea Island, an area dominated by industry; this led to limited change in *AfP* per phase, until the completion of the fifth phases of the project that linked the project together. However, the change in *FA* compared to the change in *AfP* for NPCS Phase 5 reflects the low population density of the area, and suggest a strong link between the impacts of SCFP and the land-use of the local area. Moreover, as demonstrated by census and LiDAR change data, there was limited change in the residential area by the NPCS Phase 1 SCFP, this may also indicate an upper capacity limit that would also influence the impacts of SCFP, and hence there was no statistically significant difference in the change in population distribution (**Table 40**). *Therefore, to summarise, the overall effect of the combined SCFP schemes in Portsmouth meant that AfP did not return to levels prior to the completion of the Old Portsmouth structural defence. The repeated SCFP projects limited inundation, and pre-existing land-use and urban development reduced potential socio-economic impacts*.

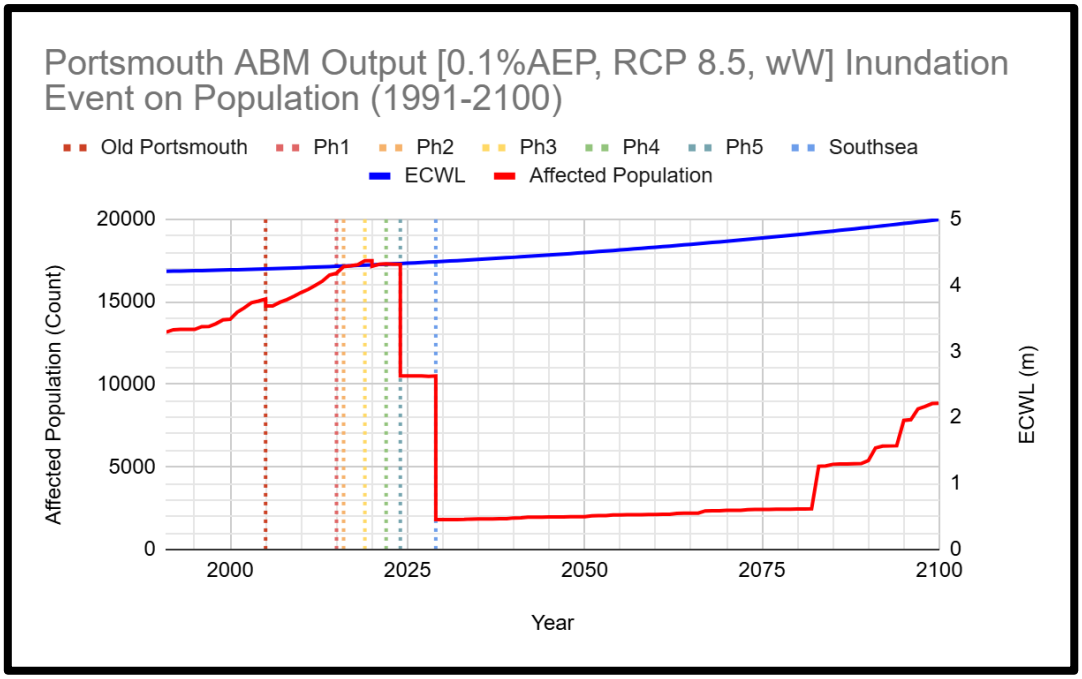


Figure 102 ECWLs and population exposed to coastal flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

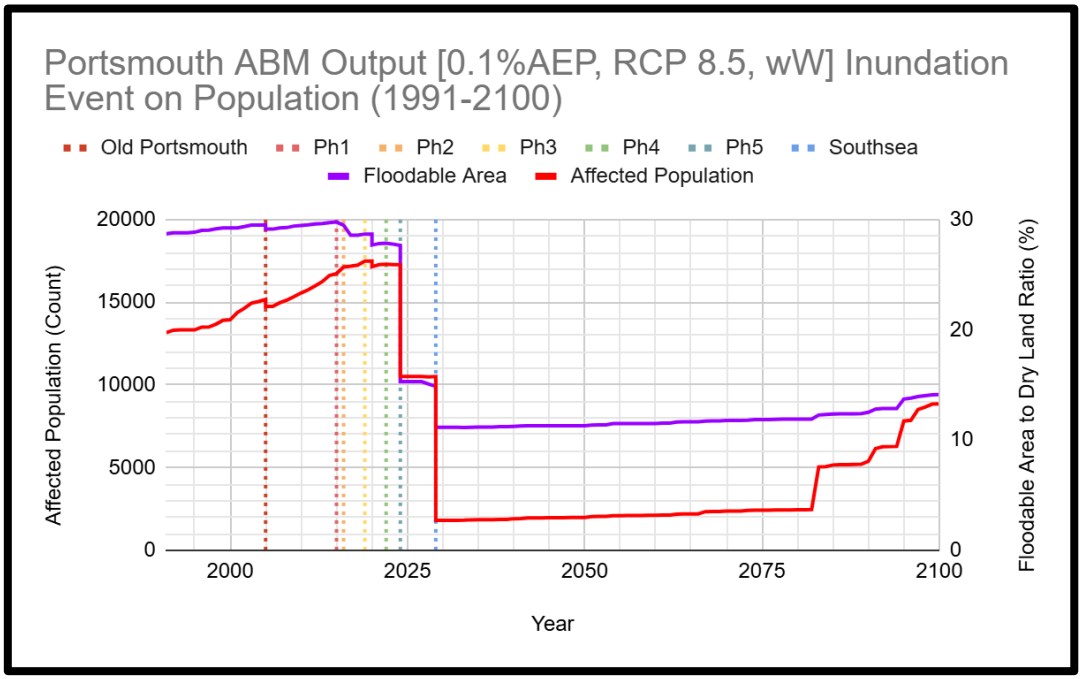


Figure 103 The ratio of dry land to wet land (*FA*) and population exposed to coastal flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

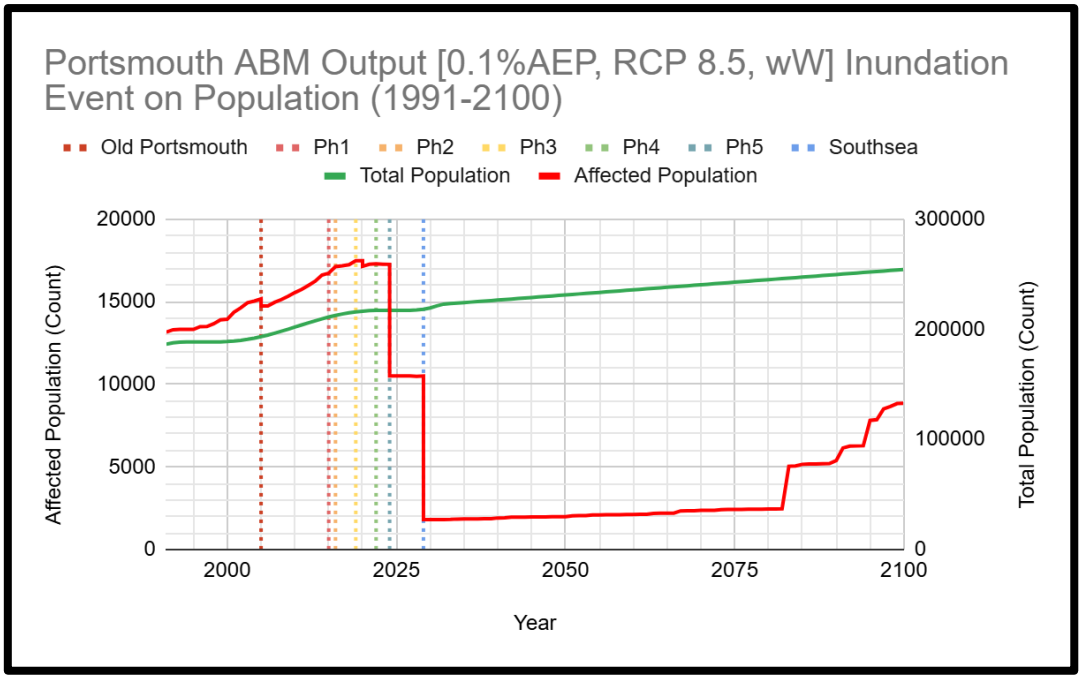


Figure 104 ABM Total population and population exposed to coastal flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

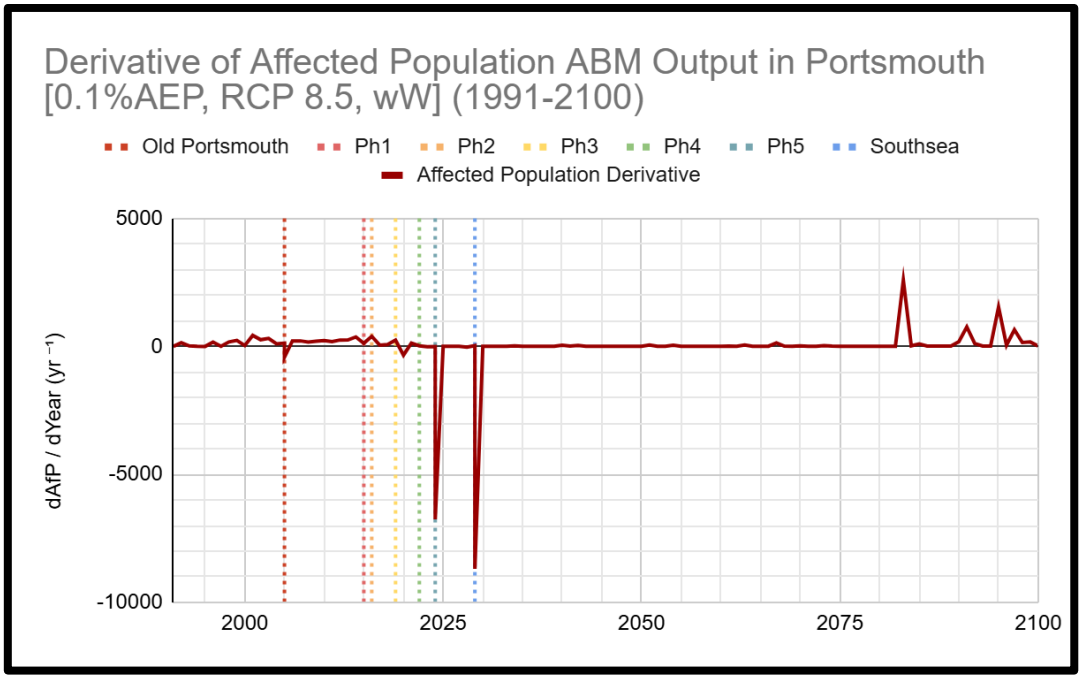


Figure 105 The derivation (dAfP/dYear) of the population exposed to coastal flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

4.2.4 Agent-based Modelling Output Synthesis

The agent-based modelling sought to capture, and project, the socio-hydrological processes within coastal settlements originating from newly constructed, or majorly upgraded, SCFPs, based on data and patterns obtained from the longitudinal spatial analysis in Subsection 4.1. This was done focusing on three contrasting primary case study sites, Southport, Weston-super-Mare, and Portsmouth. A conceptualisation of these interlinked socio-hydrological processes is detailed in **Figure 106**.

Southport had a newly constructed SCFP along the Merseyside coastline, protecting an area that had previously been unprotected. Prior to the construction of the flood defence, the *AfP* of the area had been steadily declining due to a decline in the Total Population. Then, as the construction of the new coastal protection was completed, *AfP* had a sharp decline, despite an increase in Total Population: the seawall had led to a decrease in the number of people who would be exposed to flooding. Similarly, in Weston-super-Mare the major upgrade of the SCFP, a seawall, led to a decrease in *AfP* despite an increase in Total Population. The same also occurred in Portsmouth with the Old Portsmouth SCFP, floodwalls and floodgates installed following the perimeter of the peninsula, there was a decrease in *AfP* despite increases in Total Population. These outcomes are hardly surprising; it should be the case that such SCFPs would lead, as intended, to a decrease in *AfP*, such capital (and associated maintenance) costs would, otherwise, be socio-economically unjustifiable and politically unpalatable.

However, maintaining these immediate benefits, over the long-term, presents various challenges. In the Southport ABM, after 82 years the defences were exceeded under higher ECWL scenarios, flooding the town and inundating residents who had never been exposed before. As the SCFP was constructed, not only did residents move to the immediate area, but vast swathes of the town are now protected from some level of flooding and would therefore, over time, lose their flood memory (as in Ridolfi *et al*., 2021), leading to decreases in flood awareness, and as such flood preparedness and responsiveness. Hence there is a much larger increase in *AfP* than those initially protected by the defence. This differential is even more extreme in Weston-super-Mare: due to pre-existing defences already having a relatively high SoP, the upgrade to the seawall did not lead to a substantive decrease in *AfP*, as many were already protected. Although when the newly upgraded seawall in Weston-super-Mare gets exceeded, there is a far larger number of people who are affected than those protected by the initial upgrade. Moreover, these people would have most likely not been flooded before in their lifetimes and would therefore, without adequate flood risk communication, be very vulnerable to flooding. Therefore, there are two processes that increase the amount of population affected once defences are exceeded, population increase at the coastal flood defence itself and ECWL increase which would be able to permeate deeper into the town. These effects have been deemed the Latency period (**Figure 106**).

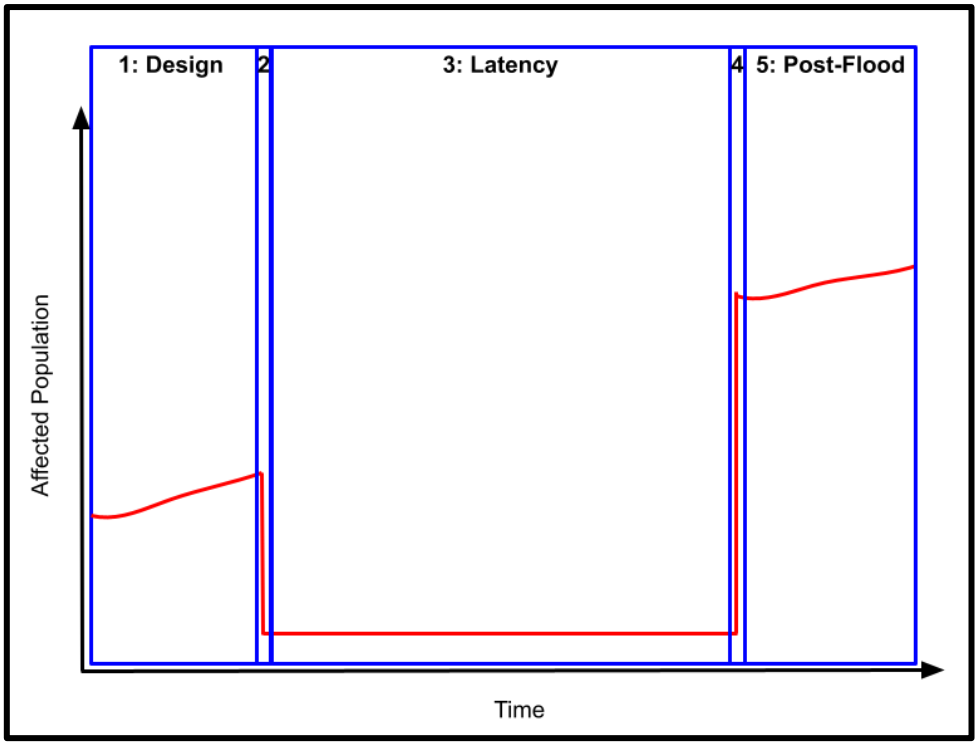


Figure 106 A conceptualisation of the socio-hydrological processes in a hypothetical town before, during, and after a SCFP was constructed (or majorly upgraded) and a resulting flood once ECWL was greater than the SCFP crest height.

Consequently, there is a clear pattern on the implications of SCFP on socio-hydrological processes, which can be broken down into five stages (**Figure 106**):

- **Stage 1: Design**
  During this stage the SCFP is being designed and has not yet been implemented. *AfP* is affected by both, the extent of coastal flood inundation and natural population changes.
- **Stage 2: Implementation**
  This stage references the construction of the SCFP and a dramatic decrease in *AfP* driven by a decrease in the ability of coastal flooding to permeate deeply into the settlement.
- **Stage 3: Latency**
  During this period, population increases behind the newly constructed coastal flood defence and ECWL also increases. *AfP* sees little change outside of natural population change.
- **Stage 4: Flood**
  This stage sees the SCFP being exceeded by higher ECWL scenarios and flooding the settlement behind it. *AfP* increases dramatically as coastal flooding becomes a large driver of it again. Due to increases in ECWL, coastal flooding travels further and affects populations at higher elevations of the town than it was able to previously.
- **Stage 5: Post-Flood**
  This is the final stage and presents the new normal following Stage 4, which now occurs regularly as the ECWL remains higher than the defence itself (unless upgraded inline with the increase in ECWL). *AfP* again returns to being affected by both, the extent of coastal flood inundation and population changes, both, spatially and fundamentally.

However, there does appear to be a limit to these processes, such as in Portsmouth, which did not see increases in *AfP* outperforming the decreases created by the SCFP projects. Portsmouth, unlike both Southport and Weston-super-Mare is a much more populated coastal settlement, but one that is confined by Portsea Island, and whilst some of it does grow onto the mainland, the majority of the population, and SCFP, lies on the island itself. The high urban density limits new development and a pre-existing high population density limits population growth. The north of Portsea Island is mostly industrial, which becomes apparent with the large decrease in *FA*, but comparatively small decrease in *AfP*, compared to the Southsea scheme. Southport and Weston-super-Mare, on the other hand, are mid-sized towns with room to grow and develop. This would suggest then that land-use is the largest influencer on the impacts of SCFP, followed by pre-existing population density, which must have an upper limit. This would of course, make sense; there cannot be changes in population if there is no ability to build residential development, and even if there is a residential development, if population and urban density is already so high then it will be difficult to increase population further. Therefore, there has to be opportunity for urban development and an increase in population density for these processes to occur. Due to these limits, the only significant changes of *AfP* would be due to increases in ECWL, which would inundate further into the settlement once the defence has been exceeded.

This means then, that the ABM of Portsmouth reflects reality, as data obtained from the population and LiDAR mapping suggested that there were two potential ways that the unintended effects of these SCFPs could be inhibited, Population Driven or Economy Driven:

A. Population Driven
The already very high population density limits population increases, either due to the economics of supply and demand in the area, or physically limits the number of people that can live in the area.

B. Economy Driven
The economy of the city is powerful enough to overcome the unintended impacts of the SCFP on its population and that is the primary driving force.

Using data and outputs from the ABM it can now be concluded that these potential pathways of inhibition of these unintended consequences should be controlled in FRM, and also that they work in sequence. Whilst Population Driven remains an accurate representation of population density limits described within this subsection, Economy Driven does not, with land-use affecting these socio-hydrological interactions more so than local economy. Therefore, the two pathways that inhibit coastal population growth and development occurring due to local increases in SCFP are, in sequence, Land-use Driven and Population Driven:

1. Land-use Driven
The pre-existing use of land, whether used for industrial, commercial, or residential purposes. If non-residential, then population increase cannot occur.

2. Population Driven
The already very high population density limits population increases, either due to the economics of supply and demand in the area, or physically limits the number of people that can live in the area.

These pathways work in sequence: if land-use of the area is non-residential, then it will not lead to coastal population growth following a SCFP, nor will it if it is overpopulated (**Figure 107**).

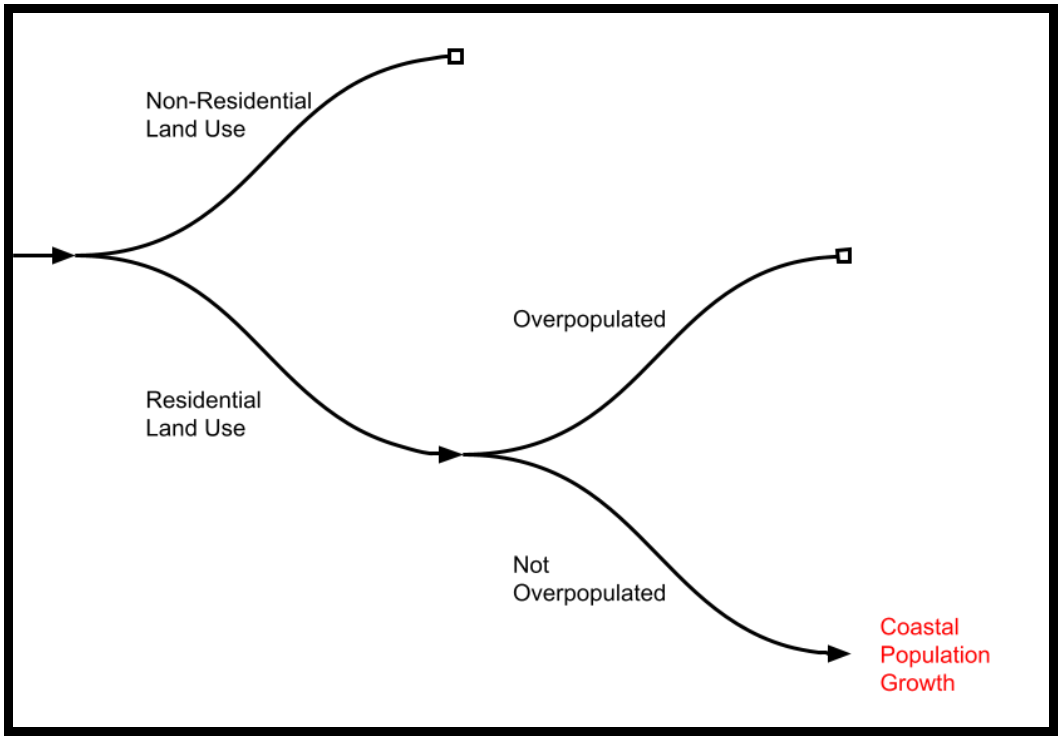


Figure 107 A conceptualisation of the inhibition pathways that hinder the coastal population growth during the latency period as an unintended consequence of SCFP.

4.3 Conceptual Model

Understanding the complex interactions between SCFP schemes and socio-economic dynamics is paramount for effective coastal management and resilience planning. A conceptual model is developed synthesising the comprehensive and holistic analyses conducted in this study, integrating data, both, physical and socio-economic, and theoretical frameworks, to identify the multifaceted relationships between structural coastal flood infrastructure development and population dynamics, both, socio-economic and spatial. By synthesising insights from diverse datasets and methodologies, the conceptual model provides a holistic understanding of the unintended consequences of SCFP, and provides a framework for policy- and decision-makers to create more sustainable and resilient coastal communities in the face of a changing climate and the inherent uncertainty it will bring. At its core, the ABM delineates the causal pathways and feedback loops that underpin the interactions between SCFP schemes, urban development, and socio-spatial and socio-economic variables; drawing upon data collected/generated and patterns observed (as detailed in earlier sections) in the three primary case studies (and associated *comparative sites*): Southport (*Blackpool* and *Crosby*), Weston-super-Mare (*Burnham-on-Sea* and *Clevedon*), and Portsmouth (*Gosport*).

An ABM was produced to simulate these socio-hydrological processes and project forwards in tandem with several climatic and flood inundation probability scenarios. Similar to the output of the Southport ABM (**Figure 92**), the major upgrade of the SCFP in Weston-super-Mare saw a decrease in *AfP* (**Figure 97**), albeit a lower decrease than that of Southport (**Figure 92**) as many residents were already protected by the defence. During this period of protection, deemed the latency period, coastal population and ECWL both increased. These increases translated to a significant increase in *AfP* once the SCFP had been exceeded. This increase was due to increased coastal population at the defence and the increased extent of inundation due to ECWL increase from SLR. This would mean that the increase in *AfP* was much larger than those initially saved by the major upgrade of the seawall in the first place (**Figure 100**). Moreover, these newly affected populations would have limited flood memory as they would have most likely never been flooded before, leading to decreases in flood awareness, and consequently flood preparedness and responsiveness, and, unfortunately, this would translate to increases in casualties without effective flood risk communication.

Weston-super-Mare presents a town already caught in the lock-in effects of SCFP from previous iterations; the population have been protected from flooding for an extended period and so have limited flood memory, leading to increases in coastal populations and infrastructure and then necessitating further increases in coastal flood protection. The large gap between the population protected and the population affected by the flooding, once ECWL surpasses the SCFP crest height, will mean that another future structural coastal flood upgrade will be deemed necessary to prevent this from occurring. These projects will increase until it becomes financially prohibitive to increase the SoP for the benefits brought (Turner *et al.*, 1996): the cost-benefit analysis fails. In contrast, Southport shows a newly constructed SCFP, which is clearly illustrated by the smaller gap between population protected and the population affected by flooding. These people in Southport, now protected, would otherwise have been flooded and so when flooding occurs they would have greater flood memory and therefore be better prepared. However, this does not apply to the entire population; there will be people in Southport farther away from the coastline that will also be affected by the increase in ECWL. These populations, that have never been flooded, will form a smaller subset in Southport than in Weston-super-Mare. Over time, the socio-hydrological processes in Southport will tend towards that of Weston-super-Mare as infrastructural lock-in cycles begin to occur and the SCFP will need to be upgraded (**Figure 108**). In the future, these upgrades to the SCFP in Southport will see similar decreases in the change in *AfP* (ΔAfP) due to the upgrade, and therefore a larger gap between the increases due to the flood, when ECWL surpasses the SCFP crest height, and the number of people initially protected when the defence was upgraded (**Figure 108**).

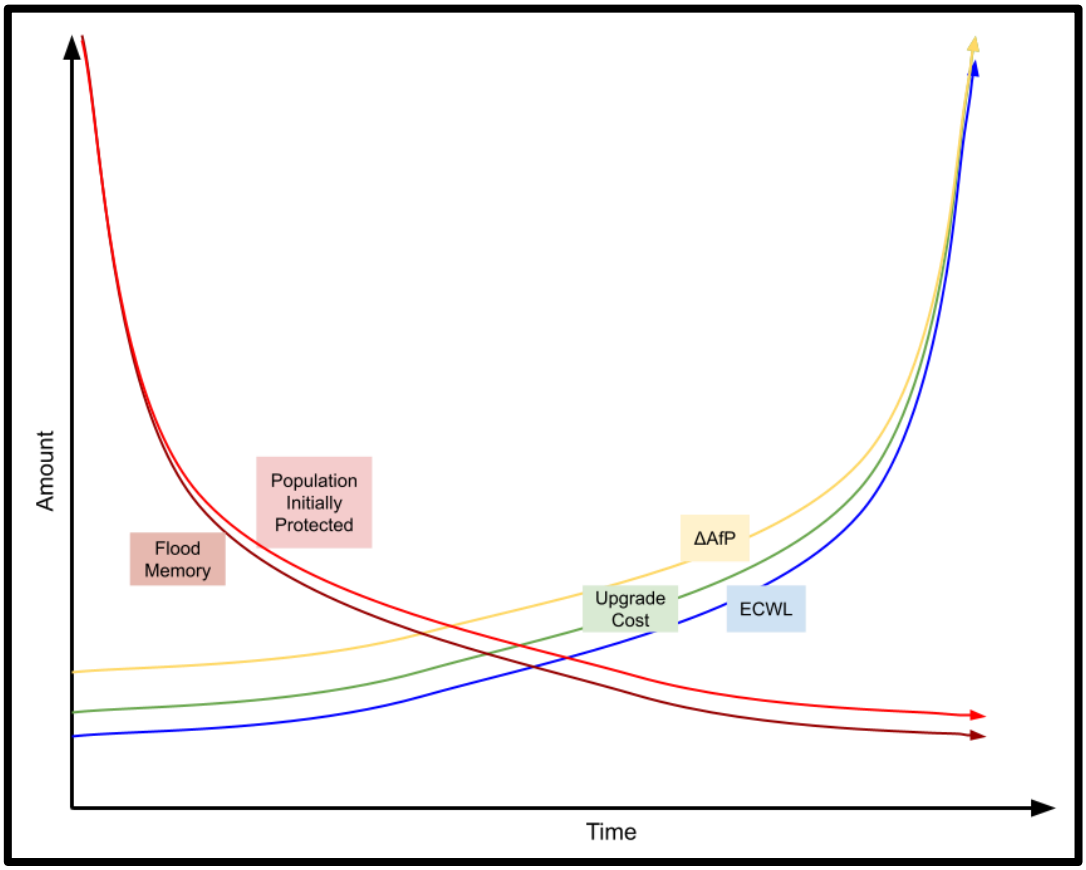


Figure 108 A conceptualisation of the effects of progressive SCFP upgrades on select metrics: Flood Memory (brown), Population Initially Protected by the defence (red), the difference between population affected by flooding and population initially protected by the upgrade (yellow), the potential cost of SCFP upgrade at that moment (green), and the ECWL (blue).

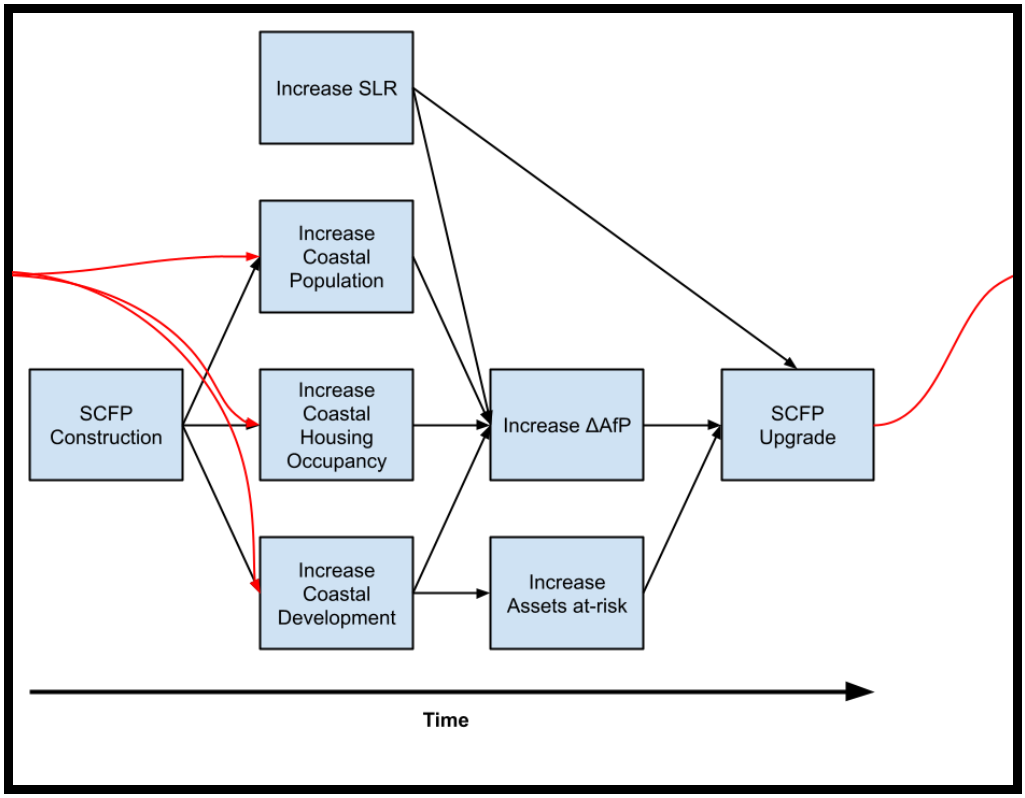


Figure 109 A conceptualisation of the socio-hydrological processes that occur due to the construction and then upgrading of a SCFP. The graphic presents Cycle 1 of the progression of the unintended consequences. The red arrows show the transition into Cycle 2, brought on by an upgrade.

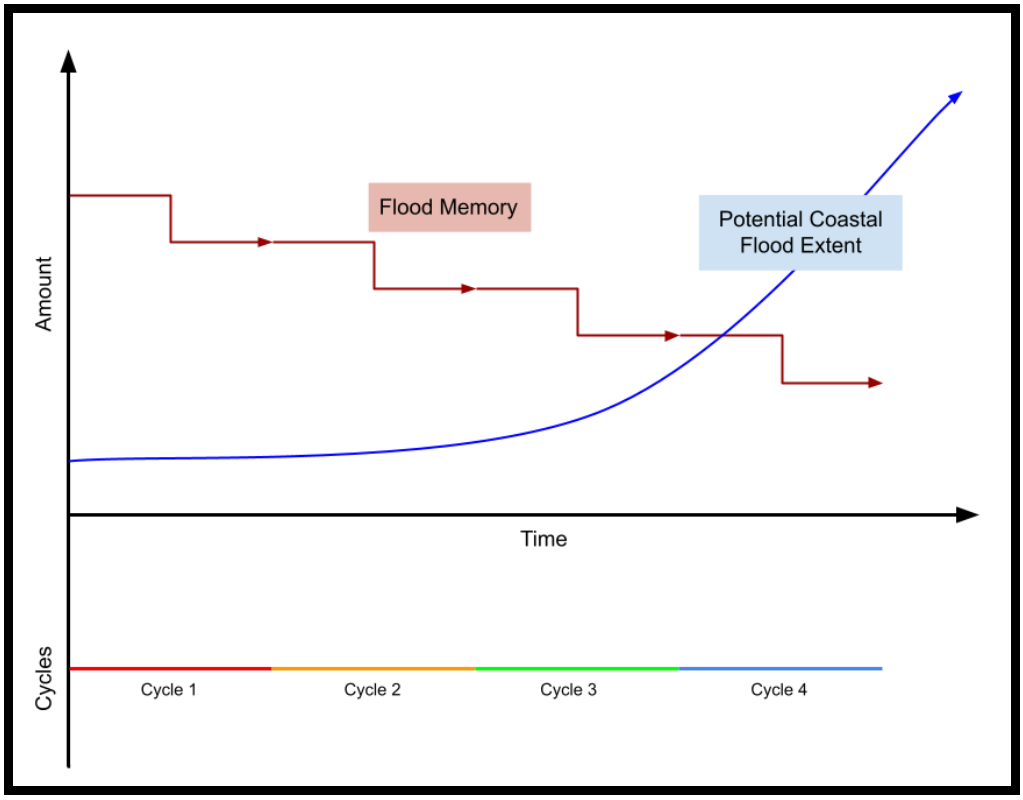


Figure 110 A conceptual line graph of the effects of the SCFP upgrade cycles on the Flood Memory of the population (brown) and the potential flood extent of the settlement if a flood were to occur due to defence being exceeded by ECWL scenario.

Inhibition pathways can be reversed to observe what happened in Southport and Weston-super-Mare: the towns had room to expand and develop due to a lower population density. Southport had the Ocean Plaza development and Weston-super-Mare the Dolphin Square development. Setting a limit to which type of development could occur in this area or an artificial population density limit may have hindered development and the populations not to increase in these areas. These would have led to a Portsmouth-style controlled growth and development, and reduced the change in ΔAfP: the value created by the difference in the population that was initially protected by the defence and the number of people who will be inundated once the SCFPs is exceeded, by affecting the number of people who will be exposed in the future. Although, it is likely that as coastal settlements develop that they will tend to a more Portsmouth-style of pathway inhibition.

Therefore, based on the patterns and data observed, there appears to be a clear order how these socio-hydrological processes develop with the apparent appearance of cycles (**Figure 109**): Cycle 1 being the initial construction of the SCFP and Cycles ≥2 being subsequent upgrades. Each upgrade follows the trajectory of the conceptual line graph (**Figure 108**), with each upgrade becoming increasingly expensive, as ECWL and the SoP required increases, causing Flood Memory to decrease, as populations start to assume that they are no longer floodable (**Figure 110**).

These processes can be mapped onto the order uncovered by the models, with slight variation to reflect the combined information. There are four stages to every cycle, but this will be a representation of Cycle 1:

- **Stage 1: Implementation**
  The SCFP is constructed, leading to a decrease in *AfP*, driven by a decrease in the ability of the coastal flooding to travel into the settlement and affected people and assets.
- **Stage 2: Latency**
  During this period, coastal population and housing occupancy per residence increases behind the newly constructed coastal flood defence, and there is an increase in coastal urban development. Meanwhile, ECWL is also increasing seaward of the newly constructed defence. Flood Memory decreases as populations are no longer directly at risk.
- **Stage 3: Potential Flooding**
  This stage sees the newly constructed SCFP being exceeded by higher ECWL scenarios and flooding in the settlement behind it. Due to growth during the latency period there is an increased number of people and assets behind the defence. Moreover, due to increases in ECWL the floodwater has the potential to travel further into the settlement than it ever had previously.
- **Stage 4: Upgrade**
  To prevent the defence being highly compromised by higher ECWL scenarios and resulting inundation of seawater into the settlement, it becomes necessary to perform an upgrade of the structural flood defence. This in turn leads to a new latency period and the cycle begins again, with weaker Flood Memory than before the start of the cycle.

These cycles reoccur until it either becomes too prohibitively expensive to upgrade the SCFP, or until due to the inhibition pathways the amount of assets at risk and the ΔAfP has decreased sufficiently enough to lead to limited overall change in coastal areas. This provides two scenarios, Scenario 1, such as that in Southport and Weston-super-Mare where the two inhibition pathways are not growth-limited, and Scenario 2, such as in Portsmouth, where pre-existing conditions limit the ability for growth.

Scenario 1 presents a two-dimensional source-pathway-receptor (SPR) model capturing the socio-hydrological processes in mid-sized towns such as Southport and Weston-super-Mare (**Figure 111**). These mid-sized towns are not limited by the inhibition pathways, and so therefore when defence is exceeded by ECWL the coastal flooding can proceed through the low density coastal residential areas and into the subsequent areas. These low-density residential areas allow for growth in coastal population, housing occupancy, and coastal urban development.

Scenario 2 presents a contrast to Scenario 1, one in which coastal population, housing occupancy, and coastal residential urban development are limited (**Figure 112**). Here coastal urban development may occur, but would be limited to non-residential properties due to the interaction of the socio-hydrological processes instigated, and propagated, by the SCFP upgrades, and the inhibition pathways. When the coastal flood defence is exceeded, flooding proceeds into the high density residential area and the industrial areas, here coastal residential urban growth, coastal population, and housing occupancy growth were limited, and therefore the change in *AfP* (ΔAfP) would be limited to natural population change in the inundated areas. Land-use therefore, is the primary factor that limits change in residential development, ΔAfP, and consequently its associated coastal population increase along with its housing occupancy.

From the patterns that emerged from the mapping and the agent-based modelling it was possible to create a high-level conceptualisation, one that captures the socio-hydrological interactions between the construction, and subsequent upgrades, of SCFPs, local changes in population, and urban development (**Figure 113**). This diagram forms the culmination of the previous graphics from this section.

The cycle begins with the initial construction of the SCFP; if land adjacent to the newly constructed defence is industrial or parkland, it will not see increases in coastal population (**Figure 113**). However, if the area is residential, but already highly populated, it may not see the increases in coastal population and housing occupancy associated with the increases in SCFP, as in Portsmouth.

If the area behind the newly constructed defence is primarily residential, but not overpopulated, and therefore has room to grow, then coastal population will increase, and not only increase, but increase to form a greater share of the overall population. Moreover, there will be an increase in coastal development, although this would also occur in industrial areas, and is therefore not limited by land-use. However, the increase in coastal urban development is not enough to match pace with population, leading to an increase in housing occupancy in the area, the strongest increase out of all of the factors (**Table 42**).

Without Flood Risk Communication, reminding local residents of their exposure to potential flood inundation (and where possible take, e.g., property-level resilience measures), Flood Memory decreases as residents are no longer flooded (**Figure 113**). The decrease in Flood Memory leads to a decrease in the Flood Preparedness, Flood Awareness, and Flood Responsiveness of the protected population. Flood Preparedness can be defined as the preparations previously taken to reduce the impacts of flooding, such as sandbags or other household-level preparations, as well as putting into place other management strategies. Flood Awareness is related to Flood Memory, and represents the knowledge, potential frequency and impacts of flooding. Methods of improving Flood Awareness can include flood warnings and alerts, prior to, and during, a flood by keeping residents informed and limiting their risk when a flood does occur. Flood Responsiveness, on the other hand, is the measure of how quickly and easily a household can respond to a flood and act accordingly. Without proper Flood Risk Communication, these three factors decrease as a population becomes exposed to less frequent flooding, leading to lapses over time (**Figure 110**). The decreases in these values lead a population to becoming more vulnerable.

Over time, during the Latency Period (**Figure 106**), the Extreme Coastal Water Level increases seaward of the SCFP, which in turn increases the Potential Flood Extent (**Figure 110**). The increase in Potential Flood Extent is due to higher ECWL leading to greater elevations being affected in the town, and an increased two-dimensional extent, with greater longitudinal and latitudinal inundation.

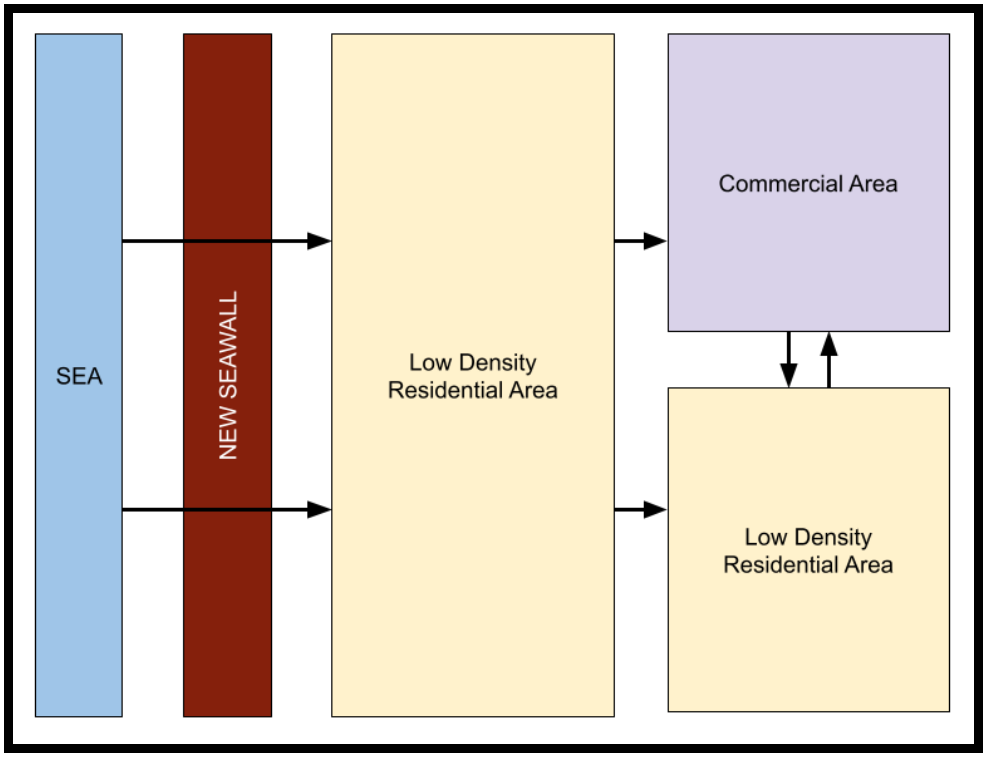


Figure 111 A two-dimensional SPR conceptualisation of an inundation event in a mid-sized town.

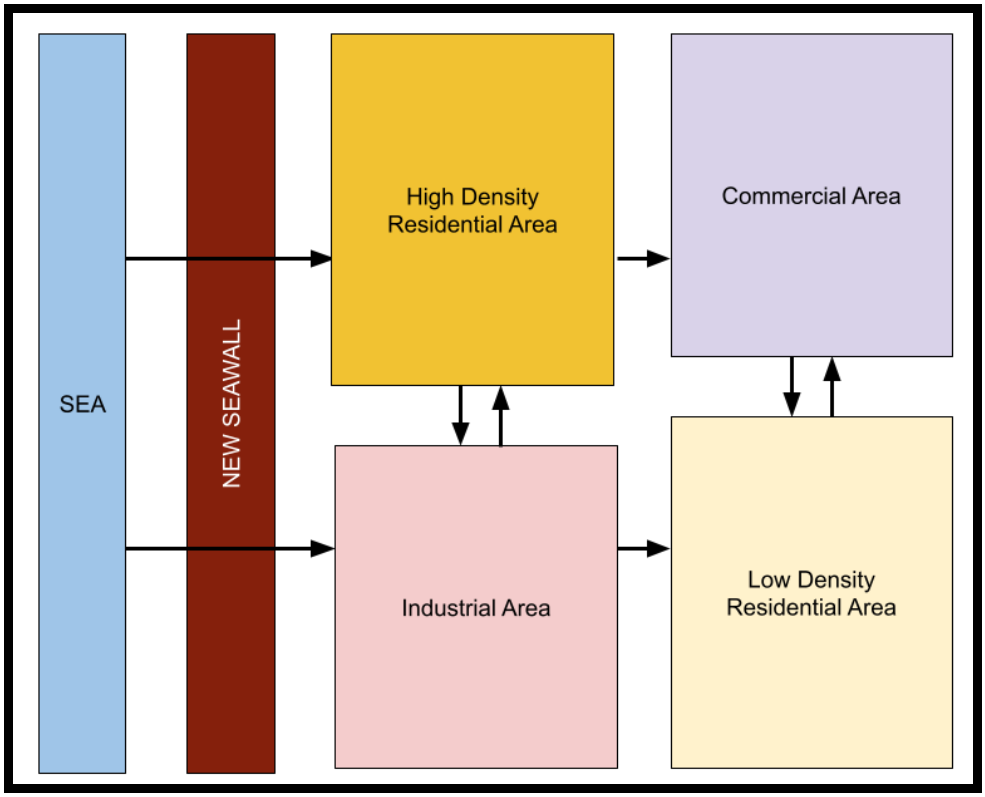


Figure 112 A two-dimensional SPR conceptualisation of an inundation event in a larger settlement affected by the inhibition pathways.

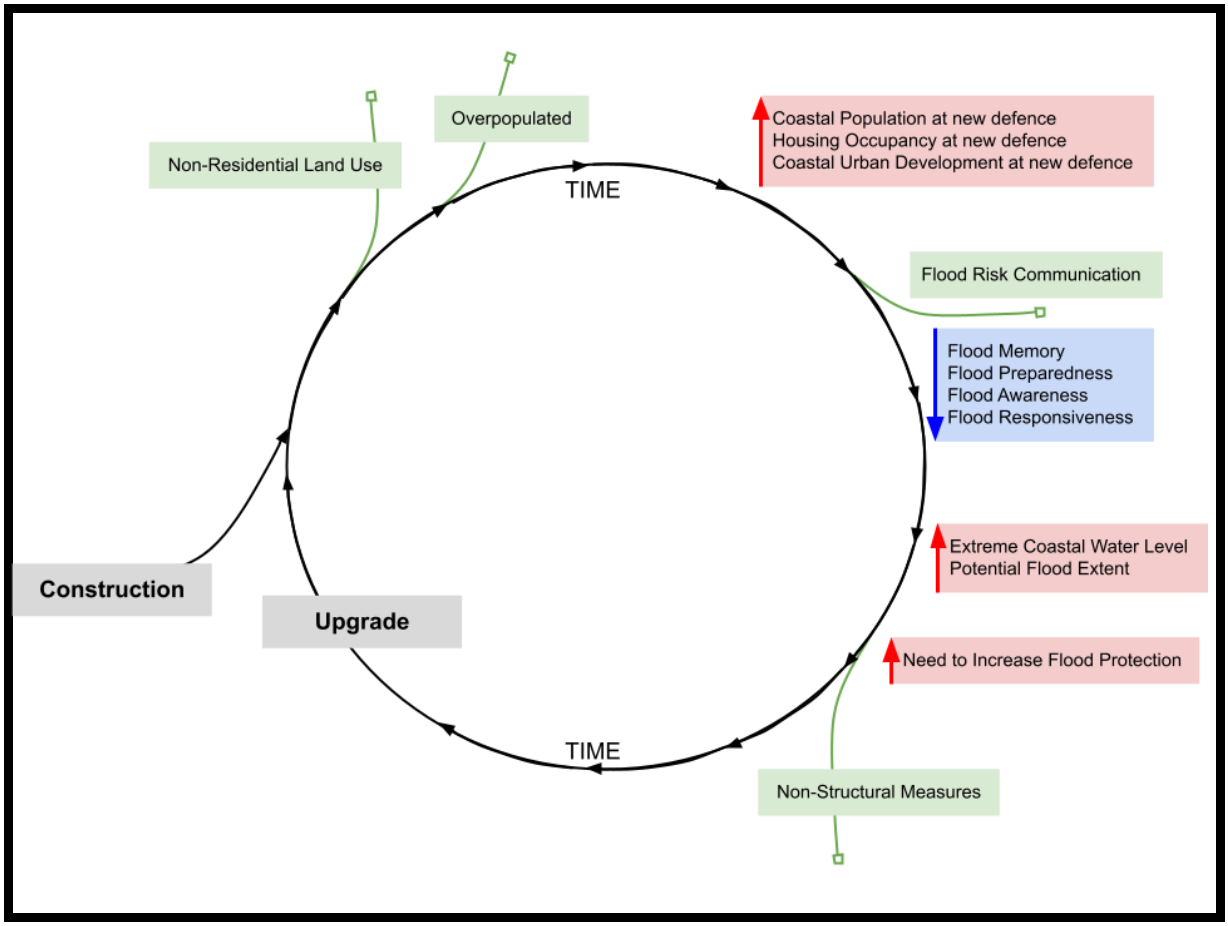


Figure 113 A combined cyclic conceptual model of the unintended consequences of SCFP. Increases in factors are listed in red, while decreases are listed in blue. Methods of limiting the socio-hydrological lock-in impacts of SCFP are in green.

The greater Potential Flood Extent and combined increase in *AfP* leads to a greater necessity to upgrade the SCFP due to the increased number of people and assets caused by both, growth due to the new defence and due to the increase in the extent of a potential flood. The FRM authority must now decide whether to upgrade the SCFP to reduce the probability of flooding and therefore to reduce the assets and populations directly at risk, or pursue non-structural measures (**Figure 113**). Without knowledge of the unintended consequences of SCFP the decision to upgrade is obvious; it leads to a decrease in coastal flood risk and Expected Annual Damage. This decrease in coastal flood risk becomes apparent in the modelling as the Implementation phase (**Figure 106**), which begins the cycle again (**Figure 113**), and leads to further increases in *AfP*, Coastal Development, and Housing Occupancy (**Figure 109**), and resulting decreases in Flood Memory (**Figure 110**). When selecting coastal flood protection measures, FRM authorities conduct cost-benefit analyses that do not take into account these unintended consequences, and therefore overestimate the effectiveness of SCFPs. These overestimations eventually lead into infrastructural lock-ins in which the increases in coastal population and development, which when combined with increasing ECWL, create an ever-increasing need for a higher and higher SoP, which becomes increasingly expensive (**Figure 108**). Over time this also leads to an ever-decreasing Flood Memory, which in turn, leads to an ever-increasing population vulnerability (**Figure 110**). This cycle continues until either one of the inhibition pathways, Non-Residential Land-use or Overpopulation (**Figure 112**) is present, or one of the de-escalation pathways is used (**Figure 113**). These de-escalation pathways provide a way to break the cycle, or at least weaken it, using existing FRM policies, such as Flood Risk Communication and Non-Structural Measures. Flood Risk Communication is a group of methods and means of getting the message across that assets and populations are at risk of coastal flooding and that people should be aware and take appropriate actions, where possible. Whereas, Non-Structural Measures can take the form of flood forecasting and warning, land-use control and regulations, household or community floodproofing, increases to emergency

preparedness and recovery, and teaching residents how to live with flooding. Efforts to break, or mitigate, the unintended impacts of SCFP upgrade cycle should be pursued. This would ultimately lead to more resilient coastal communities. These points-of-attack are presented within the final conceptualisation of unintended consequences of SCFP and present a portfolio of the best methods of tackling these impacts and reducing the likelihood of infrastructural lock-ins and prohibitively expensive structural coastal FRM schemes.

5.0 Discussion

This chapter forms a critical component of this project, synthesising the research findings, interpreting their significance, and contextualising them within the broader academic and practical contexts, bridging the gap between the data presented in the previous results chapter and the broader theoretical and practical implications of these findings.

5.1 Introduction to the Discussion Chapter

Failure to integrate spatial planning, with sustainable management of the hazard, exposure, and vulnerability factors of coastal flood risk, leads to communities that are less resilient, less prepared to combat climate change, and more prone to the unintended consequences of SCFP, known as the *SDP* (SDP). However, literature on the topic, especially within the context of coastal environments, is limited, as is the current understanding within the field, mostly driven by a lack of data, and a biased emphasis towards fluvial flooding. Therefore, the purpose of this research is to review the state-of-the-art in the field, determine knowledge gaps, and develop and apply a modelling framework and tool to provide a comprehensive understanding of the unintended consequences of coastal flood defences. This is crucial for providing evidence-based advice to flood agencies and policymakers regarding the often unincorporated changes in coastal flood hazard, exposure, and vulnerability. The research outputs will also provide insights that can support efforts in building more resilient communities as coastal flooding grows to become one of the largest modern challenges facing the UK, and many other coastal countries.

The study focused on three contrasting case studies: Portsmouth, Hampshire; Weston-super-Mare, Somerset; and Southport, Merseyside. Each settlement provides a unique perspective into the influence of potential unintended consequences from SCFP in the context of their specific social and economic environments. The project combined emerging and current methods used within prominent studies in socio-hydrology, modelling, statistical and geospatial analysis, and conceptual frameworks in a novel way to achieve the objectives, and answer the research questions.

Geospatial analysis provided the primary basis for achieving **Objective 1**, using differential analysis: comparing LiDAR data from before the C/U of SCFPs to afterwards, and quantifying changes in the urban environment. For **Objective 2**, an investigation into socio-spatial and socio-economics was followed: georeferencing census data from the past four censuses and looking at the changes in local population, internal migration, and the changes in economic inactivity incidence, used as a proxy for vulnerability analysis. Case studies were compared to each other and to nearby settlements, to provide context and determine the likelihood of whether changes in population or urban development were connected to the flood defences or wider regional/national changes. See **Section 4.1** for the output of these analyses across the three case studies.

Data from these investigations then went into the development and application of an ABM for each case study, this aided in the completion of **Objective 3**. These ABMs used ONS population projections and Met Office's RCP-based climate scenarios for future ECWL , running until the year 2100. The modelled output of *AfP*, *FA ratio*, and *the Derivative of AfP* across time are plotted and represented in **Section 4.2**.

The final output of the research was a conceptual model, that provides generalised insights that are easily understandable by relevant stakeholders: the general public, policy workers, and flood risk managers alike to achieve **Objective 4**. The conceptual model, presented in **Section 4.3**, offers insights towards making communities more resilient as sea levels rise and coastal flooding presents a greater and more frequent hazard for unprepared communities. Actions to be taken to prevent further lock-in effects and an exacerbation of the current flooding issues were discussed within **Objective 5**; highlighting the need for a science-engineering-policy nexus approach, integrating spatial planning system with FRM.

5.2 Interpretation of Key Findings

This section discusses the key findings of the project, providing a comprehensive analysis of the research outputs. By examining these data and research outputs through various analytical lenses, this section leads to insights into the understanding of the complex interactions between population socio-spatial dynamics, coastal urban development, and flood risk in coastal areas as an unintended consequence of SCFP.

5.2.1 Main Conclusions and Outcomes

Methods used for **Objective 1** saw the identification of coastal urban development following SCFP. LiDAR data identified distinct outcomes in each of the three case studies. In Southport, there was a statistically significant increase in coastal urban growth following the construction of the SCFP. This is in line with key SDP studies (Burby 2006; Di Baldassarre *et al.,* 2015), which argue that increased structural flood protection often leads to urban development and population growth in areas that would otherwise not have been developed to that extent. These urban growth patterns were not mirrored in comparative sites which implies that the presence of the SCFP may have been a major catalyst for this urban development.

Similarly, in Weston-super-Mare, urban development increased following the major upgrade of the SCFP, further supporting the link between structural coastal flood defences and urban growth (as in Di Baldassarre *et al*., 2018). However, Portsmouth showed a different pattern: urban development at the Old Portsmouth SCFP was residential, but following the NPCS, development in that area was predominantly industrial. This location highlights the importance of land-use planning in managing the unintended consequences of SCFPs (as in Kousky & Kunreuther, 2010), which would suggest that industrial development, unlike residential, may not contribute to coastal population increases. In addition, Gosport, the comparative site for Portsmouth, saw significant urban development, but without associated population growth. This hints at external drivers also influencing urban change beyond SCFPs, such as broader economic and industrial trends (as in Jongman *et al.,* 2012).

Coastal population dynamics at SCFPs, identified within **Objective 2**, followed a pattern consistent with socio-hydrological feedback loops (as in Sivapalan *et al.*, 2011). In Southport, there was a notable increase in coastal population after SCFP construction, which was statistically significant compared to other areas of the town and comparative sites. This also aligns with the SDP, whereby perceived safety from structural flood protection encourages internal migration towards the newly protected area, driving population growth (Di Baldassarre *et al*., 2013a). Similarly, these processes were observed in Weston-super-Mare, although in the town, population increase was more evenly distributed across coastal areas of the town, possibly due to pre-existing urbanisation and flood protection mechanisms (as in Moel *et al.*, 2011).

Although, in contrast, Portsmouth did not experience a significant increase in coastal population following the NPCS phases. This absence of coastal population growth, due to the urban development being predominantly industrial, suggests land-use driven limitations where pre-existing high population density and industrial land-use exist, limit new residential developments (as in Eriksen *et al.*, 2021). This reflects an inhibition pathway, whereby urban density can act as a natural break on coastal population growth after a SCFP C/U project.

Agent-based modelling of the socio-hydrological processes at the SCFP, as a part of **Objective 3**, demonstrated clear emergent phenomena. In Southport the SCFP initially reduced the *AfP*, but over time this protection led to a greater *ΔAfP* when the ECWL surpassed the SCFP crest height due to increased settlement behind the SCFP (as in Di Baldassarre *et al*., 2018). This pattern again aligns with the SDP, leading to increased exposure once SCFP are overwhelmed (as in Ludy & Kondolf, 2012). Weston-super-Mare showed a larger *ΔAfP* once the ECWL surpasses the SCFP crest height as many areas were already defended by a seawall. This echoes findings from Hurricane Katrina whereby the failure of the levee system resulted in disproportionately high impacts on populations who believed they were safe (Burby 2006; Gotham *et al.*, 2018). Portsmouth, on the other hand, demonstrated that with

limited residential development around the NPCS, the role of the SCFPs in shaping population socio-spatial dynamics is diminished, illustrating again how land-use can moderate the socio-hydrological impacts of SCFPs in densely populated and highly developed areas, such as Portsmouth (as in Fletcher, 1992).

As a part of **Objective** 4, the modelling of Southport and Weston-super-Mare revealed a cyclical pattern to the construction, and then upgrading, of SCFPs: as new SCFPs are built, population and urban development behind them increase during a latency period (see **Subsection 4.2.3**), followed by a potential inundation event, which with the new development and population at risk, would necessitate a structural upgrade to mitigate the increase in both hazard and exposure. This cycle mirrors findings from studies on the flood defences in New Orleans, where repeated upgrades to flood infrastructure did little to mitigate long-term risks (Burby, 2006; Ludy & Kondolf, 2012). This cyclicity demonstrates a structural lock-in process, whereby continuous upgrades drive urban growth that exacerbates future flood hazard (Di Baldassarre *et al*., 2018).

The modelling and socio-spatial dynamics observed in Portsmouth demonstrated a potential pathway for breaking this cycle through land-use control and strategic planning. The industrial development around the NPCS highlights how non-residential land-use can inhibit population growth, thereby reducing risk of socio-hydrological feedback loops, demonstrating the need for an integrated spatial planning and coastal zone management policy to balance flood protection with sustainable urban growth. SCFPs play a critical role in managing flood risk to coastal communities, but their often unintended role in shaping urban development and population dynamics, and long-term implications, should be carefully considered. Although, it is vital that these considerations occur proactively, before a SCFP is constructed, as retroactive management of urban development can be challenging with current planning regulations, necessitating an integrated flood risk management strategy (Van Der Planck *et al.*, 2021).

5.2.2 Inhibition Pathways

The analysis of the SCFP schemes in Southport, Weston-super-Mare, and Portsmouth has uncovered intrinsic inhibition pathways that may be able to play a pivotal role in understanding and mitigating the unintended consequences of SCFPs. These inhibition pathways, observed from comprehensive research and the conceptual frameworks, offer insights into how socio-hydrological processes unfold and how they can be harnessed to create more sustainable coastal management strategies. In essence, inhibition pathways can serve as a mechanism to lever, that limits or mitigates the adverse impacts of SCFP interventions, thereby reducing overall coastal flood risk and enhancing resilience in coastal communities. Understanding these pathways is crucial for policymakers and decision-makers seeking to develop effective coastal management and resilience plans.

The concept of inhibition pathways extends beyond demographic trends to encompass flood risk communication, flood memory, and urban development patterns. Effective communication of flood risks and awareness amongst residents can help maintain flood memory and flood awareness and preparedness, thereby reducing exposure to future inundation events. Additionally, non-structural measures such as land-use regulations and community floodproofing initiatives can complement structural interventions, mitigating the escalation of infrastructure costs and limiting future population and asset exposure. These inhibition pathways underscore the importance of adopting a holistic approach to coastal management, integrating structural and non-structural measures whilst considering inhibition pathways and socio-hydrological dynamics. By leveraging these insights, policymakers can develop more resilient coastal communities capable of adapting to the evolving challenges of climate change and sea-level rise.

Evidence for the existence of inhibition pathways has also been observed in the literature. A 2024 study of flooding and land-use in Taiwan found that limiting new development in exposed areas and comprehensive watershed management is needed for reducing overall damages (Ku, 2024). Moreover, it was found that the strategy of regulating and controlling growth in flood-prone areas can be more effective than a comprehensive watershed management strategy when considering the cumulative

damage reductions over a century (Ku, 2024). Similarly, in Lebanon, in an investigation of how lack of land-use planning and randomised land cover around the Assi watershed it was found that land-use planning measures minimise development in the floodplain (Sarkissian *et al.*, 2022). Moreover, a comprehensive FRM strategy, one that also incorporates accommodating urban growth and expansion in flood-safe areas, referred to as resettlement and reconstruction, and can lead to a culture of living with risk, which also propagates social cohesion (Sarkissian *et al.*, 2022). Living with flood through land-use planning can increase public awareness and, ultimately, resilience. However, some constraints, specific to developing countries, can hinder the adoption and implementation of the proposed land-use planning (Sarkissian *et al.*, 2022).

The link between population density and urbanisation is apparent in the literature, and they have a significant impact on flood risk because both increase exposure and losses during flood events due to increases in population and development in coastal areas (Kundzewicz *et al.* 2014). Population growth and urban development leads to a modification of the terrain and land cover which can exacerbate flooding (Salman and Li, 2018). Although this link suggests that population growth leads to land-use change, which is the opposite to the sequence of the inhibition pathways. However, this would only be true if there were the physical space to expand into, which Portsmouth does not have. Rising sea levels are expected to have a larger effect on exposure in the future, and for small coastal island communities, such as Portsmouth, the area available for development can become a limiting factor (Stevens *et al.*, 2015).

Cities must have the space, or make room, for urban growth and to accommodate a growing population. These cities must make the population capacity, and therefore the required urban growth, to remain productive, affordable, and sustainable (Angel *et al.*, 2021). However, it has been identified that there are upper limits to population density in all cities, noted to be 552 people per hectare (Angel *et al.*, 2021). This upper limit links in with what was identified by the population density inhibition pathway, and would elaborate on the lack of population change at the NPCS Phase 1 SCFP. Even if the population change was not entirely limited, as it was not at the 552 people per hectare maximum observed prior, it would indicate that perhaps there is a different maximum for lower urban density, but still relatively high population density areas. Whilst this is not within the remit of this analysis, it would provide an opportunity for further study.

Therefore, operating these inhibition pathways would be able to play a crucial role in limiting the adverse unintended consequences of SCFPs. Understanding these pathways is essential for developing effective strategies to break the cycle of infrastructure lock-ins (and hence SDPs) and reduce flood risk in coastal communities, especially as time progresses.

These pathways could be leveraged by implementing targeted land-use regulations and development policies (as in Junger *et al.*, 2022). By controlling the type, and density, of coastal urban development in coastal areas policymakers can prevent unchecked growth and mitigate any escalations of population and population density (Mustafa *et al.*, 2018), during the latency period, near new SCFPs. For example, land zoning regulations could prioritise non-residential land-use in areas directly protected by SCFP, thereby limiting potential increases in AfP and residential infrastructure (as in Thaler *et al.,* 2020).

Furthermore, integrating flood risk communication strategies alongside these inhibition pathways can help to maintain flood memory and awareness amongst residents. Flood memory decline can work against at-risk communities, and negate knowledge of the real potential for disaster caused by unmonitored development and land-use change (Vries, 2011). Regular dissemination of information through public awareness campaigns, community workshops, or digital platforms for example, regarding flood risk, evacuation procedures, and resilience measures can empower residents to make informed decisions and take proactive steps to limit their vulnerability and exposure to coastal flooding, and foster a culture of resilience (Sufri *et al.,* 2020).

5.2.4 Alternative Explanations

Whilst the analysis has provided valuable insights into the complex socio-hydrological dynamics of SCFP, and its unintended consequences, it is crucial to acknowledge the alternative explanations that may account for some of the observed patterns and examine their validity. Understanding these alternative interpretations not only enhances the robustness of the findings, but also contributes to a more comprehensive understanding of the multifaceted and many layered interactions between human activities and coastal environments. This subsection explores several alternative explanations that warrant consideration in the interpretation of the results. These alternative perspectives offer valuable insights into the drivers behind the observed trends and provide avenues for future research to delve deeper into the complexities of coastal management and resilience planning. By critically examining these alternative explanations alongside the main findings it enriches the discourse surrounding holistic coastal FRM and can contribute to a more informed decision-making processes in coastal zones.

From **Objective** 1, statistical analyses revealed that there was statistically significant coastal urban growth after the SCFP was C/U. Whilst hypothetically, this urban growth could not be linked to the C/U or the SCFP, this coastal urban development occurred consistently, in all primary locations. Moreover, it happened across multiple time periods: mid-2000s in Southport, early 2010s in Weston-super-Mare, and late 2000s and mid-2010s in Portsmouth. Although, it could be argued that perhaps there were increases in the economy either nationally or regionally that led to the increases in coastal urban development. Yet this was not true otherwise it would have led to similar urban development in coastal areas in the comparative locations, which did not occur. Coastal urban development only occurred in the FZ at locations where there was the construction, or major upgrade, of a SCFP.

From **Objective 2,** it was identified that there was little noticeable link between EiA and SCFP C/U overall (see **Subsection 4.1.4**). However, coastal population and housing occupancy increases were seen at the SCFP, which was not replicated in the comparative sites or elsewhere in the towns. Also, there was not an increase in coastal population at the Old Portsmouth or NPCS defences, but there was an increase in housing occupancy at the Old Portsmouth SCFP. Increases in the population of coastal towns and cities are occurring across the UK (Stevens *et al.*, 2015), and this should be acknowledged within this analysis. The coastal zone provides a wealth of natural resources, both, tangible and not, that create a strong pull factor that has been drawing populations for millennia. However, this population increase is not occurring in a spatially equal way across settlements, something also observed in the literature (Di Baldassarre *et al.*, 2018). Areas adjacent to the newly constructed, or majorly upgraded, SCFP had a statistically significant growth in population from before the structural FRM project to afterwards, compared to those areas more internal in the settlement: the population share that the areas adjacent to the defence had become larger following its construction or major upgrade. This was replicated across all primary sites, with the exception of the NPCS Phase 1, which did not see a statistically significant change in population distribution. Although, as noted by previous research, the intense population density and land-use of Portsea Island will limit population growth (Stevens *et al.*, 2015). Moreover, this statistically significant change in population distribution was not observed in any of the comparative locations, which displayed a more equal population distribution change across the same time period. If the change in population were purely down to socio-economics and natural growth, then there would not be this increase in population in coastal areas at the defence, or it would be replicated in the comparative sites (as in Di Baldassarre *et al.,* 2013a), which it was not. This would therefore indicate that the construction, or major upgrade, of the SCFP had an impact on the population of the settlement.

Likewise, it could be argued that the increase in the housing occupancy in these coastal areas could be a result of some economic instability, and whilst it is true that the Great Recession of 2008 led to an increase in the HMOs and people moving in together (Mehrotra and Carter, 2017), this rise in housing occupancy did not occur to the same extent in other coastal areas of the primary study sites nor did it occur in the comparative sites, with the exception of Gosport during the NPCS Phase 1-4 period. This led housing occupancy to receive the largest summary output score of all of the factors studied, with +0.75 compared to -0.5 for both, the other coastal areas of the settlements and the comparative sites. The effects of the Great Recession would be more likely to be temporary and occur more spatially

distributed than localised to coastal areas, particularly for properties affected by sea-level rise (Gourevitch *et al.*, 2023).

For **Objective 3**, three ABMs, one for each case study, were developed. These models suggested that during a Latency phase population would continue to increase behind the SCFP whilst the ECWL continues to increase. This would continue until the ECWL surpasses the SCFP crest height and, in locations with flatter topography, the flood extent would reach a far greater area than before. The combination of an increased presence behind the SCFP and a larger flood extent would see a far greater proportion affected by the flooding than when the defence was initially built, leading to the large ΔAfPs. From the lack of flooding, this population would have a lower flood memory, and therefore be less prepared if the event of low-frequency, high-impact flooding (Ridolfi *et al.*, 2021), an event exacerbated by the SCFP which limits higher-frequency, lower-impact inundations (Haer *et al*., 2020). Whilst the phenomena replicated by the ABM matches the expected impacts of the SDP, as an unintended consequence of SCFP, it is essential to examine whether alternative explanations might account for the observed changes seen in **Section 4.2**.

A possible explanation for the population growth behind the SCFPs, if it were hypothetically independent of the SDP, could be natural population and economic shifts. Through this hypothetical lens, it could be possible that natural population growth would have occurred regardless of the C/U of the SCFP. For instance, populations may be driven to coastal areas by economic opportunities related to tourism, infrastructure, and real estate, rather than a direct response to the presence of SCFPs. Therefore, in this scenario, it could be proposed that changes in population distribution could reflect broader socio-economic trends rather than as a direct consequence of a perceived reduction in flood risk.

However, whilst these socio-economic shifts naturally play a role, the magnitude of the population increase in the Southport and Weston-super-Mare ABMs aligns too closely with the C/U of the SCFPs to be entirely coincidental (as in Haer *et al.*, 2020). Sensitivity experiments have shown that even under varying external economic conditions, the presence of structural protection can be a dominant control on development trajectories (McNamara & Werner, 2008b). Furthermore, whilst natural population dynamics do influence urban growth, SCFP creates a perceived reduction in risk, leading to concentrated development in protected areas, consistent with the SDP (Di Baldassarre *et al*., 2015; Haer *et al.*, 2020). The increase in population in both towns near the SCFP suggests that residents and developers are responding to a false sense of security, unaware of the long-term risks posed by ECWL exceeding the design capacity of the SCFP (Aerts *et al*., 2018). Moreover, natural growth fails to account for the observed *ΔAfP* after the SCFP was exceeding in the ABM; if natural population growth were merely the result of economic or natural changes, it would be expected a more gradual and distributed increase in flood exposure over time. However, the sharp rise in *AfP,* observed once the ECWL surpasses the SCFP crest height, suggests that a latent vulnerability has developed, one that was only realised once the SCFPs had failed to hold the ECWL, leading to an inundation event (Myers *et al.,* 2008). The sudden increase in flood exposure directly supports the SDP interpretation: protection offered by the SCFPs delays, but does not prevent, catastrophic flooding, leading to greater impacts when the SCFPs are eventually breached (Troy *et al.*, 2015). In particular, the results from Portsmouth (see **Subsection 4.2.3**), illustrate how land-use and urban density can moderate the effects of the SDP. Unlike the other case studies, Portsmouth did not experience the same degree of population increase near the SCFPs, this was replicated in the ABM. This would suggest that in highly urbanised and limited environments, such as Portsea Island, the limitations on new urban development due to pre-existing density and infrastructure may suppress the population growth.

For **Objective 4** a conceptual model was developed, a culmination of the research output from the previous three objectives. The conceptual model of the unintended consequences of SCFP (see **Section 4.3**), suggested after each cycle the Standard of Protection increases as FRM authority seeks to increase protection to combat increased ECWL and coastal population and infrastructure growth. Whilst in tandem, flood memory decreases as people are flooded less often, but the *AfP* is increasing. The cycle continues until costs become prohibitively high, but at which point the *AfP* is at very high levels and with very low levels of flood memory (Turner *et al.*, 1996). A decrease in flood memory is therefore

directly related to the frequency of flooding, however, it is also a function of flood risk communication and established strategies thereof. This reduction in the perception of flood risk, a hallmark of the SDP, played a dominating role in the attraction of populations to these newly protected areas (Aerts *et al.*, 2018). If economic growth and pre-existing infrastructure were the primary drivers, and the conceptual model were incorrectly capturing these processes, it would be expected that there would be a more uniform distribution of population growth across all areas, not concentrated specifically behind the SCFPs: the perception of safety introduced by these SCFPs is leading concentrated development in previously less desirable locations (Di Baldassarre *et al*., 2015).

The conceptual model operates on an assumption of a lack of flood risk communication, however, this is suggested as a way to break the cycle. Further, the communication of flood risk has been identified to be lacking in the UK, limiting the impact of increasing flood risk awareness and resulting resilient behaviours. Low levels of information penetration and personal preparedness are often accompanied by a high level of distrust in FRM strategy and governmental organisations (O'Sullivan *et al.*, 2012; Rollason *et al.*, 2018). It has been found that 45% of exposed people appreciate their own personal flood risk and 7% appreciate the risk to their property, similarly 31% of exposed households have no flood plan and no idea of what strategies to employ or do in the event of flooding (Davies, 2015; Rollason *et al.*, 2018). Flood risk communication can be effective, but it must be done well, and current standards are lacklustre, and therefore the decline of flood memory across time based on the current flood risk communication strategies is well-grounded.

The SDP remains the most plausible explanation for the socio-hydrological dynamics observed and therefore validate the conceptual model. The cyclical nature of the SCFPs construction, and then subsequent upgrades, and the subsequent increases in population and assets exposure, as demonstrated in the conceptual model, align closely with the SDP (Di Baldassarre *et al*., 2018). Each new upgrade leads to a temporary reduction in *AfP*, followed by an increase in urban development and population, and a subsequent rise in *AfP*, and eventually, once ECWL surpasses the SCFP crest height, it leads to a large *ΔAfP*. This cycle continues until it becomes financially or physically unfeasible to continue to upgrade the SCFP (Turner *et al*., 1996), or until the cycle is broken.

5.3 Theoretical Contributions

This section examines how the research outputs advance the existing body of knowledge in FRM, urban planning and socio-spatial patterns, and socio-hydrology. By introducing new concepts, frameworks, and models this section provides a fresh perspective of these unintended consequences of structural flood protection in coastal environments. These theoretical contributions evaluate the novel theoretical insights gained from the research, such as the concept of inhibition pathways and the application of agent-based modelling of socio-spatial and socio-hydrological processes. The subsection also explores how these contributions enhance the understanding of these complex interactions between SCFPs, urban development, population growth, and changes in population distribution, offering new avenues for future academic inquiry and practical applications.

5.3.1 Evaluation of Research Output and Conclusions

Despite the results from **Objective 1**, coastal urban development is often difficult; these locations have either been previously developed, limiting scope in the size and density of such structures, and/or are being constrained by the sea itself. Moreover, the development, and redevelopment, of these coastal brownfield sites are unlikely to withstand the front-loaded costs of regeneration, especially in weak economies (Leger *et al.*, 2016). Coastal regeneration and development, and redevelopment, schemes often face viability issues due to their peripheral locations and narrow local economies, frequently relying on a single industry and facing interdependency challenges with other sectors and/or regions. This is compounded by the economic circumstances of the study sites in the years following the Great Recession, which created greater pressure on greenfield land in coastal areas, rather than brownfield (Leger *et al.*, 2016). The analysis also highlighted that the newly constructed urban development in Portsmouth occurred 5 years after the completion of the Old Portsmouth SCFP in 2005. The second tranche of development was built from 2017 to 2019, 3 years after the North Portsea Island Coastal

Scheme Phase 1. In Weston-super-Mare, the LiDAR analysis revealed that new buildings were constructed across the 2014 to 2018 period, all within the FZ. These were built over a 4 to 8 year period following the SCFP upgrades. Then, in Southport, the analysis revealed that the retail estate was completed later in the same year as the SCFP scheme, and then continued two years after until 2004. These are represented in the timeline below (**Figure 114**). Phase 2 and Phase 3 of the North Portsea Coastal Scheme are not included due to a lack of definitive exposed development. Whilst some development also occurred in non-exposed areas, medium to large scale development consistently was constructed in exposed areas hydrologically connected to the new SCFP in all three primary sites. This consistency was not replicated in the comparative sites. The timeline also suggests that the largest gap between the completion of a defence to the start of associated urban development was 5 years, at Old Portsmouth. The second iteration of exposed development from Phase 1 took place 2 years after the completion of the defence. The average time from the completion of the defence to the start of construction of the exposed buildings was approximately 2 years.

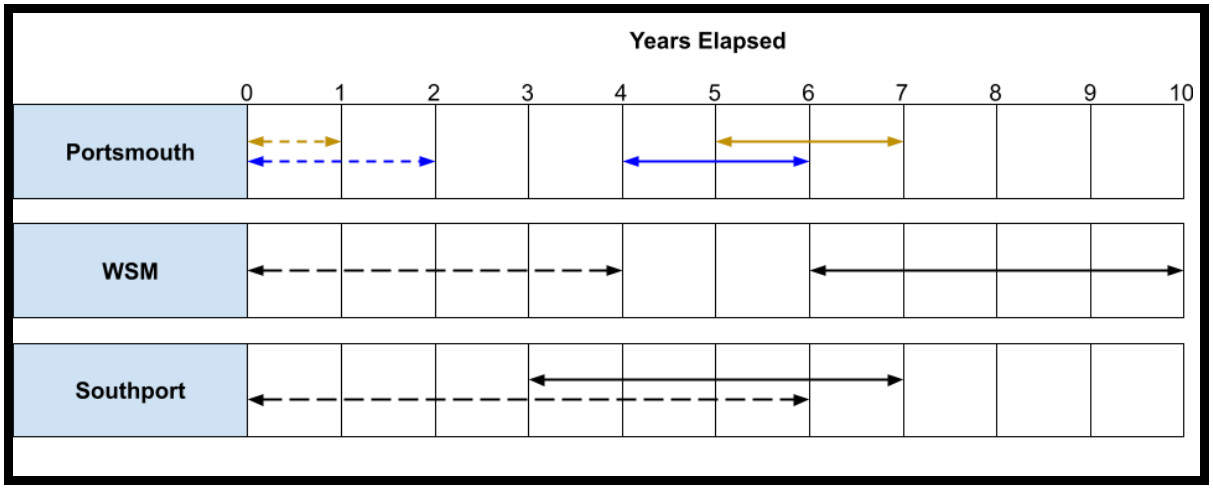


Figure 114 Relative timeline of SCFP construction or upgrading (dashed) and nearby urban development (solid) since the start of the scheme. A yellow arrow represents the Old Portsmouth SCFP, and the blue arrow refers to the NPCS Phase 1 flood defence.

If coastal urban development was solely created by socio-economic trends, such as population growth, the spatial distribution of urban growth would remain equal. However, it has also been identified in the literature that the presence of SCFP tends to create an incentive to build in *FA*s and therefore can lead to increases in flood exposure (Di Baldassarre *et al.*, 2018). This unintended phenomenon can offset the benefits of SCFPs, and can paradoxically increase flood risk in the medium- to long-term after the construction or upgrade of a SCFP (Di Baldassarre *et al.*, 2018). Such lock-in and amplification dynamics are consistent with coupled human–landscape modelling frameworks and coastal simulations that capture emergent system behaviour arising from interactions between protective works, market responses, and morphological change (Werner & McNamara, 2007; McNamara & Werner, 2008b)

Whilst this study investigated three case studies in the UK, the influence of SCFPs on coastal urban development has also been observed in other areas of the world, in both, the Global North and the Global South: along the Jamuna River in Bangladesh (Ferdous *et al.*, 2018), deltaic flooding across the Netherlands (Moel *et al.*, 2011), the Po River in Italy (Di Baldassarre *et al.*, 2013b), the levee breach in New Orleans (Kates *et al.*, 2006). An investigation of the deltaic flooding in the Netherlands revealed that the urban area that can be potentially flooded in the country has increased by a factor of six over the twentieth century, a majority of which occurred in areas recently protected and could potentially reach a flood depth of 2.5m (Moel *et al.*, 2011). In addition, the study also revealed that the proportion of urban areas that are exposed decreased substantially after the North Sea flood of 1953 (*Watersnoodramp*, in Dutch), although this has started to increase again over recent decades as flood protection was upgraded and improved by numerous structural works, such as the Delta Works (Moel *et al.*, 2011). The increase in exposed urban development has brought economic benefits to the area (Hallegatte, 2017), but also offsets the decline in flood risk that was brought about by the initial

upgrading of the flood protection (Di Baldassarre *et al.*, 2018). Although, in some cases, this can be one of the goals of investment in flood protection, not only to reduce flood risk, but to facilitate economic growth in areas that are exposed to flooding, but also, due to the ecosystem services and natural capital provided at coastlines, are valuable. However, in other cases, exposed urban growth expands beyond what was originally planned, leading to unintended increases in flood risk, although whether this happens does not appear to depend on the SoP, but on effective risk communication and the specific societal and political context (Di Baldassarre *et al.*, 2018).

The outcome of **Objective 2** also aligns with literature in the field, such as an investigation of the impacts of the 1953 North Sea flood on long-term population growth in the Netherlands. The results suggested that over the long-term population growth is not massively affected by flooding, and instead were by policy interventions following the flood (Husby *et al.*, 2014). In the decades following when the 1953 North Sea flood hit the Netherlands, areas that were affected by flooding had a 0.6%/yr lower population growth, compared to areas that were not affected by flooding, although this negative impact did not extend into the long-term. However, these same areas, now protected by the Delta Works saw an increase of 0.75%/yr compared to areas that were not flooded (Husby *et al.*, 2014). As countries grow more wealthy, their ability to protect against flooding also increases, and as such a flood inundation event happens less frequently, but there are great financial, and economic costs, if a flood were to occur. People respond to disasters by moving away from hazardous areas, but governments have a strong incentive to respond to a flood disaster by increasing the SoP, reducing the need for individual and household-level responses. These increases in population may either be driven by decreases in societal and individual flood memory from an increase in the SoP (Collenteur *et al.*, 2014) or from a decrease in property values from flooding (Bin and Polasky, 2004). Bin and Polasky (2004) investigated if, and how, Hurricane Floyd affected house prices in North Carolina after it made landfall in September 1999. It was identified that the price of a residential property located inside the floodplain was lower than an otherwise similar house located outside the floodplain. Before Hurricane Floyd this average difference was $4,888, but in the years after the hurricane had passed through this difference between houses in the floodplain and out of it was $10,825 (Bin and Polasky, 2004). Whilst the authors note that they are not clear on how long the increased differential will last, it is more plausible to assume that it will exist for as long as flood memory of the flood event continues. Although the increases in housing occupancy following the construction, or major upgrade, of the SCFPs would be in contrast with decreases in property prices: if house prices go down, people would not be as likely to opt to move in together into denser packed housing. Furthermore, these increases in the amount of people together were also found to occur in a study in Bangladesh, for example, where it has been identified in areas where flood protection has been structurally developed, population density has increased greatly over the past decades as well as the number of assets exposed to flooding, so much so that flood mortality rates associated with the 2017 flooding in Bangladesh were lower in the areas with a lower protection level (Ferdous *et al.*, 2020). The same process was also observed in a study of American metropolitan areas, which saw changes in population density and socio-economics of affected people, the societal memory of past floods, education and experience levels, perceptions of risks and recovery potential are factors that drive population changes in flood-exposed areas (Knighton *et al.*, 2021).

The results from the case studies reveal that the link between the proportion of EiA residents and the construction, or major upgrades, of nearby coastal structural flood protection was weak. A connection between the two was either limited or was easily exceeded by external factors such as the Covid-19 pandemic. A study of flooding in Australia observed that following a flood, relocation does not improve the resilience of a flood-impacted community as in most instance the out-migration consists of younger, EiA members of the community, which not only reduces overall community resilience but also contributes to the economic decline of the town (King and Gurtner, 2017). In larger cities the suburbs can absorb these internal migrants, but in smaller towns relocation would lead to populations moving to a different town, and it is often younger families on middle incomes that rent that do: home ownership often forms a constraint to relocate and older people were found to have a strong sense of place and commitment to the community (King and Gurtner, 2017). A decrease in flood hazard, due to the construction of the SCFP, would not have led to these incentives to relocate, and therefore the economically active population would have remained and therefore continued to maintain their

proportion, which in turn would have maintained the proportion of EiA residents. Although, this would change if an inundation event were to occur, and the proportion of EiA residents at the SCFP would increase, as those who were economically active may seek to relocate. Although, in a proactive FRM authority, the SCFP would get upgraded beforehand (Haer *et al*., 2020), and the flood would never happen. Therefore, it is not that there is no link between SCFP construction, or upgrades, and changes in the proportion of EiA residents at the defence, it is that it keeps it artificially at a net zero change due to the reduction in coastal flood hazard.

These increases in *AfP* overall, an output of **Objective 3**, matches were also replicated in a similar ABM developed to assess the impact of extreme flood events for the European Union. Within this ABM, flood hazard and events evolve dynamically, and occur stochastically, meanwhile socio-economic changes affect exposed values and residential building surface area (Haer *et al.*, 2020). The study found that population growth in *FA*s leads to higher exposure and higher damages, and that depending on how governments act, whether to upgrade again or not, can affect population growth. Continuous upgrading led to an increase of Expected Damages of between 12 and 38 billion euros for a 0.2%AEP event under RCP8.5, and between 8 and 26 billion euros under RCP2.6 across the EU (Haer *et al.*, 2020). Moreover, it was uncovered that whilst continuous cyclic upgrading leads to a lower yearly flood risk, it leads to higher impacts in an extreme event, compared to not upgrading. This was also found within the ABM developed within this project, once the ECWL surpasses the SCFP crest height, it leads to greater impacts at the structural coastal defence from greater coastal population, but also due to the increased depth, and extent, of the floodwater, affecting populations that have never been flooded before. Moreover, the ABM of Haer *et al.* (2020) identified that unless efforts are made to retain societal flood memory and flood preparedness through flood risk communication and building level protective efforts, this would lead to Expected Damages, across the EU, for a 0.2%AEP event of 53 billion euros under RCP8.5 and 28 billion euros under RCP2.6 (Haer *et al.*, 2020).

This European study shows the impacts of these upgrade cycles and infrastructural lock-ins that also became apparent from the analysis conducted within this project. These findings suggest that there is an intangible risk measure that increased from an upgrade compared to the initial construction, which would then suggest a cyclicality. The Portsmouth ABM further exemplified this with the appearance of the inhibition pathways. These pathways mitigate the unintended impacts of newly constructed, or upgraded, SCFPs, and from the modelling it became apparent that pre-existing land-use or high density population can limit growth in population during the latency period and therefore minimise the absolute change in *AfP* from before the SCFP was constructed to the time that the ECWL surpasses the SCFP crest height.

The output of **Objective 4** showed that the decrease in flood memory and the increase in *AfP* during the Latency period creates a necessity to upgrade the SCFP or risk coastal flooding. The decision to upgrade the SCFP renews the cycle, leading to greater population behind the defence, greater housing occupancy, and greater urban development. As the ECWL rises these new assets and populations are placed at risk again necessitating another upgrade, and continuing the cycle. The longer the time between flood events, the less a community can remember a flood. Whereas, high levels of flood memory can lead to an appropriate flood disaster response, increasing flood awareness and preparedness (Scolobig *et al.* 2012). Flood memory can help to provide personal, and local, sustained resilience and therefore it is imperative to increase learning opportunities and increase the resilience of at-risk communities (Garde-Hanser *et al.*, 2017; McEwan *et al.*, 2017). Therefore, resilience, in this context, can be understood as the strength of a community to escape from the infrastructural upgrades lock-in cycle, and minimise the unintended consequences of SCFP, which occurs due to the decay in flood memory (Di Baldassarre *et al.*, 2021).

The decay in flood memory over time was investigated by a socio-hydrological model of a case study in the Czech Republic, assessing the link between proximity to rivers and flood memory (Ridolfi *et al.*, 2021). The findings of the study indicate that flood memory serves as a key mechanism shaping human-flood interactions, influencing the spatial and temporal patterns of human settlement as well as the dynamics of flood risk. The frequency of major flood events drives these changes, and thus underscores the importance of public education and awareness campaigns in enhancing community flood

preparedness. Initiatives such as these can encourage individual household-based FRM strategies (Owusu *et al*., 2015). Furthermore, inclusive and participatory approaches within communities significantly reduce flood losses, emphasising the importance of understanding exposure is essential for flood preparedness and resilience in the face of future flood events (Kreibich *et al.* 2017).

The cycle continues due to the commonly held belief that protected areas are safe and flood problems can be solved permanently by structural engineering. In these areas structural flood defences exacerbate growing flood exposure, and consequently increase flood risk. This eventually leads to the decision to upgrade the SCFP, continuing the cycle, as modelled by the conceptual model. This is due to the implication that, based on a traditional cost benefit analysis, it becomes economically beneficial to strengthen the flood protection again (Kind, 2014, Di Baldassarre, 2018). However, it is becoming increasingly recognised and stressed that there is a residual risk of flooding behind these structural flood defence (Di Baldassarre, 2018), it is this residual risk that is modelled as the Latency period in the ABM. For a more comprehensive cost-benefit analysis it has been argued that, whilst flood damage models, considering depth-damage curves and average flood damages, are effective, they should be augmented with social factors such as risk aversion (a function of flood memory) and social equity weighting, instead of processing purely based on a reduction of Expected Damage (Kind, 2014). Building on this, and incorporating elements from the analysis of this project, a new and more comprehensive cost-benefit analysis, as part of a new overarching holistic spatial planning system, should be developed that not only includes the immediate changes during the latency period but knock-on effects into the next upgrade cycle. This analysis should be pragmatic and realise the real, tangible benefits of SCFP whilst appreciating and internalising the unintended socio-spatial effects and increases in potential losses, and intangible losses in community resilience and flood memory.

5.3.2 Identification of New Concepts, Frameworks, and Methodologies

In this research project, innovative methods were developed to advance the understanding of socio-hydrological interactions between structural coastal FRM and the socio-spatial dynamics of coastal communities. This project has contributed to the field by developing geostatistical testing and projection techniques and an ABM to analyse and simulate socio-spatial changes following the construction, or major upgrade, of SCFP. These advancements will provide robust tools for understanding and managing the intricate socio-hydrological dynamics of coastal urbanisation and the changes in SCFP.

One of the key methodological advancements developed in this project was the application of geostatistical testing in assessing the statistical significance of new urban development through raster *t*-testing. This technique had been used on smaller scales, for the assessment of carbon in soil samples, with 220 samples (Zhang and McGrath, 2004), and comparing the effectiveness of raster resampling, with samples ranging between 345 and 11,162 (Kienzle, 2004). However, the application of geostatistical testing undertaken in this study was not only the first using such large-scale urban data, it is also used first in the context of an assessment of the SDP. Moreover, this developed technique enables a direct comparative statistical analysis of the urban development of coastal settlements from before to after the construction, or major upgrade, of SCFPs. This method leveraged high resolution spatial elevation data from different points in time, before the SCFP to after, to detect statistically significant changes in urban development. Furthermore, this method facilitates temporal comparisons, identifying trends and shifts in urban growth. This geostatistical *t*-testing provides a quantitative measure of this associated urban development, offering a robust statistical foundation for assessing the impacts of SCFP on urban development.

Geostatistics were also used to project the spatial population distribution used in the ABM forwards post-2021. Firstly, to determine if the C/U of a SCFP affects population distribution, a statistical *t*-test was performed. This geostatistical test compared the changes in population distribution at the new SCFP to changes elsewhere in the settlements away from the new defence. Using a *t*-test on population data has been used before, for example, comparing tuberculosis incidence and climate (Beiranvand *et al.*, 2016), and also comparing dasymetric and even-distribution population georeferencing (Langford *et al.*, 2008). However, the use of geostatistical testing to compare population distribution changes in

relation to the C/U of a SCFP was novel. This comparison helped to identify whether there was a statistically significant change in population distribution near to a new, or majorly upgraded, SCFP. The *t*-test compared population distribution changes over time, using census data from before to afterwards the completion of SCFP, at the 0.05 significance level. From the testing if a significant change in population distribution was detected at the SCFP, then it would indicate that the construction, or major upgrade, of the defence influenced the spatial distribution of where people lived. A statistically significant change in population distribution at SCFPs would give strength to the projection of population distribution for the ABM. The projected population distribution, referred to as the *Population Share Change Rate*, which compared the population distribution from before the SCFP was constructed to afterwards, and then projected that forwards post-2021. Whilst this method of projecting population distribution using agent-based modelling was novel, ABMs have been used to simulate population distribution before in other ways, such as one simulating economic behaviours and residential decisions of populations (Li *et al.*, 2013), and one simulating land-use, which it also used to project for the next twenty years (Kocabas and Dragicevic, 2012). However, the method used within this project was the first to capture and project these processes in the context of the C/U of SCFP, and enabled a direct link between coastal flooding and population distribution, and therefore the future changes in *AfP*.

These geostatistical data fed into the development of the ABM that was designed to simulate the socio-hydrological changes and developments following the construction of a SCFP. The ABM simulates the behaviour of coastal flooding and the socio-spatial dynamics. By integrating data and patterns from the novel geostatistical analyses, the ABM captured the evolving nature, and cyclical lock-ins of urban development, population distribution, and coastal flood risk over time. This simulation allowed for the exploration of various inundation probabilities and climate scenarios, providing critical insights into potential future outcomes and effectiveness of FRM strategies. The capacity of the ABM code to incorporate socio-spatial factors alongside hydrological variables makes it a powerful tool, modelling the complex feedback mechanisms between population dynamics and environmental changes, revealing how urban development and population growth interact with flood protection infrastructure. The ABM, differing from others used in the simulation of the unintended consequences of SCFP, focuses on georeferenced population distribution, and models and projects, instead of buildings and infrastructure (Haer *et al.*, 2020), individual behaviour (Michaelis *et al.*, 2020), household behaviour (Tierolf *et al*., 2023), or community behaviour (Tonn and Guikema, 2018), for example. In an island such as the UK, with much of the population living on the coastline, assessing changes in population dynamics associated with the C/U of an SCFP is an imperative (Environment Agency, 2020).

An important concept that became apparent from the agent-based modelling was the latency period, the period between the construction of the SCFP and the eventual inundation event when the ECWL surpasses the SCFP crest height. During this period, population and urban development increased behind the defence leading to greater exposure and potential flood extent, particularly in locations with flatter topography. This concept underscores the importance of anticipating and controlling these long-term consequences in coastal FRM. Moreover, the project identified the concept of the absolute change in *AfP* from the protection construction to the eventual time at which point the ECWL surpasses the SCFP crest height (*ΔAfP*), which tends towards Portsmouth-style controlled growth and development over time, suggesting that the inhibition pathways, pre-existing land-use and population density, determines the level of the unintended impacts of the SCFP. Therefore, a key concept that emerged from this analysis is that *ΔAfP* would have a sigmoid growth curve, with sharp increases following initial upgrades, but over an extended period, eventually stabilise as population density increases. This *ΔAfP* curve, in reality, forms a cycle, with an initial construction, and following upgrades, aligning with an increase of potential flood extent and therefore increases in potential *AfP*.

5.4 Practical Implications

This section explores the practical implications of the research outputs, focusing on how the findings can inform stakeholders, influence decision-making, and lead to actionable recommendations. Emphasis is placed on achieving desirable FRM outcomes and enabling sustainable planning to create more resilience communities, as outlined in **Objective 5**.

5.4.1 Research Implications for Stakeholders

This project has revealed that SCFPs can significantly impact urban development patterns leading to an increase of coastal urban development in areas adjacent to new/majorly upgraded defences. For stakeholders and planners this means that careful consideration must be given to where and how these defences are constructed, and potential fallout in adjacent areas. Urban planners should use the insights to guide potential development away from high-risk areas, reducing future exposure to flooding. This urban management should take the form of a more broad and holistic spatial planning system (Ran and Nedovic-Budic, 2016: Mustafa *et al*., 2018), using insights from the maps and models to create safe areas for future growth; urban development is going to occur and so guiding it to safer areas should be encouraged.

A more comprehensive spatial planning system, incorporating elements of FRM, can lead to greater flood resilience for coastal communities, and present a framework for tackling the socio-hydrological processes of the unintended consequences of SCFP. Infrastructure investment would therefore also be affected, with a more comprehensive system leading to coastal development becoming financially unviable, which would, and should, lead to the promotion of green spaces and wiser land-use in areas adjacent to new, and newly upgraded, SCFPs.

The mapping and modelling also revealed that the socio-spatial dynamics of the local coastal population can be influenced by the C/U of a local SCFP. Understanding these fluctuations and developments can allow for more effective coastal flood risk planning, mitigation, and resource allocation. Practitioners can use these data to anticipate future areas of increased population density and ensure that adequate infrastructure and services are in place. The data and outcomes from this project can give local authorities a better understanding of these issues, and can therefore better allocate resources for the public services that would be required in future inundation events, such as healthcare, emergency services, communications etc. Moreover, these population socio-spatial and socio-hydrological dynamics can be developed to manage housing supply in exposed areas, potentially including incentives to relocate to safer areas.

From an understanding, mapping, and modelling of these processes, the concept of inhibition pathways were identified. These provide the potential for non-structural measures to limit these unintended consequences of SCFPs which can have the impact to form a more integrated approach to FRM that combines both structural, and non-structural, strategies to enhance resilience in coastal communities. The combination of structural and non-structural spatial planning control in Meuse, in the Netherlands, led to a 45% decrease in flood risk over three decades (Poussin *et al*., 2012), and has the potential to reduce long-term flood risk in developing countries also (Seddeek, 2023). These can be focused on resilience building, and using the insights provided by this analysis, these strategies should be aimed at improving household and individual level resilience, focusing on capacity building and further adaptation strategies. Using the information of the impacts of SCFPs on population socio-spatial dynamics, can impact future flood risk communication strategies, targeting them to specific areas, with early warning systems for example or community education.

Understanding these dynamics is essential for an island nation such as the UK, and the outcomes of this research also provide insights that can inform climate adaptation strategies, seeking to include them in a future more holistic spatial planning system. Stakeholders and decision-makers can integrate these climate projections and socio-hydrological interrelationships to ensure the long-term sustainability and resilience of coastal communities. The research findings can also inform future scenario planning, and when modelling climate risks, such as sea-level rise, and suggesting a newly constructed, or majorly upgraded, SCFP, should be taken in tandem with influences on local population and urban development to ensure that they are robust against a range of possible climate scenarios. Moreover, on a broader scale, these impacts need to be considered as part of an integration with the SDGs, and any assessment of aligning FRM efforts with them. Sustainability is aligned with resilience, and a more sustainable community arises from those with greater flood resilience. Therefore, these results provide useful insights on how a sustainable and resilient community is determined, and reflect the feedback loops apparent from the mapping and modelling analysis.

5.4.2 Strategies for Better Flood Risk Management

The findings obtained from this research provide actionable insights that can inform future policy- and decision-making in more effective coastal FRM strategies. The research outputs can help in developing regulations to control urban development and manage population growth in flood exposed areas. By understanding the dynamics of population growth and urbanisation in response to the C/U of a SCFP that can be designed to limit exposure to flood and enhance community resilience. These could be in the form of regulatory frameworks, such as controlled land zoning and building codes that restrict urban development in flood exposed areas (as in Poussin *et al*., 2012). From the research it was evident that land-use is important and has an impact on the socio-hydrological effects of new structural flood protection methods: increased urban growth cannot occur if there is not the room for this growth to occur safely, nor if it is in the wrong type of land-use. For example, there is unlikely to be any residential urban growth in parkland or industrial estates, and therefore there would unlikely be any associated increase in *AfP* in areas adjacent to the newly constructed, or majorly upgraded, SCFP. To manage this growth a new spatial planning system is proposed, one that better predicts and manages urban growth in exposed coastal areas. This would allow for greater flood resilience and ensure that new urban development is sustainable and less vulnerable to flooding. An integration of flood risk and these unintended socio-hydrological processes into land-use policy should be strategically developed to minimise coastal flood risk and ensure that future growth can be accommodated safely and sustainably.

However, this enhanced spatial planning system should not solely focus on urban and population growth, but should also include incentive programs. These could either be market-led, guiding investment to safer areas, or state-led, offering financial incentives for residents to move or through a public flood insurance policy, and then either reusing these lands as parkland or preventing new growth in exposed areas. Market-led policies, such as in Canada, allows insurance providers to set premiums that reflect flood risks, which can incentivise property owners to move to areas with lower flood risks by reducing insurance costs in safer areas, indirectly guiding development away from hazardous regions (Thistlethwaite *et al*., 2020). In contrast, a public flood risk insurance strategy aims to distribute the financial burden of flood damage across a wider population, such as in Special Flood Hazard Areas in the USA (Choi *et al*., 2024). This has the double policy effect of internalising flood risk as a direct cost to the resident, and therefore continuously propagating flood memory, whilst also being able to provide immediate financial relief post-flood to residents who could not have afforded to move away. However, the effectiveness of insurance relies on accurate flood risk assessment and the suitability of the insurance model in the face of increasing climate risk (Surminski and Eldridge, 2015). Whereas, using financial incentives to encourage AfPs to move away, and therefore limit population growth and changes in population distribution before it can begin, can potentially offer a more permanent solution to flood exposure. However, its success depends on the willingness of residents to move, level of the incentive, and the availability of infrastructure in the relocation area (Bukvic and Owen, 2016).

Using financial incentives can be costly upfront, but can save money in the longer term by reducing the need for future disaster recovery efforts and flood risk mitigation strategies. However, the initial financial cost and logistical challenges of not only moving communities, but encouraging and reaching them in the first place, can be significant (Bukvic and Owen, 2016). Although, whilst flood insurance spreads financial risk, making it more inexpensive in the short-term, it becomes increasingly more expensive and less viable as sea level continues to rise; the long-term sustainability of flood insurance schemes, such as Flood Re in the UK is uncertain if extreme weather events become more frequent and severe (Surminski and Eldridge, 2015). However, encouraging relocation can disrupt social networks and community cohesion, reducing community resilience for those who remain. Therefore, effective relocation policies should not only address financial compensation but also the emotional and social support required for resettlement and redevelopment (Seebauer and Winkler, 2020). In contrast, flood insurance maintains the social fabric of communities, and is therefore more politically palatable, by allowing residents to stay in their homes. Although, of course, this would encourage the continued habitation of exposed areas, increasing long-term coastal flood risk. Yet if operated in tandem with a

strict spatial planning policy it offers the chance to be successful at limiting urban development at the coastline, whilst also granting those who choose to remain greater resilience and the chance for recovery following a flood inundation of a coastal settlement. This improved and more holistic spatial planning system should inform, or even replace, cost-benefit analyses for the development of SCFPs. Previously intangible data such as future changes in urban development and population socio-spatial dynamics due to the C/U of a SCFP (see **Section 4.3**) should be internalised, and costed accordingly. This analysis should realise the real, tangible benefits of SCFP whilst incorporating these future potential unintended socio-spatial effects and increases in potential losses, and intangible losses in community resilience and flood memory.

However, resettlement and flood insurance is not always an option, and a stricter spatial planning scheme may not be possible due to the varied stakeholders and their often opposing stakes in coastal urban development and population growth. Therefore, it is essential to be pragmatic in these recommendations and operate with Realpolitik. Furthermore, in addition to the recommendation to use the inhibition pathways concept to reduce the unintended socio-hydrological processes of SCFP, there is also the recommendation to improve use of non-structural measures, namely community engagement (as in Tyler *et al.*, 2019). Flood memory is essential to these processes, and with a decaying flood memory comes greater coastal urban development and population at the new, or majorly upgraded, SCFP: the SDP cannot occur without a decay in flood memory (Di Baldassarre *et al.*, 2019). Therefore, if a more comprehensive spatial planning system is not yet possible, or alongside if it is, should be community engagement: strategies to engage with communities and inform about the risks of coastal flooding, as well as the benefits and limitations of SCFPs. Maintaining these links is crucial, and should include effective communication strategies that retain flood awareness and preparedness, and therefore flood memory amongst its residents. These strategies could be public information campaigns, to raise awareness of residential flood risk and promote preparedness activities, and stakeholder participation, fostering inclusive decision-making processes that directly involve local communities in flood risk planning and management. However, it has been identified that flood risk communication itself is presently insufficient, and needs to take a more heterogeneous approach, based on individual needs and requirements (Martens *et al.*, 2009). Moreover, developing simple, threat-focused messages rather than engaging with communities often leads to non-protective behaviours, such as wishful thinking, excessive reliance on governmental organisations, denial, and feelings of helplessness. Cultivating both individual and community *flood literacy,* therefore, is essential (Rollason *et al.*, 2018). At-risk populations prefer comprehensive and wide-ranging information to better grasp their personal flood risk and its consequences. Providing this information effectively empowers individuals and communities to decide for themselves what protective measures to adopt and when to act, reducing dependency on FRM authorities. Furthermore, without clear and realistic demonstrations of flood extent, AfPs struggle to gauge the potential severity of future flooding, undermining their ability to respond proactively (Rollason *et al.*, 2018). However, flood risk communication using maps of flood extents has its own inherent issues, with populations treating these maps as literal, and not an informative tool (Percival *et al.*, 2020).

5.4.3 Actionable Recommendations for FRM Strategies

This subsection outlines numerous actionable recommendations that help realise the full potential of the strategies proposed in **Subsection 5.4.2** These may be implemented through an integrated coastal plan, developing and implementing a stronger integrated coastal zone management plan and policy framework that combines structural defences, and non-structural measures to manage coastal flood risk through controlling flood exposure, such as land-use regulations (Mustafa *et al.*, 2018), and community-based initiatives to improve vulnerability and manage flood risk more effectively. This would encourage a more holistic approach, and the integration of environmental, social, and economic considerations into coastal management strategies. This comprehensive approach would require cross-sectoral collaboration, promoting policy and strategy alignment between government agencies, NGOs, and local communities to develop a more cohesive management plan. Although at present, communication between relevant stakeholders at the science-engineering-policy nexus is weak and limits effective rollout (Ballinger *et al.*, 2010), this should be resolved in order to create a cross-policy framework.

These plans should be adaptive and include planning strategies that are flexible and can be adjusted as new data and climate projections become available. This would ensure that FRM remains effective under changing conditions as the uncertainty behind which future climate pathway will develop remains. There is a direct relationship between climate projections and these socio-hydrological processes (Haer *et al.*, 2020); the more extreme the climate scenario the greater the potential flood extent will be as ECWL increases, exacerbated by flatter urban topography. Therefore, dynamic policy at the science-engineering-policy nexus, incorporating the latest climate and socio-hydrological data should be encouraged. These policies should establish metrics for assessing resilience using information and patterns gathered from this analysis and use them to guide adaptive planning efforts and establish robust monitoring and evaluation frameworks. These frameworks and policies should continuously assess and model the effectiveness of flood defence and urban development policies in tandem in order to identify and address these unintended consequences early, and limit the structural lock-in feedback loops, using data to inform policy adjustments and improvements.

In addition, community engagement should also be encouraged to stakeholder participation in FRM planning and decision-making (Ran and Nedovic-Budic, 2016), educating and involving local population in order to enhance community resilience and ensure that members of the local population are aware of the coastal flood risk and directly engage in mitigation efforts. Populations could be encouraged to participate through the creation of platforms for community participation in the planning process and also the incorporation of local knowledge and experiences into future coastal FRM strategies.

5.5 Methodological Reflections

This section investigates the methodology used within this project and provides a critical assessment thereof. These methodological reflections highlight the strengths and limitations of the geospatial analysis, census data georeferencing, and agent-based modelling techniques used to investigate the unintended consequences of SCFPs. In addition, the section discusses the challenges encountered during data collection and analysis, providing insights into how these challenges were addressed and what lessons were learnt. Moreover, it also suggests areas for methodological improvement and future research, emphasising the need for robust data, continuous model refinement, and the integration of diverse data sources to enhance the validity and applicability of the research findings.

5.5.1 Evaluation of Research Methods

This subsection provides a critical assessment of the strengths, and limitations, of the methodological approaches used within this project to investigate the complex socio-hydrological dynamics of SCFP and its unintended consequences. By examining these strengths and limitations it will provide insights into the validity and reliability of the findings and offer recommendations for future research directions.

Central to the methodology is its interdisciplinary nature, which integrates elements from geography, sociology, economics, environmental engineering, and computational modelling, to name a few. This interdisciplinary approach allowed for a more comprehensive and holistic investigation of the complex relationships between SCFP, population socio-spatial dynamics, and consequent changes within the built environment. Drawing on diverse multidisciplinary perspectives has enabled this project to capture these complex socio-hydrological interactions and feedback loops that shape coastal communities, and their risk and resilience to flooding, and aims to inform effective and adaptive FRM strategies.

Furthermore, the research has benefited from a combination of quantitative analysis, spatial modelling, and qualitative geographic case studies, providing a holistic understanding of these emergent and unintended phenomena. The use of quantitative methods such as the geostatistical analyses and agent-based modelling, facilitates a quantification of the socio-hydrological impacts of SCFP and simulate future scenarios, whilst the qualitative geographic case studies offer contextualisation and insights into the factors shaping local responses to coastal flood risk. The combination and interdisciplinarity of these methods enhances the robustness of the findings by gathering and analysing evidence from different sources and perspectives.

To complete **Objective 1**, LiDAR differential analysis and geostatistical testing was used, the use of both in this context is novel. Whilst LiDAR Digital Surface Models have been established in studying settlements for many years (e.g. Priestnall *et al.*, 2000; Yan *et al.*, 2015), DSM differencing, a process used often in physical geography, has seen limited use in this field. Using these methods to analyse the changes in the urban layout of an exposed settlement however is novel, but is built on a well-established methodology. LiDAR differential analysis provided a robust and effective technique for quantifying the changes in coastal urban development over time (see **Section 4.1** for output). By comparing high-resolution LiDAR data collected before, to after the C/U of a SCFP, the exact location and elevation changes were able to be measured, only limited in its utility by the resolution of the input rasters.

One of the key strengths of LiDAR differential analysis is its ability to capture subtle changes in the landscape with a high spatial resolution, each raster having a resolution ranging between 0.25m and 2m. Therefore, even the most granular resolutions at 2m were still effective for mapping changes in the urban landscape; it would be unlikely that any structure constructed for human use would be less than $4m^2$ (Heris *et al.*, 2020). Moreover, the EA provides these data freely, they are openly accessible, and provide almost full temporal coverage, with raster produced annually in many locations across the country.

While LiDAR data offers numerous advantages, it does come with certain limitations. One key issue is that the data was not collected firsthand, making it difficult to verify its accuracy, although the Environment Agency indicates a root mean square error of ±15cm for this data. To mitigate potential inaccuracies, each newly constructed building from the differential analysis was cross-checked and validated using satellite imagery. This step ensures that the structures are indeed present and not artefacts, which can frequently occur in LiDAR datasets due to the methods of data collection and the inherent uncertainty of using aircraft to collect these data. This can lead to *vertical displacement* which must be rectified, often this results in an entire section seemingly displaced by a few metres, which results in the differential analysis suggesting that an entire area has either been constructed or razed. Moreover, especially in coastal areas there are many transient craft, often large boats, especially around Portsmouth. These boats appear in the LiDAR differential analysis as either large increases or decreases in elevation in the middle of the sea, or occasionally in port. Without validation with satellite data it would be easy to mistake these as construction, or demolitions, in coastal exposed areas. These errors were rare though and were caught early. Future users of this methodology should be aware of these potential errors.

To complement the LiDAR differential analysis and provide statistical significance to the results, a geostatistical testing technique was implemented. One of the strengths of conducting a geospatial test is its ability to account for spatial dependence and heterogeneity, and isolating significant changes in urban development. These data revealed whether there had been a statistically significant change in urban development on the coastline arising from the construction, or major upgrade of a SCFP, and if this had been replicated in the comparative sites.

Firstly, the sample selection method used a transect along the SCFP and a random $250{,}000m^2$ raster was generated from the raster data, one from a DSM raster before and one from a DSM raster afterwards. This sample size was the largest that was computationally possible (8GB RAM - 512GB SSD) for the geostatistical test to be performed and the random sampling eliminated selection bias. This demonstrates one of the limitations of LiDAR geostatistical analyses, the testing is only as valid as the inputs, any bias introduced into the input rasters will affect the output of the test, which can influence results and interpretations. The random sample selection, however, demonstrated that at sample sites there was an increase in exposed urban development adjacent to the SCFP. It is likely that the large sample size, 500m lengths, compared to the relatively short distance of the defences, ~1.5km for Weston-super-Mare for example, captured the cores of the urban development associated with the SCFP.

Objective 2 aimed to quantify changes and drivers in coastal flood risk temporally and spatially arising from SCFP construction. To achieve this objective, census data was georeferenced, with location within the FZ as determined to count as exposure (see **Section 4.1** for output). Originating from the ONS, the use of census data provided a comprehensive and reliable source of information for assessing changes

in population distribution and associated risk factors over time. By observing demographic trends and socio-spatial indicators, areas of increased exposure to flood risk following the construction of the SCFP could be identified.

The ONS provides all census data, and the boundaries to map them onto, providing consistency over time and facilitating the longitudinal analysis of demographic and socio-spatial changes. This enabled the tracking of coastal population, housing occupancy, and the proportion of EiA residents across time from before a SCFP was constructed, or majorly upgraded, to afterwards, with a range of 1991 to 2021.

However, these data do have limitations, firstly this data was not collected first hand and relies on the robustness of the ONS. Whilst overcounting has not historically been a problem with UK censuses, a study estimated that 0.38% of the population responded twice in the 2001 census (Abbott, 2009). However, no corrections are made for these potential overcounts (Abbott, 2009). The main type of error, overcounting, most often occurs when an individual, or household, makes more than one return. For example, when a student is counted at both, their university accommodation and at their parents' home. The main causes of census overcounts are students, children of separated parents and those with second residency (Abbott, 2009). However, an error of 0.38% was not considered detrimental to the analysis. Additionally, as it would be difficult to localise this risk and therefore this error can be considered spatially uniform across all OAs. Although this is not the only error that can occur with census data: the ONS does not count transient populations or seasonal changes, or those who are undocumented. This may lead to an undercount of these populations, underrepresenting those who may be at an increased vulnerability compared to those more permanent populations, and therefore underreporting potential vulnerability for the coastal area as a whole. However, mapping of census data still remains an effective way of displaying real-world population data and evaluating their locations in regard to the coastal FZ. Geospatial analysis can compare these alterations and provide an exact comparison between the spatial distributions of population and the FZ.

Objective 3 aimed to develop an ABM to capture, and project, the socio-hydrological processes occurring around SCFP sites. ABMs offer several strengths in simulating socio-hydrological processes and assessing future scenarios of coastal flood risk. One of their key strengths is their ability to capture these complex interactions and emergent phenomena (Bonabeau, 2002), ABMs can provide detailed insights into the emergent socio-hydrological dynamics of coastal communities under various climatic and annual exceedance probability scenarios. Furthermore, this agent-process coupling approach aligns with established human-landscape modelling that integrates heterogeneous decision rules with simplified, process-based environmental modules to reproduce non-linear feedbacks and cyclic protection-development-exposure patterns (Werner & McNamara, 2007; McNamara & Werner, 2008a). In addition, ABMs allow for integration of spatial and temporal dynamics, enabling a modelling of the spatial distribution of population and SCFP infrastructure, and how they evolve over time in response to environmental change, such as sea-level rise (Han *et al.*, 2020). This spatially explicit approach is particularly valuable for assessing local impacts of SCFP and identifying areas, and populations of increased vulnerability to flooding (Haer *et al.*, 2016). Moreover, ABMs can incorporate uncertainty and variability into the modelling framework, allowing for potential future scenarios to be assessed to determine their likelihood and inherent consequences. This probabilistic approach can provide decision-makers with valuable information for future risk assessment and adaptive planning in the face of climate change and sea level rise (Erdlenbruch and Bonté, 2018).

However, there are also several limitations and challenges associated with using ABMs for coastal flood risk assessment, and this ABM should therefore be considered as a *square-one* step toward addressing the problem of interest, rather than a finished product. For example, one of the main challenges is the complexity of model calibration and validation, particularly when incorporating multiple interacting factors (Sun *et al.*, 2016). Ensuring that the ABM accurately represents real-world processes and behaviours requires extensive data collection and validation efforts, which can be time-consuming and resource-intensive. Over time, as their usage develops, ABMs are becoming more complicated (Sun *et al.*, 2016). Complicated ABMs become more difficult to initialise and parameterise, which may introduce uncertainty and bias into the ABM (Smajgl *et al.*, 2011), and by their very nature are not

transparent, reducing the ease of evaluation (Müller *et al.*, 2014), which can also lead to potential difficulties in analysing multidimensional data and outputs (Lee *et al.*, 2015; Sun *et al.*, 2016).

Whilst this study adopts a population-centric perspective, an alternative approach could focus on real-estate markets and property valuation. Viewing the SDP through such a lens may reveal how SCFP influences housing demand, pricing, and investment patterns in coastal zones, potentially amplifying socio-economic lock-ins. Literature on property markers in these areas (e.g. Filatova *et al*., 2009; Votsis & Perrels, 2016) suggests that the perceived safety from SCFPs can increase property values, reinforcing development pressure and creating new vulnerabilities.

Furthermore, the current ABM framework is limited by its reliance on population change as the primary driver of socio-spatial dynamics. For example, if the ABM were based on real estate market dynamics rather than solely population change, the model could capture property value fluctuations, investment cycles, and risk perception feedbacks, which may amplify or dampen the SDP (Filatova, 2015; Taberna e*t al.,* 2020). This highlights a key limitation of the current approach and an opportunity for future research, particularly in understanding how economic incentives and market behaviours influence settlement patterns and flood risk exposure.Potential bias was reduced by using real-world data obtained from external resources: population projection data from the ONS, SLR projections from the Met Office, and elevation data from the Environment Agency. The data outputs (**Section 4.2**) reduce three-dimensional spatial data into a single dimensional measure, enhancing analysis. Moreover, by limiting the amount of input parameters the computational demand was reduced, facilitating quicker model runs, and therefore increasing the number of simulations that could be run. Computational complexity, especially when modelling large-scale spatial systems with a high level of detail, requires substantial computational resources that may result in long simulation times, which limits the scalability and applicability of the ABM. This was a flaw to using this type of simulation: if a 1m DTM was used, for example, the ABM would not run due to a lack of processing capability (8GB RAM), and therefore the DTM rasters had to be resampled, increasing cell size and therefore reducing accuracy. Resampling rasters was done as parsimoniously as possible, aiming to retain as much accuracy as allowable, whilst also ensuring the ABM was runnable.

Despite these challenges, agent-based modelling remains a valuable tool for exploring socio-hydrological processes and associated emergent phenomena, and assessing the impacts of SCFPs under future climate scenarios. By integrating socio-spatial and environmental dynamics, ABMs have the ability to inform more robust and adaptive coastal management strategies for building resilience to coastal flooding (Haer *et al.*, 2020).

Objective 4 saw the development of a conceptual model and the creation of a Source-Pathway-Receptor (SPR) framework to encapsulate the socio-hydrological processes and phenomena that emerged from the previous analyses and data outputs from the completion of previous objectives. Conceptual models provide simplicity and clarity, simplifying complex systems into understandable components and relationships. This heuristic simplification can facilitate the clear communication of how these various factors such as government FRM policy, population socio-spatial dynamics, and flood risk interrelate (Collins *et al.*, 2018). Moreover, conceptual models provide a comprehensive and holistic perspective of an entire system, integrating data and patterns from the multiple case studies, comparative sites, and objectives. This approach helps to identify any overarching trends or feedback loops, such as the cycle of increasing population exposure, potential flood extent, and trending towards prohibitively increasing costs of structural coastal flood upgrades. Moreover, by mapping the system, key variables and their inherent interactions become apparent, for example the relations between SoP, ΔAfP (change in *AfP*), and flood memory provide insights into the drivers of flood risk, which also provides a framework for guiding analysis and helping to structure the investigation of how FRM policy decisions can lead to unintended consequences (Herath and Wijesekera, 2020).

However, the limitations of such conceptualisations should be acknowledged. Firstly, conceptual models often oversimplify, and while simplification is a strength when it enhances clear communication and representation, it comes at the cost of potential nuance and the complex interactions which may be

overlooked, and can lead to a user drawing incomplete or inaccurate conclusions. However, the conceptual model produced within this project was developed parsimoniously to keep as many parameters and processes as possible, whilst still facilitating readability and utility. Moreover, the development of a conceptual model can be subjective, relying heavily on the understanding and interpretation of the system, which can introduce unintentional bias and potentially decrease validity (Gober and Wheater, 2015). Bias was removed as much as possible by only gathering patterns and conclusions from neutral and third hand data, such as from the ONS and the EA. Although, these conceptualisations should be considered as an educated hypothesis of the coupled human-flood system operating in a generalised way, rather than a predictive tool for a particular location. This generalised conceptualisation of these processes enables the unravelling of the unintended feedback loops between the social-spatial and hydrological processes. However, the conceptual model is heuristic and it therefore should be acknowledged that the social and FRM interactions are more complex than those represented within the conceptual model (Di Baldassarre *et al.*, 2013a; Gober and Wheater, 2015).

5.5.2 Challenges with Data Collection and Analysis

During the course of this project, several challenges were encountered in both data collection and analysis phases. These challenges, while sometimes hindering progress, also provided opportunities to develop innovative solutions and refine methodologies. This subsection details some of the key obstacles faced and the strategies employed to overcome them.

The variability in geodata from the EA necessitated validation to ensure that the changes detected in the urban landscape were real and not artefacts of data collection methods. One type of error encountered when producing a DoD was created by transient objects such as boats in coastal areas which often appeared in the LiDAR data, requiring careful filtering and validation to avoid misinterpretation. Furthermore, there were errors in the rasters themselves, such as vertical displacement, whereby an area may have been displaced by a few metres for example. This was corrected by firstly identifying the vertical displacement: comparing adjacent cells that are spatially connected with an unlikely immediate change in the vertical dimension, such as on roads, and finding the difference, and taking as many samples as possible. The vertically displaced area was then extracted, the displacement corrected using a raster calculator, the area was then reintegrated into the raster using the *r.series* tool. This tool has significant advantages over the *mosaic* tool and can ensure that only the values from corrected raster samples are reintegrated.

In addition, some rasters did not come with a correct Coordinate Reference System (CRS). Mapping was conducted in the British National Grid (EPSG:27700) spatial reference system, which uses the OSGB36 geodetic datum and a single Modified Transverse Mercator projection for the whole of Great Britain. Positions on this projection are described using northing and easting coordinates, and metre distance units. This was corrected using the *Georeferencer* tool. The tool requires the manual realignment of a raster to a satellite map and adds a custom CRS, which almost exactly matches the satellite map, which can then be reprojected into the British National Grid. This data can then be verified with the raster data from alternative years that have the correct CRS.

Accurate CRS was necessary to align with geodata and other spatially aligned data, and ensured accurate running within the ABM. Due to computational capability limitations, resampling was performed, which proved to be a challenge and was not as simple as initially perceived; the geospatial NetLogo library relies on an old raster format, ASCII. This format cannot handle non-square cells, which from resampling often led to a dy/dx format instead of a square number cell size. Therefore, resampling was completed heuristically, maintaining as much quality as possible and preserving square cell size, whilst also resampling to increase the probability of a successful model run. Cell size was determined by extent, and spatial positioning, and therefore could not be automated. This process of resampling was the most time-consuming element of the project.

The challenges encountered during the data collection and analysis were mainly limited to the use of LiDAR rasters. Whilst for this analysis these issues were remedied, other less experienced users may encounter difficulties, and moreover, these issues limit the easy implementation of future automation.

However, these issues are circumnavigable and the deployment of a more strategic framework for these data should be developed, one that facilitates the automation of these processes. Better computational capability, facilitated by artificial intelligence and machine learning, could help to address the limitations, especially necessitated as geospatial big data and automation become more prevalent (Song and Wu, 2021). Moreover, the EA as a public body should work to improve their raster offering, maintaining raster resolution, CRS, and regularity with publication.

6.0 Conclusion & Outlook

In essence, the common belief in coastal FRM programmes that the exposure of an urban area depends solely on socio-economic development and natural urban growth is false. If this were true, and growth was driven by demographic change, the spatial distribution would not tend towards SCFPs. Instead, increasing population and assets tend to be located near newly constructed, or majorly upgraded, SCFP and in flood hazard areas. This dynamic perpetuates the need for the continuous upgrading of protection, leading to greater population and assets, and negating previous savings in flood risk in the long-term ─ this process has now been observed in the UK. This chapter not only summarises these findings, but also explores the future of this research, and how it can be a springboard for future discoveries in the field.

6.1 Primary Outputs

This section outlines the primary outputs and key findings, examined through the lens of their significance and potential impacts to facilitate the uptake and integration of this research along the science-engineering-policy nexus.

6.1.1 Key Messages

SCFP, whilst primarily used for reducing flood risk, can significantly influence urban development and socio-spatial dynamics in coastal areas. The construction, or major upgrade, of these flood protection measures often encourages urban growth in protected, but still exposed, areas, creating new economic opportunities but increasing flood exposure over time. However, these defences not only alter the urban fabric of the coastal settlement, but also population spatial distribution, and ultimately community resilience. The non-institutionalised interaction between structural flood protection and building and population distribution underscores the need for an integrated FRM strategy that balances immediate protection with long-term sustainability. This project has explored the multifaceted impacts of SCFP construction, or major upgrade, and examining how they shape urban expansion, influence socio-economic and socio-spatial trends, and present challenges for coastal communities.

SCFP Schemes influence Urban Development

The construction, or major upgrade, of SCFP has a significant impact on coastal urban development. Geospatial analysis and geostatistical testing revealed a statistically significant increase in urban development in all three study sites after the SCFP was constructed, or majorly upgraded. This pattern of urban growth was particularly evident in flood exposed areas. For example, in Southport, a new retail estate was completed adjacent to the new defence, only metres from the coastline. This was not observed in the comparative sites which would indicate that the presence of a flood defence can act as a catalyst for urban expansion in these areas due to a negation of residual risk and an overreliance on the SCFP.

However, the timeline of urban development varies, for instance, in Old Portsmouth, there was a five-year gap between the completion of the SCFP and new urban development in the area. Whereas, in Southport, urban development occurred almost immediately. This inconsistency highlights that whilst new structural flood defence can incentivise growth, the timing and extent of this growth can differ based on local factors, namely, space and local economy. If there is space to expand in coastal areas, then development will occur; these areas are high value. But this development will only occur if the local economy is strong; investment is unlikely to happen if the area is not already predisposed to development and there is not a high chance for increased returns.

SCFP Schemes influence Population Dynamics

The presence of SCFP influences population dynamics and flood exposure patterns. This project found that SCFP tends to lead to a greater amount of population at the defence. In Southport and Weston-super-Mare there was a noticeable population increase at the newly constructed, or upgraded, SCFP that was not present in the comparative sites. This change in population was not only nominal, but by

population distribution also: there was a statistically significant change in population distribution at the structural flood defences, compared to the rest of the town. However, this was not replicated in Portsmouth, with increases in coastal population not apparent at the SCFPs, which would suggest a limiting factor unique to Portsmouth that could limit the unintended impacts and consequences that would usually be observed. Whilst this is the first time this has been documented in the UK, it has been identified in other locations across the globe in various contexts, such as the Jamuna River in Bangladesh, deltaic flooding in the Netherlands, and the Po River in Italy.

Housing occupancy data provided the strongest link between the construction, or major upgrade, of SCFP. Both, Southport and Weston-super-Mare saw increased housing occupancy in areas adjacent to the new structural flood protection, a trend not observed in the comparative locations. Although this was not as apparent in Portsmouth, which saw an increase in household occupancy at the Old Portsmouth, but at the NPCS phases. The exception of Portsmouth proves the rule, SCFP schemes do influence population dynamics. The NPCS project protected mainly greenspace, industrial land, and residential land, with little room to grow, and in the case of NPCS Phase 1, which had room to grow, it occurred in an industrial area and so did not translate into an increase in coastal population. These were termed the *inhibition pathways*.

SCFP Schemes Influence can be Naturally Mitigated

The geospatial and comparative analyses of these impacts and consequences of SCFP schemes in Southport, Weston-super-Mare, and Portsmouth has identified two ways in which the unintended consequences of SCFP are naturally mitigating themselves, without external influence ─ the inhibition pathways. These pathways provide insights into socio-hydrological processes and suggest ways to develop more sustainable coastal FRM strategies. Essentially, these inhibition pathways act as mechanisms to limit the adverse and unintended effect of SCFP, thereby enhancing community resilience.

In both, Southport and Weston-super-Mare, the SCFP schemes led to an increase in coastal population, housing occupancy, and urban development in flood exposed areas adjacent to the defence. However, in Portsmouth, this did not occur to the same extent: despite significant infrastructure upgrades there was limited urban growth and population growth. The population density of Portsmouth makes it unique, not just amongst the study sites, but also other British towns and cities, having ~205,000 people living on a relatively small island. Therefore, space is at a premium. This comes to the first inhibition pathway, for increases in population and assets to occur, there must be land available, and for population increases to occur this land must be zoned residential. Whilst there was an increase in urban development at the NPCS Phase 1, this was in an industrial area and so does not lead to an increase in population of the area. However, say the area was primarily residential, this would not suggest an increase in population; there is a limit to density. A residential area can buffer some increase in population without external development, through for example the conversion of properties into HMOs, however, even this has a limit; it is only possible to fit a finite number of people living into one area. This is the second inhibition pathway.

Urban development and population growth could occur in Southport and Weston-super-Mare because there was room to grow. It is these mid-sized towns that will see the greatest unintended consequences of SCFP, because the land space is available and it is in the interest of the local area to expand its local economy to remain competitive, and therefore these coastal developments continue to get greenlit, especially as an area has now been perceived to be *safe* due to a structural coastal flood upgrade. This cycle will continue, until broken through policy, costs to upgrade become too prohibitive, or the inhibition pathways naturally take hold. Understanding and leveraging these inhibition pathways is essential for breaking the cycle of infrastructure lock-ins and developing adaptive strategies to manage coastal flood risks effectively.

SCFP Schemes Influence is Cyclic

From the geospatial analysis and ABM simulations, it became apparent that SCFP schemes have a cyclic influence on coastal socio-hydrological process, revealed by a pattern of recurrent phases driven by the interplay between these structural flood protection measures and the socio-spatial distribution of the local population as a coupled human-flood dynamic. Initially, the construction of SCFPs lead to a significant reduction in the probability of flooding, and therefore the flood risk of population, infrastructure, and assets. This phase of the development and construction of the SCFP, and the immediate decrease in hazard, was termed the *Protection phase*, fostering a sense of security amongst exposed residents. This decrease in flood memory leads to the secondary stage, the *Latency phase*. During this period there is a notable increase in coastal population, housing occupancy, and urban development adjacent to the newly constructed SCFP. This phase sees further declines in flood memory as communities become more accustomed to reduced flood inundation frequency and consequently, their flood awareness, preparedness, and responsiveness decrease.

As time progresses, ECWL continues to increase, the rate and extent of which is determined by climate change, gradually increasing the potential of the ECWL surpassing the crest height of the SCFP and inundation. When such an event occurs, it will affect not just more people due to the increase in population adjacent to the defence but also due to increased extent of the flood as a result of the increase in ECWL, particularly in areas with flatter topography. These populations will have a lack of or limited flood memory and therefore are vulnerable to the effects of flooding; they are no longer resilient as the flood was not expected ─ this is the third stage, the *Potential Inundation phase*. This scenario is unpalatable, and an event structurally proactive flood risk managers seek to avoid, therefore necessitating an upgrade to the SCFP ─ the *Upgrade phase*. Each upgrade initiates a new cycle, further decreasing the flood probability initially but perpetuating the long-term cycle of increased urban development and population behind the defences.

This cyclic nature is underscored by the concept of infrastructural lock-ins, whereby each upgrade, whilst providing short-term protection, inadvertently encourages further development in exposed areas, which in turn creates an escalating need for a higher SoP, which becomes increasingly expensive over time as stronger and stronger protection is required. These cycles continue until they are either financially unsustainable or mitigated by a policy that leverages the inhibition pathways, such as via land-use control, or at least one that uses non-structural measures to encourage people to become aware of their residual risk. As, if it could be distilled down to anything, flood risk communication and flood memory, or a lack thereof, is the main driver of these processes, and should be the initial target to break this cycle.

SCFP Schemes are not the Issue

From the research and results obtained in this project it is clear that there is a link between the construction of SCFPs and changes in population dynamics and urban development. The expansion of urban development at sites protected by SCFPs is, in fact, symptomatic of a deeper underlying issue related to flood risk communication and the retention of flood memory of a coastal community. Initially, the construction of these SCFPs provides a strong sense of security, significantly reducing immediate flood risks and thereby encouraging urban development in protected areas.

Over time, as the structural flood defences prove to be effective in mitigating immediate flood threats the perceived necessity for maintaining a heightened flood awareness, and maintenance of flood preparedness for flooding diminishes. This reduction in flood memory fosters a complacent attitude to flood risk, not just individually, but across the community and in FRM, which in turn leads to further urbanisation and population growth in areas adjacent to the defences. These coastal areas are valuable, and offer an intangible ecosystem service, with good views and seaside access, and therefore will be developed, especially by a mid-sized town such as Southport or Weston-super-Mare. This demonstrates that the real issue lies not with the construction of the SCFP, they are performing as designed, but in the inadequate communication and education of residual flood risk, which consequently fails to remind and prepare communities for future potential time when the ECWL surpasses the SCFP crest height.

SCFP does effectively mitigate immediate flood hazard, but their long-term effectiveness is compromised by the associated socio-hydrological behavioural responses, driven by a decrease in flood memory. Addressing this root cause should require a dual approach that integrates robust flood risk communication, to maintain flood preparedness and awareness, boosting community resilience, alongside traditional structural and non-structural flood protection measures. By sustaining high levels of resilience and flood risk literacy, communities and flood risk managers can avoid overdevelopment of flood exposed areas and support and enhance uptake of property-level resilience measures, thereby breaking the cycle of dependency on an ever-increasing level of structural flood protection. Flood risk management should tend towards pragmatism and see the real value of SCFP measures, whilst also operating participatory and inclusive flood risk communication schemes in tandem, in order to provide a comprehensive approach that ensures that structural flood protection functions as part of a broader and more resilient flood management strategy, rather than being perceived as a panacea for flood risk.

However, a more robust flood risk communication strategy does not ensure an institutionalisation of these unintended consequences, just operating at the practice side of the science-engineering-policy nexus and is just an immediate solution. More SCFPs will inevitably be constructed, or upgraded, around the UK in order to combat the threat of rising sea levels and to ensure a more sustainable and resilient future, these findings should be incorporated into policy and the creation of an integrated cost-benefit analysis and spatial planning system for coastal communities, a truly integrated coastal zone management strategy.

SCFP Schemes as a Coastal Community Element

Future SCFP measures should be considered as integral elements within a comprehensive community planning framework that incorporates both cost-benefit analysis and spatial planning. Traditionally, cost-benefit analyses for SCFPs focus on direct, quantifiable benefits such as reduced flood damage and impacts on local economy. However, this approach neglects the unintended socio-hydrological consequences of these structures, such as changes in the growth and layout of urban development and shifts in population distribution and count. The real impacts of these structural flood defences extend beyond their physical capabilities and must include, and internalise, the influence on community behaviour and urban growth.

Integrating these unintended consequences into cost-benefit analyses requires a shift towards a more holistic analysis that internalises the broader socio-spatial effects of structural flood protection. For example, the construction of a new structural flood defence can lead to an increase in urban development in the protected area due to a perceived reduction in risk, and consequently a decrease in flood memory. By incorporating these potential future scenarios into cost-benefit analysis, decision-makers can better evaluate the true costs and benefits of proposed structural flood protection, ensuring that long-term community resilience is not compromised for short-term gains.

This cost-benefit system should be geographically driven, not financially, perhaps using future agent-based modelling. This system should be capable of running *what-if?* scenarios that simulate the socio-hydrological impacts of construction of structural flood defences. By using advanced mapping and modelling techniques planners and risk managers can better estimate how new structural flood defences might influence local population dynamics and urban development patterns. Such simulations can provide critical insights into whether the construction of a proposed structural flood defence will actually be beneficial or whether it will lead to too extreme unintended consequences, and which scenarios may reduce these effects. For instance, if the system reveals that a new SCFP would lead to unintended urban development in exposed areas with residual risk, it may advise against construction or suggest alternative measures.

To achieve this the geographical cost-benefit analysis system should combine with spatial planning, often seen as an entirely separate entity, it should be integrated into it and form a geographic and socio-spatial backdrop for the *what-if?* scenarios. These integrated spatial planning and cost-benefit analysis scenarios may suggest that a SCFP is worth it if development can be guided away from high-risk areas or combined with other property-level resilience measures, thereby reducing future exposure to or risk

of flooding. This could involve the strategic designation of *safe(r) zones* for urban development to occur, to still grow the local economy, and the promotion of greenspace in areas adjacent to newly constructed, or majorly upgraded, SCFPs. By aligning spatial planning with FRM, coastal settlements can facilitate sustainable development that enhances resilience and the local economy. Additionally, having these models open and transparent can increase community engagement and education into this process, ensuring that residents remain aware of flood risks and prepared for future flood events.

In essence, proposed SCFP schemes should not be viewed as purely engineering solutions, but as community-integrated elements within a broader planning and decision-making framework. By incorporating unintended socio-hydrological phenomena into cost-benefit analyses and leveraging an integrated spatial planning system stakeholders can make more informed decisions that enhance long-term coastal community resilience and sustainability. This holistic approach, viewing the coastal zone as a whole and the SCFP as an integrated part of that, not just hydrologically but socially also, ensures that the benefits of structural flood protection are maximised whilst mitigating the potential negative impacts on coastal flood risk, urban development, and local population.

6.1.2 Key Contributions

This project addresses critical gaps in the current understanding of socio-hydrological dynamics within the context of coastal FRM in the UK. Whilst existing literature has covered the unintended consequences of structural flood protection in a fluvial environment, the specific challenges inherent to coastal environments, especially within the UK, remain underexplored. The importance of this research is underscored by the fact that a large amount of the UK population lives in coastal areas, and a vast majority of this population is protected by SCFPs. Yet any assessments of these unintended consequences in the UK have been exceptionally low, if not almost non-existent. By bridging this knowledge gap through a comprehensive analysis of three contrasting coastal case studies, this research offers valuable insights into these so-far unassessed and non-institutionalised socio-hydrological interactions, and thereby contribute to the broader understanding of coastal FRM and offer essential guidance for policymakers and practitioners engaged in FRM and coastal resilience planning.

The Project offers New Research into Coastal Socio-hydrological Processes in the UK

One of the primary contributions is to the wider research community, providing a comprehensive analysis of the socio-hydrological interactions as a coupled human-flood phenomenon in coastal environments. At present, existing literature primarily is focused on the fluvial environment, whilst the coast presents its own unique challenges and dynamics. Knowledge transfer between the two domains should be encouraged, but it is also necessary to build knowledge and develop research of the unintended consequences of SCFP also. The multidisciplinary approach adopted in this project advances the theoretical framework of FRM, emphasising the need for a more holistic and integrated understanding and policymaking regarding these coupled human-flood complex systems. The insights gained from the analyses of the three case studies offers a robust foundation for future research and practical application, particularly in the face of climate change induced sea-level rise and increased storminess.

The identification of socio-hydrologically induced cyclic infrastructural lock-in phenomena in the UK, similar to those observed in international research, is a significant finding. These lock-in cycles arise from an initial construction, or major upgrade, of the SCFPs, leading to subsequent adjacent urban development and population growth. Meanwhile, sea-level rise, which once ECWL rises past the SCFP crest height, can affect the increased population now behind the defence: the savings in flood risk created by the decrease in flood hazard are negated by the long-term increases in flood exposure. This negation is exacerbated by the increase in flood hazard due to climate change, which consequently necessitates an increased demand for a higher SoP, creating a feedback loop that influences socio-spatial distribution and urban development in coastal areas. Recognising these cycles in the UK underpins the importance of anticipating and managing the unintended long-term socio-hydrological and socio-spatial consequences of SCFP.

The Project offers New Methodologies for Research and FRM Toolkits

To obtain these findings, this research also significantly contributes to the methodological toolkit of FRM science and wider geographical methodologies through the development and application of novel geostatistical testing and the use of socio-spatial agent-based modelling to track and project these unintended socio-hydrological processes. Techniques such as raster *t*-testing and urban differential analysis provided a quantitative measure of building changes and construction, offering a robust statistical foundation for assessing the impacts of SCFP on urban growth, a key contributor to the first objective of this study. In addition, the development of the socio-spatial ABM to simulate socio-hydrological changes following the construction, or major upgrade, of a SCFP managed to dynamically capture the evolving nature of population distribution and coastal flood risk over time. This approach, focusing on socio-spatial dynamics in relation to coastal flooding, provides critical insights into potential future outcomes and the effectiveness of current structural FRM strategies under different climate scenarios. The methodological advancements of this research should act as a springboard for future studies, encouraging more holistic and integrative approaches to FRM in the UK and beyond.

The Project offers New FRM Strategies for a New Integrated Coastal Zone

From the research it is evident that SCFP significantly influences population dynamics and urban development patterns. However, the issue is not with the structural protection measures themselves per se; it is the decline of flood memory and an inadequate communication of residual flood risk. Initially these structural flood defences offer a strong sense of security, reducing immediate flood risk. However, over time, as these defences effectively mitigate flood hazard, communities become complacent, leading to an increase in urban development and population growth in areas adjacent to the defences. This phenomenon highlights the need for flood risk communication strategies that maintain flood awareness and preparedness amongst coastal population, and to ensure that the benefits of SCFP are realised, and savings in coastal flood risk are not negated by increased AfP.

To address this, future SCFP measures should be considered as integral elements with a comprehensive community planning framework that incorporates spatial planning and cost-benefit analysis. Traditionally, cost-benefit analysis for SCFPs focuses on direct, quantifiable benefits such as reduced flood damage. However, this approach neglects the unintended, and so far, non-institutionalised, socio-hydrological consequences such as changes in urban development and population distribution. By integrating these unintended consequences into cost-benefit analyses, decision-makers can better evaluate the true costs and benefits of proposed structural flood protection, ensuring that long-term resilience is not compromised for short-term gains. Advanced mapping and modelling techniques, such as ABM, can be used to simulate the socio-hydrological impacts of structural flood defences, and provide critical insights into where their construction will be beneficial or detrimental. This would enable a more geographically focused cost-benefit analysis which would also allow integration with spatial planning, enabling *what-if?* scenarios to be conducted and determine potential socio-hydrological consequences before it happens, and how to spatially plan the area to ensure the benefits of the structural flood defence are realised without compromising flood risk savings. This approach facilitates sustainable growth that benefits the local economy and reduces future exposure to flooding. By viewing proposed SCFP schemes as community-integrated elements within a broader planning framework, stakeholders can make informed decisions that enhance long-term coastal community resilience and sustainability.

6.2 Future Directions

This project has provided a comprehensive analysis of the interplay between SCFP and consequent socio-hydrological dynamics in the UK. The findings demonstrate the necessity for a multi- and interdisciplinary approach to FRM, one that transcends traditionally structural engineering focused solutions. In this effort, this project provides a springboard for future research to not only enhance the understanding of these dynamics but also to inform the development of innovative and resilient coastal flood management strategies, mitigating these potentially escalating flood risks in the face of a changing climate, rising sea level, and increased storminess.

Assessing Long-term Transitional Socio-Hydrological Dynamics

Future research should investigate the long-term socio-hydrological dynamics influenced by SCFPs expanding on, e.g., case studies, and addressing the limitations outlined earlier. From this investigation, the impacts of the unintended consequences of SCFP were observed in both, Southport and Weston-super-Mare but only some elements were observed in Portsmouth, despite the logical conclusion that a larger population would be more affected by these dynamics. However, this was not the case, in fact it was the density and zoning of Portsmouth that affected these outcomes. Therefore, there are two categories of coastal settlement: those that can be affected by these outcomes, and those that cannot or are mitigated. However, it is not entirely clear how a settlement transitions to another, of course population density and land-use must be a component, but it is not clear at which point criticality is reached. Nor is it clear what musters a settlement to reach this point, whether that be through several cycles of structural flood upgrades, and if so, how many cycles, or if it be through population density, and if so, how many people per kilometre-square, or perhaps something else entirely.

To investigate this tendency, it would be sensible to acquire a far larger sample than that in this study and research several coastal settlements, ranging from villages to metropolises. In these settlements population and urban development, and changes thereof, should be mapped across the time that SCFPs were implemented. The point at which noticeable increases in population and urban development change becomes less frequent should then be identified.

The output of the project would provide valuable insights for policymakers into which areas should strategies to mitigate these unintended consequences be focused first. Moreover, the research output would provide long-term data to the proposed spatially integrated cost-benefit analysis system providing a new exit strategy.

Assessing the Relationship of SoP Upgrades and Flood Exposure

Future research should be conducted into the relationship between the SoP of structural flood protection upgrades and the associated increases in population and development in flood exposed areas from that cycle. The research has identified the impacts of both, the construction of SCFPs and major upgrades, however, has not investigated the costs of such projects.

Due to increasing sea levels coastal settlements will want to upgrade their SCFP and consequently increase the SoP of their flood protection. However, this cannot continue indefinitely and, assuming the worst possible climate change scenario, eventually will lead to there being a need to upgrade, but not the financial ability; the costs to upgrade will become prohibitive. Therefore, there must be a relationship between the SoP and increases in flood exposure, whether that be, e.g., population or buildings. This link should be determined.

Whilst the relationship between the upgrading of an SCFP to a greater SoP and subsequent decrease of exposed populations and buildings already exists, whereby an upgrade to an SCFP will reduce the size of the hazardous area, there is not yet a quantifiable measure of the then increase of population and buildings in this protected area. This project has demonstrated that there is a link, however, there is yet no common factor or function that can be easily applied to policy and risk management strategies. A larger dataset, comprised of more case studies across a greater range of geographies, economies, topographies, will enable a pattern to emerge. Selecting a consistent AEP and changes to SoP, graphs could be plotted with time along the y-axis and ΔAfP along the x-axis, with points, each decade, for example, of how many people would be flooded compared to how many people were initially protected by the upgrade of the SCFP. These graphs can then be overlaid and averaged, providing a common equation for calculating.

Assessing the Compatibility of Fluvial and Coastal Socio-Hydrological Research

One of the key findings of the literature review was the imbalance between the fluvial and coastal research in the field of unintended consequences of structural flood protection, with fluvial case studies vastly outnumbering those focused on coastal flooding. This is in spite of the fact that population is

increasing in coastal flood exposed areas than in fluvial flood exposed areas. However, this should not be a disservice to the investigation of the unintended consequences of SCFP. In fact, it provides an opportunity for knowledge transfer between the two closely related research areas.

Future research should be conducted into how closely related these two epistemologically adjacent research areas are and to which extent conclusions and outputs from one another are transferable. This would enable growth in the comprehension of these unintended socio-hydrological phenomena in the coastal environment, and an increase in knowledge would facilitate transfer at the science-engineering-policy nexus.

The project could be conducted through a large systematic literature comparison, investigating how similar the methodologies and research output of both fluvial and coastal studies are. Alternatively, it could be completed through a comparative analysis of real-world case studies investigating how similar coastal and fluvial settlements undergoing these processes are and if the same consequences and impacts appear in both. Even a determination of how similar these outputs are, and which processes appear where, would be useful and help to restore the balance in the literature. Moreover, if the outcome of the project is that the unintended socio-hydrological impacts are the same in both, fluvial and coastal contexts, then these two environments, and their associated research, can be combined, vastly increasing the amount of research for both, and enabling better cross-comparisons, and ultimately better policy and risk management.

Exploring Economic Drivers and Market-based Dynamics

Future research could investigate how economic incentives and property market behaviours may interact with SCFPs to shape long-term socio-hydrological trajectories. Whilst this thesis adopts a population-centric perspective, previous studies has suggested that the perceived safety from SCFP may also influence housing demand, property values, and investment patterns in coastal zones. These dynamics may amplify socio-economic and socio-spatial lock-ins, reinforce development pressure and create new opportunities. Understanding these processes is critical because they represent feedback loops that operate alongside demographic change yet remain largely unaccounted for in current modelling frameworks.

A future ABM could incorporate real-estate market dynamics, such as property value fluctuations, investment cycles, and risk perception feedback, capturing a more nuanced representation of settlement behaviour under flood risk. Integrating these processes into the ABM would allow for exploration of, for example, how market signals interact with policy interventions, insurance schemes, and SCFP upgrades influence development patterns. Information for the development of the ABM would need to be collected, this could be via collecting longitudinal data on property transactions, zoning changes, and SCFP implementation across a diverse set of coastal settlements. Coupling these datasets with behavioural economic models and spatially-explicit ABMs could reveal critical thresholds where market-driven development accelerates, or even stabilises. Identifying these tipping points would enable policymakers to anticipate lock-in effects and design interventions that mitigate these unintended consequences before they take effect.

6.3 Final Thoughts

This project was guided by the overall aim, *to develop a comprehensive understanding of the unintended consequences of coastal flood defence construction (or major upgrade), in order to provide evidence-based advice to flood agencies and policymakers regarding the often unincorporated changes in coastal flood hazard, exposure, and vulnerability. Creating more resilient communities, in a changing climate, as coastal flooding grows to become one of the largest modern challenges facing the UK, and many other coastal countries.* It sought to comprehend and internalise the unintended consequences of SCFP, and to help coastal communities achieve better FRM outcomes. Whilst policy and practice changes have not been achieved, this project should be the first step into integrating these phenomena and mitigate and prevent the unintended socio-hydrological consequences of SCFP.

6.3.1 Concluding Remarks

The UK is an island nation in northwestern Europe, with around 31,500km of coastline, if islands off the mainland are also included, and 5,300,000 living in these coastal areas. Despite this, the UK has previously had no major studies conducted on it that evaluate the unintended consequences of structural flood protection, in either a coastal or a fluvial setting. For an island nation this is of concern, particularly in the face of rising sea levels and increased storminess associated with climate change. Unlike many nations, residents of the UK have limited option to retreat further inland to be away from the sea, with the farthest point being only 72km away from the nearest tidal water. Therefore, to protect residents, infrastructure, and assets it is essential to look towards SCFP.

However, these SCFPs come with a fundamental issue: they are large overbearing structures that influence the communities around them. The SCFP performs then as designed, and brings protection from coastal flooding, but this decrease in flood probability has the unintended consequences of creating a misconception of flood risk, leading communities to neglect their residual risk. This process can negate short-term gains against flood risk from decreased flood hazard by increasing coastal flood exposure through changing socio-spatial and urban development distribution in the long-term.

This project identified that the UK, like other coastal countries, endures the unintended consequences of SCFP. The study showed that a newly constructed, or majorly upgraded, SCFP leads to an increase in coastal population and new development adjacent to the defence. However, this increase in population and development is not replicated elsewhere across town; in fact, both of these factors appear to tend towards the SCFP, increasing flood exposure in the area. Moreover, it is the cyclic nature of these unintended consequences that exacerbates these outcomes further, even if local development was intended, the structural flood defence must be upgraded again as sea levels rise, and once development has been constructed, FRM strategies and spatial planners are powerless to stop an increase in population in the area.

However, these processes can be managed, with immediate strategies such as better flood risk communication to maintain flood memory, or increase flood awareness, preparedness, and responsiveness for improving resilience in the meanwhile. Whilst also, these processes can be self-terminating; at some point the population density will reach a critical point at which there can simply be no more people in the area without major reconstruction, or in areas with strict zoning, residential development cannot occur, or greenspace can be designated to prevent such expansionist development. Therefore, these unintended consequences of SCFP can be managed.

In the longer term, the management of the unintended consequences of SCFP should be sought to gain the benefits of structural flood protection without inducing the unintended socio-hydrological consequences. This should start with mitigation from the very beginning and the internalisation into cost-benefit analysis of the future costs due to socio-hydrological processes. Moreover, cost-benefit analyses should move away from traditional methods and become a more spatially integrated process, looking at how a proposed SCFP may lead to increases in AfP and development during and beyond its design life. This new system should include potential future *what-if?* scenarios which include spatial planning strategy, and can give output advice. For example, the system may advise that a SCFP is cost-effective if no more development is allowed in the area adjacent to it, at which case this land should be designated, e.g., as greenspace complementing the FRM strategy and providing additional socio-economic and environmental benefits.

Whatever the strategy employed, the unintended consequences of SCFP in the UK should be mitigated and unintended socio-hydrological processes internalised into the determination of whether to construct SCFP. The institutionalisation of the socio-hydrological processes presents an opportunity to create a truly integrated coastal zone, considering each individual element as part of a wider coastal system delivering a more sustainable and resilient future for its residents and communities.

6.3.2 Reflection

Completing this project proved to be challenging, but rewarding. Each objective required new thinking, and there were many hurdles along the way that appeared insurmountable at the time. The biggest was the integration of spatial data into the ABM, which whilst simple in theory was difficult to implement due to the relative incompatibility between the input and the base: NetLogo, the tool used for ABM creation and running, could not allow no-data to be a value. This is understandable when conducting conceptualisations, however, geospatial data by its very nature contains data in some areas and not in others. For example, a vector of population distribution is not going to have data of population in the English Channel or Liverpool Bay, nor is a raster, as a discrete data type, going to have information about every metre, depending on the resolution. Enabling concordance between these two systems was achieved via coding, ensuring that the rasters and the ABM cells well aligned, and by manipulating geospatial data, created new values of zero in areas previously undefined.

However, once the ABM was up and running and tested and verified it provided valuable insights, revealing the medium- to long-term impacts if the unintended consequences of SCFP are allowed to run on. This then shed light on the sequence of processes, starting with the initial construction of the structural flood defence, the increase of population and urban development behind the defence, and then the potential inundation. It was this time when the ECWL surpassed the SCFP crest height, and the change compared to the construction in the first place that then provided the link between Southport and Weston-super-Mare, and suggested a cyclicality to the processes: the upgrade of a SCFPs begins the cycle again, culminating in another upgrade, and so on. Whilst the occasional failure of Portsmouth to show these processes was initially surprising, when it was framed from the perspective of the cyclicality of these unintended socio-hydrological processes it became apparent that Portsmouth, with its long history of habitation, densification, and network of SCFPs presented a future scenario for both, Southport and Weston-super-Mare and that these processes may be finite. It was this discovery that enabled the inhibition pathways to be uncovered, leading into the idea to incorporate spatial planning into the final proposal, a new spatially integrated cost-benefit analysis system that considers the proposed SCFP and integral element of coastal communities, instead of being socially disconnected. This proposed approach will enable future flood risk managers to ensure more sustainable and resilient coastal communities.

The largest takeaway from this project is that coastal communities should be considered holistically as complex integrated systems. A cost-benefit analysis of proposed SCFP based on economic and financial considerations fails to include many of these social dynamics. To the residents the seawall, or whichever the structural project, becomes a part of their community, something they see each day, and so it would be difficult for them to believe that this monolith could fail and so despite the warnings they will always feel *safe*, often mistakenly, and this unfortunately leads to casualties, and in extreme situations, deaths, in the event of structural or major functional failure of these defences. It is the duty of FRM authorities to manage these risks and prevent these catastrophes; floods will always occur, that cannot be changed, but how we respond to them can. In the future we must learn to live with flooding, not in fear of it and seek to control it and project outwardly as much. One of the key challenges of the 21st century will be how we respond to climate change and the impacts it brings; we cannot afford to bring a 20th century mindset to these modern challenges. A sustainable and resilient coastal zone is possible, and it does not mean the cessation of SCFP projects, nor does it mean to rely exclusively on non-structural measures: we must simply find a secure balance between the two. These challenges will become ever present as the climate changes, sea level rises, and storminess increases. However, it is up to us, society, practitioners and decision-makers, how we will respond collectively.

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Appendix A

The Safe Development Paradox in Flood Risk Management: A Critical Review

Abstract

Flooding accounts for a quarter of natural disasters yet it is responsible for more than half of the victims of all natural disasters. Climate change and continued urban development in flood-prone areas exacerbate these risks. Flood risk management authorities often turn to hard engineering to reduce risk and minimise losses, which can be effective when operating within design capacity. However, a changing climate and rapid urbanisation lead many authorities to upgrade existing defences which often result in infrastructural lock-ins with potential of unintended consequences; increased safety can induce increased development, ultimately leading to higher losses during breaching or overtopping. This process has been referred to as the *Safe Development Paradox*: a cross-cutting science-policy-practice challenge that requires a systematic understanding in the context of climate change and the United Nations Sustainable Development Goals. This paper provides an evidence base on the Safe Development Paradox based on a critical review of the state-of-the-art through a quantitative analysis of peer-reviewed literature since 2000, highlighting key knowledge gaps and issues hindering progress in addressing the Safe Development Paradox. The published research is compounded by a lack of consistent terminology, limited geographic distribution of case studies (Global North-focused), and skewed emphasis on fluvial flooding. The limited knowledge on the Safe Development Paradox in the coastal context leaves coastal environments/communities locked into these processes vulnerable. The review identifies potential directions for increasing knowledge and tackling the Safe Development Paradox: enhancing knowledge transfer through engaging with adjacent sciences (e.g. socio-ecology), collaborating in multidisciplinary teams (e.g. social scientists, civil engineers etc.), including grey literature (e.g. government reports), integrating current frameworks (spatial planning) and emerging strategies (nature-based solutions) with flood risk management practices, and educating the public to the limitations of hard defences and engaging them as stakeholders to improve resilience and sustainability.

Key words:
Safe Development Paradox, Coastal Flooding, Flood Risk Management, Spatial Planning, Coastal Resilience, Climate Change.

Introduction

Natural hazards, such as floods, cause severe disruption to daily life, often leading to significant socio-economic losses and environmental impacts worldwide (Sharples et al., 2016; Natho and Thieken, 2018). Climate change and continued development in hazard-prone areas will exacerbate these risks (Gbadegesin et al., 2011; Leichenko, 2011). Therefore, mitigation of these hazards is essential to protect communities and infrastructure from current and future risks. Numerous strategies are employed in practice for hazard mitigation: ranging from flood control channels for flash floods (Sanders and Grant, 2020) to levees for fluvial flooding (Vora et al., 2018) and seawalls for coastal flooding (Betzold and Mohamed, 2016). Structural measures are often selected and are historically the preferred countermeasures in many parts of the world to combat flooding. However, these measures often lead to infrastructural lock-ins (path dependency) and may produce unintended consequences as increased safety can induce increased development, ultimately leading to higher losses in the event of failures of the structural safeguards in place (Kates et al., 2007). This process has been diversely referred to as the *Safe Development Paradox* (Burby, 2006), *Levee Effect* (Di Baldassarre et al., 2015), and *Safety Dilemma* (Di Baldassarre et al., 2018). Throughout this paper the Safe Development Paradox shall refer to all three keyphrases for the process described. Even outside of flood risk, structural measures are often used in an effort to mitigate natural hazards with similar challenges in tackling the Safe Development Paradox: strengthening infrastructure in earthquake zones (Erdik and Durukal, 2007); larger dams for avalanches (Höller, 2007); stronger housing design in tornado zones (Ripberger et al., 2018); and the fire paradox, whereby preventing forest fires against a steady increase in fire risk and subsequent wildfire damage (Arévalo and Naranjo-Cigala, 2018), to name a few.

Existing hazard mitigation infrastructure can be effective at reducing risk and minimising losses when operating within its design capacity. However, communities are increasingly vulnerable to hazard events larger than the planned capacity of the structure due to climate change, extreme events and a lack of knowledge on the limitations of defences and an increasing amount of assets placed behind the defence as time passes without a flood event (Burningham et al., 2007; Collenteur et al., 2014). Furthermore, urban layout may have changed since construction, placing infrastructure and populations at risk that did not exist when the initial design was drawn (Sanders and Grant, 2020). These mitigation structures can create a false sense of safety that leaves these exposed populations unaware and underprepared to cope with potential disasters (Burningham et al., 2007). Furthermore, as the climate changes, low-probability, high-consequence events may happen more frequently, placing an inexperienced population at risk (Van Aalst, 2006; Merz et al., 2009).

A solution to combat changing natural hazards is to upgrade existing mitigation structures, however this merely produces a new design capacity, albeit higher than previously (Hallegatte et al., 2013). There is a common belief in flood risk management programmes that the exposure of urban areas depends solely on socio-economic development and natural urban growth. However, numerous scholars, starting with White (1945), have shown that increasing levels of flood protection can result in unintended consequences: increases in flood exposure, and, in turn, vulnerability (Tobin, 1995; Burby, 2006; Kates et al., 2006; Burton and Cutter, 2008; Montz and Tobin, 2008; Ludy and Kondolf, 2012; Di Baldassarre et al., 2013a). If the growth of coastal urban areas were driven by population increases alone

the spatial distribution of new settlements would be the same (Di Baldassarre et al., 2013b). The cycle continues as greater populations and high-value assets are placed either within or in close proximity of at-risk areas, producing a need for even greater structural strengthening and/or heightening (or expansion) of existing structures. These structures also interact with natural processes (e.g., morphological evolution of river deltas) altering the physical characteristics of hazards and hence their likelihood (Welch et al., 2017). This can ultimately lead to the lock-in effect of a cycle of continued and prohibitively expensive investments on maintenance and upgrades of defence. Whilst the defences may be built to a high-standard, such as the Dutch coastal policy of constructing flood defences with a 10,000 year return period (Winter et al., 2012), inevitably disasters do happen. A term from economics, 'tail risk' is the chance of a loss occurring due to an extremely rare event. However, over a long enough period, nothing is unlikely, and it was this that led to the financial crisis in 2008 (Acharya et al., 2010), and in the event of an unexpected defence failure, loss of human life and economic damages, as demonstrated by Hurricane Katrina and its impacts in New Orleans (Burby, 2006).

Of the many natural hazards, flooding presents some of the most frequent and with severe consequences: it impacts more people than any other natural disaster (Banks et al., 2013). Approximately, three quarters of natural disasters over recent decades were water related, of which flooding accounts for a third. More than half of the victims of natural disasters were as a result of a storm surge, a river flood, or a flash flood. Between 1985 and 2003 approximately 300,000 people lost their lives as a result of flooding. On average, the global death toll varies between 5000 and 15,000 casualties annually (Douben, 2006). Even those areas protected by flood protection measures are still vulnerable: floods in New Orleans (2005), Thailand (2011), France (2011), and Germany (2021) were characterised by a large number of breaches in flood defences. Overloading the protection system can lead to multiple failures, exacerbating the extent of the flooding and the damage (Jonkman and Schweckendiek, 2015). Overtopping of flood defences in New Orleans resulted in hundreds of deaths and billions of US dollars worth of damage (Burby, 2006). The Thailand floods caused the national and global economy to be disrupted for several months and caused a significant drop in economic growth (Jonkman and Schweckendiek, 2015). The 2011 French coastal floods resulted in the deaths of 50 people (Lumbroso and Vinet, 2011). In both the New Orleans and France floods elderly people were the most vulnerable (Lumbroso and Vinet, 2011; Jonkman and Schweckendiek, 2015). Such disasters emerge when natural hazards meet vulnerable communities and infrastructure, with mitigation efforts often needed to keep destructive waters away from people or vice-versa or a combination of both. Whilst present in other hazards, viewing the Safe Development Paradox through the scope of flooding provides an ideal foundation to examine the ever-present and unsustainable conflict between risk management and spatial planning practices. The Safe Development Paradox presents a cross-cutting science, policy, and practice challenge that requires a systematic understanding in the context of climate change and the United Nations Sustainable Development Goals (SDGs). The aim of this paper is to provide an evidence base on the Safe Development Paradox in the context of flood risk management. The paper also provides insights on the key knowledge gaps in the Safe Development Paradox and potential ways forward for addressing them.

Methods

To assess the collective evidence on the Safe Development Paradox, a critical review of the published literature was conducted within the scope of flood risk management. The review examined the state-of-the-art through a quantitative analysis of the peer-reviewed scientific literature by applying the advanced search function of Web of Science and Scopus (following a similar approach outlined in Sudmeier-Rieux et al., 2021). Google Scholar was used to corroborate the results returned by both databases. For transparency, searches were conducted in the United Kingdom. To ensure reliability, only peer-reviewed articles were considered, and grey literature was disregarded. The Safe Development Paradox and alternative terms (i.e. Levee Effect and Safety Dilemma) were used in query strings to ensure that all relevant papers were brought up by the search. Inclusion for further analysis was based on a pre-examination of the title, keywords, and abstract of the papers returned by the search based on a pre-defined filter and inclusion/exclusion criteria (see Appendices). Furthermore, due to the extremely sporadic nature of usage of these terms in the twentieth century, and to ensure continued applicability and scientific relevancy, only articles from 2000 until the end of 2021 were reviewed. Reviewing only complete years ensures that there is fair representation across time. However, the background context has been informed by selected articles published prior to this period, highlighting the emergence and evolution of the Safe Development Paradox and other key interrelated concepts, but these do not feature in the analysis. The Safe Development Paradox and alternative terms (i.e. Levee Effect and Safety Dilemma) were used in query strings to ensure that all relevant papers were brought up by the search. The overall review approach, rationale, and specific criteria behind the article selection are provided in more detail in the Appendices section.

Results and Discussion

A total of forty-two articles, regarding the Safe Development Paradox in the context of flood risk management, were analysed for this review. Articles were assessed within five themes: year published, terminology, types of hydrological hazard, geographic distribution, and their recommendations for addressing the Safe Development Paradox.

Temporal Distribution

The amount of literature increased throughout the research period, with the greatest sustained increase beginning 2013, with the exception of the 2016-2017 lull (**Figure A1**). Meanwhile other closely related concepts emerged: Integrated Water Resource Management (IWRM) developing in 2006, from a UN and Global Water Partnership taskforce (Petit, 2016); Coupled Human and Natural Systems (CHANS) emerging in academia in 2007 (Liu et al., 2007); and then Socio-hydrology in 2011 (Sivapalan et al., 2011). Literature peaked and troughed as these closely related concepts emerged. However, following the emergence of Socio-hydrology, paper publications followed a steady increase, with many following publications being completed in that context (e.g. Di Baldassarre et al., 2013). The increase in publications is also coupled with a general increase in flood risk literature (**Figure A1**), rising steadily since the turn of the century.

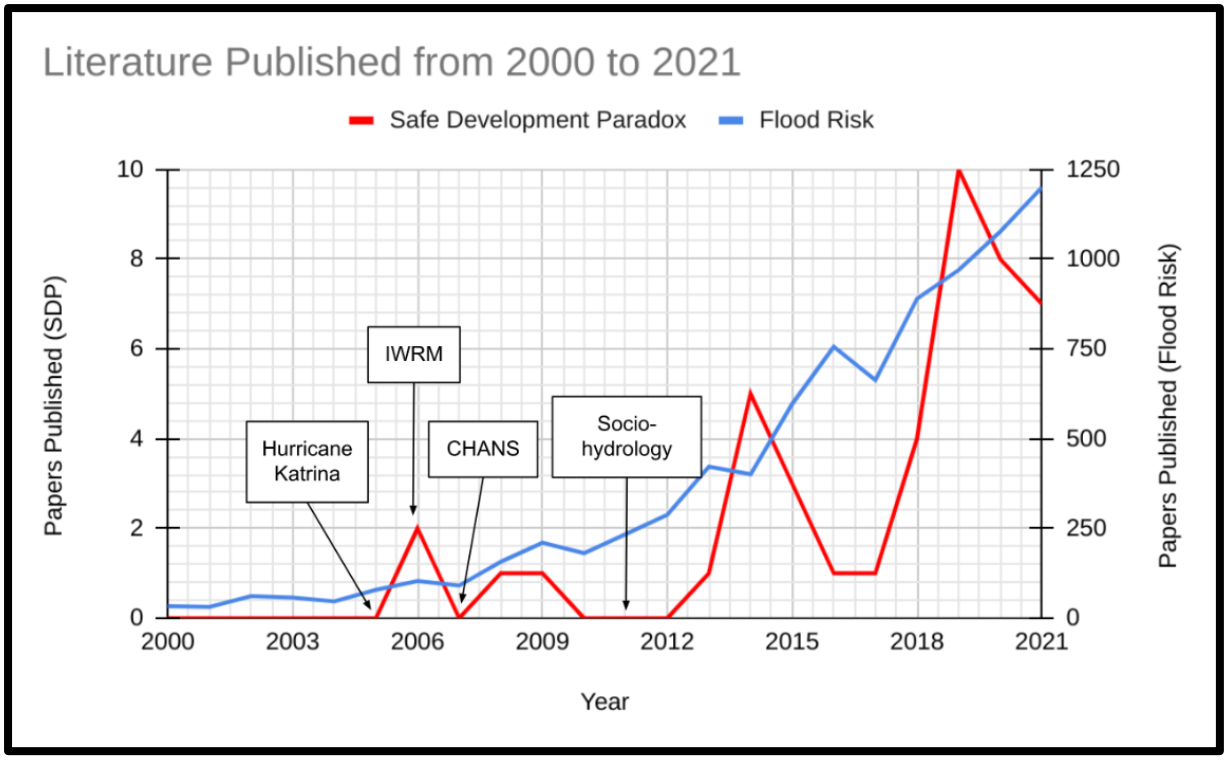


Figure A1: Distribution of Safe Development Paradox/ Levee Effect/ Safety Dilemma articles and general flood risk articles over the review period (2000 to 2021), with Hurricane Katrina and emergence of new related concepts are annotated.

Terminology

In the literature, three terms are used to refer to the same process of unintended consequences of hard flood defence: *Safe Development Paradox* (Burby, 2006), *Levee Effect* (Di Baldassarre et al., 2015), and *Safety Dilemma* (Di Baldassarre et al., 2018). When reviewing the graphs it should be noted that some articles use the terms interchangeably within the same article (e.g. Di Baldassarre et al., 2018). Originally, the *Safe Development Paradox* was used, and it continued to be used steadily throughout the 2010s (**Figure A2**). However, the term was superseded by the *Levee Effect*, a term often used by authors approaching the lock-in cyclical process from a socio-hydrological perspective (e.g. Sivapalan et al., 2015). In fact, authors who use the term *Safe Development Paradox* often discuss a real-world case study and recommend better planning control to solve the lock-in effects (e.g. Stevens et al., 2009). Whereas, authors that use the *Levee Effect* focus on recommending further developing the scientific knowledge and engage more in modelling and theory (e.g. Angelo et al., 2020). These connections are discussed in greater detail in later sections.

At present, the *Levee Effect* is the most used term for this process (**Figure A2**), and partly reflects the growth of socio-hydrology, as well as flood risk literature in general. However, the *Levee Effect* has the chance of being misused, when discussing how a levee may affect the studied topic, such as Saito and Fukuoka (2011) discussing the effects of natural levees. Likewise, use of the *Safety Dilemma* was broad, and at present, there is only one paper in which the *Safety Dilemma* was used in the context of the Safe Development Paradox for this paper (i.e. Di Baldassarre et al., 2018). In contrast, once grey literature has been discarded,

the *Safe Development Paradox* was used in the correct context in each paper that mentioned it.

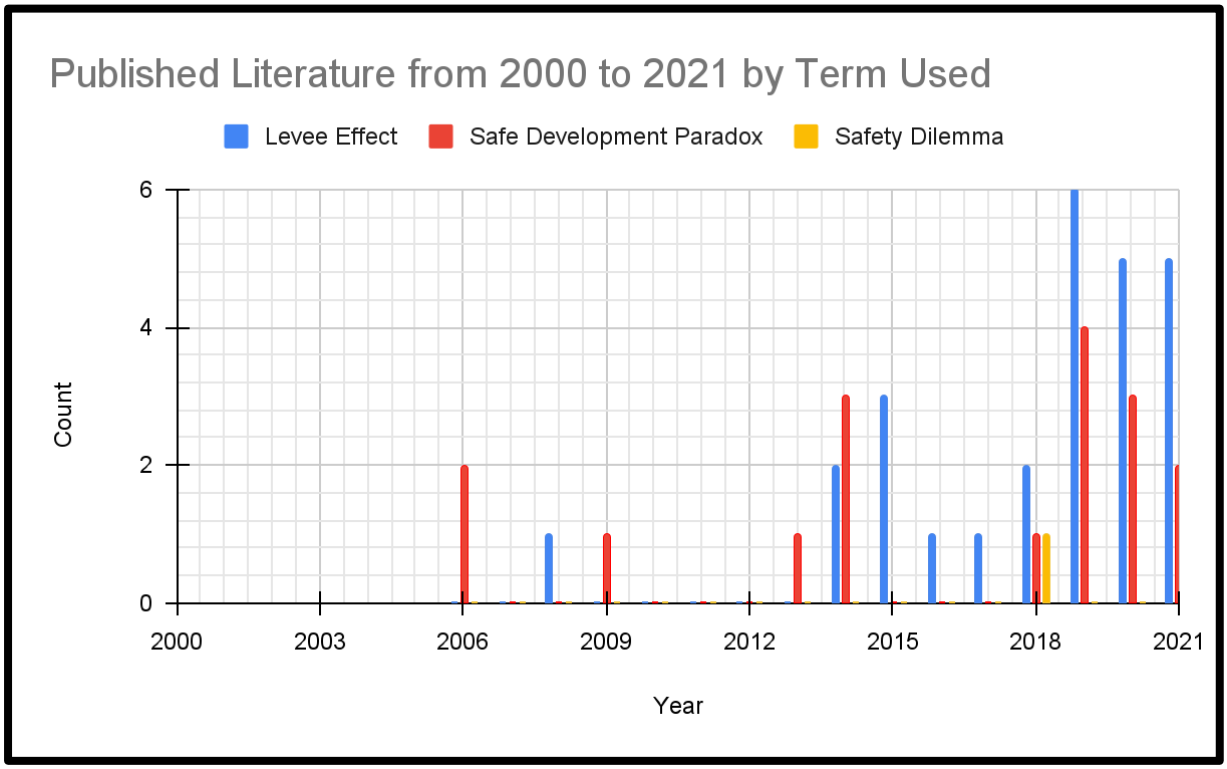


Figure A2: Distribution of published literature regarding the lock-in cyclical process, referred to in this article as the *Safe Development Paradox* over the review period (2000 to 2021). Articles have been divided by the terminology used.

Hydrological Hazard

The majority of the literature focuses on fluvial flooding and the unintended lock-in consequences thereof: fluvial flooding consists of **69%** of analysed literature, coastal flooding is **17%**, and papers studying both account for **14%**. Of the thirteen papers that discuss coastal flooding, seven specifically focus on coastal flooding; the other six discuss both, fluvial and coastal flooding (**Figure A3**). These papers were often review papers or compared between case studies (e.g. Tyler et al., 2019). Consequently, disregarding papers that discuss both, as mentioned previously, for every paper that investigates the Safe Development Paradox in a coastal setting, there are four in a fluvial setting. The majority of purely coastal flooding papers used the term *Safe Development Paradox*; only one used the term *Levee Effect*. Moreover, all articles that specifically focus on coastal flooding study case studies in Western countries: nine studying an American case study, and one studying a European case study. Ultimately, research attempting to understand the interplay between coastal flooding and the Safe Development Paradox is lacking.

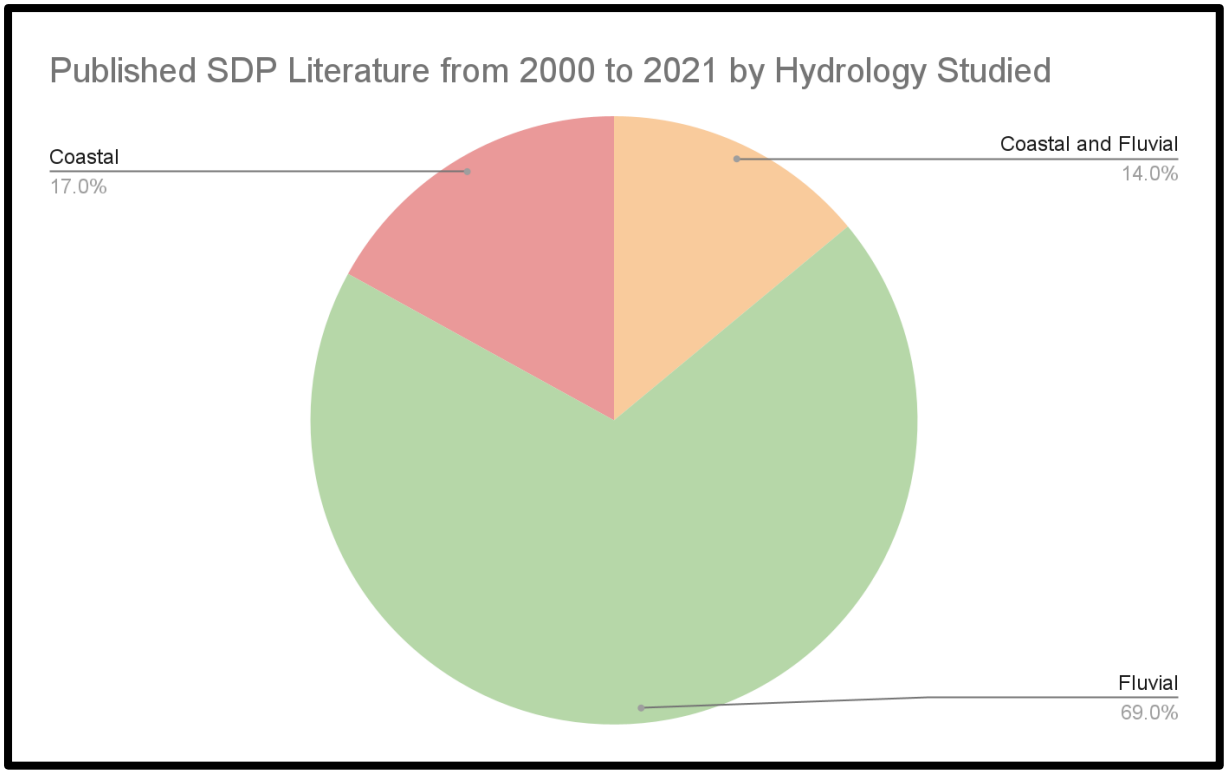


Figure A3: Published literature, divided by the hydrological hazard studied (coastal or fluvial) over the review period (2000 to 2021).

Between 1970 and 2010, populations in North America have observed a 13.3% population increase in coastal flood risk areas, compared to a 0.5% population decrease in fluvial flood risk areas (Jongman et al., 2012). Similar changes occurred across continents of the Global North during the same period: in Europe, a 6% increase in populations at risk of coastal flooding compared to a 0.3% decrease in those at risk of fluvial flooding; and in Australasia, a 2.5% increase in populations at risk of coastal flooding, compared to a 0.7% decrease in those at risk of fluvial flooding (Jongman et al., 2012). New populations moving to the coast lead to increased communities, assets, and infrastructure placed on the coastline than would have been there previously. In coastal areas locked into the cycle of the Safe Development Paradox, additional populations can further drive this process.

Geographic Distribution

The majority of published articles focus on cases in the USA (25), followed by Italy (10), Bangladesh (6), Austria (4), China (4), and Germany (4). Then France and the Netherlands (3 each) and Denmark, Ireland, Australia, Croatia, Greece, India, Portugal, Spain, and the UK (2 each). All other countries highlighted in the map below have one paper each (**Figure A4**). Use of the term *Safe Development Paradox* was more predominant in papers from the USA, with **65%** of papers using the term researching cases in the country. In contrast, use of the term *Levee Effect* was more predominant in European case studies. Europe and the USA were the predominant locations studied in the literature. These locations of the Global North are often more economically developed than others in the Global South (Lees, 2020), and represent a greater proportion of the literature (**Figure A4**). This may be due to the Safe Development Paradox not being a present issue in many places in the Global South where major structural flood defences are limited, with an opportunity for lessons from the Global

North for avoiding the development of similar infrastructural lock-in conditions (Scussolini et al., 2016). Furthermore, a focus on English-language articles may have contributed to this skew.

Developed economies may have already fallen into the infrastructural lock-in effects of the *Safe Development Paradox*, and may already be trapped in a cycle of an ever-increasing need for defences (Di Baldassarre et al., 2015). Lock-in conditions can lead to high levels of flood protections and highly urbanised floodplains (Di Baldassarre et al., 2018). In contrast, as emerging countries develop, the effects of the Safe Development Paradox have begun to take hold. In Bangladesh, for example, it has been identified in areas where flood protection has been structurally developed, population density has increased greatly over the past decades as well as the number of assets exposed to flooding (Ferdous et al., 2020). Flood mortality rates associated with the 2017 flooding in Bangladesh were lower in the areas with a lower protection level (Ferdous et al., 2020). As countries continue to develop, more research regarding the Global South will provide a better understanding of emerging flood risk management approaches and the challenge/opportunities for safe and sustainable development in hazard-prone areas.

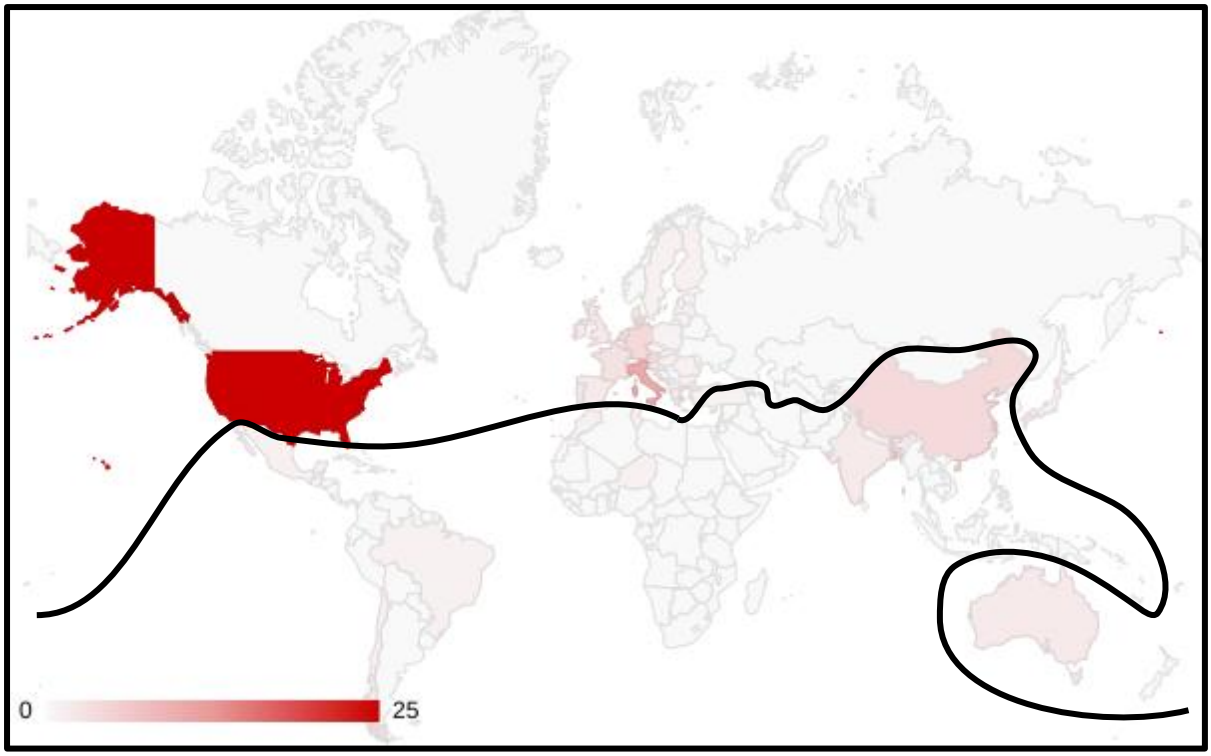


Figure A4: Geographic distribution of locations studied in literature by country (2000 to 2021). The map features the Brandt line, delineating the Global North and Global South (Lees, 2020). Colour scale represents the paper count.

Literature Recommendations

The majority of analysed literature recommends *Improved Science* when discussing how to break the lock-in cycle of the Safe Development Paradox (**Figure A5**). Proponents for improving knowledge and bettering the science surrounding the process come from a range of backgrounds: the *Levee Effect* (e.g. Michaelis et al., 2020) and the *Safe Development Paradox* (Armstrong and Lazarus, 2019) terms are used in papers recommending it, both in fluvial and coastal settings, and from a variety of locations around the world. With the majority of papers being produced focussing on the Global North, increasing Safe Development Paradox knowledge may be produced from studying a greater number of case studies, especially those from developing nations in the understudied Global South.

In total, twelve articles suggested stronger *Planning Control* as a way to alleviate the Safe Development Paradox, with two-thirds of these articles focussed on case studies in the USA. Better *Planning Control* would require the use of governing bodies to coordinate urban development to ensure that the placement of populations and infrastructure did not increase following the upgrade of a flood defence (Hutton et al., 2019; Richert et al., 2019). Other papers suggested *Improved Communication* of flood risk would break the Safe Development Paradox (e.g. Fox-Rogers et al., 2016), some suggested *Improved Modelling* to understand risk and the impacts of new development better (e.g. Barendrecht et al., 2017), others proposed using flood *Insurance* policies to provide an incentive for building more sustainably (e.g. Haer et al., 2020). In some papers, *Relocation*, as part of a mixed package, was the best suggested way to ultimately combat the Safe Development Paradox and the effects of climate change (e.g. Ferdous et al., 2019). One paper suggested that better *House Defences* were the most appropriate measure in order to reduce the cost of flood defences

and at-risk houses should have flood doors and windows (Ventimiglia et al., 2020). However, not all papers offered a recommendation.

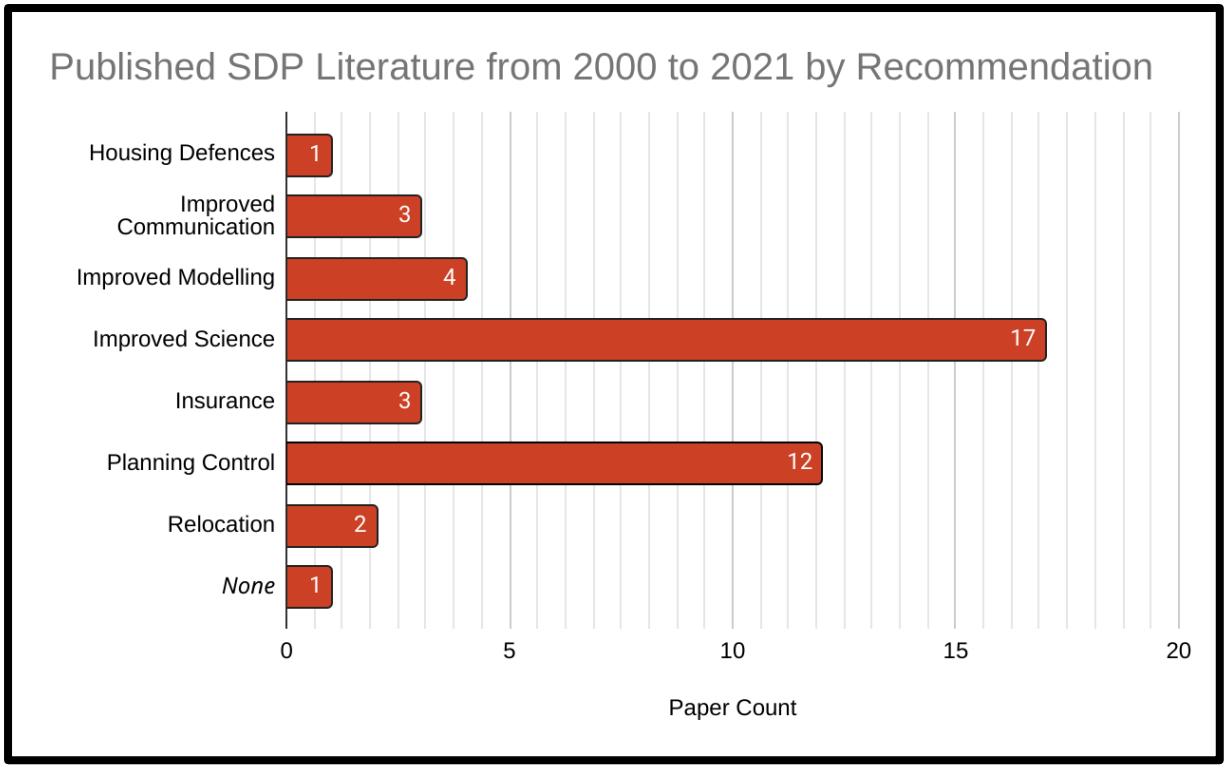


Figure A5: Published analysed literature divided by the key recommendation provided by the authors in the papers published throughout the review period (2000 to 2021).

Conclusion and Outlook

Upgrading flood defences continuously can result in a greater number of populations and assets being placed in areas prone to flooding than located there previously. Without control, this results in a cyclical, ever-increasing amount of infrastructure and complacent populations placed in at-risk areas and unprepared for large-scale flood events that could overwhelm existing defence systems. This process and its unintended consequences and feedbacks is referred to as the *Safe Development Paradox*. Whilst research into the Safe Development Paradox has increased since the first paper in the selected research period was published in 2006, only forty-two papers were published over the review period.

The increase in Safe Development Paradox literature follows a general upwards trend in flood risk publications, and is partly as a result of growing knowledge of climate change and its effects upon sea levels and rainfall patterns. Since the emergence of socio-hydrology in the early-to-mid 2010s, most of the literature has been created within this sphere, and this is a trend that is most likely going to continue as socio-hydrology establishes itself. However, approaching the phenomenon from different angles has created ambiguity and division within the community regarding the terminology. To date, the Levee Effect supersedes the Safe Development Paradox as the most often used term, with the Safe Development Paradox often used most by authors studying American case studies. Whereas, the Levee Effect is used more often in European case studies and by authors approaching the topic

from a more human, sociological side. A number of studies also tend to use these terms interchangeably. This often results in divergence or duplication of research, highlighting the need for using consistent terminology when researching these processes. This will also avoid the use of non-standard terminology, which may not have been picked up by this review. Semantically, the Levee Effect appears to present the phenomena as one-directional and linear as opposed to its true cyclicality. Furthermore, the term may restrict study to areas defended by levees, and may hinder knowledge transfer within natural hazard sciences; the process of the Safe Development Paradox has been identified in alternative lock-in cycles of unintended consequences of structural protection. Therefore, the Levee Effect may be understood to be a subset of the wider Safe Development Paradox. Consistent future use of the term the Safe Development Paradox when discussing the unintended consequences of building/upgrading structural flood protection would help avoid confusion or misinterpretation and advance the scientific understanding of the issue.

Moreover, the ratio between fluvial and coastal flood hazard papers does not reflect population changes; in contrast populations in the Global North are generally growing quicker in areas at risk of coastal flooding, than in areas at risk of fluvial flooding. Lessons can be transferred from fluvial studies to future studies in coastal settings. In addition, further studies are needed to better understand the growing challenges in coastal zones and promote the sustainability of coastal communities in the face of rising sea-levels and increased storminess. These issues are not limited to disparities between the amount of literature by hydrology as case studies in the Global South are also limited. Most papers review locations in the USA, followed by locations in Europe. Then, as developing nations grow and begin to encounter the initial effects of the Safe Development Paradox, lessons can be learnt from existing situations in developed countries. This will enable communities in the Global South to grow sustainably and minimise flood risk through better land-use management practices. Indeed, the most frequent recommendation of the published research was to further develop the science and expand knowledge of the Safe Development Paradox.

Investigating coastal flood Safe Development Paradox situations in the Global South can also help expand knowledge and diversify the case studies to strengthen the science. Furthermore, the success of strategies used to break the Safe Development Paradox in existing communities can demonstrate how to further sustainable flood risk management. Better planning control emerged as the second most noted recommendation and following an expected growth in Safe Development Paradox knowledge, will provide the best method of managing the *Safe Development Paradox* and preventing its emergence in developing communities and nations. Therefore, it is the recommendation of this paper for further research into the Safe Development Paradox to include more case studies of areas that are at-risk of coastal flooding. Future work should also aim to diversify current knowledge; the Global South requires particular attention to better understand the effect of varied underlying contexts in spatial planning and flood risk management practices.

In essence, further research into the Safe Development Paradox can bring benefits at the science-policy-practice nexus. The twenty-first century will bring novel challenges and increasing confrontation between human infrastructure and an increasingly uncertain and strengthening pattern of natural hazards. The Safe Development Paradox will be one of these challenges, and future flood risk management strategies must seek to incorporate

these emerging feedbacks. Addressing these changes will need to begin within the scientific sphere and begin with consistent terminology and increasing the breadth of case studies and Safe Development Paradox data. Knowledge transfer from adjacent scientific branches (i.e. socio-ecology), between fluvial and coastal case studies, and on a broader scale between nations and economies, can enable sustained growth of the field and better understanding of the issue. For such cross-cutting scientific and policy issues, future research may choose to include grey literature, such as government reports and investigations to bolster Safe Development Paradox knowledge. In the policy sphere, governments and flood risk management agencies should look towards managing the Safe Development Paradox using existing frameworks, such as reformed spatial planning practices to enable sustainable growth, or emerging alternative risk management methods, such as nature-based and blue-green infrastructure solutions instead of heavy and sole reliance of large-scale hard flood defences. This highlights the urgent need for further research to investigate these solutions and work with flood risk management agencies to identify the best outcomes and methods of tackling the Safe Development Paradox, whether that be generally, or site-specific. Furthermore, as a cross-cutting issue, such research will require multi-disciplinary approaches, incorporating, for example, social scientists to aid with spatial planning solutions, or civil engineers to aid with nature-based solutions. Ultimately however, the end goal will be to break the Safe Development Paradox and untangle continued urban growth from unsustainable reliance on flood protection. Putting research and policy into practice would also require civil and political will. Raising awareness of the limitations of hard defences and involving those at risk in management decisions as a stakeholder is an essential component of flood risk management. In the face of climate change, it is also vital to increase household adaptation and flood resilience to create more sustainable communities, as well as to engage communities and the wider public and governments in the conversation of future flood risk and its management.

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Appendices

Information within this section provides further detail on the overall method and specific protocol used to conduct the review. Research papers were first obtained from the Web of Science and Scopus databases. This was then expanded through further search in Google Scholar.

These papers were then filtered using the query strings outlined in the table below (**Appendix AA**). To ensure relevancy, only peer-reviewed articles between the years 2000 and 2021 were directly involved in the analysis. Literature prior to 2000 informed the background context. Only literature pertaining to flooding were chosen to be included in order to provide a scope and context for the paper. As the contents of the papers could not be directly searched, indicators were relied on. In Scopus, the search function *TITLE-ABS-KEY* provided a good proxy for searching within the documents; it searched for mentions of the keyphrase in the title, the abstract, and the author keywords. For consistency, the same method was also applied to the Web of Science database, translating as *TI=("_") OR AB=("_")* OR *AK=("_")*, whereby underscores represent the keyphrase being searched and OR is a Boolean operator. Other search parameters, such as *ALL=("_")*, were not used as prior iterations had shown that this yielded a high number of returns that were not directly relevant.. Therefore, after several trials the Title, Abstract, Author Keywords parameters provided the most accurate results. These papers were then manually checked to ensure they discussed the Safe Development Paradox.

Database	Query Strings
Web of Science	AK=("Safe Development Paradox") OR TI=("Safe Development Paradox") OR AB=("Safe Development Paradox") Timespan=2000-2021 AK=("Levee Effect") OR TI=("Levee Effect") OR AB=("Levee Effect") Timespan=2000-2021 AK=("Safety Dilemma") OR TI=("Safety Dilemma") OR AB=("Safety Dilemma") Timespan=2000-2021
Scopus	TITLE-ABS-KEY (“Safe Development Paradox”) AND PUBYEAR > 1999 TITLE-ABS-KEY (“Levee Effect”) AND PUBYEAR > 1999 TITLE-ABS-KEY (“Safety Dilemma”) AND PUBYEAR > 1999

Google Scholar	“Safe Development Paradox” “Levee Effect” “Safety Dilemma”

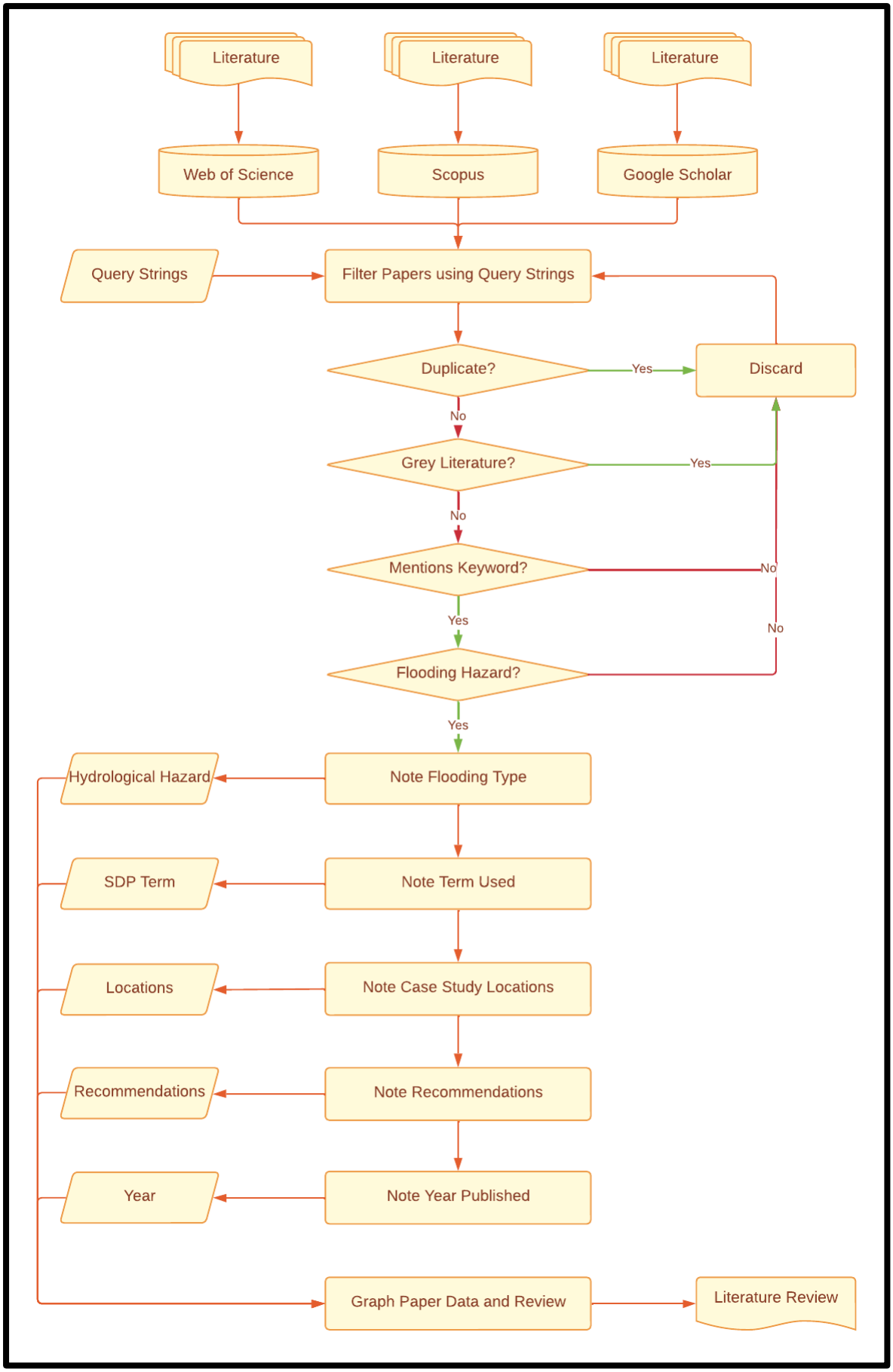
Appendix AA: Query Strings used in the identification of literature.

In total, the three query strings returned 58 papers from Scopus and 37 papers from Web of Science. Duplicates between the searches were removed. Using Google Scholar, 16 relevant papers were identified that were not returned by either Scopus or Web of Science database queries. To ensure relevancy, literature was included only if there was a primary focus on the Safe Development Paradox, Levee Effect, or Safety Dilemma demonstrated by the phrase occurrence in the title, abstract or as a keyword.. The papers were then filtered using the method described in the flowchart below (**Appendix AB**). The inclusion criteria for the filters are described in the table below (**Appendix AC**). Of the papers, grey literature was excluded due to the difficulty of estimating the quality of the studies, and many were discarded for not discussing the human-water coupled process referred to as the Safe Developmnent Paradox within this paper. The remaining 43 then proceeded through the filter. Only one paper was discarded at the *flooding hazard?* stage, as it was referring to the Safe Development Paradox processes in earthquake zones.

The remaining 42 papers were then sorted into categories within five themes: the year published, the terminology used, the local hydrology (fluvial or coastal) presenting the hazard, the geographic location of the case studies used in the article, and the final recommendations of the paper. The inclusion criteria for each category is presented in the table below (**Appendix AD**). Relevant information gathered from the articles was recorded and provides the data for the **Results and Discussion** section of this paper.

In order to provide a context for the growth of Safe Development Paradox literature against flood risk literature in general, the amount of papers published per year was determined. The query strings used for the searching of these papers are displayed below (**Appendix AE**).

Literature used within the analysis are recorded at the end of the document (**Appendix AF**).



Appendix AB: High-level flowchart of data collection from literature review.

Filter	Criteria
Grey Literature?	• Has not been peer-reviewed • Is not from a journal • Governmental/ NGO report
Mentions Keyword?	• Mentions the Safe Development Paradox, Levee Effect, or Safety Dilemma in the abstract, title, or as a keyword
Flooding Hazard?	• Discusses the hazard of flooding in the context of the *Safe Development Paradox* • Flooding impacts a population or infrastructure

Appendix AC: Inclusion criteria for initial paper filters.

Theme	Category	Inclusion Criteria
Local Hydrology	Fluvial	• River case study • Mentions fluvial flooding • Features riverside settlements
	Coastal	• Coastal case study • Mentions coastal flooding • Features coastal settlements
Terminology	Safe Development Paradox	• Uses the term the *Safe Development Paradox* when referring to the cycle of unintended consequences as increased safety can induce increased development, ultimately producing increased losses.
	Levee Effect	• Uses the term the *Levee Effect* when referring to the cycle of unintended consequences as increased safety can induce increased development, ultimately producing increased losses.
	Safety Dilemma	• Uses the term the *Safety Dilemma* when referring to the cycle of unintended consequences as increased safety can induce increased development, ultimately producing increased losses.
Geographic Distribution	Nation	• A case study from a paper is set in this nation.

Theme	Category	Inclusion Criteria
Recommendation	Housing Defence	• Suggests improved housing-level defences as the best way to break the Safe Development Paradox. • Suggests personal responsibility as the best way to end the Safe Development Paradox.
	Improved Communication	• Suggests improved risk communication between an authority and residents as the best way to break the Safe Development Paradox. • Suggests including local residents as stakeholders in flood risk management discussions as the best way to break the Safe Development Paradox.
	Improved Modelling	• Suggests improved flood risk or sociological numerical modelling will help to break the Safe Development Paradox. • Suggests improved flood risk or sociological conceptual modelling will help to break the Safe Development Paradox.
	Improved Science	• Suggests increasing knowledge of the Safe Development Paradox will break it. • Suggests more case studies will be required in order to break the Safe Development Paradox.
	Insurance	• Suggests using an insurance system to encourage sustainable development and break the Safe Development Paradox.
	Planning Control	• Suggests developing a better spatial planning system can help to break the Safe Development Paradox. • Suggests using the current planning system to limit at-risk infrastructure and populations construction.
	Relocation	• Suggests moving infrastructure and populations away from at-risk areas is the best way to break the Safe Development Paradox.
	None	• Offers no recommendation on how to break the Safe Development Paradox.

Appendix AD: Inclusion criteria for sorting categories.

Database	Query Strings
Web of Science	AK=("Flood Risk") OR TI=("Flood Risk") OR AB=("Flood Risk")
Scopus	TITLE-ABS-KEY (“Flood Risk”) AND PUBYEAR > 1999

Appendix AE: Query strings used in the identification of Flood Risk literature.

Authors	Year Published	Title	Journal	DOI
Akhter, F., Mazzoleni, M., Brandimarte, L.	2021	Analysis of 220 Years of Floodplain Population Dynamics in the US at Different Spatial Scales	Water	10.3390/w13020141
Anderson, W., Kjar, S.	2008	Hurricane Katrina and the levees: taxation, calculation, and the matrix of capital	International Journal of Social Economics	10.1108/03068290810889198
Angelo, C., Fiori, A., Volpi, E.	2020	Structural, dynamic and anthropic conditions that trigger the emergence of the levee effect: insight from a simplified risk-based framework	Hydrological Sciences Journal	10.1080/02626667.2020.1729985
Armstrong, S., Lazarus, E.	2019	Reconstructing patterns of coastal risk in space and time along the US Atlantic coast, 1970–2016	Natural Hazards and Earth System Sciences	10.5194/nhess-19-2497-2019
Auerswald, K., Moyle, P., Selbert, S., Gelst, J.	2019	HESS Opinions: Socio-economic and ecological trade-offs of flood management-benefits of a transdisciplinary approach	Hydrology and Earth System Sciences	10.5194/hess-23-1035-2019
Barendrecht, M., Viglione, A., Blöschl. G.	2017	A dynamic framework for flood risk	Water Security	10.1016/j.wasec.2017.02.001

Authors	Year Published	Title	Journal	DOI
Burby, R.	2006	Hurricane Katrina and the Paradoxes of Government Disaster Policy: Bringing About Wise Governmental Decisions for Hazardous Areas	The ANNALS of the American Academy of Political and Social Science	10.1177/0002716205284676
Collenteur, R., De Moel, H., Jongman, B., Di Baldassarre, G.	2014	The failed-levee effect: Do societies learn from flood disasters?	Natural Hazards	10.1007/s11069-014-1496-6
Cutter, S., Emrich, C., Gall, M., Reeves, R.	2018	Flash Flood Risk and the Paradox of Urban Development	Natural Hazards Review	10.1061/(ASCE)NH.1527-6996.0000268
Di Baldassarre, G., Kemerink, J., Kooy, M., Brandimarte, L.,	2014	Floods and societies: the spatial distribution of water-related disaster risk and its dynamics	WIREs Water	10.1002/wat2.1015
Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L., Blöschl, G.	2015	Debates—Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes	Water Resources Research	10.1002/2014WR016416
Di Baldassarre, G., Kreibich, H., Vorogushyn, S., Aerts, J., Arnbjerg-Nielsen, K., Barendrecht, M., Bates, P., Borga, M., Botzen, W., Bubeck,P., De Marchi, B., Llasat, C., Mazzoleni, M., Molinari, D.,	2018	Hess Opinions: An interdisciplinary research agenda to explore the unintended consequences of structural flood protection	Hydrology and Earth System Sciences	10.5194/hess-22-5629-2018

Authors	Year Published	Title	Journal	DOI
Mondino,E., Mård, J., Petrucci, O., Scolobig, A., Viglione, A., Ward, P.				
Domeneghetti, A., Carisi, F., Castellarin, A., Brath, A.	2015	Evolution of flood risk over large areas: Quantitative assessment for the Po river	Journal of Hydrology	10.1016/j.jhydrol.2015.05.043
Eakin, H., Lemos, M., Nelson, D.	2014	Differentiating capacities as a means to sustainable climate change adaptation	Global Environmental Change	10.1016/j.gloenvcha.2014.04.013
Ferdous, M., Wesselink, A., Brandimarte, L., Di Baldassarre, G., Rahman, M.	2019	The levee effect along the Jamuna River in Bangladesh	Water International	10.1080/02508060.2019.1619048
Ferdous, M., Di Baldassarre, G., Brandimarte, L., Wesselink, A.	2020	The interplay between structural flood protection, population density, and flood mortality along the Jamuna River, Bangladesh	Regional Environmental Change	10.1007/s10113-020-01600-1
Ferreira, S., Hamilton, K., Vincent, J.	2013	Does development reduce fatalities from natural disasters? New evidence for floods	Environment and Development Economics	10.1017/S1355770X13000387
Fox-Rogers, L., Devitt, C., O'Neil, E., Brereton, F., Clinch, J.	2016	Is there really “nothing you can do”? Pathways to enhanced flood-risk preparedness	Journal of Hydrology	10.1016/j.jhydrol.2016.10.009
Georgic, W., Klaiber, H.	2021	A Flood of Construction: The Role of Levees in Urban Floodplain Development	Land Economics	10.3368/le.98.1.071520-0106R1

Authors	Year Published	Title	Journal	DOI
Gissing, A., Van Leeuwen, J., Tofa, M., Haynes, K.	2018	Flood levee influences on community preparedness: a paradox?	Australian Institute for Disaster Resilience	10.3316/agispt.20180827001081
Haer, T., Husby, T., Botzen, W., Aerts, J.	2020	The safe development paradox: An agent-based model for flood risk under climate change in the European Union	Global Environmental Change	10.1016/j.gloenvcha.2019.102009
Harwood, S., Carson, D., Wensing, E., Jackson, L.	2014	Natural Hazard Resilient Communities and Land-use Planning: The Limitations of Planning Governance in Tropical Australia	Journal of Geography & Natural Disasters	10.4172/2167-0587.1000130
Herreros-Cantis, P., Olivotto, V., Grabowski, Z., McPhearson, T.	2019	Shifting landscapes of coastal flood risk: environmental (in)justice of urban change, sea level rise, and differential vulnerability in New York City	Urban Transformations	10.1186/s42854-020-00014-w
Hutton, N., Tobin, G., Montz, B.	2019	The levee effect revisited: Processes and policies enabling development in Yuba County, California	Journal of Flood Risk Management	10.1111/jfr3.12469
Jiao, S., Li, W., Wen, J.	2021	Spatiotemporal changes of manufacturing firms in the flood prone Yangtze Delta	Environmental Hazards	10.1080/17477891.2021.1988502
Kates, R., Colten, C., Laska, S., Leatherman, S.	2006	Reconstruction of New Orleans after Hurricane Katrina: A research perspective	PNAS	10.1073/pnas.0605726103
Lazarus, E., Ziros, L.	2021	Yachts and marinas as hotspots of coastal risk	Anthropocene Coasts	10.1139/anc-2020-0012
Malecha, M., Woodruff, S., Berke, P.	2021	Planning to Exacerbate Flooding: Evaluating a Houston, Texas, Network of	Natural Hazards Review	10.1061/(ASCE)NH.1527-

Authors	Year Published	Title	Journal	DOI
		Plans in Place during Hurricane Harvey Using a Plan Integration for Resilience Scorecard		6996.0000470
Mallakpour, I, Sadegh, M., AghaKouchak, A.	2020	Changes in the exposure of California's levee-protected critical infrastructure to flooding hazard in a warming climate	Environmental Research Letters	10.1088/1748-9326/ab80ed
Massazza, G., Bacci, M., Descroix, L., Ibrahim, M., Fiorillo, E., Katiellou, G., Panthou, G., Pezzoli, A., Rosso, M., Sauzedde, E., Terenziani, A., De Filippis, T., Rocchi, L., Burrone, S., Tiepolo, M., Vischel, T., Tarchiani, V.	2021	Recent Changes in Hydroclimatic Patterns over Medium Niger River Basins at the Origin of the 2020 Flood in Niamey (Niger)	Water	10.3390/w13121659
Mazzoleni, M., Mård, J., Rusca, M., Odongo, V., Lindersson, S., Di Baldassarre, G.	2019	Floodplains in the Anthropocene: A Global Analysis of the Interplay Between Human Population, Built Environment, and Flood Severity	Water Resources Research	10.1029/2020WR027744
Michaelis, T., Brandimarte, L., Mazzeloni, M.	2020	Capturing flood-risk dynamics with a coupled agent-based and hydraulic modelling framework	Hydrological Sciences Journal	10.1080/02626667.2020.1750617
Mochizuki, J., Mechler, R., Hochrainer-Stigler, S., Keating, A., Williges, K.	2014	Revisiting the ‘disaster and development’ debate – Toward a broader understanding of	Climate Risk Management	10.1016/j.crm.2014.05.002

Authors	Year Published	Title	Journal	DOI
		macroeconomic risk and resilience		
Richert, C., Erdlenbruch, K., Grelot, F.	2019	The impact of flood management policies on individual adaptation actions: Insights from a French case study	Ecological Economics	10.1016/j.ecolecon.2019.106387
Sisi, J. Li, W., Wen, J,	2021	Spatiotemporal changes of manufacturing firms in the flood prone Yangtze Delta	Environmental Hazards	10.1080/17477891.2021.1988502
Sivapalan, M., Blöschl, G.	2015	Time scale interactions and the coevolution of humans and water	Water Resources Research	10.1002/2015WR017896
Stevens, M., Song, Y., Berke, P.	2009	New Urbanist developments in flood-prone areas: safe development, or safe development paradox?	Natural Hazards	10.1007/s11069-009-9450-8
Toshiharu, K., Narantsetseg, C.	2019	Long term changes in flooding around Gifu City	The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences	10.5194/isprs-archives-XLII-3-W8-421-2019
Tyler, J., Abdul-Akeem, S., Noonan, D.	2019	A review of the community flood risk management literature in the USA: lessons for improving community resilience to floods	Natural Hazards	10.1007/s11069-019-03606-3
Undurraga, R., Vicuña, S., Melo, O.	2020	Compensating Water Service Interruptions to Implement a Safe-to-Fail Approach to Climate	Water	10.3390/w12061540

Authors	Year Published	Title	Journal	DOI
		Change Adaptation in Urban Water Supply		
Ventimiglia, U., Candela, A., Aronica, G.	2020	A Cost Efficiency Analysis of Flood Proofing Measures for Hydraulic Risk Mitigation in an Urbanized Riverine Area	Water	10.3390/w12092395
Wasson, R., Jain, V., Katuri, A., Lahiri, S., Parkash, S., Singhvi, A., Varma, N., Bansal, P., Chuah, C.	2019	Riverine Flood Hazard: Part B. Disaster risk reduction in India	Proceedings of the Indian National Science Academy	10.16943/ptinsa/2018/49502
Yu, D., Chang, H., Davis, T., Hillis, V., Marston, L., Oh, W., Sivapalan, M., Waring, T.	2020	Socio-hydrology: an interplay of design and self-organization in a multilevel world	Ecology and Society	10.5751/ES-11887-250422

Appendix AF: Peer-reviewed literature used within the analysis.

Appendix B

Assessing Coupled Human-Flood Interactions using LiDAR Geostatistics and Neighbourhood Analyses

Abstract

The paper integrates well-established methods from other spheres of flood risk assessment in a novel way to explore the Safe Development Paradox (SDP) phenomenon in coastal settings, which is currently poorly understood. The study contributes to addressing this knowledge gap based on key insights from three contrasting UK case studies: Portsmouth, Weston-super-Mare, and Southport. Differential analysis of historic LiDAR Digital Surface Models (DSMs) was used to identify temporal changes in the urban landscape to create a DSM of Difference (DoD), representing elevation change between two locations over time. Geostatistical testing, specifically *t*-tests, were then used to infer statistical significance of changes in urban development. The findings reveal a consistent pattern: following completion or improvement of large-scale structural coastal flood defences, there is subsequent, and statistically significant, increases in urban development within/near flood-exposed areas across all three case studies, contrary to the limited flood-exposed development in neighbouring settlements during the same period. The results also show that, on average, new urban development occurs approximately 2.75 years after the completion of coastal flood defence projects. The study emphasises the importance of context-specific and neighbourhood analyses, considering settlement size, economy, and extraneous factors influencing the nature of development to better understand the SDP's long-term implications. The discussion also highlights the challenges of coastal (re)development, emphasising the economic constraints and viability issues faced by these and other similar coastal areas, particularly in the context of climate change and sea-level rise, highlighting the need for continued research in coastal SDP. The paper contributes to this effort, providing valuable insights into the coupled human-flood interactions induced by structural coastal flood protection. The use of LiDAR and geostatistical analyses offers a robust method for identifying and understanding the SDP, shedding light on the complexities of structural coastal flood protection, urban development, and coupled human-flood interactions.

Keywords

Safe Development Paradox; Flood Risk Management; Structural Flood Protection; LiDAR; GIS; Raster Statistics.

Introduction

Across the world, the number of urban residents has increased from 700 million, in 1950, to 4.35 billion at present. Meanwhile, sea level has risen, on average, 20cm over the past 2 centuries, with the rate of change accelerating to 3.2mm/yr in the early 21st century (Siegert, 2015). Meanwhile an estimated 687 million people live within the ≤ 5m Low Elevation Coastal Zone globally (MacManus et al., 2021). The rapid growth of urbanisation, coupled with rising sea levels, results in tensions at the coastal zone, the interface between the two spheres (land and the sea), raising long-term sustainability challenges. Yet, population growth and flood-exposed development continues (Hallegatte et al., 2013), increasing the likelihood of catastrophic consequences.

For example, Hurricane Katrina cost US$200 billion in economic losses (King, 2005), a disaster Burby (2006) argues was wholly avoidable and predictable. Exacerbated by well-intentioned yet short-sighted decisions to make hazardous areas 'safe', a process the author calls 'safe development'. The fundamental idea behind safe development is that land, exposed to natural hazard, can be made profitable by the construction of defences leading to 'productive use'. The paradox lies within the reasoning of planning authorities justifying a defence project, would lead to new urban development, infrastructure and populations that would have not been there if the levee system was not constructed, creating a feedback loop. The Safe Development Paradox (SDP) refers to the issue of seeking to protect communities from flooding while simultaneously ensuring that these protective measures do not inadvertently lead to increased exposure or vulnerability in the long-term (e.g., Breen et al., 2022).

Interventions geared towards vulnerability reduction or adaptations, may in fact, inadvertently reinforce, redistribute, or create new sources of vulnerability (Magnan *et al*., 2016; Eriksen *et al*., 2021). In many areas coastal defences are built to protect people and assets against flooding, which in turn encourage further development in high-risk areas. Case studies illustrate what may happen when policymakers are focussed on avoiding near-term disruption at the cost of reducing long-term future risk; there is a preference for incremental adaptation that preserves existing behaviours over 'transformative adaptation' that will disrupt embedded societal norms (Eriksen *et al*., 2021). Structures that preserve existing flood behaviour can lead to extreme, low probability flooding, with devastating consequences that are not evenly distributed spatially or socially. For example, in the case of the New Orleans levee breach, it was identified that pre-existing socio-economic conditions played a key role in the inability of certain social groups to respond to the disaster well and cope with the flooding (Masozera *et al*., 2007).

Furthermore, public pressure limits the growth of new ideas within coastal risk management, strongly preferring structural options (Mallette *et al*., 2021). Hence, there is a bias towards structural defence policy, partly due to shorter government cycles. For example, in the UK when increased funding for risk management was announced by the Department of Environment, Food, and Rural Affairs in 2007, it was depicted as a funding increase for flood defence, rather than money for impact reduction (Harries and Penning-Rowsell, 2011). Harries (2008) argues that humans feel comforted when 'protected' from nature. The framing of the human-nature dynamic is not easily changed, thus only repeated, and severe, events prompt change in representations and associated behaviours (Kates, 1971). Furthermore, there is a growing shift toward an increase in community consultation in public sector decision-making (Nye *et al*., 2011). Whilst the democratisation of environmental policy is encouraging, it tends to attract the involvement of those most directly and personally affected by the environmental issue at hand. Thus, policymakers perceive this group as 'the public' and their opinions as representative of the population, leaving flood management policies skewed towards those views that concentrate on the elimination of risk in the localities of the groups (Harries and Penning-Rowsell, 2011).

This manifests as a common belief in flood risk management (FRM) programmes that the exposure of urban areas depends solely on socio-economic development and natural urban growth. Had the expansion of urban growth been solely driven by demographic change, the spatial distribution would

remain unaffected and not tend towards structural flood defences (Di Baldassarre *et al*., 2013b). Instead, growing populations and higher value assets tend to be located near to the newly constructed defence and in exposed areas. This dynamic perpetuated the need for continuous upgrading of the pre-existing defences, leading to great population and asset placement, and negating previous decreases in flood hazard with an increase in exposure, and potentially vulnerability (Tobin, 1995; Burby, 2006; Kates *et al*., 2006; Burton and Cutter, 2008; Montz and Tobin, 2008; Ludy and Kondolf, 2012; Di Baldassarre *et al*., 2013a). This can ultimately lead to the lock-in effect of a cycle of continued and prohibitively expensive investments on maintenance and upgrades of defence. Whilst the defences may be built to a high-standard, such as the Dutch coastal policy of constructing flood defences with a 10,000 year return period, inevitably even the most improbable events do happen, and disaster can occur. Even those areas protected by flood protection measures are still exposed and potentially vulnerable: floods in New Orleans (2005), Thailand (2011), France (2011), and Germany (2021) (Fekete and Sandholz, 2021) were characterised by a large number of breaches in flood defences.

Research investigating this emergent human-flood coupled phenomena is heavily biassed towards the impacts of fluvial flooding, so much so that for every journal paper that investigates the SDP in a coastal setting, there are four published in a fluvial setting (Breen *et al*., 2022). Greater research into this area can bring benefits at the science-policy-practice nexus. This nexus approach provides a holistic perspective, becoming increasingly necessary due to escalating issues at the intersection between human populations and infrastructure and an increasingly uncertain and strengthening natural hazards. Addressing such cross-cutting issues as the SDP, must begin within the scientific sphere, which must increase its base in order to enhance knowledge transfer to policy and practice. This expansion should increase the breadth of case studies to more locations, such as those outside of the Global North, and to those within coastal environments (Breen *et al*., 2022). Moreover, due to the inherently broad nature of the SDP, interdisciplinarity is required, enabling and facilitating knowledge transfer between scientific branches also, engaging scientists from a diverse range of fields.

It is therefore of ever-growing importance to expand the pool of case studies and knowledge of the SDP, to aid translation from research to policy and practice. The application of LiDAR (Light Detection and Ranging) presents a widely used method of fast and remote data collection, allowing for changes in the built environment in flood risk areas to be quickly identified. This allows for faster processing, risk identification, and detection of the hallmarks of the SDP: increasing exposed population and assets following a structural flood defence. Once the completion date of a structural project is known this method can be deployed using historic LiDAR data to compare development before the defence was upgraded/constructed to afterwards, identifying new buildings potentially linked to the structure. This paper presents a new method using readily available data, to assess the unintended consequences of structural coastal flood protection, using Portsmouth, Southport, and Weston-super-Mare as case studies. These findings will advance understanding of the SDP, and other coupled human-flood emergent phenomena.

Data and Methods

The United Kingdom provides an ideal backdrop for an analysis of the unintended consequences of structural coastal flood protection due to the long history of coastal engineering (e.g., Palmer, 2018) coupled with large amount of (largely open-access) geospatial data availability (e.g., Rumson *et al*., 2020). Geospatial data can facilitate analysis of comparative or historical changes in an urban environment, and will provide an essential component of SDP analysis.

Exploiting the time dimension of LiDAR differential analysis allowed for longitudinal analysis within this paper, showing changes in urban development, both before and after a structural coastal flood defences project. These changes in the height of buildings/urban landscape were statistically tested to identify significance. This analysis was employed as part of a case study approach, in order to assess urban development in tandem with local, national, and global economics, to unpick whether local FRM strategy had an unintended impact on urban layout, which facilitated cross-sectional

comparative analyses. These combined analyses draw key insights by applying this approach to selected contrasting case study sites to better understand the SDP in coastal settings.

Study Site Selection

The study focused on coastal settlements that had seen a structural coastal flood risk management project (building new or upgrading existing flood defences) being completed, whilst neighbouring settlements did not across this same time period. To identify candidate case study sites, locations with the greatest flood exposure, defined as population and housing density, shops, local government buildings, essential transportation, telecommunications, and utility assets within the Flood Zone, FZ (0.1%AEP, Annual Exceedance Probability) and satisfy the above criteria were analysed. Furthermore, data on critical services and infrastructure, such as police, fire, and ambulance stations, hospitals, council buildings, supermarkets, and key transport hubs were identified from online sources (constabulary websites, county councils etc.). The comparative examination of these key elements on the maps combined with information on long-term Shoreline Management Plan (SMP) policy resulted in 3 candidate sites: providing a comprehensive overview to ensure a selection of representative case study sites (Rumson *et al*., 2020). **Figure B1** illustrates the overarching approach for the site selection process.

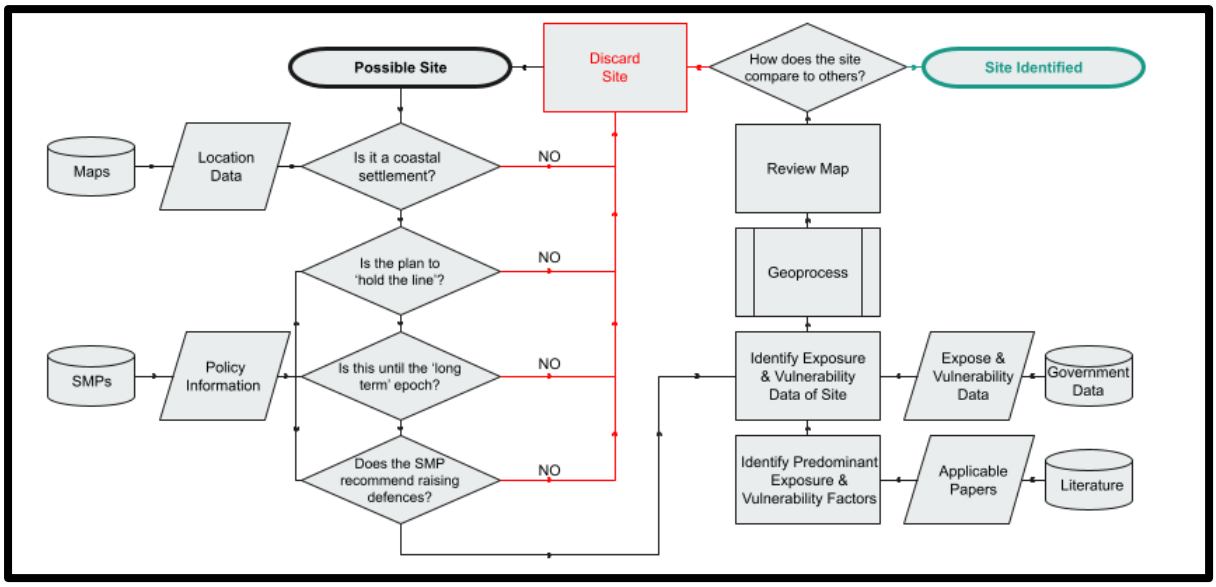


Figure B1 The process of site selection.

Three contrasting case studies are identified: Southport, Weston-super-Mare, and Portsmouth, that fully satisfy the selection criteria (**Figure B1**). Southport has the most significant amount of exposed infrastructure out of the three study sites, with a significant amount of the retail placed on the coastline, leaving food supply chains vulnerable (MacMahon et al., 2015). Weston-super-Mare had the largest area exposed of the sites, with the flat North Somerset Levels providing a large low-level hinterland for coastal flood water to proceed into. Furthermore, all essential services are in the exposed area, causing issues in the ability of critical sectors to provide services in the event of a flooding emergency. Portsmouth has a high population density in the exposed area, especially towards the southern tip of Portsea Island. Towards the north-east of the island, there is heavy industry placed in the FZ, threatening the local economy. Furthermore, Portsmouth is an island city and relies heavily on the Portsmouth Direct Line (railway) as well as the A2030 and A3/M275 road corridors for traffic in and out of the island. These access routes pass through flood zones, and are vulnerable to coastal flooding, endangering those on the heavily populated island.

Differential Analysis

The study used historic LiDAR DSM raster datasets, which represent functionally large matrices of elevation data arranged in a grid with northings and eastings as row and column numbers, respectively (**Figure B2**), and allow mathematical operations to be performed. Consequently, geospatial analysis is conducted to identify temporal changes in urban development of an area by subtracting two DSMs of the same location at different points in time, providing a DSM of Difference (DoD) (see **Eq. B1**).

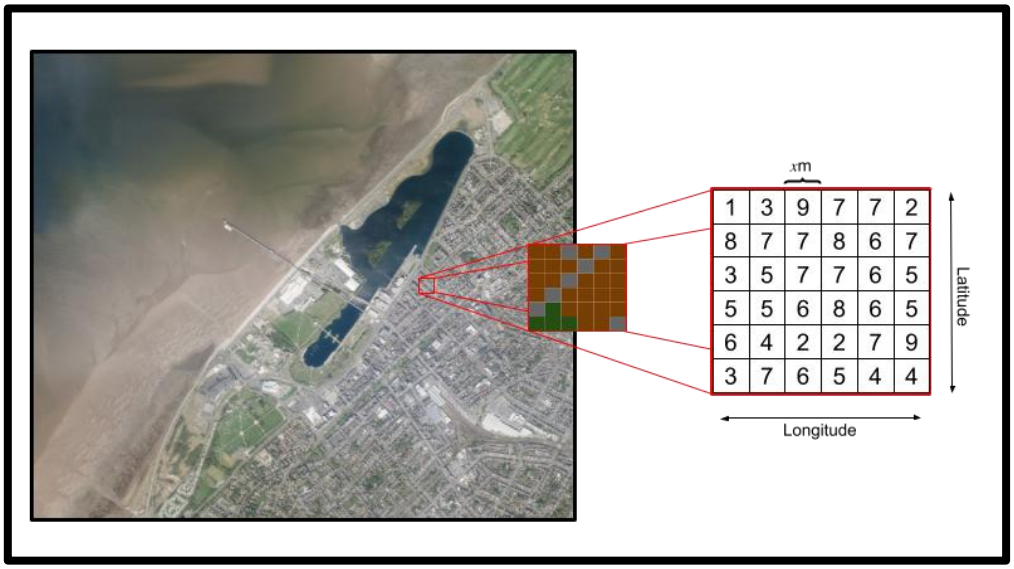


Figure B2 Demonstration of the components of a geospatial raster. Elevation values are contained within the two-dimensional cell, size dependent on the resolution of the raster.

$$DoD = \Delta DSM = R_2 - R_1 \qquad \text{(Eq. B1)}$$

Where R_1 is the oldest DSM and R_2 is the most recent DSM. The DoD simulation procedure, estimating elevation change, has been described as DSM differencing or differential analysis, and is widely used in physical geography, e.g., assessing the evolution of drainage basins (Brasington *et al*., 2003), detection and estimation of landslides (Tsutsui *et al*., 2007), and estimating the change in sediment budgets (Wheaton *et al*., 2009). While the simulation of DoDs to identify flood exposure and urban environment change is a novel approach, the use of DSMs has long been established in studying human settlements (e.g. Priestnall *et al*., 2000; Yan *et al*., 2015). Coupled with the large amount of research already using DSM differencing in physical geography, the analysis reported here also demonstrates knowledge transfer of the method to human geography.

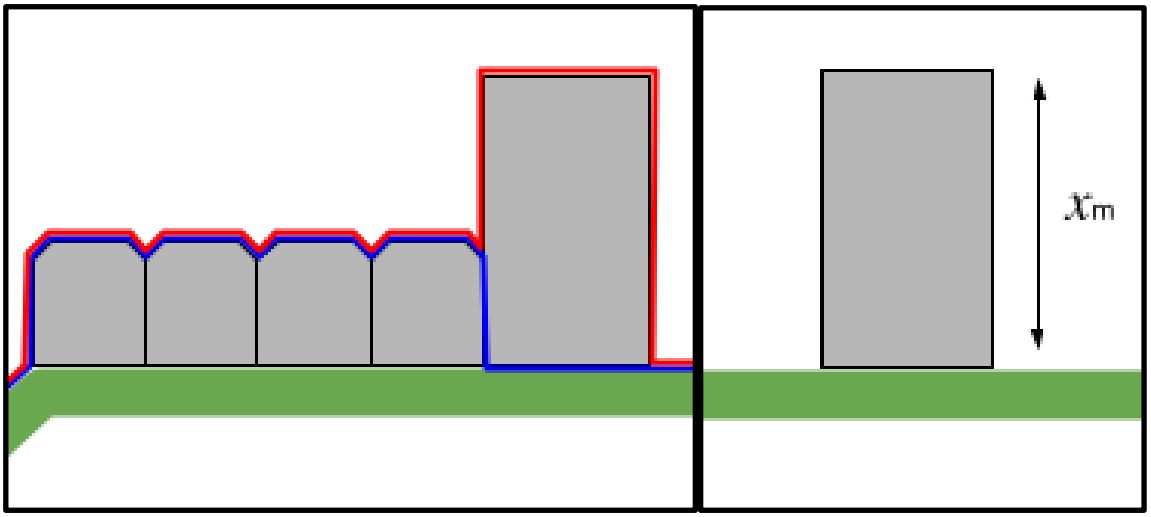


Figure B3 Two DSMs overlaid: the blue line (older DSM) and the red line (newer DSM) (left panel); the resulting DoD (Xm) from the above differential analysis, using **Eq. B1** (right panel).

The simulated DoD of settlement shows direct change in the urban landscape across time, providing an accurate method of longitudinal urban analysis, with the accuracy of the model directly linked to the spatial resolution of the DSM input. A conceptual schematic of the modelling process is shown in **Figure B3**. If the blue line represents an earlier DSM, say for example from 2010, and the red line represents a later DSM of the same location, for example 2020. Following **Eq. B1**, urban change over the decade can be represented as shown in **Figure B3**. Hence, the new high-rise building constructed between the DSMs will be the only difference, and theoretically all else will be zero. However, in reality, this is unlikely. Natural elements of the landscape can also change, resulting in an increasing effect the larger the period between the DSMs is, producing *natural noise*: trees grow, foliage develop, beach morphology, and even tides can affect the DoD. Nevertheless, natural noise and LiDAR artefacts can be reduced, or often eliminated due to their scale: with disregard to large tidal ranges, most natural growth/changes will be on the scale of centimetres (Sharma *et al.,* 2010). Artificial structural changes would be primarily constructed for human habitation or use, providing a lower limit on identifying new development. This study assumes that a lower limit for identifying human-made construction to be 3m (Erener *et al*., 2020) (for excluding the effect of natural growth and changes from the analysis).

If a DoD shows a significant increase in growth adjacent to a newly built or upgraded structural flood defence, that could suggest a link between the two, but this could be considered as a simple correlation. If this same process has not been observed in a neighbouring coastal settlement (of similar population but with no/limited comparable flood defence provision) across the same timeframe, then this would suggest some causality. If this same process repeats across different case studies then it would more likely imply stronger causality. The significance of this link was tested in this study using inferential statistics, as detailed below.

Geostatistical Testing

Due to the large size of the DSMs, containing thousands of observations, the central limit theorem and the law of large numbers apply, enabling parametric inferential statistical analyses (Mascha and Vetter, 2018). However, to minimise the computational demand associated with the length or direction of some coastlines, a threshold limit is considered for the sampling. Iterative optimisation revealed that a 500m by 500m square was best for all resolutions, and enabled compatibility with smaller resolutions whilst also ensuring the stability of the program.

Samples were collected randomly using a transect along the urban coastline from DSMs that were captured an equal amount of time preceding the construction of the defence to afterwards, based on

data availability. Maintaining time period consistency when conducting the neighbourhood analysis was essential for comparability and minimisation of external influences.

The sampled DSMs were then put through a t-test, where each pixel of the raster was compared to the exact same point at the chosen later point in time, where L_{R1} represents the selected pixel of R_1, L_{R2} the selected pixel of R_2 (**Eq. B2**). The raster t-test (**Eq. B3**) then produced a t-statistic which was compared to the significance level (α=0.05). Whilst a z-test should be used for large samples (n > 30) (Chang *et al.*, 2006), at the time this was computationally not possible using R, and therefore t-test was used. However, at such high amounts of data points, differences between the resulting t- and z-score are infinitesimal (**Eq. B4**, **Figure B4**).

$$L_{R1} = (x, y) \in R_1 \quad \text{(Eq. B2a)}$$

$$L_{R2} = (x, y) \in R_2 \quad \text{(Eq. B2b)}$$

$$t = \frac{\Sigma\,(L_{R2} - L_{R1})}{\sqrt{\frac{n(\,\Sigma(L_{R2} - L_{R1})^2) - \Sigma\,(L_{R2} - L_{R1})^{\,2}}{n-1}}} \quad \text{(Eq. B3)}$$

$$\lim_{n\to\infty} \frac{\Sigma\,(L_{R2} - L_{R1})}{\sqrt{\frac{n(\,\Sigma(L_{R2} - L_{R1})^2) - \Sigma\,(L_{R2} - L_{R1})^{\,2}}{n-1}}} = Z \quad \text{(Eq. B4)}$$

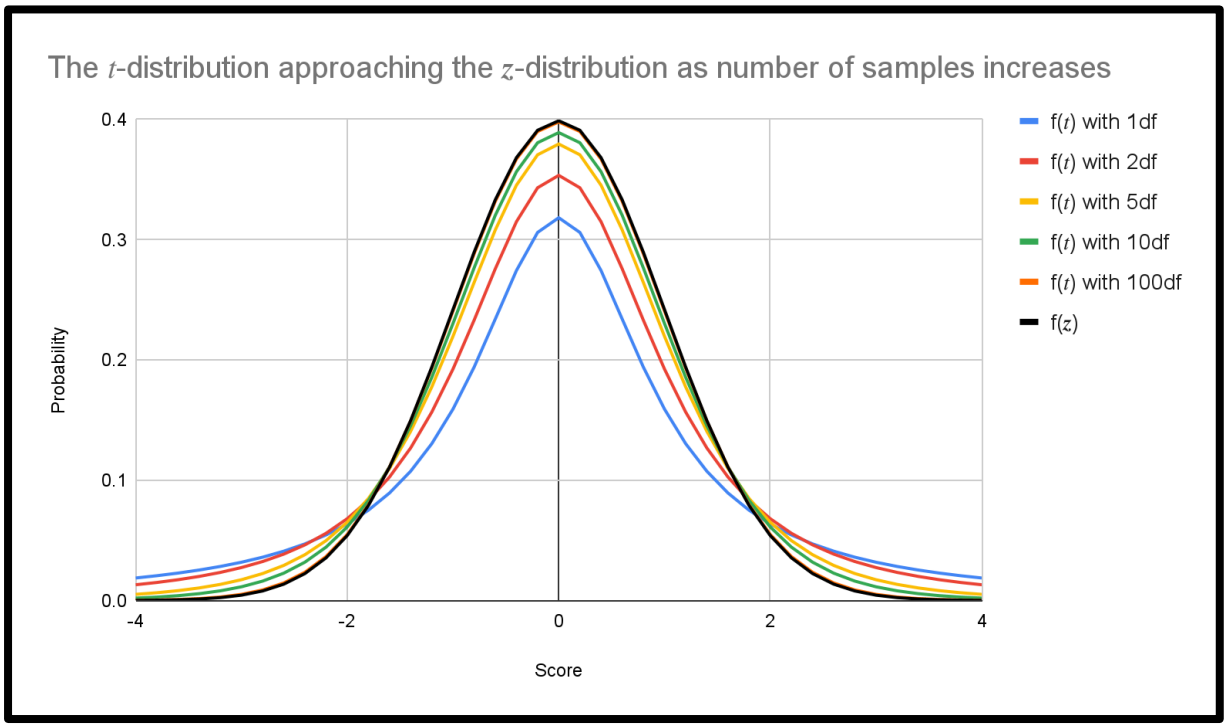


Figure B4 The t-distribution approaching the normal distribution as ($n \to \infty$), where the degree of freedom, df, is n-1.

Results

This section presents the key results and insights on the SDP based on the findings from the three contrasting coastal case study sites. The maps show the spatial footprint of the urban landscape change dynamics while the tables summarise the statistical analyses results.

Portsmouth

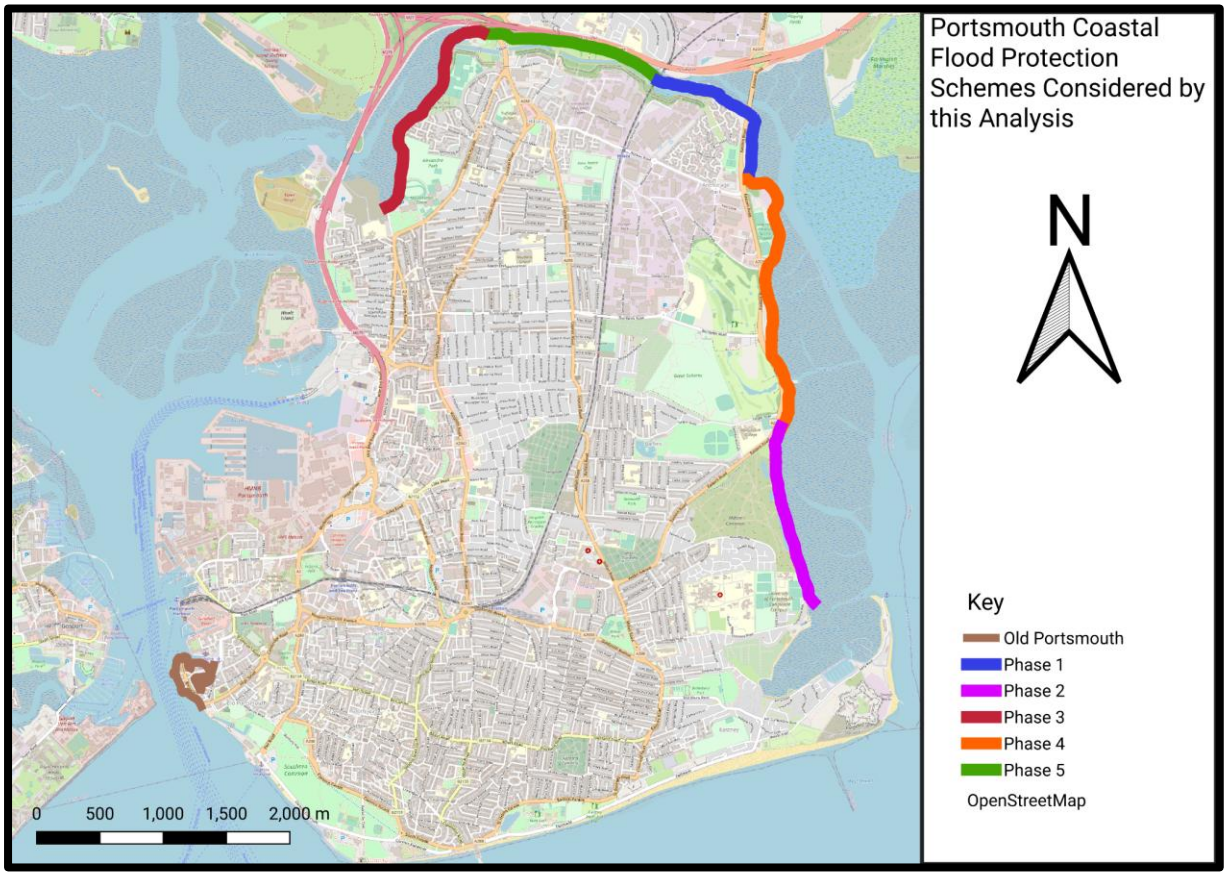


Figure B5 Map of the structural flood protection schemes development across Portsea Island from 2000 to 2020. This map does not include the currently in development Southsea scheme.

Table B1 The results of the Portsmouth raster t-test comparing the 2002 raster to the 2013 raster, and the 2013 raster to the 2022 raster.

Location	Rasters	Result	Lower Bound	Upper Bound	p-Value
Portsmouth	2002 to 2013	0.97206	0.81798	1.12613	≤0.05
	2013 to 2022	0.32892	0.27324	0.38460	≤0.05
Gosport	2002 to 2013	0.05297	-0.06895	0.17488	≤0.05
	2013 to 2022	0.07792	0.01556	0.17139	0.10233

The Old Portsmouth and The North Portsea Coastal Scheme covers 10km of the coastline of Portsmouth (**Figure B5**), most of the area is low-lying and the structural coastal flood defences that existed there before the scheme were reaching the end of their operational life. Using LiDAR vertical change as a proxy for the construction of new buildings yielded little near to the first coastal defence upgrades in Portsmouth (**Figure B6**): despite there being new development, Admiralty Tower and the new industrial estate in the north-east of the island, little was constructed near the newly upgraded coastal flood defence itself. Similarly, the construction of new buildings also occurred in Gosport, and whilst a lower density development than those in Portsmouth, there were still numerous new buildings (**Figure B7**), leading to the equal results from the geostatistical testing for this period. The t-score was lower in Gosport compared to Portsmouth (**Table B1**), being 0.053 and 0.972 (3dp), respectively. These data reflect the changes that occurred in both locations, high-density development occurred in Portsmouth, and low-density in Gosport, however, this is more a reflection of the locations themselves: Portsmouth is already a city with a larger population, constrained by Portsea Island, whereas Gosport is relatively less populated.

During the second wave of coastal flood defence schemes, mostly dominating the northern and eastern side of Portsea Island, more new buildings were constructed, predominantly in the FZ in Portsmouth (**Figure B8**). Whereas, in Gosport little development occurred outside of the Defence Munitions Gosport base (**Figure B9**). Changes within military bases should not be considered as they are extraneous to factors affecting the civilian population.

In Portsmouth, a large new commercial centre was built on the seafront at Old Portsmouth, constructed 10 years after the original flood protection scheme was constructed. Thereafter, other new medium-scale development was constructed in the area, completed in 2019 as part of the upgrades to the WightLink ferry terminal. Towards the north-east of the island, a new large-scale industrial estate had also been constructed. The estate is entirely within the FZ and opened in 2018, two years after the flood defence scheme for that area of the island was constructed. This industrial estate, the largest industrial development in the city, brings 0.026km^2 of brownfield land back into use. The first phase of the North Portsea Coastal Scheme was designed to reduce the risk of flooding from the sea to 4,200 homes, 500 businesses and critical infrastructure over the next 100 years. The construction and upgrading of coastal flood defence structures can induce development within exposed areas greater than would otherwise be the case if the scheme was not conducted (Haer *et al*., 2020). Whereas Phase 2 and Phase 3 saw little development within the adjacent the FZ boundary, but both run alongside primarily outdoor recreation areas. The upcoming Phase 4, Phase 5, and Southsea scheme will give greater insights once they have been completed. Across this period there was limited new development or urban growth in Gosport, represented by the failure of the 2013-2022 Gosport raster t-test to be statistically significant. Despite similar economic conditions affecting both areas, new development occurred mostly in Portsmouth, in flood exposed areas, near to newly constructed or upgraded structural flood defences, as identified by the LiDAR differential analysis ─ this is a direct indication of the SDP.

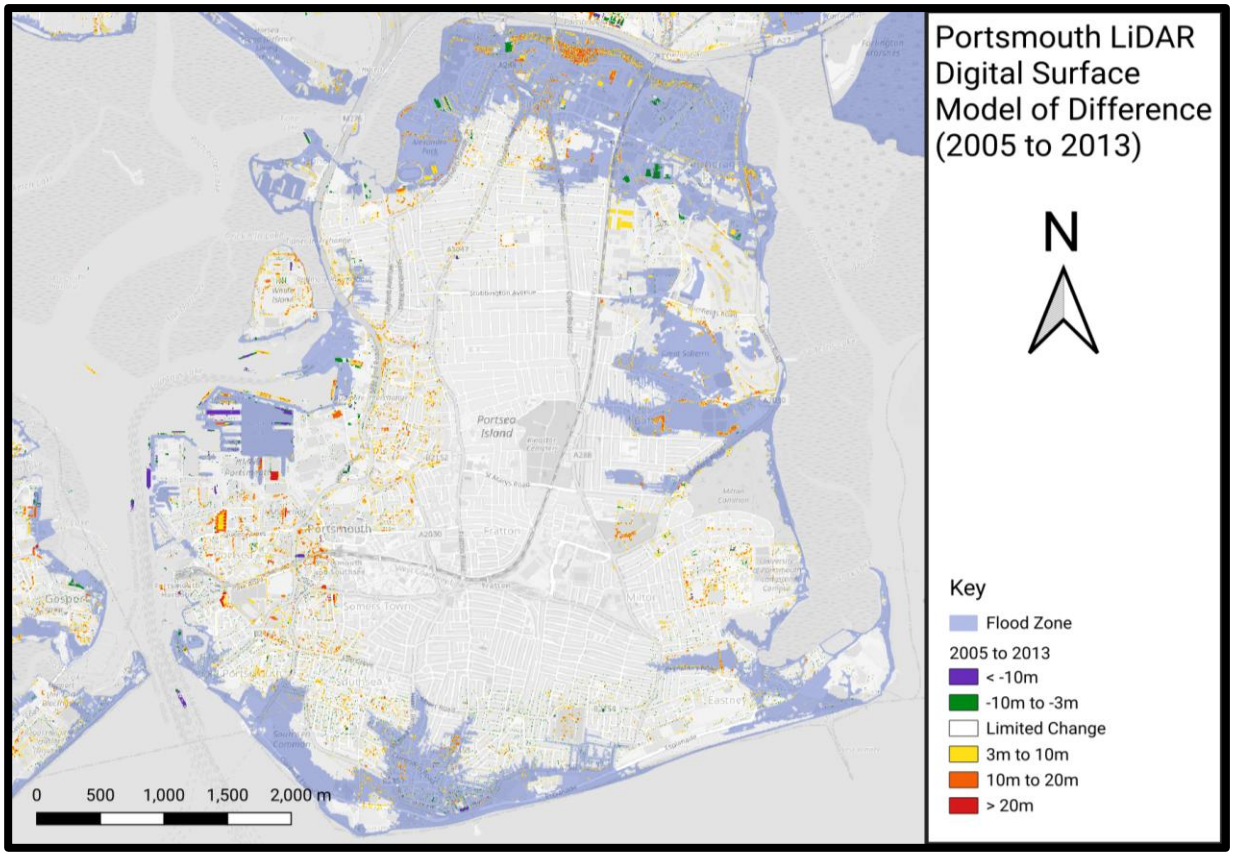


Figure B6 Portsmouth 2005 and 2013 LiDAR DSM comparison (OpenStreetMap)

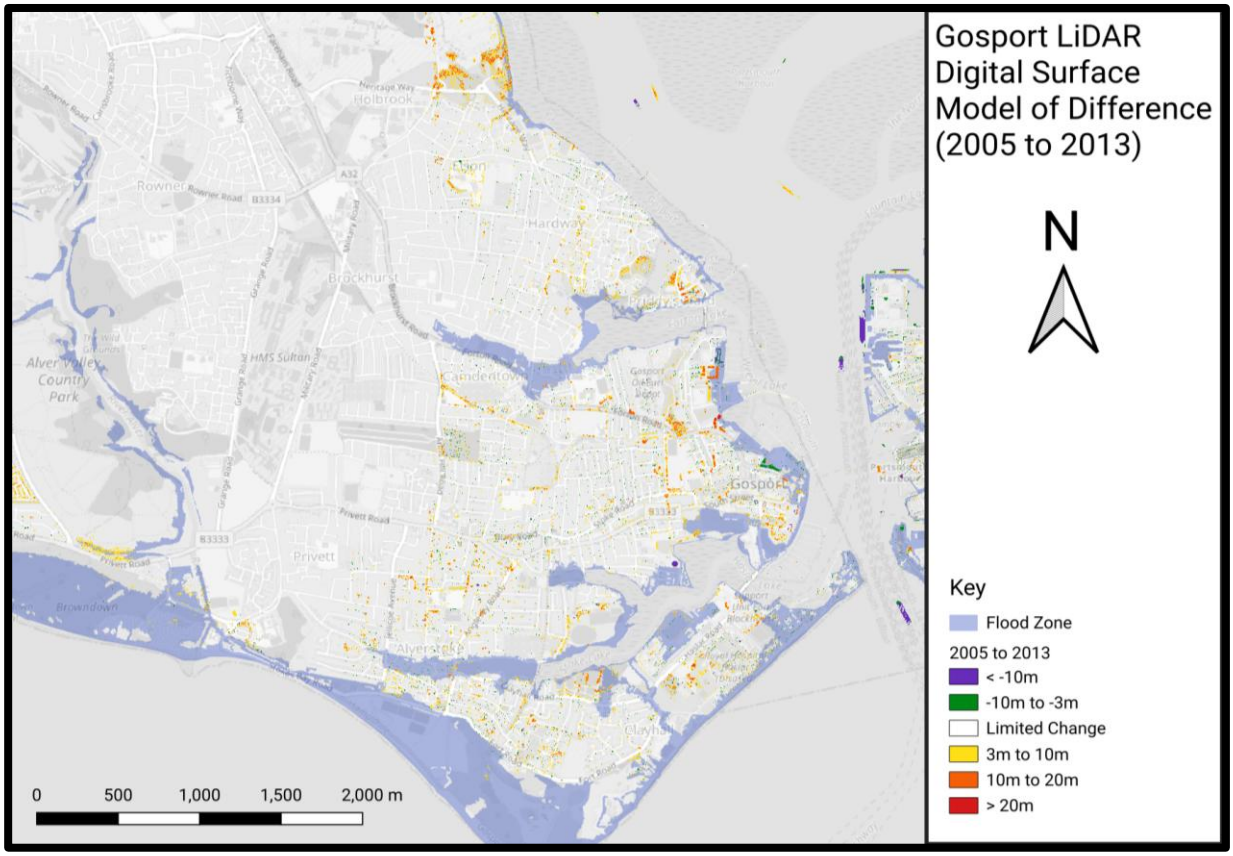


Figure B7 Gosport 2005 and 2013 LiDAR DSM comparison (OpenStreetMap)

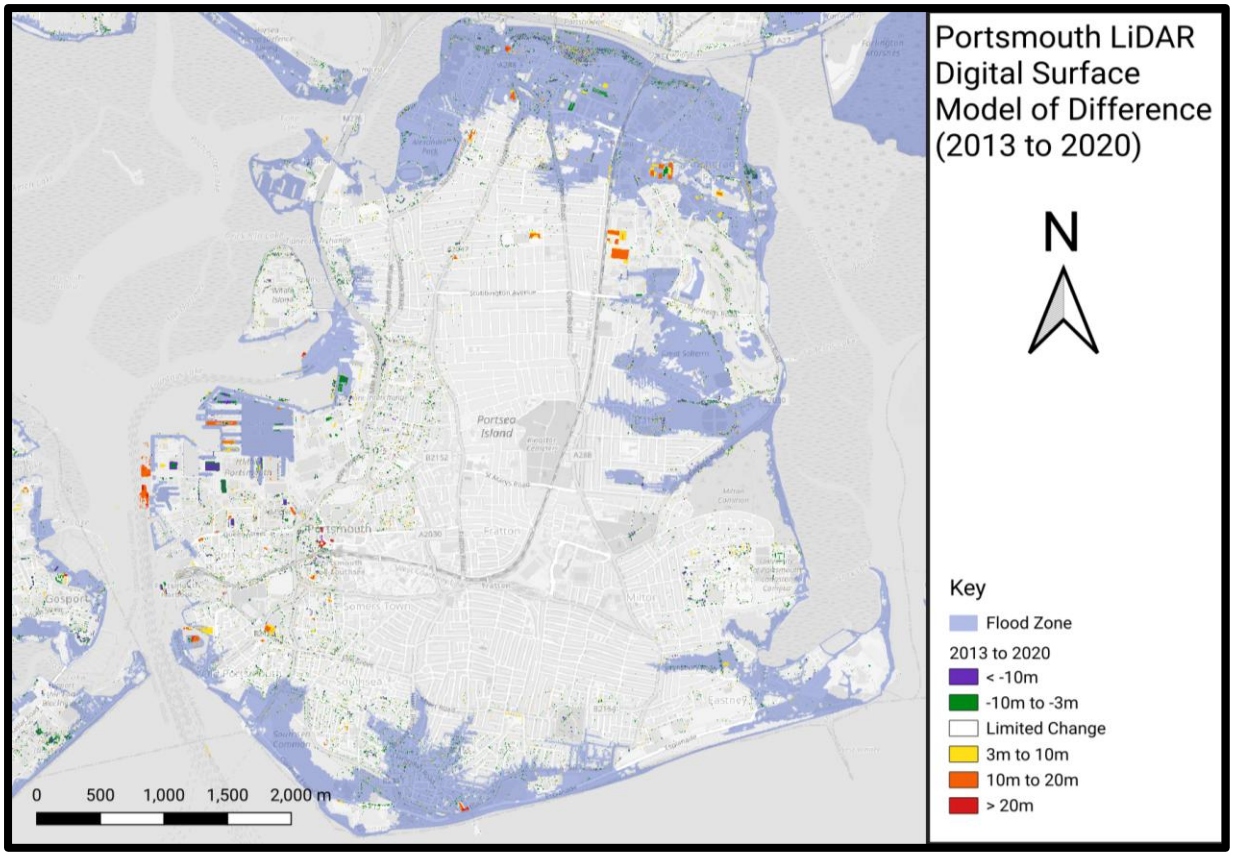


Figure B8 Portsmouth 2013 and 2020 LiDAR DSM comparison (OpenStreetMap)

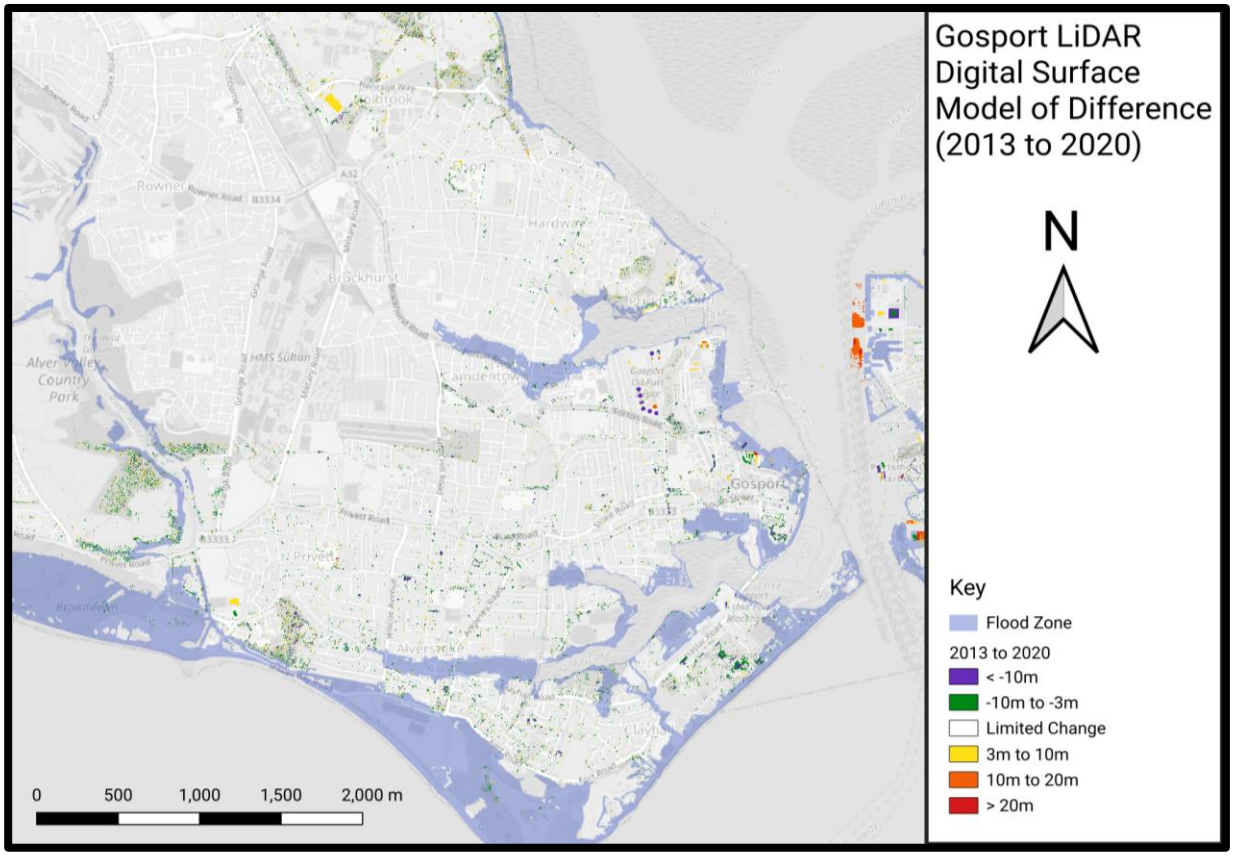


Figure B9 Gosport 2013 and 2020 LiDAR DSM comparison (OpenStreetMap)

Weston-super-Mare

Table B2 The results of the Weston-super-Mare raster t-test comparing the 2007 raster to the 2014 raster, and likewise for the Burnham-on-Sea and Clevedon rasters.

Location	Rasters	Result	Lower Bound	Upper Bound	p-Value
WSM	2007 to 2014	0.62158	0.548219	0.69496	≤0.05
B-o-S	2007 to 2014	-0.05201	-0.10734	0.00331	0.06538
Clevedon	2007 to 2014	0.00507	-0.08048	0.09062	0.90751

Upgrades to the structural coastal flood defence at Weston-super-Mare were completed in 2010. Past coastal flooding events have extended beyond the frontage properties into the town centre and up to one mile from the seafront. The scheme aimed to protect 3,830 residential and 637 commercial properties from flooding and improve the quality of the promenade for businesses, residents and visitors, to provide a major boost to the tourism trade and economic prosperity of the area. Meanwhile, the LiDAR DoD, produced by the differential analysis, suggests that a great amount of new development occurred over this period (**Figure B10**). Starting from the west and heading eastwards, the map shows new development on the pier, a new 5-10m tall building, most likely the 2010 pier reconstruction following the fire in 2008. Continuing eastwards to the bulk of the new urban development where many tall buildings were constructed, and a couple of buildings were demolished, reflected in the map (**Figure B10**). Buildings to the south of the development were completed by 2014, whereas proceeding north the buildings were complete by 2018. Construction for all projects in this core started after the coastal flood defence upgrades were complete. Proceeding further east, there are two new residential estates constructed between 2012 and 2015. All of these new developments in Weston-super-Mare are located within the FZ. However, in contrast, there was little development in the nearby town of Clevedon (**Figure B11**) and in Burnham-on-Sea there was the construction of a small housing estate 2km from the coastline (**Figure B12**). Weston-super-Mare had statistically significant change of 0.622 (3 dp, ≤0.05 p-Value), compared to -0.052 (0.065 p-Value) for Burnham-on-Sea and 0.005 (0.143 p-Value) for Clevedon (**Table B2**). With such low t-scores for both, Burnham-on-Sea and Clevedon, and a p-Value greater than the 0.05 α-level, only Weston-super-Mare had statistically significant change from before its coastal flood defence was upgraded compared to afterwards.



Figure B10 Weston-super-Mare LiDAR 2003 to 2022 DSM comparison (OpenStreetMap)

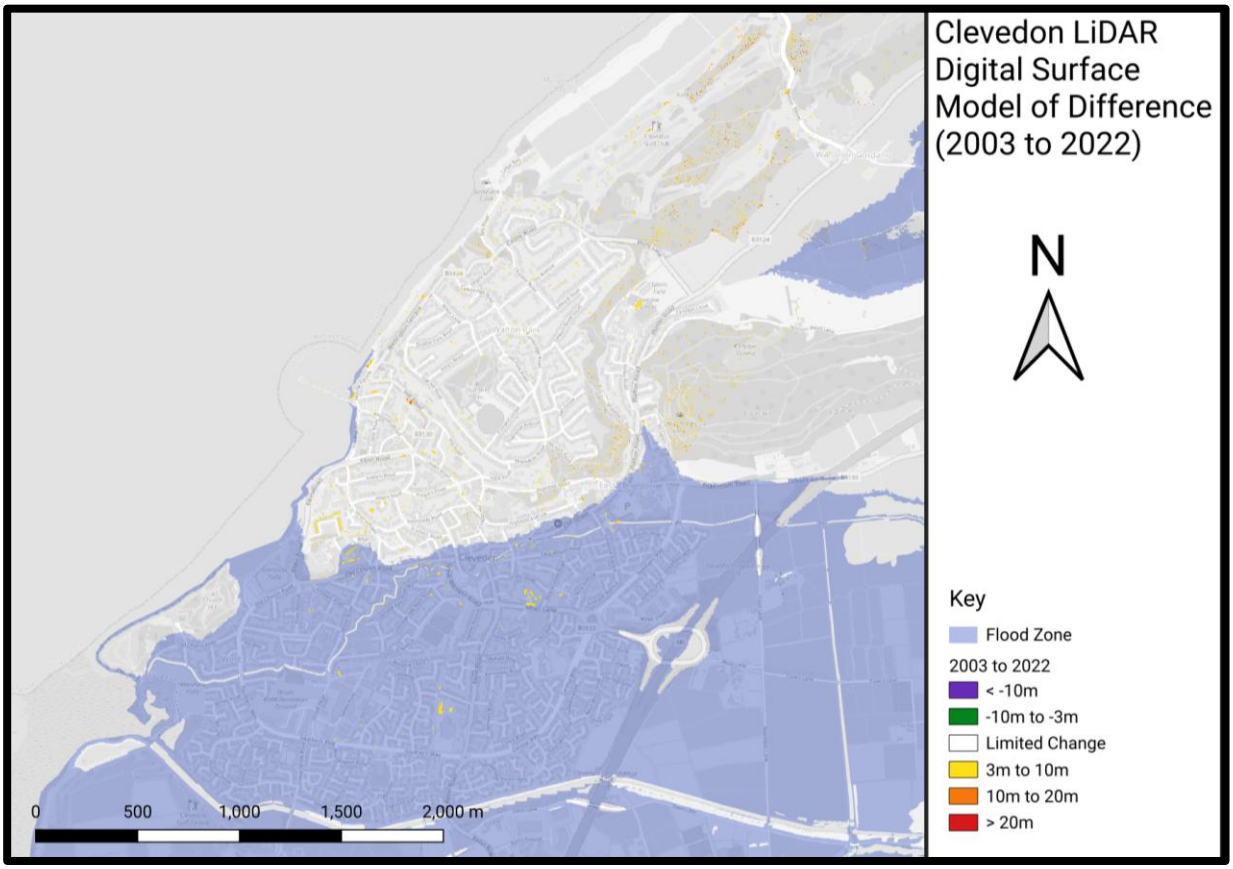


Figure B11 Clevedon LiDAR 2003 to 2022 DSM comparison (OpenStreetMap)

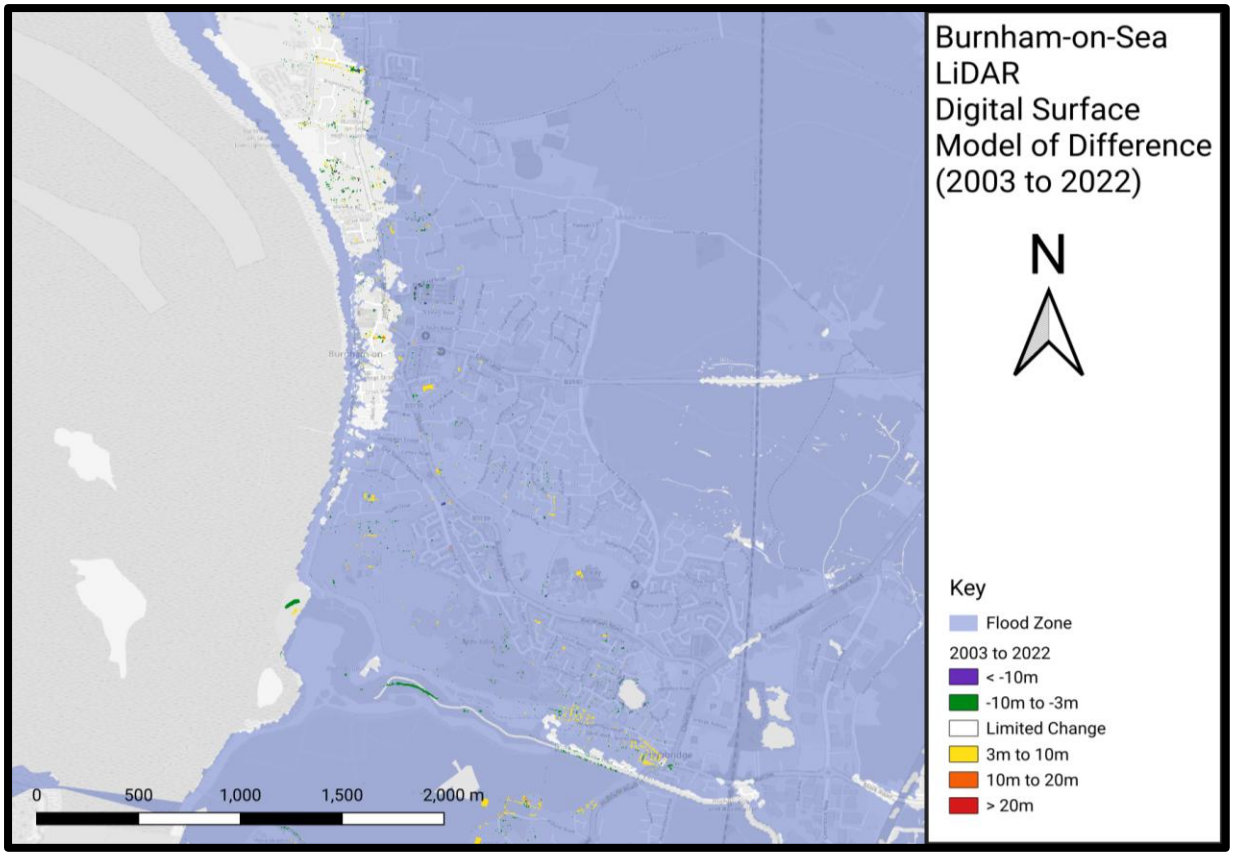


Figure B12 Burnham-on-Sea LiDAR 2003 to 2022 DSM comparison (OpenStreetMap)

Southport

Table B3 The results of the Southport raster t-test comparing the 2007 raster to the 2014 raster, and likewise for the Blackpool and Crosby rasters.

Location	Rasters	Result	Lower Bound	Upper Bound	p-Value
Southport	1999 to 2006	2.547624	1.783226	3.312021	≤0.05
Blackpool	1999 to 2006	0.0425846	-0.4757089	0.5608781	0.8720645
Crosby	2002 to 2008	-0.136953	-0.351811	0.07790507	0.2115541

New urban development following a structural coastal flood defence scheme was also apparent in Southport, whereby following the construction of the structural coastal flood defence in 2002 was followed by a large increase in building construction in the area adjacent, all within the FZ (**Figure B13**). This new development, Ocean Plaza, was completed in 2002, with extensions to the site in 2004, linking the new retail park to the town centre. In contrast, Crosby (**Figure B14**) saw little coastal development, and none in the FZ. Likewise, for Blackpool, which over the 1999 to 2022 period saw urban growth around the railway station in the centre and a new stadium built towards the south, but none occurring in the FZ (**Figure B15**). The construction of the seawall began in 1997, taking 5 years, whilst the planning application for the Ocean Plaza retail park was received in 2000. Despite the inherent flood risk to the area, the retail park was constructed, as the LiDAR analysis demonstrates. This growth in Southport is also demonstrable statistically, which had statistically significant change in urban development of 2.548 (3 dp, ≤0.05 p-Value), compared to 0.043 (0.872 p-Value) in Blackpool across the same time period (**Table 3**). The large urban growth in Blackpool (**Figure B15**) around the railway station was built as part of the Talbot Gateway project, approved in 2010 and then again in 2016, and is a large regeneration project, hence would not be picked up by the geostatistical analysis of Blackpool. In Crosby, between 2002 and 2008, the t-test produced a score of -0.137 (0.211 p-Value) (**Table B3**). However, similar to Burnham-on-Sea, it is unlikely that Crosby encountered negative growth: growth in the town was so limited that the lower bound of the t-score pushed into the negative.

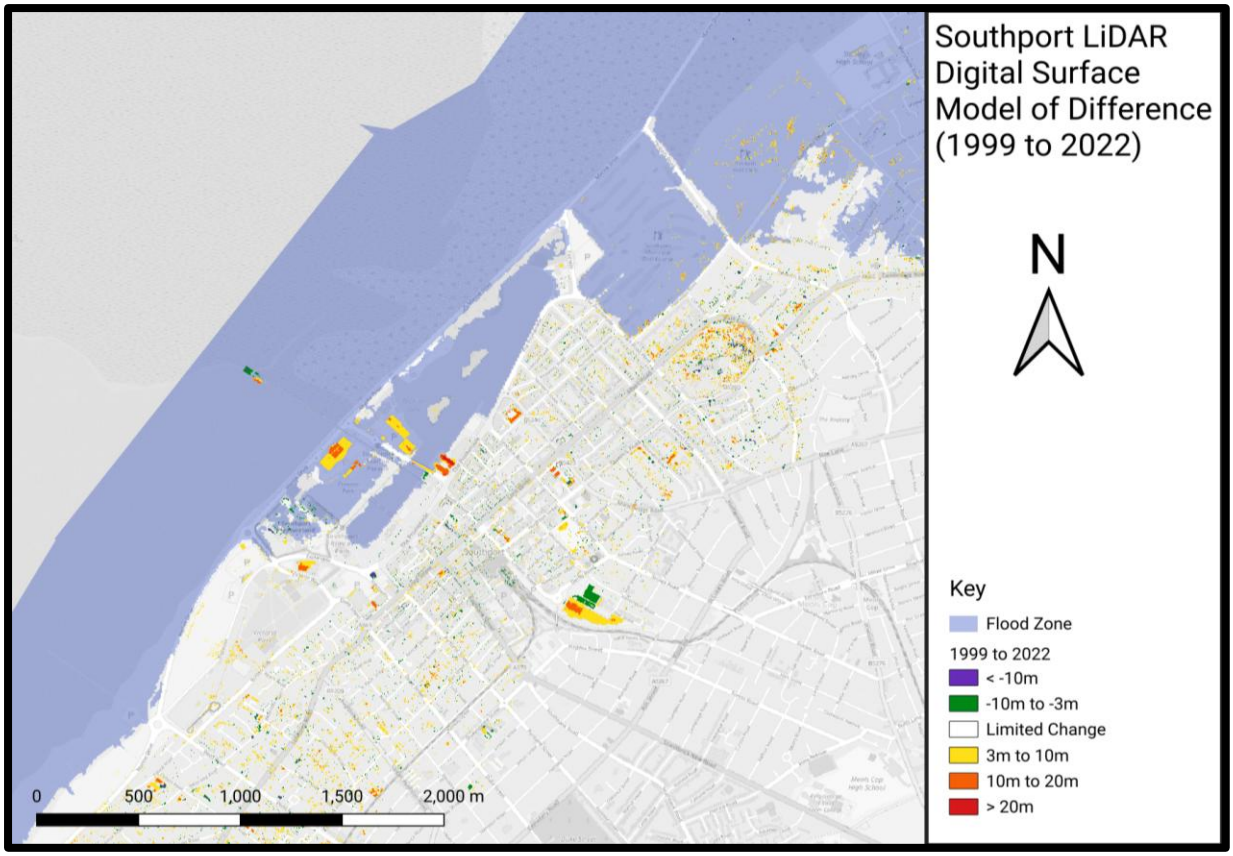


Figure B13 Southport LiDAR 1999 to 2022 DSM comparison (OpenStreetMap)



Figure B14 Crosby LiDAR 2002 to 2022 DSM comparison (OpenStreetMap)

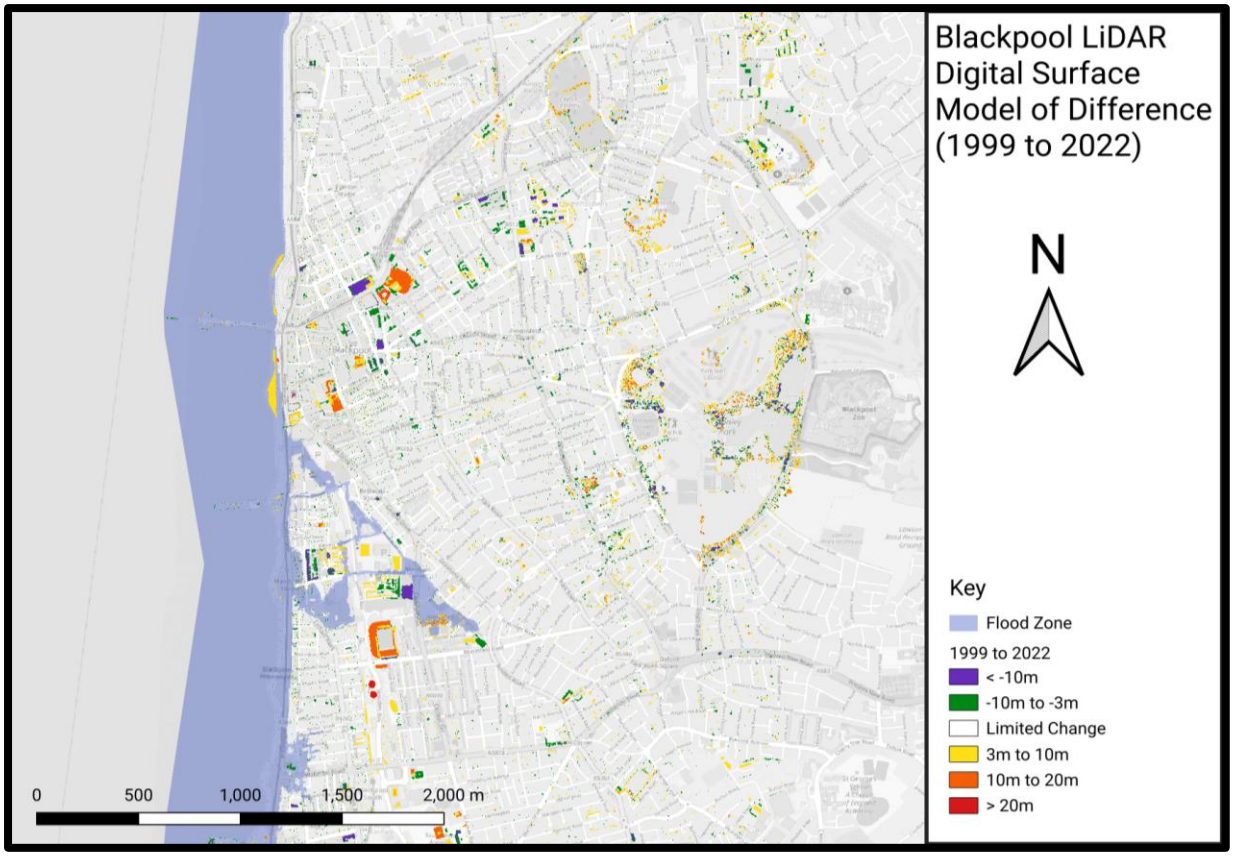


Figure B15 Blackpool LiDAR 1999 to 2022 DSM comparison (OpenStreetMap)

Discussion

As a phenomena, the coupled human-flood feedback of the SDP (also levee effect) is relatively understudied, especially in coastal settings. Since its inception in 1945 (White, 1945), research has been limited over the twentieth century, before increasing over the past two decades (e.g., Haer *et al*., 2020; Breen *et al*., 2022). The interlinks of policy and decision-making, and its potential lock-in effects, played out in the lead up to and aftermath of Hurricane Katrina and the subsequent damages to New Orleans, leading to the emergence of the terminology *Safe Development Paradox*, SDP (Burby, 2006).

Despite the increases in research output, coastal research of the topic is limited, accounting for only 17% of all papers researching this emergent phenomena (Breen *et al*., 2022). The method presented here, used to identify development linked to the upgrade of existing or construction of a new coastal flood defence, can help accelerate case study identification with the effect of having great impact on the existing sparse literature. LiDAR is frequently used in the coastal research community such as for mapping shoreline changes (Lin *et al*., 2019); identifying nearshore submerged and emergent ecosystems, coastal morphodynamics, and hazards created by SLR and storms (Brock and Purkis, 2009); and determining vegetation height (Schmid *et al*., 2011). Furthermore, the use of LiDAR has even been discussed within papers researching these coupled human-flood feedbacks, albeit a limited amount in the discussion of how LiDAR can be used to estimate elevation compared to local sea level (Armstrong and Lazarus, 2019; Gesch, 2009; Jiao *et al.,* 2022). Moreover, the use of LiDAR has had application in the identification and delineation of new urban construction: there are papers that reference the use of LiDAR to aid three-dimensional modelling and the extraction of property dimensions, and how changes in LiDAR can be used to update city maps with new development (Chen *et al*., 2010; Zhou *et al*., 2020). Yet these have never previously been combined as a method for the identification of potential coupled human-flood feedbacks between coastal flood defence upgrade or construction and associated increases in urban development. This paper addresses that gap focusing on the selected UK case studies of Portsmouth, Weston-super-Mare, and Southport, representing contrasting settlement sizes with different economies. The quantity of the freely available geospatial data within the UK provides an ideal test bed, however, future research should endeavour to increase the internationality of this research and further global reach of SDP research, especially within the Global South (Breen *et al*., 2022).

The case study results reported in this paper also highlight the challenges in (re)developing a coastline: often these locations have either been previously developed, limiting scope in the size and density of such structures, and/or are being constrained by the sea itself. Moreover, the (re)development of these coastal brownfield sites are unlikely to withstand the front-loaded costs of regeneration, especially in weak economies (Leger *et al*., 2016). Coastal regeneration and (re)development schemes often face viability issues due to their peripheral locations and narrow local economies, frequently relying on a single industry and facing interdependency challenges with other sectors and/or regions. This is compounded by the economic circumstances of the study sites in the years following the Great Recession, which created greater pressure on greenfield land in coastal areas, rather than brownfield (Leger *et al*., 2016). The analysis also highlighted that the new exposed urban development in Portsmouth occurred 8 years after the completion of the initial structural coastal flood defence in 2005. The second tranche of development was built from 2017 to 2019, 3 years after the North Portsea Island Coastal Scheme Phase 1. In Weston-super-Mare, the LiDAR analysis revealed that new buildings were constructed across the 2014 to 2018 period, all within the FZ. These were built 4 to 8 years following the coastal flood defence upgrades. Then, in Southport, the analysis revealed that the retail estate was completed later in the same year as the structural coastal flood defence scheme, and then continued two years after until 2004. These are represented in the timeline below (**Figure 16**). Phase 2 and

Phase 3 of the North Portsea Coastal Scheme are not included due to a lack of definitive exposed development.

The timeline (**Figure B16**) suggests that the largest gap between the completion of a defence to the start of associated urban development was 8 years, at Old Portsmouth. The second iteration of exposed development from Phase 1 took place 2 years after the completion of the defence. The average time from the completion of the defence to the start of construction of the exposed buildings was 2.75 years (2 years and 9 months).

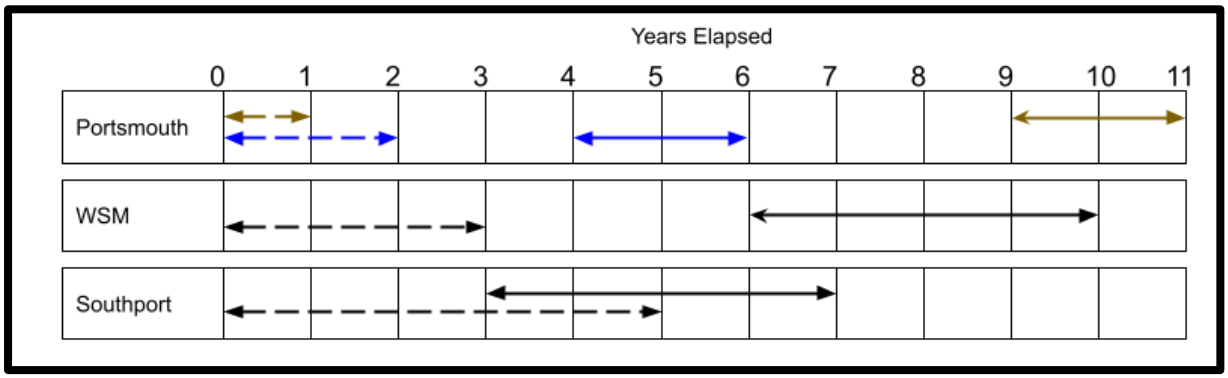


Figure B16 Relative timeline of structural coastal flood defence construction or upgrading (dashed) and nearby exposed urban development (solid) since the start of the scheme. Portsmouth arrows are colour-coordinated to those used to schemes with associated development in **Figure B1**.

Conclusion and Outlook

As the coastal population continues to increase and as sea levels rise, challenges at the interface between these two spheres will become more commonplace: more people need more housing, more assets, more infrastructure, leading to an increasing amount in exposed areas and therefore inevitably requiring a greater standard of protection. The SDP is a product of this, an infrastructural lock-in of coupled human-flood interactions induced by structural flood protection. Whilst research concerning this issue is growing, there is a skewed focus towards fluvial flooding, with limited understanding of the issue in a coastal context. Therefore, a method of identifying new urban development within flood risk areas and adjacent to these structural coastal defence structures would facilitate the research of new comparative case studies and increase the global coverage of study sites and draw generalisable lessons about the SDP in coastal areas. LiDAR has been used in adjacent scientific fields for decades now and its use in exposed urban development identification is novel, should not be particularly revolutionary; the technology is proven and is employed widely. It presents a quick and easily replicable method for the identification of the emergence of these potential lock-ins.

This paper used Portsmouth, Weston-super-Mare, and Southport as case studies, comparing them to nearby settlements to draw key insights and to better understand the issues of SDP in coastal areas. Geostatistics were used in the three case studies, a differential analysis comparing two rasters of the same location across time to identify changes between the images, and a raster t-test to determine whether these changes were statistically significant. In all three locations, the construction or upgrading of structural coastal flood defence is followed by subsequent, and statistically significant, urban development, an indication of the presence of the SDP. All major new development in each case study was located within, or just outside of the FZ: despite the inherent flood risk, construction occurs in these exposed areas regardless. On average, this development

occurs 2.75 years from the completion of the flood defence project, and the start of building construction.

Case studies were diverse, representing different settlement sizes and economies, to give an insight and testing the operability of the method across varying urban magnitudes. Portsmouth is an established city with a sizable population and independent and multilayer economy, Weston-super-Mare and Southport are smaller towns, Weston-super-Mare independent, and Southport economically tied to Liverpool. The size of a settlement had an impact on the density and type of development, Portsmouth had residential high-rises and large-scale industrial estates constructed in the FZ and adjacent areas. Weston-super-Mare had a mixture of high-density residential and medium-density service construction, with a new hotel, car park, restaurant, and retail centre built. Southport growth was primarily focused at the new retail centre, with low-density large-scale development. Whilst case studies share the commonalities of post-defence exposed urban development, the distinct characteristics of each location contribute to the variations in how this development occurs. These nuances highlight the complexity of the SDP issue and the need for context-specific analyses in understanding the interplay between structural coastal flood defence and subsequent urban growth. Studying new locations, especially globally, can help to expand the information base and gain better insights into these phenomena. Facilitating data collection in assessing the coupled human-flood interactions induced by structural coastal flood protection can aid in the pursuit of solutions and the development of policy that can aim to prevent these potential infrastructure lock-ins as greater protection incites greater development which necessitates further higher protection, resulting in the locked-in cycle, i.e., the SDP, highlighting the need for further research.

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Appendix C

A Comparative Analysis of the Impacts of Flood Embankments on Socio-spatial Distribution in Canada and the UK

Abstract

As urban centres grow there is increasing interest in the development of flood-prone areas, leading flood risk management (FRM) authorities to consider the implementation of structural flood protection measures. As such, FRM authorities may either choose to incorporate spatial planning policies into these measures and actively develop flood-prone areas of land, or may opt to construct structural measures to maintain existing infrastructure and properties at risk of flooding. However, this latter strategy may have the unintended effect of instigating new urban development and increasing populations in areas where this was not planned, and therefore not included in initial flood risk analysis, a process referred to the *Safe Development Paradox*. In these areas residual risk still occurs, however, these new populations are often unaware. This paper assesses these dilemmas focusing on two comparable case studies: Corktown Common (Toronto, Canada) and Castle Irwell (Greater Manchester, UK). It uses high resolution LiDAR DSMs and census data for geospatial longitudinal analysis, comparing the changes in urban development and population from before the construction of the flood protection landform, to afterwards, and then to each other. The Corktown Common embankment was built to enable planned development, leading to high-density and concentrated development and a significant increase in population within the Flood Hazard Area (FHA). In contrast, the Castle Irwell embankment was designed primarily to protect existing development, and yet unintentionally enabled low-density, uncoordinated urban development along the River Irwell, with increases in both, population and housing occupancy. The study underscores the importance of integrating FRM with urban planning to prevent exacerbating flood risks and ensure sustainable urban resilience. Future research should explore the integration of flood risk communication strategies and land-use policies to mitigate the unintended socio-spatial impacts of flood embankments based on the comparative analysis of FRM strategies in both, Toronto and Manchester – similar cities, with different FRM strategies and socio-spatial outcomes.

Keywords

flood embankments, unintended consequences, safe development paradox; flood risk; flood risk management; spatial planning.

1.0 Introduction

The impacts of climate change have become increasingly evident, with one of the most pronounced consequences being the heightened frequency and severity of flooding events across the globe often leading to significant socio-economic losses and environmental impacts worldwide (Sharples *et al.*, 2016; Natho and Thieken, 2018). Urban centres, as dynamic hubs of human activity, infrastructure, and commerce, have been particularly susceptible to the cascading effects of flooding.

One method to manage flood risk is building flood embankments, and in an era of escalating impacts of climate change, they are being adopted in resilient urban planning and environmental adaptation policies. Flood embankments, or levees, serve as physical barriers that can effectively mitigate flood hazards by confining floodwater and preventing inundation of populated areas (Wenger, 2015). Embankments have been used for centuries as flood risk management (FRM) strategies offering immediate and tangible protection to communities at risk. Furthermore, flood embankments offer secondary benefits, providing meaningful amenities for local and, often, urban populations for recreation, wildlife habitats and also transport corridors (Rittelmeyer, 2020). These features underscore the multifunctional potential of flood embankments in promoting sustainable urban development in the face of projected climatic uncertainty.

However, the use of flood embankments as FRM strategies also presents certain challenges and complications, such as the possibility of embankments inadvertently incentivising further (less-/un-planned) urban expansion within exposed areas due to the perceived safety they offer. Structural measures are often selected and are historically the preferred countermeasures in many parts of the world to combat flooding. However, these measures often lead to infrastructural lock-ins (path dependency) and may produce unintended consequences as increased safety can induce increased development, ultimately leading to higher losses in the event of failures of the structural safeguards in place (Kates *et al.*, 2007). This process has been diversely referred to as the *Safe Development Paradox* (Burby, 2006), *Levee Effect* (Di Baldassarre *et al.*, 2015), and *Safety Dilemma* (Di Baldassarre *et al.*, 2018). This paradox of flood protection leading to greater flood losses is based on a false sense of security (Burningham *et al.*, 2007; Collenteur *et al.*, 2014), potentially leading to a disregard of more comprehensive FRM strategies such as land-use zoning, adaptive urban planning, or ecosystem-based approaches (Busayo *et al.*, 2022). Furthermore, as the climate changes, low-probability, high-consequence events may happen more frequently, placing an inexperienced population at greater risk (Van Aalst, 2006; Merz *et al.*, 2009). Whilst flood embankments do offer tangible benefits, their implementation must be balanced with a holistic understanding of their limitations and the broader context of sustainable urban resilience.

Therefore, to study this phenomenon further, this comparative analysis aims to delve into the potential emergent coupled human-flood interactions caused by the construction of flood embankments in two prominent urban areas: Toronto in Canada and Greater Manchester in the UK, referred to as Manchester herein. These cities, though geographically distinct, both grapple with the intricate interplay of natural hydrological processes, urban development, and human responses in the face of fluvial flooding events.

Both, Toronto and Manchester, have an historic industrial past, as centres of empire and industrialisation, to decline, and re-emergence as a twenty-first century service-based economy. Both cities continue to be analogous with similar amounts of population and cultural similarity, but also with a common vulnerability to fluvial flooding due to their intricate interactions with the natural hydrological systems that surround them. The changing of urban morphology, land-use patterns, and climatic conditions can bring increasing uncertainty and the intensification of precipitation events due to climate change accentuates the vulnerability of both cities to flash flooding, thereby exacerbating the risk of fluvial flooding. The Don River, from a major watershed in Toronto, holds historical significance and substantial hydrological influence. As urban development has encroached upon its floodplain, the capacity of the river to accommodate surges in water volume has been compromised. Over the past century, Toronto has experienced four major floods: Hurricane Hazel in 1954, the August 1976 floods, the August 2005 flood, and the July 2013 flood (Nirupama *et al.*, 2014). Hurricane Hazel caused the most significant damage with 81 fatalities, 7,000 made homeless, and widespread destruction of infrastructure, leading to the establishment of the Toronto and Region Conservation Authority (TRCA). The August 2005 flood was a 100-year event causing $500 million in damage, while the July 2013 flood became the most costly natural disaster in Ontario, resulting in over $850 million in insured property losses, power outages for 300,000 residents, and severe disruptions to transportation systems (Nirupama *et al.*, 2014). Similarly, the River Irwell, running through much of Manchester and Salford, has been shaped by industrial expansion and urbanisation. Its course has been constrained and altered over time, creating conditions conducive to fluvial flooding during intense rainfall events. In the past, Manchester has experienced several large flood such as in 1954, which saw six hundred homes flooded, 1877, where the River Irwell rose by 2.7m, flooding surrounding towns and low-lying regions, and in 1866 where it rained for three days continuously (MacDonald and Dietz, 2024). These rivers and locations provide ideal case studies for exploring the intricate dynamics of coupled human-flood interactions in an urban fluvially-dominated setting.

Both cities have implemented FRM strategies to contend with the challenges posed by fluvial flooding, such as structural interventions like flood barriers and reservoir construction to non-structural measures like land-use planning and public awareness campaigns. However, a major strategy employed by both FRM agencies in their respective cities is the creation of flood embankments, providing an earthen structural defence to either develop the floodplain land, such as that in Toronto, or to protect what is there already, as in the case of Manchester.

This paper presents lessons learnt from a comparative assessment of the intricate interconnections between natural hydrological processes, urban development, and human responses in the two cities in the face of climate-induced challenges. By examining the impacts, vulnerabilities, and adaptive measures of FRM strategies in these two cities, this research endeavours to contribute to the broader discourse surrounding urban resilience and sustainable development in the context of a changing and deeply uncertain climate and societal development futures.

2.0 Data and Methods

Toronto and Manchester (**Figure C1**) are both very similar cities, both in terms of population, industry, culture, and the economic renaissance both are currently undergoing. Toronto has chosen a policy of constructing flood embankments as part of a project to rejuvenate an ex-industrial area. Whereas, Manchester has opted to construct the embankment to protect existing housing stock. Both flood protection schemes are comparable with similar sized rivers, industrial heritage and reworking of the river channel, and naturalisation projects occurring just downstream.



Figure C1 A map of the two case study locations: Toronto, Canada (Green) and Manchester, UK (Blue).

2.1 Site A – Toronto, Canada

Located at (43.65416°N, -79.35378°E).

Throughout the 19th century, urban and industrial development proceeded continuously toward Lake Ontario as Toronto became established as a major economic centre in North America. In the 1830s the lakefront was at Front Street, running immediately north of the present-day Union Railway Station. As industry developed there was concern over public access to the lake, which led to extensive lake filling and as part of the 1912 Waterfront Plan, 5.2km^2 of land was reclaimed from the lake, turning it into a major industrial port, the present-day Port Lands.

As part of the Waterfront Plan, the Don River was straightened and the Keating Channel constructed leaving the river at its present alignment. The straightened Don operates as a

low gradient, rectangular-shaped channel with vertical sheet-pile retaining walls, with a largely featureless bed (TRCA, 2005). However, due to the large sediment loads of the Don River regular dredging was necessary to maintain the Keating Channel. Furthermore, widespread development within the Don watershed during the post-war period led to significant increases in sedimentation (TRCA, 2005). A reduction in shipping activities and limits on dredging resulted in increased sedimentation and debris leading to higher flood risk across the Lower Don. Although, in an effort to mitigate flood risk, regular dredging of the basin resumed in 1992.

The Lower Don West Remedial Flood Protection Project was one of the four priority projects of the Toronto Waterfront Revitalization Corporation, aimed at redeveloping the Toronto waterfront around the outlet of the Don River into Lake Ontario. The scheme aimed to provide 'permanent flood protection' for the area within the regulatory floodplain to the west of the Don River. The purpose of the project was to limit flooding on 2.1km^2 of the floodplain. The construction of the flood protection landform began in 2006, and was completed in 2015. The scheme has cost C$135 million (~£75 million) crest height ranging from 2.8m to 3.8m, with a width of 200m, using 400,000m^3 of soil (TRCA, 2005), and was *designed to withstand all failures*, flooding across the area could be extreme, with a flood depth greater than 1m projected across much of the area (**Figure C2**).

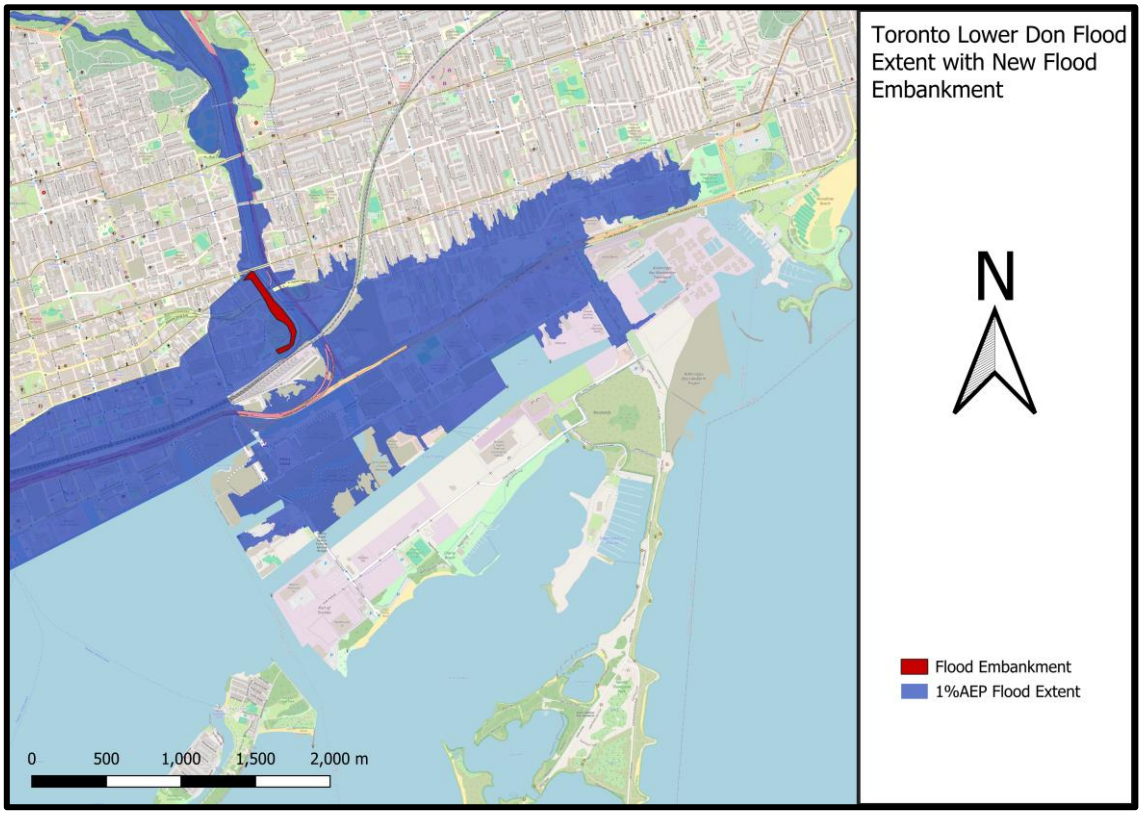


Figure C2 1% Annual Exceedance Probability (AEP) flood extent across the Lower Don River floodplain, with the flood embankment marked.

Before the construction of the flood protection embankment, flooding of the lower Don River Valley was mainly affected by two factors: the non-confining floodplain of the Don north of the railway bridge, consisting of deltaic sediments and lakefill; and the backwater effects produced by the railway embankment and other low-lying bridges, water levels in Lake

Ontario, and potential ice jams. The Corktown Common flood protection landform aims to mitigate these factors.

2.2 Site B – Manchester, United Kingdom

Located at (53.50240°N, -2.27317°E).

Manchester has a well recorded history of flooding originating from the River Irwell: the river led to great floods in 1866, 1946, 1954, 1980, and more recently in 2008, 2015, and 2020 (**Figure C3**). With the increasing frequency of rainfall leading to increased frequency and magnitude of fluvial flooding, it became necessary to construct flood defences.

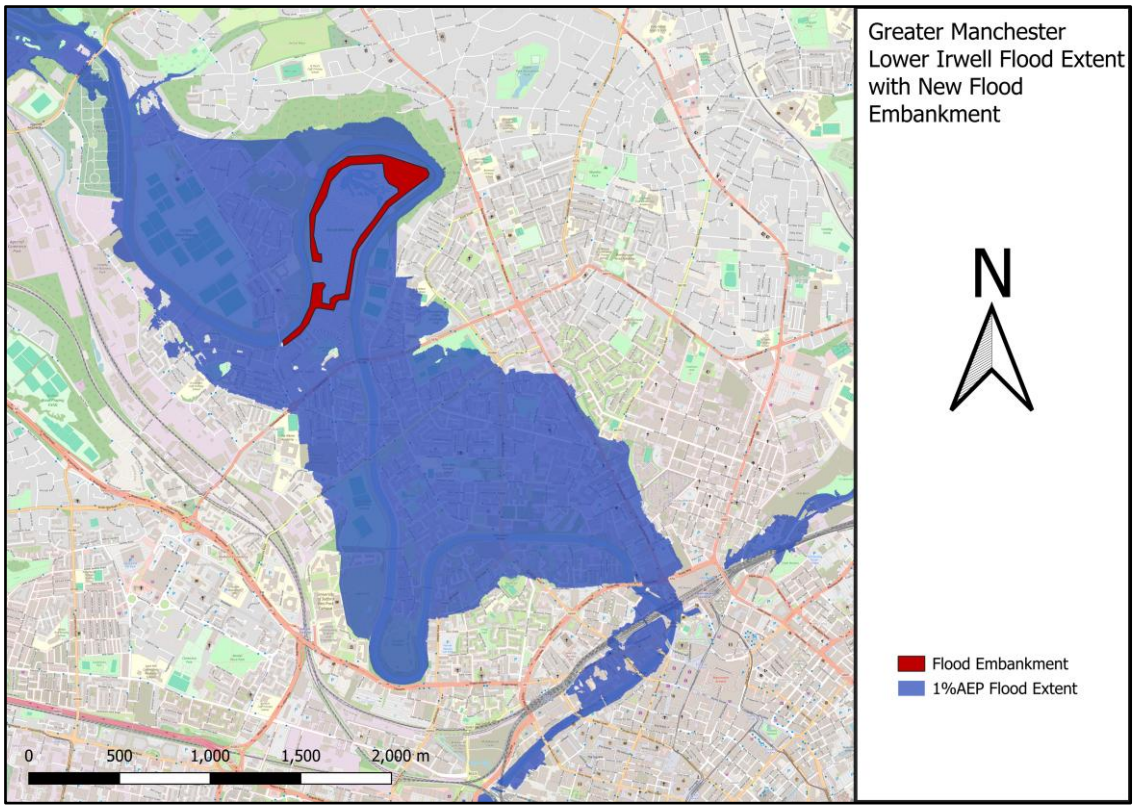


Figure C3 1% Annual Exceedance Probability (AEP) flood extent across the Lower Irwell River floodplain, with the flood embankment marked

As Salford and Manchester became the focal point for industrial Victorian Britain and an economic powerhouse for the empire, the river quickly became culverted and had its meanders removed. In the modern day, this culverting and straightening leads to problems further downstream of the study site in Manchester and Salford city centres, where frequent flooding occurs. In Salford city centre, projects to increase flood storage capacity and improve the meandering of the river have been implemented to reduce the frequency of flooding. Similar schemes have been implemented in other UK cities, such as Stoke-on-Trent and Birmingham.

To provide greater flood protection, whilst preserving local utility and ecology, the design aimed to be unobstructive. The project increased the standard of flood protection from 1.33%AEP to 1%AEP, other similar projects downstream will increase this further. The earth was removed from some areas and mounded in others, to create a large embankment, 3m in height. This created a *wet side* for flood storage and a *dry side* protected by the

embankment, in which 1400 houses and 500 businesses reside. Design work for the scheme began in 2013, with construction commencing in 2015, and the project completed in 2017. The entire scheme cost approximately £10.3 million (~C$18 million), with £9.1 million from central government and £1.2 million from the local council (Salford City Council, 2015).

Historic utility and industrialisation of Manchester has left much of the metropolitan area an urban desert, with little in the way of greenery and natural space. The *wet side* of the project created a new 0.5km^2 urban wetland 2km away from Salford city centre, and 2.8km from Manchester city centre. At full capacity, the storage area can hold 650,000m^3 of water. Ultimately, the scheme protects 0.8km^2 of development along the river, and whilst not the explicit aim, the local council hope the scheme will provide more opportunities to develop land along the river corridor.

2.3 Climate and Biophysical Data

In recent years LiDAR has developed to provide an accurate representation of urban development without the need to digitise existing mapping. Although in Canada, there is no central repository for LiDAR data, with Digital Surface Models (DSMs) available in various locations with limited year and location consistency. Only two consistent accessible DSMs existed for Toronto, of the same place, but different years. The Ontario DSM (Lidar-Derived) data providing LiDAR data from 2014 and High-Resolution Digital Elevation Model (HRDEM) offering data from 2020. These data were extracted using the Canadian Geospatial Data Extractor tool and used in this study to create the DEM of Difference (DoD).

However, in the UK, the Government is currently undertaking the Environment Agency National LiDAR Programme. The programme aimed to provide accurate elevation data at 1m spatial resolution for all of England and was undertaken between January 2017 and February 2023. Surveys are undertaken during winter months (approximately November to April each year) and published through the DEFRA Data Services Portal. LiDAR data has been provided by the Environment Agency in England and Wales since the mid-1990s, however this was with a resolution of 2m (Crutchley, 2006). Whilst this is adequate for large-scale modelling, such as for catchment flooding, it is not as useful for analysing an urban landscape, therefore 1m resolution LiDAR was selected where possible.

Constructing a DoD, estimating elevation change, has been described as DSM differencing or differential analysis, and is widely used in physical geography, e.g., assessing the evolution of drainage basins (Brasington *et al.*, 2003), detection and estimation of landslides (Tsutsui *et al.*, 2007), and estimating the change in sediment budgets (Wheaton *et al.*, 2009). While the simulation of DoDs to identify flood exposure and urban environment change is relatively novel (Breen *et al.*, 2024), the use of DSMs has long been established in studying human settlements (e.g. Priestnall *et al.*, 2000; Yan *et al.*, 2015). Coupled with the large amount of research already using DSM differencing in physical geography, the analysis reported here also demonstrates knowledge transfer of the method to human geography, and structure identification. The simulated DoD of a settlement shows direct change in the urban landscape across time, providing an accurate method of longitudinal urban analysis, with the accuracy of the model directly linked to the spatial resolution of the DSM input.

In Canada, FRM has largely been down to individual provinces and lower level governance instead of being managed on a federal level. This, as a consequence, may have led to there also being no central repository of these data (Henstra *et al.*, 2019). Moreover, despite many

municipalities having flood extent maps available, many are difficult to locate and were generally unsuitable for risk communication purposes (Henstra *et al.*, 2019). The Toronto flood hazard extent data can be sought from the ArcGIS online repository *FloodPlainMappingIndex*, this extent is based on a 1%AEP flood event or a Hurricane Hazel level event (Minano *et al.*, 2021). However, unlike flood modelling in the UK, the Canadian Government Flood Hazard Area (GFHA), includes the impacts of flood defences on flood extent. Although, Insurance Flood Hazard Areas (IFHAs) do not, and therefore provide an absolute flood extent if the impacts of flood defences are ignored. Although in combination with the extent of Spill Zone 3, the GFHA can replicate the IFHA (Michael Van Valkenburgh Associates Inc, 2014). Furthermore, due to the combination of Hurricane Hazel level events, as well as 1%AEP events, in TRCA flood hazard extent mapping and planning, unique to Toronto, the difference between mapping using flood defences or not is minimal for a flood 30cm or greater (Minano *et al.*, 2021). This similarity means that the TRCA GFHA provides a useful and openly accessible facsimile for the hidden privatised IFHA spatial data, and facilitates comparison to the UK flood extent, obtained from the Environment Agency, and socio-spatial impact mapping.

2.4 Socio-economic Data

In Canada, census data is gathered by Statistics Canada in five-year cycles. The population is divided into four levels: first-level divisions of provinces and territories, then divided into second-level census divisions, then by third-level municipalities, and finally fourth-level dissemination areas (DAs). These DAs are small and relatively stable geographic units with a population generally ranging between 400 and 700 people and together, they cover the entire Canadian land mass.

Despite Canadian population data being collected every 5 years, census data used in this project was from 2011 and 2021, to bring the analysis in line with that conducted by the UK Office for National Statistics (ONS), which only collects data once per decade. The ONS is responsible for the collection of statistics related to the economy, population and society of the UK, although some responsibility is devolved to Scotland, Northern Ireland and Wales. Several subdivisions range from national statistics covering the entirety of England, to Output Areas (OAs), the smallest geographic unit. Similar to DAs, OAs generally contain between 100 and 625 people.

These high-resolution datasets are important; the greater the spatial resolution of population, the better it can be spatially linked and georeferenced, and in the context of this analysis, provide a truer representation of population affected by flooding and protection from flood embankments, and the unintended socio-spatial impacts thereof. Therefore, for this analysis, both, population count and household occupancy was used. Population count provides an absolute indication of where people were living at that period. Household occupancy, on the other hand, adds some context, describing how people were living: the number of people living in a single household unit, and, when compared longitudinally, can give insights into internal migration and movement. If there are then no increases in housing stock, increases in household occupancy can also infer an increase in population density as more people squeeze into smaller spaces.

3.0 Results

3.1 Toronto

The total population in Toronto has increased from 2,575,920 (2011) to 2,794,360 people (2021), a ~0.9% rise per annum. To accommodate this growth, the city has allowed the construction of new development in previously underdeveloped areas. Over time, the historic industrial areas of the West Don lands, those areas in the Flood Hazard Area (FHA) immediately west of the Don River, have been redeveloped into residential and commercial property.

Changes in urban growth can be seen when comparing before the embankment (2014) and after construction (2022) DSMs (**Figure C4**) of the Lower Don valley. A lot of development in the West Don lands area occurs in the 1%AEP FHA, the area of land floodable if current defences were to be ignored, the most striking of which is a high rise between 80m and 160m tall immediately adjacent to the Don River. Other development also occurred in the FHA, some smaller scale development in the immediate area, and others further to the south-west closer to the lakeshore.

These urban changes are also replicated socio-spatially, with increased population growth in the area, raising by 2.7% per year, from 2011 to 2021, across the Lower Don area. However, the population living in the FHA increased by 4.7% annually (**Table C1**). In contrast, across the same timeframe, the average housing occupancy in the Lower Don area fell by -0.02% annually, almost negligible. Yet, of those in the FHA, the average housing occupancy fell by -0.45% per year (**Table C1**). The combination of an increasing population and falling housing occupancy rate suggests a large growth in housing construction (horizontal development) in the FHA.

This increase in population between the 2011 and 2021 censuses, across the Lower Don area, both, inside the FHA and outside, is evident in the mapping. Across the decade population increased dramatically in the West Don lands, potentially trebling from 0-2000 people to 4000-6000 people, highlighting a dramatic increase in population in these areas (**Figure C5**). Other DAs in surrounding areas also increased. However, those closer to downtown, to the west of the FHA, decreased, one even falling by a similar amount of people that increased in the West Don lands (**Figure C5**). Outside of the FHA, increases in population were less spatially focused, with DAs increasing to the north-west of the study site, and those just outside the FHA also increasing. However, these increases were more diffuse than those inside the FHA.

In contrast, decreases in the average housing occupancy in the FHA were less apparent: only two DAs visibly decreased, one from the 3-4 occupants' band to the 1-2 occupants' band, and another closer to downtown falling from the 2-3 band to the 1-2 band (**Figure C6**). Whereas the other DAs in the FHA in the West Don lands were less apparent in theirs decreasing within the band, rather than between them. However, this was not unique to the FHA, with not many DAs showing any visible change between the 2011 and 2021 censuses. However, outside of the FHA there is a decrease in average housing occupancy in a grouping of DAs to the north of the FHA in the Regent Park area (**Figure C6**), tied with an increase in population (**Figure C5**), and some development evident in the LiDAR comparison (**Figure C4**). These new buildings are a connected collection of high-rises on

Dundas Street, outside of the sphere of the West Don lands development. This alternative development suggests a multipolar area, with development occurring in multiple areas. However, development outside of the West Don lands FHA is more diffuse and growing slower than those inside the FHA (**Table C1**).

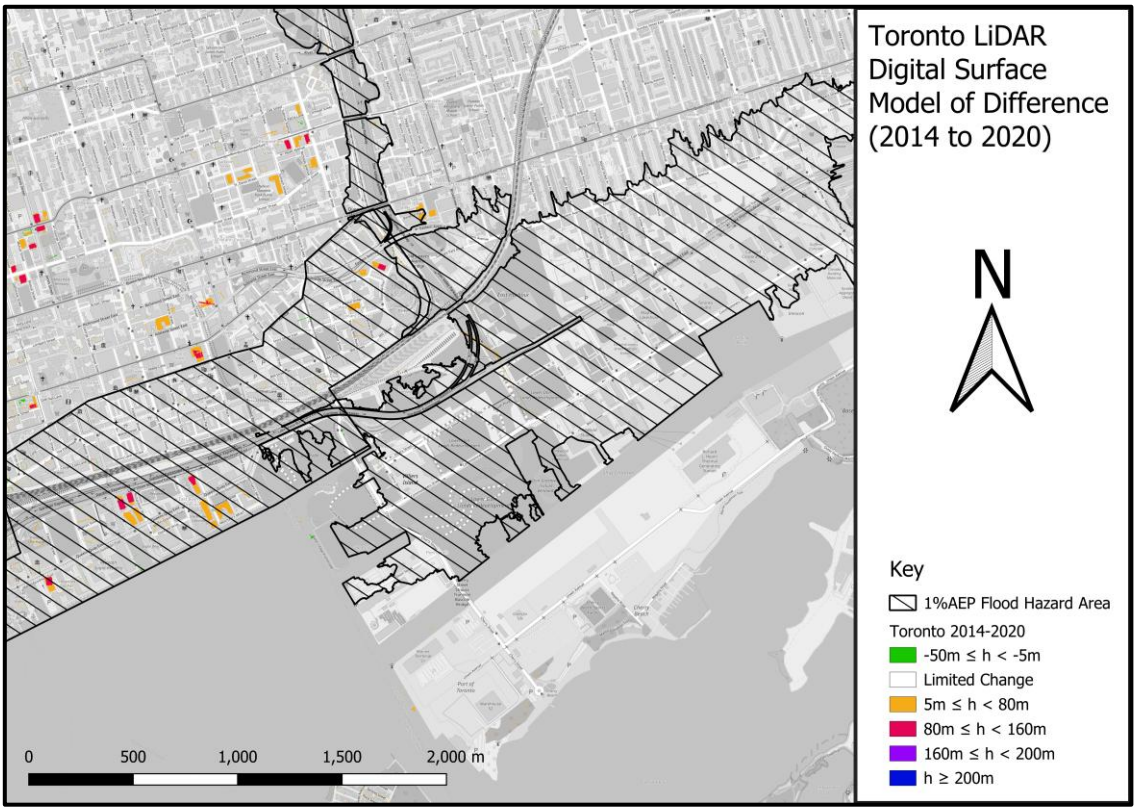


Figure C4 LiDAR Digital Surface Model of Difference for the Lower Don Valley, Toronto (2014 to 2020)

Table C1 Census data from the Lower Don Valley (37.48km²). Exposed population is determined by residing in the 1%AEP Lower Don Hazard Zone (4.87km²). AGR represents the Annual Growth Rate, the change per year. Density is measured in km^{-2}. HO represents housing occupancy, people per household.

Risk Category	Year	Population	Density	AGR
Total Lower Don Population	2011	348,687	9,303	+2.68%
	2021	442,226	11,799	
Exposed Population	2011	49,469	10,158	+4.69%
	2021	68,277	14,020	
Average HO in Lower Don	2011	2.09		-0.02%
	2021	2.09		
Average HO in Exposed Areas	2011	2.02		-0.45%

	2021	1.93	

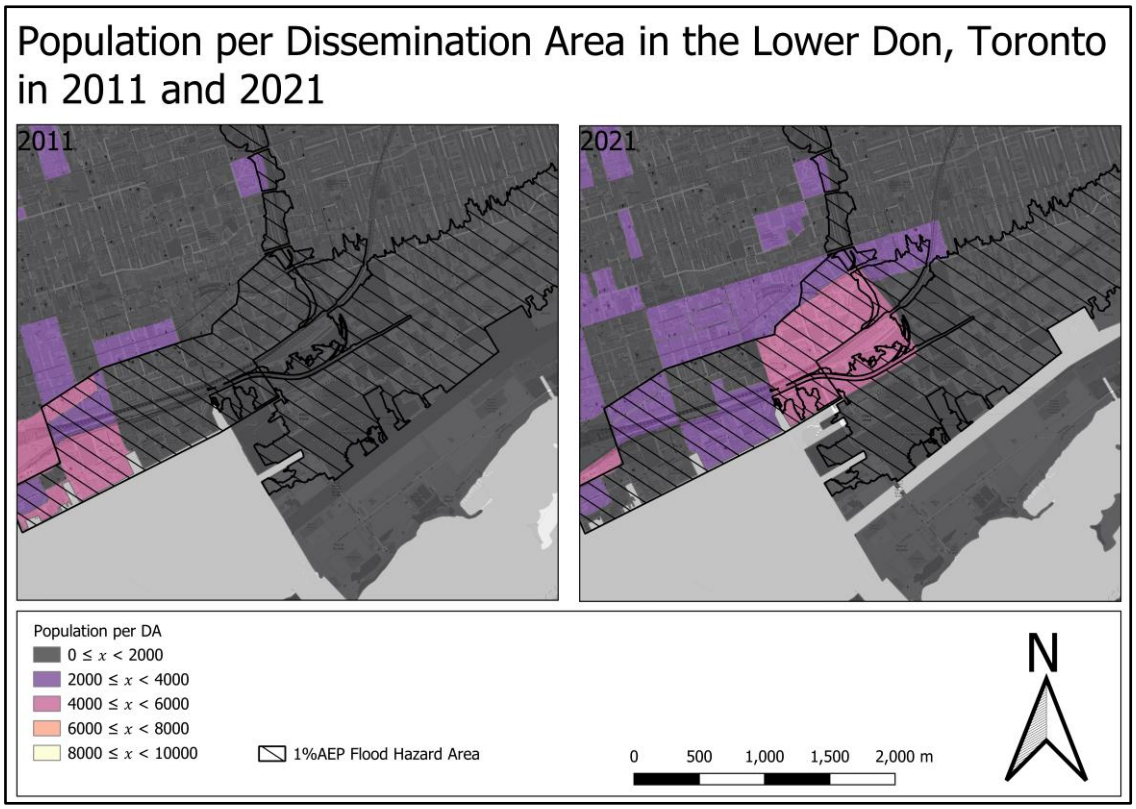


Figure C5 The population per DA across the Lower Don area from both the 2011 (left) and 2021 (right) censuses.

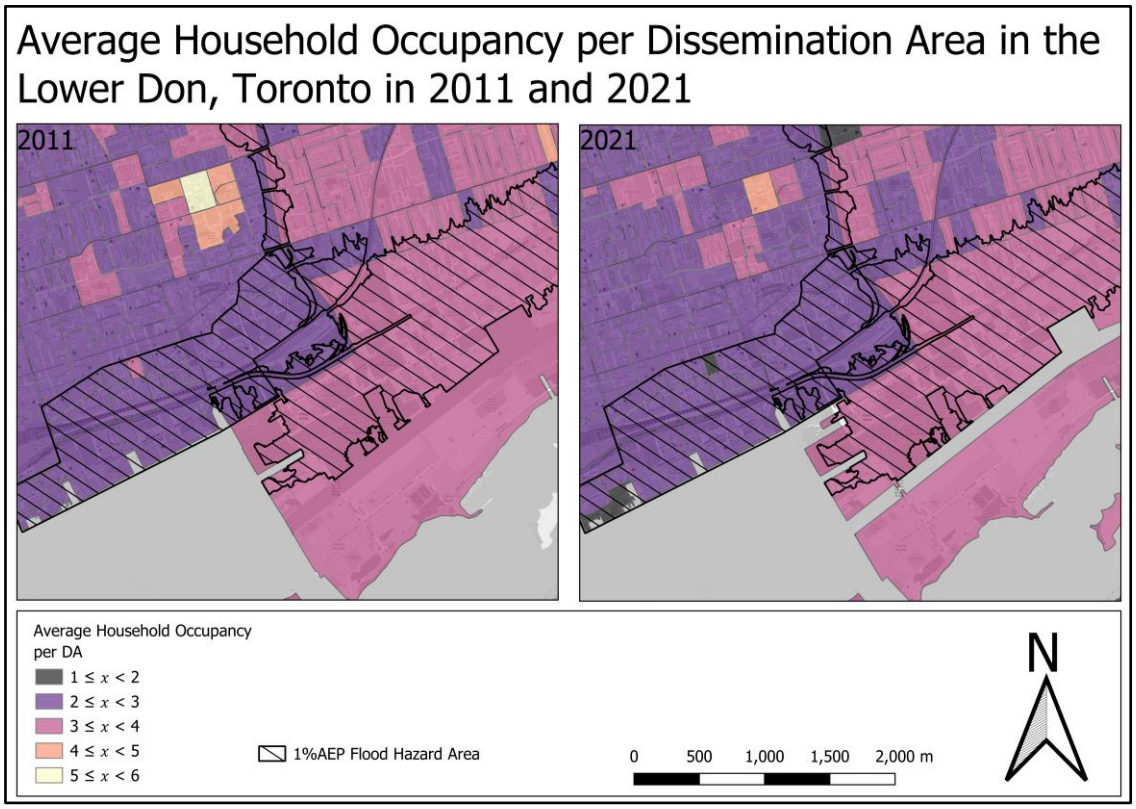


Figure C6 The average housing occupancy of households per DA across the Lower Don area from both, the 2011 (left) and 2021 (right) censuses.

3.2 Manchester

Manchester has a population of 2,682,528, as of the 2011 census. Rising by about 0.7% per annum to 2,867,769 people in 2021. Manchester has a long industrial history with many brownfield sites. FRM within the urban area tends towards maintaining rather than encouraging new development. The new flood embankment at Castle Irwell aimed to reduce the impact of flooding from the River Irwell whilst naturalisation works also take place further downstream. This area of Manchester has been developed for decades, with many early 20th century terraces, however, new development began towards the latter end of the 2010s along the banks of the Irwell and at the rear of the Castle Irwell site.

This urban development continued across the decade. Between the 2011 and 2020 DSM, a new urban development was constructed, replacing old industry and existing terraced houses (**Figure C7**), although this also occurred in the FHA across the river from the Castle Irwell site. However, the LiDAR data of this image is not recent enough to show new development, encroaching onto the Castle Irwell loop, less than 20m from the flood embankment, or a new large-scale housing estate completed in 2023, replacing the disused industrial buildings to the east of the peninsula, also in the FHA (**Figure C7**). Outside of the FHA, there is the construction of a new housing estate adjacent to the railway to the north-west of the Castle Irwell site, as well as new medium density development at the University of Salford site to the south (**Figure C7**).

In total, exposed population at the study site rose by 4.0% per annum, from 34,544 from before the embankment, to 48,207 afterwards, rising at a greater rate than that of the total Lower Irwell population, 2.7% annually (**Table C2**). Similarly, across the decade, the average housing occupancy in exposed areas increased from 2.05 to 2.18 people per household, compared to the increase of 2.16 to 2.28 people per household in areas outside of the FHA (**Table C2**).

Across the decade, the population at the immediate Lower Irwell site decreased, most likely as the old terraced houses were demolished. However, those slightly farther away from the site but still in the FHA increased, such as the OA to the south of the site which increased from the 400-700 band to the 1300-1600 band (**Figure C8**). Whilst the largest increase was driven by development at the University of Salford, even with this area disregarded, FHA population increases by 3.56% annually, primarily along riverside OAs. Whereas, outside of the FHA there was little change, with the exception of some decreases, but by only one band, from 700-1000 people to 400-700 people (**Figure C8**). Little visible change, but increasing population (**Table C2**), would suggest that outside of the FHA, population increase is more diffuse and not localised to a specific area.

Household occupancy remains stable across the FHA, with OAs continuing to operate in the 2-3 people per household band (**Figure C9**). With an increasing housing occupancy, but visually stable changes, this would suggest that household occupancy increases are more diffuse across the Lower Irwell area in the FHA (**Table C2**). However, there were many decreases in the average household occupancy in areas outside of the FHA (**Figure C9**), and therefore in these areas less people are living together. However, overall the annual change in household occupancy in both areas remains positive (**Table C2**).

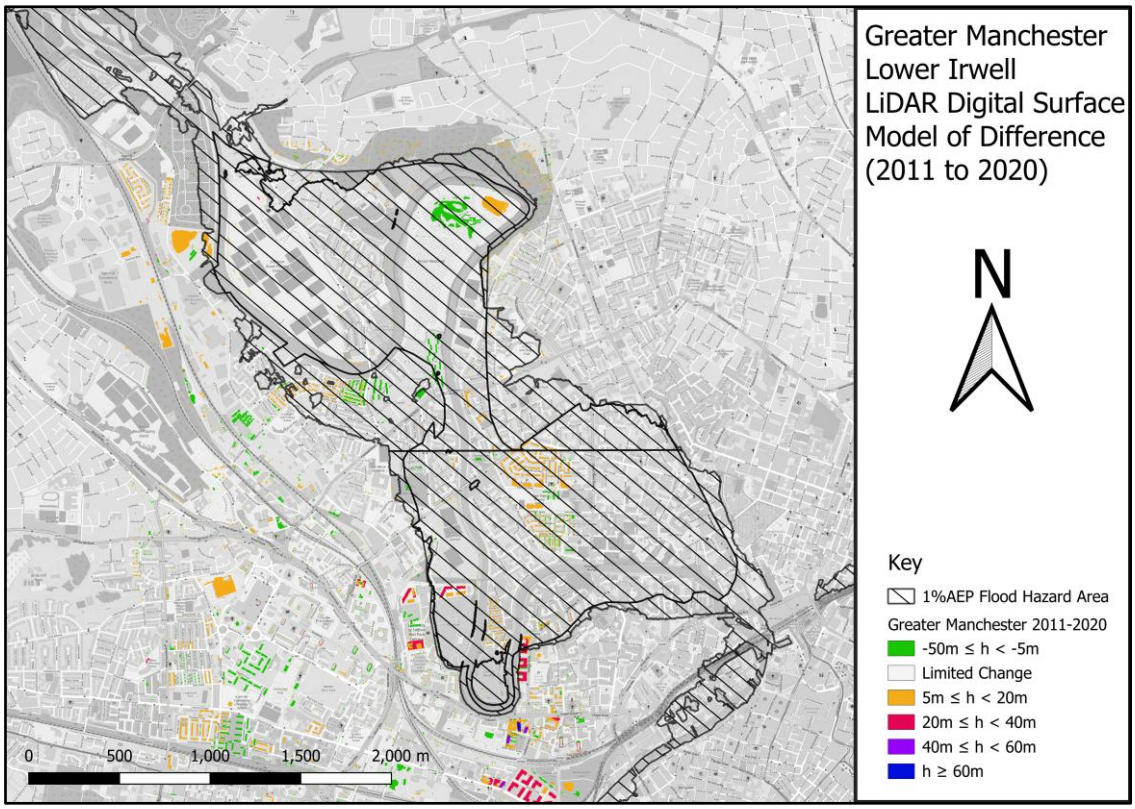


Figure C7 LiDAR Digital Surface Model of Difference for the Lower Irwell Valley, Manchester (2011 to 2020)

Table C2 Census data from the Lower Irwell Valley (9.37km²). Exposed population is determined by residing in the 1%AEP Lower Irwell Hazard Zone (3.05km²). AGR represents the Annual Growth Rate, the change per year. Density is measured in km^{-2}. HO represents housing occupancy, people per household.

Risk Category	Year	Population	Density	AGR
Total Lower Irwell Population	2011	121,417	12,958	+2.72%
	2021	154,423	16,481	
Exposed Population	2011	34,544	11,326	+3.96%
	2021	48,207	15,805	
Average HO in Lower Irwell	2011	2.16		+0.55%
	2021	2.28		
Average HO in Exposed Areas	2011	2.05		+0.63%
	2021	2.18		

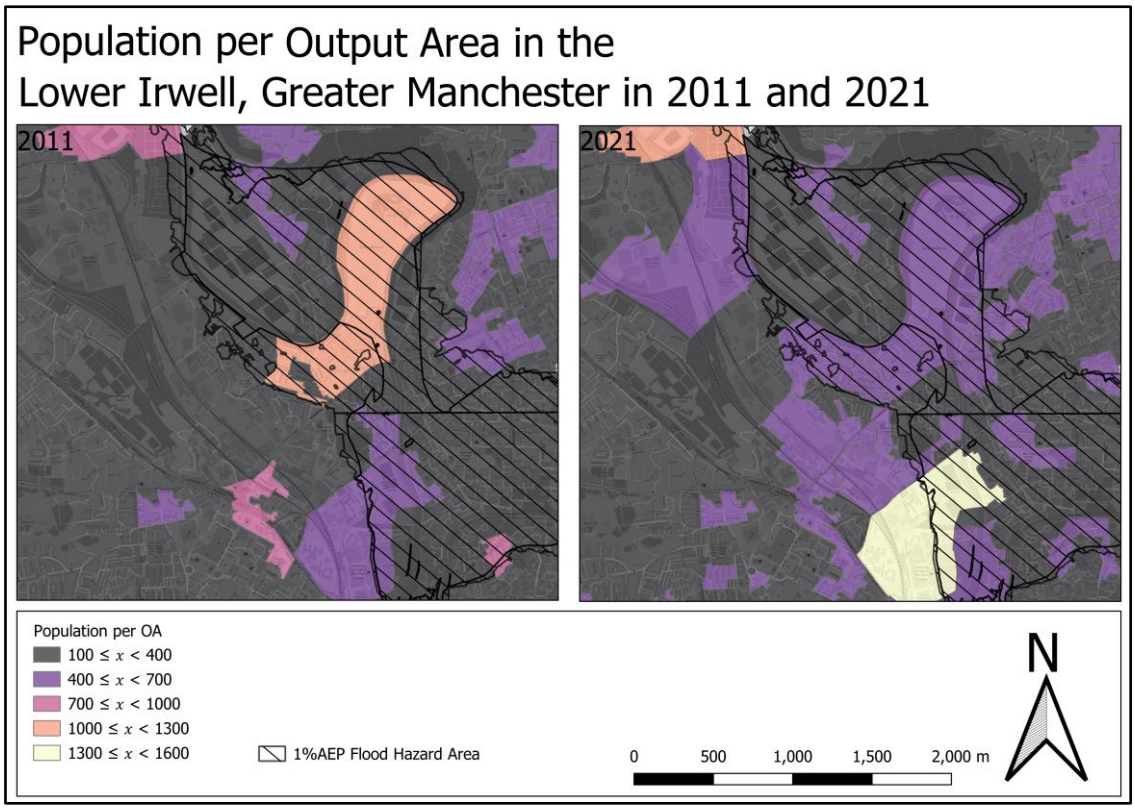


Figure C8 The population per OA across the Lower Irwell area from both the 2011 (left) and 2021 (right) censuses.

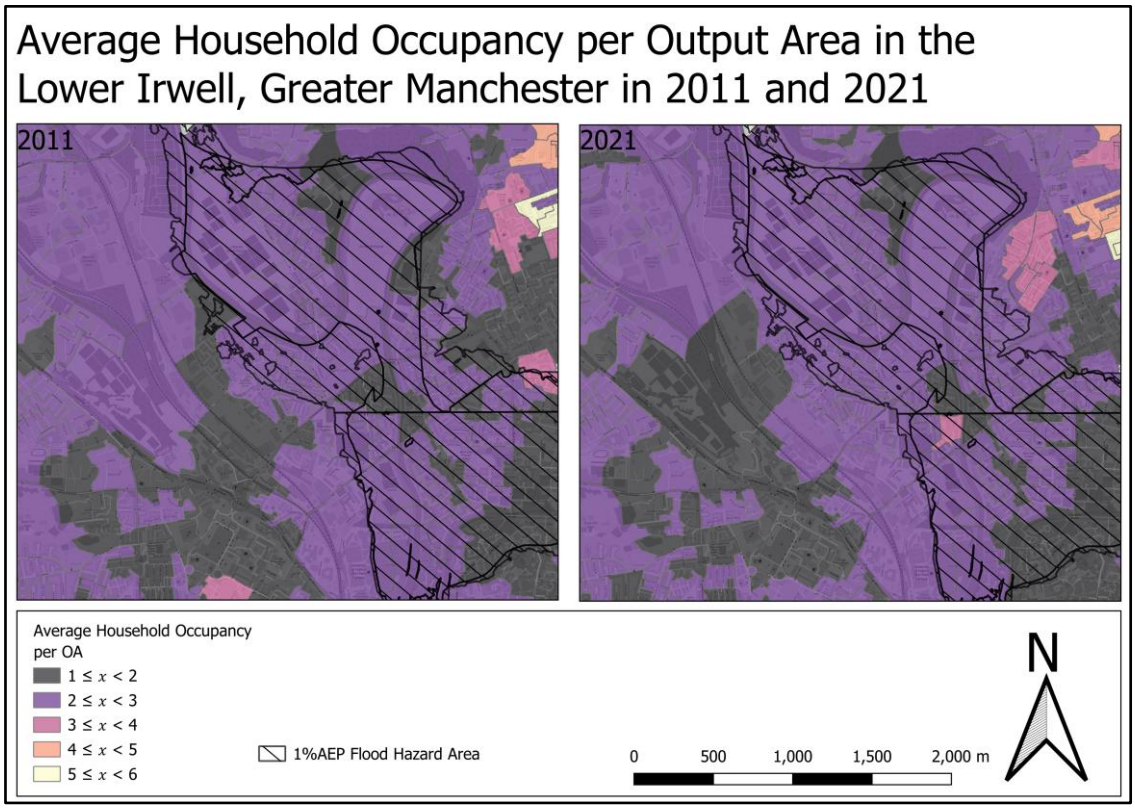


Figure C9 The average housing occupancy of households per DA across the Lower Irwell area from both the 2011 (left) and 2021 (right) censuses.

4.0 Discussion

The primary purpose of riverside flood embankments is to constrain and direct the flow of water along a river valley. In the Don River (Toronto) and the River Irwell (Manchester) these defences have been enhanced further by the construction of flood embankments back from the river channel to incorporate certain sections of the floodplain, referred to as the *wet side* of the embankment. The Don Valley frequently floods, exacerbated by continued upstream urbanisation and development, leading to greater runoff into the Don River. Climate change has the potential for more frequent and intense rainfall (Arnell and Gosling, 2014). Hence the creation of the Corktown Common flood embankment was to protect areas in order to develop them. In contrast, the Castle Irwell flood embankment was built to protect areas in order to maintain the existing stock. These newly protected sites can provide an amenity for local populations, although overuse for recreation may increase the risk of breach formation as a result of structural weakening: flood embankments are not infallible (Dyer, 2004).

In Toronto, constriction of the Corktown Common flood embankment, led to an increase in urban development in the FHA with the construction of high-rise buildings in the area immediately adjacent to the Don River, reflecting a planned transformation of the previously underutilised area towards high-density urbanisation (**Figure C4**). The increase in FHA urban development is also mirrored by the increases in exposed population of 4.7% annually, compared to 2.7% outside the FHA (**Table C1**). Although, this growth was accompanied by a decrease of household occupancy by 0.45% annually, compared to ±0% outside of the FHA, indicating that the new development likely catered to smaller household sizes from the construction of high-rise apartment buildings rather than lower density family homes (**Figure C6**), a hallmark of a planned urban neighbourhoods (Broitman and Koomen, 2015).

In contrast, the Castle Irwell embankment was constructed with the primary aim of protecting existing housing stock, rather than encouraging new development. Yet, the embankment was accompanied by unplanned new development within the FHA, leading to a population increase of 4.0% annually, compared to 2.7% outside the FHA (**Table C2**). Although, in opposition to the planned development in Toronto, the immediate development at the Castle Irwell site was low density housing along the River Irwell (**Figure C7**). Moreover, whilst FHA urban development was concentrated and localised in Toronto, along the River Irwell, development was more spatially diffuse; an output of undirected urban expansion. This is reflected by the more diffuse changes in exposed population, with a decrease in population at the immediate Castle Irwell site but increases along the River Irwell (**Figure C8**), leading to a general increase in population across the FHA in areas protected by the embankment. Moreover, in these protected, but still exposed, areas, housing occupancy increased annually by 0.63% (**Table C2**), in direct contrast to the controlled development in Toronto. This increase in the FHA ,though, is nominally more than the 0.55% annual increase outside of the FHA in the Lower Irwell area (**Figure C9**).

These two metropolitan areas demonstrate distinct socio-spatial impacts, shaped by differing objectives and planning frameworks. The creation of the Corktown Common flood embankment in Toronto, aimed at enabling medium- and high-density development, which led to significant urban transformation. The population increase and the shift towards a decrease in housing occupancy reflect a deliberate attempt to urbanise a previously

underutilised area. In contrast, the Castle Irwell embankment, primarily designed to protect existing building stock, yet inadvertently spurring new unplanned development, leading to a more dispersed and low-density housing growth along the River Irwell.

These findings underscore the complexity of FRM strategies and the unintended consequences, particularly when urban development is influenced by the perceived safety provided by flood defences. This identified phenomenon underpins the concept of the *Safe Development Paradox*, where efforts to mitigate flood risks through infrastructure such as flood embankments, which can inadvertently encourage development in hazard-prone areas, increasing overall exposure, potentially negating gains obtained from managing flood hazard, and unintentionally increasing flood risk (Burby, 2006). Flood protection structures and landforms can reduce immediate risks, however, a false sense of security associated with them can drive risky development, leading to greater potential for catastrophic losses in the long-term (Breen *et al.*, 2022).

The differences in urban development and socio-spatial patterns at the Corktown Common and Castle Irwell sites, and their surrounding areas, highlight the importance of integrated urban planning and flood risk management. In Toronto, urban development was planned alongside FRM measure, constructing and managing with a more controlled and comprehensive approach, in contrast to the unplanned, diffuse development along the River Irwell. These outcomes illustrate the challenges of managing urban expansion in the absence of coordinated FRM and planning policy. This comparison reinforces the ideal that a successful and comprehensive FRM strategies must be coupled with land-use policy and proactive urban planning to prevent the escalation of risk driven by the Safe Development Paradox and associated unintended socio-spatial impacts and outcomes. As populations grow and cities become more urbanised, houses and buildings will inevitably be built, to which building-level flood protection measures can counteract the potential negative effects of flood protection structures, which can lead to a decrease in annual flood risk (Haer *et al.*, 2020). Disaster risk reduction and urban resilience must incorporate a holistic approach that integrates flood risk management, urban planning, and community engagement to sustainably manage flood risk and ensure long-term resilience (Rehman *et al.*, 2019; Hemmati *et al*., 2020).

5.0 Conclusion and Outlook

This comparative analysis of the socio-spatial impacts of flood embankments in the metropolitan areas of Toronto, Canada, and Manchester, UK, highlights the significant influence of flood protection structures on urban development patterns and population distribution in areas protected from flooding, and the impacts and utility of spatial planning and land-use policies when operated in tandem with FRM strategies.

The Corktown Common flood embankment was built in order to reduce flood hazard and facilitate the growth of housing in Toronto, transforming previously underutilised industrial land into high-density residential and commercial spaces, leading to a significant and localised increase in population within the FHA. In contrast, the Castle Irwell flood embankment was constructed to protect existing development from flooding, and did not aim to reduce flood hazard in order to stimulate urban growth as its primary purpose (CLES, 2015). Yet population and urban development increased regardless unplanned, without consideration of residential risk, reducing the sustainability of the flood protection landform.

This growth was more diffuse and of lower density than that in Toronto, which spatially managed population growth in accordance with planning policy and the design of the overall Corktown site.

These findings underscore the importance of integrating flood risk management with urban planning and development policies to ensure that the benefits of flood protection are achieved and potential unintended consequences are minimised. The study contributes to the growing body of literature that advocates for a more holistic approach, one that considers not only the immediate protection offered by flood protection measures, but also knock-on broader socio-spatial impacts and future flood risks when these emergent phenomena are not controlled. The implications of this research extend beyond the specific cases of Toronto and Manchester; as urban populations continue to grow and climate change intensifies, cities worldwide will face increasing pressure to manage flood risk whilst accommodating new development, creating policies and a new local paradigm that balances urban growth with the need to maintain and enhance community resilience.

Future research should focus on developing these integrative measures, and assessing their potential impacts based on real-world evidence from areas that currently manage and integrate urban growth and flood risk management, and those that do not. Moreover, risk communication strategies should also be considered, including their impacts and potential as a way to mitigate the unintended consequences of flood protection measures, such as embankments. These communication strategies should enable residents to remain aware of residential risks which are crucial for reducing vulnerability and enhancing disaster preparedness and responsiveness. These strategies could help mitigate the unintended consequences of overreliance on structural defences and promote more sustainable patterns of urban development as well as nature-based solutions to mitigate risks of flooding.

Flood embankments play a vital role in protecting our urban areas from flooding, and their socio-spatial impacts must be carefully managed to avoid creating new risks. By adopting a more integrated and proactive approach to flood risk management, cities can better navigate the challenges of urban growth and climate change, ensuring that their communities remain resilient and sustainable in the face of future uncertainties.

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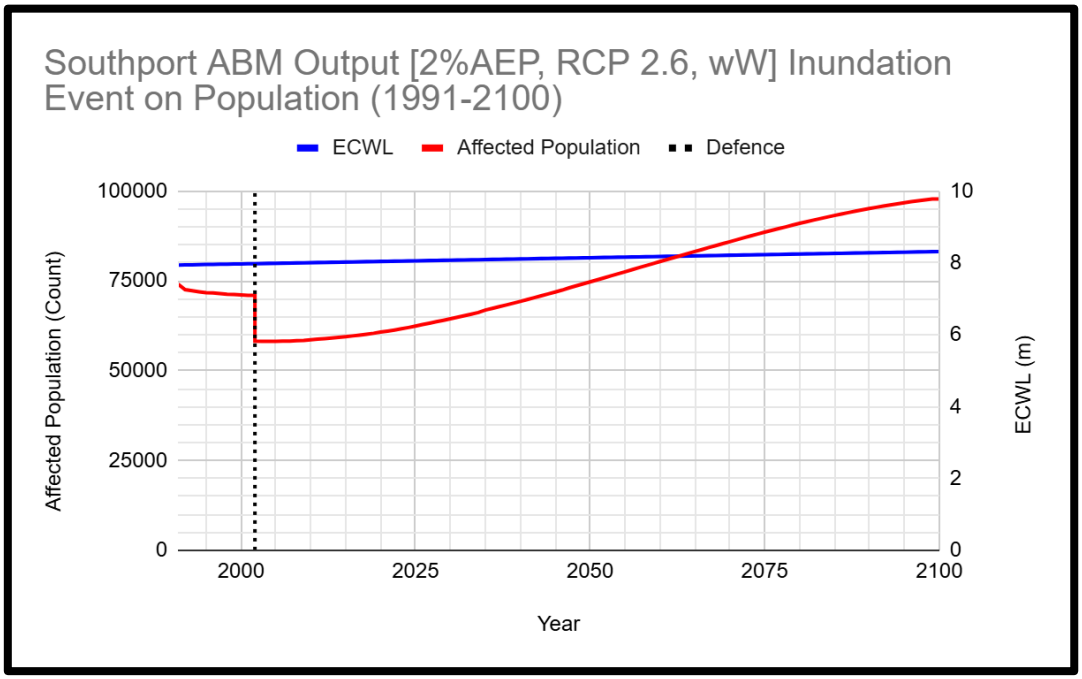
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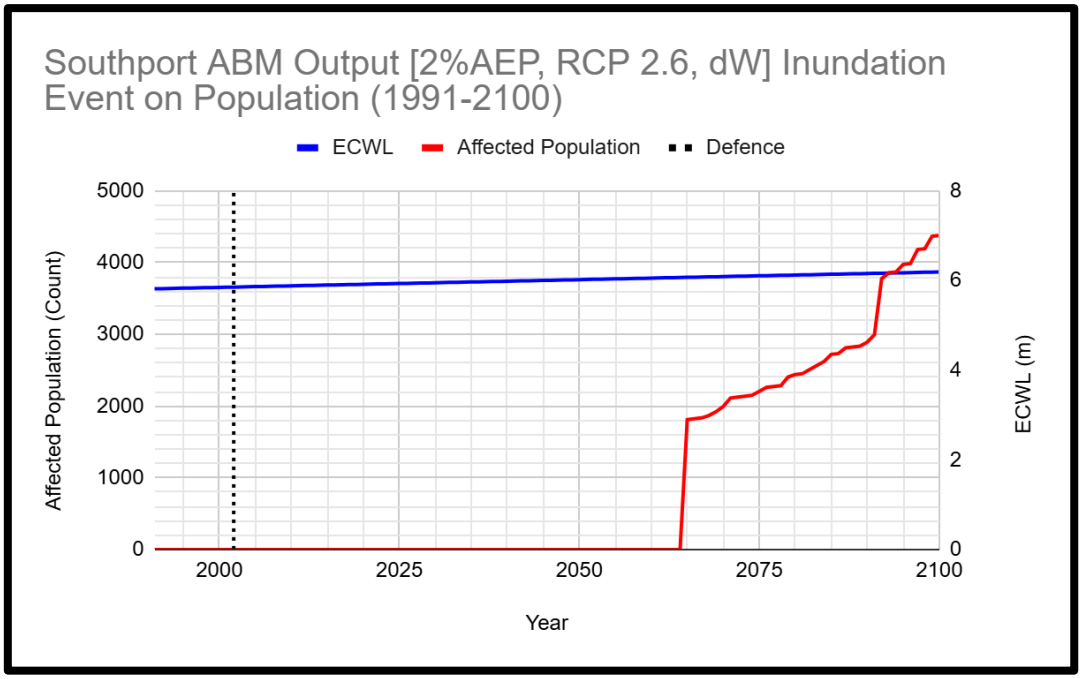
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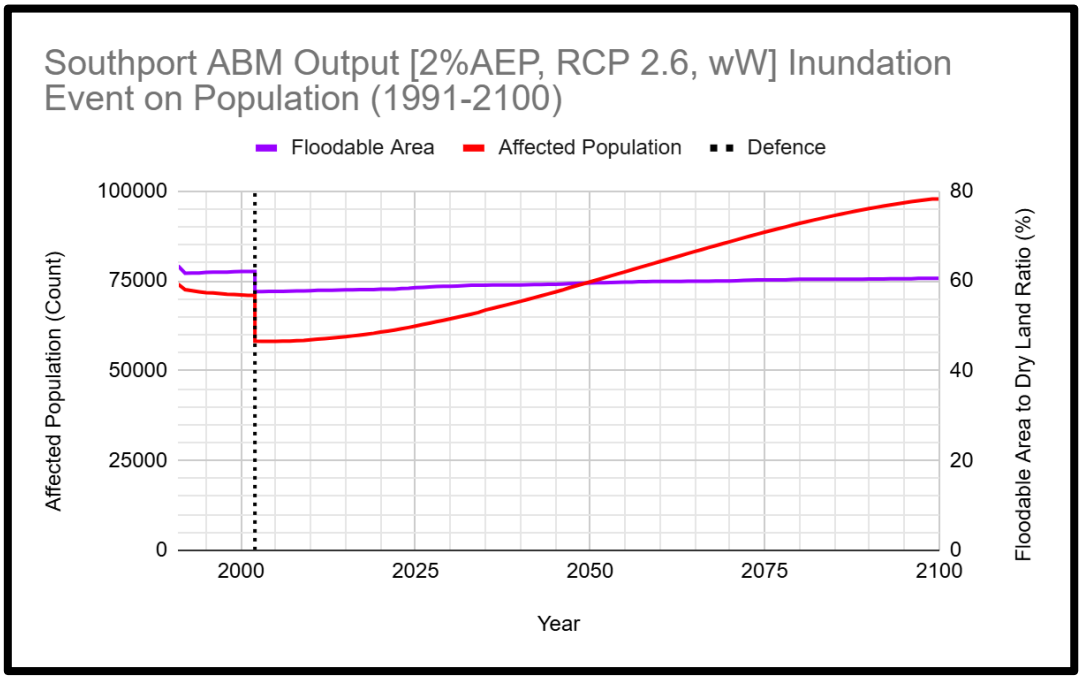
Site	Scenario	Probability	Page
Southport	RCP 2.6	2% AEP	317
		0.5% AEP	319
		0.1% AEP	321
	RCP 4.5	2% AEP	323
		0.5% AEP	325
		0.1% AEP	327
	RCP 8.5	2% AEP	329
		0.5% AEP	331
		0.1% AEP	333
Weston-super-Mare	RCP 2.6	2% AEP	334
		0.5% AEP	336
		0.1% AEP	338
	RCP 4.5	2% AEP	340
		0.5% AEP	342
		0.1% AEP	344
	RCP 8.5	2% AEP	346
		0.5% AEP	348
		0.1% AEP	350
Portsmouth	RCP 2.6	2% AEP	351
		0.5% AEP	353
		0.1% AEP	355
	RCP 4.5	2% AEP	357
		0.5% AEP	359
		0.1% AEP	361
	RCP 8.5	2% AEP	363
		0.5% AEP	365
		0.1% AEP	367

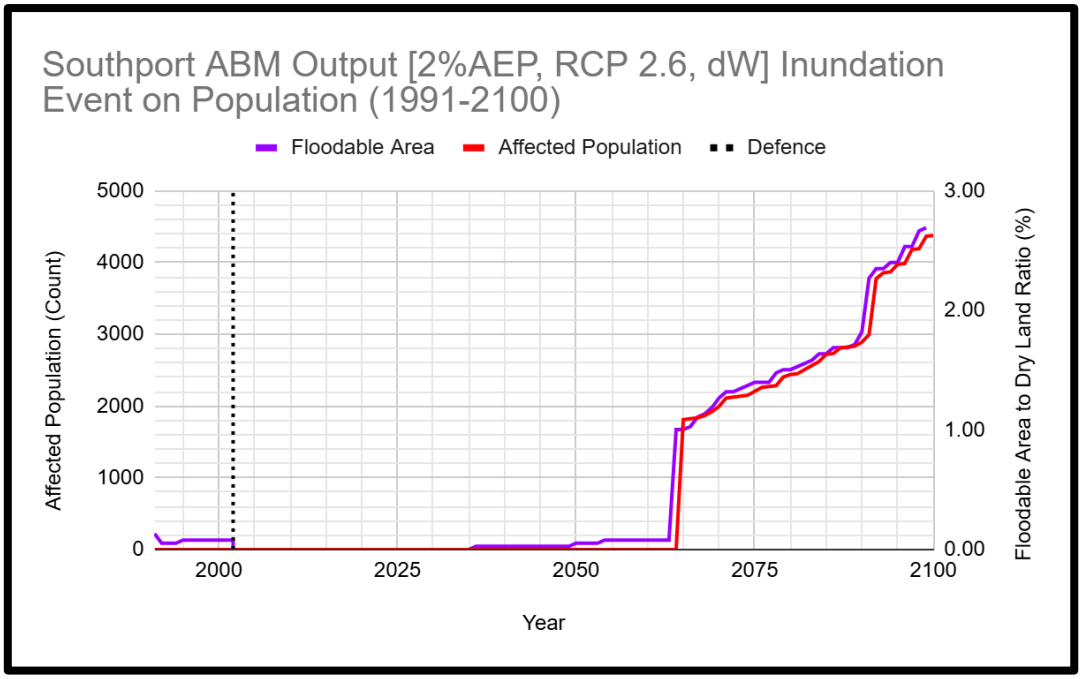
Case Study A

RCP2.6 - 2%AEP

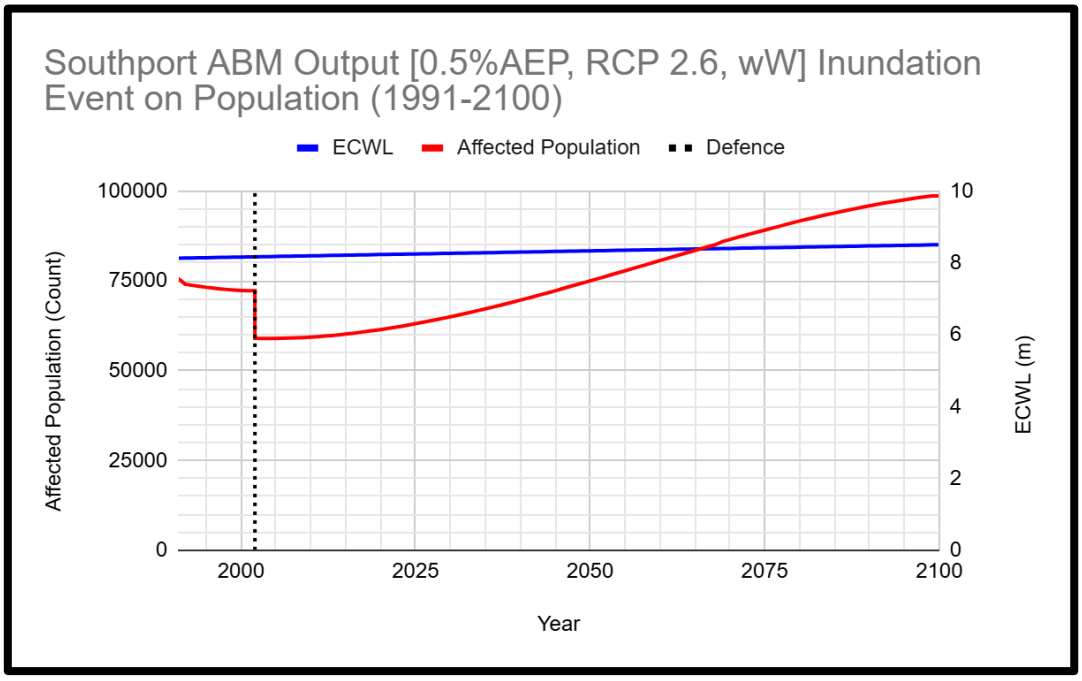


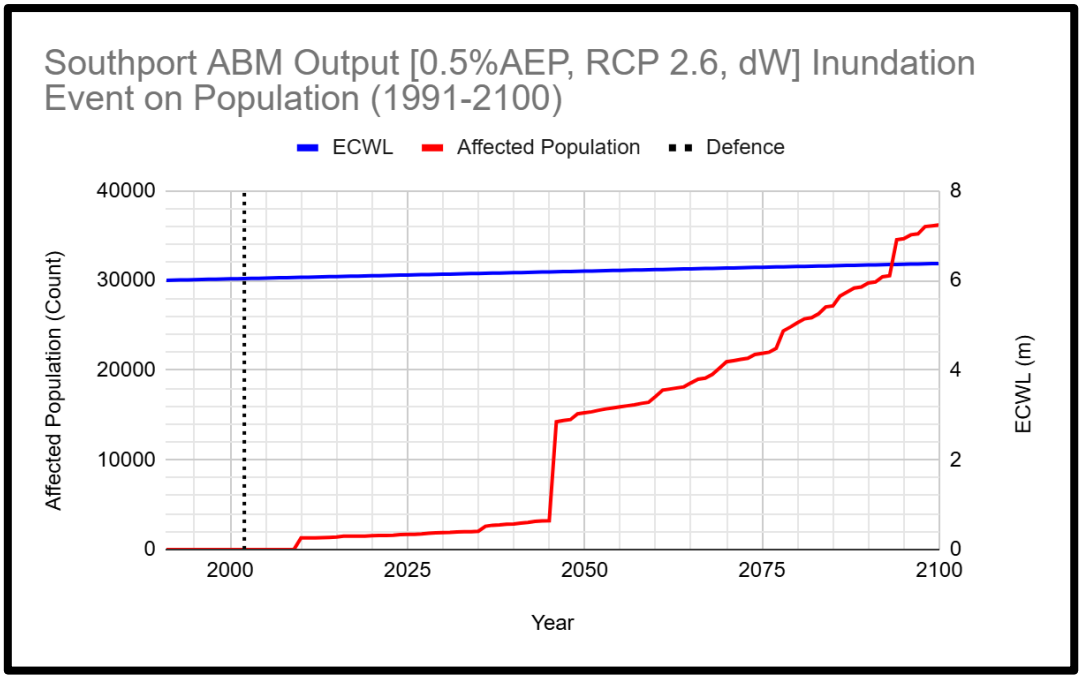


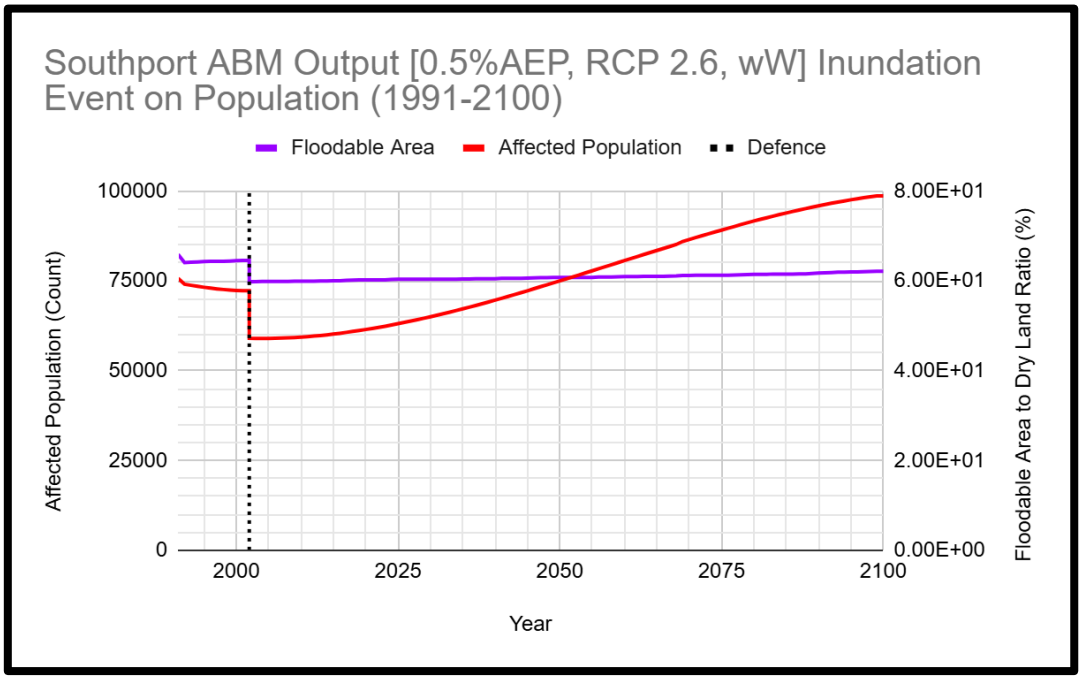

Southport ABM Output [2%AEP, RCP 2.6, wW] Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
100000
75000
50000
25000
0
80
60
40
20
0
2000
2025
2050
2075
2100
Year

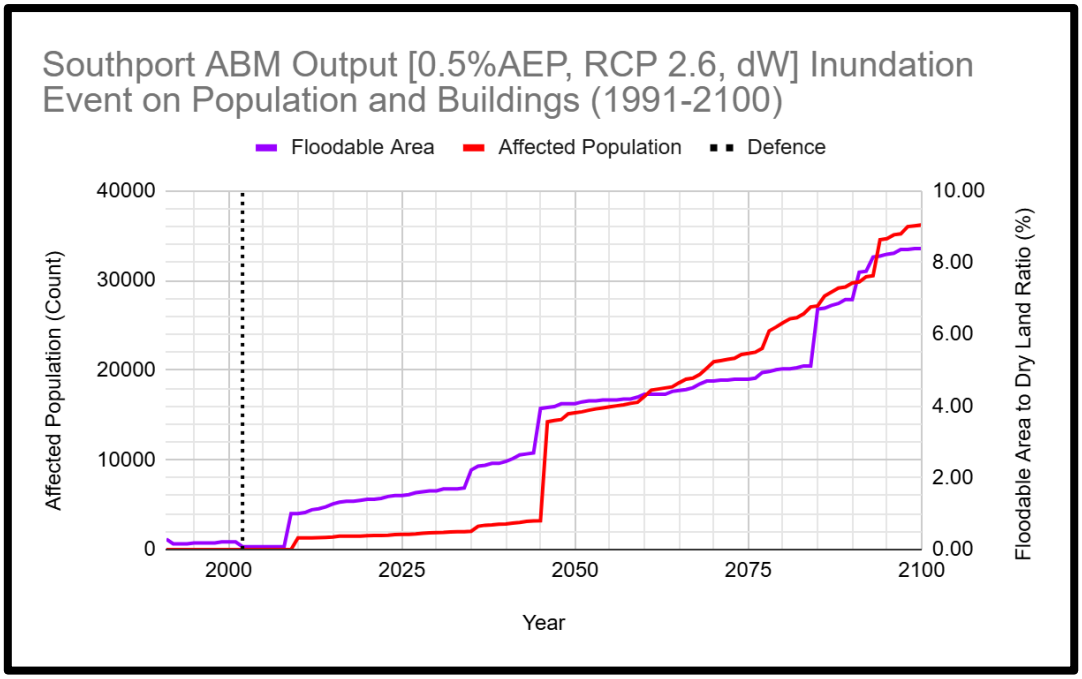

Southport ABM Output [2%AEP, RCP 2.6, dW] Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
5000
4000
3000
2000
1000
0
3.00
2.00
1.00
0.00
2000
2025
2050
2075
2100
Year

RCP2.6 - 0.5%AEP

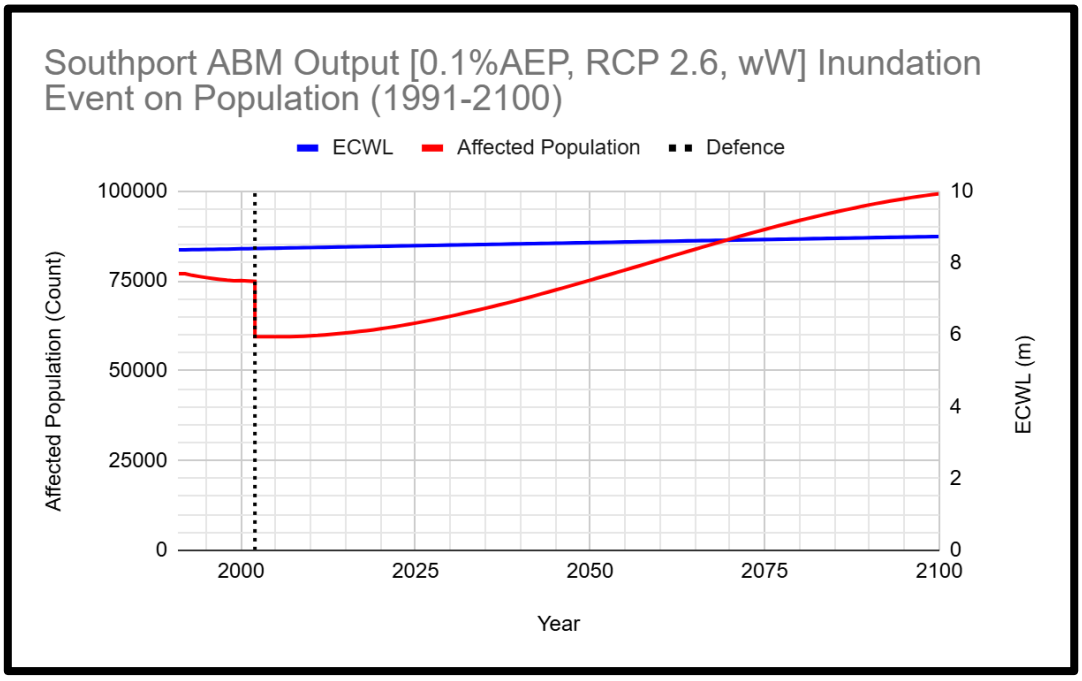

Southport ABM Output [0.5%AEP, RCP 2.6, wW] Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
100000
75000
50000
25000
0
10
8
6
4
2
0
2000
2025
2050
2075
2100
Year

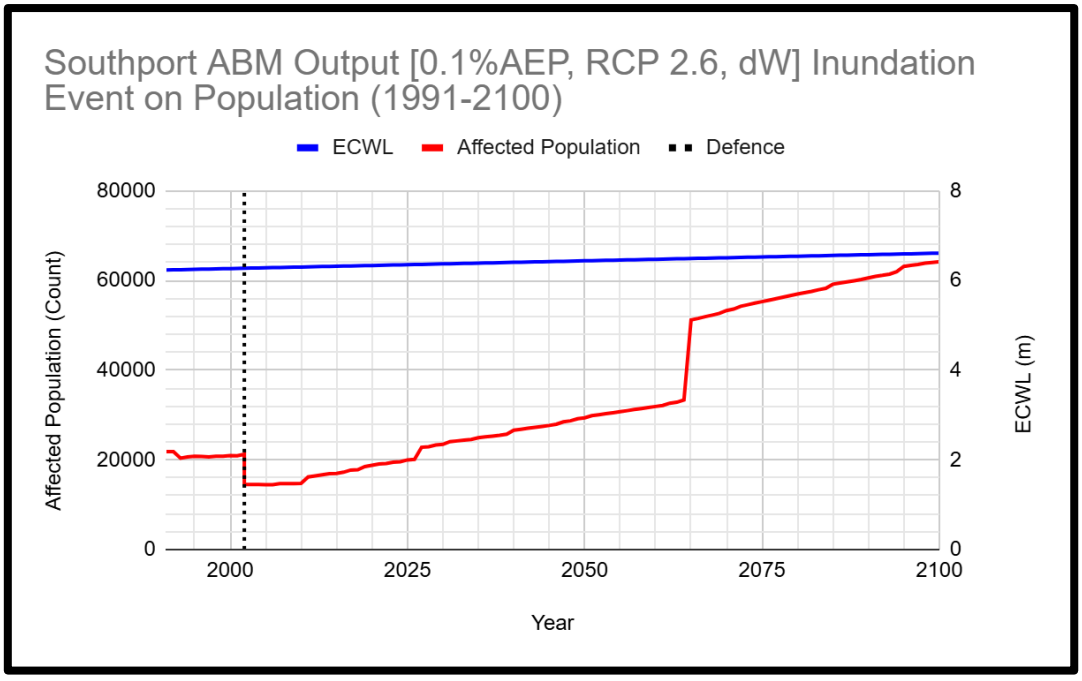

Southport ABM Output [0.5%AEP, RCP 2.6, dW] Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
40000
30000
20000
10000
0
8
6
4
2
0
2000
2025
2050
2075
2100
Year

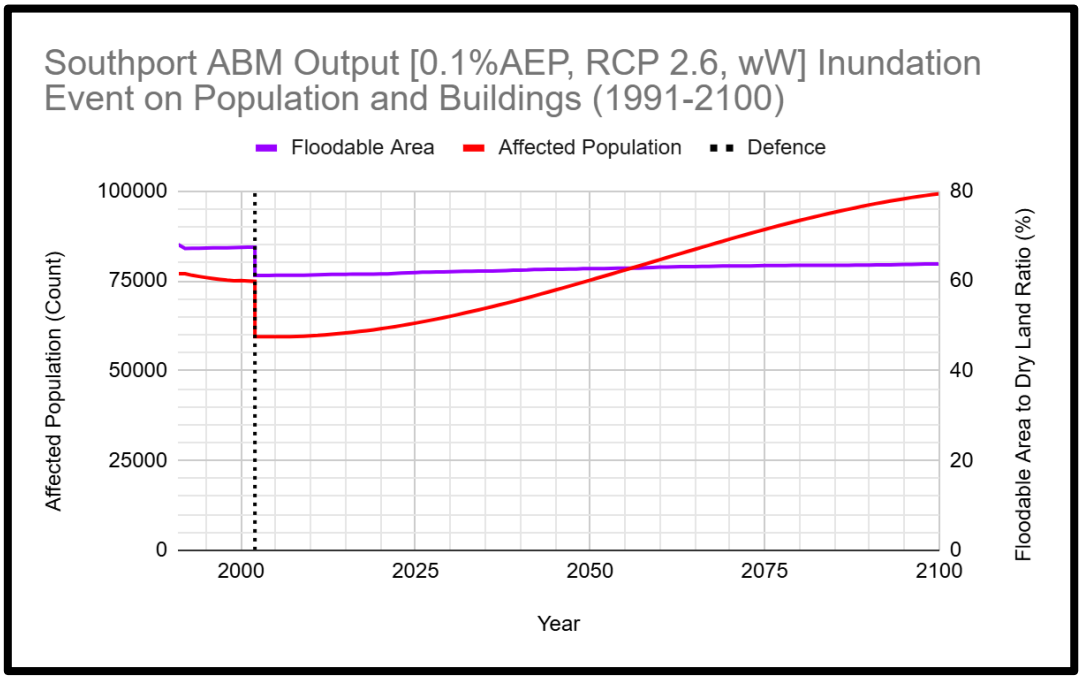

Southport ABM Output [0.5%AEP, RCP 2.6, wW] Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
100000
75000
50000
25000
0
8.00E+01
6.00E+01
4.00E+01
2.00E+01
0.00E+00
2000
2025
2050
2075
2100
Year
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)

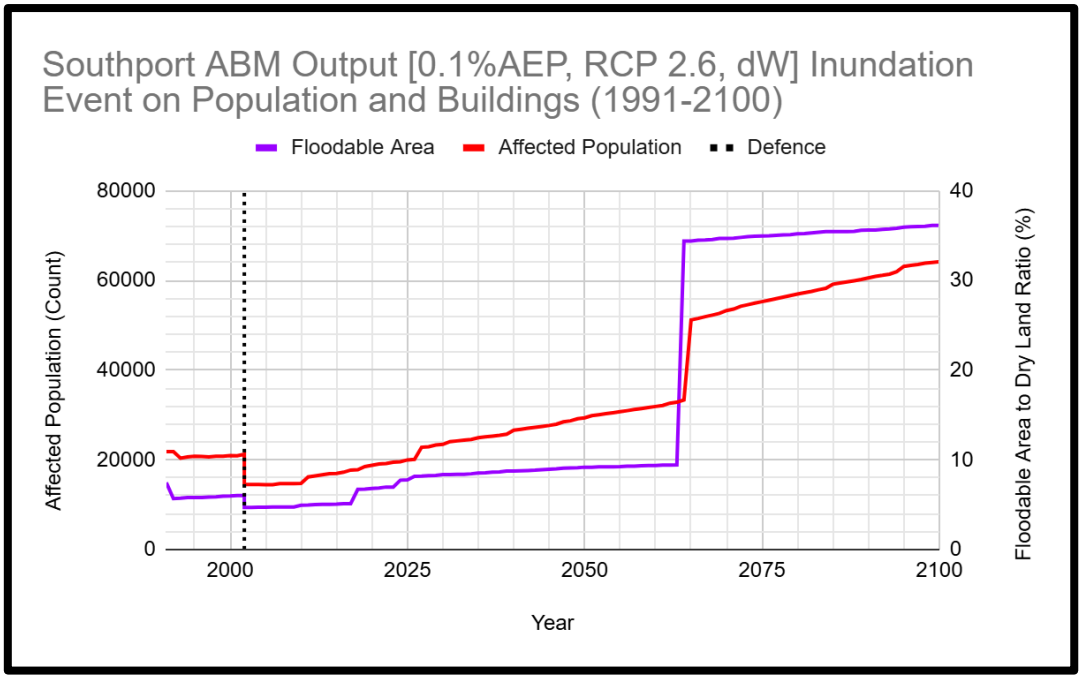

Southport ABM Output [0.5%AEP, RCP 2.6, dW] Inundation Event on Population and Buildings (1991-2100)
Floodable Area
Affected Population
Defence
40000
30000
20000
10000
0
10.00
8.00
6.00
4.00
2.00
0.00
2000
2025
2050
2075
2100
Year
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)

RCP2.6 - 0.1%AEP

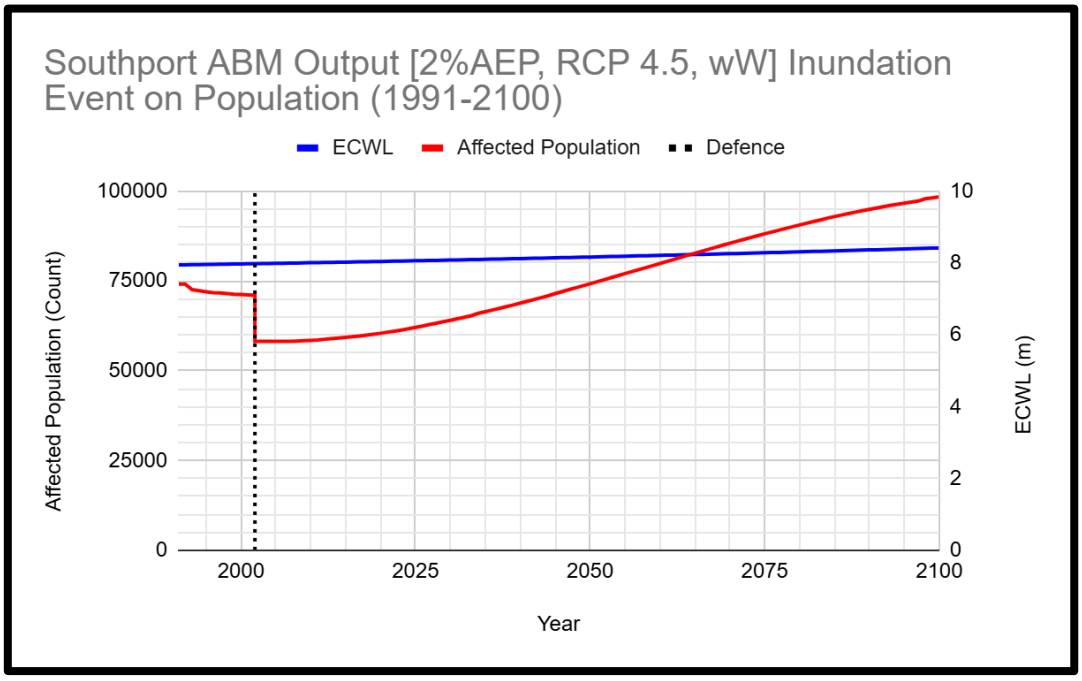

Southport ABM Output [0.1%AEP, RCP 2.6, wW] Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
100000
75000
50000
25000
0
10
8
6
4
2
0
2000
2025
2050
2075
2100
Year

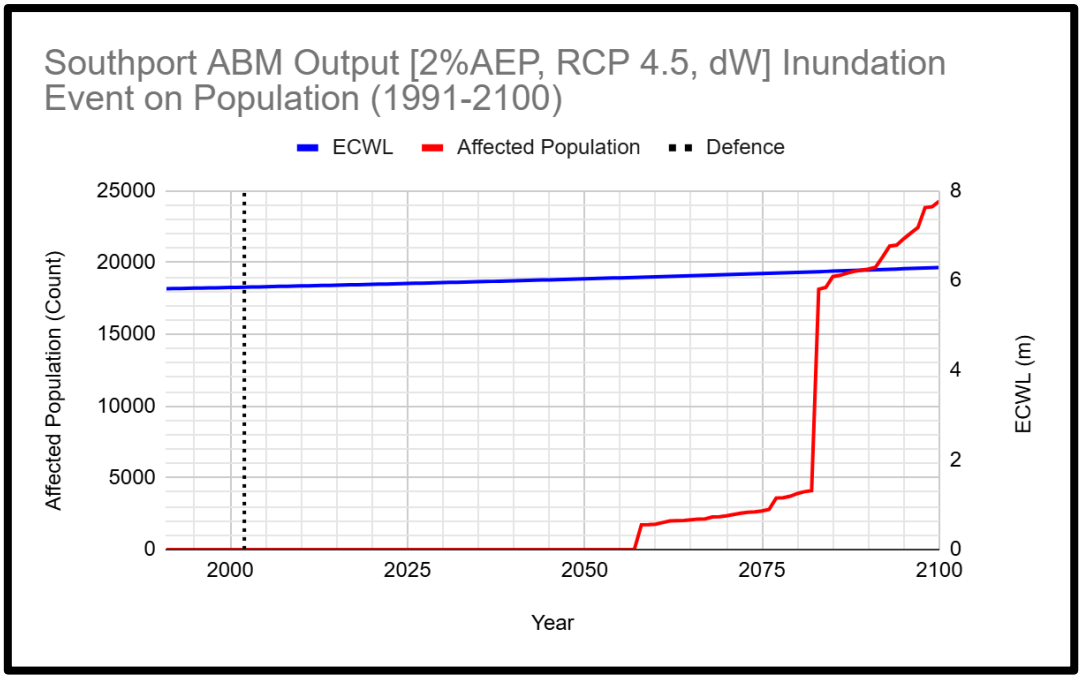

Southport ABM Output [0.1%AEP, RCP 2.6, dW] Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
80000
60000
40000
20000
0
8
6
4
2
0
2000
2025
2050
2075
2100
Year

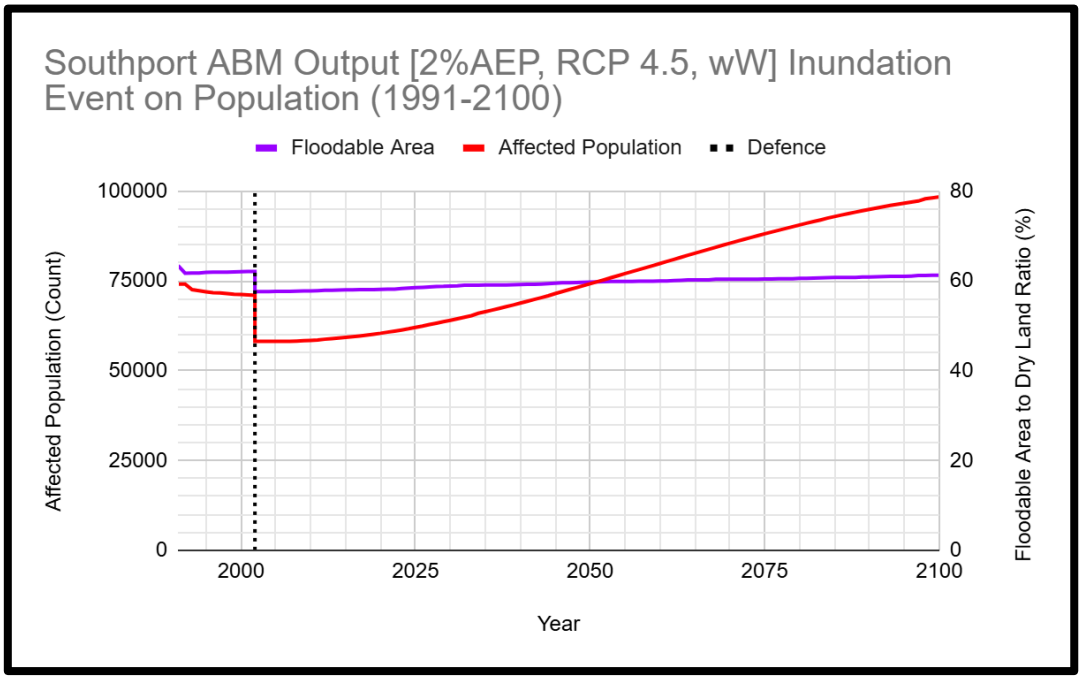

Southport ABM Output [0.1%AEP, RCP 2.6, wW] Inundation Event on Population and Buildings (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
100000
75000
50000
25000
0
80
60
40
20
0
2000
2025
2050
2075
2100
Year

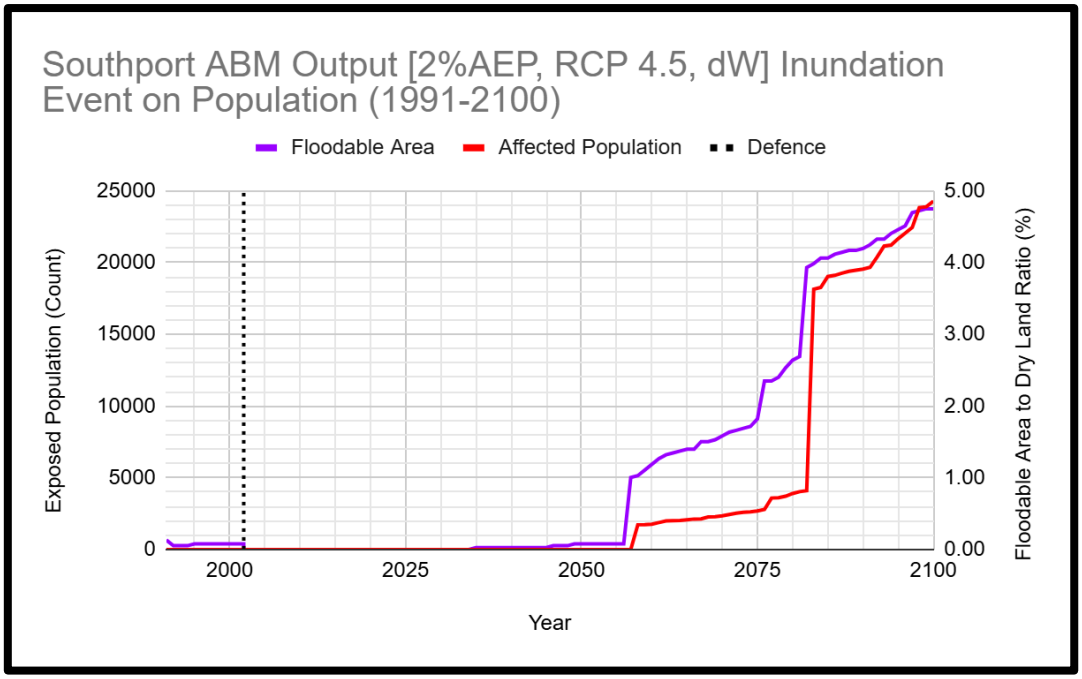

Southport ABM Output [0.1%AEP, RCP 2.6, dW] Inundation Event on Population and Buildings (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
80000
60000
40000
20000
0
40
30
20
10
0
2000
2025
2050
2075
2100
Year

RCP4.5 - 2%AEP

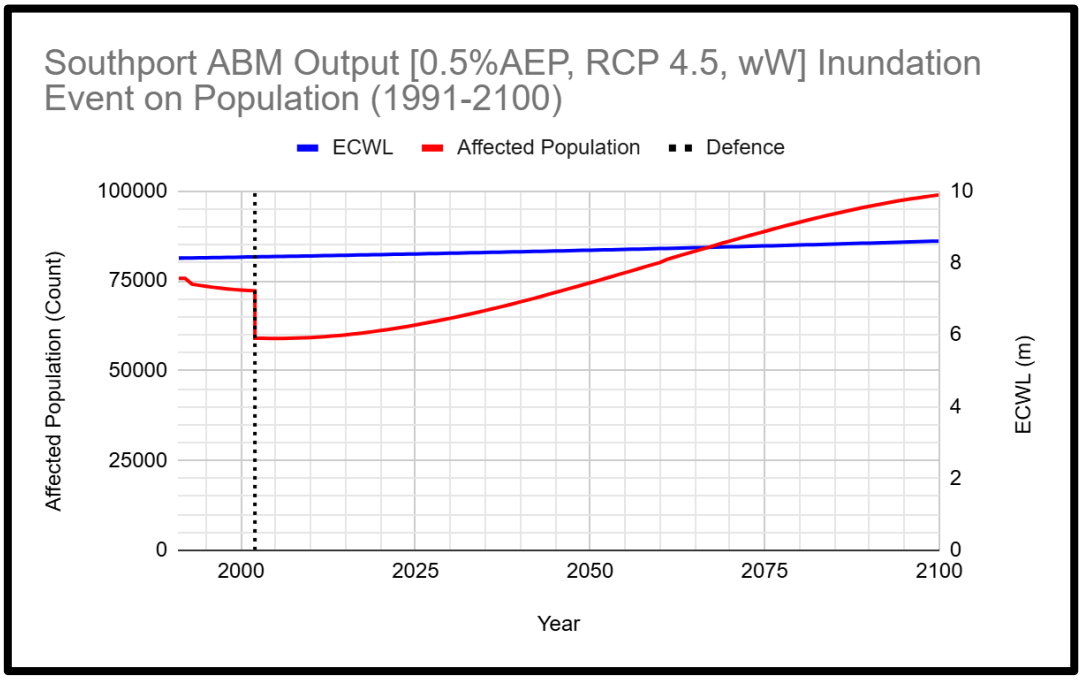

Southport ABM Output [2%AEP, RCP 4.5, wW] Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
100000
75000
50000
25000
0
ECWL (m)
10
8
6
4
2
0
2000
2025
2050
2075
2100
Year

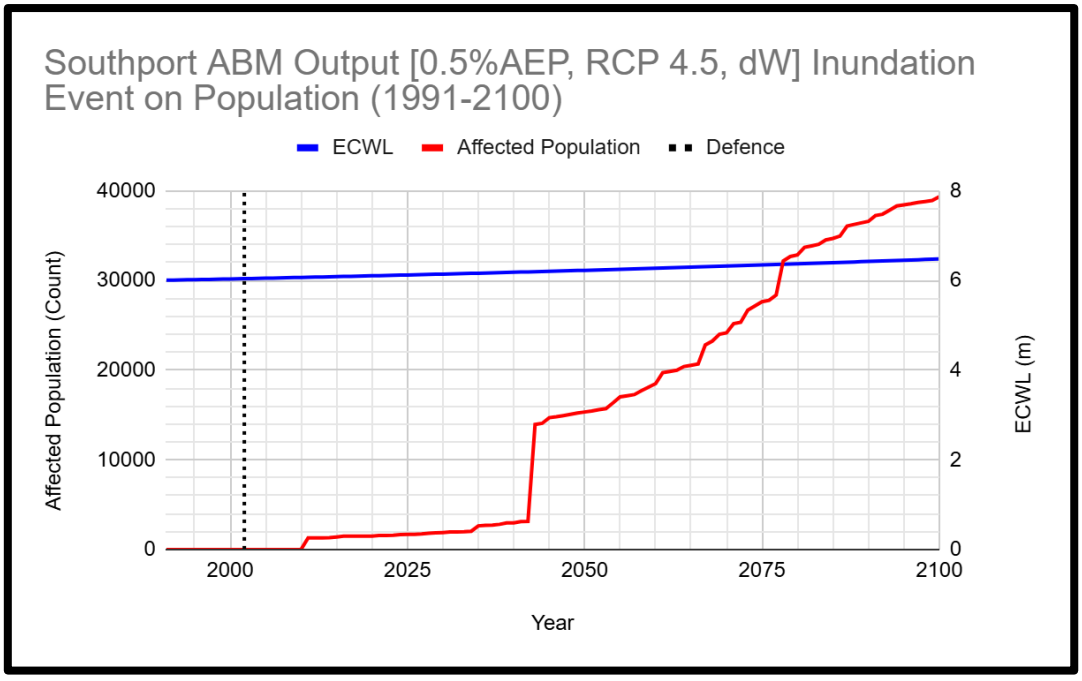

Southport ABM Output [2%AEP, RCP 4.5, dW] Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
25000
20000
15000
10000
5000
0
ECWL (m)
8
6
4
2
0
2000
2025
2050
2075
2100
Year

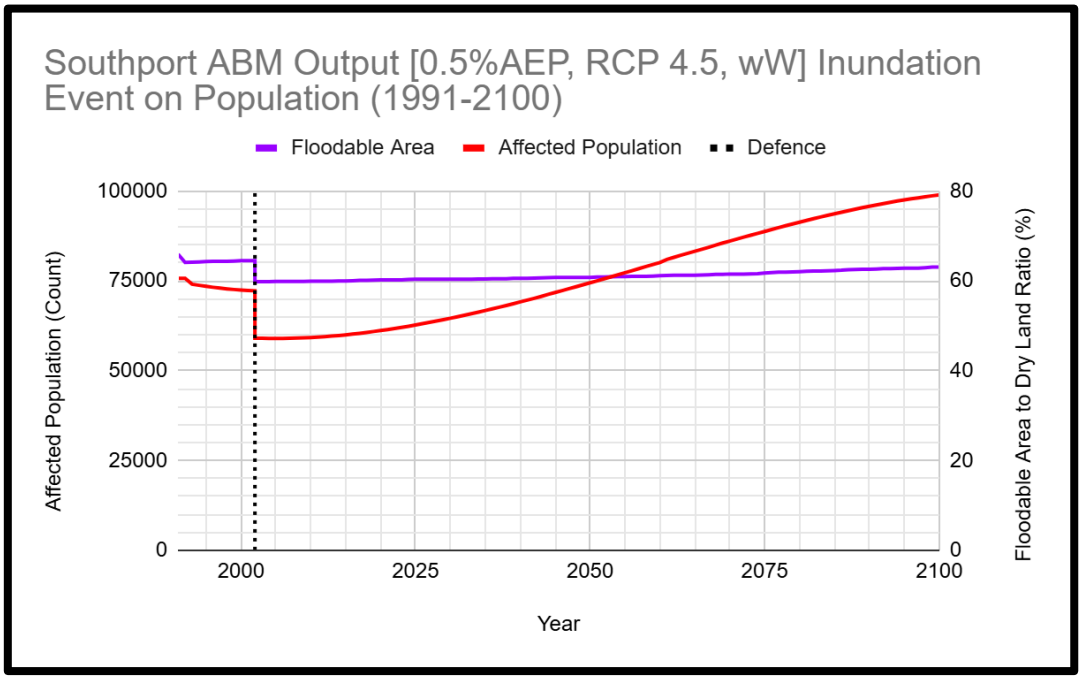

Southport ABM Output [2%AEP, RCP 4.5, wW] Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
100000
75000
50000
25000
0
80
60
40
20
0
Floodable Area to Dry Land Ratio (%)
2000
2025
2050
2075
2100
Year

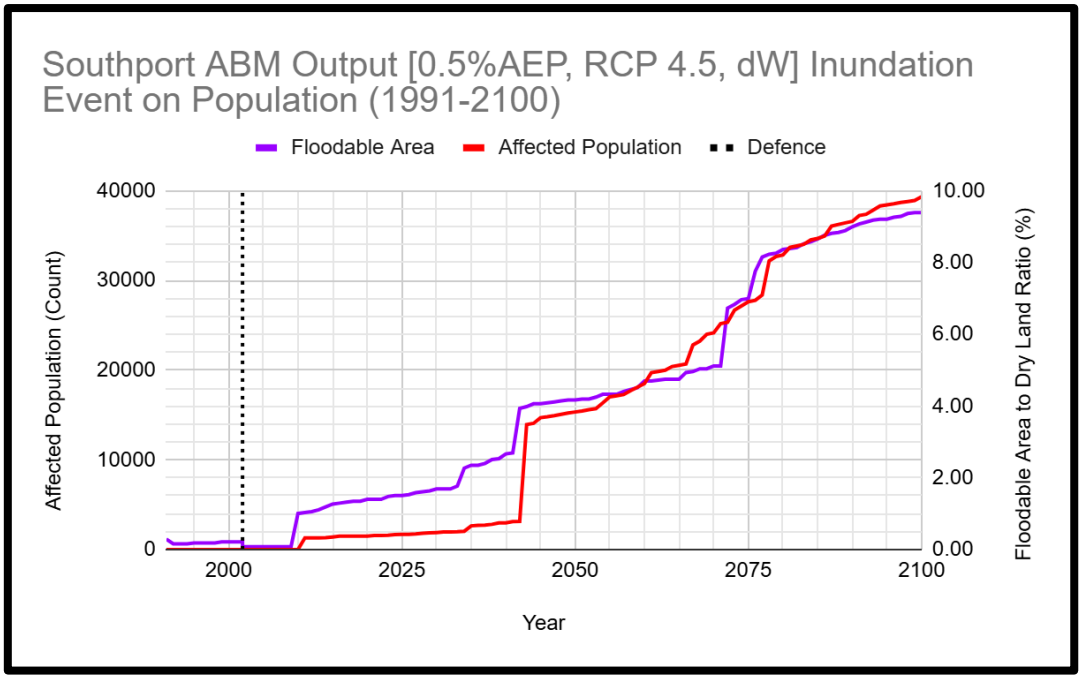

Southport ABM Output [2%AEP, RCP 4.5, dW] Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Exposed Population (Count)
25000
20000
15000
10000
5000
0
5.00
4.00
3.00
2.00
1.00
0.00
Floodable Area to Dry Land Ratio (%)
2000
2025
2050
2075
2100
Year

RCP4.5 - 0.5%AEP

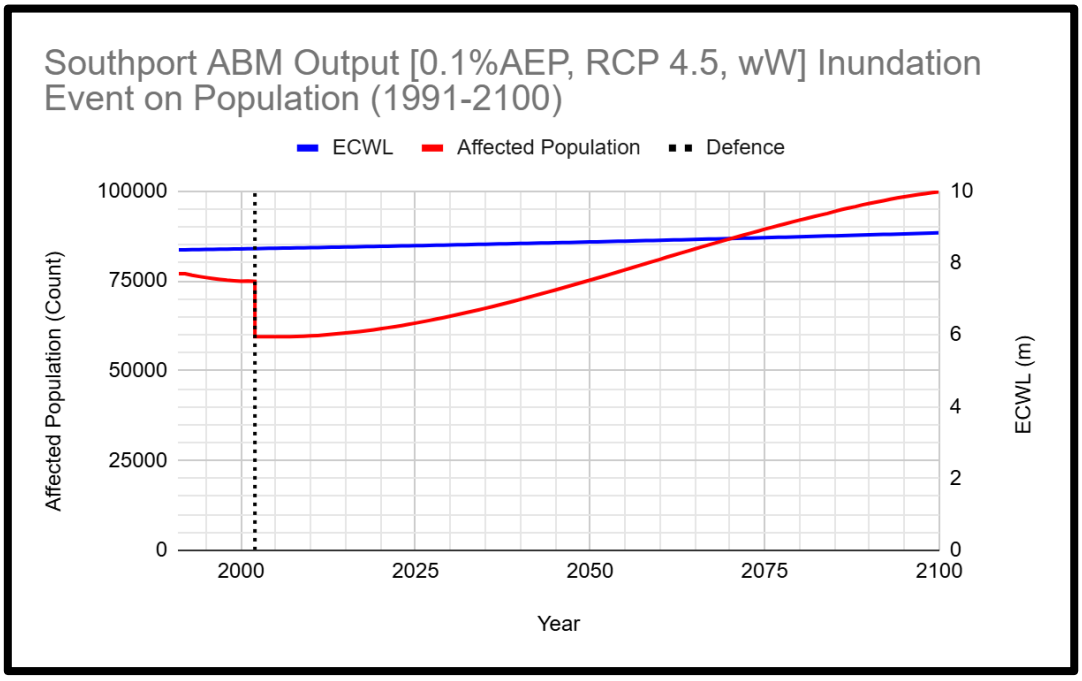

Southport ABM Output [0.5%AEP, RCP 4.5, wW] Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
Year
100000
75000
50000
25000
0
10
8
6
4
2
0
2000
2025
2050
2075
2100

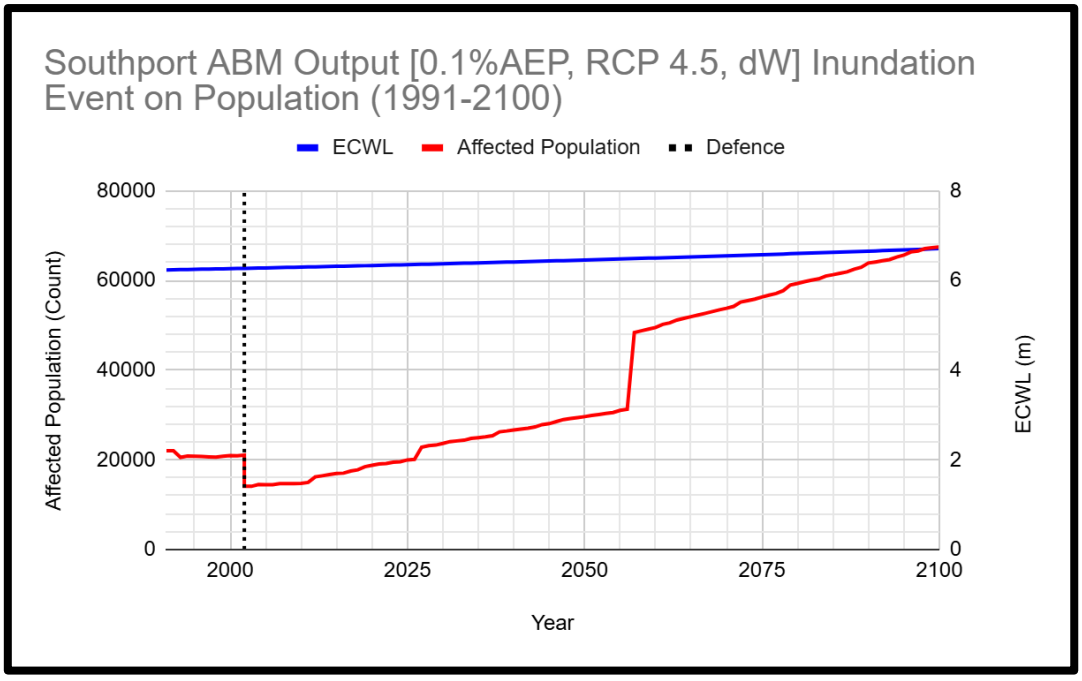

Southport ABM Output [0.5%AEP, RCP 4.5, dW] Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
Year
40000
30000
20000
10000
0
8
6
4
2
0
2000
2025
2050
2075
2100

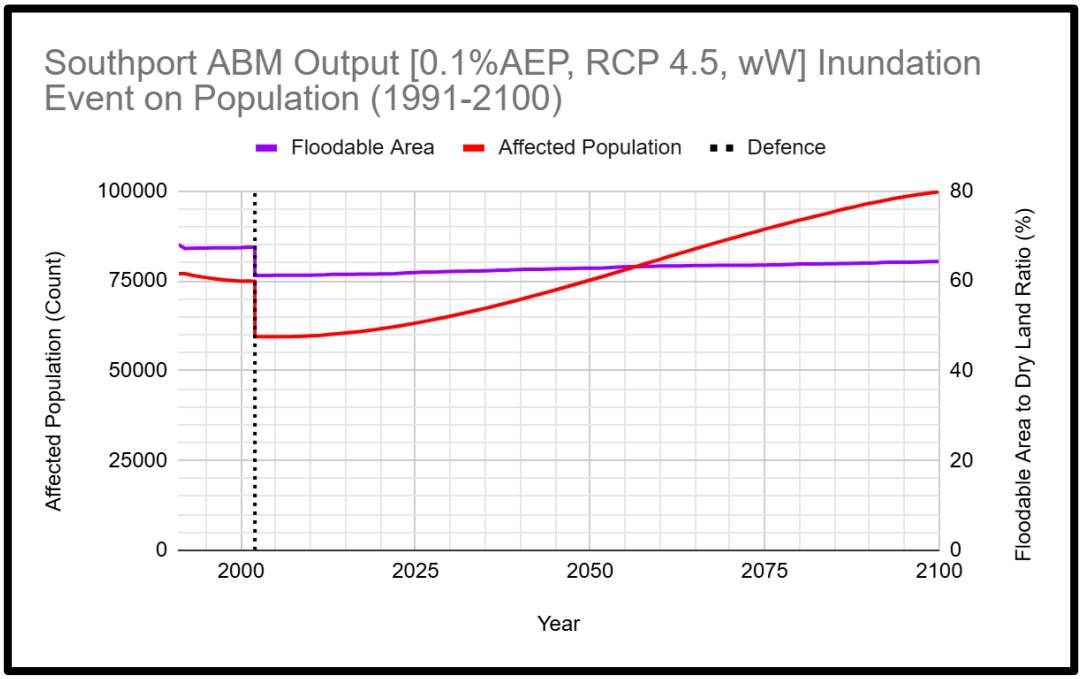

Southport ABM Output [0.5%AEP, RCP 4.5, wW] Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
100000
75000
50000
25000
0
80
60
40
20
0
Floodable Area to Dry Land Ratio (%)
2000
2025
2050
2075
2100
Year

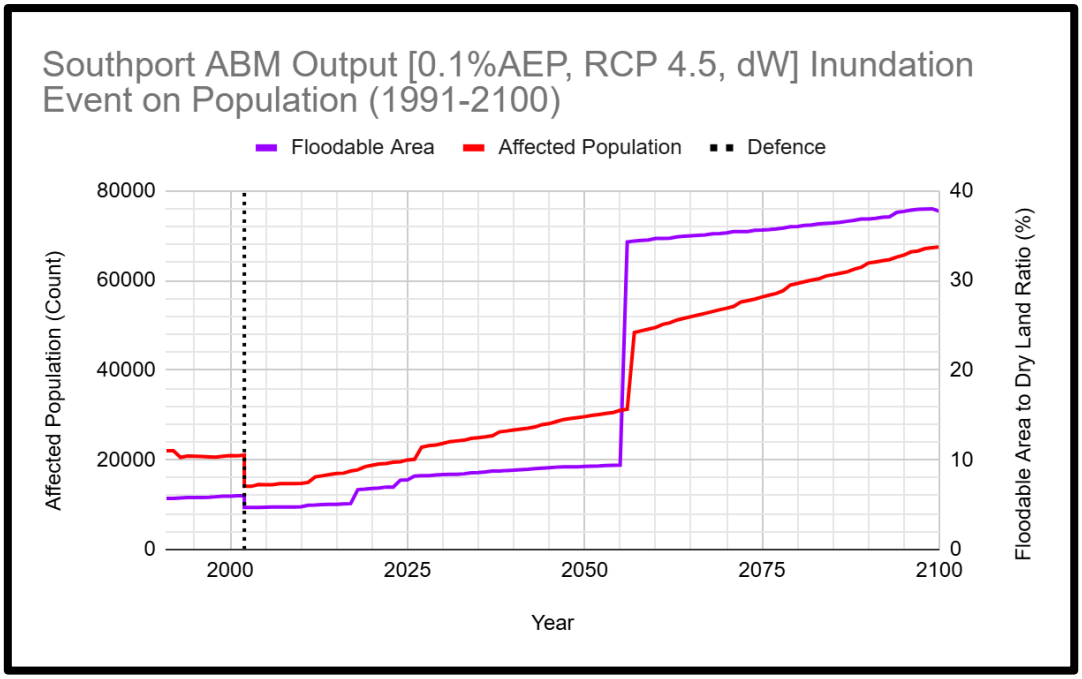

Southport ABM Output [0.5%AEP, RCP 4.5, dW] Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
40000
30000
20000
10000
0
10.00
8.00
6.00
4.00
2.00
0.00
Floodable Area to Dry Land Ratio (%)
2000
2025
2050
2075
2100
Year

RCP4.5 - 0.1%AEP

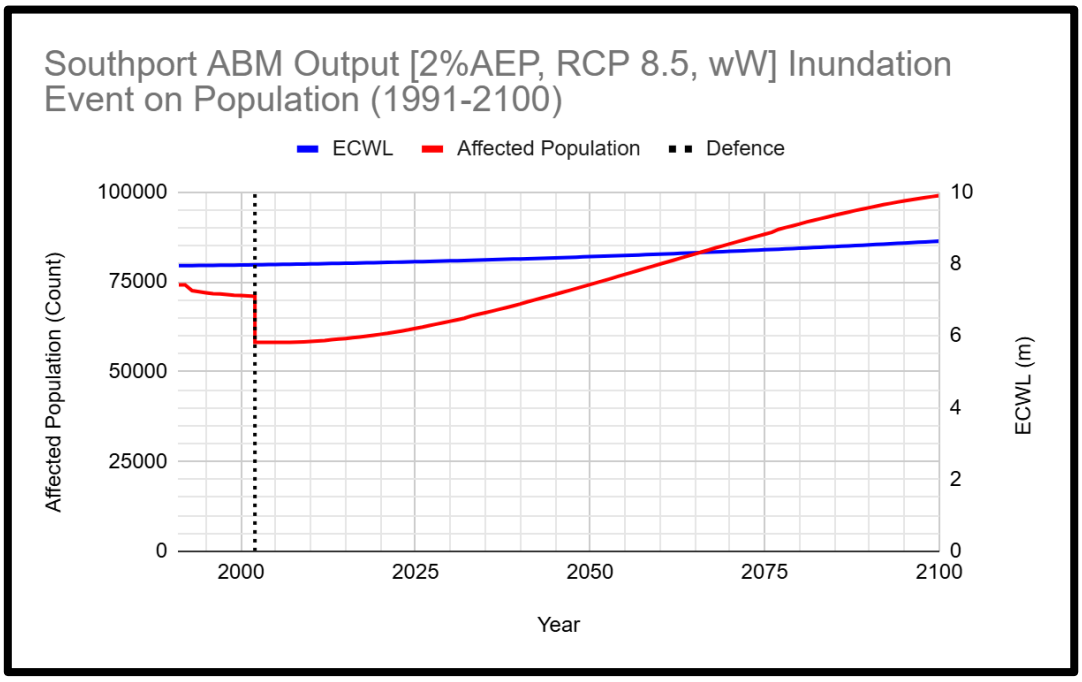

Southport ABM Output [0.1%AEP, RCP 4.5, wW] Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
100000
75000
50000
25000
0
10
8
6
4
2
0
2000
2025
2050
2075
2100
Year

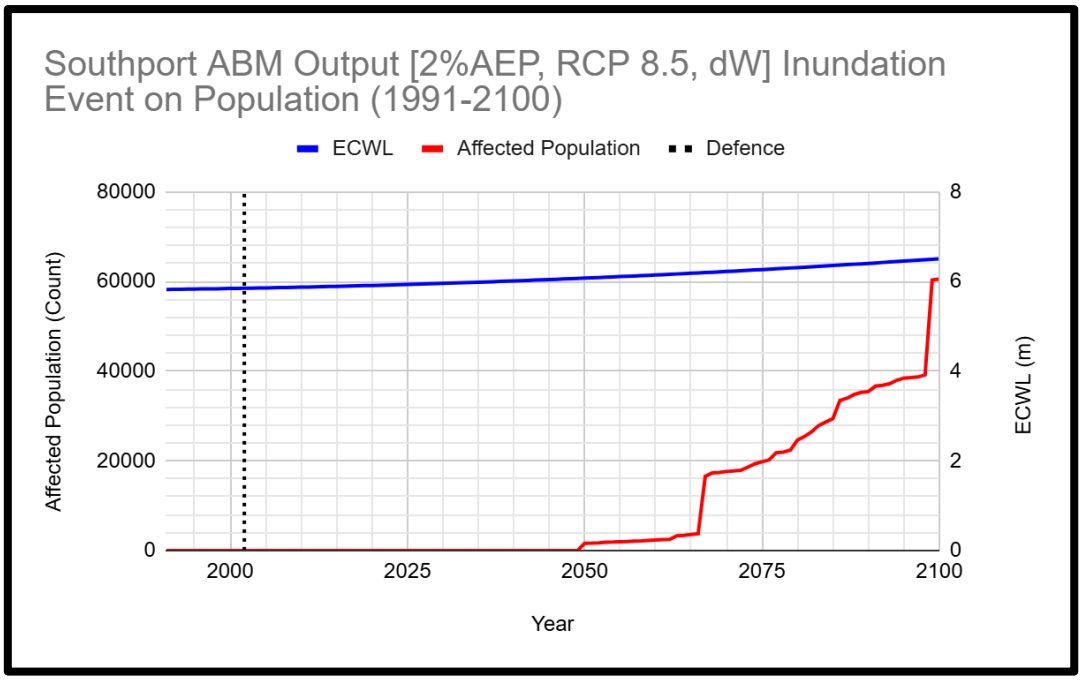

Southport ABM Output [0.1%AEP, RCP 4.5, dW] Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
80000
60000
40000
20000
0
8
6
4
2
0
2000
2025
2050
2075
2100
Year

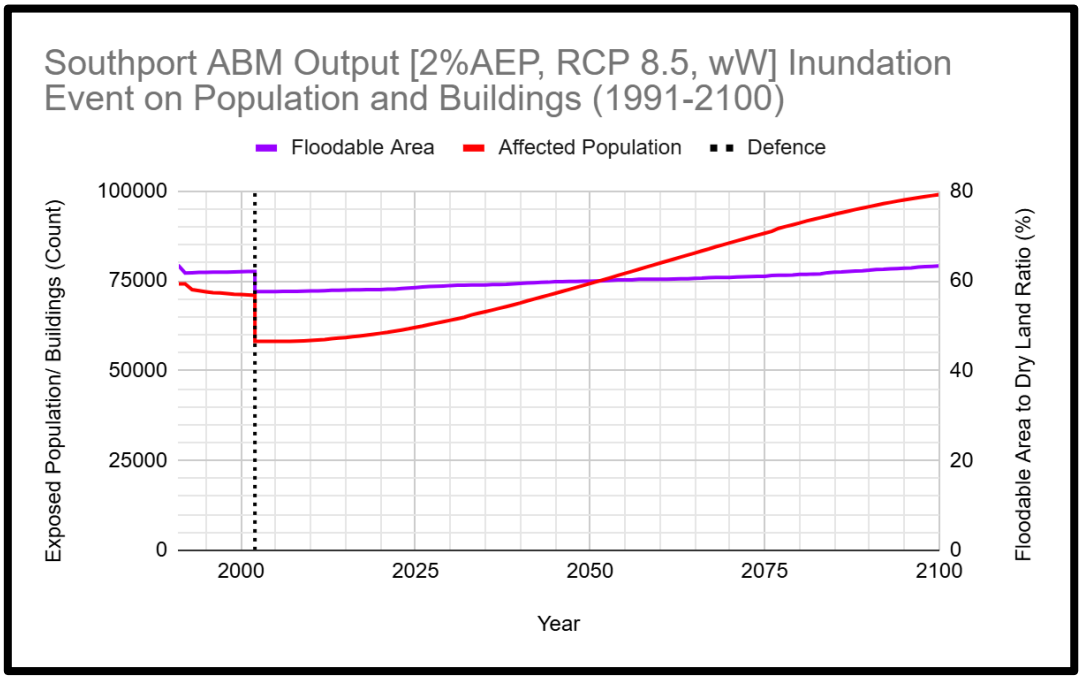

Southport ABM Output [0.1%AEP, RCP 4.5, wW] Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
100000
75000
50000
25000
0
80
60
40
20
0
2000
2025
2050
2075
2100
Year

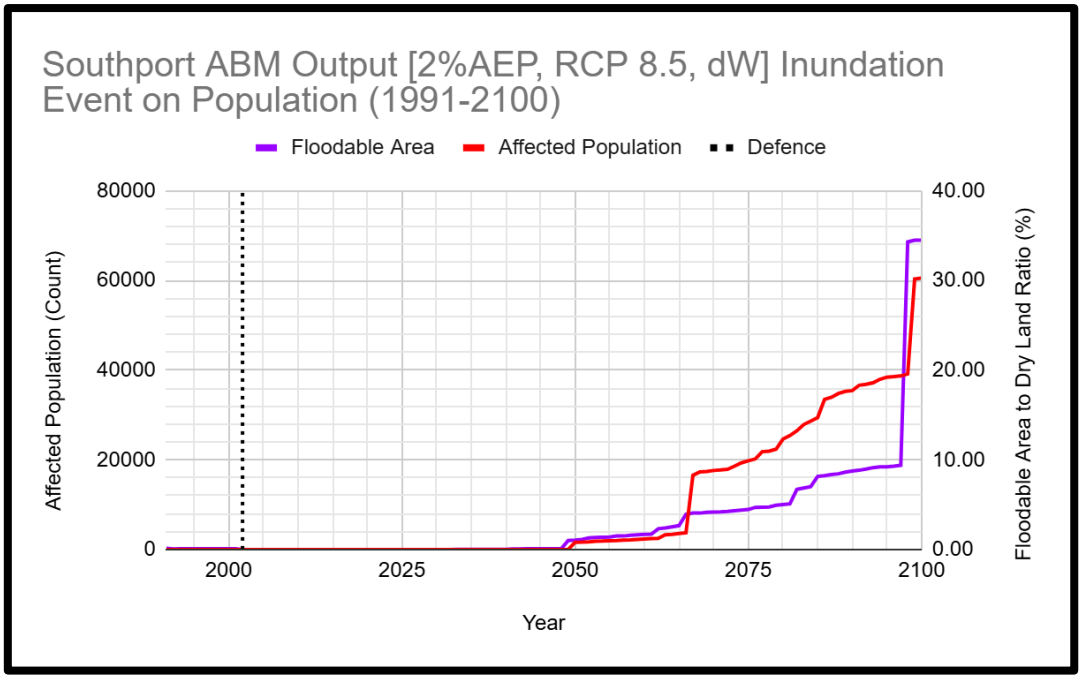

Southport ABM Output [0.1%AEP, RCP 4.5, dW] Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
80000
60000
40000
20000
0
40
30
20
10
0
2000
2025
2050
2075
2100
Year

RCP8.5 - 2%AEP

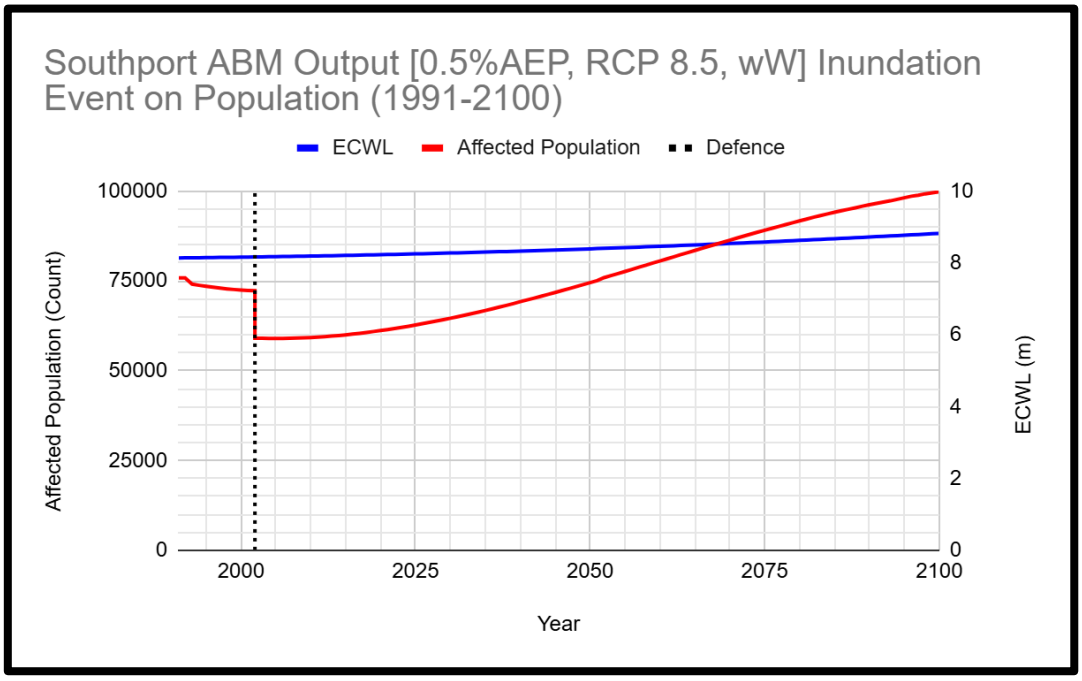

Southport ABM Output [2%AEP, RCP 8.5, wW] Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
100000
75000
50000
25000
0
ECWL (m)
10
8
6
4
2
0
2000
2025
2050
2075
2100
Year

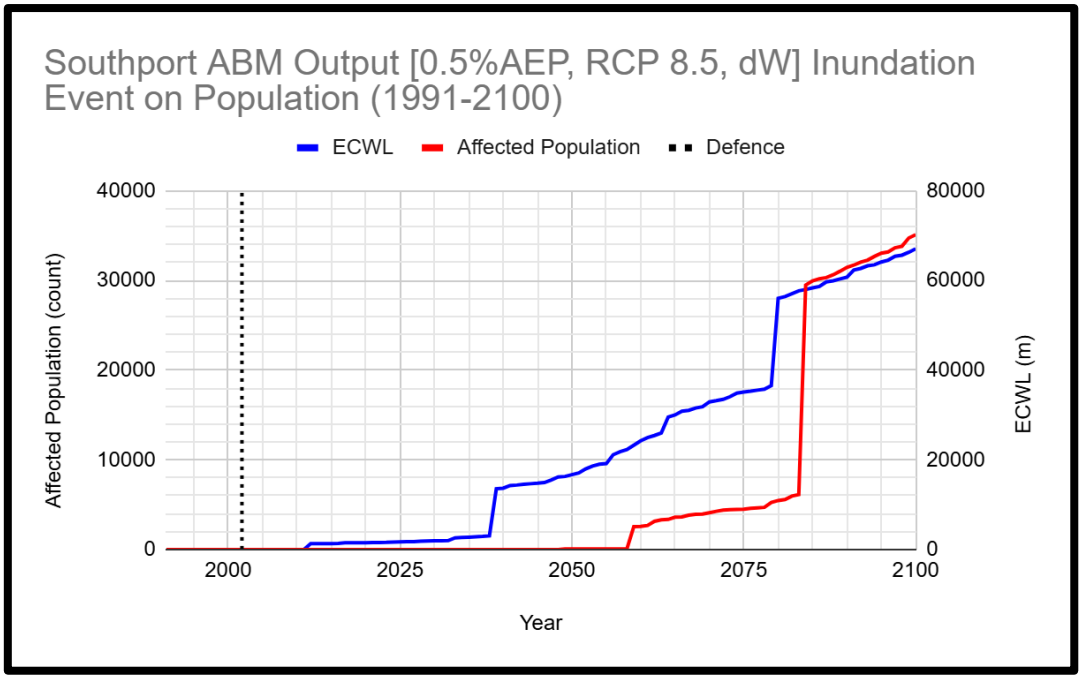

Southport ABM Output [2%AEP, RCP 8.5, dW] Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
80000
60000
40000
20000
0
ECWL (m)
8
6
4
2
0
2000
2025
2050
2075
2100
Year

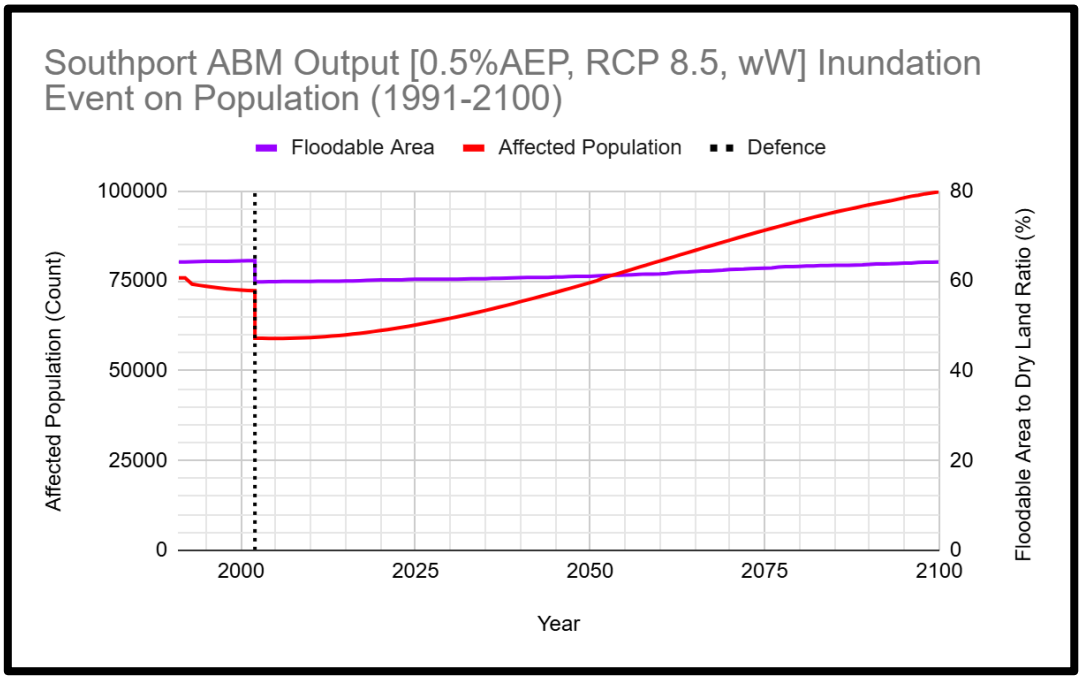

Southport ABM Output [2%AEP, RCP 8.5, wW] Inundation Event on Population and Buildings (1991-2100)
Floodable Area
Affected Population
Defence
Exposed Population/ Buildings (Count)
100000
75000
50000
25000
0
2000
2025
2050
2075
2100
Year
80
60
40
20
0
Floodable Area to Dry Land Ratio (%)

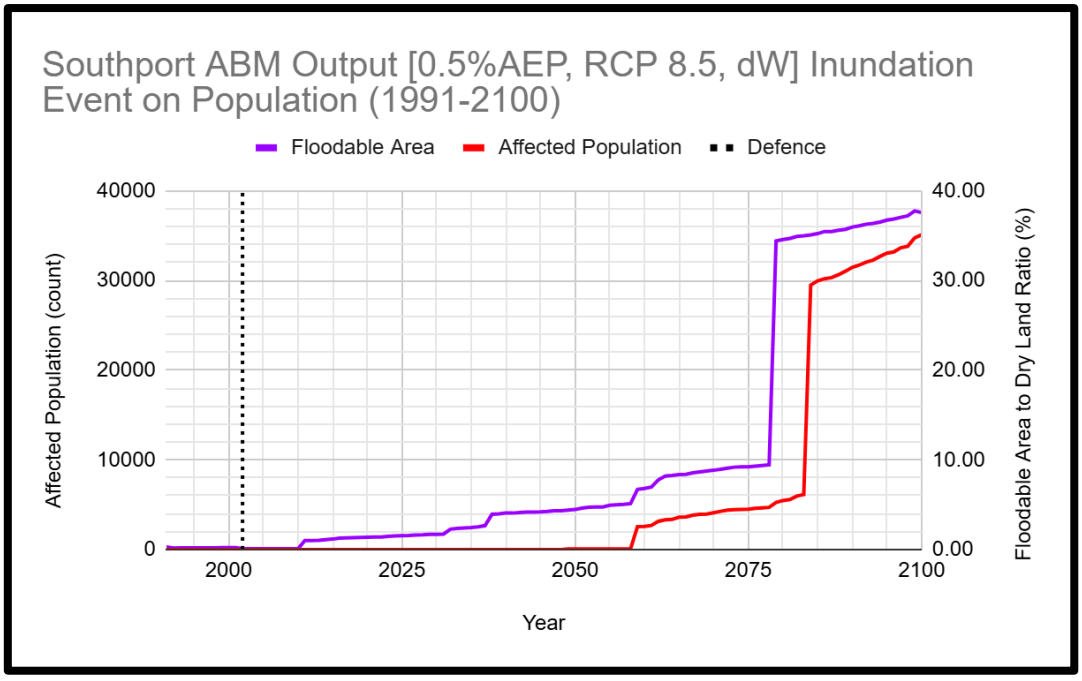

Southport ABM Output [2%AEP, RCP 8.5, dW] Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
80000
60000
40000
20000
0
2000
2025
2050
2075
2100
Year
40.00
30.00
20.00
10.00
0.00
Floodable Area to Dry Land Ratio (%)

RCP8.5 - 0.5%AEP

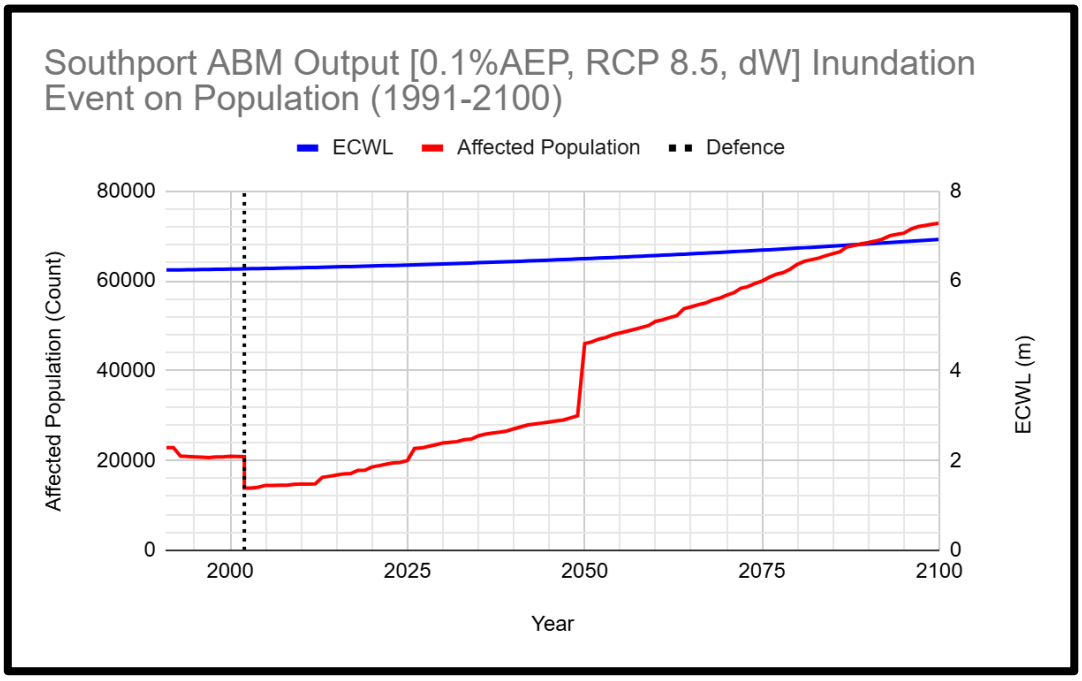

Southport ABM Output [0.5%AEP, RCP 8.5, wW] Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
100000
75000
50000
25000
0
2000
2025
2050
2075
2100
Year
10
8
6
4
2
0
ECWL (m)

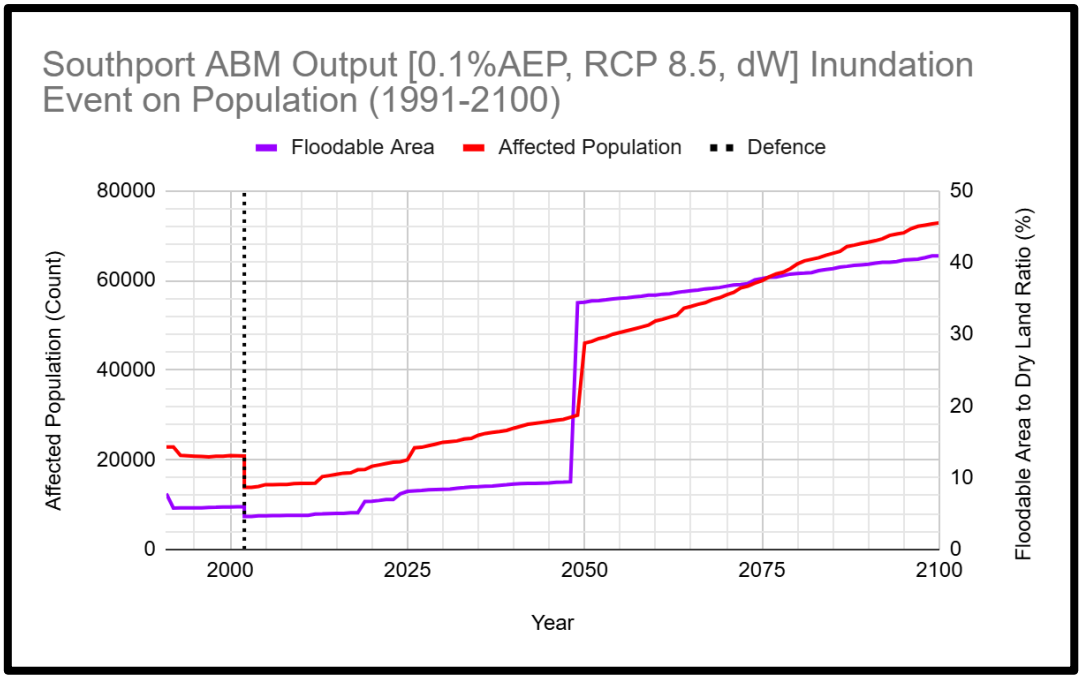

Southport ABM Output [0.5%AEP, RCP 8.5, dW] Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (count)
40000
30000
20000
10000
0
2000
2025
2050
2075
2100
Year
80000
60000
40000
20000
0
ECWL (m)


Southport ABM Output [0.5%AEP, RCP 8.5, wW] Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
100000
75000
50000
25000
0
80
60
40
20
0
Floodable Area to Dry Land Ratio (%)
2000
2025
2050
2075
2100
Year


Southport ABM Output [0.5%AEP, RCP 8.5, dW] Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (count)
40000
30000
20000
10000
0
40.00
30.00
20.00
10.00
0.00
Floodable Area to Dry Land Ratio (%)
2000
2025
2050
2075
2100
Year

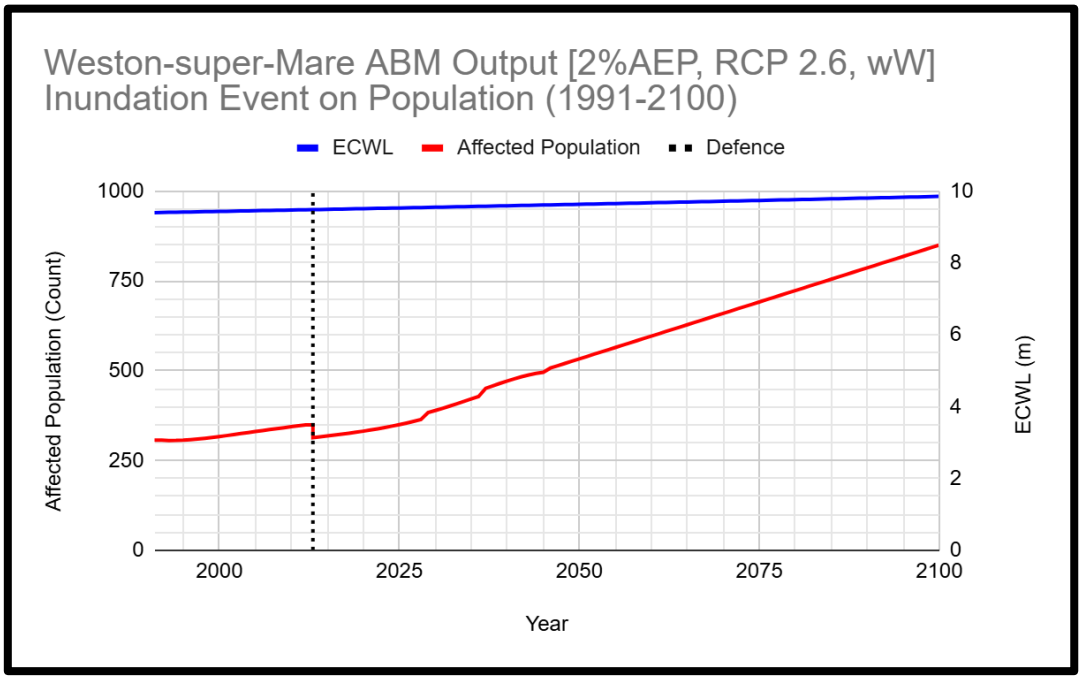
RP8.5 - 0.1%AEP

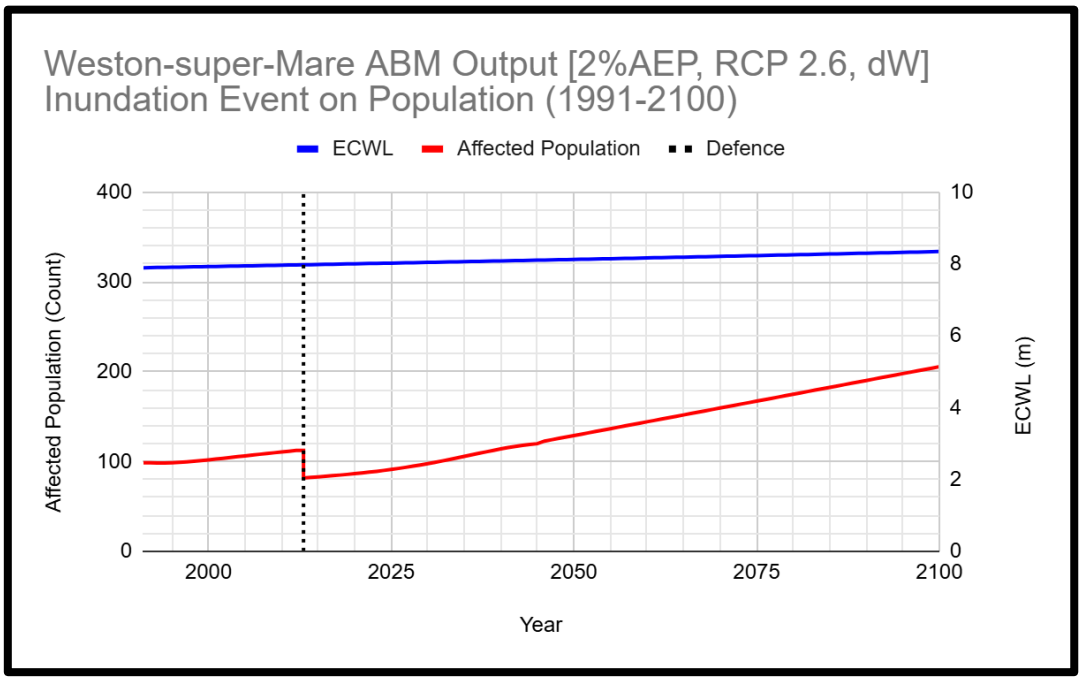

Southport ABM Output [0.1%AEP, RCP 8.5, dW] Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
80000
60000
40000
20000
0
8
6
4
2
0
2000
2025
2050
2075
2100
Year

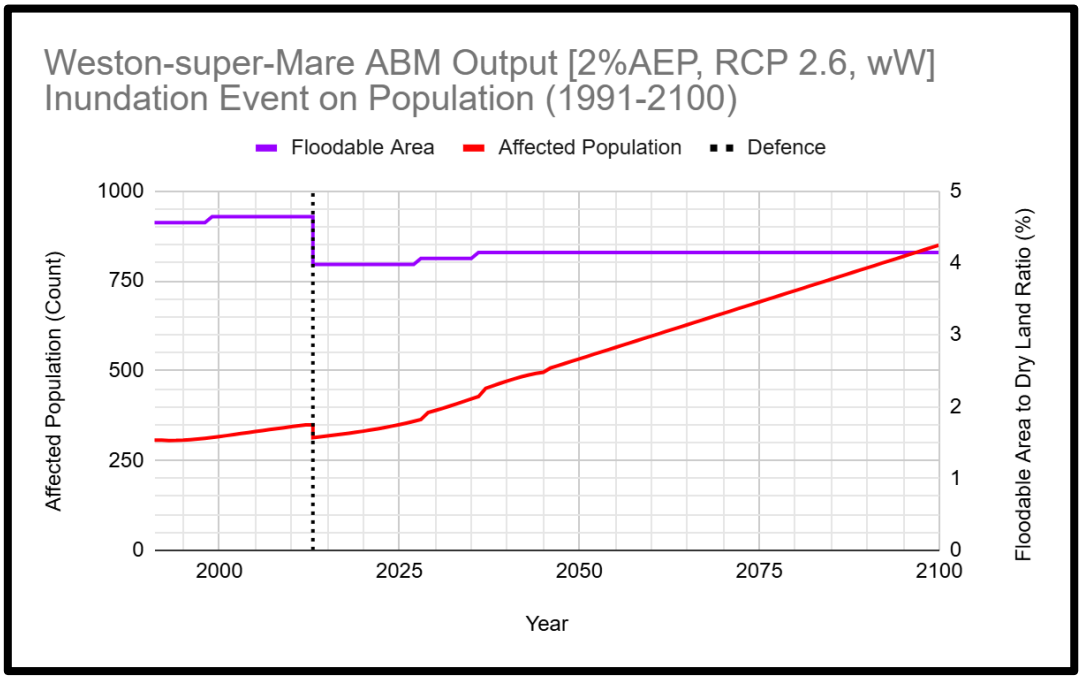

Southport ABM Output [0.1%AEP, RCP 8.5, dW] Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
80000
60000
40000
20000
0
50
40
30
20
10
0
2000
2025
2050
2075
2100
Year

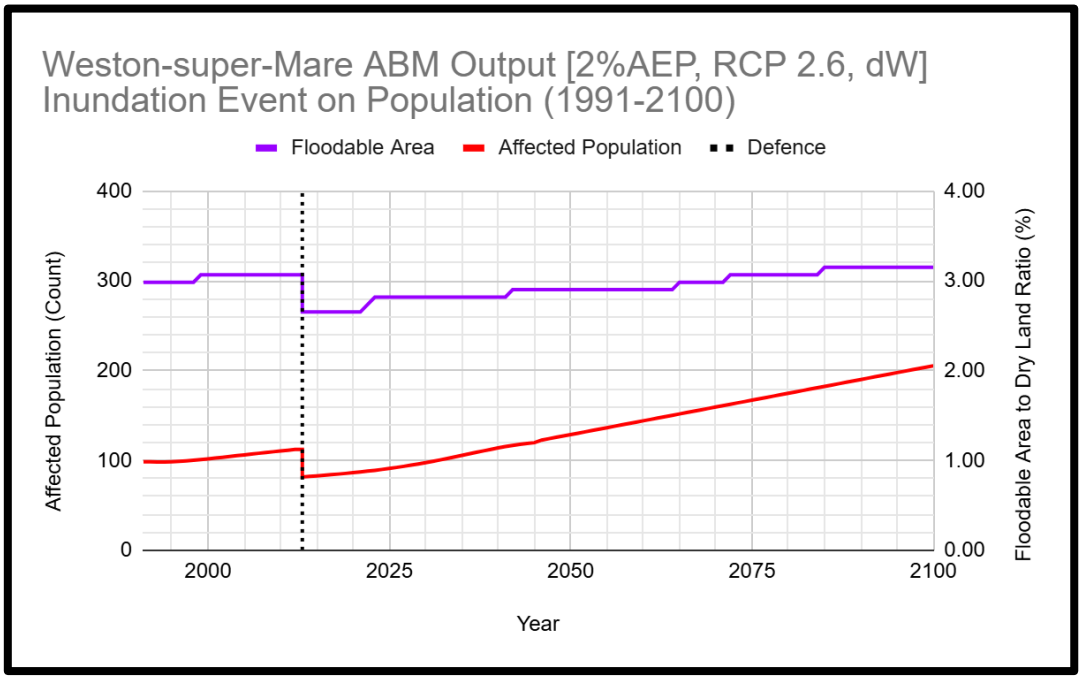
Case Study B

RCP2.6 - 2%AEP

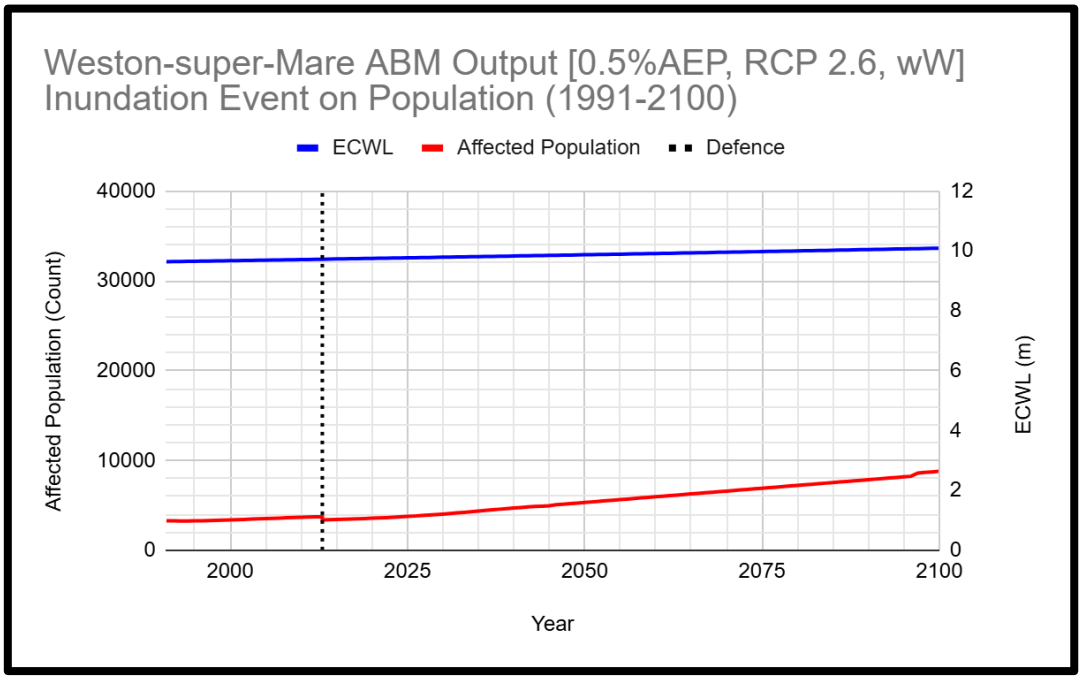


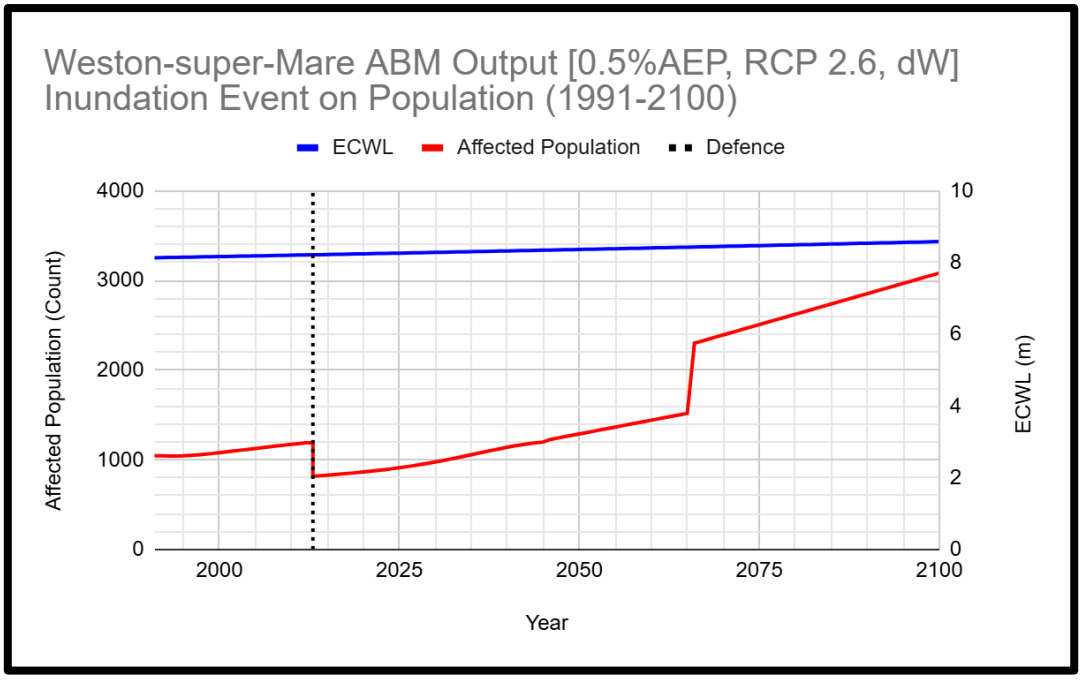


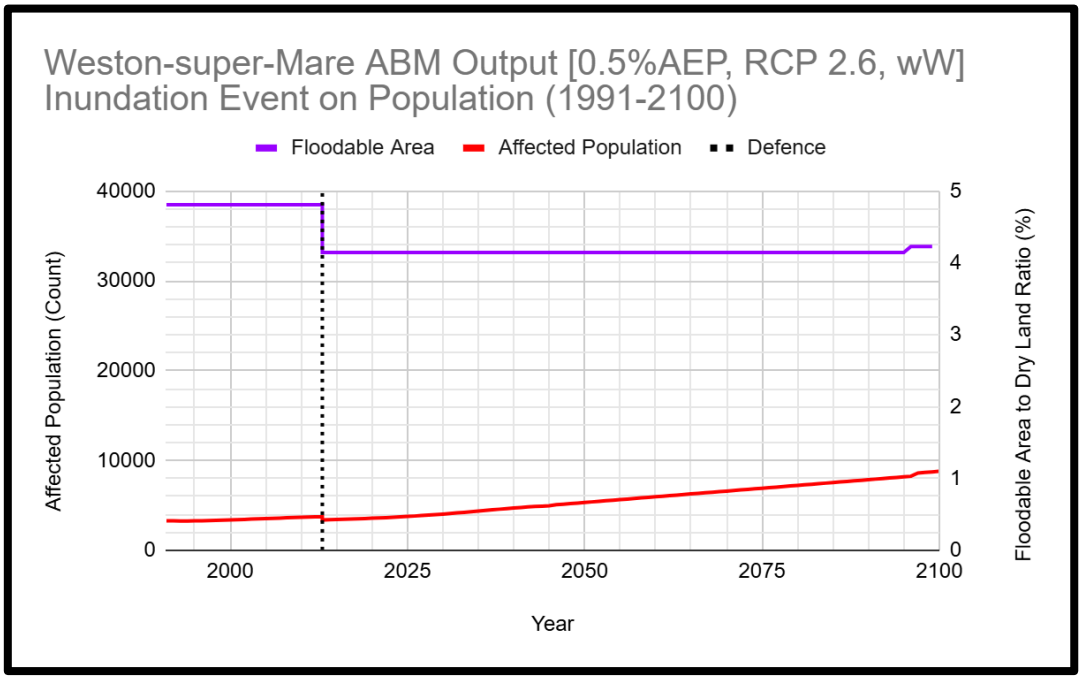

Weston-super-Mare ABM Output [2%AEP, RCP 2.6, wW]
Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
1000
750
500
250
0
5
4
3
2
1
0
2000
2025
2050
2075
2100
Year

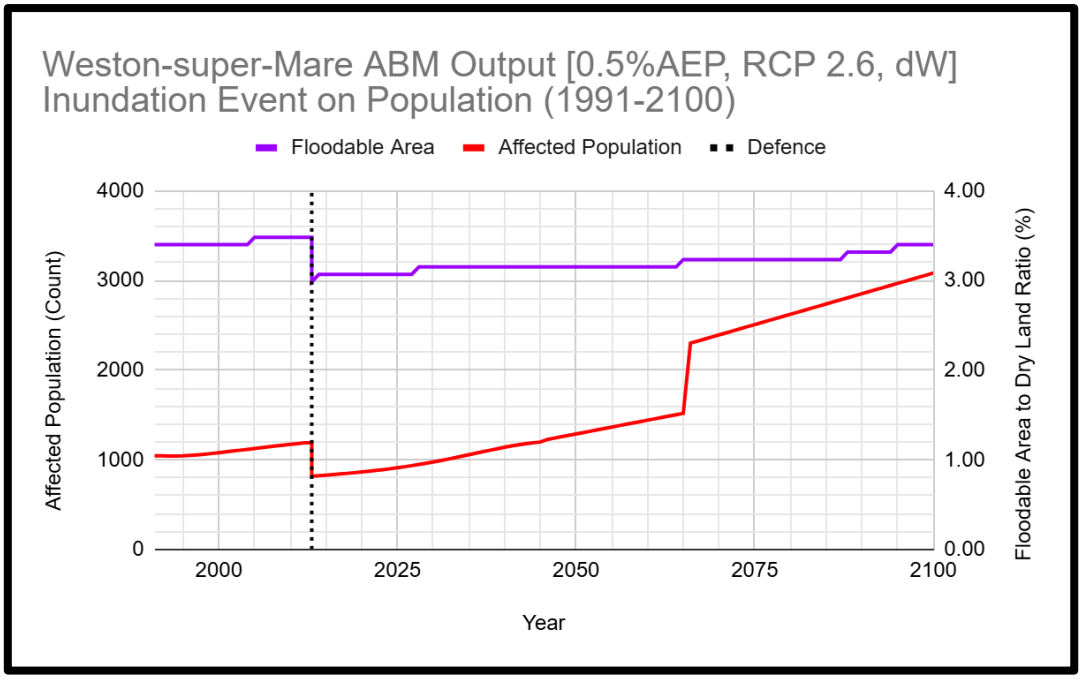

Weston-super-Mare ABM Output [2%AEP, RCP 2.6, dW]
Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
400
300
200
100
0
4.00
3.00
2.00
1.00
0.00
2000
2025
2050
2075
2100
Year

RCP2.6 - 0.5%AEP

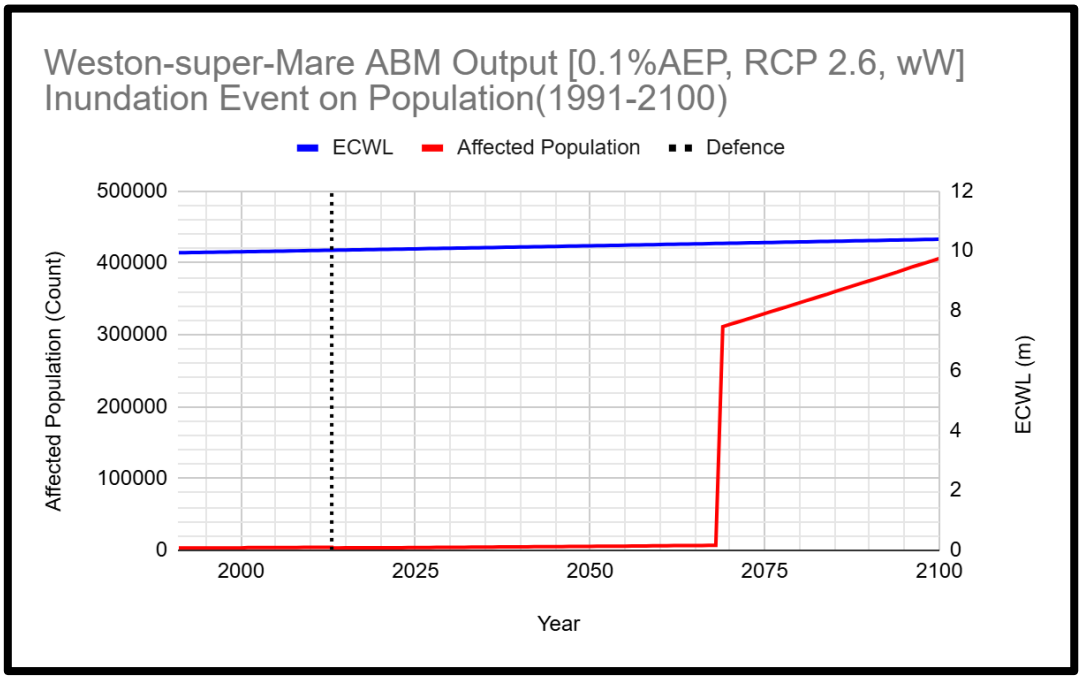

Weston-super-Mare ABM Output [0.5%AEP, RCP 2.6, wW]
Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
40000
30000
20000
10000
0
12
10
8
6
4
2
0
2000
2025
2050
2075
2100
Year

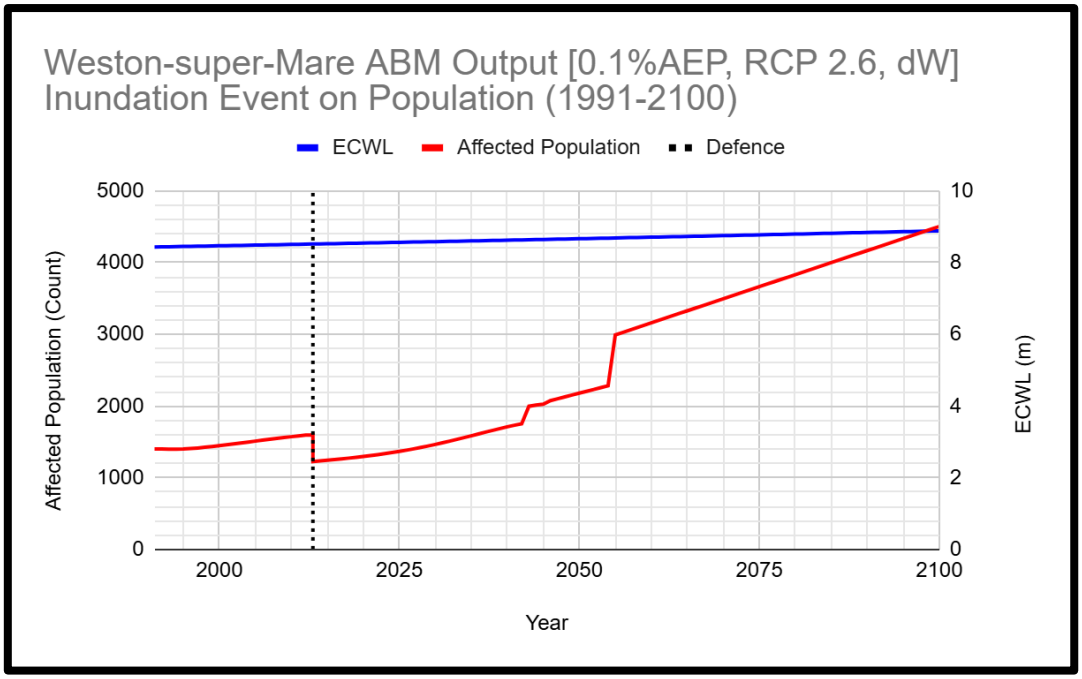

Weston-super-Mare ABM Output [0.5%AEP, RCP 2.6, dW]
Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
4000
3000
2000
1000
0
10
8
6
4
2
0
2000
2025
2050
2075
2100
Year

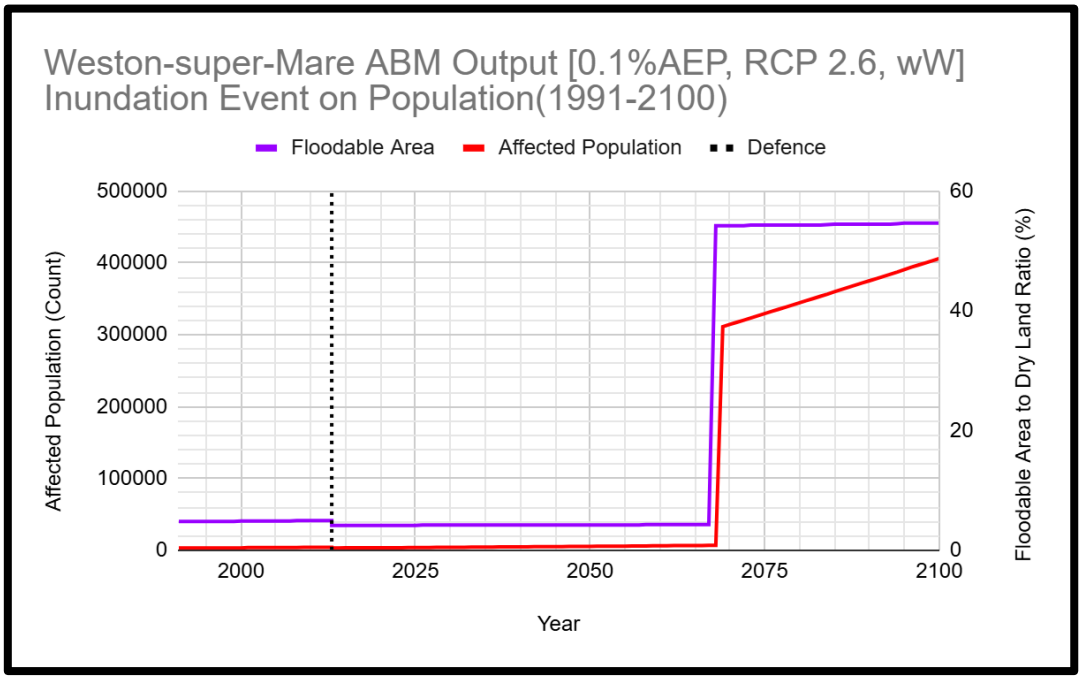

Weston-super-Mare ABM Output [0.5%AEP, RCP 2.6, wW]
Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
40000
30000
20000
10000
0
5
4
3
2
1
0
2000
2025
2050
2075
2100
Year

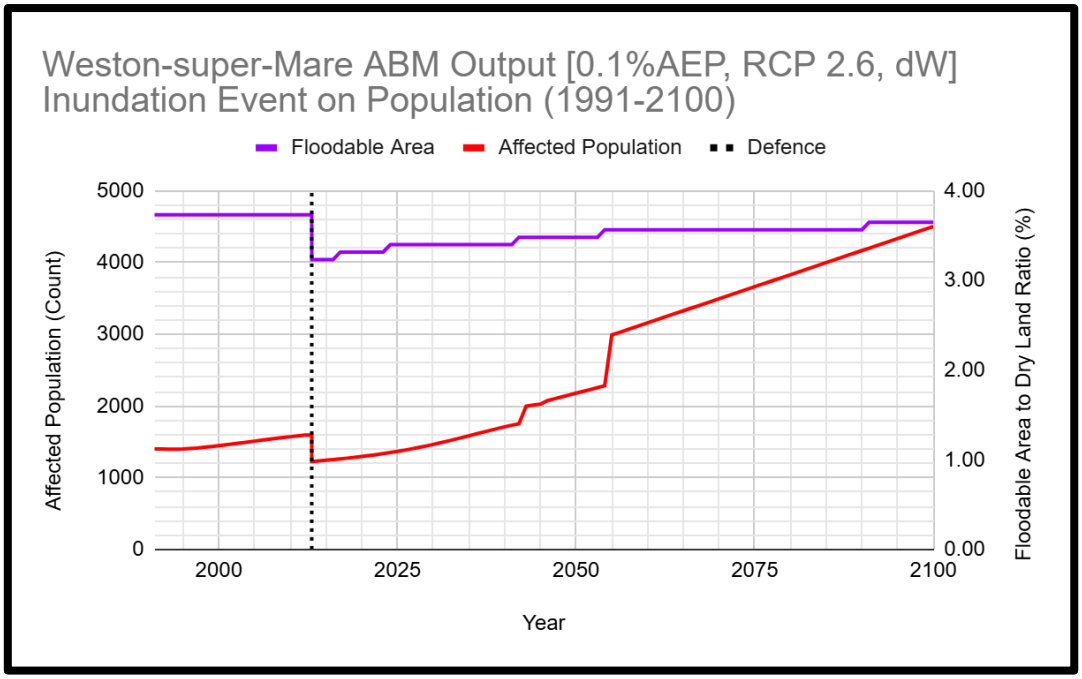

Weston-super-Mare ABM Output [0.5%AEP, RCP 2.6, dW]
Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
4000
3000
2000
1000
0
4.00
3.00
2.00
1.00
0.00
2000
2025
2050
2075
2100
Year

RCP2.6 - 0.1%AEP

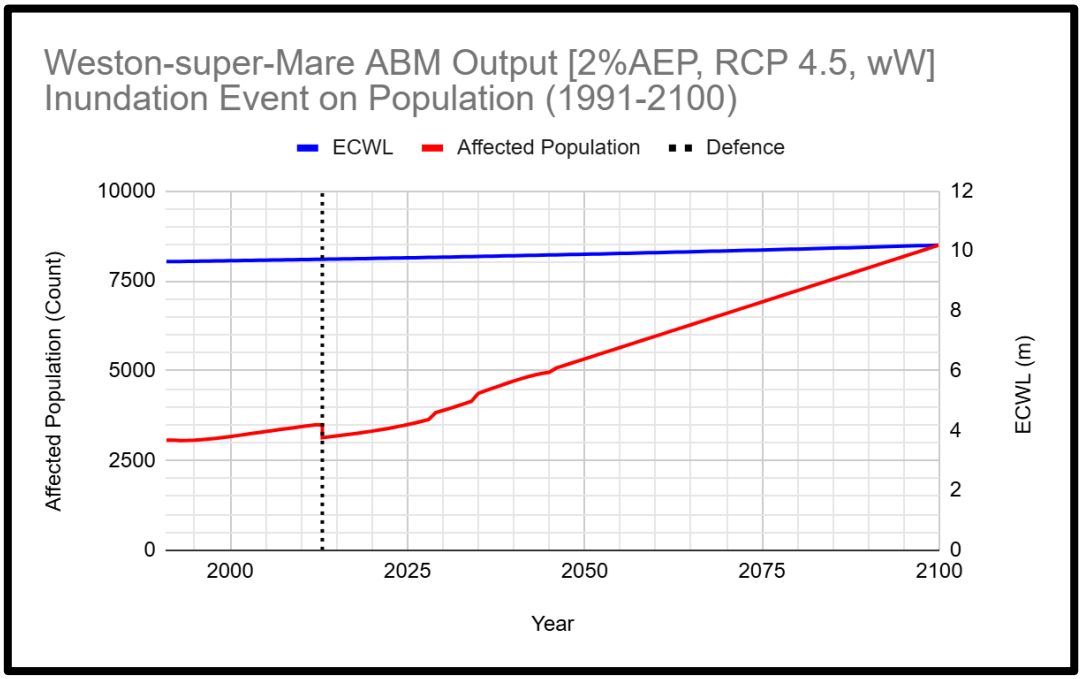

Weston-super-Mare ABM Output [0.1%AEP, RCP 2.6, wW]
Inundation Event on Population(1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
Year
500000
400000
300000
200000
100000
0
12
10
8
6
4
2
0
2000
2025
2050
2075
2100

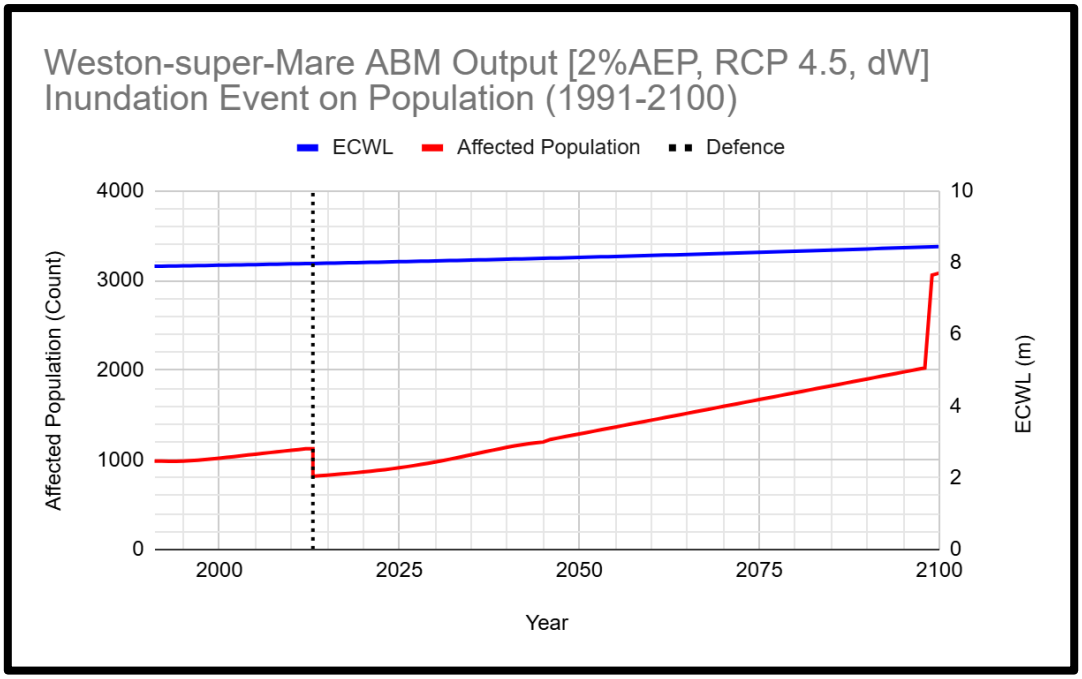

Weston-super-Mare ABM Output [0.1%AEP, RCP 2.6, dW]
Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
Year
5000
4000
3000
2000
1000
0
10
8
6
4
2
0
2000
2025
2050
2075
2100

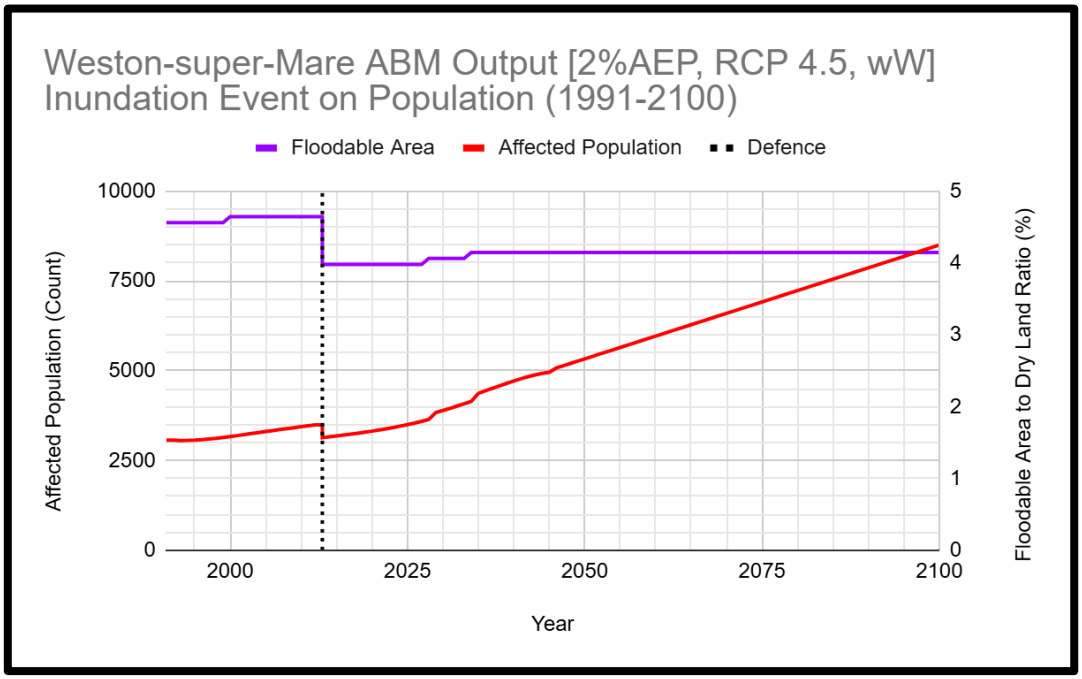

Weston-super-Mare ABM Output [0.1%AEP, RCP 2.6, wW]
Inundation Event on Population(1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
500000
400000
300000
200000
100000
0
60
40
20
0
Floodable Area to Dry Land Ratio (%)
2000
2025
2050
2075
2100
Year

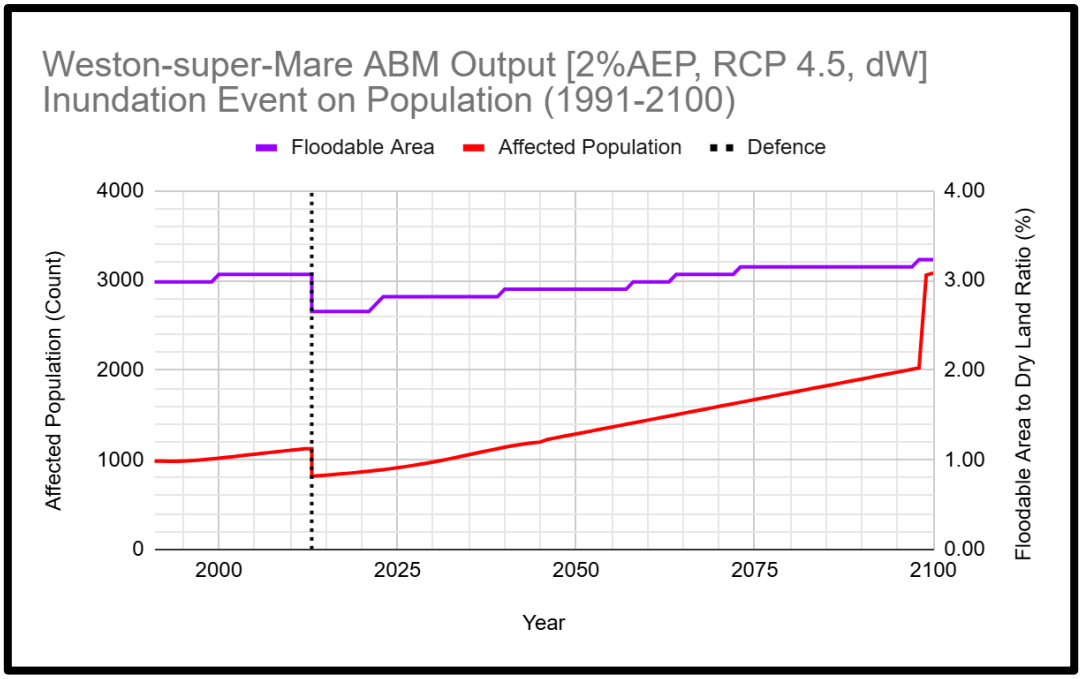

Weston-super-Mare ABM Output [0.1%AEP, RCP 2.6, dW]
Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
5000
4000
3000
2000
1000
0
4.00
3.00
2.00
1.00
0.00
Floodable Area to Dry Land Ratio (%)
2000
2025
2050
2075
2100
Year

RCP4.5 - 2%AEP

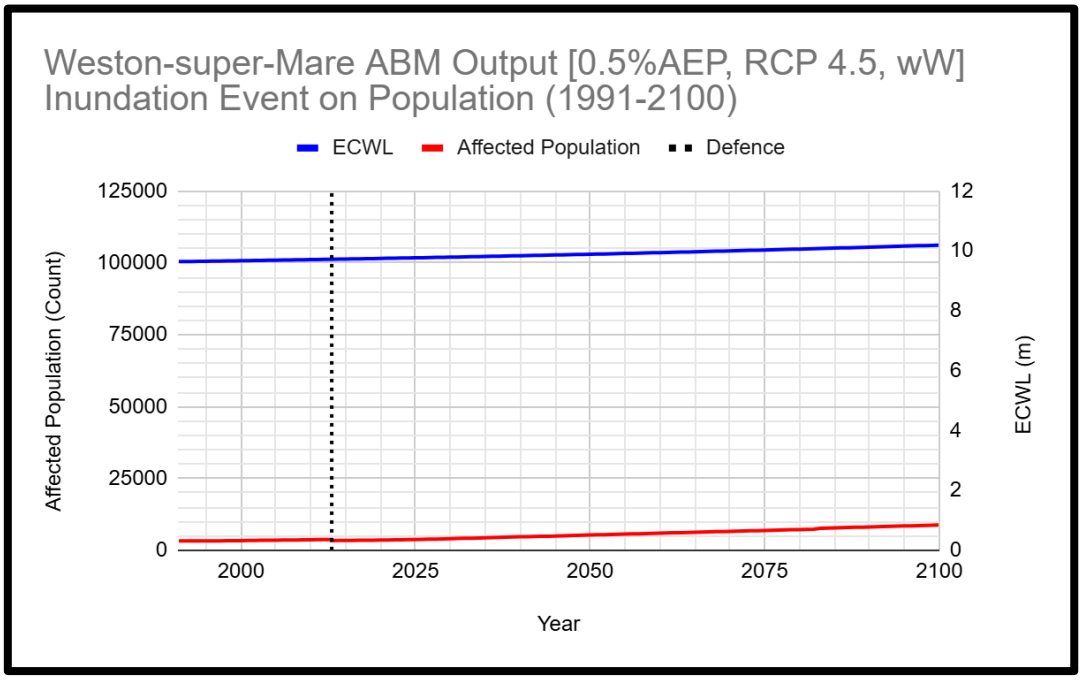

Weston-super-Mare ABM Output [2%AEP, RCP 4.5, wW]
Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
Year
0
2500
5000
7500
10000
0
2
4
6
8
10
12
2000
2025
2050
2075
2100

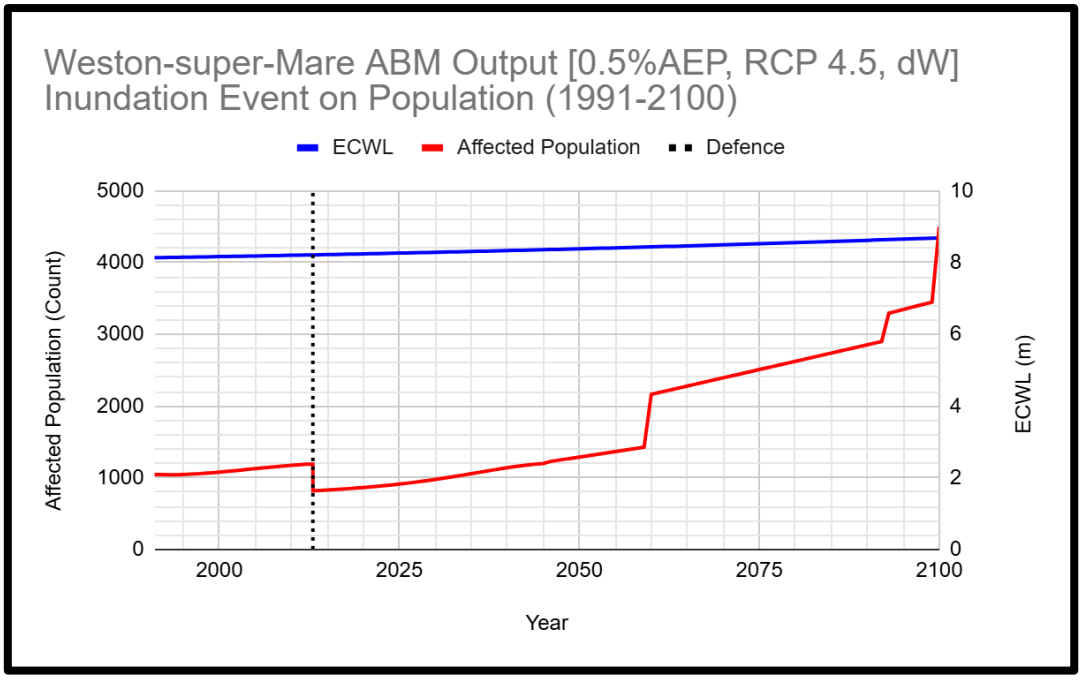

Weston-super-Mare ABM Output [2%AEP, RCP 4.5, dW]
Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
Year
0
1000
2000
3000
4000
0
2
4
6
8
10
2000
2025
2050
2075
2100

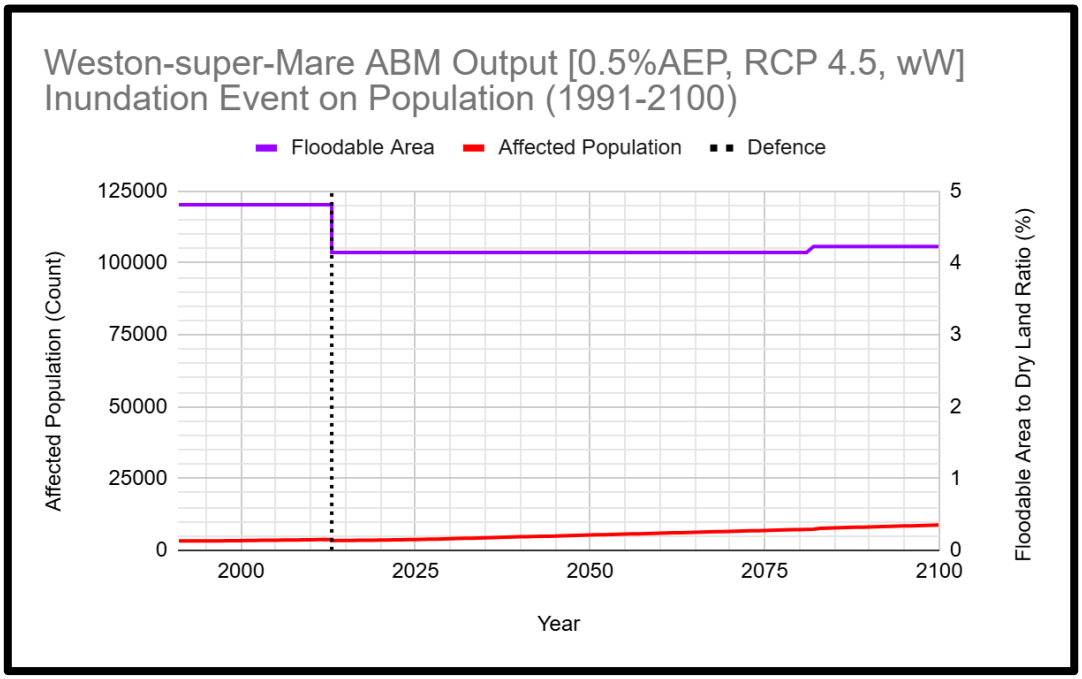

Weston-super-Mare ABM Output [2%AEP, RCP 4.5, wW]
Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
10000
7500
5000
2500
0
5
4
3
2
1
0
2000
2025
2050
2075
2100
Year

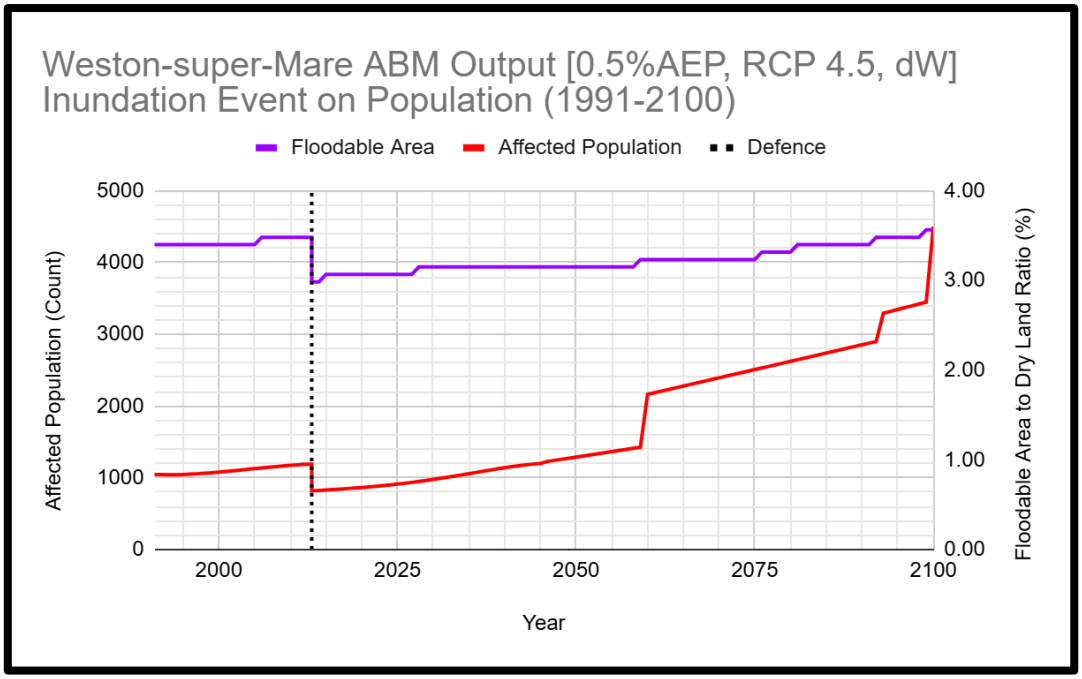

Weston-super-Mare ABM Output [2%AEP, RCP 4.5, dW]
Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
4000
3000
2000
1000
0
4.00
3.00
2.00
1.00
0.00
2000
2025
2050
2075
2100
Year

RCP4.5 - 0.5%AEP

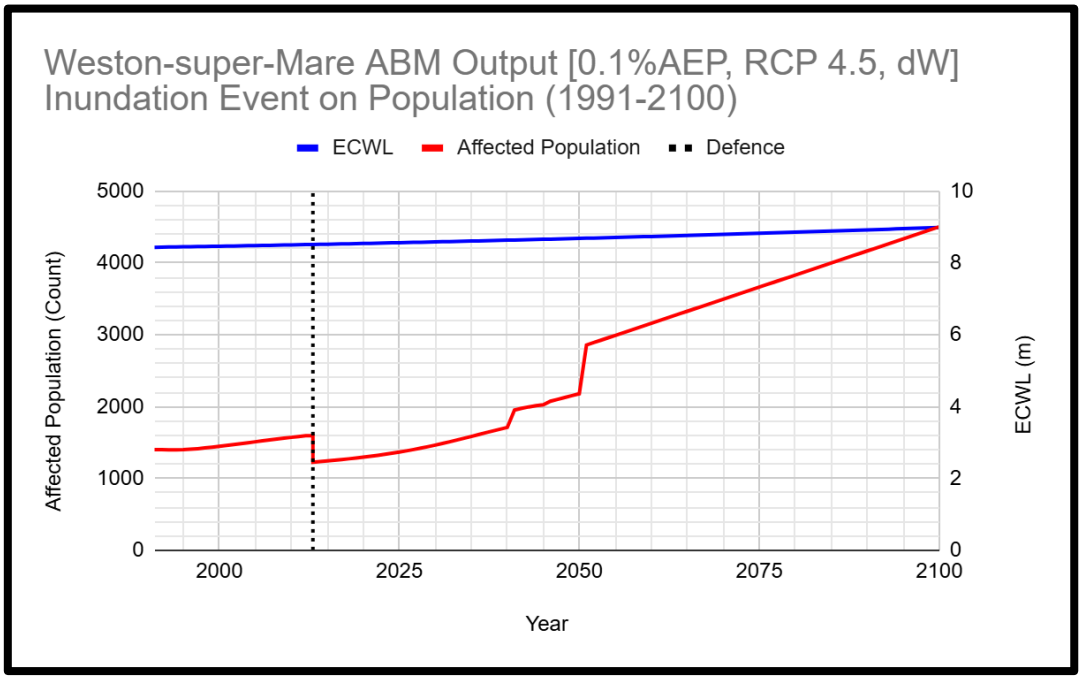

Weston-super-Mare ABM Output [0.5%AEP, RCP 4.5, wW]
Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
125000
100000
75000
50000
25000
0
ECWL (m)
12
10
8
6
4
2
0
2000
2025
2050
2075
2100
Year

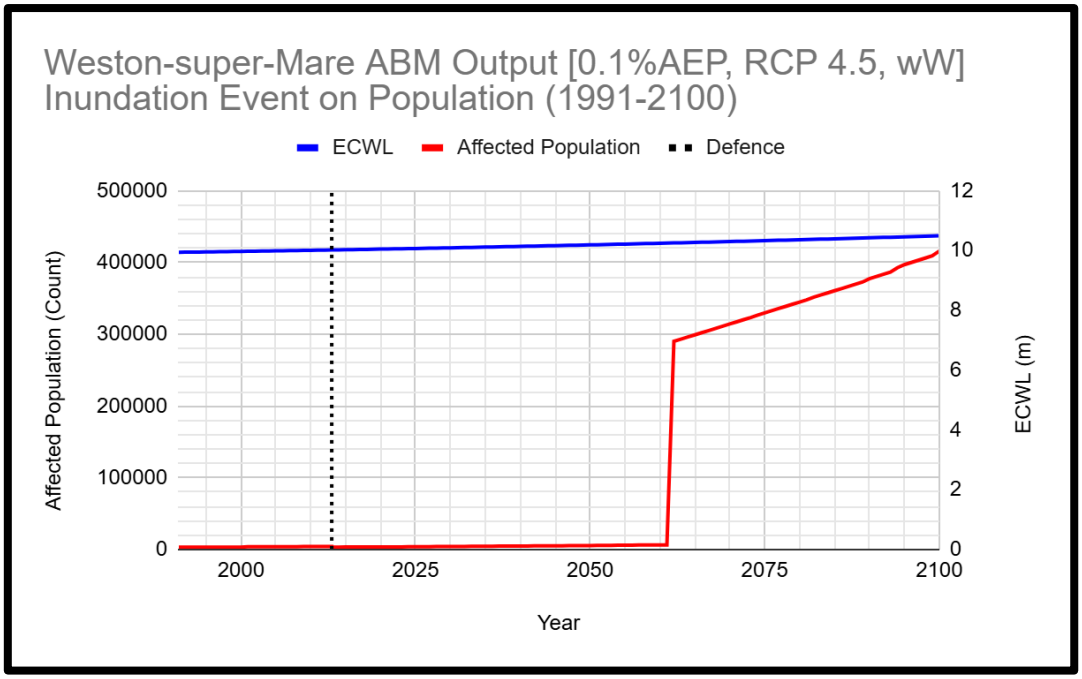

Weston-super-Mare ABM Output [0.5%AEP, RCP 4.5, dW]
Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
5000
4000
3000
2000
1000
0
ECWL (m)
10
8
6
4
2
0
2000
2025
2050
2075
2100
Year

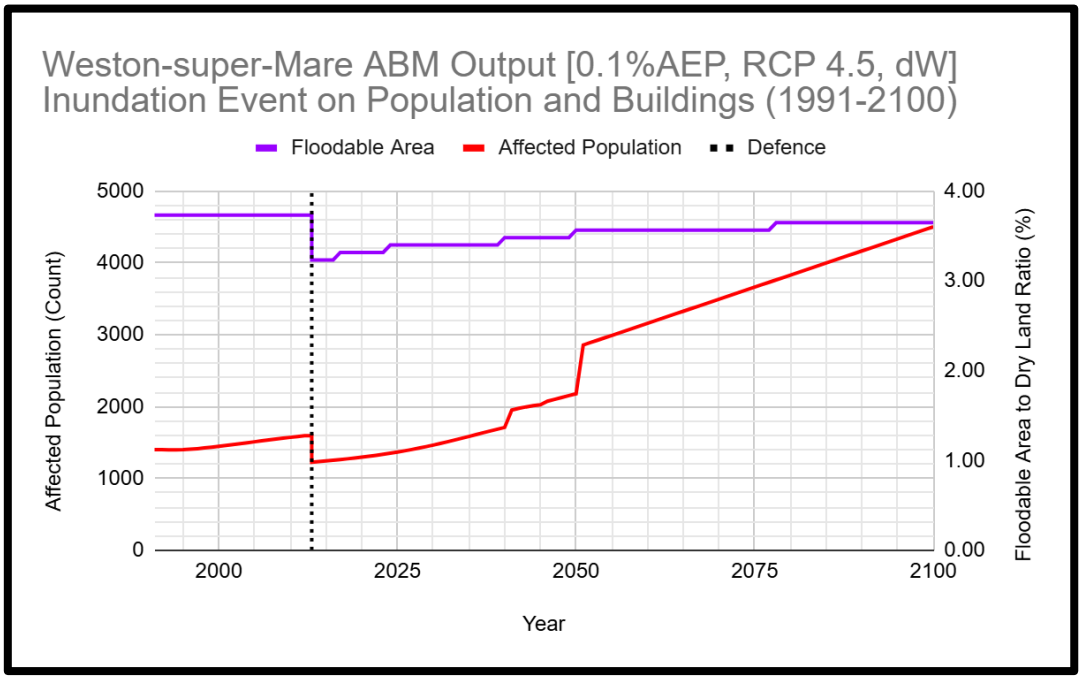

Weston-super-Mare ABM Output [0.5%AEP, RCP 4.5, wW]
Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
125000
100000
75000
50000
25000
0
2000
2025
2050
2075
2100
Year
5
4
3
2
1
0
Floodable Area to Dry Land Ratio (%)

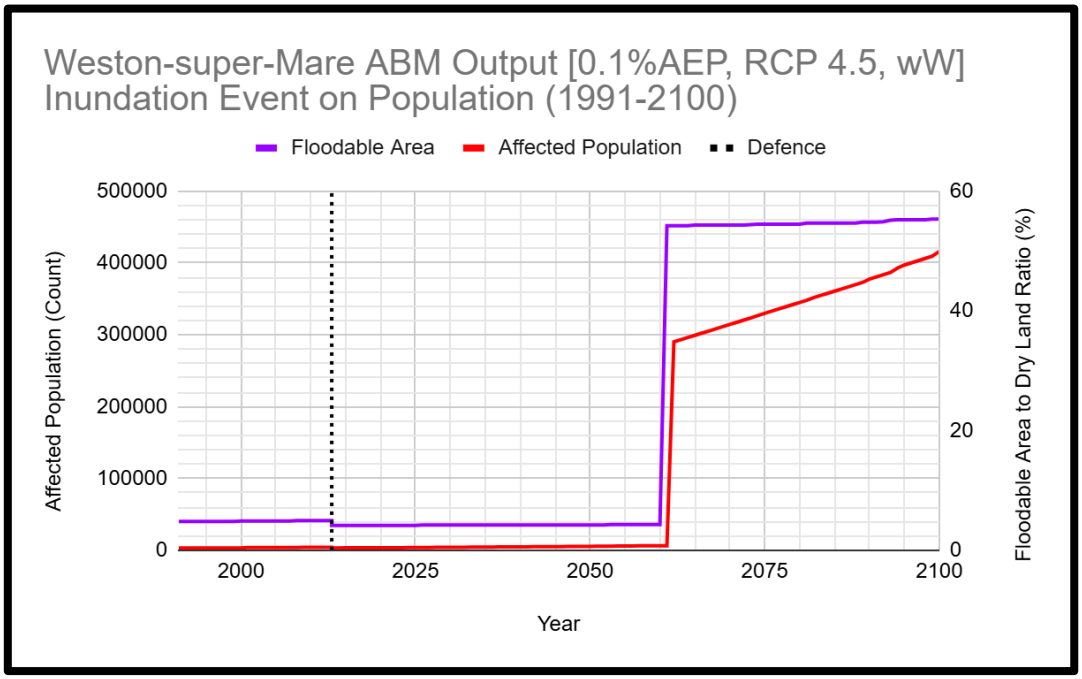

Weston-super-Mare ABM Output [0.5%AEP, RCP 4.5, dW]
Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
5000
4000
3000
2000
1000
0
2000
2025
2050
2075
2100
Year
4.00
3.00
2.00
1.00
0.00
Floodable Area to Dry Land Ratio (%)

RCP4.5 - 0.1%AEP

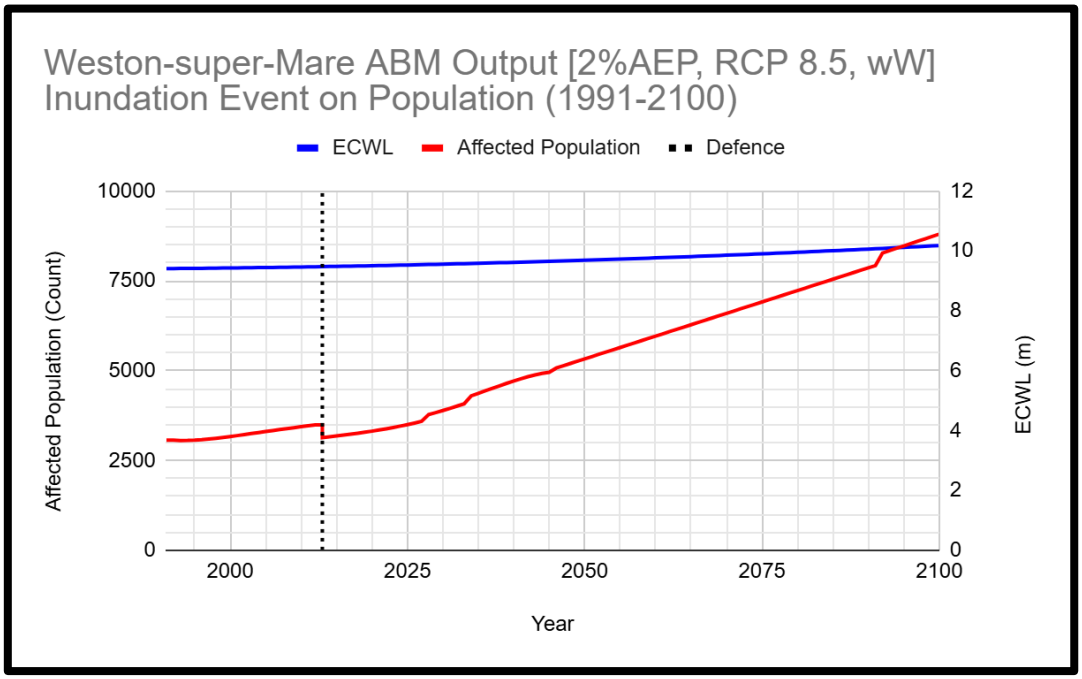

Weston-super-Mare ABM Output [0.1%AEP, RCP 4.5, dW]
Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
5000
4000
3000
2000
1000
0
10
8
6
4
2
0
2000
2025
2050
2075
2100
Year

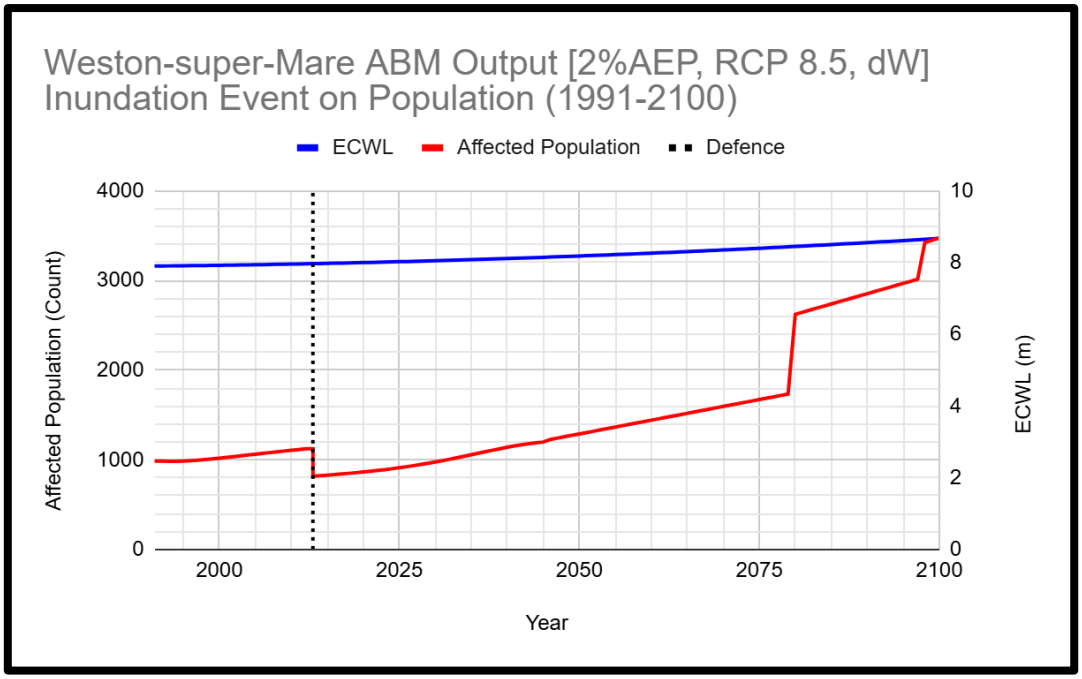

Weston-super-Mare ABM Output [0.1%AEP, RCP 4.5, wW]
Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
500000
400000
300000
200000
100000
0
12
10
8
6
4
2
0
2000
2025
2050
2075
2100
Year

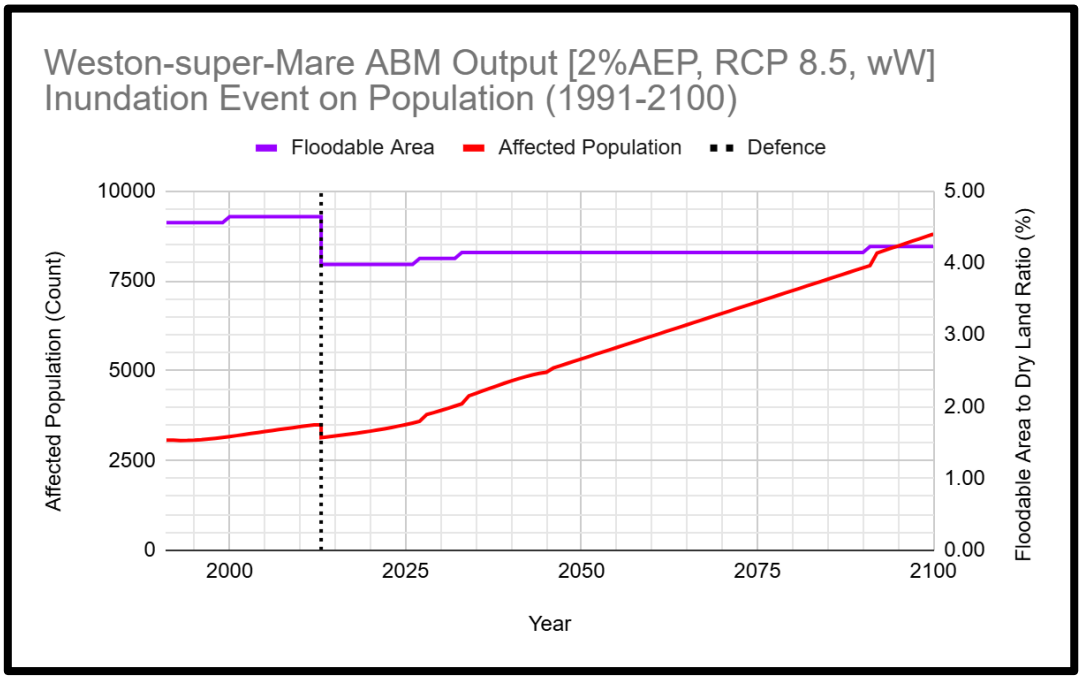

Weston-super-Mare ABM Output [0.1%AEP, RCP 4.5, dW]
Inundation Event on Population and Buildings (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
5000
4000
3000
2000
1000
0
4.00
3.00
2.00
1.00
0.00
2000
2025
2050
2075
2100
Year

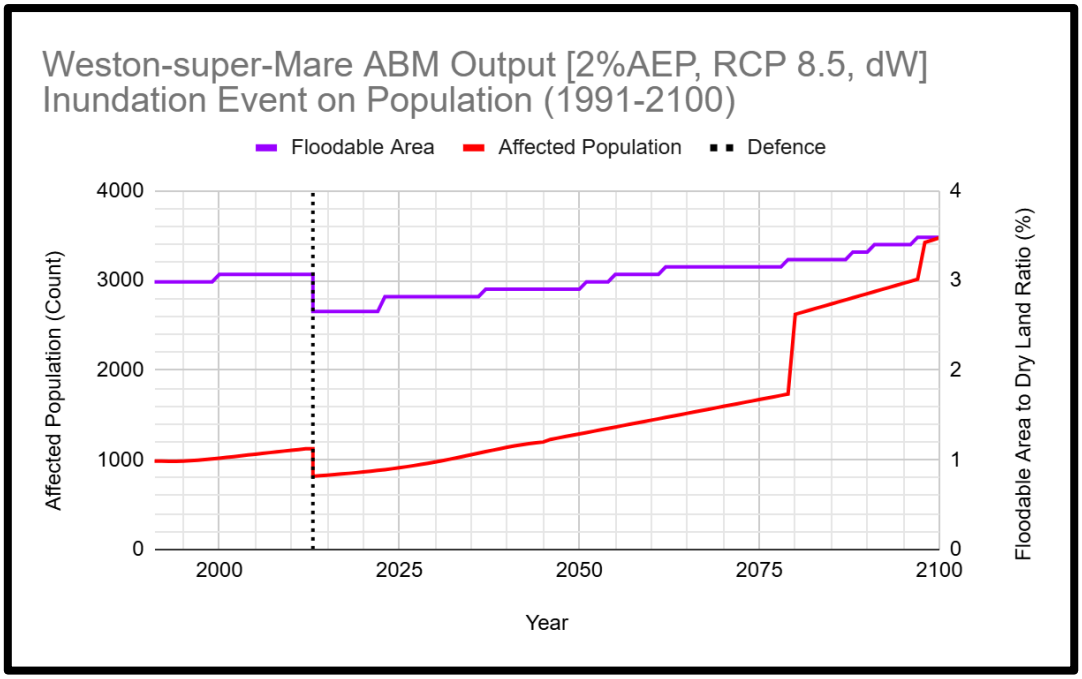

Weston-super-Mare ABM Output [0.1%AEP, RCP 4.5, wW]
Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
500000
400000
300000
200000
100000
0
60
40
20
0
2000
2025
2050
2075
2100
Year

RCP8.5 - 2%AEP

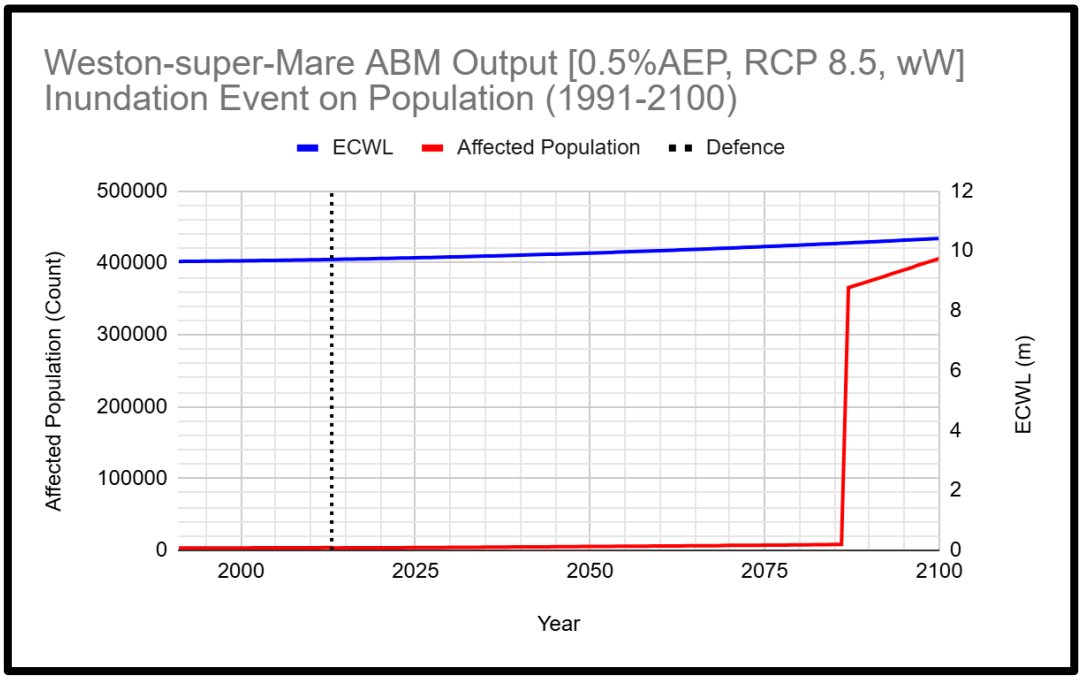

Weston-super-Mare ABM Output [2%AEP, RCP 8.5, wW]
Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
Year
0
2500
5000
7500
10000
0
2
4
6
8
10
12
2000
2025
2050
2075
2100

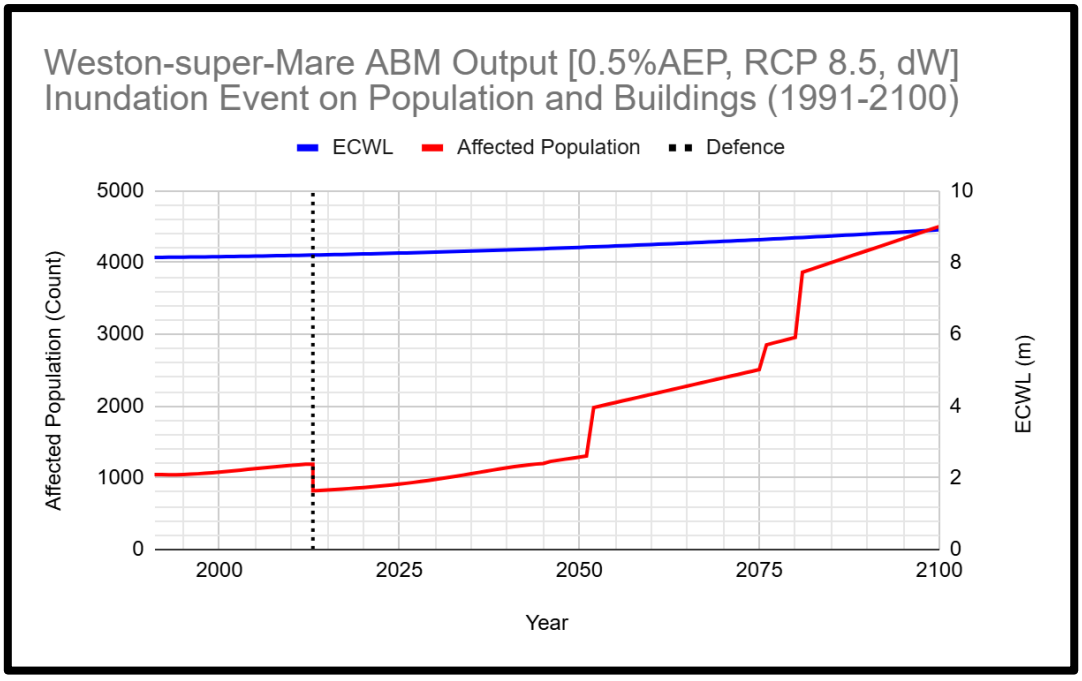

Weston-super-Mare ABM Output [2%AEP, RCP 8.5, dW]
Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
Year
0
1000
2000
3000
4000
0
2
4
6
8
10
2000
2025
2050
2075
2100

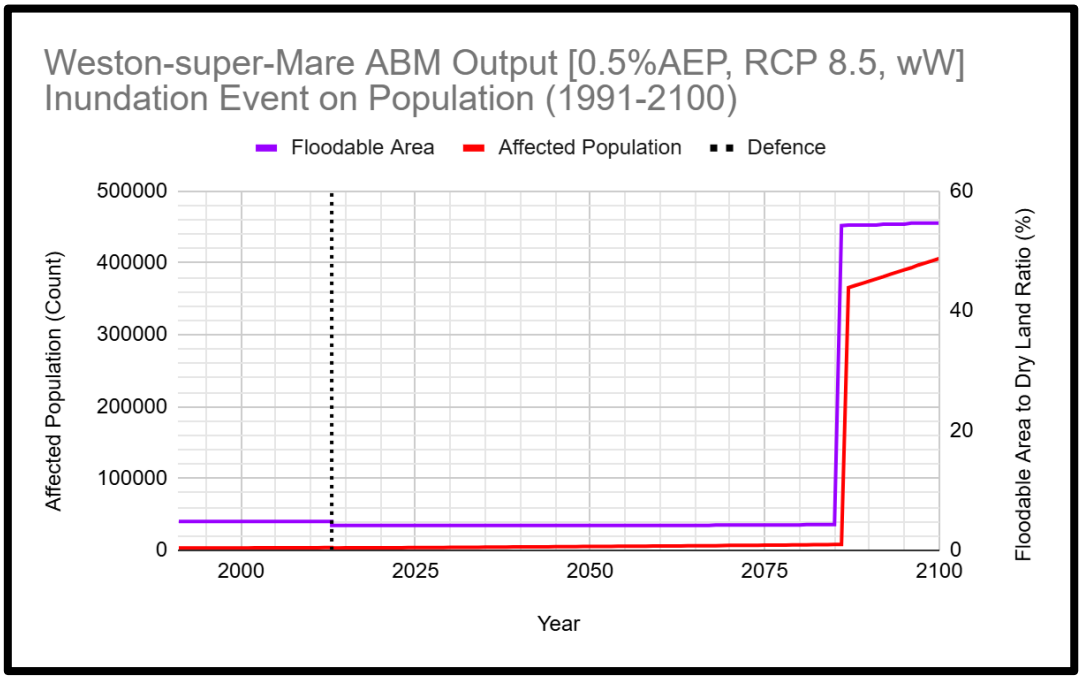

Weston-super-Mare ABM Output [2%AEP, RCP 8.5, wW]
Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
10000
7500
5000
2500
0
5.00
4.00
3.00
2.00
1.00
0.00
2000
2025
2050
2075
2100
Year

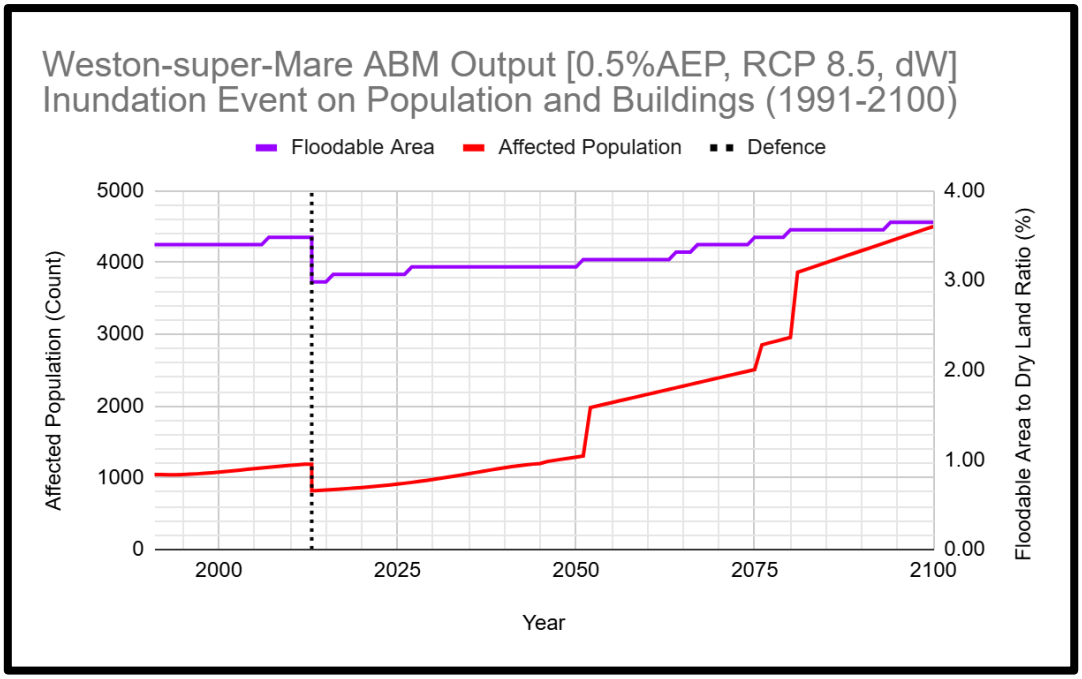

Weston-super-Mare ABM Output [2%AEP, RCP 8.5, dW]
Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
4000
3000
2000
1000
0
4
3
2
1
0
2000
2025
2050
2075
2100
Year

RCP8.5 - 0.5%AEP

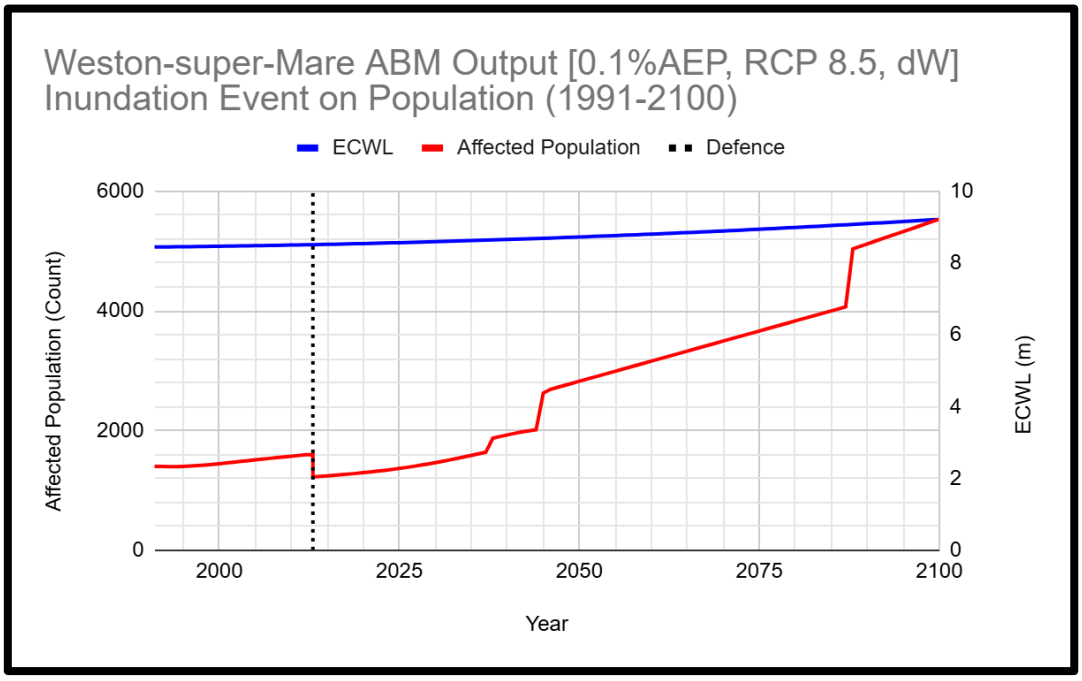

Weston-super-Mare ABM Output [0.5%AEP, RCP 8.5, wW]
Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
500000
400000
300000
200000
100000
0
ECWL (m)
12
10
8
6
4
2
0
2000
2025
2050
2075
2100
Year

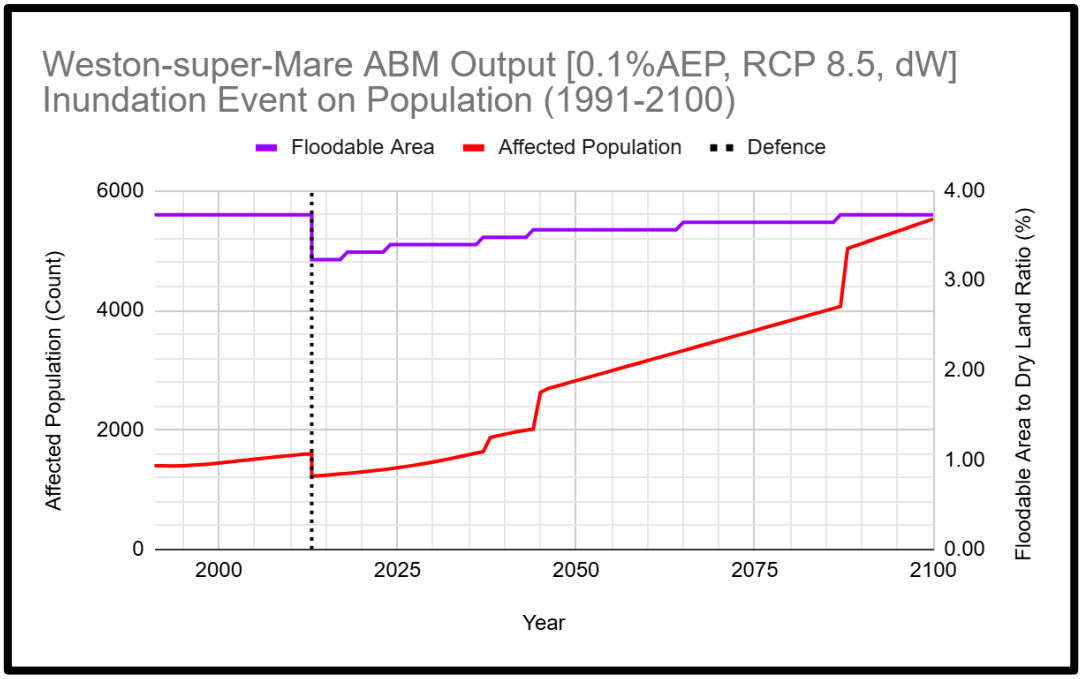

Weston-super-Mare ABM Output [0.5%AEP, RCP 8.5, dW]
Inundation Event on Population and Buildings (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
5000
4000
3000
2000
1000
0
ECWL (m)
10
8
6
4
2
0
2000
2025
2050
2075
2100
Year


Weston-super-Mare ABM Output [0.5%AEP, RCP 8.5, wW]
Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
500000
400000
300000
200000
100000
0
60
40
20
0
Floodable Area to Dry Land Ratio (%)
2000
2025
2050
2075
2100
Year


Weston-super-Mare ABM Output [0.5%AEP, RCP 8.5, dW]
Inundation Event on Population and Buildings (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
5000
4000
3000
2000
1000
0
4.00
3.00
2.00
1.00
0.00
Floodable Area to Dry Land Ratio (%)
2000
2025
2050
2075
2100
Year

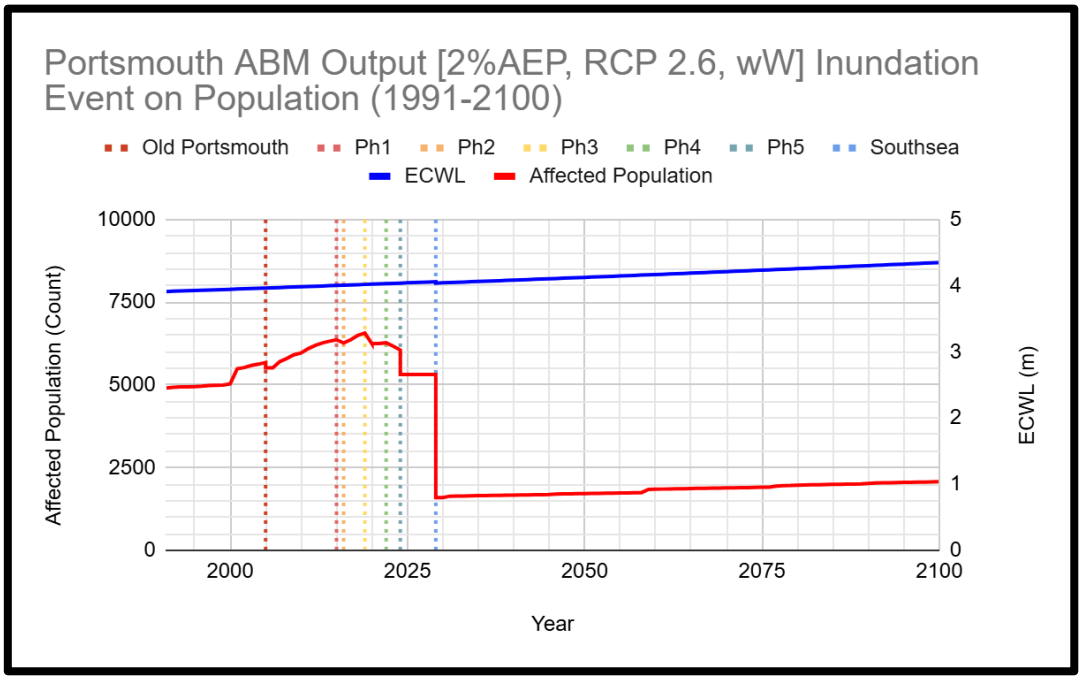
RCP8.5 - 0.1%AEP

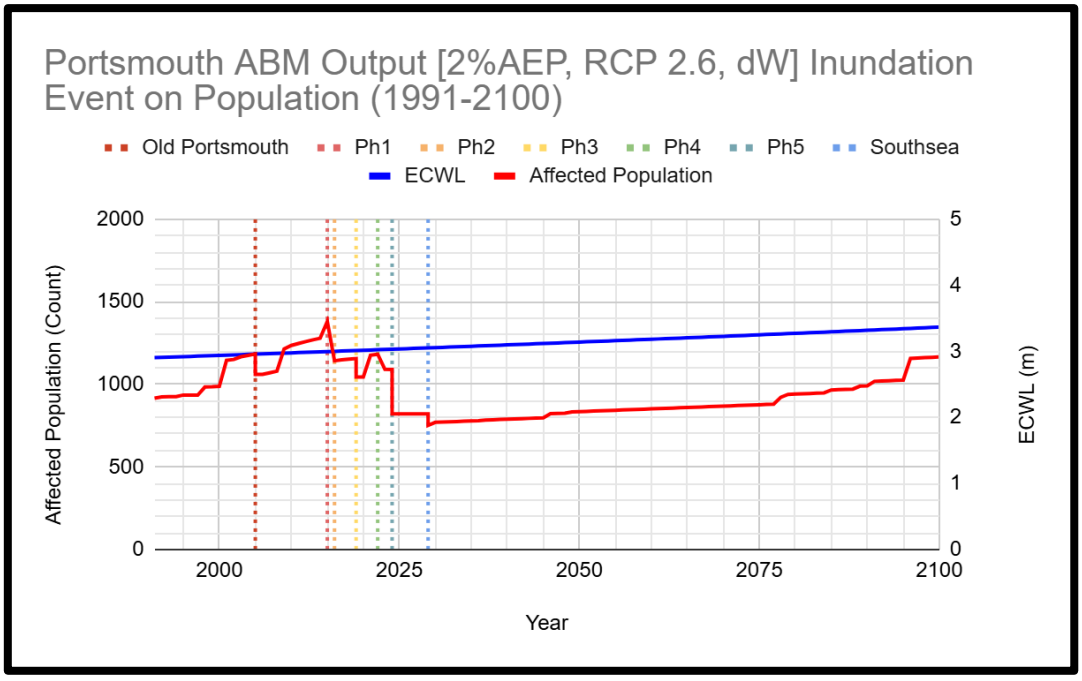

Weston-super-Mare ABM Output [0.1%AEP, RCP 8.5, dW]
Inundation Event on Population (1991-2100)
ECWL
Affected Population
Defence
Affected Population (Count)
ECWL (m)
Year
0
2000
4000
6000
0
2
4
6
8
10
2000
2025
2050
2075
2100

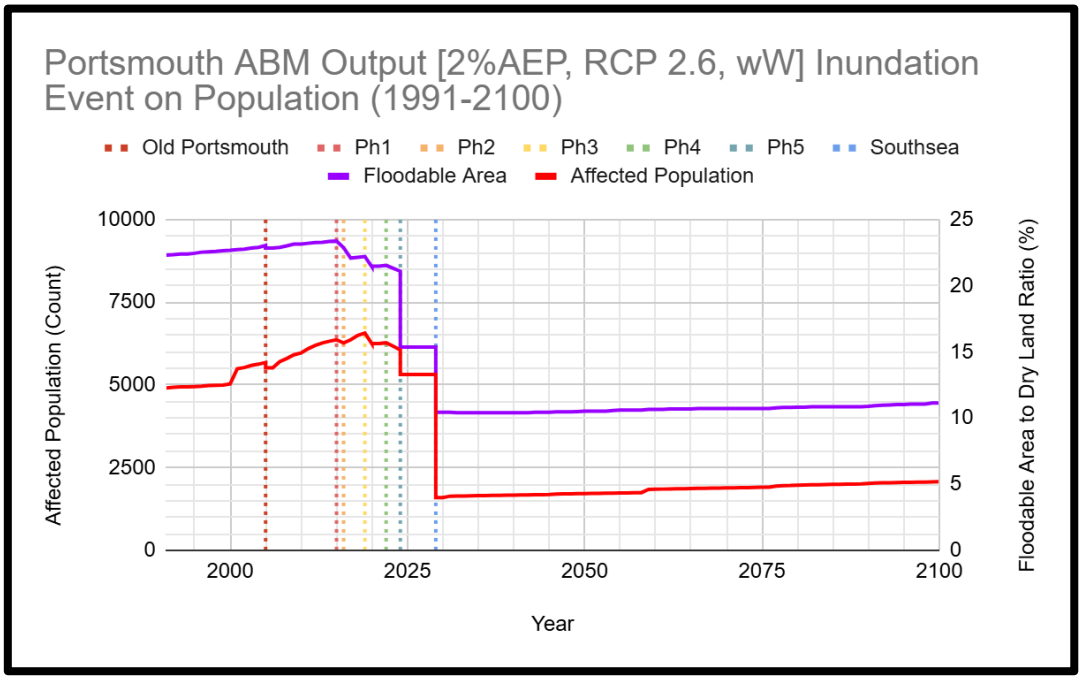

Weston-super-Mare ABM Output [0.1%AEP, RCP 8.5, dW]
Inundation Event on Population (1991-2100)
Floodable Area
Affected Population
Defence
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
Year
0
2000
4000
6000
0.00
1.00
2.00
3.00
4.00
2000
2025
2050
2075
2100

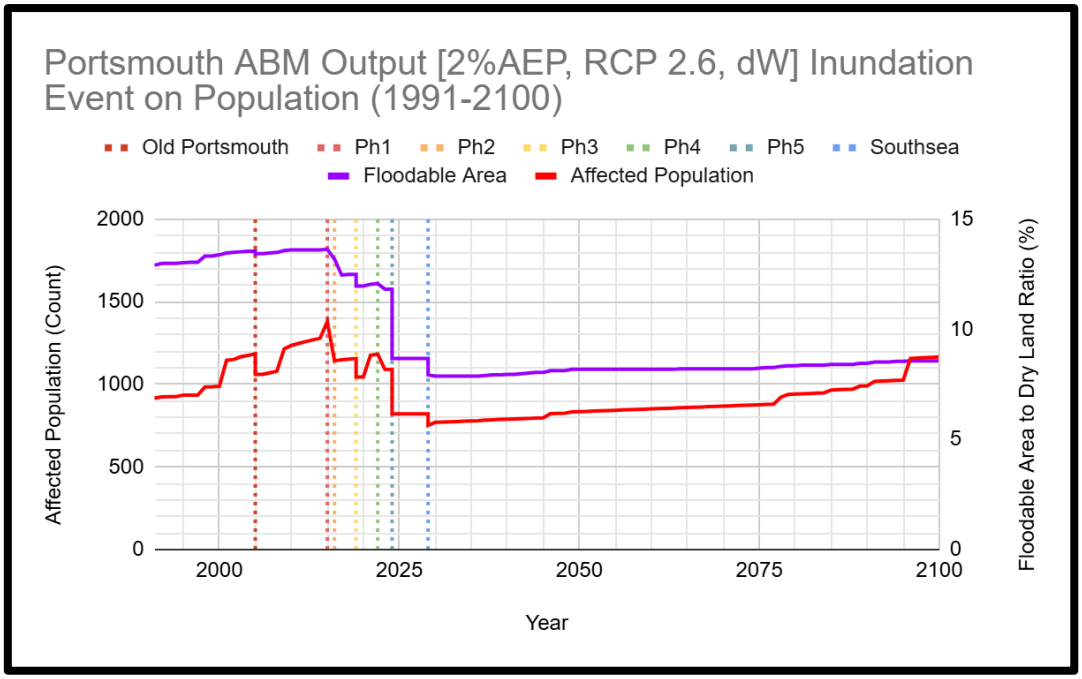
Case Study C

RCP2.6 - 2%AEP

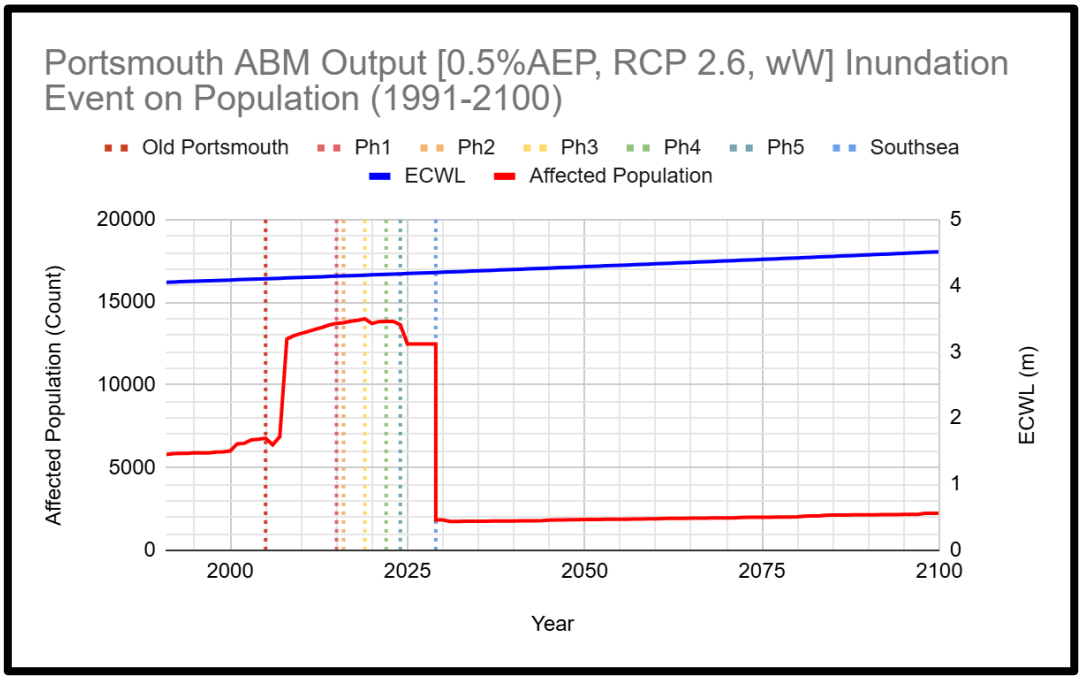


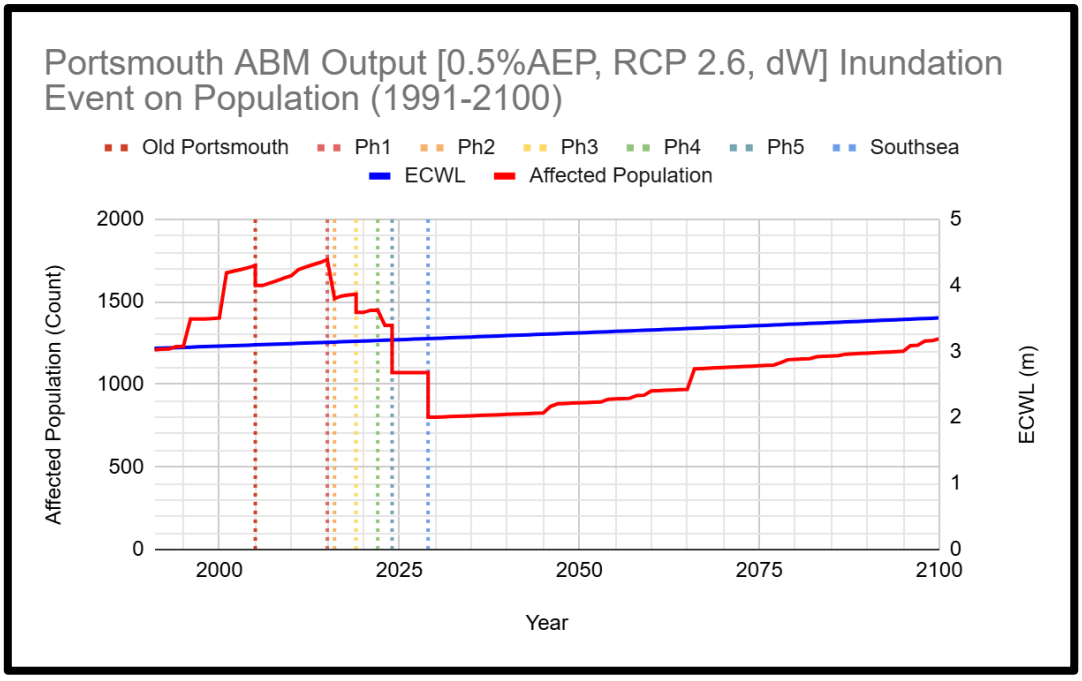


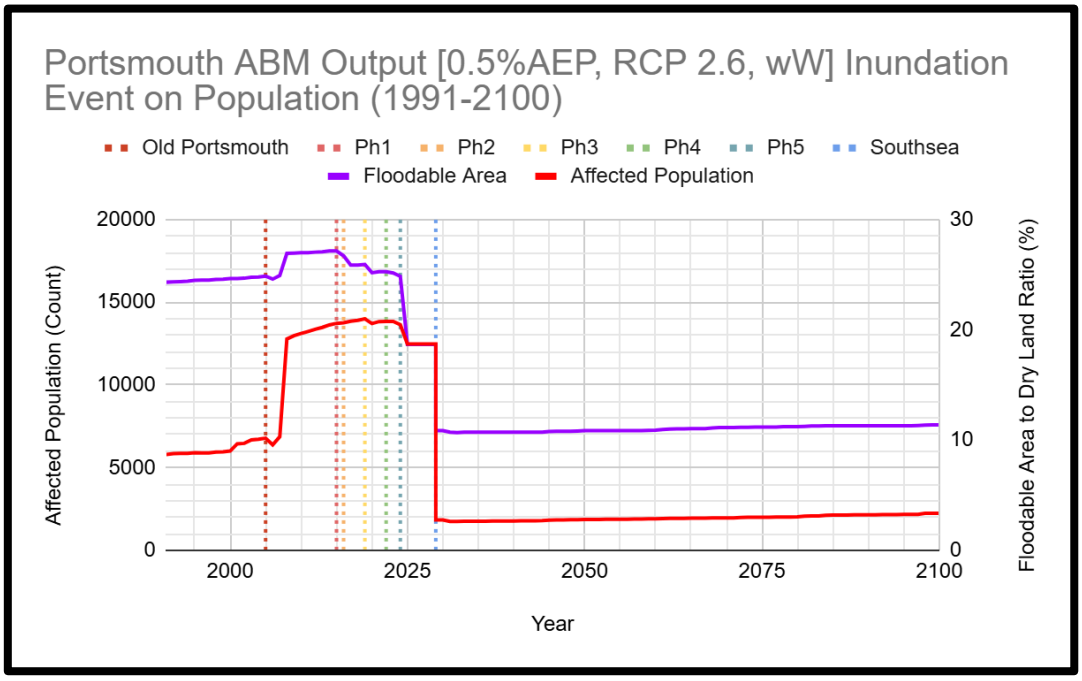

Portsmouth ABM Output [2%AEP, RCP 2.6, wW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
10000
7500
5000
2500
0
25
20
15
10
5
0
2000
2025
2050
2075
2100
Year

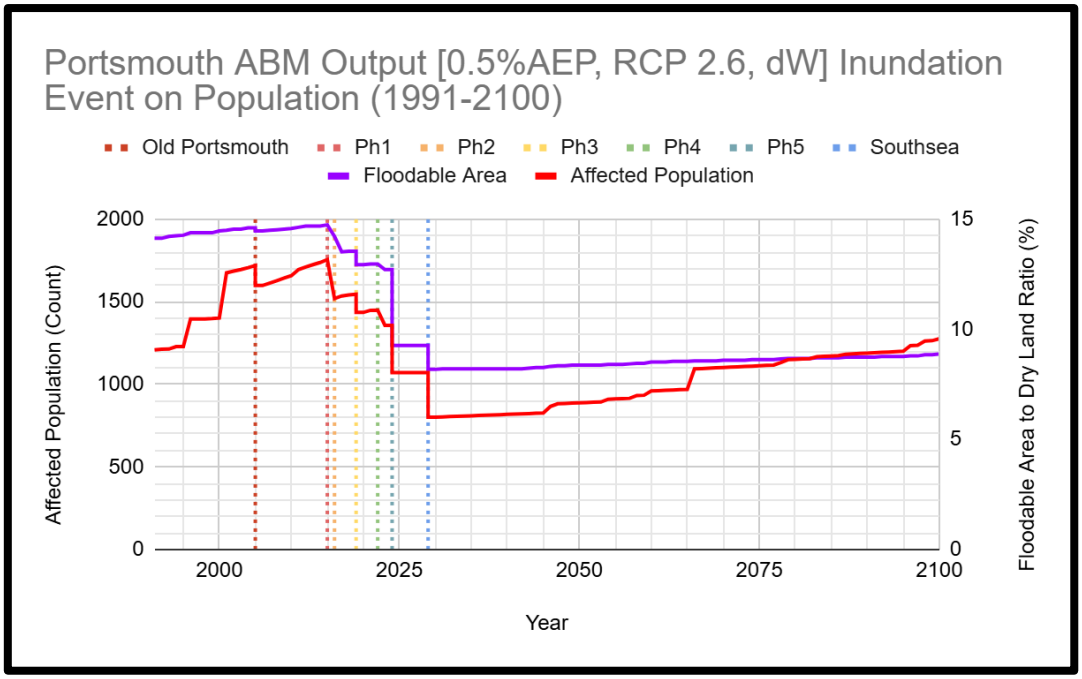

Portsmouth ABM Output [2%AEP, RCP 2.6, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
2000
1500
1000
500
0
15
10
5
0
2000
2025
2050
2075
2100
Year

RCP2.6 - 0.5%AEP

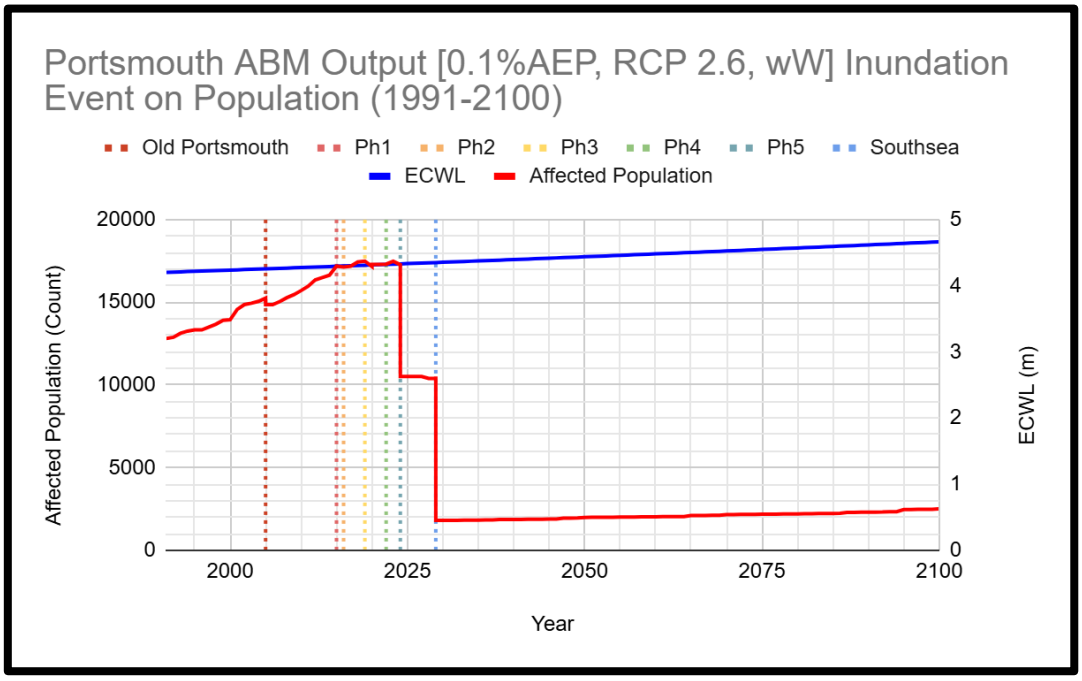

Portsmouth ABM Output [0.5%AEP, RCP 2.6, wW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
ECWL
Affected Population
Affected Population (Count)
ECWL (m)
Year
0
5000
10000
15000
20000
0
1
2
3
4
5
2000
2025
2050
2075
2100

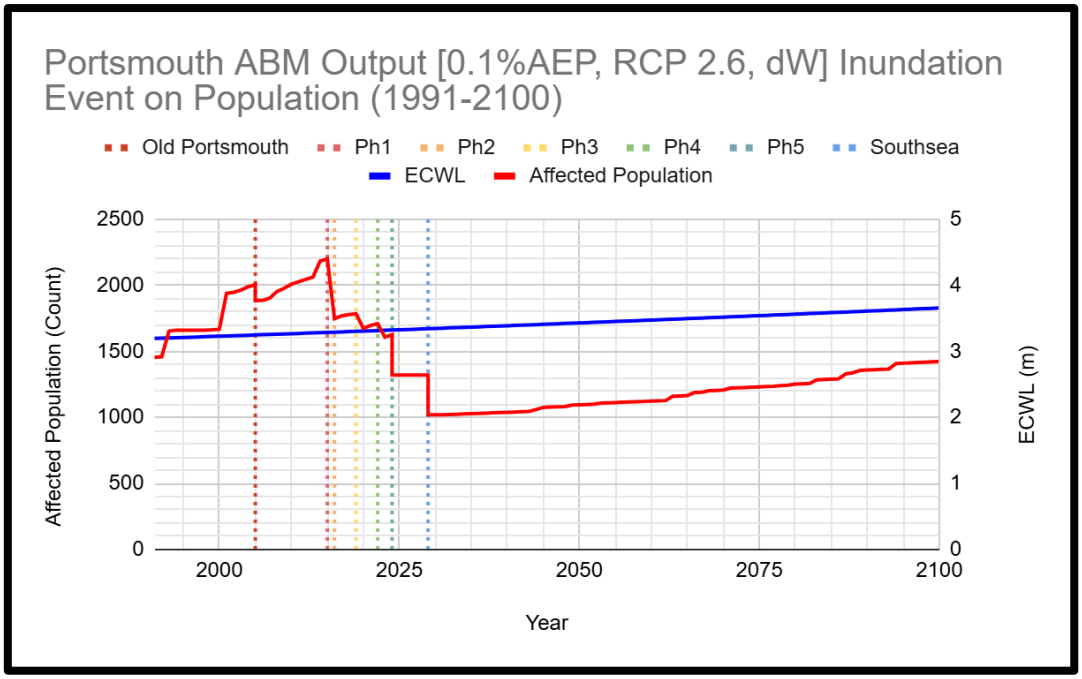

Portsmouth ABM Output [0.5%AEP, RCP 2.6, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
ECWL
Affected Population
Affected Population (Count)
ECWL (m)
Year
0
500
1000
1500
2000
0
1
2
3
4
5
2000
2025
2050
2075
2100

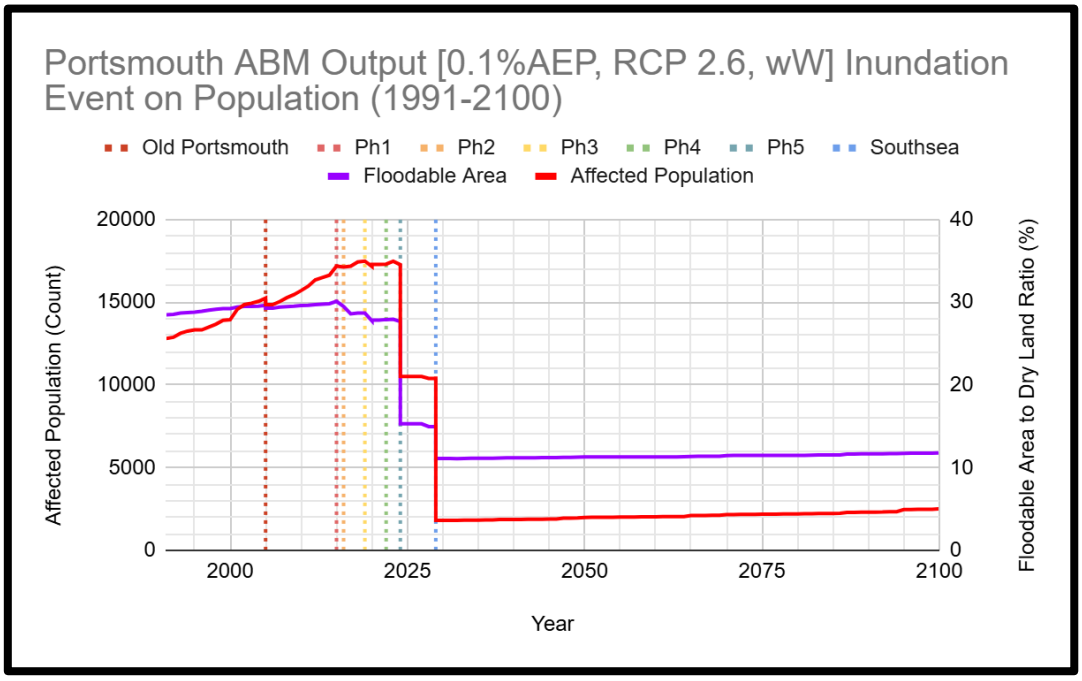

Portsmouth ABM Output [0.5%AEP, RCP 2.6, wW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
Year
0
5000
10000
15000
20000
0
10
20
30
2000
2025
2050
2075
2100

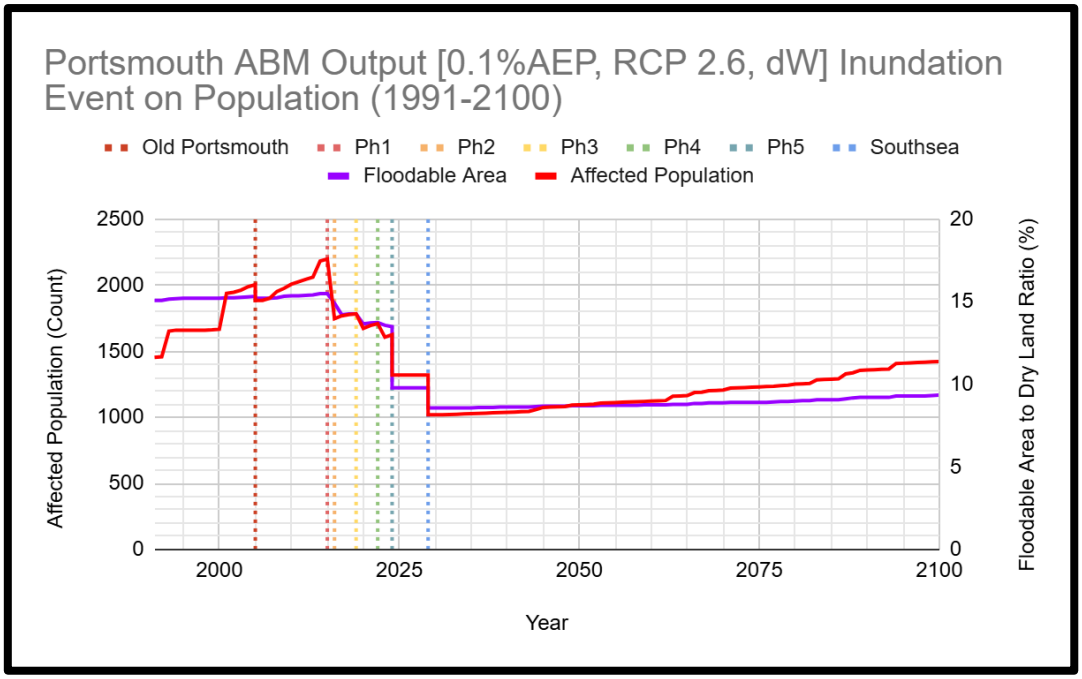

Portsmouth ABM Output [0.5%AEP, RCP 2.6, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
Year
0
500
1000
1500
2000
0
5
10
15
2000
2025
2050
2075
2100

RCP2.6 - 0.1%AEP

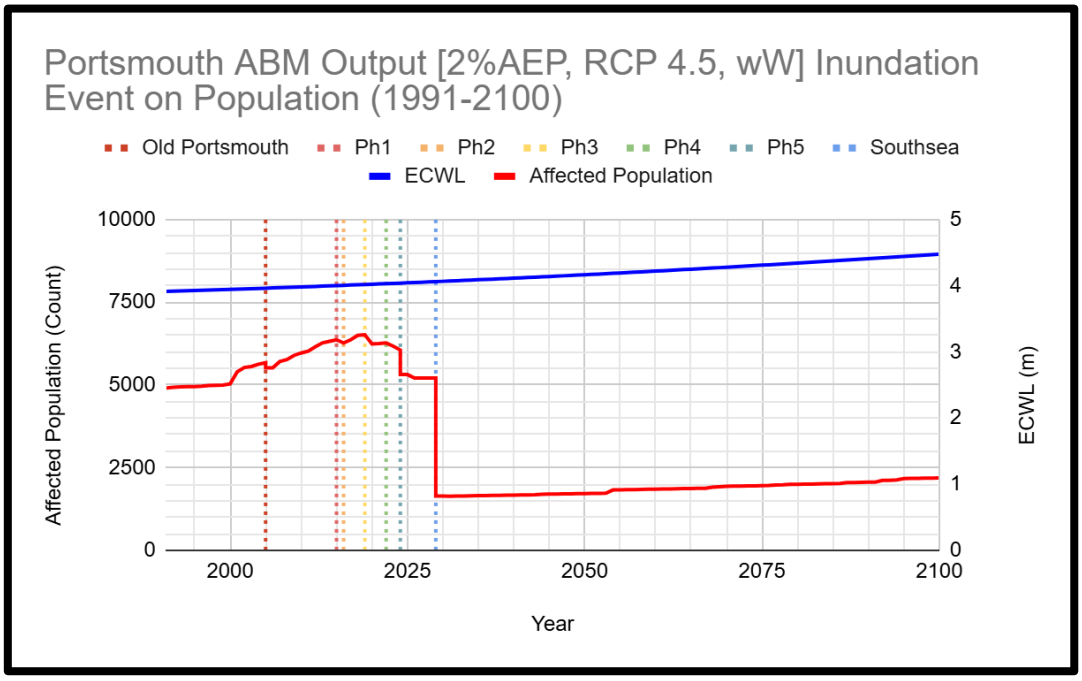

Portsmouth ABM Output [0.1%AEP, RCP 2.6, wW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
ECWL
Affected Population
Affected Population (Count)
ECWL (m)
Year
0
5000
10000
15000
20000
0
1
2
3
4
5
2000
2025
2050
2075
2100

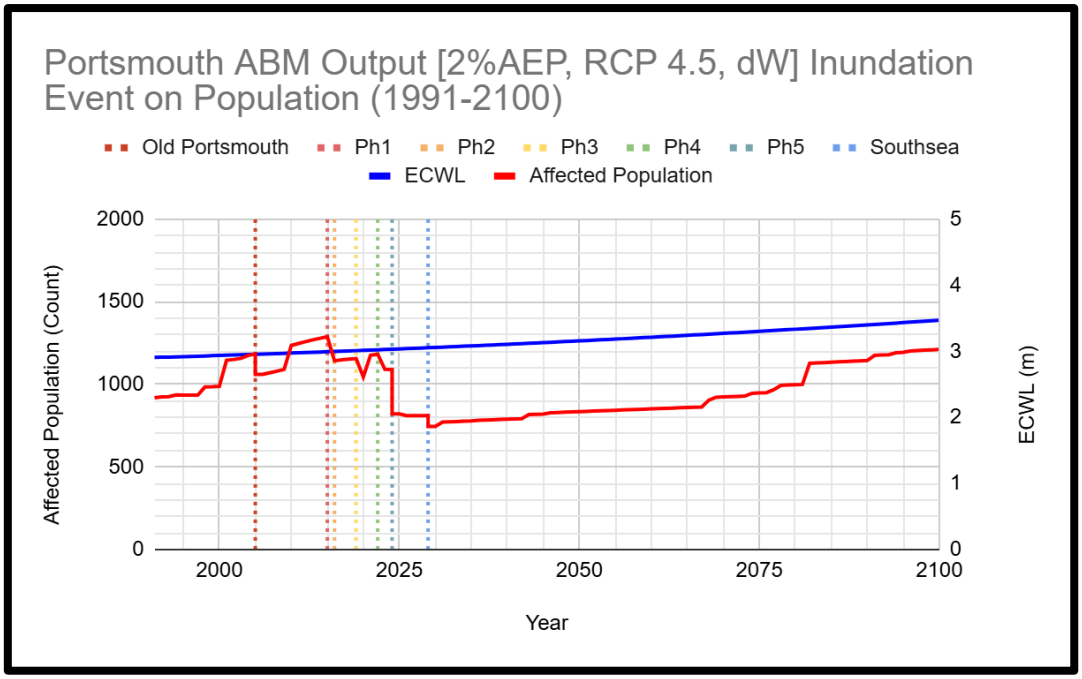

Portsmouth ABM Output [0.1%AEP, RCP 2.6, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
ECWL
Affected Population
Affected Population (Count)
ECWL (m)
Year
0
500
1000
1500
2000
2500
0
1
2
3
4
5
2000
2025
2050
2075
2100

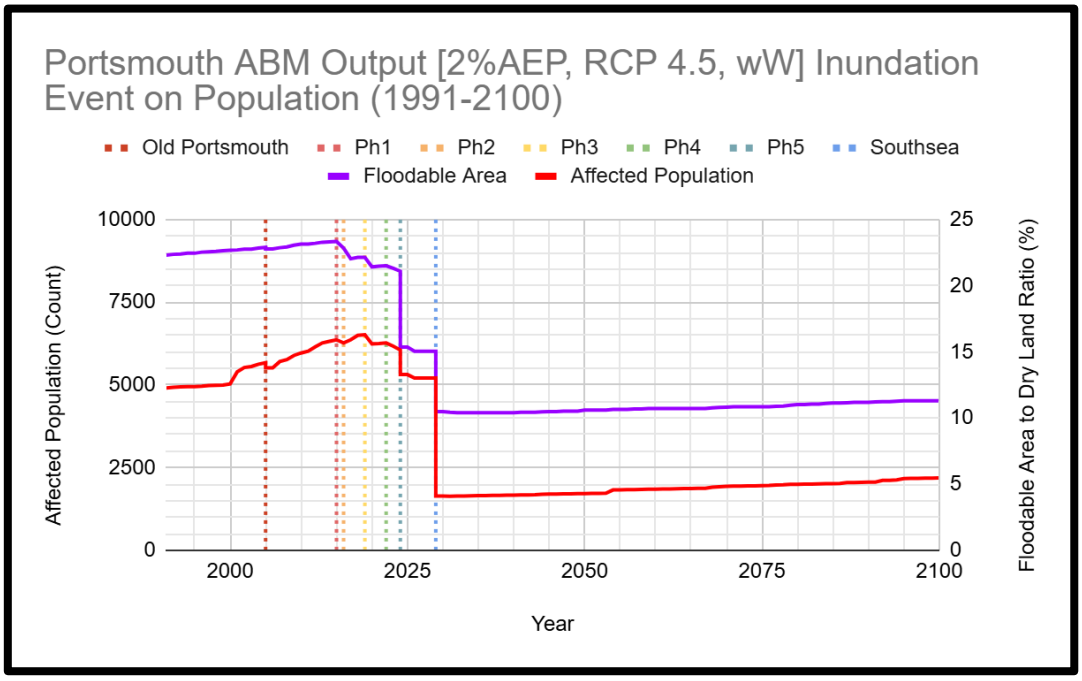

Portsmouth ABM Output [0.1%AEP, RCP 2.6, wW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
Year
0
5000
10000
15000
20000
0
10
20
30
40
2000
2025
2050
2075
2100

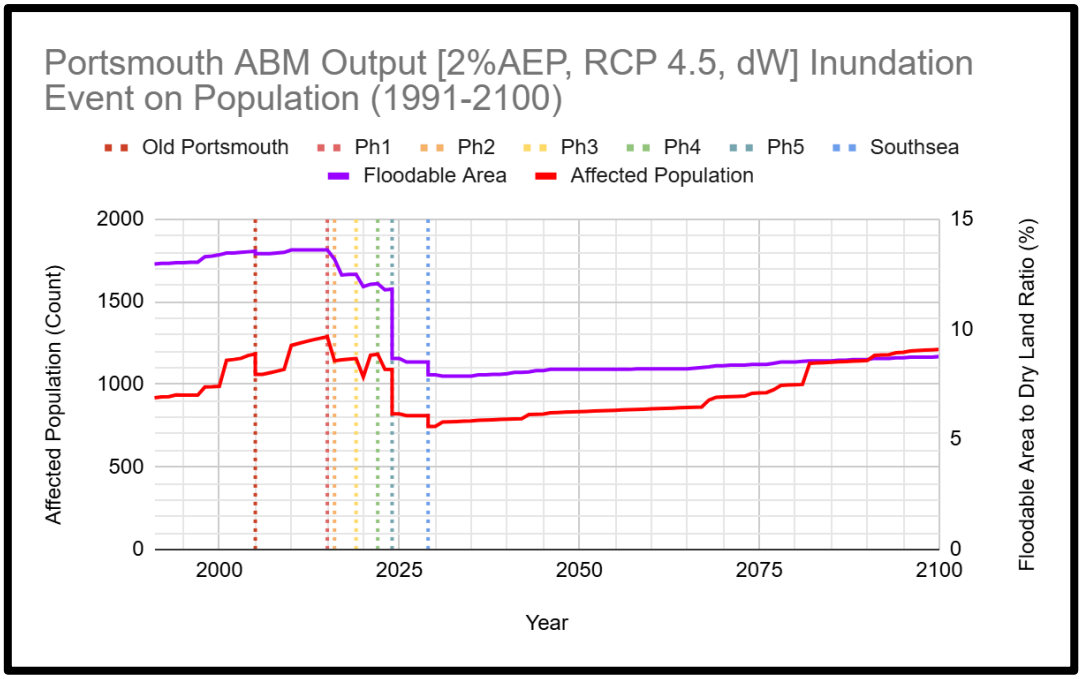

Portsmouth ABM Output [0.1%AEP, RCP 2.6, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
Year
0
500
1000
1500
2000
2500
0
5
10
15
20
2000
2025
2050
2075
2100

RCP4.5 - 2%AEP

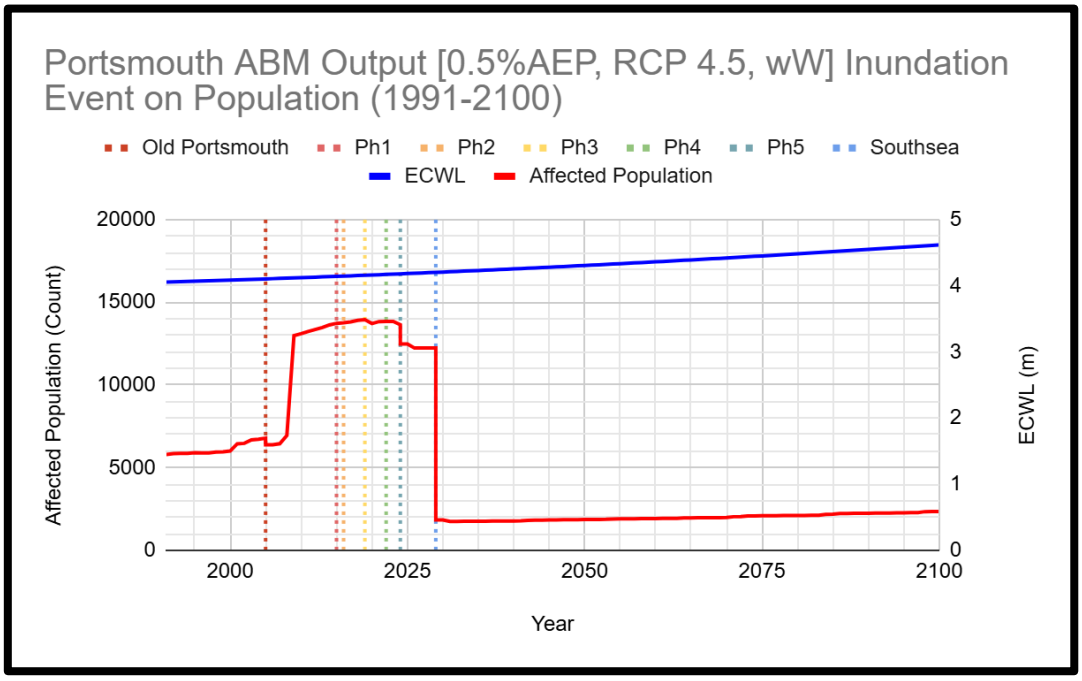

Portsmouth ABM Output [2%AEP, RCP 4.5, wW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
ECWL
Affected Population
Affected Population (Count)
ECWL (m)
Year
0
2500
5000
7500
10000
0
1
2
3
4
5
2000
2025
2050
2075
2100

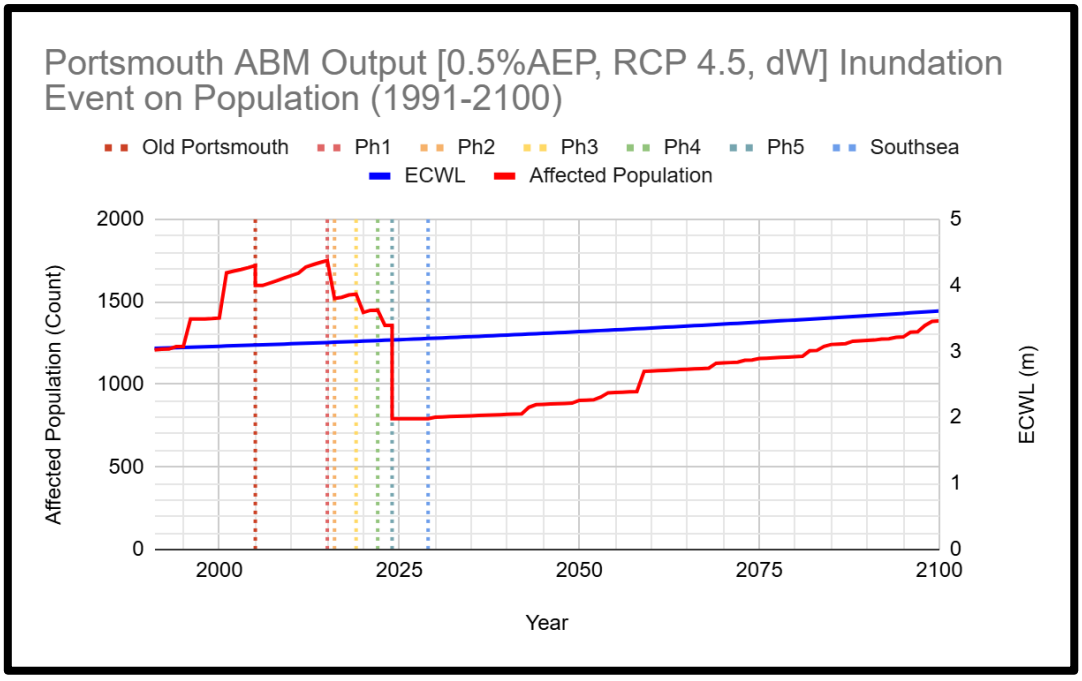

Portsmouth ABM Output [2%AEP, RCP 4.5, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
ECWL
Affected Population
Affected Population (Count)
ECWL (m)
Year
0
500
1000
1500
2000
0
1
2
3
4
5
2000
2025
2050
2075
2100

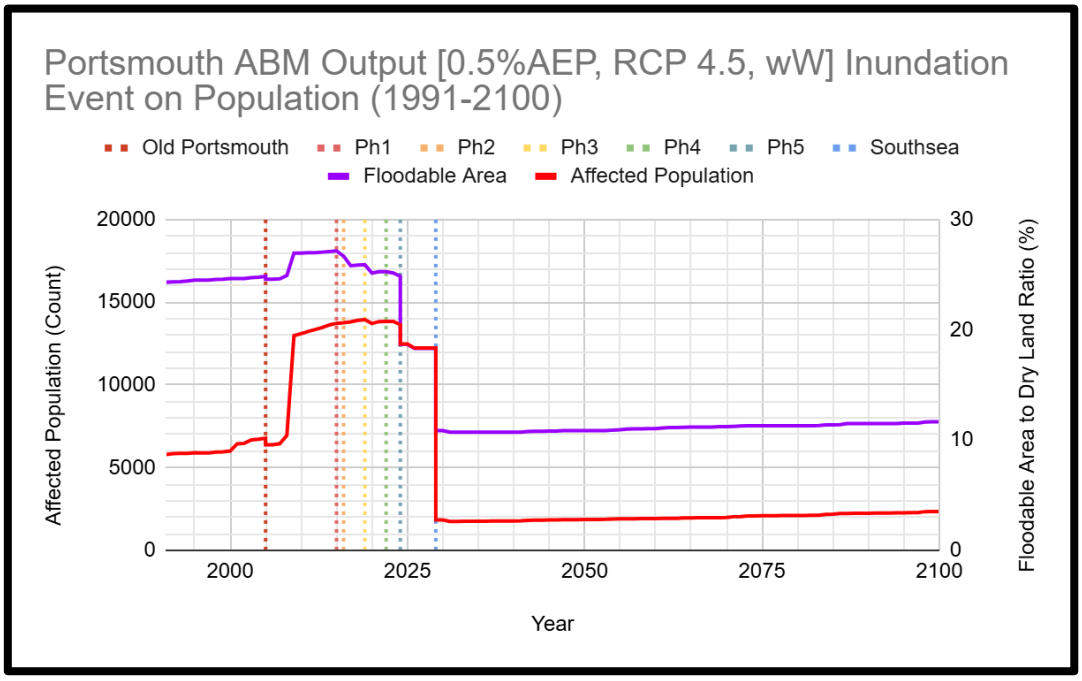

Portsmouth ABM Output [2%AEP, RCP 4.5, wW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
10000
7500
5000
2500
0
25
20
15
10
5
0
2000
2025
2050
2075
2100
Year

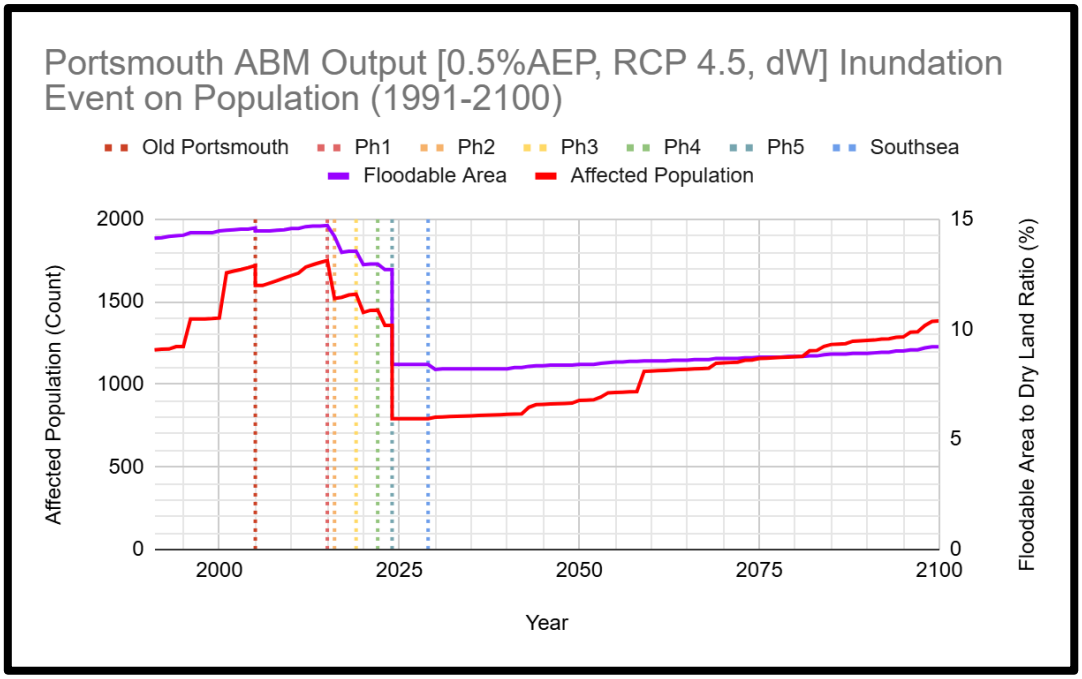

Portsmouth ABM Output [2%AEP, RCP 4.5, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
2000
1500
1000
500
0
15
10
5
0
2000
2025
2050
2075
2100
Year

RCP4.5 - 0.5%AEP

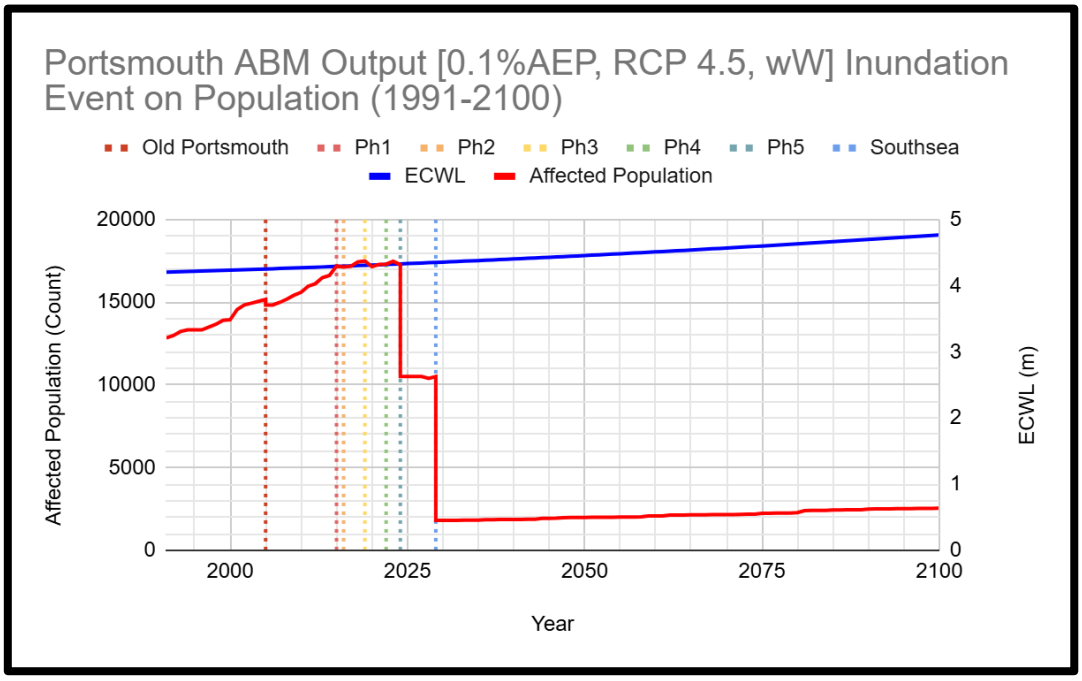

Portsmouth ABM Output [0.5%AEP, RCP 4.5, wW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
ECWL
Affected Population
Affected Population (Count)
ECWL (m)
Year
0
5000
10000
15000
20000
0
1
2
3
4
5
2000
2025
2050
2075
2100

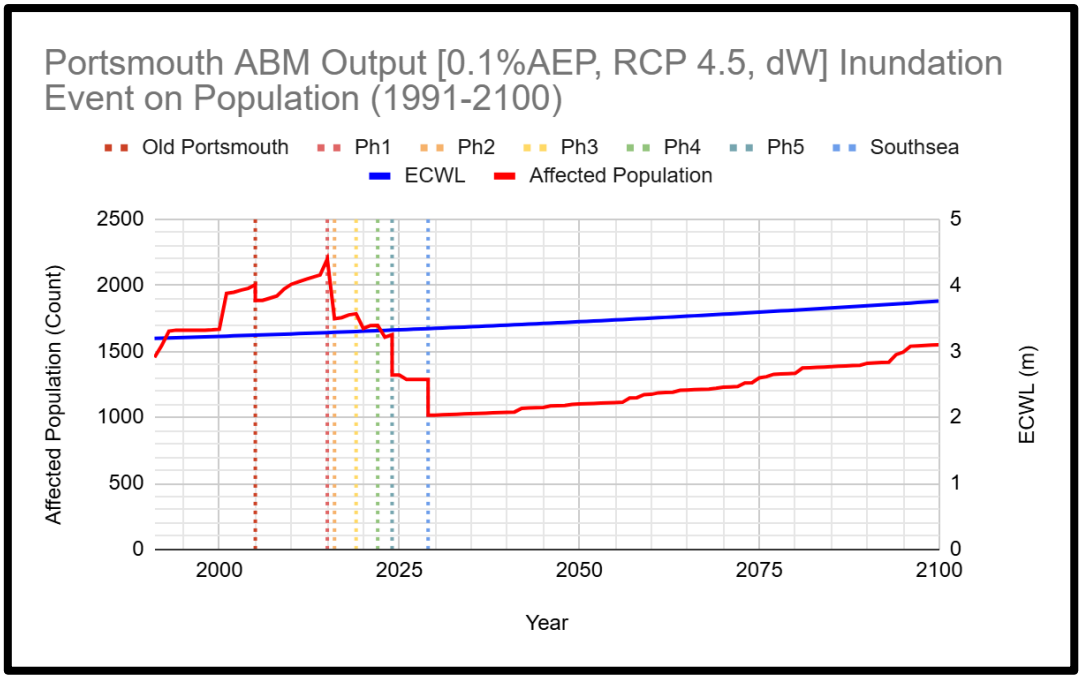

Portsmouth ABM Output [0.5%AEP, RCP 4.5, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
ECWL
Affected Population
Affected Population (Count)
ECWL (m)
Year
0
500
1000
1500
2000
0
1
2
3
4
5
2000
2025
2050
2075
2100

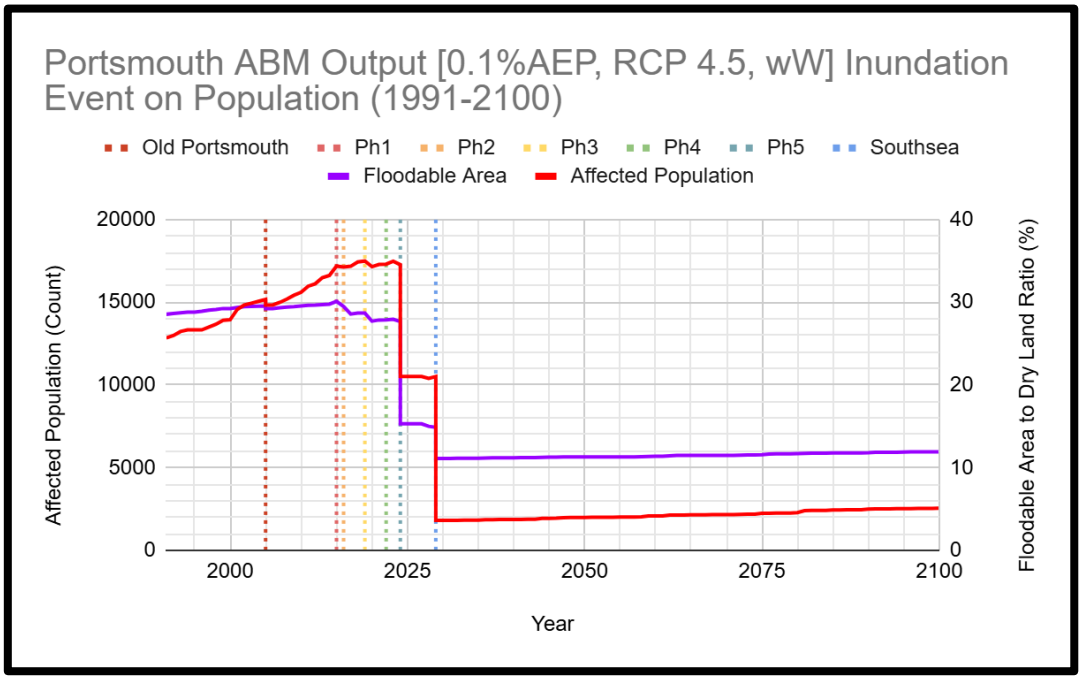

Portsmouth ABM Output [0.5%AEP, RCP 4.5, wW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
20000
15000
10000
5000
0
30
20
10
0
2000
2025
2050
2075
2100
Year

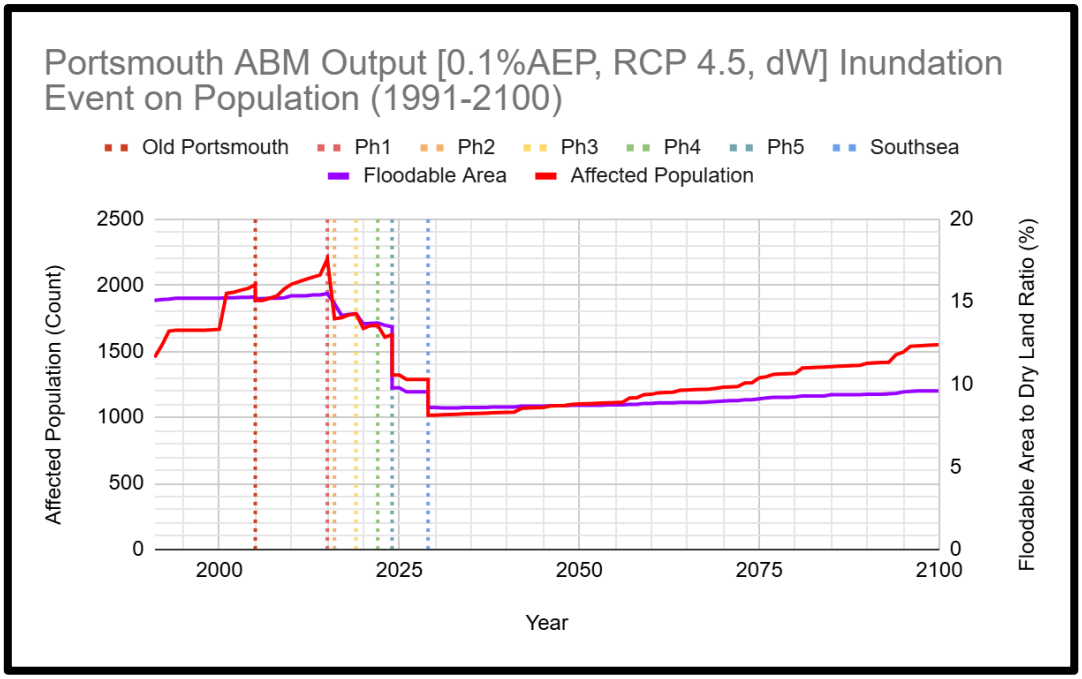

Portsmouth ABM Output [0.5%AEP, RCP 4.5, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
2000
1500
1000
500
0
15
10
5
0
2000
2025
2050
2075
2100
Year

RCP4.5 - 0.1%AEP

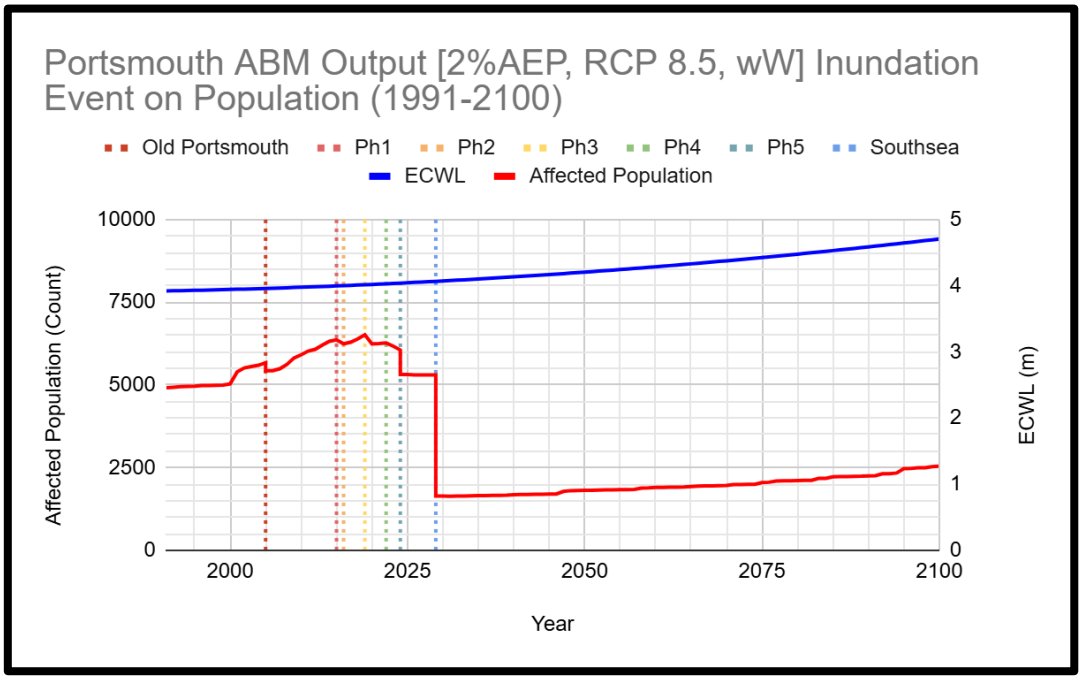

Portsmouth ABM Output [0.1%AEP, RCP 4.5, wW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
ECWL
Affected Population
Affected Population (Count)
ECWL (m)
Year
0
5000
10000
15000
20000
0
1
2
3
4
5
2000
2025
2050
2075
2100

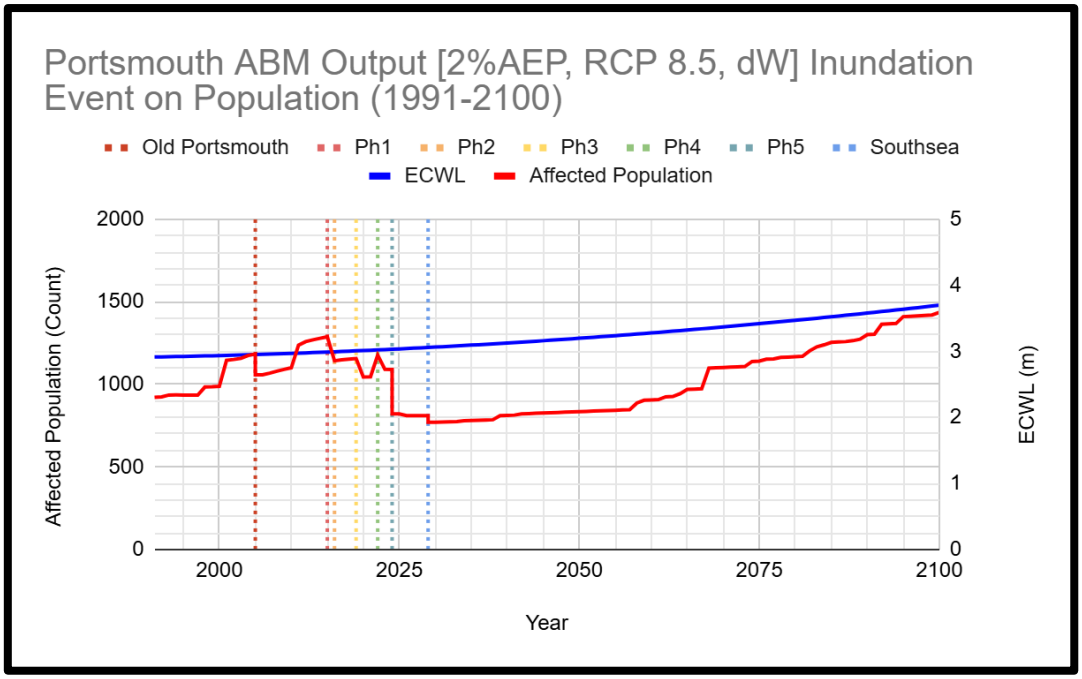

Portsmouth ABM Output [0.1%AEP, RCP 4.5, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
ECWL
Affected Population
Affected Population (Count)
ECWL (m)
Year
0
500
1000
1500
2000
2500
0
1
2
3
4
5
2000
2025
2050
2075
2100

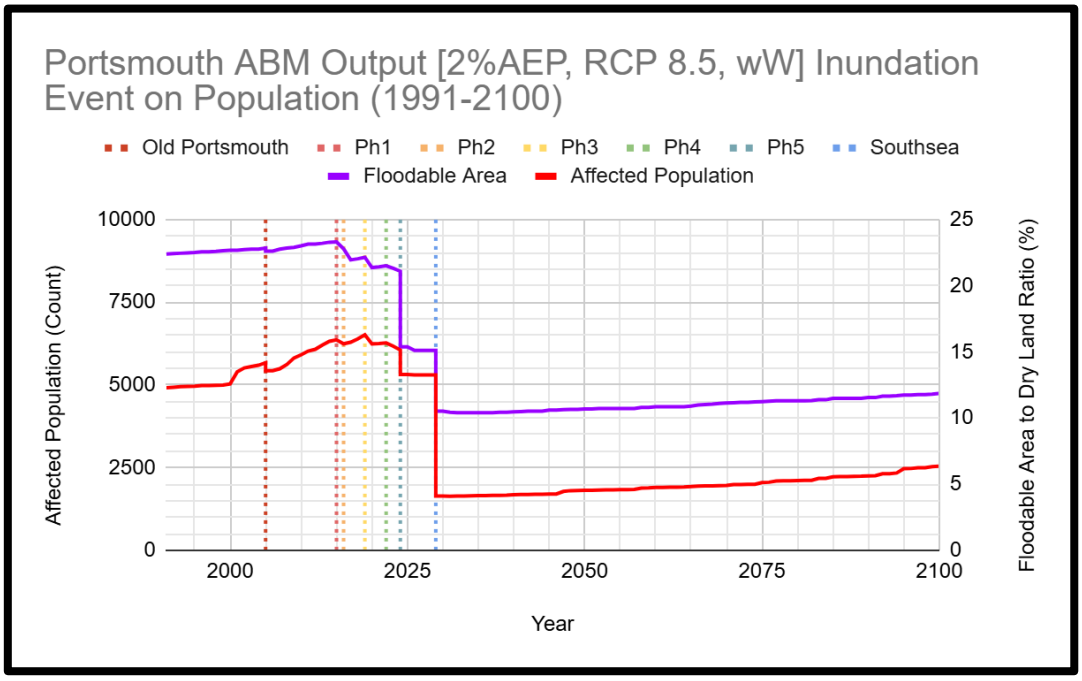

Portsmouth ABM Output [0.1%AEP, RCP 4.5, wW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
20000
15000
10000
5000
0
40
30
20
10
0
2000
2025
2050
2075
2100
Year

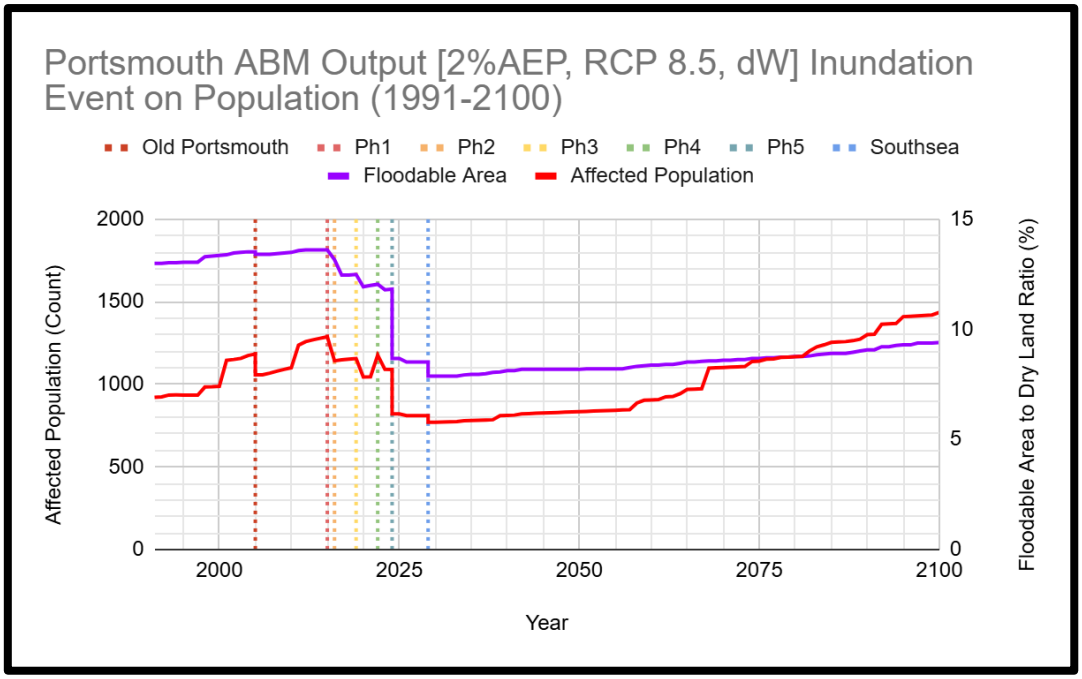

Portsmouth ABM Output [0.1%AEP, RCP 4.5, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
2500
2000
1500
1000
500
0
20
15
10
5
0
2000
2025
2050
2075
2100
Year

RCP8.5 - 2%AEP

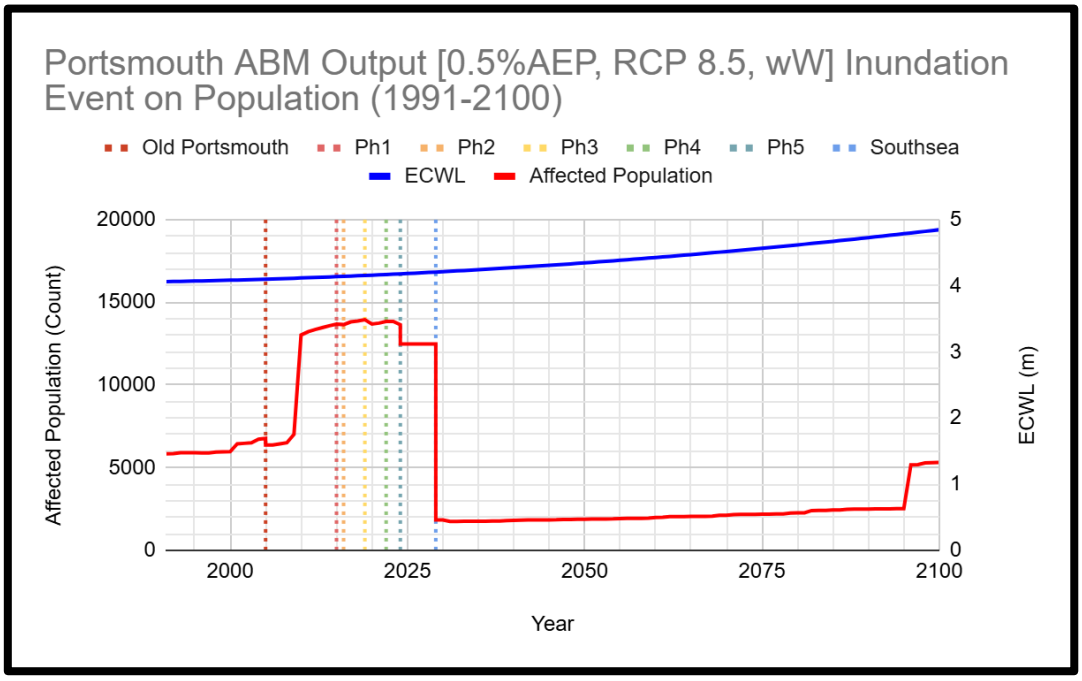

Portsmouth ABM Output [2%AEP, RCP 8.5, wW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
ECWL
Affected Population
Affected Population (Count)
ECWL (m)
Year
0
2500
5000
7500
10000
0
1
2
3
4
5
2000
2025
2050
2075
2100

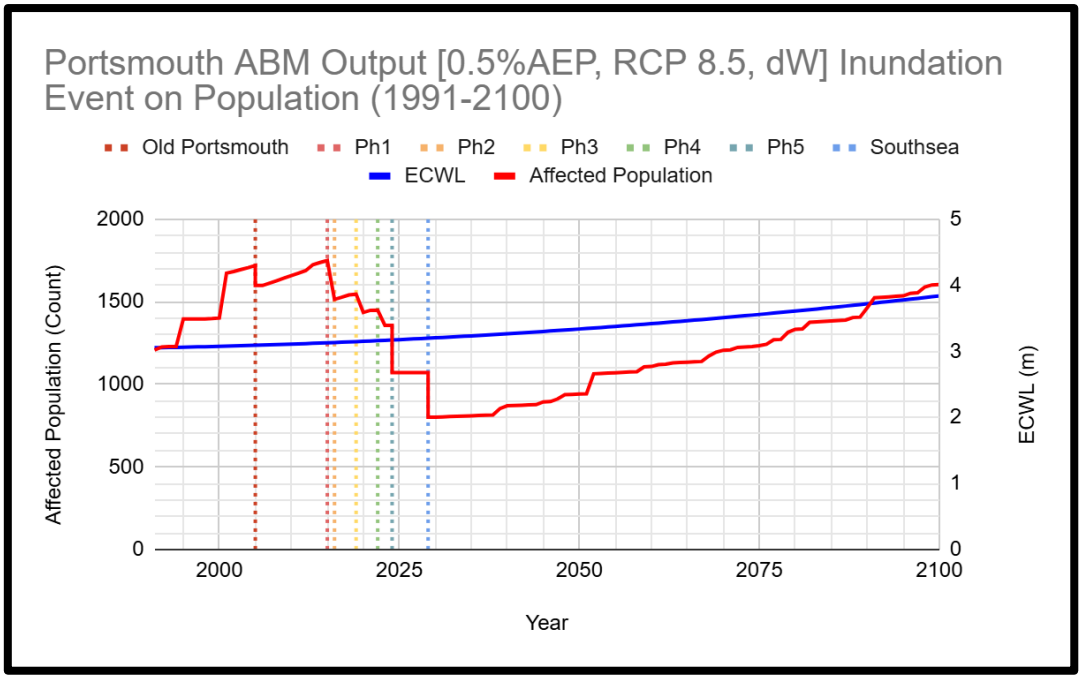

Portsmouth ABM Output [2%AEP, RCP 8.5, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
ECWL
Affected Population
Affected Population (Count)
ECWL (m)
Year
0
500
1000
1500
2000
0
1
2
3
4
5
2000
2025
2050
2075
2100

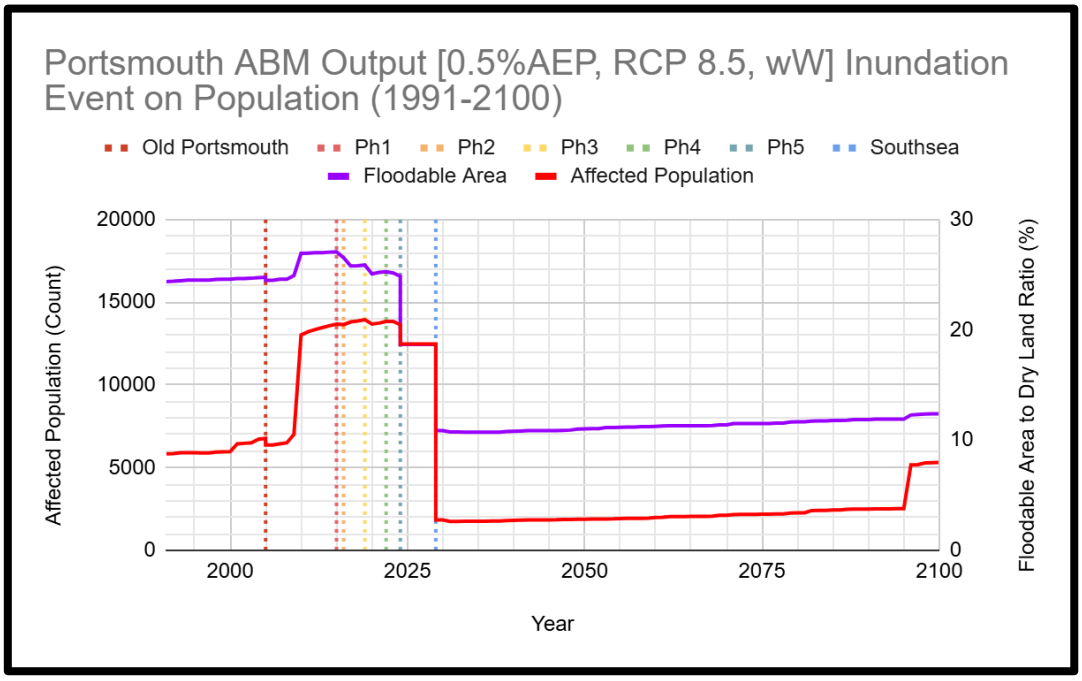

Portsmouth ABM Output [2%AEP, RCP 8.5, wW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
10000
7500
5000
2500
0
25
20
15
10
5
0
2000
2025
2050
2075
2100
Year

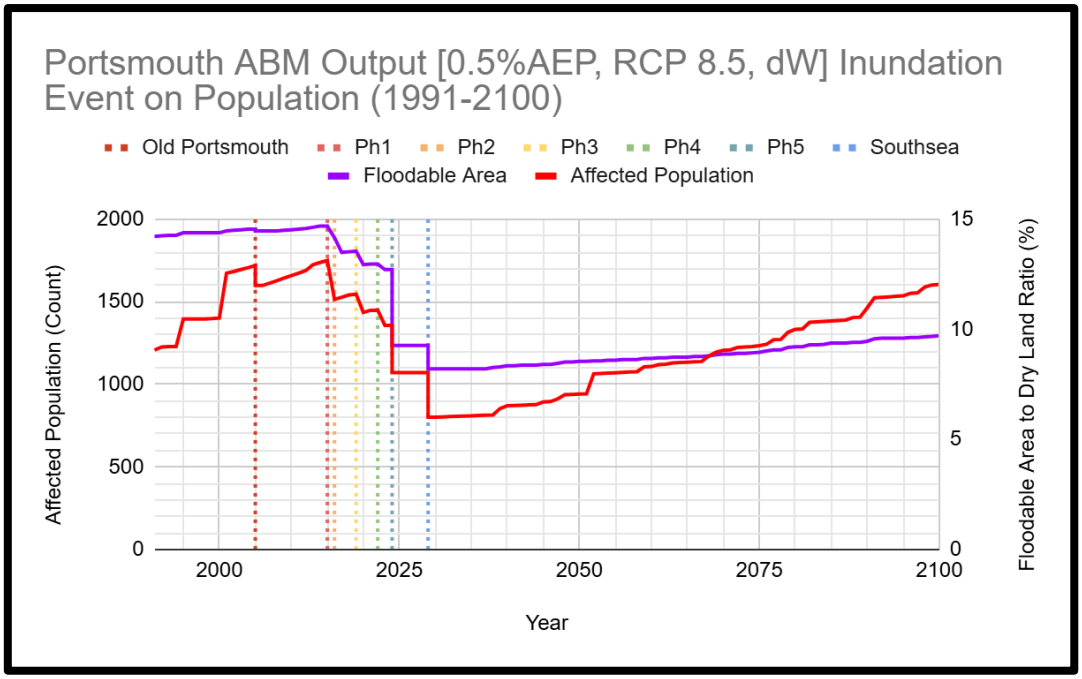

Portsmouth ABM Output [2%AEP, RCP 8.5, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
2000
1500
1000
500
0
15
10
5
0
2000
2025
2050
2075
2100
Year

RCP8.5 - 0.5%AEP

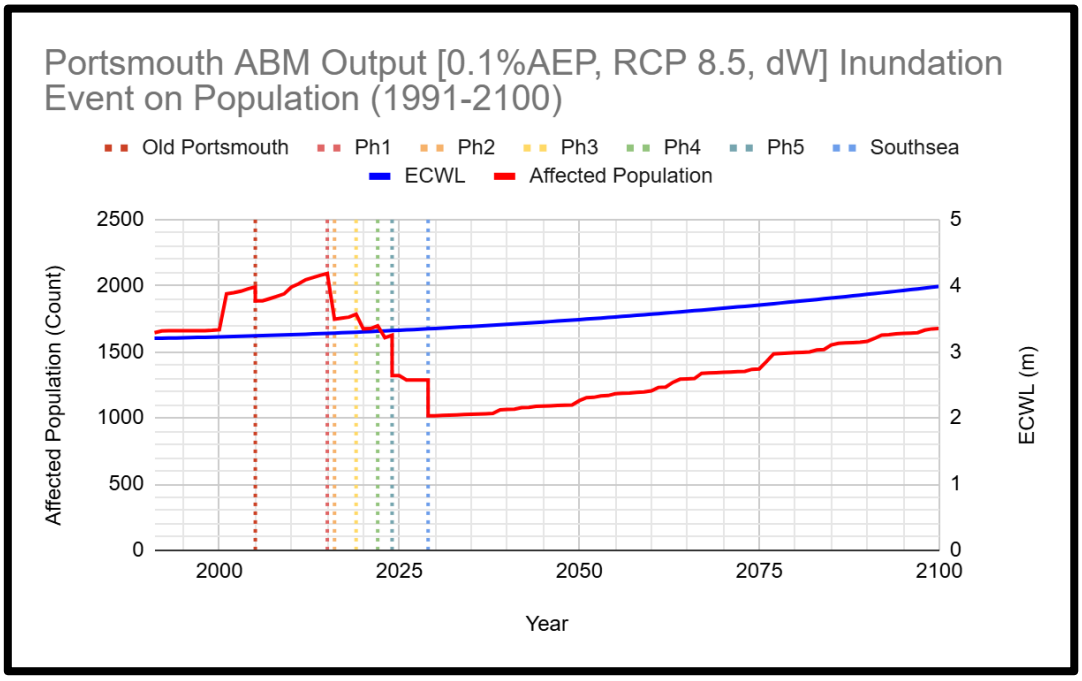

Portsmouth ABM Output [0.5%AEP, RCP 8.5, wW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
ECWL
Affected Population
Affected Population (Count)
ECWL (m)
Year
0
5000
10000
15000
20000
0
1
2
3
4
5
2000
2025
2050
2075
2100

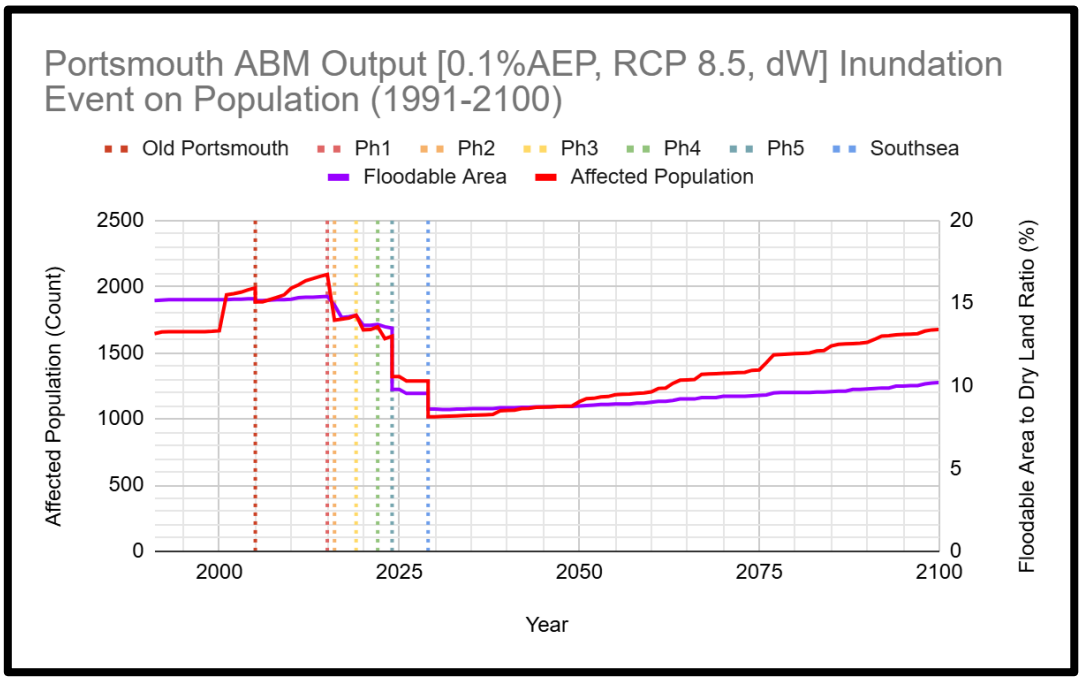

Portsmouth ABM Output [0.5%AEP, RCP 8.5, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
ECWL
Affected Population
Affected Population (Count)
ECWL (m)
Year
0
500
1000
1500
2000
0
1
2
3
4
5
2000
2025
2050
2075
2100


Portsmouth ABM Output [0.5%AEP, RCP 8.5, wW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
Year
0
5000
10000
15000
20000
0
10
20
30
2000
2025
2050
2075
2100


Portsmouth ABM Output [0.5%AEP, RCP 8.5, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
Year
0
500
1000
1500
2000
0
5
10
15
2000
2025
2050
2075
2100

RCP8.5 - 0.1%AEP


Portsmouth ABM Output [0.1%AEP, RCP 8.5, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
ECWL
Affected Population
Affected Population (Count)
ECWL (m)
2500
2000
1500
1000
500
0
5
4
3
2
1
0
2000
2025
2050
2075
2100
Year


Portsmouth ABM Output [0.1%AEP, RCP 8.5, dW] Inundation Event on Population (1991-2100)
Old Portsmouth
Ph1
Ph2
Ph3
Ph4
Ph5
Southsea
Floodable Area
Affected Population
Affected Population (Count)
Floodable Area to Dry Land Ratio (%)
2500
2000
1500
1000
500
0
20
15
10
5
0
2000
2025
2050
2075
2100
Year

Appendix E

A generalised and universal version of the code used to run the agent-based modelling. Code that is not changed by location or iteration is presented in indigo, whereas inputs and elements that change are presented in pink.

```
;;;
```

```
  ask patches gis:intersecting anti-boundary [set patch-distro 0]
  if (ticks >= 10)
  [
    gis:apply-coverage census2001-dataset "DISTRO" patch-distro
  ]
  if (ticks >= 20)
  [
    gis:apply-coverage census2011-dataset "DISTRO" patch-distro
  ]
  if (ticks >= 30)
  [
    gis:apply-coverage census2021-dataset "DISTRO" patch-distro
    gis:apply-coverage census2021-dataset "RATECHANGE" patch-distrorate
  ]
  ask patches
  ifelse (ticks >= 30)
  [
    set patch-population (((1 + (patch-distrorate * x )) * patch-distro) * population)
  ]
  [
    set patch-population (patch-distro * population)
  ]
  ask patches gis:intersecting anti-boundary [set patch-population 0]
end



to defend?
   if (ticks > (year defence was complete - 1991))
  [
   set flood-defence gis:load-dataset "flood-defence.shp"
   gis:set-drawing-color violet
   gis:draw boundary 1
   ask patches gis:intersecting seawall [set patch-elevation defence height]
  ]
end



to flood?
  let mx gis:maximum-of elevation
  ifelse any? patches with [(pcolor = blue) AND (any? neighbors with [patch-elevation < sea-level-flood AND pcolor = lime])]
    [set target true]
  [set target false]
  while [target = true]
  [
    ask patches with [(pcolor = blue)]
      [
        ask neighbors with [(patch-elevation < sea-level-flood) AND (pcolor = lime)]
        [
         set pcolor blue
          let land patches gis:intersecting boundary
          set output (sum [patch-population] of land with [pcolor = blue])
        ]
      ]
      if (not any? patches with [(pcolor = blue) AND (any? neighbors with [patch-elevation < sea-level-flood AND pcolor = lime])])
      [
       set target false
      ]
  ]
  if (target = false)
   [
    export-images?
    tick
    ask patches gis:intersecting boundary [set pcolor lime]
   ]
end

to export?
  if ticks = 109
  [
    export-plot "AfP"  "Model Output/AfP.csv"
    export-plot "Flooded Area"  "Model Output/Area.csv"
  ]
end
```

```
to export-images?
  if image? = 1
  [
    export-view (word (ticks + 1991) ".png")
  ]
end

;;;
```

```
104
Build World
setup
NIL
1
T
OBSERVER
NIL
NIL
NIL
NIL
1

BUTTON
200
66
310
99
Run
 if ticks < 109\n  [go]
T
1
T
OBSERVER
NIL
NIL
NIL
NIL
1

MONITOR
19
123
357
168
Years Elapsed
ticks + 1991
1
1
11

MONITOR
18
180
358
225
Model Population
Population
0
1
11

MONITOR
16
239
375
284
At-risk Population (%)
((count turtles with [patch-elevation < 9.07]) / (count turtles)) * 100
1
1
11

MONITOR
115
500
222
545
NIL
sea-level-flood
3
1
11
```

```
PLOT
1340
635
1540
785
AfP
Years Elapsed
Population (count)
0.0
10.0
0.0
10.0
true
false
"" ""
PENS
"default" 1.0 0 -16777216 true "" "plot(population-at-risk) / 1000"

PLOT
1565
635
1765
785
Flooded Area
Years Elapsed
FA (%)
0.0
10.0
0.0
10.0
true
false
"" ""
PENS
"default" 1.0 0 -16777216 true "" "plot flooded-area"

PLOT
190
610
390
760
plot 1
NIL
NIL
0.0
10.0
0.0
10.0
true
false
"" ""
PENS
"default" 1.0 0 -16777216 true "" "plot count turtles-on patches with [pcolor = blue]"

SLIDER
46
295
234
328
Image?
Image?
0
1
0.0
1
1
NIL
HORIZONTAL

INPUTBOX
1415
69
```

```
1741
129
A1
-3.695937667E-7
1
0
Number

INPUTBOX
1416
138
1741
198
B1
0.0049534217030082
1
0
Number

INPUTBOX
1416
206
1742
266
C1
2.58268494683074
1
0
Number

INPUTBOX
1409
320
1753
380
A2
-3.695937667E-7
1
0
Number

INPUTBOX
1415
394
1748
454
B2
0.00495342170301159
1
0
Number

INPUTBOX
1413
473
1748
533
C2
-0.454984946834229
1
0
Number

SLIDER
1413
556
1586
589
Waves?
Waves?
0
1
0.0
```

```
1
1
NIL
HORIZONTAL
```

Appendix F

Projecting Coupled Human-Flood Interactions using Agent-Based Socio-Spatial Modelling

Abstract

This study uses agent-based modelling (ABM) to explore the socio-hydrological impacts of structural coastal flood protections (SCFPs) under projected climate scenarios in three UK case studies: Southport, Weston-super-Mare, and Portsmouth. By integrating extreme coastal water level (ECWL) projections and population dynamics, the ABMs reveal five distinct phases: Design, Implementation, Latency, Flood, and Post-Flood. The results highlight the Latency phase, whereby SCFP initially stabilises at-risk populations; however, it inadvertently encourages population growth in residual risk areas. This process exacerbates long-term flood exposure, leading to large increases in at-risk population (AfP) once ECWL surpass SCFP crest height, negating gains in flood protection from the initial construction/upgrade. Significant increases in AfP were observed at each site when the ECWL exceeded the SCFP crest height. In Southport and Weston-super-Mare, saw an increase in coastal population in protected areas, these populations had limited flood memory, preparedness, and consequently heightened vulnerability. Conversely, Portsmouth, with limited residential development near SCFPs, demonstrated how land-use and high population density can weaken the Safe Development Paradox (SDP) in densely-populated coastal settings. These findings reveal two key pathways that influence coastal population in response to SCFP: Land-use Driven, where non-residential land-use limits population increase, and Population Driven, where high-density areas limit further growth. This research advances our understanding of the SDP by illustrating how SCFP can increase flood risk over long-term by influencing socio-spatial distribution over the medium-term. Moreover, it demonstrates how ABMs can prove valuable for simulating complex flood dynamics and supporting adaptive, resilient coastal management strategies in a changing climate.

Introduction

Natural hazards often lead to significant socio-economic losses and environmental impacts worldwide (Sharples *et al.*, 2016; Natho and Thieken, 2018). The impacts of climate change and continued urban development in flood-prone areas exacerbate these risks (Gbadegesin *et al.*, 2011; Leichenko, 2011). It is therefore critical to manage these risks, both current and future, to protect our communities and infrastructure. In many instances structural measures are often selected as the hazard mitigation strategy, such as, flood control channels (as in Sanders and Grant 2020), levees (as in Vora *et al*., 2018), and seawalls (as in Betzold and Mohamed, 2016). However, numerous scholars, starting with White (1945), have shown that increasing levels of flood protection can result in unintended consequences (Tobin, 1995; Burby, 2006; Kates *et al.*, 2006; Burton and Cutter, 2008; Montz and Tobin, 2008; Ludy and Kondolf, 2012; Di Baldassarre *et al.*, 2013a). If the growth of coastal urban areas were driven by population increases alone the spatial distribution of new settlements would be the same (Di Baldassarre *et al.*, 2013b). The cycle continues as greater populations and high-value assets are placed either within or in close proximity of at-risk areas, producing a need for even greater structural strengthening and/or heightening (or expansion) of existing structures. Increased safety can induce increased urban development, for example, ultimately leading to high losses in the event of a structural failure (Kates *et al,* 2007). This coupled human-flood phenomena has been referred to as the *Safe Development Paradox* (Burby, 2006), *Levee Effect* (Di Baldassarre *et al.*, 2015), and *Safety Dilemma* (Di Baldassarre *et al.*, 2018).

Understanding the coupled human-flood dynamics of these unintended consequences of structural coastal flood protection (SCFP) and comprehending them as a function of coastal flood risk and poor spatial planning is essential in the wake of climate change and induced sea level rise and increased storminess. Research of these unintended consequences in fluvial environments is increasing, but there remains a notable gap in the literature regarding the specific challenges and interactions that arise in coastal environments, and the socio-hydrological and socio-spatial interactions thereof (Breen *et al.*, 2022). Almost 70% of literature regarding this topic was focused on flooding from rivers, compared to 17% in just coastal (Breen *et al.*, 2022), meanwhile, between 1970 and 2010, floodable coastal areas have seen 13.3% increase in population, whereas fluvial at-risk areas saw a 0.5% decrease (Jongman *et al.*, 2012).This knowledge gap presents a challenge, particularly for coastal urban areas, where socio-spatial and socio-economic factors and existing land-use patterns may intensity the unintended socio-hydrological impacts of SCFPs, understanding these phenomena are essential (Loucks, 2015).

This paper expands upon prior research into the unintended consequences of SCFPs by developing an agent-based model (ABM) to simulate how these coupled human-flood processes and dynamics evolve across three case studies: Southport, Weston-super-Mare, and Portsmouth. By simulating the potential future impacts of Extreme Coastal Water Levels (ECWL) under the extreme RCP8.5-0.1%AEP scenario, this research seeks to understand how SCFPs influence population growth and socio-spatial changes in protected areas, and to quantify the subsequent impacts when the ECWL surpasses the crest height of the SCFP, flooding areas initially protected.

This ABM incorporated real-world elevation, sea level, and population spatial data, as well as projections for sea level rise, and changes in population distribution and socio-spatial processes associated with the construction, or major upgrade, of the local SCFP. The ABM showed an increase in SCFP-adjacent *AfP* following construction/upgrade, a conclusion supported by current literature (e.g. Di Baldassarre *et al.* 2018, Haer *et al.*, 2020). This demonstrates that there are lock-in processes in coastal areas in the UK. This paper concludes by discussing the limitations of ABMs in representing real-world flood dynamics, while also emphasising their unique ability to integrate geographical, sociological, and environmental factors. By advancing our understanding of the emergent socio-hydrological consequences of coastal flood protection, this study aims to inform adaptive management strategies that balance urban development and flood resilience.

Data & Methods

Hydrometry and Sea Level Rise

Tidal data (T), Sea Level Rise (*SLR*), storm surge (SS), and wave height (WH) data were used for modelling Extreme Coastal Water Levels (ECWL) used as input to the ABMs. These were provided by the UK Met Office and Environment Agency.

$$ECWL = SLR + SS + T + WH \quad \text{(Eq. F1)}$$

The following graphs present ECWL up to 2100 on RCP8.5, derived using **Eq. F1**, for each case study: Southport, shown in blue; Weston-super-Mare, shown in red; and Portsmouth, shown in green (**Figure F1**). The lighter shades represent a 2%AEP flood event, the core colour represents a 0.5%AEP flood event, and finally the darkest shades represent a 0.1%AEP event, the most extreme considered within this analysis.

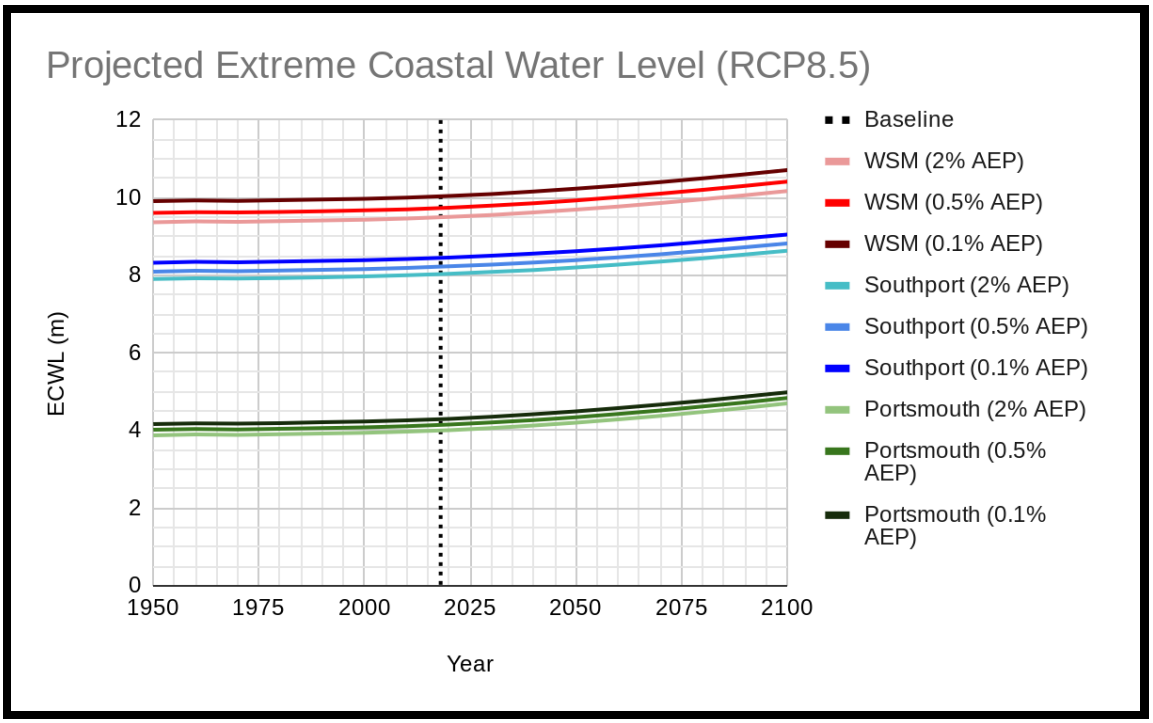


Figure 1 Historic and projected (1950-2100) ECWL at case studies under the RCP8.5 scenario.

Agent-Based Modelling

The use of ABMs in flood risk analysis and management is growing: Sobiech (2013) developed an ABM of coastal flooding in Germany with the aim of simulating the dynamics of vulnerability, focusing on the social context and preconceptions in which decisions, when a flood event occurs, are taken. Whereas McNamara and Keeler (2013) link sociological and physical models in their ABM, simulating the impact on the housing market of sea-level rises and an increase in storminess on the American East Coast. Similarly, Chandra-Putra *et al.* (2015) developed an ABM to simulate the effect of sea-level rise and insurance programmes on where people choose to live. Du *et al.* (2017) developed an ABM to understand the coupling between public opinion and flood evacuation processes, and how these dynamics are influenced.

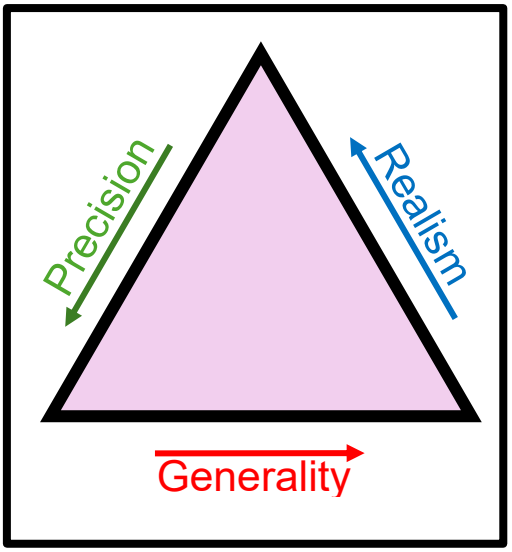


Figure F2 Trade-offs in model construction between precision, realism, and generality.

ABMs provide a method of replicating emergent behavioural patterns they can generate (Bonabeau, 2002). However, in pursuit of being realistic they often require many parameters, inevitably becoming more complex, and so move away from comprehensibility and transparency (Dubbelboer *et al.*, 2017), becoming less generalisable (Janssen and Ostrom, 2006). To maintain precision, realism may be sacrificed to produce a more generalised model, applicable in a wider range of case studies, yet losing its tangibility. Whereas, sometimes generality is lost to focus on accurate predictions for specific case studies (Troy *et al.*, 2015). These trade-offs are demonstrated in **Figure F2**, and represent the decisions that must be made in order to replicate reality in some form.

The ABM interface used for this project was the NetLogo platform and language (as in Dawson *et al*, 2011), and had five inputs (**Figure F3**): population data, both historic and projections (from the ONS); the LiDAR DTM data (from the EA); extreme coastal water levels, historic and projections (from the Met Office); population share boundaries, data, and projections; and SCFP projects, construction date and height obtained from government/council documentation. These inputs are processed by the ABM to produce two key outputs: 1, *AfP* (the amount of population living in floodable areas) and 2, the Floodable Area, the *FA* (the ratio of dry land to flooded land at each iteration).

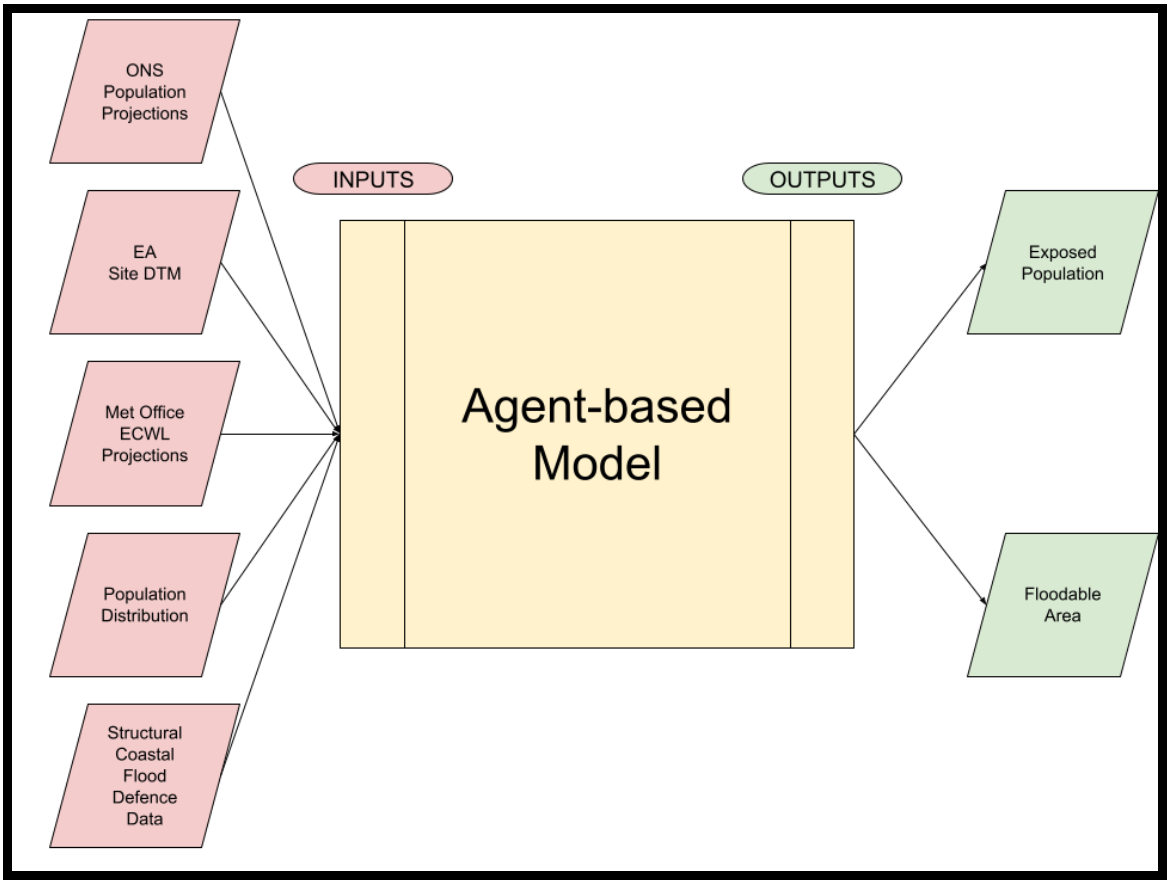


Figure F3 ABM inputs (red) and outputs (green).

The backdrop of the ABM is a DTM of the location, with a resolution of 100m × 100m, green for land, and blue for water. Cells were assigned three-dimensional values, x as longitude, y as latitude, and z as elevation. To increase processing speed, polynomial equations were used to model population, developed using ONS projections. Treating population count as the y-axis, time as the x-axis, and historic population and population projections as points, an equation was derived. This equation was verified using R-squared: if the polynomial estimated the data with a high enough R-squared then it could be used to represent the data ($R^2 \geq 0.995$, when $1991 \leq x \leq 2043$). Beyond 2043, towards 2100, the accuracy of the ABM decreases, as the ABM runs on the polynomial and without ONS projections. Past 2043, the polynomial follows the trend from the last vertex within the ONS population data, and carries that trend onto 2100. This output of this equation each year forms the *Total Population.*

A secondary value was added to the ABM, *Population Share*, the share of the settlement-wide population that an individual cell has. The product of the *Total Population* and the *Population Share* of the cells produces the *Population Distribution* for that year. However, after 2021 there is no population spatial distribution data or high resolution population data as the censuses have not been taken yet. To resolve this a *Population Share Change Rate* was calculated. This was determined by spatially linking and numerically comparing the 2011 and 2021 *Population Share* vectors (**Figure F4**) and obtaining a rate that reflects the change over time. The *Population Share Rate Change* vectors were supported by the geostatistical testing conducted on the boundaries with real-world Population and comparing the difference across time between those OAs at the coastline and those elsewhere in the town. A statistically significant difference would give strength to the *Population Share Rate Change* as it would suggest that the patterns and trends observed from the rate change at the coastline compared to those landward of the defence are valuable and should be continued (as in Schoppa *et al.*, 2024).

Then, to calculate *Population Share* following the 2021 census, the *Population Share Rate Change* is multiplied by the current year of the ABM subtracted by 2021, to give years elapsed. These changes are then also multiplied by the 2021 *Population Share* vector to give how the *Population Share Rate Change* has changed over time, and thus the *Population Share* for that year (**Figure F5**). Consequently, the product of the *Population Share* and *Total Population* of a given year post-2021 gives the modelled *Population Distribution*. This *Population Distribution* is then applied to the ABM and the flood model is run.

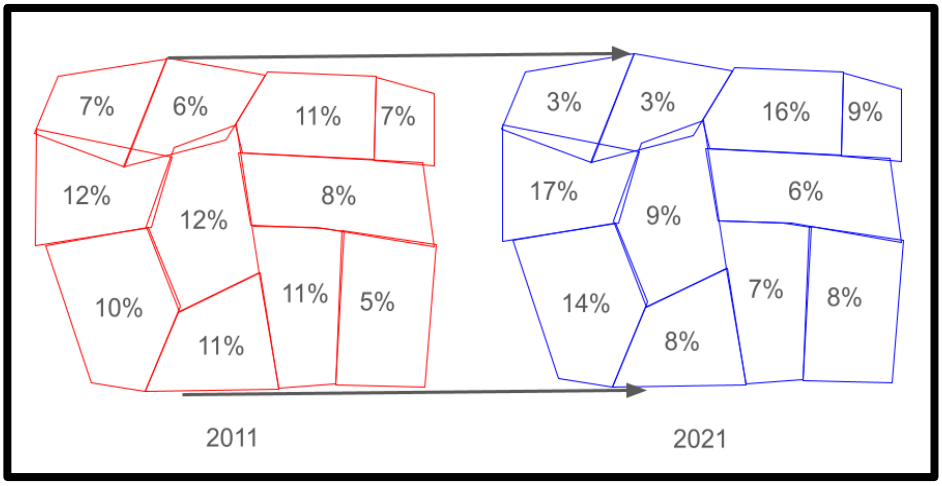


Figure F4 *Population Share* of a hypothetical settlement and the comparison of it across time, from the 2011 census compared to the 2021 census.

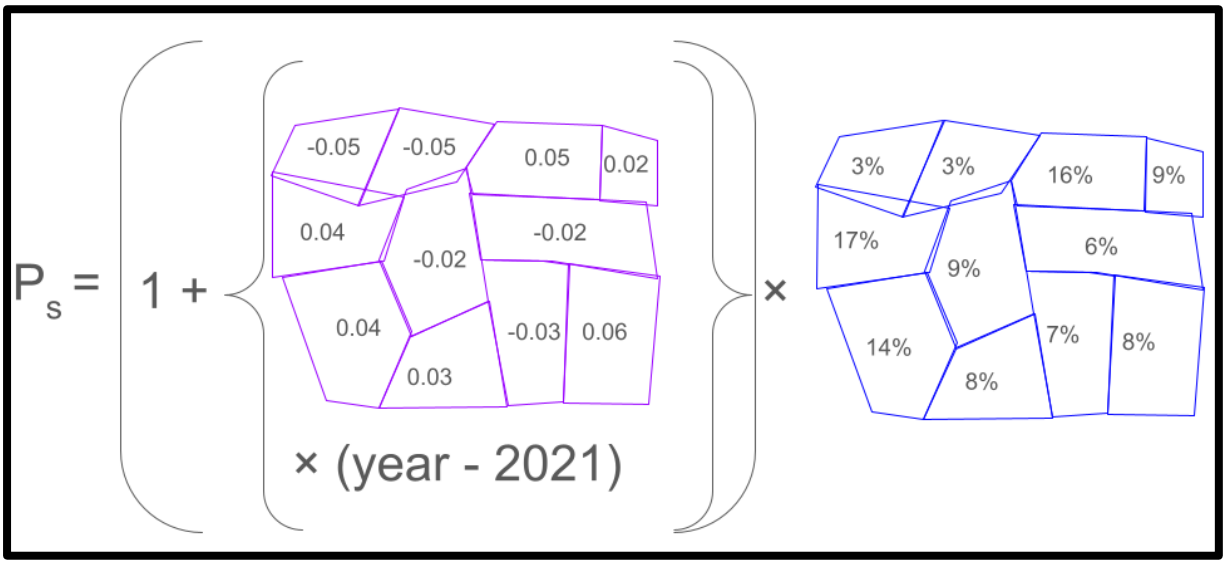


Figure F5 Modelled equation to produce *Population Share* (P_S) following 2021. The purple shapes are the *Population Share Rate Change* vector. The blue shapes are the 2021 *Population Share* from Figure 40. This is represented mathematically in Eq. 12.

Once a cell comes into contact with the floodwater it is marked as *flooded*, and the *AfP* is summated. At the end of each year the land area is reset and the *flooded* cells returned to their normal state for the next iteration. Each year the sea rises following the ECWL scenarios. In a similar manner to population approximation, annual ECWL changes were interpolated using a polynomial and the Met Office decadal predictions as datapoints, ensuring that ECWL was continuous. The SCFP is represented using real-world dimensions and location in the ABM. Once the ECWL is higher than the SCFP the land around it is assumed that areas are flooded, this happens cell by cell until the floodwater cannot go any further due to the elevation of the land surrounding it (as in **Figure F6**). This is one of the key strengths of ABM, allowing the integration of spatial and temporal dynamics, and modelling long-term responses to environmental change (Haer *et al.*, 2016; Han *et al.*, 2020).

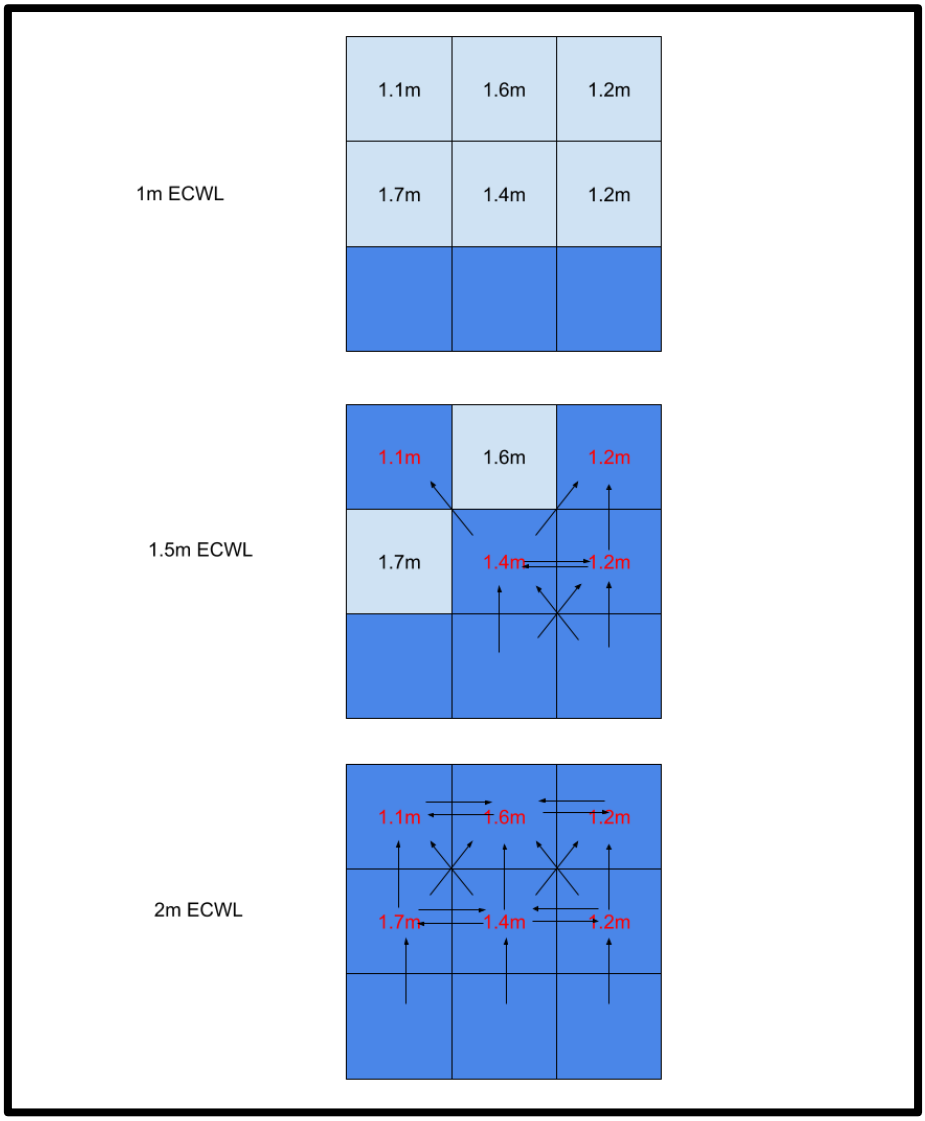


Figure F6 The processes by which cells become flooded by the sea, if there were no SCFP. This can occur in all eight directions.

Model Code

The agent-based socio-hydrological model can be split into five main stages (**Figure F7**): Set-up, Populate, FRM, Flood, and Export. The full code is displayed in **Appendix A**.

Set-up (setup), firstly clears the ABM of anything from previous iterations (clear-all) and resets the time elapsed to zero (reset-ticks). It then loads the GIS libraries and imports the geospatial data (setup-gis): the raster DTM, the dimensions of the raster DTM, and the several population distribution shapefiles. Then it calls the creation of the boundary (setup-boundary), this boundary shapefile ensures that at the end of every iteration the land returns to being land and the sea returns to being the sea. Whilst this subroutine does nothing directly, it provides a failsafe should the flood coding fail or an error to be produced, and ensures that the data is accurate. Finally, the set-up process applies the elevation values from the DTM to the cells (ask patches [set patch-elevation (gis:raster-sample elevation self)), anything below ECWL values and outside of the land boundary is then classed as the sea and coloured blue, with land coloured green. The ABM is now ready and is currently in t=0, once the ABM is allowed to run it becomes 1991 and the population is applied.

Populate (populate?) is the second stage and is activated as soon as the ABM is allowed to run. Firstly, the process calls for the creation of the anti-boundary, a shapefile that covers the sea, this is to ensure errors are not produced within the ABM: the population distribution shapefile only covers the land, as that is where people live, however during rasterisation this creates an error as rasters must be a quadrilateral. The anti-boundary handles this by instructing the ABM that cells within the sea have a population distribution of zero. Next the ABM checks if a decade has passed yet, if it has it applies the new population share boundaries from that year (gis:apply-coverage census2001-dataset "DISTRO" patch-distro). If the ABM gets to 2021, the process applies the 2021 population share but also gives cells a new value, patch-distrorate. The ABM then either applies this rate change and multiplies by the population, or uses the population share and then multiplies by the population as determined by whether it is before 2021 or after..

FRM (defend?) is the third process involved in the running of the ABM. This process is relatively simple in its operation. Firstly, the process checks whether enough time has passed and if the defence should be built yet. If it has, the process calls the SCFP shapefile, a digitisation of the real-world defence. The process then adds the defence to the ABM, and instructs the underlying cells within its boundaries to change their elevation based on the real-world height of the defence (ask patches gis:intersecting seawall [set patch-elevation defence height]).

On the other hand, the Flood (flood?) process is the most complex; using bathtub flood modelling whilst also ensuring flood cell connectivity. The process asks sea cells if they have any land neighbours with an elevation less than the ECWL (ifelse any? patches with [(pcolor = blue) AND (any? neighbors with [patch-elevation < sea-level-flood AND pcolor = lime])]). Whilst this condition is TRUE, the subroutine repeats, with sea cells asking neighbouring land cells if their elevation is lower than the ECWL, if it is marking it *flooded*, and temporarily making it part of the sea. This repeats until there are no more land squares that can be flooded. Then once this subroutine cannot go any further, the ABM counts the squares that have been flooded and summates their populations (set output (sum [patch-population] of land with [pcolor = blue])), as determined by the population share shapefile and the Total Population equation. The ABM then checks if the operator has asked for an image of the maximum flooded extent of that year (export-images?), outputs one if so, and then progresses a year (tick).

Export (export?) forms the final stage of the ABM. This process ends the ABM once it reaches the year 2100, and exports the *AfP* and *FA* data collected from the ABM run as a .csv file, which can then be loaded into a spreadsheet and analysed.

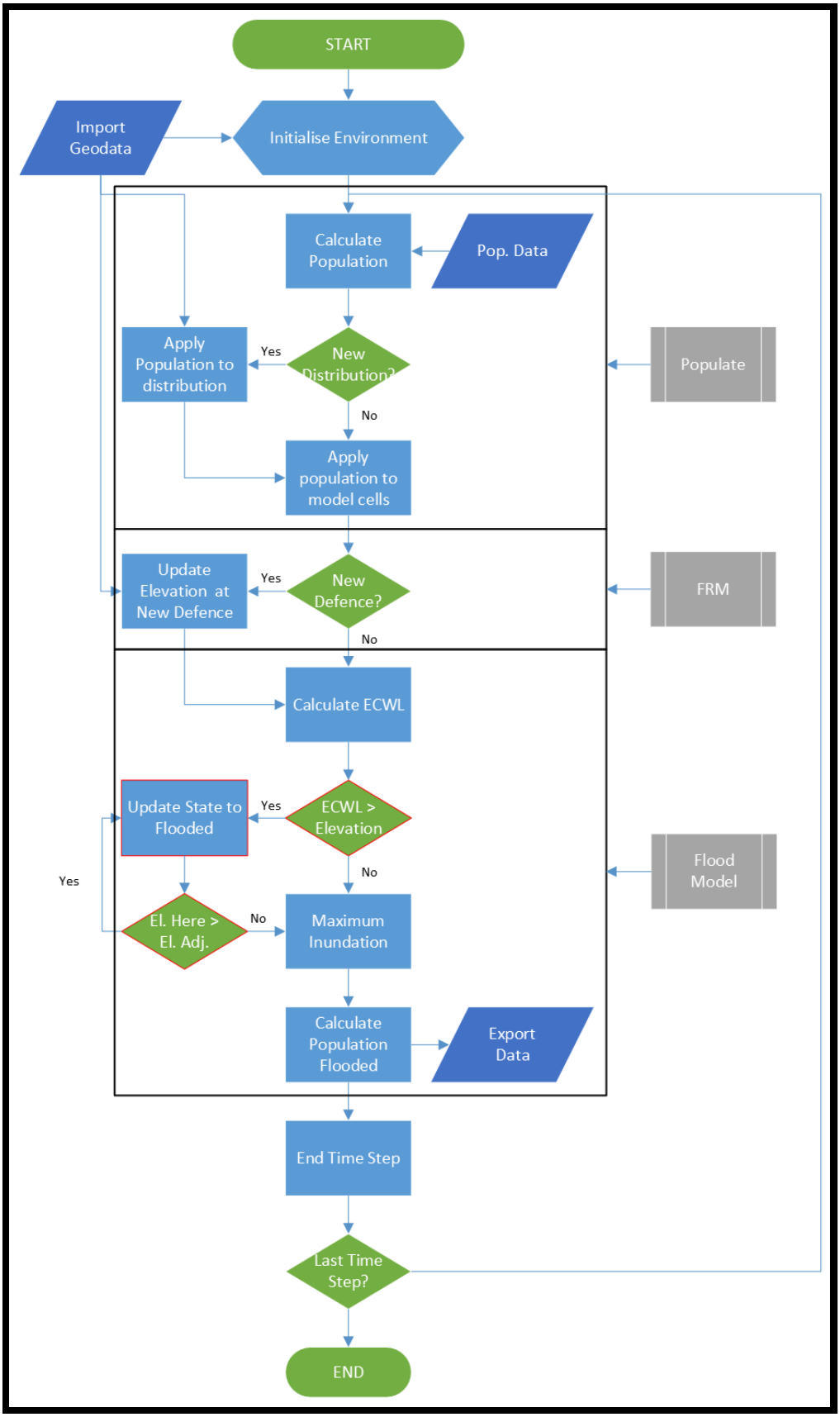


Figure F7 Flowchart of the ABM processes. Starting from *t=0* to *t=109 years*, 1991 to 2100.

Model Validation

Using Portsmouth as an example, and plotting the output of the *Total Population* equation against ONS data, has a coefficient-of-determination (R^2) of 0.992 (**Figure F8**), indicating that the *Total Population* polynomial is effective. However, the polynomial does not capture the small-scale peaks and troughs, and are therefore not represented by the ABM (**Figure F9**). Although, georeferenced population analysis revealed that changes in coastal population at these areas does not reflect the size of the natural variation within the ONS data. Therefore, these natural variations are not limited to SCFPs, but spread across the city, confirming that the ABM projects population well, and is validated in this regard.

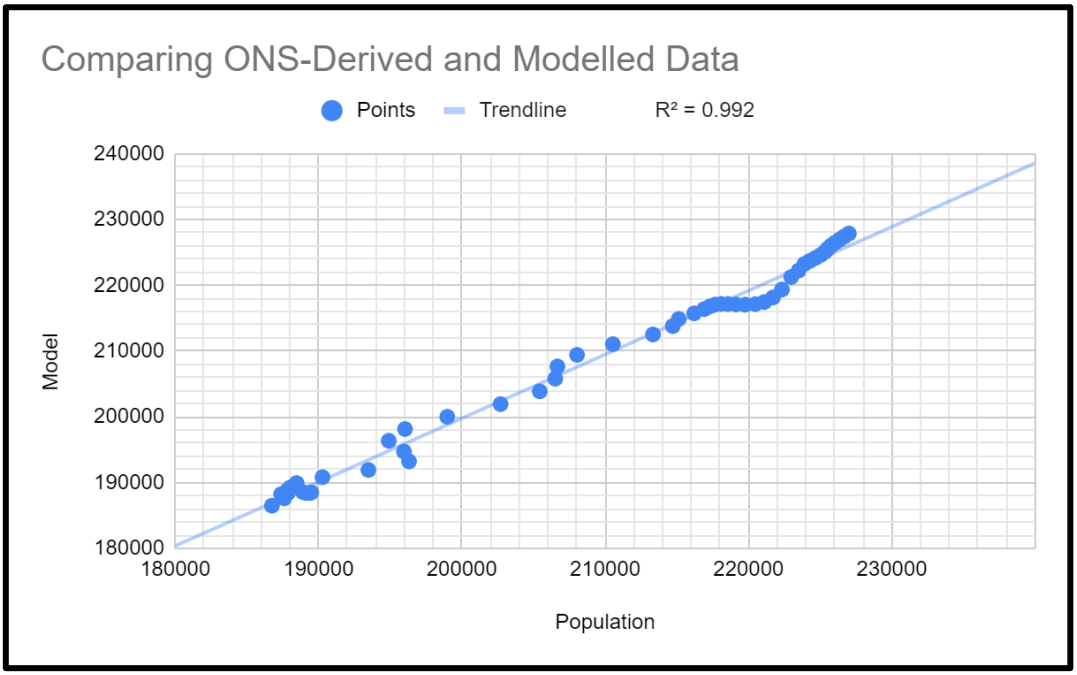


Figure F8 Comparative scatterplot representing the output of the polynomial population equation of the Portsmouth ABM compared to the ONS data with the R^2 value of the two of 0.99 displayed.

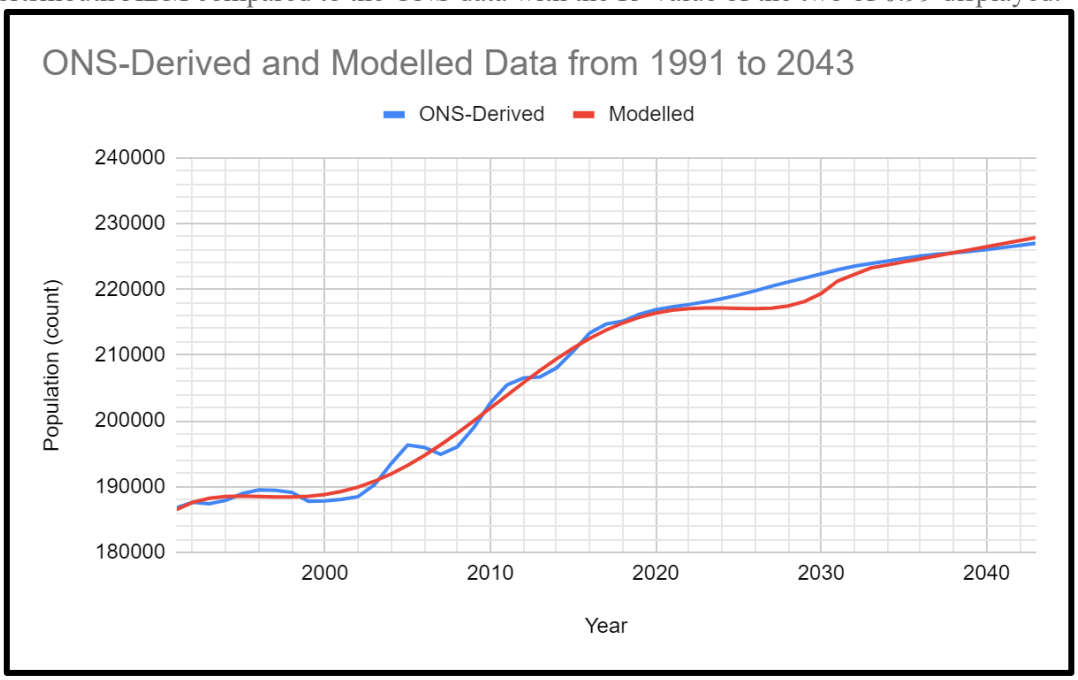


Figure F9 Comparative line graph comparing the ONS historic and projected population data for Portsmouth, and the output of the polynomial modelling equation used within the Portsmouth ABM.

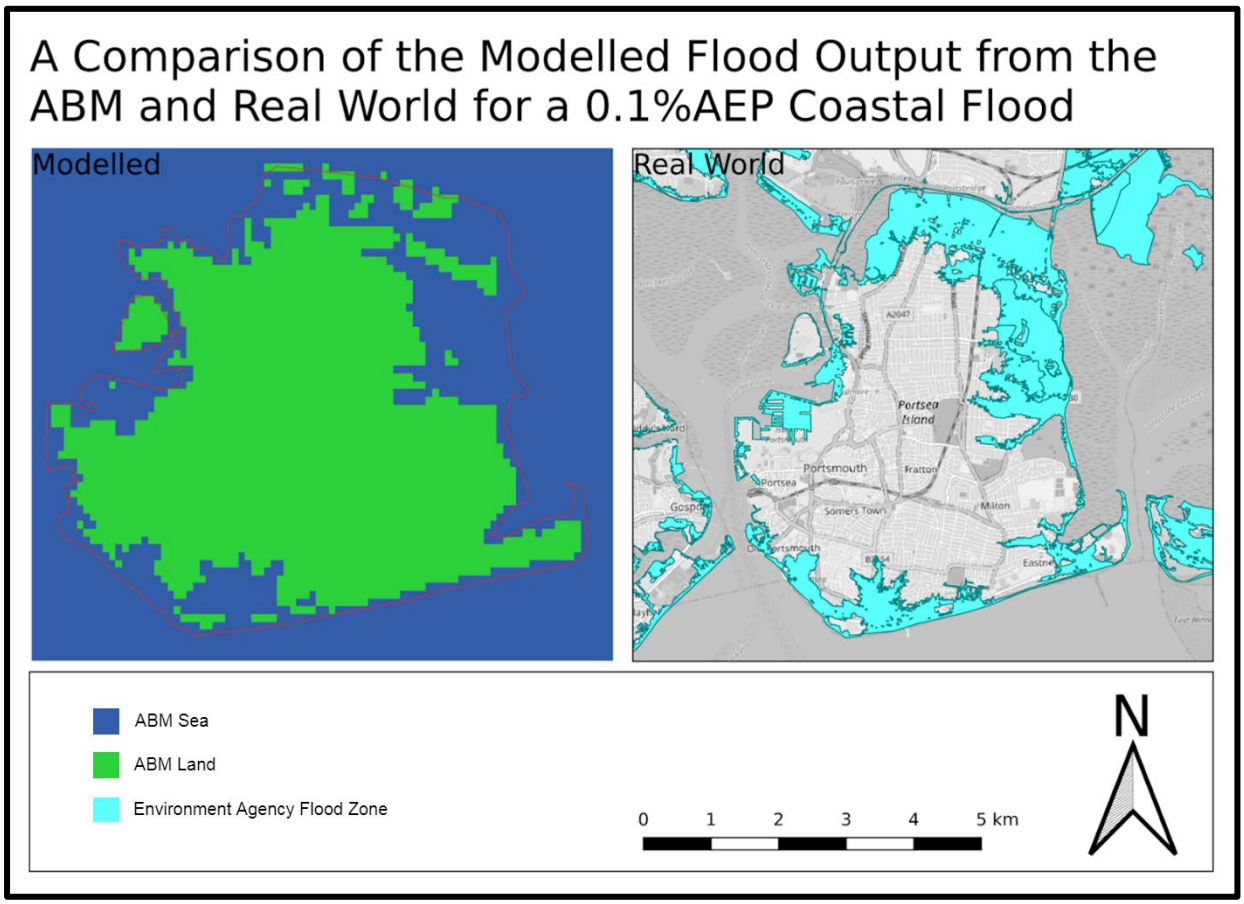


Figure F10 Comparing the flood extent of a 0.1%AEP coastal flood output from the ABM to the exposed area determined by the EA for Portsmouth.

Secondly, it was necessary to validate that flooding is accurate. The Gamma flood model, indicated that there are 4,630 properties at risk of 1%AEP flooding in Portsmouth at the baseline period, 2017 (Cantwell, 2020). Using the 2.5 people per household assumption often used in LFRMS modelling (Metropolitan Borough of Sefton Council, 2014), this amount of houses affected translates to 11,575 people. The Portsmouth ABM simulation, when running on a 1%AEP event, produces an output of 11,234 people who are exposed in 2017. Comparing the *AfP* output from the Gamma flood model to the one produced by the Portsmouth ABM gives the Portsmouth ABM an accuracy of 97% for 2017, confirming that the ABM simulates *AfP* well, and is validated in this regard.

One of the main drivers of *AfP*, determining whether a person will be flooded or not, is the coastal flood extent. To run the flood model, the ABM relies on an accurate DTM, a bare earth model of elevation derived from the Environment Agency, and accurate ECWL equations, derived using data from the Met Office. To flood, the ABM relies on a bathtub approach, flooding by simply comparing the elevation of a flooded cell to its eight adjacent cells, and if any of those cells are lower than those cells also become flooded. The bathtub approach tends to overestimate flooding due to a lack of connectivity (Kasmalkar *et al.*, 2023), and whilst the ABM does consider connectivity it will also slightly overestimate as it does not account for many of the relevant underlying hydrodynamic processes.

Nevertheless, the ABM flood extent maps well onto that of the Environment Agency, and provides a good facsimile of flood extent into Portsmouth. This is evidenced by both, the comparative map (**Figure F10**) and the similarity of the *AfP* output to that produced by the Gamma flood model, confirming that *the ABM simulates coastal flood extent well, and is validated in this regard*.

Results

This subsection presents the ABM socio-hydrological simulation outputs for the three primary case study sites: Southport, Weston-super-Mare, and Portsmouth

Case Study A

The new defence at Southport was finished in 2002 and provides a 150-year SoP. This would provide protection against a 0.66%AEP event in 2002. The ECWLs considered are presented in **Figure F1**. The topography of the landscape is presented in **Figure F11**.

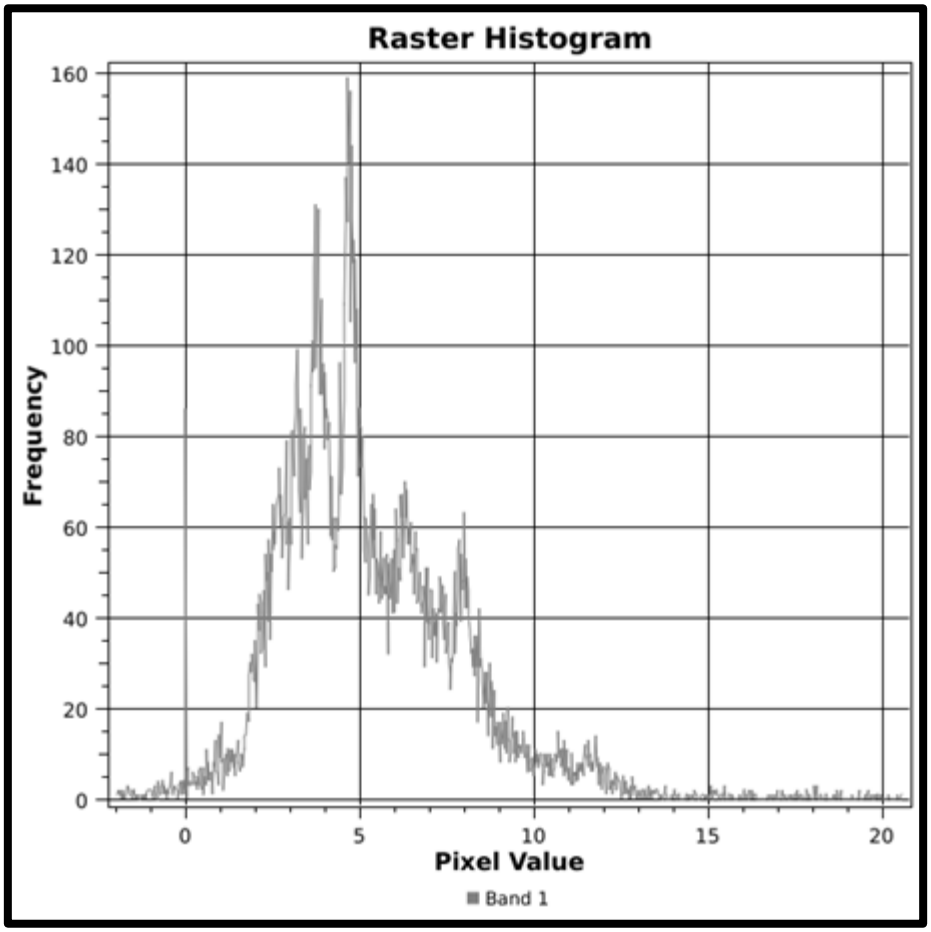


Figure F11 Raster histogram based on the DTM data used in the Southport ABM.

Before the construction of the SCFP, the *AfP* in Southport was decreasing (**Figure F12**), ECWL was increasing (**Figure F13**), and the *FA* was remaining stable (**Figure F14**). The construction in 2003 led to a sharp decrease in *AfP* (**Figure F12**) and *FA* (**Figure F14**), the severity of this decrease is represented by the steep decrease in the *AfP* derivative (**Figure F15**). The negative derivative output demonstrates a decreasing gradient in *AfP*, that quickly reverts to zero in the following year: it is clear that the construction of the new SCFP had an impact on *AfP*, as would be expected.

After the construction of the new SCFP, population at the new SCFP increased, followed by a steady increase in the *AfP* of Southport, and then *AfP* recovers to pre-defence amounts by 2045. Afterwards, *AfP* mirrors the growth in Total Population until around 2086 (**Figure F12**), at which point the growth rate stabilises (**Figure F15**). In spite of increasing ECWL (**Figure F13**), growth in the *FA* of Southport also slows down and eventually stabilises in the 2050s (**Figure F14**). The elevation of Southport is predominantly <5m above sea level (**Figure F11**), and this land is mostly flooded even after the construction of the new SCFP, with *FA* decreasing to its lowest of 60% after the defence, and

its highest 78% in 2100 (**Figure F14**). This is an example of diminishing returns: the higher elevated places are more likely to be more difficult to flood, and so would require much higher ECWL, hence the slowdown in *AfP* around this period (**Figure F12**, **Figure F15**).

In 2085 the SCFP in Southport will be exceeded (unless upgraded), flooding the area previously defended. *AfP* increases dramatically as some locations become floodable, whilst they were not before, this leads to an increase far greater than the growth of Total Population (**Figure F12**) and a large increase in *FA* (**Figure F14**). This sudden high-level growth is also represented as a large increase in the *AfP* derivative (**Figure F15**), jumping to over 33,033yr^{-1}, far greater than the 15,585yr^{-1} saved generated by the initial construction: the SCFP becoming exceeded led to an extra 17,448 people now exposed. These populations protected by the SCFP would not have been flooded during the 2003 to 2085 period and would therefore have limited flood memory, decreasing flood awareness and preparedness, putting them at a high level of risk. It is unlikely that new urban development would have been sanctioned in the area where new buildings were built in Southport following the new SCFP construction, and that these new populations would have moved there, had it not been built. Moreover, due to the increase in ECWL between the 2003 and 2085 period (**Figure F13**), when the SCFP is exceeded, areas that had not been flooded previously would now be floodable, without flood risk communication, these populations would not be prepared for such an event. *Therefore, the short-term savings provided by the construction of the new SCFP in Southport would be greatly overshadowed by the long-term losses, highlighting the importance of considering these unintended consequences in future coastal FRM and spatial planning*.

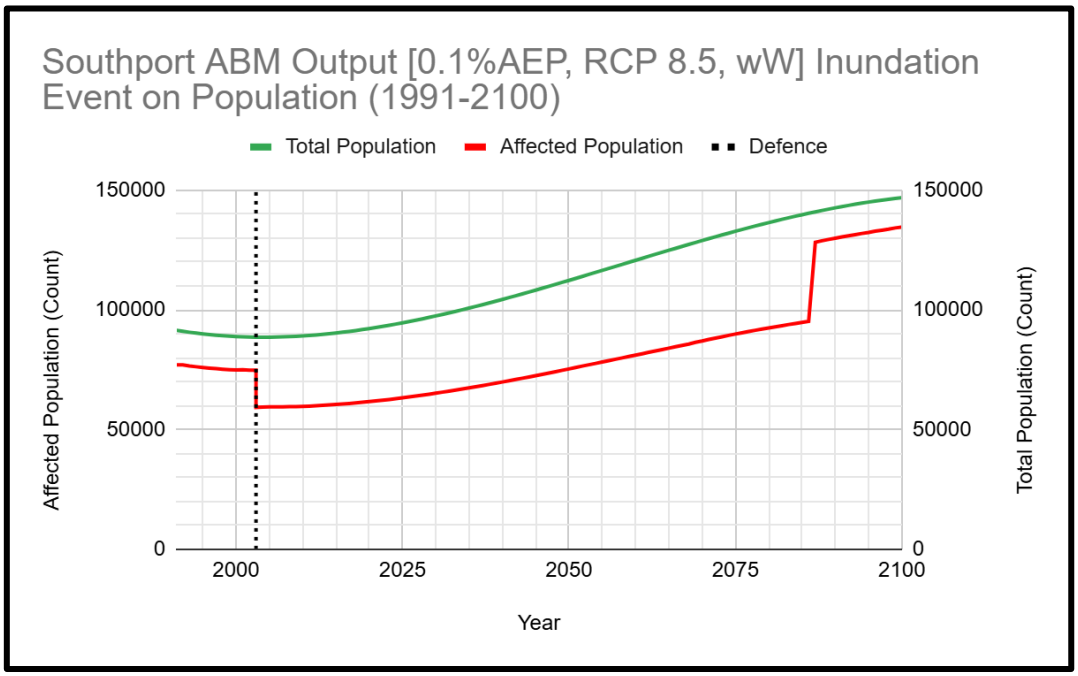


Figure F12 Total population and population exposed to flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

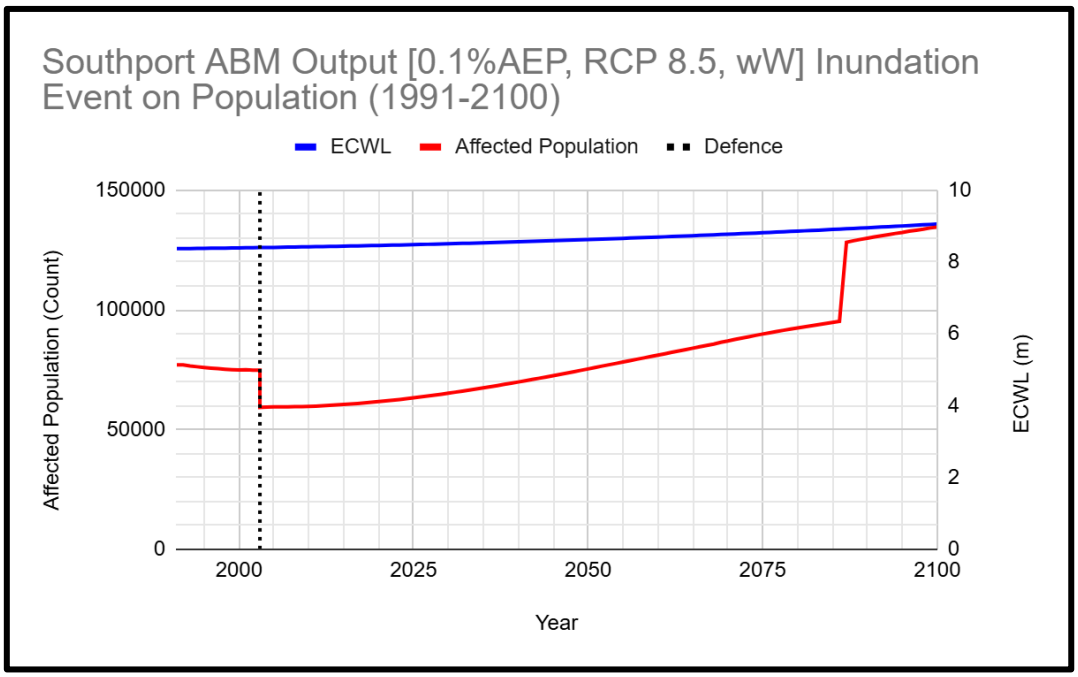


Figure F13 ECWL and population exposed to flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

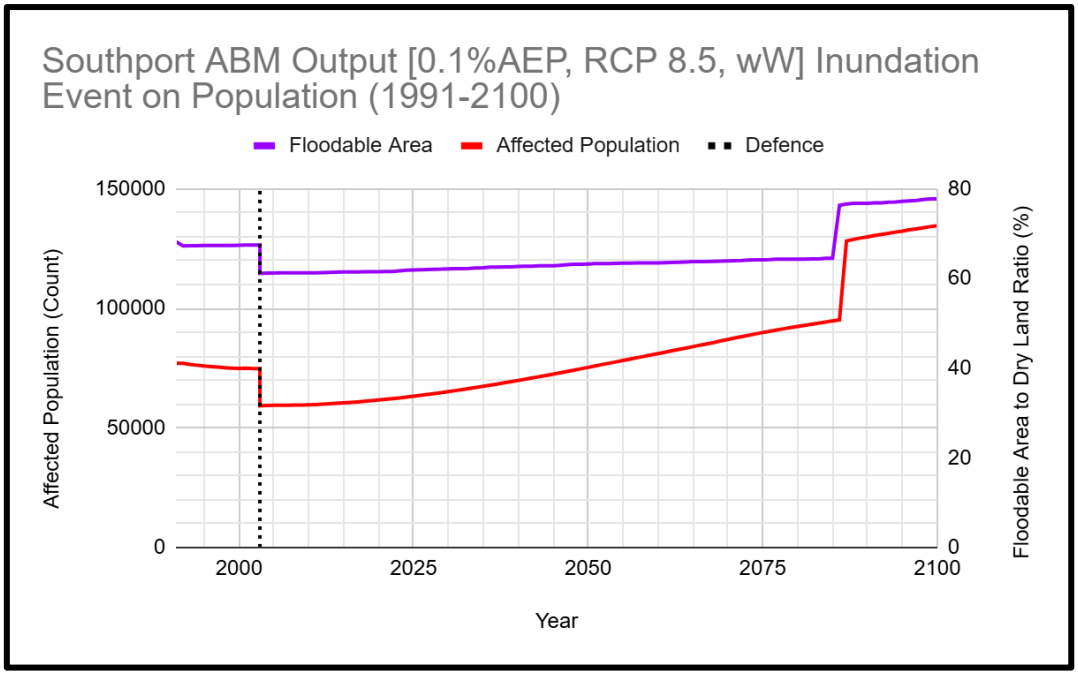


Figure F14 Ratio of dry land to wet land (*FA*) and population exposed to flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

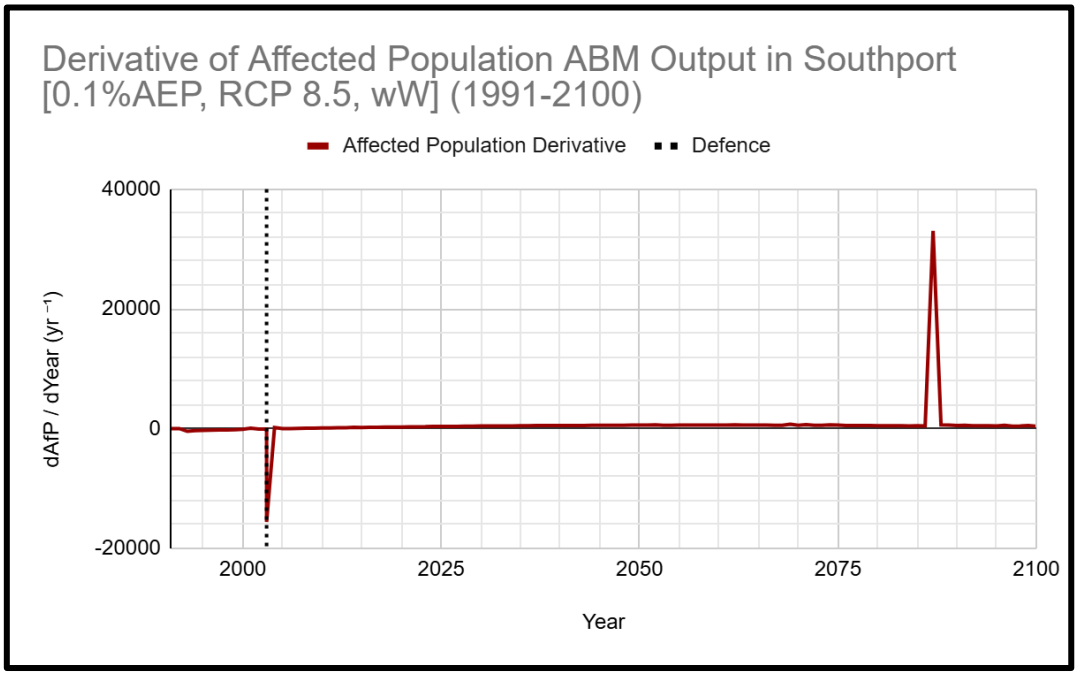


Figure F15 Derivation (dAfP/dYear) of the population exposed to flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

Case Study B

The new SCFP at Weston-super-Mare was finished in 2011 and provides a 200-year SoP. This would provide protection against a 0.5%AEP event in 2011. The ECWLs considered are presented in **Figure F1** and the topography of the landscape in **Figure F16**.

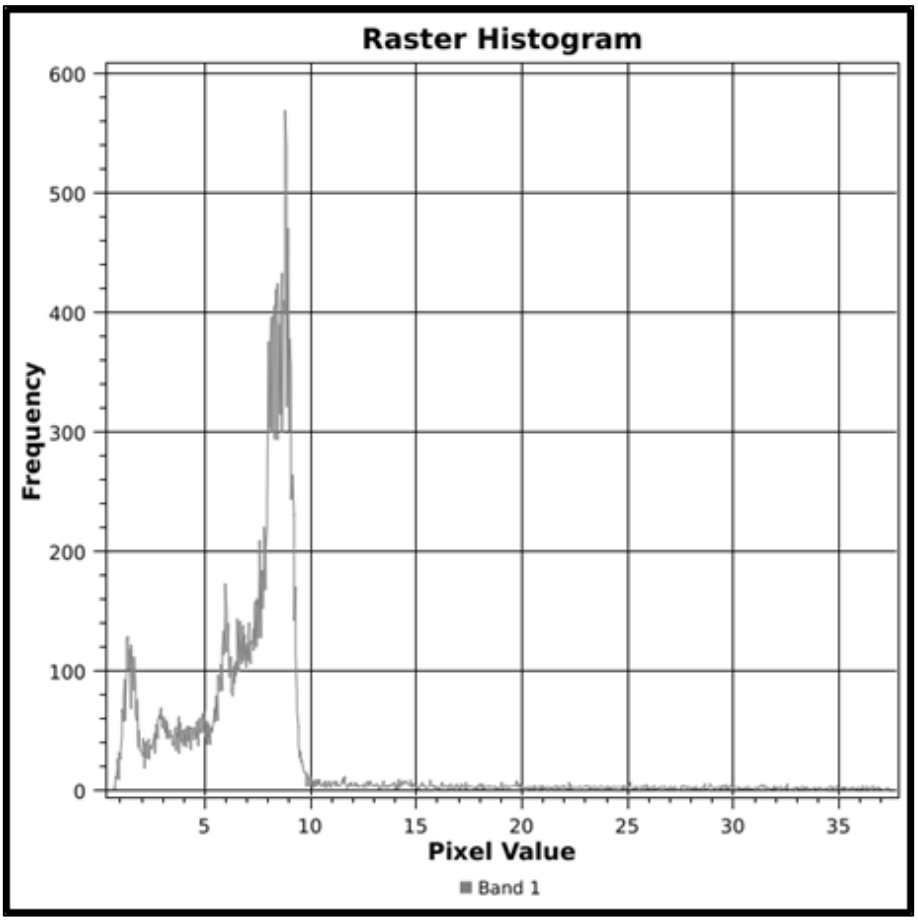


Figure F16 Raster histogram based on the DTM data used in the Weston-super-Mare ABM.

Before the upgrading of the new defence in Weston-super-Mare, *AfP* was steadily increasing by $3yr^{-1}$ (**Figure F17**), ECWL was also steadily increasing (**Figure F18**), and the *FA* remained stable (**Figure F19**). The upgrading of the SCFP in Weston-super-Mare led to a decrease in *AfP* by 78 people (**Figure F17**), *FA* by 0.8% (**Figure F19**), and the derivative of *AfP* (**Figure F20**). The decrease in *AfP* per year is too few to be apparent in the graphs due to the large *AfP* increase when the ECWL becoming higher than the crest height of the SCFP and a flood occurs. This is due to the fact that Weston-super-Mare already had a mostly effective SCFP, protecting not only itself but also the North Somerset Levels behind with an upgrade to a 1-in-200 year SoP from a 1-in-50. If there was no other SCFP present, then the decrease in *AfP* would likely be much greater.

Following the upgrading of the SCFP in Weston-super-Mare, the *AfP* derivative quickly returns to around $2yr^{-1}$ steadily increasing to $6yr^{-1}$ before the defence is exceeded in 2054 (**Figure F20**); although, there are several smaller peaks in the run up to it being exceeded: a temporary increase to $18yr^{-1}$ in 2026, $12yr^{-1}$ in 2046, and $25yr^{-1}$ in 2048. These slight increases in the *AfP* derivative are most likely driven by the interaction between the ECWL and the underlying DTM raster data, which has several smaller frequency peaks between 0m and 5m (**Figure F16**), these interactions also translate to the slight increases in *FA* across this period (**Figure F19**). Moreover, changes in population distribution attributed to the SCFP upgrades may have led to increases, and decreases, in both, *AfP* and its derivative.

Following this period, there was a very steady increase in the *AfP* of Weston-super-Mare, which recovers to pre-upgrade levels by 2031 (**Figure F17**). The SCFP led to a decrease in *FA* from 5.0% to 4.1% the year after (**Figure F19**). However, once the SCFP is exceeded, the *FA* increases from 4.3% to 54.2% in a single year, rising to 56.5% by 2100 (**Figure F19**). The upgraded SCFP in Weston-super-Mare is exceeded in 2054 under the ECWL scenario explored, flooding the area previously defended by it, and new land that had never been flooded before due to higher ECWLs than had hitherto never been experienced. *AfP* (**Figure F17**) and *FA* (**Figure F19**) increases drastically. This sudden increase in *AfP* translates to a large increase in its derivative (**Figure F20**), jumping to 26,008yr^{-1}, far greater than the 78yr^{-1} protected when the defence was initially upgraded. The upgraded SCFP in Weston-super-Mare being exceeded leads to an extra 25,930 people being exposed than before the defence was upgraded. These populations would have no flood memory, and this would likely impair flood awareness, preparedness, and consequently responsiveness. This highlights the importance of flood risk communication, so that when large-scale inundation events do occur, the population is ready and capable. *Therefore, the short-term savings provided by the upgrading of the SCFP in Weston-super-Mare would be greatly overshadowed by the long-term losses, highlighting the importance of considering these unintended consequences in future coastal FRM and spatial planning*.

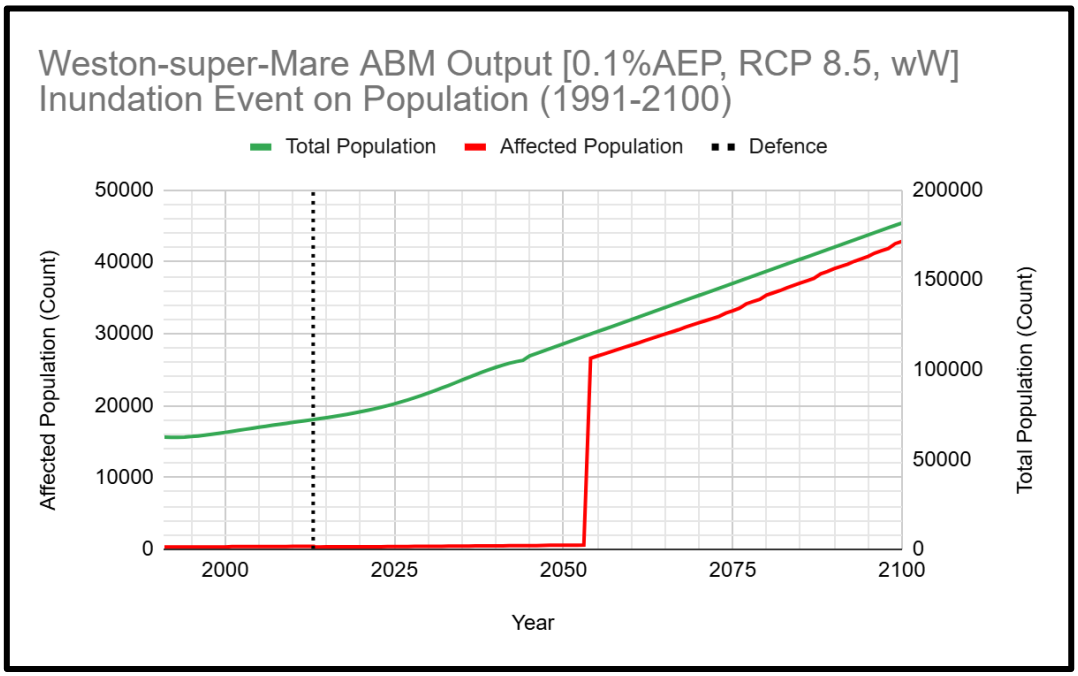


Figure F17 Total population and population exposed to coastal flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

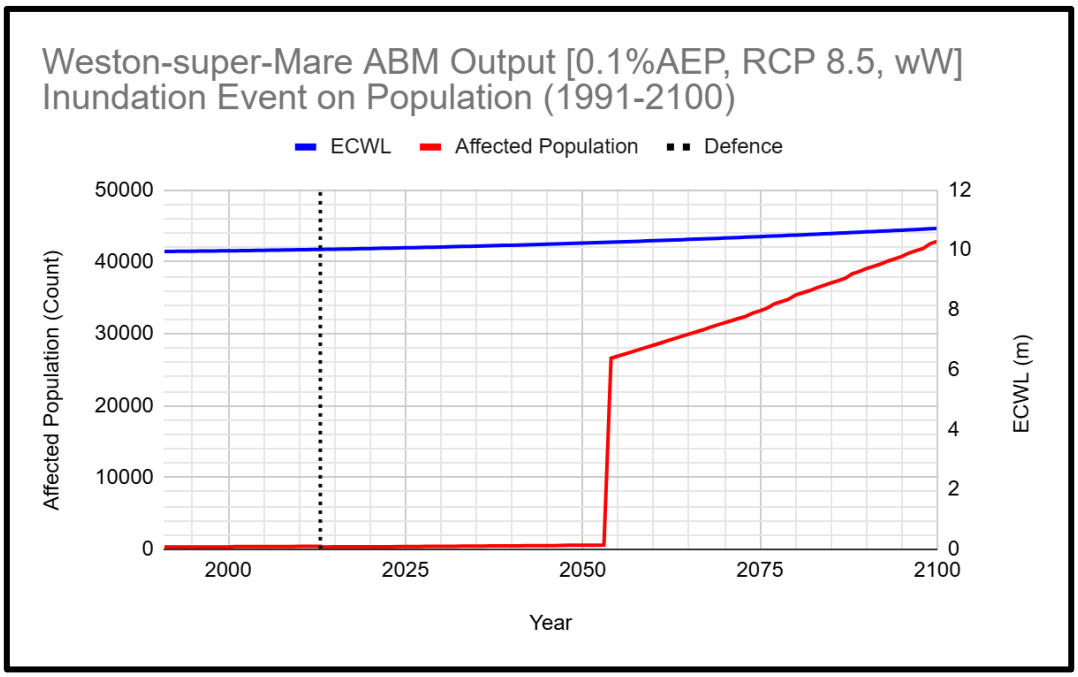


Figure F18 ECWL and population exposed to coastal flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

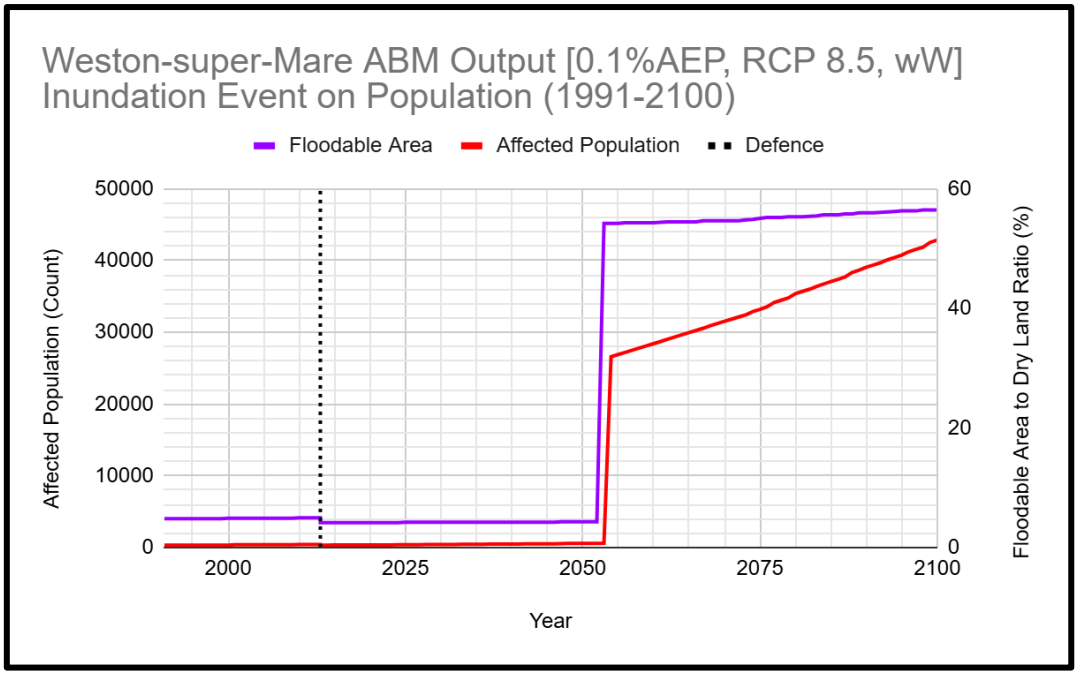


Figure F19 Ratio of dry land to wet land (*FA*) and population exposed to coastal flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

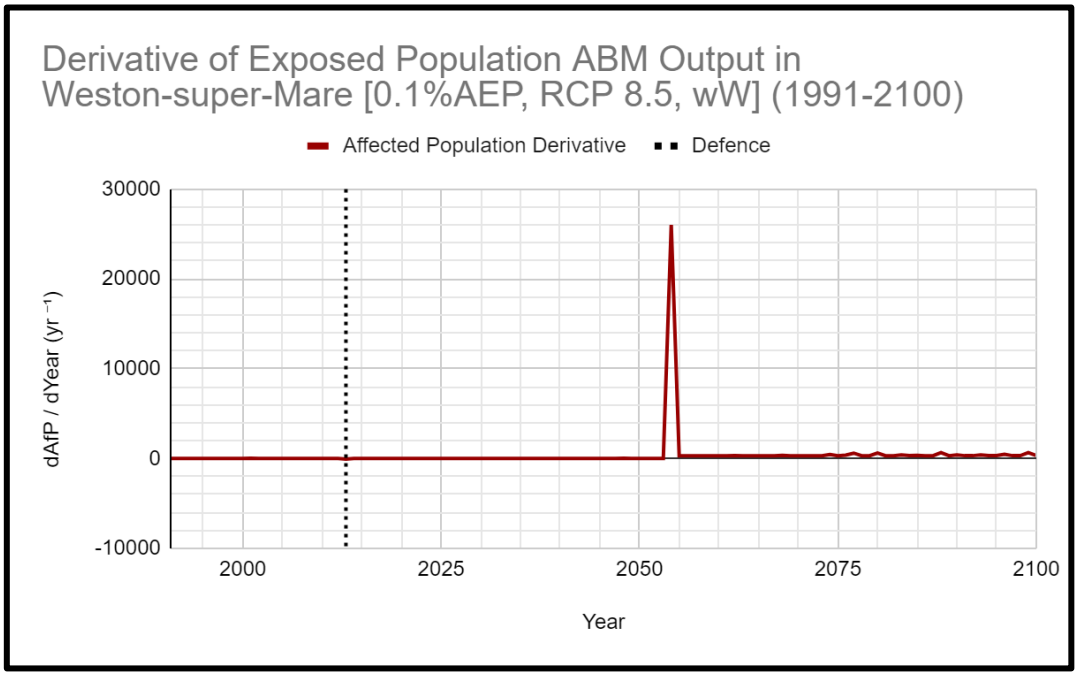


Figure F20 Derivation (dAfP/dYear) of population exposed to coastal flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

Case Study C

The defences at Portsmouth were constructed or upgraded multiple times over the decades: Old Portsmouth site in 2005, NPCS Phase 1 in 2015, NPCS Phase 2 in 2016, NPCS Phase 3 in 2019, as well as the ongoing Southsea scheme starting in 2022 and finishing in 2029. Some defences were yet to be built, and information from these came from planning documentation, these include NPCS Phase 4 (2024), NPCS Phase 5 (2026), and subsections of the Southsea scheme. The six sub-projects of the Southsea projected have not been represented in the charts below for better visualisation, but are represented by the final Southsea line graph (2029) which connects the project together. The Extreme Coastal Water Levels (ECWLs) considered are presented in **Figure F1** and the topography of the landscape in **Figure F21**.

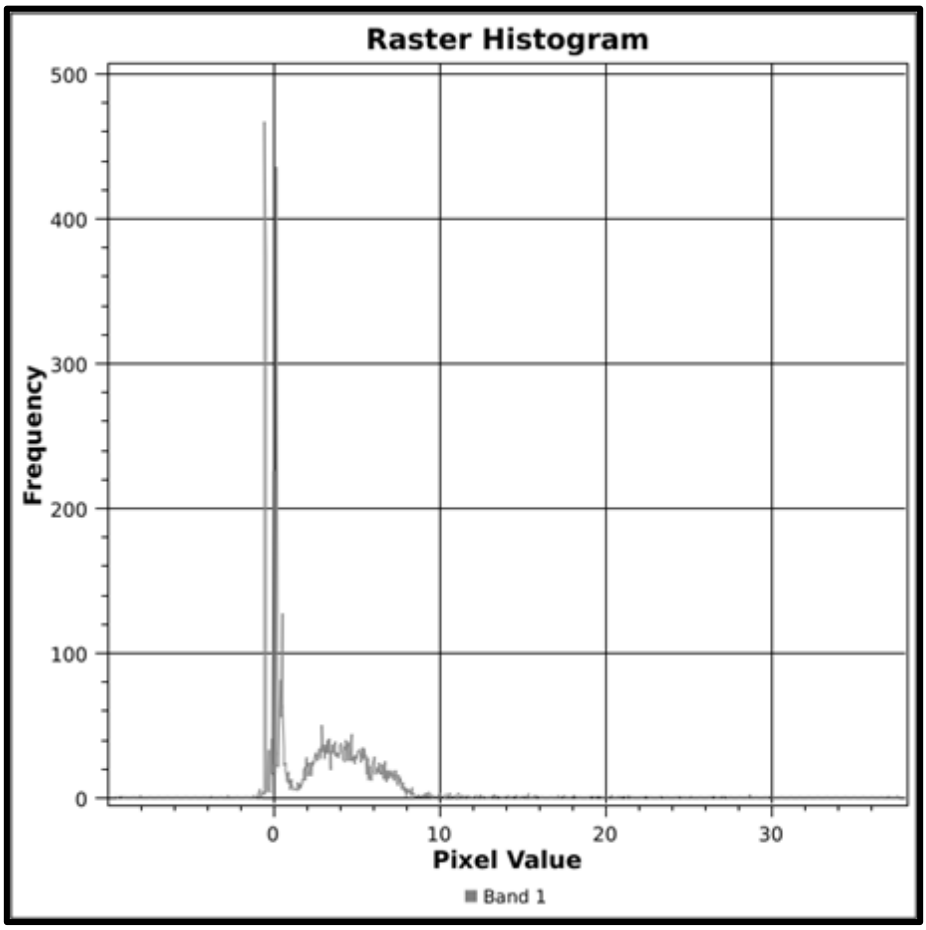


Figure F21 Raster histogram based on the DTM data used in the Portsmouth ABM.

Before the Old Portsmouth SCFP, *AfP* in Portsmouth was initially flat, then increased year-on-year up to the construction (**Figure F22**). Following the completion of the Old Portsmouth SCFP in 2009, *AfP* (**Figure F22**), *FA* (**Figure F24**), and the derivative of *AfP* (**Figure F25**) all showed decreases, amounting to a fall of 421yr^{-1}. However, the overall amount of *AfP* increased again to that of before the Old Portsmouth coastal defence, due to coastal flooding in other unprotected areas of the city (**Figure F22**), confirmed by a continuous rise in *FA* of the city after the initial decrease (**Figure F24**).

During the period following the Old Portsmouth SCFP and NPCS Phase 1 there was an increase in *AfP*, increasing exponentially with the *AfP* derivative not only remaining positive, but increasing (**Figure F25**). Whilst *FA* did increase over this period, the rise was steady, whereas the citywide Total Population rose at its greatest rate (**Figure F22**) and was therefore the most likely primary driver of *AfP* growth over this period. Then, as NPCS phases continue, *AfP* remained relatively stable, oscillating between positive and negative growth, with Phase 3 leading to a 341 *AfP* decrease (**Figure**

F25). This phase directly protected the north-west of Portsea Island and did not see a Total Population decrease over this period, therefore, the large decrease must originate from the SCFP being implemented. The NPCS was designed to operate at its best together, and therefore linking with already implemented phases would also provide greater flood protection and impact reduction.

The completion of the NPCS Phase 5 and Southsea scheme saw the greatest reduction in *AfP* (**Figure F22**), with a decrease of 7200yr^{-1} (**Figure F25**). Then, once the Southsea scheme had been completed, there was an even greater decrease of 8807yr^{-1} (**Figure F25**). However, the completion of the NPCS Phase 5 scheme led to the greatest decrease in *FA*, decreasing by 11.4%, from 26.7% to 15.3%, compared to a decrease of 3% from the Southsea scheme (**Figure F24**). This would suggest that Southsea is a much more populated area than north Portsmouth, where the NPCS protects. Moreover, this is concordant with the idea that the area protected by the NPCS is primarily industrial with limited residential population and that the unintended consequences of SCFPs primarily are determined by land-use.

Following the large decrease in *AfP* and *FA* in Portsmouth, both factors remain comparatively low, with minimal growth rate: *AfP* growth remains around 4yr^{-1} (**Figure F25**). This continues up until 2067 at which point *AfP* increases by 137yr^{-1}, and is the last spike before the significant increase later towards the end of the century (**Figure F25**). These increases begin as the ECWL exceeds the SCFP crest height (**Figure F23**) and inundating areas with higher elevations, less frequent than those around the 4m mark (**Figure F21**). The SCFPs are first exceeded significantly in 2083, and despite the *FA* only increasing by 0.4% (**Figure F24**), there is a 2581 increase in *AfP* (**Figure F25**), suggesting a densely populated area had become flooded, the city centre, as the Old Portsmouth defence being exceeded.As time progresses such instances become more common with the next major one is in 2091, with an increase of 759 people who are exposed (**Figure F25**) and an increase of 0.3% in *FA* (**Figure F24**). After this, there was an increase of 1533 people who were exposed, and a corresponding increase of 0.9% in the *FA*. This matching increase in *FA* was triple the 2091 increase, despite having double the population; this reflects the sizable variance within the underlying DTM in Portsmouth (**Figure F21**). The final large increase in *AfP* occurred not too long after in 2097 when the ABM projected an increase of 652 people in the *AfP* output (**Figure F25**) and a corresponding 0.2% increase in *FA* (**Figure F24**).

AfP (**Figure F22**) and *FA* (**Figure F24**) outputs never returned to the levels of before Old Portsmouth. Moreover, the decreases in *AfP* caused by the construction of the NPCS Phase 5 and Southsea SCFPs were much greater than any of the increases in *d*AfP/*d*t generated by the ECWL rising to higher than the crest height of any of the SCFPs. Although if the ABM were to run for longer, this may become apparent. Exploratory ECWL scenarios beyond 2100 are available, but they are of less statistical certainty than those used up to the end of the twenty-first century. The NPCS protected the northern part of Portsea Island, an area dominated by industry; this led to limited change in *AfP* per phase, until the completion of the fifth phases of the project that linked the project together. However, the change in *FA* compared to the change in *AfP* for NPCS Phase 5 reflects the low population density of the area, and suggest a strong link between the impacts of SCFPs and the land-use of the local area. Moreover, as demonstrated by census and LiDAR change data, there was limited change in the residential area by the NPCS Phase 1 SCFP, this may also indicate an upper capacity limit that would also influence the impacts of SCFP, and hence there was no statistically significant difference in the change in population distribution. *Therefore, to summarise, the overall effect of the combined SCFP schemes in Portsmouth meant that AfP did not increase back to levels prior to the completion of the Old Portsmouth SCFP. The repeated SCFP schemes limited inundation, and pre-existing land-use and urban development reduced potential socio-economic impacts*.

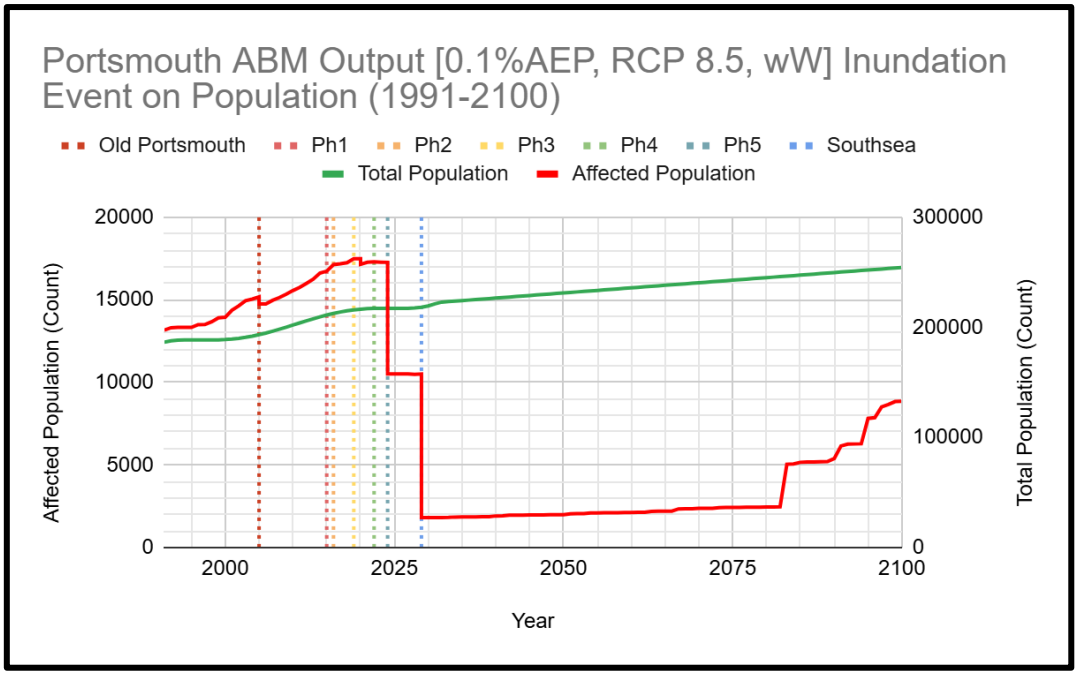


Figure F22 ABM Total population and population exposed to coastal flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

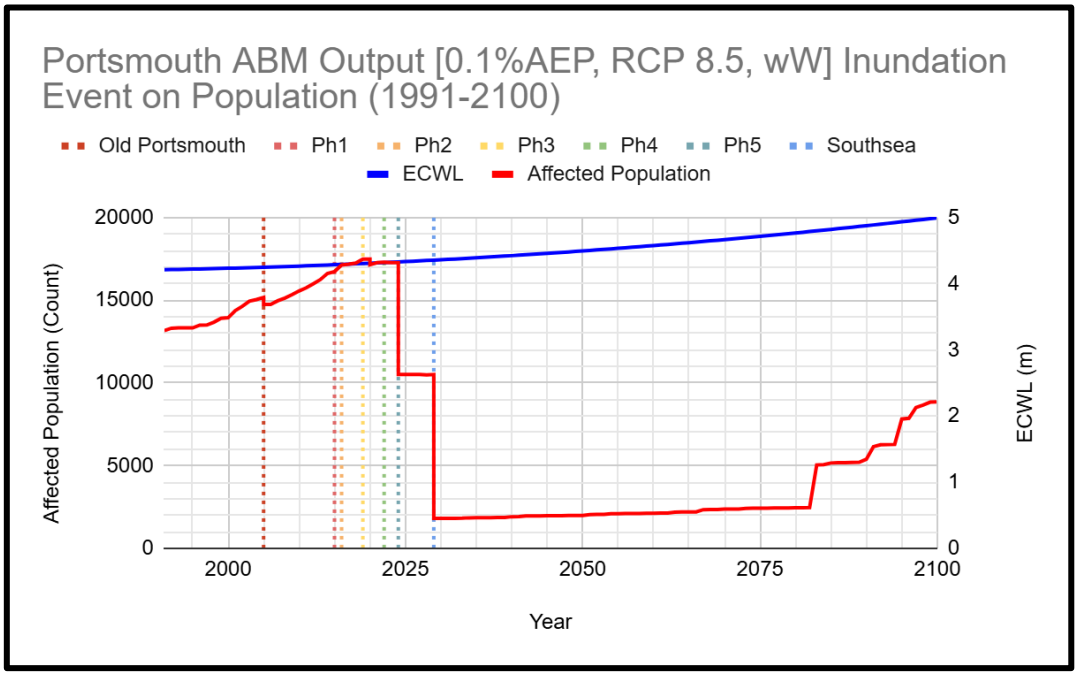


Figure F23 ECWLs and population exposed to coastal flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

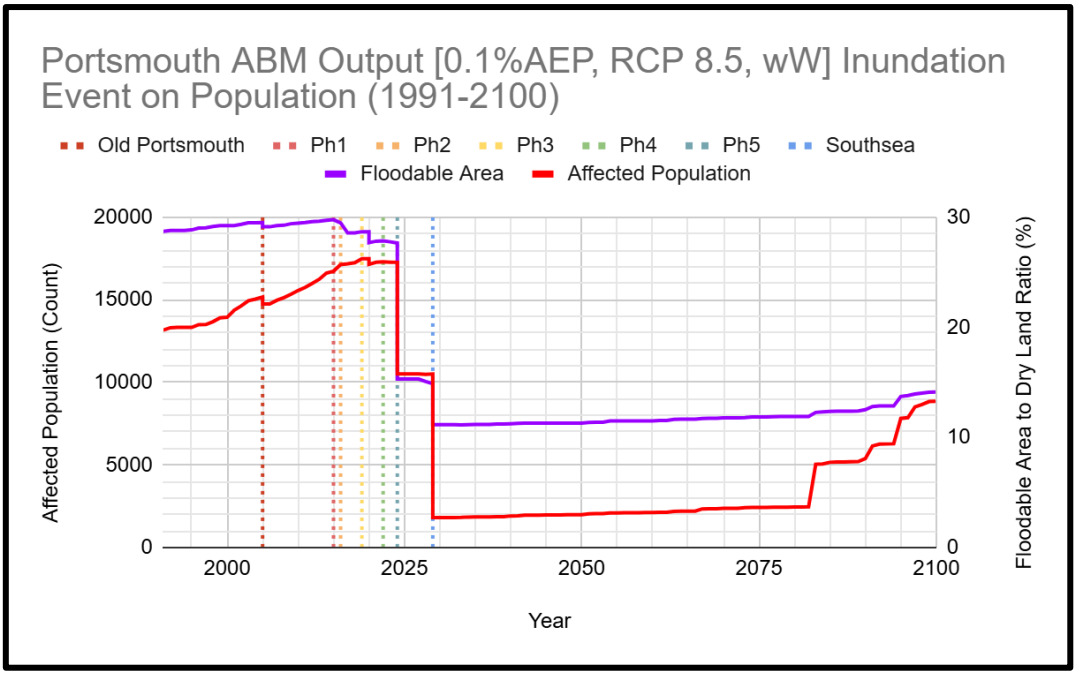


Figure F24 Ratio of dry land to wet land (*FA*) and population exposed to coastal flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

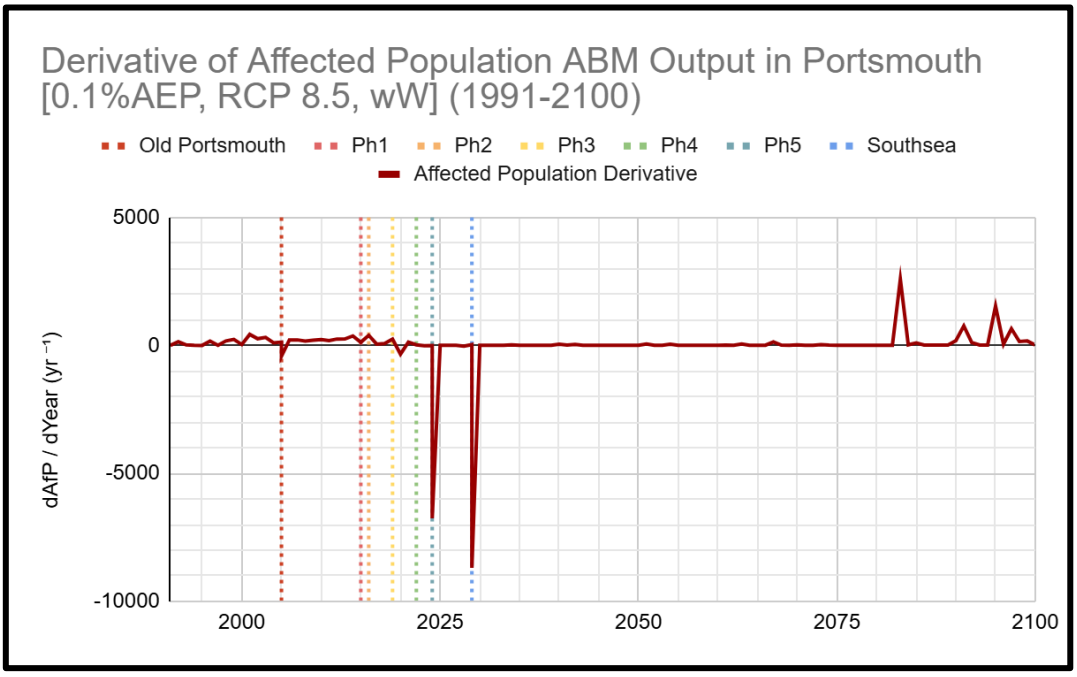


Figure F25 Derivation (dAfP/dYear) of the population exposed to coastal flooding with a 0.1% AEP under the RCP8.5 scenario with waves.

Discussion & Conclusion

Agent-based modelling of the socio-hydrological processes at the SCFP demonstrated clear emergent phenomena. These models suggested that during a Latency phase (**Figure F26**), population would continue to increase behind the SCFP whilst the ECWL continues to increase. This would continue until the ECWL surpasses the SCFP crest height and, in locations with flatter topography, the flood extent would reach a far greater area than before. The combination of an increased presence behind the SCFP and a larger flood extent would see a far greater proportion affected by the flooding than when the defence was initially built, leading to the large ΔAfPs. From the lack of flooding, this population would have a lower flood memory, and therefore be less prepared in the event of low-frequency, high-impact flooding (Ridolfi et al., 2021), an event exacerbated by the SCFP which limits higher-frequency, lower-impact inundations (Haer et al., 2020).

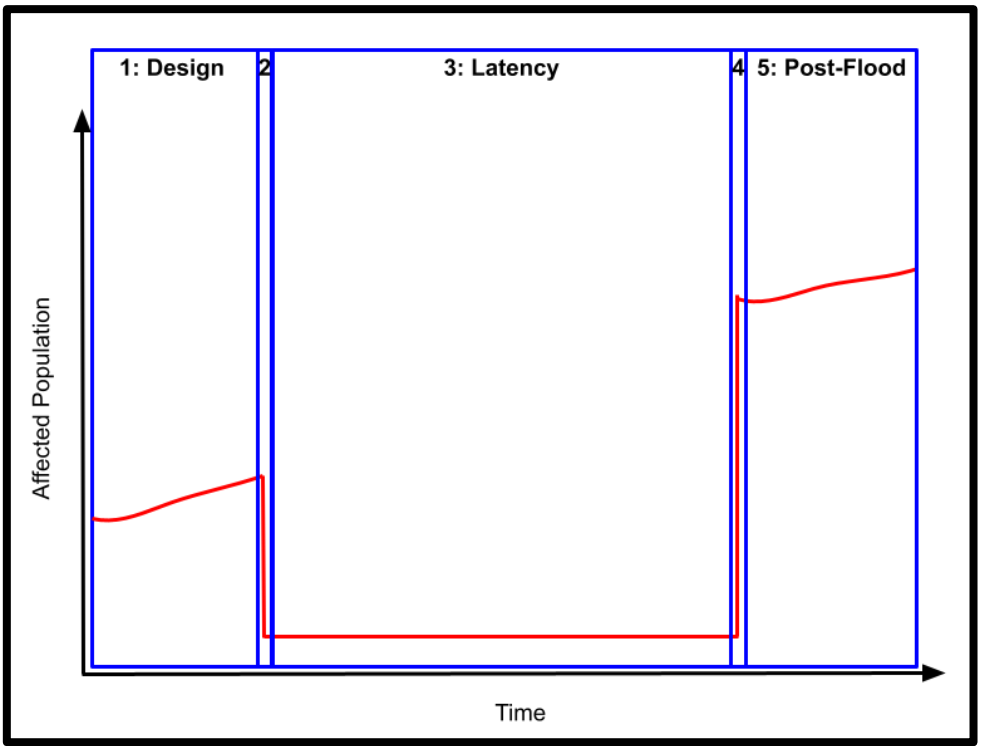


Figure F26 Conceptualisation of the socio-hydrological processes in a hypothetical town before, during, and after a SCFP was constructed (or majorly upgraded) and a resulting flood once ECWL was greater than the SCFP crest height.

Consequently, there is a clear pattern on the implications of SCFP on socio-hydrological processes, which can be broken down into five stages (**Figure F26**):

- **Stage 1: Design**
  During this stage the SCFP is being designed and has not yet been implemented. *AfP* is affected by both the extent of coastal flood inundation and natural population changes.
- **Stage 2: Implementation**
  This stage references the construction of the SCFP and a dramatic decrease in *AfP* driven by a decrease in the ability of coastal flooding to permeate deeply into the settlement.
- **Stage 3: Latency**
  During this period, population increases behind the newly constructed coastal flood defence and ECWL also increases. *AfP* sees little change outside of natural population change.
- **Stage 4: Flood**
  This stage sees the SCFP being exceeded by higher ECWL scenarios and flooding the settlement behind it. *AfP* increases dramatically as coastal flooding becomes a large driver of

it again. Due to increases in ECWL, coastal flooding travels further and affects populations at higher elevations of the town than it was able to previously.

- **Stage 5: Post-Flood**
  This is the final stage and presents the new normal following Stage 4, which now occurs regularly as the ECWL remains higher than the defence itself (unless upgraded inline with the increase in ECWL). *AfP* again returns to being affected by both the extent of coastal flood inundation and population changes, both, spatially and fundamentally.

In Southport the SCFP initially reduced the *AfP* , but over time this protection led to a greater *ΔAfP* when the ECWL surpassed the SCFP crest height due to increased settlement behind the SCFP (as in Di Baldassarre *et al*., 2018). This pattern again aligns with the SDP, leading to increased exposure once SCFP are overwhelmed (as in Ludy & Kondolf, 2012). Weston-super-Mare showed a larger *ΔAfP* once the ECWL surpasses the SCFP crest height as many areas were already defended by a seawall. This echoes findings from Hurricane Katrina whereby the failure of the levee system resulted in disproportionately high impacts on populations who believed they were safe (Burby 2006; Gotham *et al.*, 2018). Portsmouth, on the other hand, demonstrated that with limited residential development around the NPCS, the role of the SCFPs in shaping population socio-spatial dynamics is diminished, illustrating again how land-use can moderate the socio-hydrological impacts of SCFPs in densely populated and highly developed areas, such as Portsmouth (as in Fletcher, 1992).

Therefore, there are two pathways that inhibit coastal population growth and development occurring due to local increases in SCFP are Land-use Driven and Population Driven (**Figure F27**):

1. Land-use Driven
The pre-existing use of land, whether used for industrial, commercial, or residential purposes. If non-residential, then population increase cannot occur.

2. Population Driven
The already very high population density limits population increases, either due to the economics of supply and demand in the area, or physically limits the number of people that can live in the area.

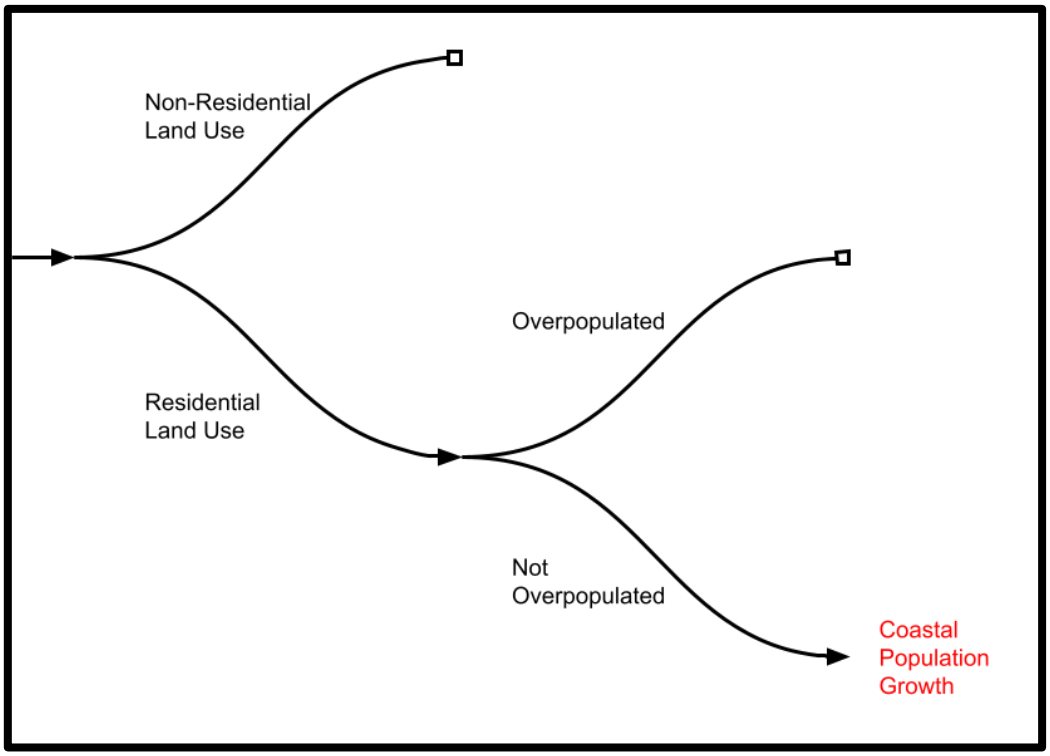


Figure F27 Conceptualisation of the inhibition pathways that hinder the coastal population growth during the latency period as an unintended consequence of SCFP.

These increases in *AfP* overall were also replicated in a similar ABM developed to assess the impact of extreme flood events for the European Union, which found that population growth in FAs leads to higher exposure and higher damages, and whether an FRM authority chooses to upgrade again or not, can affect population growth (Haer *et al.*, 2020). Moreover, it was uncovered that whilst continuous cyclic upgrading leads to a lower yearly flood risk, it leads to higher impacts in an extreme event, compared to not upgrading. This was also found within the ABM created within this project, once the ECWL surpasses the SCFP crest height, it leads to greater impacts at the SCFP from greater coastal population, but also due to the increased depth, and therefore extent, of the floodwater, affecting populations that have never been flooded before. In addition, the ABM of Haer *et al.* (2020) identified that unless efforts are made to retain societal flood memory and flood preparedness through flood risk communication and building level protective efforts.

The findings of this study, combined with those of others (e.g. Haer *et al.*, 2020), suggest that there is an intangible risk measure that increased from an upgrade compared to the initial construction, which would then suggest a cyclicality. The Portsmouth ABM further exemplified this with the appearance of the inhibition pathways. These pathways mitigate the unintended impacts of newly constructed, or upgraded, SCFPs, and from the modelling it became apparent that pre-existing land-use or high density population can limit growth in population during the latency period and therefore minimise the absolute change in *AfP* from before the SCFP was constructed to the time that the ECWL surpasses the SCFP crest height.

However, there are also several limitations associated with using ABMs, one of the main challenges is the complexity of model calibration and validation, particularly when incorporating multiple interacting factors (Sun *et al.*, 2016). Ensuring that the ABM accurately represents real-world processes and behaviours requires extensive data collection and validation, which can be time-consuming and resource-intensive. Additionally, overcomplicated ABMs may unintentionally introduce uncertainty and bias (Smajgl *et al.*, 2011), reduce the ease of evaluation (Müller *et al.*, 2014), and can also lead to potential difficulties in analysing multidimensional data and outputs (Lee *et al.*, 2015; Sun *et al.*, 2016).

Despite these challenges, ABM remains a valuable tool for exploring socio-hydrological processes and associated emergent phenomena, and assessing the impacts of SCFPs under future climate scenarios. By integrating socio-spatial and environmental dynamics, ABMs have the ability to inform more robust and adaptive coastal management strategies for building resilience to coastal flooding (Erdlenbruch and Bonté, 2018; Haer *et al.*, 2020).

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