

Strategic Flood Risk Management

A Systems-Based Approach

Paul Benjamin Sayers

STRATEGIC FLOOD RISK MANAGEMENT
A SYSTEMS-BASED APPROACH

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To my wife Sallie and our two wonderful children Billy and Meg.

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It is sometimes easy to focus on the competition that exists between us. In my experience, we all wish to act in a way that enriches our own lives and the lives of those around us; we have a shared goal to help people and nature flourish – *floreat populus et natura*. Flood risk management has a central role to play in this.

I dedicate this thesis to all those that have been generous in their willingness to collaborate and to share their knowledge of successes and failures without prejudice. I have been fortunate and hope this Thesis, in some small part at least, contributes to our collective endeavour.

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"with uncertainty all around, good choices standout"

SUMMARY

Throughout history, flood management practice has evolved in response to flood events. This heuristic approach has yielded some important incremental shifts in both policy and planning, including the need to plan at a catchment scale, the recognition that flooding arises from multiple sources, and that defences, no matter how reliable, may fail. Progress towards the delivery of socially just and appropriately resilient outcomes for people and nature has been painfully slow. In response, this thesis explores and distils a more strategic approach to enable delivery; an approach referred to here as Strategic Flood Risk Management (SFRM).

SFRM is shown to rely upon an adaptable portfolio of measures and policies to deliver outcomes for people that are socially just (when assessed against egalitarian, utilitarian, and Rawlsian principles) and promote healthy ecosystems. SFRM is presented not simply as a theoretical construct, but as a practical policy and planning framework to transform our understanding of risk and our approach to the management of flood risk.

The framework presented challenges the status quo, recognising flood management involves much more than simply reducing the chance of damage through the provision of "strong" structures, and that adaptive management is much more than simply "wait and see." The SFRM framework is presented as inherently risk-based and implemented through a continuous process of review and adaptation that seeks to actively manage future uncertainty; a characteristic that sets it apart from the linear flood defence planning paradigm based upon a more certain view of the future.

SFRM accepts there is no silver bullet to flood issues, and that people and economies cannot always be protected from flooding. It accepts maintaining some flooding as critical to the health of natural ecosystems and natural infrastructure as a legitimate asset with a contribution to make to the management of flood risk (Sayers *et al.,* 2017a, *in press a*). Most importantly, SFRM recognises the central role of trade-offs within the decision process. It enables the inherent conflicts (as well as opportunities) that characterise flood management choices to be openly debated, priorities to be set, and difficult choices to be made.

Some of the advances made in recent years to facilitate the transition from flood defence to SFRM are presented. These include the continued and progressive contribution of the author to the field of flood risk analysis and management over the past decades; from the early beginnings of modern flood risk system analysis in the late 1990s to the development of advanced system tools, methods and applications, and their coalescence into a coherent strategic framework.

The Thesis presents quantitative analysis as central to the understanding of risk and how best to manage it. To overcome the limited ability of conventional modelling

approaches to explore multiple futures, a highly efficient exploratory modelling approach is presented and shown to be capable of exploring how flood risks may change at a national scale in response to a range of climate change and population growth projections, and adaptation assumptions. The analysis shows both climate change and population growth to be important influences but identifies choices around adaptation to be the primary determinant of future flood risk. This reinforces the importance of including a credible representation of existing and future flood defences as well as non-structural measures with planning and appraisal tools if future risks are to be meaningfully explored.

The quantified analysis provides new insights into how risks faced by the most socially vulnerable compare to those faced by the less vulnerable. The analysis defines social vulnerability using a new metric, the Neighbourhood Flood Vulnerability Index (NFVI) and highlights how climate change influences geographic flood disadvantage (the locations with the greatest social flood risk) and, importantly, systemic flood disadvantage (the differential risk faced by the socially vulnerable compared to others). The influence of climate change on widespread spatially coherent flood events (*i.e.,* single events that impact multiple locations at the same time) is assessed. This hitherto largely ignored influence is shown to have a material influence on UK flood risk with potential implications for investment in adaptation.

The framework of SFRM and the quantified analysis continue to influence flood risk management investment and policy planning in the UK. The approaches developed and presented here, for example, have had a central role in the UK Climate Change Risk Assessment and UK adaptation policy debates around fairness and investment.

Several Golden Rules have been developed by the author to guide the implementation of SFRM and are found to be robust and readily elaborated to today's context. The re-interpretation of the Golden Rules by several organisations in recent years to influence their approach to flood management and planning is testament to their ongoing utility.

SAMENVATTING

In de loop van de geschiedenis heeft de praktijk van overstromingsbeheer zich ontwikkeld als reactie op overstromingen. Deze heuristische benadering heeft een aantal belangrijke incrementele verschuivingen in zowel beleid als planning opgeleverd, waaronder de noodzaak om op stroomgebiedschaal te plannen, de erkenning dat overstromingen meerdere oorzaken kennen en dat waterkeringen, hoe betrouwbaar ook, kunnen falen. De vooruitgang in het bouwen van een sociaal rechtvaardige en voldoende veerkrachtige samenleving voor mens en natuur is echter langzaam geweest. Om deze reden onderzoekt en identificeert dit proefschrift een meer strategische benadering; een benadering die hier wordt aangeduid met Strategic Flood Risk Management (SFRM) – strategisch overstromingsrisicobeheer.

SFRM maakt gebruik van een portfolio van maatregelen inclusief beleid dat sociale gelijkheid (gebaseerd op de principes van het egalitaritisme, utilitaristisme en Rawls) en gezonde ecosystemen bevordert. SFRM wordt niet alleen gepresenteerd als een theoretisch concept, maar ook als een praktisch beleids- en planningskader om ons begrip van risico's te vergroten en onze benadering voor het beheer van overstromingsrisico's te verbeteren.

Het in dit proefschrift gepresenteerde raamwerk stelt de status quo ter discussie, waarbij het overstromingsrisicobeheer veel meer is dan het reduceren van de kans op schade door de inzet van ‘sterke’ waterkerende maatregelen en dat adaptief management veel meer is dan simpelweg afwachten. Het SFRM raamwerk gaat uit van een op risico-gebaseerde aanpak waarbij implementatie een continue proces vergt van beoordeling en aanpassing dat erop gericht is toekomstige onzekerheid actief te managen; een karakteristiek dat zich onderscheidt van de lineaire planningsstrategie van waterkeringen gebaseerd op een meer zekere kijk op de toekomst.

SFRM accepteert dat er geen enkelvoudige, optimale oplossing bestaat voor het overstromingsvraagstuk, en dat mens en economie niet altijd beschermd kunnen worden tegen een overstroming. Het aanvaardt het handhaven van sommige overstromingen als cruciaal voor de gezondheid van natuurlijke ecosystemen en groene infrastructuur als een legitieme kwaliteit met een bijdrage aan het beheer van overstromingsrisico's. Misschien wel het belangrijkste is dat SFRM aantoont dat compromissen onderdeel zijn van het besluitvormingsproces. Het maakt het mogelijk om de inherente conflicten (en kansen) die kenmerkend zijn voor overstromingsbeheerkeuzes openlijk te bespreken, prioriteiten te stellen en moeilijke keuzes te maken.

Enkele recente ontwikkelingen die bijgedragen hebben aan een verschuiving van de oriëntatie op hoogwaterbescherming naar SFRM zijn in dit proefschrift gepresenteerd.

Deze omvatten de voortdurende en vooruitstrevende bijdragen van de auteur op het gebied van overstromingsrisicoanalyse en -beheer in de afgelopen decennia; van het vroege begin van de moderne analyse van overstromingsrisico's in de late jaren 1990 tot geavanceerde instrumenten en methoden op systeemniveau en hun toepassingen daarvan, en hun integratie tot een strategisch raamwerk van meer recente datum.

In dit proefschrift is een kwantitatieve analyse gepresenteerd als een wezenlijke component voor het kennen van de overstromingsrisico's en de beste wijze van beheersing. Om de beperkingen van de conventionele modellen voor het verkennen van toekomstscenario's te overbruggen, is een zeer efficiënte exploratieve modelaanpak ontwikkeld die laat zien dat het overstromingsrisico op nationale schaal voor een reeks van klimaat- en bevolkingsgroeiprojecties en adaptatie-interventies kan veranderen. Zo toont de analyse dat zowel klimaatverandering als bevolkingsgroei belangrijk zijn, maar ook dat het toekomstig risico vooral wordt bepaald door de wijze waarop we ons hieraan aanpassen (adaptatie). Dit onderschrijft het belang van het opnemen van een betrouwbare weergave van de bestaande en toekomstige waterkeringen en niet-structurele maatregelen met plannings- en beoordelingsinstrumenten om te komen tot een betekenisvolle verkenning van toekomstige risico's.

De kwantitative analyse biedt ook nieuwe inzichten in hoe risico's voor de meest sociaal kwetsbaren zich verhouden tot die van de minder kwetsbaren. De analyse definieert sociale kwetsbaarheid met behulp van een nieuwe parameter, de Neighborhood Flood Vulnerability Index (NFVI), en laat zien hoe klimaatverandering de locaties met het grootste sociale overstromingsrisico beïnvloedt alsook het 'systemisch overstromingsnadeel' (het risico van sociaal kwetsbaren in vergelijking met andere sociale groepen).

De invloed van klimaatverandering op de ruimtelijke structuur van overstromingsgebeurtenissen (een op meerdere locaties optredende gebeurtenis) is ook geanalyseerd. Deze tot nu toe grotendeels genegeerde invloed, blijkt van belang te zijn bij het inschatten van het overstromingsrisico in het Verenigd Koninkrijk (VK), en dit heeft mogelijk gevolgen voor investeringen in adaptatie.

Het raamwerk van SFRM en de kwantitatieve analyse zijn van invloed geweest op de investeringen in overstromingsrisicobeheer en beleidsplanning in het VK. Zo hebben bijvoorbeeld de hier ontwikkelde en gepresenteerde benaderingen een centrale rol gespeeld bij de Britse risicobeoordeling van klimaatverandering en de beleidsdebatten over eerlijkheid van en investeringen in klimaatadaptatie.

Een aantal Gouden Regels ter ondersteuning van de implementatie van stategisch overstromingsrisicobeheer (zie de figuur in de Engelse samenvatting) is door de auteur ontwikkeld. Verschillende organisaties hebben deze regels toegepast en geherinterpreteerd in overstromingsrisicobeheer en planning, en dit laat zien dat ze van praktisch nut zijn.

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1

OUTLINE OF THE THESIS

Despite continued efforts, flood risks continue to increase and are projected to increase further as the climate changes and populations grow. Conventional approaches are now recognised as ill-equipped to address the complex challenges faced and deliver the multiple outcomes for people, economies and nature society demands. A new approach is needed. This approach, a more strategic approach, is set out here.

Flooding issues are always context specific. As a result, the approach to flood management should differ and often does. Sometimes these differences appropriately reflect the nature of the risks faced; sometimes they simply reflect a lack of imagination or the constraints of poor governance (from funding structures to delivery mechanisms).

A common understanding of what constitutes 'sound' flood management planning is emerging. The past decade has seen a general convergence on the concepts of risk (*e.g.,* Sayers *et al.,* 2002a, b) and increasingly the definition of flood risk management (Hall *et al.,* 2003a; Schanze *et al.,* 2006; Samuels *et al.,* 2010). These frameworks were further developed by Sayers *et al.,* 2013, 2014a to reflect the specific attributes of a 'strategic approach' to flood risk management. This approach forms the basis for the definition of Strategic Flood Risk Management (SFRM) advocated here (as elaborated later in Chapter 4) as follows:

> ***Strategic Flood Risk Management delivers multiple outcomes for people and nature over the short and long term. The approach is inherently collaborative, inclusive, and systems-based with choices based on an understanding of risks, benefits, and uncertainties. A continuous process of review and adaptation actively manages change, incorporates new knowledge, and modifies plans and actions.***

1.1 A CONTINUING CHALLENGE

The approach to SFRM advocated here contrasts with the conventional linear paradigm of 'construct and maintain' (based on the assumption of a reasonably certain view of the future). A strategic approach urges flood managers to recognise that future conditions may change (perhaps significantly) from those that exist today and to identify robust and flexible choices (that recognise non-stationarity within the flood system, including climate, geo-spatial and socio-economic change). In doing so, a strategic approach underlines the need for a continuous process of monitoring and intervention that now reappears in contemporary thinking about adaptive management (*e.g.,* Willows and Connell, 2003; Hall *et al.,* 2003a; Sayers *et al.,* 2012, Brisley *et al.,* 2015).

The strategic systems-approach advocated here recognises that there is seldom a single solution to managing flood related opportunities and challenges (Evans *et al.,* 2004a&b, Opperman *et al.,* 2013). Instead, the use of a portfolio of flood management measures and instruments is encouraged. Such portfolios assemble multiple actions in space and time and draw upon both 'grey' infrastructure (such as construction of dykes, levees, dams *etc.*) and 'green' infrastructure (such as afforestation and wetlands) as well as 'hybrid' infrastructure (*e.g.,* vegetated foreshores in front of dykes). Local infrastructure measures (such as property level protection) as well as non-infrastructural measures (such as improved flood forecasts and warnings), and policy instruments (such as land use planning, insurance, and other funding incentives, such as homeowner grants for flood proofing) are equally important considerations.

A strategic system-based approach adopts a broad range of criteria for determining how, where and when to act; no longer solely economic, but considers a much broader set of outcomes, including social justice and ecosystem health (Sayers *et al.,* 2014a, 2017a,b,c).

Compelling as the case for adopting SFRM certainly is, it is not easily achieved. It requires risks to be assessed and evaluated at a whole system scale (*e.g.,* a catchment, a nation, region, or even a global network of goods and services) and over the long term (given alternative climate, socio-economic and adaptation futures) and the ability to engender collective action across a range of government authorities as well as those outside government (including individuals, the business and infrastructure service community and third sector organisations). Successful, SFRM therefore places an increased emphasis upon effective communication (of the risks, the uncertainties, and the case for action) and establishing decision frameworks capable of linking short-term requirements and long-term goals.

1.2 OBJECTIVES

The aim of this thesis is to develop a strategic system-based approach to the analysis and management of flood risk that delivers longer term resilience, ecosystem health and promotes social wellbeing. More specifically, the objectives of the thesis are to:

#1 Provide a perspective on the evolution of flood management, to ensure past lessons provide the foundation of the approaches presented.

#2 Ensure emerging approaches and frameworks from outside conventional flood management are appropriately considered and the opportunities they provide grasped.

#3 Present the framework of Strategic Flood Risk Management (SFRM) and distil a small number of 'golden rules' that guide this approach.

#4 Present supporting methods that enhance a system-based approach to SFRM and illustrate their utility through example applications at national and regional scales.

#5 Identify priority knowledge gaps and areas of further research.

It is recognised that the strategic approach advocated here is not the last word. Continued innovation in the concepts, analysis methods and decision approaches as well as further demonstration in real-world case studies will be required to promote progressive and effective uptake into practice.

1.3 CHAPTER LAYOUT

The structure of the thesis reflects the Objectives set out above and progresses from a historical perspective, through the concepts, methods, and applications to SFRM before presenting summary conclusions and priorities for further research (Figure 1-1).

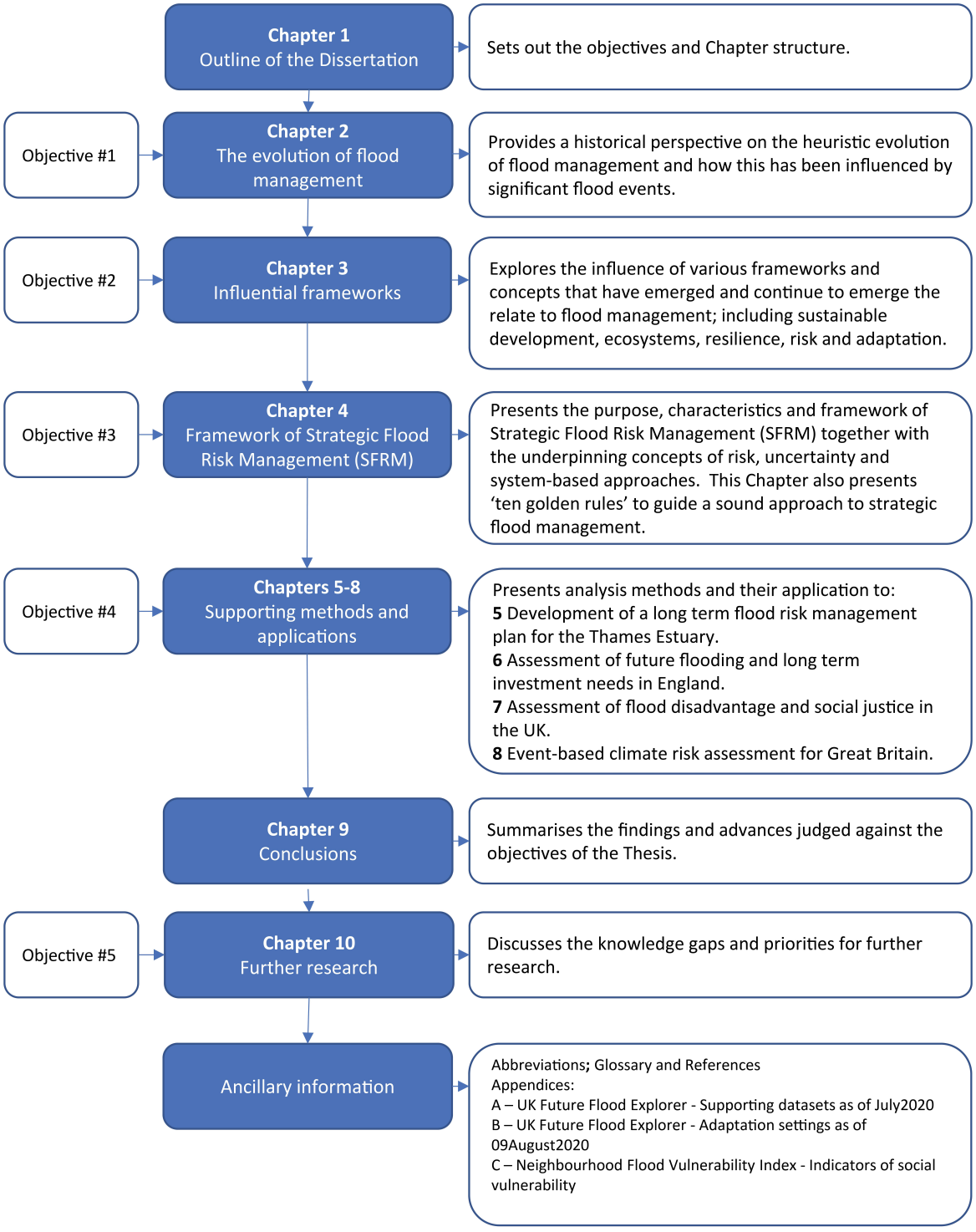


Figure 1-1 The organisational structure of the thesis

2

EVOLUTION OF FLOOD MANAGEMENT

The inherent conflict between human development and the natural function of floodplains is as old as civilisation itself. As populations grew permanent, use of the floodplain became increasingly important to maintain agricultural production as well as strategic economic and military advantage, hence periodic flooding became less acceptable; once seen to be an inconvenience, floods became a significant brake on development. In response societies began to take steps to lessen the impact of flooding. At first, these efforts were minimal but evolved to include audacious structural actions to keep flood waters away from important communities and drain vast areas of wetland for agricultural use.

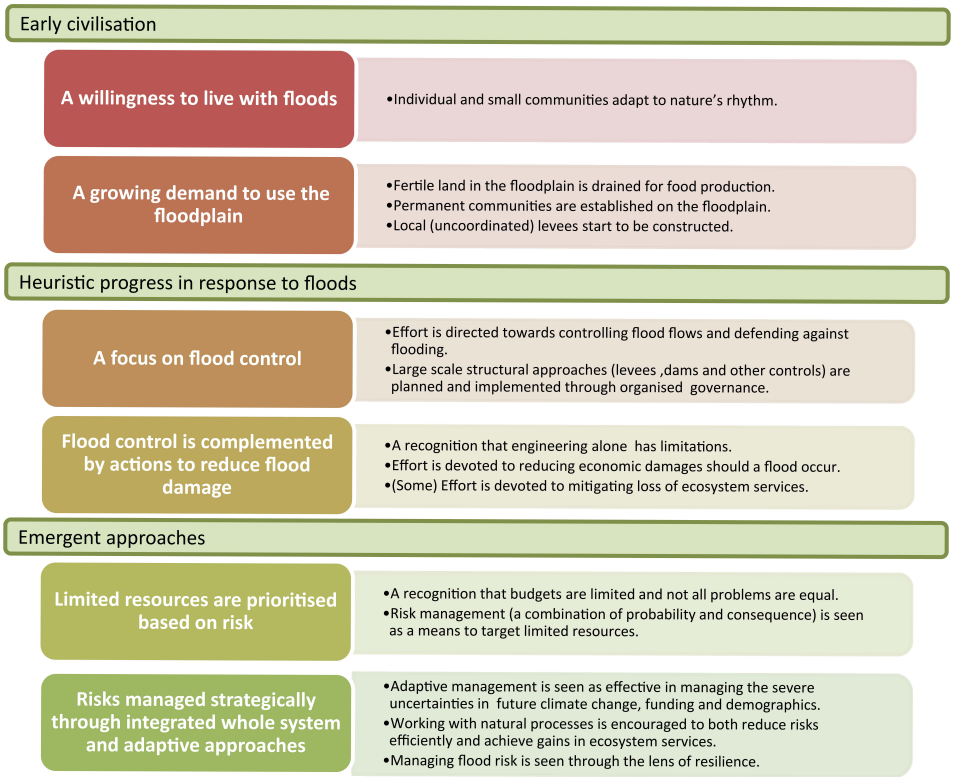
Such measures were often difficult to sustain and invariably overwhelmed by the next 'great flood' and throughout history flood management practice has evolved in response to these events. This heuristic approach has yielded some important, although largely incremental, advances in both policy and planning. This chapter explores these changes and the lessons from flood events.

This historical perspective reveals progress to have been painfully slow with sporadic lessons repeatedly 'learnt' in response to major events (*e.g.,* the 1917 floods on the Mississippi River promoting the need for basin scale planning to more recently the 2015/16 flooding in England highlighting the important of understanding the resilience of infrastructure networks). The common challenges faced throughout history to the present day are striking with many similar management actions adopted in response. This Chapter explores these and concludes by summarising the central challenges that remain and underpin the need for a new, more strategic approach to be adopted.

2.1 INTRODUCTION

The earliest civilisations recognised the need to, and were willing to, live alongside floods, organising their lives and communities around nature's rhythm. As populations grew so too did the desire to use the floodplain on a more permanent basis. People began to gather into larger villages, towns, and cities; there was a need to increase agricultural production. Floodplains became crowded with crops and permanent settlements. Inevitably, as flood-related damages became untenable, demand grew to control flood flows and defend areas from flooding. Early attempts typically focused on the construction of levees, diversion channels and dams. But despite the structural protection, and the high price in the degradation of ecosystem starved of the sediments and space upon which they rely, flood damage continued to increase. In response, flood managers recognised the need to act to 'reduce flood damages' and not just provide protection; but the inevitably limited resources limited progress and concepts of risk emerged to support the efficient prioritisation of flood management activities. This transition, towards risk-based decision-making, has been significant and continues to evolve towards an appropriately integrated 'whole systems' approach to building flood resilience (concepts that are returned to in Chapter 3).

This progression is summarised in Figure 2-1 and discussed in more detail, together with selected flood events that have played an influential role in forcing change, in the following sections.



Source: adapted from Sayers et al., 2014a

Figure 2-1 The evolution and development of flood management

2.2 A WILLINGNESS TO LIVE WITH FLOODS

Millennia ago, continuous adaptation permitted individuals and small groups, with little collective effort, to live in harmony with the flooding and progressive changes in sea level. The close relationship between people and the natural environment provided for sustainable living, as the rivers continued to enrich the land and support healthy ecosystems, local communities utilised the bountiful fish and wildlife populations they supported.

The first settlers of the floodplain quickly recognised that the best way to deal with occasional floods was to locate their settlements on the high ground near the river/coast or within the floodplain; often on naturally elevated ground created by outcrops of rock or first depositions of sediment by overflowing rivers (as seen through the churches and cathedrals of England, Murphy, 2009). When these locations were not high enough to permit activities to continue during times of flood, the settlers would move temporarily to higher ground outside of the floodplain until the flood passed. In some cases, where high ground was distant, their structures were elevated to allow the flood to pass underneath and for life to continue nearly as usual.

In the coastal parts of the Netherlands (in the provinces of Zeeland, Friesland, and Groningen), in southern Denmark and in Germany, artificial earth mounds were constructed within the floodplain (known as ‘terps’, Figure 2-2). These mounds provided safe havens at times of floods. Some historic Frisian settlements built artificial terpen up to 15m above the floodplain as they adapted to the observed sea level rise (Snyder, 2010). Similarly, in North America, there is evidence that as early as 100 BC large earthen mounds were placed strategically throughout some floodplains, especially in the Mississippi Valley, to serve as both ceremonial sites and areas of safety in times of flood. The terp-building period dates from 500 BC and continued as the primary means of managing flood risk until the widespread use of dykes to protect low-lying ground sometime around 1200AD (Snyder, 2010).



Source: unknown, https://en.wikipedia.org/wiki/Hooge,_Germany

Figure 2-2 An example of Terpen on de Hallig Hooge, Germany, 2005

2.3 A GROWING DEMAND TO USE THE FLOODPLAIN (2000 BC TO ~1000 AD)

As populations grew and people began to gather into larger villages, towns and cities, the natural functioning of floodplains became under increasing pressure as people were attracted to fertile soils, easy access to waterways and seaports for trade, and ease of construction on relatively flat topographies (*e.g.,* Jongman, *et al.,* 2014). As a result of this development, episodic, unmanaged, flooding became less acceptable. What was once seen to be an inconvenience became a major societal challenge. Some of the drivers of this change in perception during this period, and the flood management responses that they engendered, are elaborated below.

2.3.1 Ancient Egypt: Recognised the opportunities for agriculture

To access the fertile soils of the floodplains and provide food for the growing population, towns and cities required flood waters to be controlled. Early Egyptian civilisations (from as early as 5000 BC), for example, attempted to manage the waters of the Nile through elaborate irrigation and levee systems (Gulhati and Smith, 1967) and worshipped and sang hymns to Hapi, the life-giving god of the Nile. While the principal purpose of these control structures was to distribute water for agriculture, many such structures have a role in reducing the impact of floods. Government organisations oversaw the system development, recruitment of labour forces, and initiated scientific efforts to better understand the characteristics and occurrence of floods and droughts (although the source of the Nile was not known until the 19th Century; before then Ancient Egyptians believed it to be part of the great celestial ocean; a sea that enveloped the world both above the heavenly sphere and below the underworld, Mays, 2010). At the same time, in Mesopotamia (*e.g.,* Jacobsen and Adams, 1958, Mays, 2010), Roman and Greece (*e.g.,* Koutsoyiannis *et al.,* 2008, Mays, 2010), Iran (*e.g.,* Mays, 2010) Pakistan and northern India (*e.g.,* Naz and Subramanian, 2010), similar efforts were underway to ensure adequate water supplies for growing populations and, where possible, to link the irrigation works to efforts to reduce periodic flooding. In most cases, as with the Nile, small levees and dykes were built along riverbanks to protect crops and population centres. The need for adequate maintenance to prevent rapid deterioration of the levees was soon recognised together with the importance of sediment management to maintain the conveyance capacity of the channel and supply of fertile sediments to the floodplain. This tension between preventing floods and retaining a natural sediment regime marked the beginning of an enduring challenge.

2.3.2 Ancient Rome: Recognised the opportunities for strategic advantage

Access to waterways and the sea were important to the development of early empires (*e.g.,* Polanyi, 1963, Jongman, *et al.,* 2014). This led to the growth of towns around river crossings. In 43 AD, for example, Londinium (Figure 2-3, the starting point for today's London) was established on a low hill within the marshlands and at the point where the Thames was narrow enough to build a crossing but deep enough to handle sea-going marine vessels (McGlade, 2005) and its location on a busy river-crossing made it a perfect place for traders from across the Roman Empire to set up business (*e.g.,* Wallace, 2016). As Londinium grew,

flood defences and the communication of flood issues was an important strand and there was an understanding that some communities would be flooded during major river events and others would not. Clear roles and responsibilities started to be established with government officials holding responsibility for water management (Purcell, 1996).

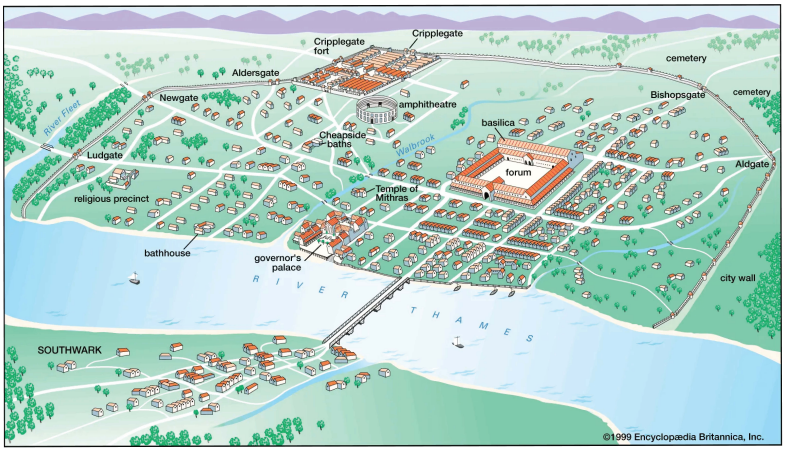


Image: Museum of London, Encyclopedia Britannica (open comms)

Figure 2-3 The Roman settlement of Londinium AD200 located at a strategic crossing of the Thames Estuary

2.3.3 Ancient China: Recognised opportunities for economic development

As far back as 4600 BC China was experiencing pressure to develop the floodplain and with it to control flood water (Qingzhou, 2002). Following a series of severe floods on the Yellow River, breaching poorly constructed dykes, mythology and fact combine to suggest that Emperor Yu (2205 BC) began to understand the concepts of system connectivity. In response, Yu, it is said, constructed nine separate diversion channels (lined with dykes through settled areas) to convey the flood waters of the Yellow River to other rivers and out to the sea, leading to the historical saying that "*Great Yu Controls the Waters"* (*e.g.,* Wu *et al.,* 2016). The period between 403 BC and 221 BC saw the construction of further major control structures, including the Dujiang Weir, Zhengguo Canal and Hong Ditch. During the Western Han Dynasty (206 BC-24 AD) development pressure continued to grow and the engineering proposals became increasingly elaborate to manage increasingly large and complex flood systems with decreasing success. In response, Jia Rang, a Chinese Government Official, published a new approach to flood management based on the philosophy '*Do not fight against water for land'* (Huang, 2014) where he proposed that space should be retained to *'retard'* flood flows and divert flood waters to less developed areas and farmland. The inferred suggestion is that levee construction should be a last resort. Although his advice went unheeded, and the focus largely remained on dyke construction, the concept of setting back secondary dykes to create storage capacity when the river was in flood was promoted (an early example of making *'room for the river'*, see later in this Chapter).

China continued to struggle to control its major rivers, especially the Yellow, throughout this period. Dyke heights were often increased to accommodate the rising river levels resulting from the increasingly restricted channel storage due to canalisation of the natural channel. The huge resources demanded for levee maintenance were difficult to find as finite resources

were often redirected during the frequent periods of war. Inevitably, flood events continued to cause significant impacts (for example, in 1194, multiple breaches along the main stem of the Yellow River led to widespread flooding and the creation of new channels flowing to adjacent river basins, Fuling, 1989). Increasingly, it was recognised that levees did not provide the only answer, that room should be left for flood waters, and that natural channels and the storage and retention provided by natural depressions should be used (Huang, 2014); a lesson that remains relevant today.

2.3.4 Ancient Japan: A need for centralised planning approaches

As the flood control structures became larger and more extensive, the need for centralised planning increased and so too did the need for resources, people, and funds, to support the flood control activity. In some places this led to the creation of more formal management groups. In Ancient Japan for example, the Yoro Code (the governing rules enacted in 757), stipulated that *"A provincial governor and district commissioners must patrol dykes along major rivers, and to order people to repair any damage after harvesting rice in autumn. For dyke breach, however, command urgent repair as soon as possible"* (Huang, 2014).

2.4 AN INTENSIFICATION OF FLOODPLAIN USE (~1000 AD TO 1900 AD)

From the Middle Ages to the UK Industrial Revolution the scale of the engineered responses continued to increase in attempt to control flood waters '*for the convenience of mankind'* (as set out in the original objects of the Institution of Civil Engineers, 1828 (ICE, 1828)). These efforts largely failed to prevent catastrophic floods and continued to bring problems of resources, maintenance, and ecosystem destruction. Some of the most important drives of flood management and responses are discussed below.

2.4.1 Northern Europe: Land drainage for agricultural production

Within the fertile coastal wetlands of Northern Europe, particularly the Netherlands and the east coast of England, land started to be drained in earnest for agricultural production (*e.g.,* Hoeksema, 2006; Knitt, 2007). The landowners in England and the Netherlands became expert at providing engineered dykes to protect the land from fluvial and coastal flooding whilst building extensive drainage networks to prevent internal waterlogging. During the 1630s, landowners, headed by the Earl of Bedford, set out to drain the east coast fens of England so that the peat soils could be used for summer cultivation and to prevent serious winter flooding. As a result, the 'Great Fen' in England's Cambridgeshire and Norfolk region was drained and protected by dykes (improving and extending many schemes initiated by the Romans). The construction of this vast network of major and minor drains carried the major rivers of England that drain east through East Anglia and exposed large areas of fertile agricultural land. In the Netherlands, a similar transformation of the coastal wetlands had started in the early 9th and 10th centuries, and by the 16th large-scale land reclamation and attendant dyke construction followed (*e.g.,* Van der Ven, 2004). An unintended consequence was the shrinking of peat as it dried and oxidised, resulting in a drop of land levels below the rivers and drains, and renewed seasonal flooding. Windpumps (Figure 2-4) were added to

pump water to high level carriers (embanked water courses carrying the main river high above the level of the surrounding floodplain) to take the drained water to the sea. Increased pumping was needed to lift the water an ever-increasing distance as the drained land subsided, through the consolidation of the underlying peat, leading to an increased threat of breach to those living and working in the natural floodplain; a risk realised many times.



Image: Wicken Fen, courtesy National Trust

Figure 2-4 Typical of the coastal wetlands of the Netherlands and England, a windmill lifts water to channelised rivers that carry water at a high level above the floodplain to the coast.

2.4.2 North America: Larger dams and levees to control flood waters

Small farm dams had often been used to store flood waters for release once the rain had passed, but the size of these dams was limited by the lack of technical knowledge and practical know-how. In the seventeenth century a better understanding of the mechanics of materials led to the growth in the size of dams and their use for both water supply and flood storage increased. By the end of the eighteenth century the first large-scale concrete gravity dams emerged, perhaps most notably the Lower Crystal Springs Dam, California, providing a significant example of a concrete gravity dam that set a precedence for future dam design. Built in 1888 near the San Andreas Fault, the Lower Crystal Springs Dam withstood the 1906 San Francisco earthquake with little damage. Spanish success in Europe carried over to settlements in central North America where small flood control dams began to appear (*e.g.,* Chanson, 1995). The industrial revolution increased the use of hydro-dams for power with some of the structures designed to help address periodic flooding (*e.g.,* Altinbilek, 2002).

Further increases in scientific knowledge and availability of monitoring tools led to better understanding of river mechanics, hydrology, and hydraulics. Development in and around cities increased the flow into nearby rivers, and the clearing of land for agriculture similarly increased runoff. Exploration of the North American continent brought greater attention to

the development of information about rivers and how flooding might be better controlled. In response, in 1860, two US engineers, Captain Humphreys and Lieutenant Abbott of the US Army Corps of Engineers (Humphreys and Abbott, 1861), conducted a major study of the hydraulics of the Mississippi River concluding that while flooding would continue to be a problem, construction of levees would dramatically reduce the impact of these events. This 'levees only' approach would guide the mitigation activities in the Mississippi River basin for the next 65 years (Figure 2-5).



Image: US Army Corps of Engineers, New Orleans District

Figure 2-5 Material is delivered to an early levee construction on the Mississippi River (circa 1928)

As lessons were learnt the design/management practice for levees improved. To prevent the continuing erosion of the riverbanks, for example, revetments of tree branches and rock were placed on the slopes of riverside levees and at critical river bends to limit surface erosion and scour. Rock and wood dykes were built into the streams to concentrate low flows in a defined channel thereby increasing the ability of the rivers to transport sediment downstream whilst maintaining larger channel cross-sections for flood flows.

2.4.3 Northern Europe: Paying for construction and maintenance of flood control infrastructure

The rising cost of building and maintaining levees was a problem across the world and Europe was no exception. In England, for example, the vital need to maintain dykes and embankments was appreciated, and landowners were taxed to pay for this work: this system had been established "*from time immemorial"* when it was confirmed by Henry III in 1252 (Sayers *et al.,* 2001). King Henry II introduced a tax (or a *'scot'*; Fry, 1867) for the maintenance of the coastal dyke systems in the agricultural areas on the south coast of England. Only those living in the floodplain, and hence benefiting from the flood defences, paid the tax whilst those living in the surrounding hills were considered to get away '*scot free*'; an early example of hypothecation! In contrast, 'Gentlemen Adventurers' (private

venture capitalists), funded the construction of the large-scale drainage of the Fens in England (discussed previously) and were rewarded with large tracts of the resulting farmland (*e.g.,* Darby, 2011). Around the same time (*i.e.,* the 13th century) Water Boards were established in the Netherlands and held each Dutch community accountable for the upkeep of their own canals and protective dykes (Van Koningsveld *et al.,* 2008).

Even with increases in technical ability and greater resource availability, those responsible for flood control struggled with the maintenance and periodic upgrade of levees, dykes, channels, and pumps. Nature was relentless in its attack on the structures. Structures that were not properly maintained were subject to collapse and continuing development in catchments brought about increased flows that strained the ability of locals to raise or strengthen structures. Something had to change.

2.5 HEURISTIC PROGRESS IN FLOOD MANAGEMENT (~1900 AD TO PRESENT DAY)

Since the early developments set out in the preceding sections, flood management approaches have continued to evolve through a heuristic process of learning lessons from observations of specific flood events. Some of the most influential of these events are discussed below.

2.5.1 Influential floods and lessons learnt: 1900 to 1950s

1917 and 1927 floods in the US and the 1931 flood in China: Promoted an awareness of the need for basin scale coordination

At the dawn of the twentieth century, the focus remained aimed at controlling floods. Continued increases in population and the agricultural potential of floodplains continued to emphasize the need to keep flood waters away from both valuable farmland and urban areas. In general flood control was a local responsibility and flood control organisations within the same watersheds only loosely coordinated their actions. Their focus was on protecting the area for which they were responsible no matter what the impact might be on other locations.

Following the 1917 floods in the Mississippi River and the Sacramento River basins in the US, federal government started to recognise that existing, siloed, local governance structures were simply unable to deal with such major basin-wide floods and they sought federal fiscal support (Galloway, 2012). In 1927, heavy storms across the Midwest led again to widespread floods across the lower Mississippi Valley that eventually breached a locally controlled levee system and displaced many thousands of people from their homes and lands for several months (Barry, 2007). It was labelled a national tragedy. These combined events brought significant change. In 1928, by act of Congress, the US federal government assumed responsibility for the construction and major maintenance of flood control structures in the lower Mississippi Valley. The so-called *'levees only'* policy was closely examined and deemed to be insufficient to deal with the challenge of major floods (Myers and White, 1993). A *comprehensive plan for flood control* was to include strengthening of the levees, improvement of the channel to provide for natural maintenance; cutoffs of river bends that were seen to be delaying the flow of waters to the Gulf of Mexico, floodways to serve as

pressure relief valves during major events, and flood storage dams on the Mississippi River tributaries (Galloway, 2012).

A major flood in China in 1931 is generally considered the deadliest natural disaster ever recorded. The number of human deaths has been estimated to be from 1 million to as many as 4 million. These widespread floods were experienced across the three major rivers: the Yellow, Yangtze, and Huai. The Yellow River flooded first between July and November 1931; killing 1-2 million people and leaving 80 million homeless. The worst period for the Yangtze was from July to August 1931 and affected 28.5 million people. The Yangtze along with the Huai River flood rendered Nanjing city, capital of China at the time, an island. The high-water mark was reached on 19th August at Hankou with the level exceeding 53ft (16m) above normal. These devastating floods were the catalyst to a more organised response to flood management in China. As one example, following the flood, the Huai River Conservancy Commission, which was formed in 1929, and was charged with immediately addressing the flood problems (GIWP, 2013). The lack of funding and support limited its effectiveness. China continued to experience severe floods during the 1930s, 40s and 50s. As part of the early years of the People's Republic of China, action was taken to improve the capacity of flood control and land drainage systems. The measures typically included river dredging, raising, and reinforcing dykes, connecting polder areas, and building sluices. In some river sections reservoirs were constructed and flood storage and retention areas developed. Increasingly more scientific and technological methods were used to support the design of control and storage works, often achieving immediate, but not always lasting, success (GIWP, 2013).

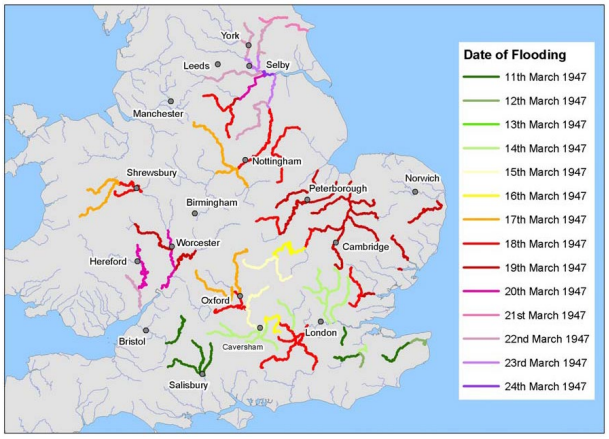
Although limited in the context of a risk management approach, this was important progress in thinking that promoted the need for basin scale infrastructure and coordination of action.

1936, 1937 and 1951 floods in the US: Reinforced flood management as a national responsibility

Floods continued to occur across the United States in 1936, 1937 and 1951, causing major property damage and widespread loss of life. Following the floods of 1936, the US Congress passed legislation establishing that *"...flood control is a proper activity of the Federal Government…the Federal Government should participate if the benefits to whomsoever they accrue are in excess of the estimated costs..."* (US 1936 Flood Control Act). This Act placed responsibility for flood control at the national (federal) level (Arnold, 1988). Immediately following the passage of this Act, the US Army Corps of Engineers (USACE) began the design and construction of dam and levee projects across the nation with a focus on a high standard of protection, providing the economic benefits could be demonstrated to be higher than the costs. To be eligible for Federal funding any flood control project had to demonstrate, prior to construction, that state or local interests would (a) provide without cost to the United States all rights in land and other property necessary for the construction of the project; (b) hold the government free from damages in connection with construction; (c) maintain and operate all the works after completion in accordance with regulations prescribed by the Secretary of War (the so-called *ABC requirements*, Arnold, 1988).

1947 and 1953 flood events in Europe: Promoted the need for clear roles and responsibilities and better warning systems

In March 1947, river floods occurred across much of Europe. The flooding was triggered by the rapid thaw of deep snow lying on a frozen catchment after one of the coldest and snowiest winters on record. The thaw was triggered by the arrival of a succession of south-westerly depressions, each bringing significant additional rainfall. Nearly all the main rivers in the south, midlands, and the northeast of England were in flood with thirty out of forty English counties impacted over a two-week period (Figure 2-6). Tens of thousands of people were temporarily displaced from their homes, and thousands of acres of crops lost (Barker, 1948).



Source: RMS, 2007

Figure 2-6 Widespread fluvial flooding in March 1947 followed in the wake of rapid snow melt and heavy rains. The flood event led to increased investment to protect agricultural land in response to the World War II food shortages.

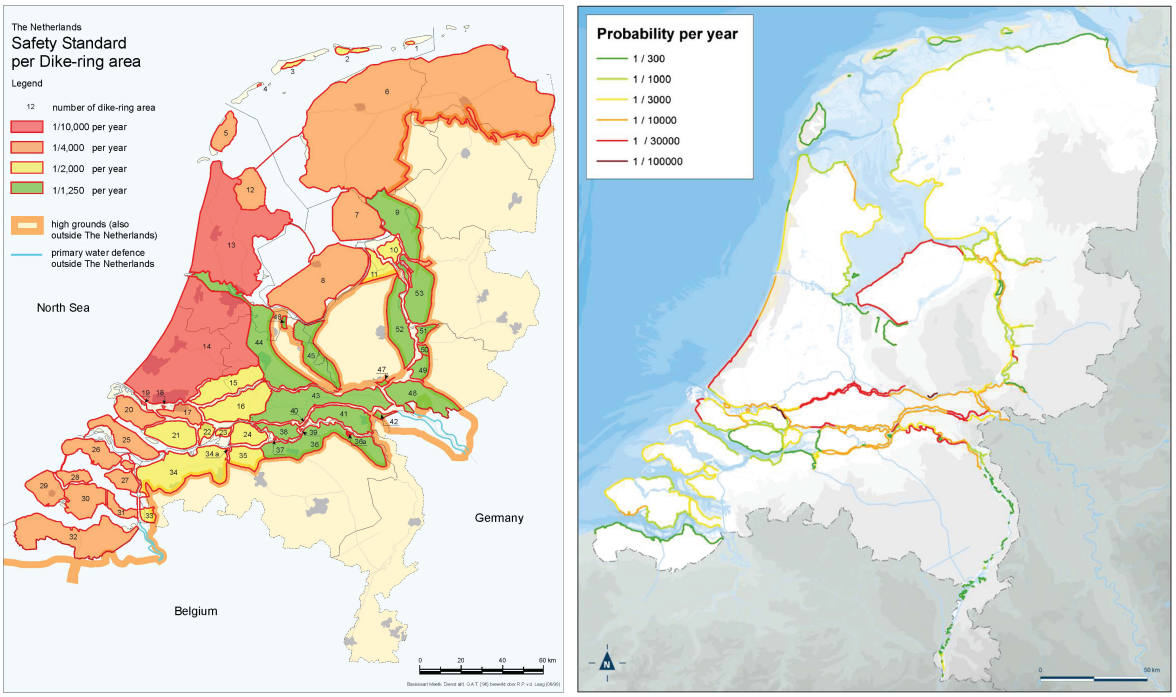
Shortly after the 1947 fluvial floods, Europe experienced devastating coastal floods in 1953 when a surge tide swept south through the North Sea overtopping and breaching many defences in England, the Netherlands and Belgium. The storm was at its peak during the night and with little or no warning. Flood waters breached defences and washed away homes as people slept. An estimated 2400 people lost their lives across Europe. On Canvey Island (Figure 2-7), at the mouth of the Thames Estuary, 58 people lost their lives as the defences breached (Pollard, 1978). The net effect of these floods was to emphasise the fragility of structural defences; yet, as throughout history, the response was to increase the investment in levees, floodwalls, floodways, and other structures. The dramatic inadequacies in early warning systems were acted upon and initiated the UK's national Storm Tide Warning Service (Johnson *et al.,* 2005), a service that continues today.



Photographer: Dennis Lee Royle (reproduced under licence)
Left: Seen from the air, 2 February 1953. Right: Attempts to raise and strengthen the embankment before the next high tide.

Figure 2-7 1953 Tidal Surge floods Canvey Island – a vulnerable community with only one route of escape and no warning. They had little chance when the 1953 surge breached defences in the night.

The 1953 flood had a profound impact on the perception of flood risk in both England and in the Netherlands (where 1835 people lost their lives). The Delta Committee (Dantzig, 1956) in the Netherlands and the Waverley Committee (Waverley, 1954) in England were both commissioned to review what happened and propose a new way forward. Both committees reported a need to establish clear responsibilities for flood defence and initiated discussions as to what was considered an acceptable level of risk. In the Netherlands, a national scale benefit-cost analysis was undertaken and used to establish standards for each protective dyke-ring for the first time (the so-called Delta Plan, Figure 2-8). The water-related planning processes in the Netherlands were reorganised and defined national and local responsibilities introduced. The first Delta Committee set out the legal framework for the periodic review and update of the Delta Plan. In 2009, in response to the national programme Adaptation of Spatial Planning to Climate Change that highlighted the largest challenges from climate change relate to flood risk management and freshwater resource management (*e.g.,* Kwadijk *et al.,* 2006, Klijn *et al.,* 2015), the second Delta Committee was established (Delta Committee, 2008). On 29th November 2011, the Delta Act was unanimously accepted in the Dutch Senate including the allocation of €1bn per year in the Delta Fund (Deltacommissaris, 2011 *apud* van Herk *et al.,* 2015) and through the Delta Programme (2011) strives to balance investment in protection, prevention and preparedness whilst taking account of future change (Gersonius *et al.,* 2012). Given the context in the Netherlands the emphasis in the Dutch policy remains on prevention, with safety standards derived from this national risk assessment translated into protection standards in support of this focus (*e.g.,* Jonkman *et al.,* 2011).



Left: Following the 1953 surge event the first Delta Committee in the Netherlands established acceptable standards of protection for each coastal dyke-ring in the Netherlands with standards for other dyke-rings subsequently developed during the 1960s and 1970s (Rijkswaterstaat). These criteria are formulated as the probability of exceedance of certain hydraulic design conditions that defences should withstand safely. Right: Proposed new protection standards based on findings of second Delta Committee (Rijkswaterstaat, 2013) that are formulated as an acceptable probability of flooding due to defence failure. Source: Rijkswaterstaat

Figure 2-8 Netherlands: Flood protection standards formally adopted in January 2017

2.5.2 Influential floods and lessons learnt: 1960s to 2016

The intense period of flood events between the 1930s and 1950s forced western governments to rethink flood management. Increasingly, academics and practitioners recognised that structural flood control measures (when used on their own) were, often, exacerbating the consequences of floods. This recognition was an important step in developing the detail of the modern flood risk management approach that has been, and continues to be, shaped by flood events. Some of the most important of these recent events are discussed below.

US, 1993 and 1997 Mississippi: Promoted the need to acknowledge uncertainty

The 1993 Mississippi River flood was the most damaging US flood of the 20th century in economic terms (Galloway, 1995). Following this event, flood risk discussions within the US began in earnest in 1994 and highlighted the need for a change in approach (*e.g.,* Galloway, 2005). The discussions focused on the uncertainties connected with the hydrology of flood events and how this uncertainty should be handled in studies being conducted by the US Army Corps of Engineers (USACE). In 1996 the USACE issued guidelines for the conduct of the hydrology and related economic aspects of studies that would assess the justification for new flood control projects (USACE, 1996) and lead to the seminal publication by the National Research Council into risk analysis and uncertainty (National Research Council , NRC, 2000). Although these documents recognised the need to extend the analysis to include a range of natural events (including those above the notional design standard of a defence),

little was done until after the New Orleans floods in 2005 (see later). Despite these advances in thinking no efforts were made to use risk methodologies to guide flood damage reduction activities in the field. At this point in time, the concept of flood risk management was not widely accepted and, in fact, was questioned by several organisations representing floodplain interests.

Europe, 1993, 1995, 1997, 1998 and 2000: Reinforced the demand for a basin-wide and strategic approach using a combination of structural and non-structural approaches

Major floods on the Rhine River in 1993, again on the Rhine in 1995 and 1997 and in the UK in 1998 and 2000 brought increased attention to the growing challenge of flooding (Marsh and Dale, 2002; Kunzewicz *et al.,* 2013). As a result, there was considerable activity as both academic and governmental organisations struggled to provide solutions to growing flood damages across Europe. In 1996, the European Union (EU) launched a three-year research project River Basin Modelling, Management and Flood Mitigation (RIBAMOD, Samuels, 1999), to, among other things, identify the past difficulties in floodplain management, current best practices, and areas for further research. The RIBAMOD process led to additional activities within the European Community that continued the exploration of new approaches, including risk, to deal with flood challenges. In 2000, the EU issued its Water Framework Directive (WFD) addressing the steps necessary to reduce pollution in European rivers and establish river basin management as the framework for cooperative efforts to accomplish the objectives of the Directive (EC, 2006).

In 2001, the UK Government commissioned an independent review by the Institution of Civil Engineers (ICE). The review, entitled Learning to Live with Rivers (Fleming *et al.,* 2001), specifically criticised the reluctance to use numerical computer models to support decision-making and the inadequate representation of the dynamic effects of land use, catchment processes and climatic variability. The review concluded that *'only by working with the natural river basin response and providing the necessary storage, attenuation and discharge capacity, can sustainable flood risk management be achieved'* and that '*floods can only be managed, not prevented, and the community must learn to live with rivers*.' The lack of a structural understanding was recognised, leading to the adoption of the Source-Pathway-Receptor model (DETR, 2000, and its translation to flood management, Sayers *et al.,* 2002a,b) together with need for structured hierarchal risk assessment method (Sayers and Meadowcroft, 2005a) and an ability to assess flood risk at a national scale to support the national prioritisation of investment in flood risk (Hall *et al.,* 2003b; Gouldby *et al.,* 2008).

In 2003, the water directors of the European Union noted that, "flood protection is never absolute and things can go wrong. The question regularly arises as to what safety is available at what price, and how much of the remaining risk must be accepted by society. Risk management will be the appropriate method to deal with this challenge". They further found that mitigation and non-structural measures *"tend to be potentially more efficient and long-term more sustainable solutions…* (Water Directors of the EU, 2003).

In 2004, the European Commission (EC) issued a communication to the Council and the Parliament proposing that Member States and the Commission work together *"…to develop*

and implement a coordinated flood prevention, protection and mitigation action programme." The communication highlighted the need for the development of flood risk management plans for each river basin within the EU and outlined steps necessary to carry out such activity. At the same time, the Commission approved the major research project, FLOODsite (Samuels *et al.,* 2010), to examine, in a five-year programme, the physical, environmental, and socio-economic aspects of floods. FLOODsite launched projects throughout Europe to follow-up on the work of RIBAMOD to further advance the knowledge of twenty-first century flood challenges and in 2009 concluded that: *"Methods and tools are available and are being continuously improved to facilitate development of basin-level flood risk management plans and flood hazard and risk maps…. Different approaches will be required for different areas with varying levels of detail and data requirements. ... Public participation and local knowledge will be invaluable in the conduct of risk management activities although the optimal method of engagement will vary depending on the country and local conditions."*

In 2006, the Dutch Cabinet initiated a major programme of investment to re-engineer the river system and improve the safety of four million people in the Dutch delta region. The Spatial Planning Key Decision (SPKD) project became known as the *'Room for the River'* programme and was active from 2006 to 2015 (Woorden, 2006; Ministry of Infrastructure and the Environment, 2006), focusing on four rivers: the Rhine, the Meuse, the Waal, and the Ijssel. The programme sought (and delivered) various schemes to reinstate temporary storage areas, lower and widened the active floodplains, and set back and reinforce dykes at many locations within the Netherlands (Rijkswaterstaat, 2016).

Following additional flood events in Europe during the first decade of the twenty-first century, the European Parliament and Council issued a directive on the *"assessment and management of flood risks"* (EC, 2007). The so-called *'Floods Directive*' established a framework for this assessment and management, with the goal of reducing adverse consequences of flooding to human health, the environment, and cultural-economic activity in the European Community. As a first step, the directive required all Member States to conduct a preliminary flood risk assessment of the river basins including the assessment of the potential impacts of climate change. Flood hazard and flood risk maps and flood risk management plans are also required. To support the implementation of the directive a working group on floods (*'Working Group F'*) was established under the Common Implementation Strategy to enable an exchange of lessons and good practice approaches to implementing the directive.

China 1991 and 1998: A major reassessment of policy and planning approaches in recognition of the need for a more efficient and effective approach

Two-thirds of the land area in China is prone to flooding. The economically developed eastern and southern regions, which are most severely threatened by floods, contain around half of the national population, one-third of the national cultivated land and produce two-thirds of the national industrial and agricultural outputs (Cheng, 2005). Despite increased investment in flood control through this period, flood losses continue to increase (echoing the experience in Europe and the US). After the major 1991 floods in the Huai River and Taihu

Lake, and the 1998 flood in the Yangtze, Songhua and Nenjiang Rivers, China began to seek new approaches. The desire of the government to support both economic development and protect the environment promoted a change in philosophy from a primary emphasis on structural flood control to one that had a greater emphasis on emergency planning and preparedness. This included accepting the need to provide a variable standard of defence depending on need. Along major rivers, levee system designs started to focus on accommodating the largest flood within the most recent 100 years, whereas for major sea dykes the designs sought to accommodate the worst storms experienced in the past 50 years. In middle and small-sized rivers flood defence standards focused on smaller 'normal' floods (General Institute of Water Resources and Hydropower Planning, China GIWP, 2012, 2013).

After the 1998 flood in the Yangtze River, China made strategic adjustments to its approach as the economic, natural, and social impacts of flooding became better understood (Cheng, 2005). The imperative for the shift was reinforced by this experience and an edict from the national government—the so-called "32-word policy" (Box 2-1). was initiated by the Ministry of Water Resources (MWR) including the return of polder lands to lake storage, resettlement of people from high-risk flood-prone land, and reforestation of upland areas—*i.e.,* a suite of non-structural flood management measures.

Box 2-1 The "32-Word" Policy

This policy statement, or more correctly a policy of 32 Chinese characters, was a quick response to the 1998 floods. It comprises eight directives which can be translated as follows:

- Protect the mountains to plant trees.
- Return arable land to forests.
- Demolish polders to release floods.
- Transform farmland into lakes.
- Contribute labour supply.
- Relocate people in new townships.
- Reinforce levees of main stem rivers.
- Dredge river channels and lakes.

Although these are little more than slogans, the underlying intention was to reforest upper basins, recover lands that had been reclaimed from lakes and floodplains, and restore flood storage lost to sediment deposition. Source: H. Wan. 2003.

The developing Chinese approach now focuses on regulating flooding by employing both structural and non-structural measures that include reforming social and economic development to be more resilient to flooding (Cheng, 2006; Sun *et al.,* 2012; Sayers *et al.,* 2014a, 2017d). As part of the shift from flood control to flood risk management, the Chinese Government began to promote risk awareness (through a national programme of flood hazard-mapping), enhance the socially focused management of flood control areas, and has moved away from attempting to eliminate floods totally, recognising the continued existence of a residual risk (GIWP, 2012). Under this approach, the focus is on protecting people and property, and minimising damage when floods do occur.

Asia, 2004, Indian Ocean (Boxing Day) tsunami: Promoted better warning, emergency planning and spatial planning as central to disaster risk reduction

An earthquake in the Indian Ocean on 26th December 2004 triggered a series of devastating tsunamis along the coasts of most landmasses bordering the Indian Ocean (Lay *et al.,* 2005), killing around 230,000 people in fourteen countries, and inundating coastal communities with waves up to 30m high. Indonesia was the hardest hit, together with Sri Lanka, India, and Thailand. This event provided many lessons, including the two most critical lessons for flood managers. The first was '*early warning leads to early action*'. Given even the shortest of lead times people can act to reduce consequences. The effectiveness of the action taken relies on the understanding of the risk and hence the motivation to appropriately prepare. Prior to the Indian tsunami neither early warning systems nor awareness campaigns were in place. The second crucial lesson reflected the loss of critical infrastructure during the event. Hospitals, transportation networks and community centres were often sited in the most exposed locations and lost at the time when they were most needed. Since 2004, considerable effort has been devoted to developing sophisticated early warning systems (UNESCO, 2006) and mapping the probability of flooding to inform spatial planning and emergency response decisions. In 2012, the system alerted the Indian islands on Andaman and Nicobar following the Banda Aceh earthquake (of 8.6 magnitude, Pollitz *et al.,* 2012); but media reports suggest a combination of a failure to sound the tsunami warning sirens in Aceh (due to power failure) and congestion of evacuation routes undermined the performance. The success of the warning systems is yet to be fully realised or tested, but it will, inevitably be.

2005, New Orleans, US: A recognition that levees fail and need for a better understanding of levee performance and wider acceptance of a risk management (rather than defence-based) approach

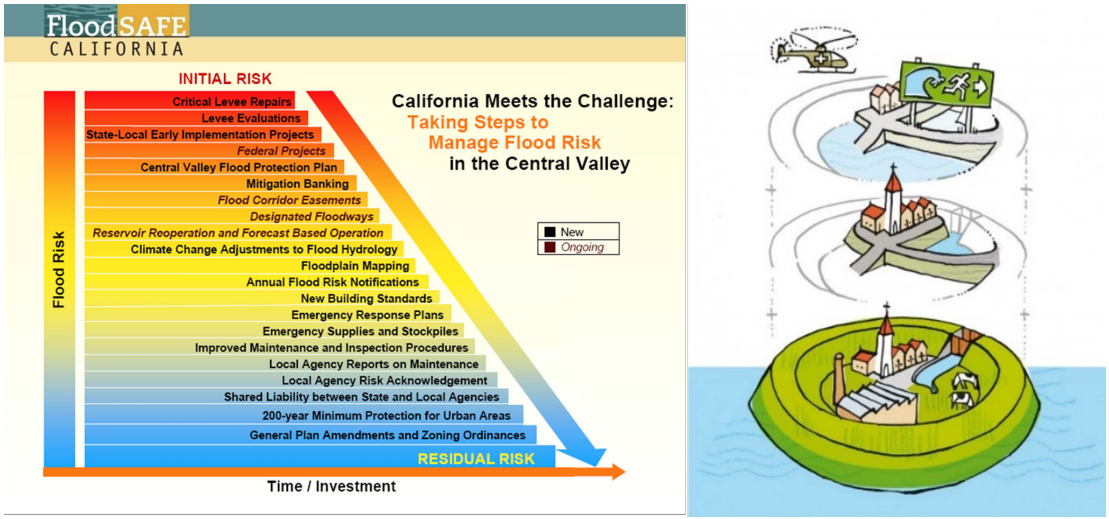
Hurricane Katrina hit the Gulf Coast of the United States in June 2005. The flooding of New Orleans that followed had devastating consequences, with an estimated 1,464 losing their lives (Jonkman *et al.,* 2009) and economic damages exceeding $150bn (Burton and Hicks, 2005). The review of the lessons that followed was highly critical, highlighting *'incompetent engineering and a reliance on a single approach of complete protection from flooding'* as important contributors (Jonkman *et al.,* 2005 *apud* Zevenbergen *et al.,* 2013). The assessment of the lessons highlighted three important strategic factors: (i) the high rate of return on investments bias decisions towards a shorter time horizon and thus the acceptance of relatively low protection levels; (ii) decentralised building policy (with a high degree of individual autonomy) creates a strong impulse for flexible economic growth, but can increase vulnerability (and bias flood management actions away from collective protection paid by general taxation towards individual choice and a focus on transferring risk through insurance), and (iii) the assumption was made that people will take the personal initiative to leave the flood-prone area (*i.e.,* in the case of New Orleans, the city) to save their lives, leaving behind their properties, but due to a lack of information and the lack of transportation, they could not evacuate.

Forensic assessment of the causes of levee failure in New Orleans brought into sharp focus the limited understanding of the integrity of existing levee systems throughout the United

States (and in other countries) and the need for new methods and techniques to better assess their condition (*e.g.,* Cigler, 2007). The preliminary analysis into the structural condition of protection measures across the United States that followed Katrina, for example, indicated that many of the tens of thousands of kilometres of levees were in an unsatisfactory condition and that the condition of many more was unknown (Link and Harris, 2007; National Committee on Levee Safety, NCLS, 2009). This experience prompted the now widely repeated phrase *'there are only two types of levees: those that have failed and those that will fail.'*

In May 2006, the US Army Corps of Engineers, and the Federal Emergency Management Agency (FEMA) established a national flood risk management program *"…to integrate and synchronize the ongoing, diverse flood risk management projects, programs and authorities of the… Federal agencies, state organizations and regional and local agencies.*" (USACE, 2011). As one part of this effort, FEMA added emphasis to its National Flood Insurance Program by increasing its efforts to improve risk identification and communication (NRC, 2013). The significance of the impacts led to the focus on *'resilience'* (NRC, 2012a, b); a concept that continues to evolve today (as discussed later in Chapter 3).

Hurricane Katrina led to a reassessment of the organisational structures in the United States. The long-standing federal leadership of flood control and flood damage reduction activities within the United States was revisited and the federal organisations identified that flood risk management should be the joint responsibility of all levels of government and those who live, work, or influence activity in flood-risk areas. The review emphasised that flood-risk management will require not only consideration of structural measures to deal with ongoing and future risks but will involve full use of available non-structural techniques (Link and Harris, 2007). Despite this broader focus within policy, the adopted flood management activities ultimately focused on flood protection; with the 15 billion US$ committed to providing new protection infrastructure for New Orleans; an outcome that highlights the continued central role of flood defence and the difficulty in delivering more radical solutions (for example, relocation). Figure 2-9 illustrates this conceptual move to a more broadly-based approach in the aftermath of Hurricane Katrina, the promotion of a multi-faceted approach to 'buying down' flood risk that emerged from these discussions; an approach that echoed the concepts of a 'portfolio-based approach' promoted in the aftermath of the 2000 floods in England (Evans *et al.,* 2004a&b) and the Multi-Layer Safety Approach promoted in the Netherlands (Ven *et al.,* 2011).



Left: The risk reduction concept as applied to the FloodSAFE program of the state of California, US (courtesy of California Department of Water Resources) Right: Multi-Layer Safety Approach (Netherlands)

Figure 2-9 The application of multiple actions to reduce risk

2007 floods, UK: Promoted the need to consider all sources of flooding, spatial coherence of events and need to protect important infrastructure services

Following a major flood in 2007, the British Government commissioned Sir Michael Pitt (the Pitt Review, Cabinet Office, 2007) to review the lessons learned from this event. The subsequent report to the government discussed both technical and organisational shortcomings. It identified that having a legislative framework for flood risk management was fundamental, noting that *"the management of flood risk requires concerted action by public and private bodies, and this must be properly supported by appropriate legislation that would address all forms of flooding"*. This was an important lesson highlighting that floods are generated by many mechanisms, and an understanding of each is required to manage flood risk effectively. Until then coastal and fluvial (river) flooding had been the responsibility of one organisation and groundwater, and perhaps more importantly, pluvial (direct rainfall) flooding another. The Pitt Review led directly to the development of Surface Water Management Plans in the UK, a layer of planning where all sources of flooding are considered and an attempt is made to develop integrated management strategies. The 2007 event highlighted the importance of protecting infrastructure services, and how impacts cascade when these fail (Figure 2-10). This observation reinforced the debate about need to the transition towards a resilient built environment (*e.g.,* Bosher *et al.,* 2007).



Source: The Floods - 10 years on (gloucestershirelive.co.uk)

Figure 2-10 Castlemead electrical substation in Gloucester (UK) during the River Severn floods of 2007

2010 Pakistan, 2011 tsunami, Japan and the 2011 Mississippi River floods and 2012 Storm Sandy USA: Reinforced the importance of spatial planning and the need to build-in resilience

In July 2010, La Niña-affected monsoon rains began to fall on most northern sections of Pakistan and the upper reaches of the Indus River. The Indus River from north to south went into exceptional flood stages, driving people out of their homes, disrupting road, rail, and electronic connectivity. By the end of September, Pakistan had seen over 6 million people displaced, over 1.8 million homes and 1.4 million acres of cropland destroyed, 1,700 people killed and damages exceeding $43bn estimated to have occurred. The unusual intensity of local rainfall (in some places more than 200mm in 24 hours) coupled with the exceptionally high levels of the Indus, flooded areas that were ill-prepared for such an event.

The Impact of the March 2011 Japanese tsunami was significant. Over 15,000 people were killed, and entire communities destroyed, when the tsunami generated by a 9.0 Richter Scale-earthquake generated a tsunami that devastated villages and cities. In the most critical case, the design of the Fukushima Nuclear Power Plant failed to prevent the tsunami destroying the critical power systems needed to maintain the safety of the plant complex. Non-structural measures such as early warning and evacuation systems prevented even larger loss of life to a public that, for the most part, understood the risk that they faced from a tsunami. Following the Indian Ocean tsunami in 2005, the Japanese government undertook a review of their tsunami protection system and initiated a series of actions to address shortfalls that surfaced in the review. The time needed to carry out major infrastructure modification is long and not everything recommended by the review had been completed when the 2011 tsunami hit. Since the 2011 tsunami continued investment in major flood defences, land raising, advanced warning, and a host of other interventions, has been on a colossal scale ($15bn US dollars, Dutch Mission, 2017).

Major rainfall events throughout the US Midwest in April and May 2011 brought the lower Mississippi River to its highest stages in over seven decades, threatening the stability of the major federal levee works along the river. Through use of floodways and backwater storage areas in the lower Mississippi Valley, a flood of 79,000m^3s (as compared to the design flood of 85,000m^3s) was successfully passed into the Gulf of Mexico and no areas, including New Orleans, protected by the federal system were flooded. Many areas between the federal levees and the river and along tributaries to the Mississippi and in backwater areas where low-level levees (*e.g.,* 100-year) provide protection were flooded, leading to considerable loss of property and cropland. Most of these areas have been protected from lower stage, more frequent floods over the years and unknowing residents took for granted that their protection would extend to larger floods. In addition, considerable concern was expressed in the use of floodways where agricultural land existed even though the government had previously acquired the rights to flood in exceptional flood conditions. The Mississippi flood of 2011 brought national attention once again to the approach being taken to deal with occupancy of the floodplain and responsibility for flood protection. Writers in newspapers across the country opined that it was time to rethink flood control.

In 2012, Hurricane Sandy caused widespread flooding and wind damage along the entire eastern seaboard of the US from Florida to Maine, with particularly severe damage in New Jersey and New York. In New York City, streets and tunnels were flooded, and subway lines power cut.

All these events emphasized the need to manage 'exposure' through better spatial planning choices and the need to prevent risks escalating through cascading impacts. In response the focus of the flood management approach changed – promoting the adoption of a resilience paradigm (although primarily from a relatively narrow perspective of an ability to resist and recover – see later in Chapter 3).

2013/4 and 2015/16 floods UK: Led to the recognition that 'the design storm is dead' and re-emphasised the importance of natural flood management

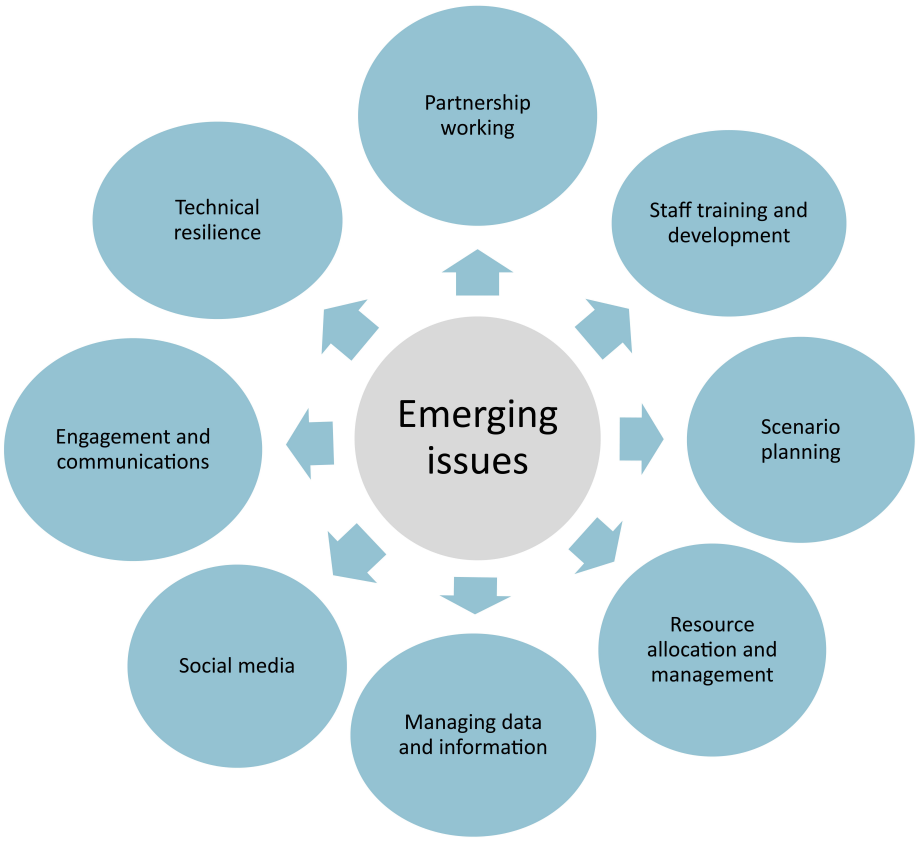
In 2013/14, a sequence of major storms were responsible for severe and prolonged flooding across much of England. The floods damaged between 8-10,000 residential properties with power disruption affecting 1 million customers, and led to the closure of Gatwick Airport and the disruption of rail and road travel, included the severing of the railway line to West Devon and Cornwall (Fenn *et al.,* 2016). At the coast, a storm surge, larger than that experienced during the devastating 1953 floods, coincided with high spring tides. On 6/7 December 2013, sequences of wind and wave events battered the south and south-west coasts, including unusually energetic, long-period swell waves (Palmer *et al.,* 2014), and caused extensive damage to coastal defences, including natural defences such as Chesil Beach (requiring repairs costing ~£140m). Inland, in late December and early January successive deep cyclonic systems led to rainfall that triggered flash flooding, particularly in south-west England. The discharge in the Thames at Kingston, for example, remained above 275m^3s^{-1} for longer than in any previous recorded flood episode. The succession of events saturated the ground leading to extensive and protracted flooding and the associated disruption of transport

and agriculture, which cut off some towns in the Somerset Levels (Met Office and CEH, 2014).

During the winter of 2015/6 a second period of remarkedly persistent rainfall began in early-November 2015 and lasting around fourteen weeks brought severe, extensive, and protracted flooding. Many existing rainfall and seasonal temperature records were eclipsed during this period and, most notably, maximum recorded river flows were exceeded over a substantial proportion of the country. As in 2013/14, the magnitude, persistence and repetitive nature of the flooding had major adverse impacts on communities, infrastructure, agriculture, and a host of other sectors of the economy (Marsh *et al.,* 2016).

These events prompted a reappraisal of the way the severity of storms is considered. During 2013/4 and 2015/6 the severity of the flooding was not in response to a single, high magnitude, event (for which classical extreme value theory would be relevant), but because the floods arose in response to repeat events. This highlighted the sensitivity of flood infrastructure (both green, grey, hybrid) to multiple storm events (both clustered (correlated) and sequenced (uncorrelated) storm events). This recognition exposed the inadequacies of conventional flood defence design approaches based on a single design storm (leading to the recognition that the *'design storm is dead'*, Sayers *et al.,* 2015a along with the assumption of climate stationarity, Milly *et al.,* 2008). This issue was brought into sharp focus when a seafront railway line in Dawlish, Devon collapsed when exposed to repeat, but moderate, storms that lowered the beach allowing large waves during subsequent storms to impact the line (Shaw *et al.,* 2016). The storms highlighted the interconnections important services (*e.g.,* the collapse of the Pooley Bridge in Cumbria echoed the collapse of a Cumbrian bridge during the 2009 floods carrying 312 fibre optic circuits serving 40,000 people using the bridge as a conduit to cross the river, Postnote, 2010).

In response, two major reviews were undertaken in 2016; the National Flood Resilience Review (HM Government, 2016) and the Environment Food and Rural Affairs committee report (EFRA, 2016). These reinforced the need to consider flooding from multiple sources (pluvial, fluvial, coastal, groundwater), underlined the importance of nature-based responses and the need to use improved numerical forecasts and catchment scale models to support decisions (echoing a similar call from 2001), and to understand the escalation of impacts that can result from loss of important municipal infrastructure (*e.g.,* the Resilience Review found 530 important infrastructure sites, such as water and telecoms, were exposed to a significant chance of flooding, with each potentially affecting at least 10,000 people). Each review contained many recommendations covering the need for more integrated modelling and planning (echoing previous reviews). The most significant new insight, perhaps, focused on the need to better understand and prepare for storm sequences and the importance of adopting a whole landscape scale approach to managing run-off from the upland catchments and within urban areas. A more operational insight into the lessons learnt from those in the front line of delivering flood management in England was provided by the retiring head of Flood Risk Management at the Environment Agency (Figure 2-11). These insights emphasise the importance of communication and partnerships and highlight the need for flood management to be a collective endeavour.



Source: David Rooke – Personal reflection presented at the Lyon, 2016 Floodrisk Conference

Figure 2-11 Lessons from a lifetime in flood management

2.6 In summary — History of flood management

The preceding sections have explored how flood management has evolved alongside change societal context and how flood events have influenced changes in policy and practice (Table 2-1). Despite remarkable progress being made through this largely heuristic approach many management challenges persist:

- How to deliver appropriate (practical) integration of flood management and other activities, including planning and social policy.
- How to work with natural processes to promote multiple benefits and still deliver appropriate certainty of flood management.
- How to provide long-term solutions capable of responding to a deeply uncertain future.

These challenges underline the need for a new approach and provide the motivation that underpins the need for the strategic framework of flood risk management and methodological advances (associated with whole system risk analysis, valuing green infrastructure, and developing appropriately adaptive and social just plans) as set out in in the following chapters.

Table 2-1 The influence of past flood events in shaping policy and practice

Flood event	Impact on thinking, policy and/or practice
1917 Mississippi and Sacramento basins, and 1927 lower Mississippi, USA	Promoted the need for basin scale infrastructure and co-ordination.
1931 and the following decades, across three major rivers: the Yellow, Yangtze, and Huai, China	Promoted the need for basin scale infrastructure and co-ordination.
Major floods across the United States in 1936 (and to a lesser extent 1937 and 1951)	Reinforced the need for national responsibility.
In March 1947, river floods across Europe and coastal floods in 1953	Issues of food security, the need for clear roles and responsibilities and the performance of warning systems.
1991 and 1998 China	A rethinking of flood issues: how to carry out disaster mitigation approaches more efficiently and effectively.
1993 and 1997 Mississippi, USA	The 1993 Mississippi River flood was the US flood of the century in economic terms. Following this event, new regulations were issued (1996) that established the need to include uncertainty in the assessment and justification for new flood control projects.
1993, 1995, 1997 on the Rhine and 1998 and 2000 in the UK	Led to a demand for a new basin-wide and strategic approach to flood management using a combination of structural and non-structural approaches.
2004, Asia Tsunami (Boxing Day)	A recognition of the vulnerability of coastal communities and need for better warning, emergency planning and spatial planning to reduce risk.
2005, New Orleans, US	A wider recognition that levees fail. A need to better understand levee performance and the wide acceptance of the need for a risk management approach and the communication of residual risks.
2007 in Hull, UK	The need to consider all sources of flooding and spatial extent of events, as pluvial, fluvial, and tidal sources combine.
2010, Pakistan, 2011, Japan, 2011, Mississippi, 2012 Sandy US	A need to re-evaluate the use of floodplains, limitations of structural systems and the need for improved resilience of critical infrastructure and prevent secondary and tertiary risks developing.
2013/4 and 2015/16 across England	The need to re-evaluate the approach to the assessment of risk use of floodplains, limitations of structural systems and the need for improved resilience of critical infrastructure and prevent secondary and tertiary risks developing.
Summer 2021 – widespread following in NW Europe	Reinforced many past lessons, including the need for improved warning and largescale catchment-based approaches to managing flood (using multiple measures). There was a recognition that climate change is leading to an increase frequency of such events.

Source: Sayers et al., 2013 updated Sayers et al., 2017a

3

INFLUENTIAL FRAMEWORKS AND CONCEPTS

Through the latter part of the 20th century, flood management started to be recognised not only as an engineering pursuit but as a social endeavour (White, 1945). Concepts of sustainable development (WCED, 1987; UN, 1992) emerged and challenged flood management to move away from the traditional paradigm of 'flood control' towards one of participatory risk-based decisions (*e.g.,* Sayers *et al.,* 2002a, b). River basin planning, spatial planning, disaster management, ecosystem management, social justice, adaptation, and resilience frameworks have had a significant influence on approaches to flood management. Together with concepts of risk and system analysis these frameworks reinforce the need to adopt whole system and whole life thinking and promote adaptive long-term solutions that both promote and safeguard ecosystem services in the delivery of 'fair' flood risk management outcomes.

This chapter introduces these frameworks and concepts (that have originated largely from outside of the flood community, including Sustainable Development, adaptation, and many others) and their influence on Strategic Flood Management (SFRM) as advocated here. The chapter concludes by presenting the differences between conventional and emerging strategic approaches; differences that laid the foundation for the discussion, analysis and applications presented in later chapters.

3.1 INTRODUCTION

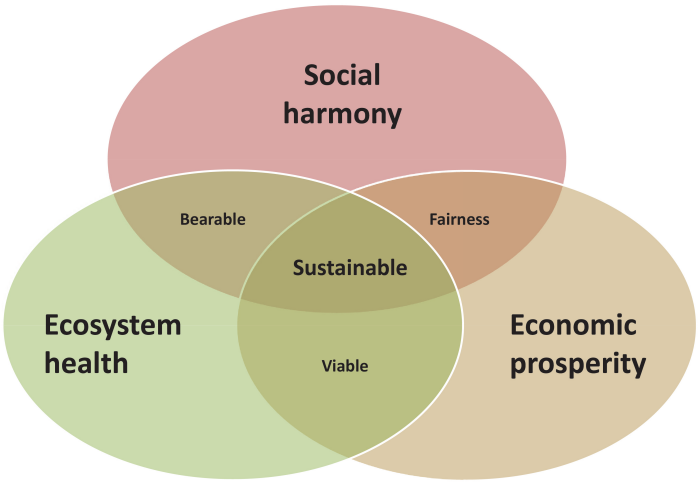
Flood risk management sits at the intersection of many other management considerations and as such flood management is influenced and shaped by multiple, often overlapping, concepts and frameworks and, in turn, flood management is supportive of multiple agendas. The objective of this chapter is to briefly summarise the most important of these frameworks and concepts (Figure 3-1) and to explore how they influence flood management and what they may mean for SFRM as advocated here.



Figure 3-1 Concepts and frameworks that have influenced the development of flood risk management

3.2 SUSTAINABLE DEVELOPMENT

In 1987, the United Nations released the Brundtland Report (Brundtland, 1987; UN, 1992) and defined sustainable development as 'development which meets the needs of the present without compromising the ability of future generations to meet their own needs'. This is a simple yet powerful concept; it emphasises the interlinkages between economic development, environmental health, and social wellbeing and demands that they are addressed not as three separate objectives but one (Figure 3-2). There are inherent conflicts and trade-offs between these objectives and hence central to delivering sustainable development is an ability to resolve conflict between the various competing goals, and seek to achieve, simultaneously, economic prosperity, ecosystem wellbeing and social harmony.



Source: Redrawn based on UN, 1992

Figure 3-2 Pillars of sustainable development

In 1992, the United Nations Conference on Environment and Development (Earth Summit) held in Rio de Janeiro, identified the need, and set out a blueprint to achieve sustainable development in practice (Agenda 21). Agenda 21 reinforces the notion of integration and stresses the need to move away from sector-centred ways of working to new approaches that involve cross-sectoral coordination and integration. Broad public participation in decision-making as a fundamental prerequisite for achieving sustainable development is emphasised.

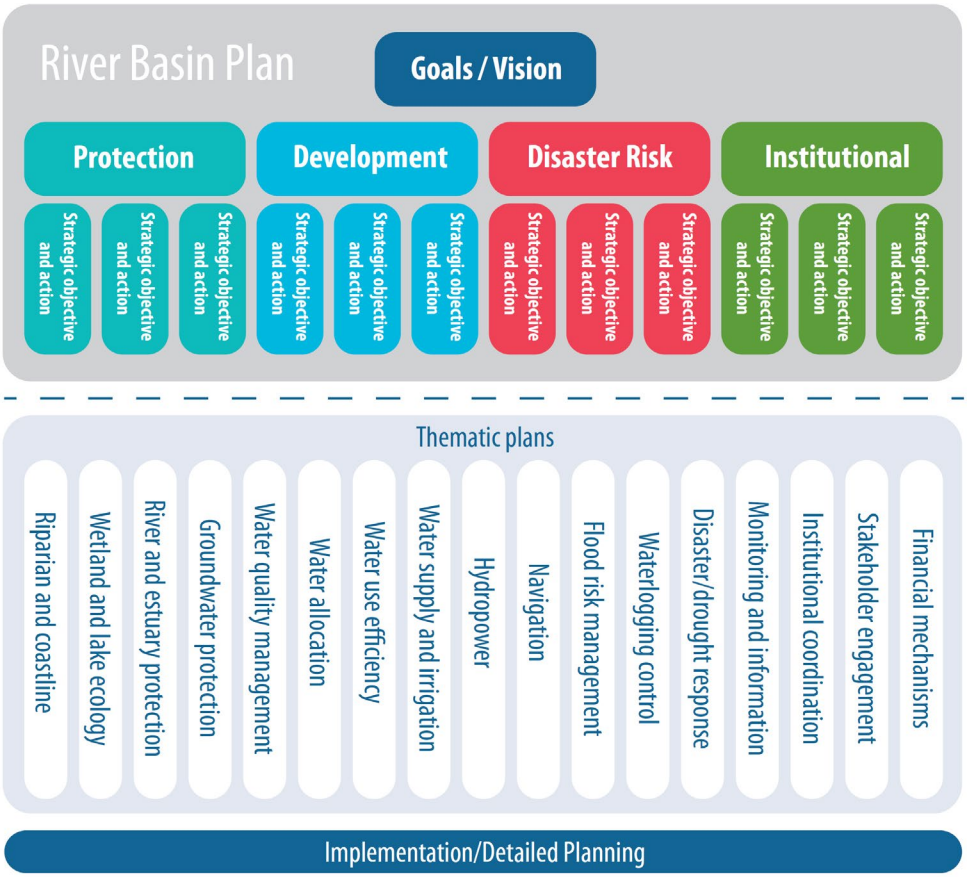
In 2000, at the Millennium Summit of the United Nations, all United Nations member states committed to supporting the principles of sustainable development and set out eight Millennium Development Goals (MDG) to be achieved by 2015. The global action in support of the MDGs has been recognised as one of the most successful anti-poverty movements in history (UN, 2015). Building upon the success of the MDGs, the 194 Member States of the UN signed up to *'Transforming our world: the 2030 Agenda for Sustainable Development'* and set out seventeen aspirational "Global Goals" (referred to as the Sustainable Development Goals, SDGs) with providing resilience, climate change, environment, and the social justice major unpinning themes.

3.2.1 Influence on flood management

Flooding, and the management of floods, is inextricably linked to achieving the SDGs. Not only do the actions taken to manage floods impact the physical environment (through the development of control structures and spatial planning measures) they provide opportunities for, and place constraints upon, human and natural activities in the long term. The ideas of sustainable development, as expressed through the SDGs, reinforce the critical need to maintain (or establish) healthy ecosystems, deliver socially just outcomes and promote resilience; themes that are central considerations in the strategic approach promoted here (see Chapter 4).

3.3 RIVER BASIN AND COASTAL PLANNING FRAMEWORKS

River basin and integrated coastal zone management (ICZM) planning frameworks represent an attempt to manage the physical processes, social and ecological demands and risks and opportunities in a coherent way (*e.g.,* World Bank, 1996; Pegram *et al.,* 2013). In addressing these goals RBM and ICZM seek to address multiple hazards (including but not limited to flooding) and socio-economic functions and set the framework for the development of multiple thematic plans (Figure 3-3).



Source: Pegram et al., 2013

Figure 3-3 River Basin Planning addresses multiple issues and set the framework for the development of supporting thematic plans

Both basin planning and ICZM share common concepts of broadly based planning; for example, an ICZM Protocol presented by the Priority Actions Programme of the UN Environment Programme (2008) defined ICZM as:

"...a dynamic process for the sustainable management and use of coastal zones, taking into account at the same time the fragility of coastal ecosystems and landscapes, the diversity of

activities and uses, their interactions, the maritime orientation of certain activities and uses and their impact on both the marine and land parts." [1]

River Basin Management (RBM) has similar broadly based and integrated goals (*e.g.,* Pegram *et al.,* 2013):

'[river basin planning]……allows the upstream-downstream hydrological interactions to be considered in holistic solutions. This whole-basin approach also allows a systemic approach to ecological and infrastructure systems.'

The practice of basin and coastal planning continues to develop and Pegram *et al.,* usefully identifies three major phases in the RBM planning process that are reflective of changes in coastal approaches:

- **Uncoordinated:** Early development, where *ad hoc* control and enforcement against minimum standards is at best applied, rather than coherent basin-wide planning.
- **Technical:** Infrastructure development and operational planning, where technical engineering solutions are the priority. The premise of these early attempts at basin planning were largely to harness the power of the river through infrastructure development, which could only be managed effectively through coordination along the entire river and dominated considerations of water allocation, water quality, navigation, hydropower, and flood control.
- **Strategic:** Multidisciplinary planning, where economic, ecological and management solutions are applied.

This distinction is highly stylised, with considerable overlap between phases. Nevertheless, these three phases represent common development pathways in many river basins and coastal areas and underpins contemporary processes that seek to:

- Assess and prioritise issues of concern to be managed within a basin.
- Decide on the way in which these priorities should be managed to achieve social objectives over time.
- Specify the way in which different competing purposes (such as abstraction, hydropower, flood control and navigation) may develop or use the basin water resources.

[1] *http: //www.pap-thecoastcentre.org/pdfs/Protocol_publikacija_May09.pdf*

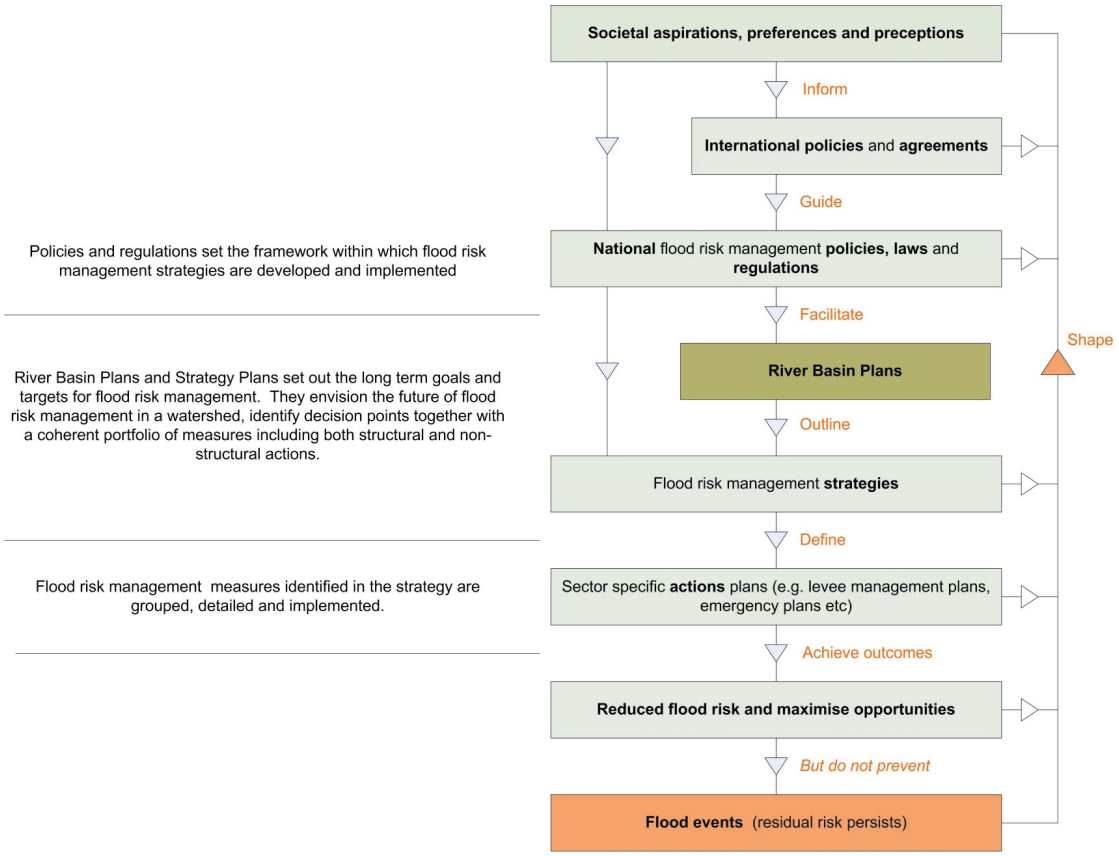
3.3.1 Influence on flood management

In 1989, the National Rivers Authority (NRA) was created to provide a lead on flood issues across England and Wales. The creation of the NRA was based upon the principles of Basin and Coastal Zone planning, placing additional focus on conservation in flood management (reinforced by the Habitats Directive, EC, 1992) and promoting the concepts of management based on physical process boundaries rather than administrative regions. Shoreline Management Plans (SMPs) were introduced to provide management of the shoreline at the scale of sediment process cells (first defined by Motyka and Brampton, 1993), and Catchment Flood Management Plans (CFMPs) followed in the mid-1990s to provide planning at a river catchment scale. Similarly, Coastal Zone Management Plans were developed in many US states and China adopted the process of Basin Master Planning (although it was not until the 2000s, following continued flooding and environmental pressures, that these plans started to seriously consider the principles of sustainability and the evolution of a *'water saving society'*, and subsequently the development of '*eco-civilisation'*[2] goals, based on implementing the *'most strict water resources management*' as set out in the 2002 Water Act).

Coordinating flood management with other functional activities through the basin and coastal zone planning processes (such as energy, economic, water, and food security) is not straightforward to achieve. This is often because governments and businesses are most comfortable operating within an organisational structure and undertaking activities that relate to their narrow field of interest. Changing these perceptions will remain a significant practical challenge. Initiatives such as the EU Water Framework and Flood Assessment and Management directives as well as the appointment of Catchment Directors in the aftermath of the 2015/6 floods in Cumbria are welcome support to making progress basin-level planning and cooperative action (*e.g.,* Samuels *et al.,* 2010; Gibbs, 2016).

The strategic flood management framing promoted is supportive of RBM and ICZM (in particular, the need to adopt a 'system-scale' planning processes to address upstream/drift-downstream/drift conflicts and other competing goals). This relationship between flood management planning and higher-level planning processes is illustrated in Figure 3-4.

[2] *https: //www.theclimategroup.org/sites/default/files/archive/files/China-Ecocivilisation.pdf Accessed July 2017*



Source: Sayers et al., 2013

Figure 3-4 The relationship between policy, basin (and coastal zone) planning, thematic strategies, action plans and on-the-ground outcomes

3.4 SYSTEM-BASED APPROACHES

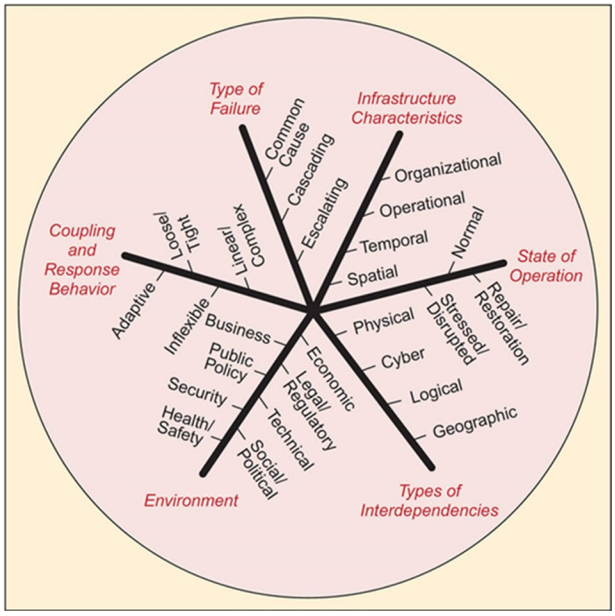
System-based approaches derive from 'systems theory' (*e.g.,* Bertalanffy, 1968, Weckowicz, 1989); the interdisciplinary study of systems where the system is defined by a cohesive conglomeration of interrelated and interdependent parts that are either natural or human constructs. Every system is delineated by its spatial and temporal boundaries, surrounded, and influenced by its environment, described by its structure and purpose and its behaviour expressed through its functions. Real systems typically exhibit emergent behaviours; that is to say the behaviour of the system cannot be determined simply from the independent study of its constituent parts. Systems therefore exhibit interdependences, and changes to one part of the system usually affects another. This relationship is rarely deterministic, and the resultant change is often only predictable in stochastic terms. Human and natural systems are rarely stationary in time and often exhibit some degree of autonomous learning and autonomous adaptation, for example a coastal dune may roll back as sea levels rise. The goal of systems theory is to systematically discover the dynamic interactions within a system and establish the governing principles and controls (the purpose, functioning, structure, relationships to internal and external influences *etc.*).

The concept of *equifinality* is central to system theory, and states that in an 'open systems' (*i.e.,* a system that interacts with environment in which it exists as typically found in the natural world) direct relationships of cause-effect do not exist, and any given end state can be reached by many potential means (emphasising that the same end state may be achieved via many different pathways). Many complex real-world natural and human systems exhibit a behaviour that can be considered to adhere to the principle of equifinality. In business, equifinality implies that firms may establish similar competitive advantages based on substantially different competencies. In geomorphology, equifinality indicates that similar landforms might arise because of quite different sets of processes. In environmental modelling studies, two models are equifinal if they lead to an equally acceptable or behavioural representation of the observed natural processes (*e.g.,* Beven and Freer, 2001).

System theory and complex systems science raise fundamental questions that remain the subject of debate (*e.g., van Kooten Niekerk and Buhld, 2023*). These academic discussions, although of interest, are not the focus here. Instead, system complexity (and system theory and complex systems) is included because the characteristics they exhibit are also important in context of the 'flood risk systems', namely:

- **Cascading, escalating and coherent failures:** The strong linkages between components in complex systems can mean that failure in one or more components can lead to cascading, and potentially escalating, impacts in space or time (*e.g.,* Buldyrev *et al.,* 2010, Berezin *et al.,* 2015). Little (2002), for example, identified three broad categories of interactions (as elaborated in Sayers *et al.,* 2013): (i) ***Cascading impacts*****:** a disruption in one infrastructure causes a disruption in a second infrastructure, or disruption to one aspect of the supply chain can have impacts to reliant business up and down the change (with potentially global reach). Such cascading risks can, on occasion, have a greater impact than the initial flood water. Access to safe drinking water and sanitation during and post a flood, for example, is vital. In places (like Bangladesh) many flood-related casualties are caused by diarrhoea after evacuation, rather than drowning. (ii) ***Escalating impacts*****:** a disruption in one infrastructure, or to one element of the supply chain, exacerbates disruption to another. (iii) ***Coherent impacts*****:** a disruption of two or more infrastructures at the same time because of a common cause (*e.g.,* directly affected by initiating natural disaster for example or indirectly where reliant on the same, failed, supply chain). Such interactions can be generated through many different types of linkages as illustrated by Rinaldi *et al.,* 2001 (Figure 3-5).
- **Hysteresis (system memory):** Complex systems are dynamic and change over time. Prior states may influence present states and functions. Relative examples here include catchment wetness, morphological change, and the flood defence deterioration (Sayers *et al.,* 2015a).
- **Systems of systems (spatial and temporal nesting):** The components of a complex system may themselves be complex sub-systems (*e.g.*, an economy is made up of organisations, which are made up of people, which are made up of cells – all of which are complex systems).

- **Local and remote network dynamics:** Dense local scale interactions and fewer, but potential profound, remote interactions between distance networks (in time or space) may exist.
- **Emergent behaviours:** An emergent behaviour appears when several simpler components (agents) that influence the system form more complex behaviours as a collective than their individual functions suggest. *"... the totality is not, as it were, a mere heap, but the whole is something besides the parts ..."*. Aristotle (384–322 BC)
- **Non-linear relationships:** In practical terms, this means a small perturbation may cause a large effect (see butterfly effect), a proportional effect, or even no effect at all. This behaviour contrasts with linear systems, in which the effect is always directly proportional to the cause.
- **Negative and positive feedbacks:** Both negative (damping) and positive (amplifying) feedback are always found in complex systems. The behaviour of one element therefore influences other aspects of the systems and itself.



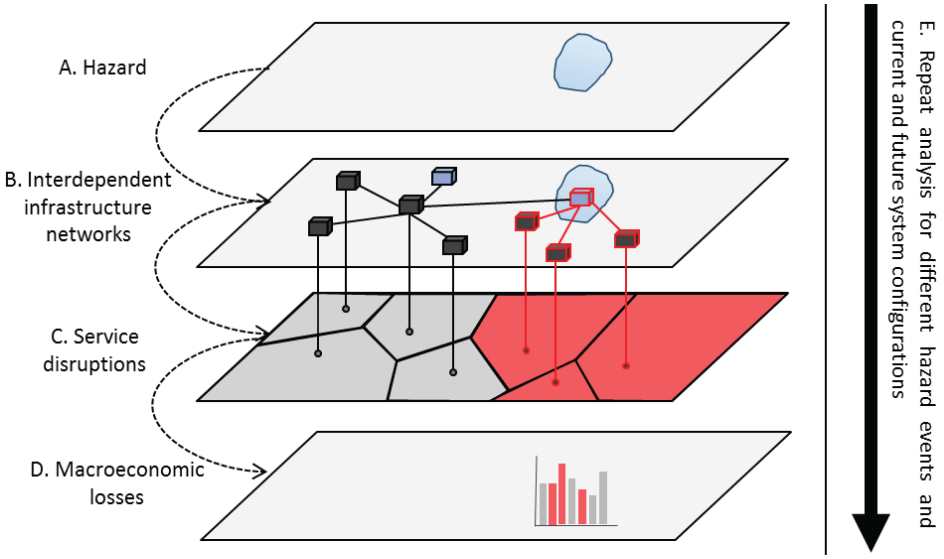
Source: Rinaldi et al., 2001

Figure 3-5 Dimensions for describing infrastructure interdependencies

System-based approaches seek to provide the practical implementation of systems theory to develop models (mental, physical, or numeric) *'that promote our understanding of events, patterns of behaviour resulting in the events, and even more importantly, the underlying structure responsible for the patterns of behaviour'*[3].

[3] *http: //www.systems-thinking.org/ accessed July 2017*

A system is any entity which maintains its existence through the interaction of its parts and its behaviour emerges from these interactions. This basic framing has led to system approaches being applied in many contexts, from medicine (Kitano, 2002) to infrastructure (*e.g.,* Hall *et al.,* 2006) and remains an activity area of development; the emergence of system-of-system approaches recognise the role of task-oriented or dedicated systems in pooling resources and capabilities to deliver an overall, more complex system, which offers more functionality and performance than simply the sum of the constituent systems (for example the pooling of energy suppliers and sources, multiple transport provides and modes, in the delivery of nationally functioning infrastructure – Hall *et al.,* 2013; Thacker *et al.,* 2017). The reliability of interdependent infrastructure networks, the cascade of impacts through such networks is increasingly recognised (Figure 3-6). This includes the interactions with spatially coherent hazards (*e.g.,* wind, temperature and potentially flooding).



Source: adapted from Thacker et al., 2018

Figure 3-6 Graphical representation of infrastructure system-of-systems risk assessment framework

3.4.1 Influence on flood management

There has often been a lack of system understanding in many flood management choices. As witnessed in aftermath of the Asian tsunami (2004), impacts are unnecessarily escalated at a local scale (*e.g.,* the hospital in Galle, Sri Lanka was overwhelmed by the tsunami and out of action when needed most, personal observation, 2004) and cascade globally (as supply chains were disrupted, as discussed in Chapter 2). Similarly, the impact of the 2010 floods in Pakistan were exacerbated by inundation of critical power generation, and supply infrastructure and comparable problems, albeit at a smaller scale, persist in the UK (Figure 3-7). Avoiding these kinds of impacts is conceptually straightforward but requires 'systems thinking'.



Top: Caton Electric Substation, Lancaster; Pooley Bridge collapse, Cumbria; A591 at Dunmail Raise, near Grasmere lost.
Bottom: West Coast Main Line north of Carlisle, flooded; Elland Bridge, West Yorkshire 'beyond repair'; Tadcaster bridge collapses

Figure 3-7 Infrastructure failures during 2015/16 in UK reinforced the need to consider the 'whole system'

In a broad sense, the 'flood system' is described by the social, ecological, and physical domain within which flood risks and opportunities arise and are managed. This includes the physical process of flooding/erosion, the inhabitants of floodplains, their supporting infrastructures and ecosystem services as well as others remote from the floodplain that rely on these services through to the organisations in the public and private sector that influence flooding and its impacts.

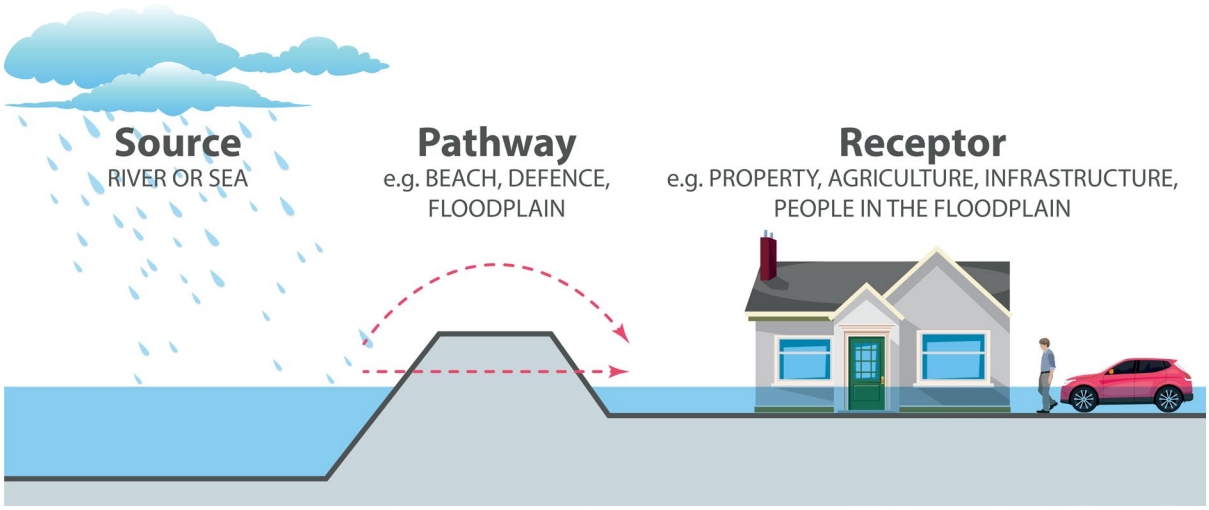
A meaningful analysis of flood risk involves consideration of this 'whole system' and presents a significant challenge to the analyst (Penning-Rowsell *et al.,* 2015a). The chance of harm, for example, is not, as it is often mistakenly supposed, equivalent to the chance that a particular storm event occurs. Equally, the consequence of a flood is not simply the direct material losses but includes the indirect and intangible impacts and the value society places on the harm incurred.

Increasingly it has been recognised that many aspects of the flooding system need to be considered if flood risks are to be assessed in a credible way (adapted from Sayers *et al.,* 2002b), including:

- The physical aspects of the water cycle (*i.e.,* the processes of rainfall and marine storms that lead to fluvial, pluvial, and coastal flooding; runoff from the land; and flood inundation in fluvial floodplains and coastal lowlands.
- The performance of the man-made defences that are intended to resist or control inundation of floodplains.

- The economic, social, and environmental assets that are impacted upon by flooding (and their interdependencies within and beyond the floodplain) as well as their impact on the flooding process.
- The organisations with a statutory and non-statutory responsibility for investing in and managing risk (including implementing warnings, carrying out real-time interventions such as operating flood barriers, and ensuring preparedness of the people at risk).
- Insurers (private and public), who provide cover for flood risks.
- Broader stakeholder groups with an interest or role in the impacts (both positive and negative) of flooding and actions that may be taken to manage flooding.

To help make sense of this complexity the source-pathway-receptor (SPR) framework (initially promoted in ecosystem modelling, DETR *et al.,* 2000) was introduced to flood management in early 2000 (Sayers *et al.,* 2002a). For a 'risk' to be present there must be a **source** (of the flood hazard, *e.g.,* an atmospheric storm), a **receptor** that is susceptible to harm (*e.g.,* a person, community or ecosystem that may experience a loss of social wellbeing or ecosystem health) and a **pathway** between the source and the receptor (Figure 3-8).



Source: Sayers et al., 2002b – Redrawn for FAIR Consortium, 2020

Figure 3-8 The Source-Pathway-Receptor framing provides a useful aid to system understanding

In recent years, flood risk system modelling methods have been increasingly sought to apply this framework. Typically, these attempts have adopted a structured hierarchical framework of thinking (seeking to cascade information from bottom-up and top-down, use local knowledge where it exists to inform broader scale and longer-term understanding, *e.g.,* Sayers and Meadowcroft, 2005).

3.5 Concepts of Risk

Risk concepts are widely used across disciplines and fields of endeavour, including finance, investment, insurance, disaster management, adaptation, conflict, and peacebuilding *etc.* The concepts vary in detail, but all rely on the same basic principle; risk is a function of two

components: **probability** of a situation occurring with the potential to cause harm (the hazard that may lead to a loss of social well-being, economic output, or ecosystem health *etc.*), and magnitude of the harm caused should that situation arise (the **consequences,** a combination of exposure and vulnerability as discussed below). Risk can be considered in general terms therefore as:

Risk = f (probability of some form of consequence and the magnitude of that harm) *Eq. 3-1*

In terms of the analysis of risk, the concept of appropriateness (finding the balance between uninformed decision-making and *paralysis by analysis*) is well established and concepts of tiered assessment methods (that provide an ability to progressively refine an assessment) are widely used within flood management (*e.g.,* Sayers *et al., 2003a,* 2004, 2005a, b) and beyond. Such approaches recognise that different decisions will have differing demands for accuracy and spatial and temporal resolution. The evidence needed to determine national policy and priorities, for example, may be different to that required to determine regional policy or more local community actions.

This versatility has enabled the concepts of risk to gain significant traction across all decision realms. Their ability to help decision-makers compare and prioritise alternative courses of actions in a structured and coherent way is the central advantage of a risk-based approach.

A discussion of the underlying principles of risk, and the alternative 'risk assessment' frameworks, are discussed below from the perspective of flood management.

3.5.1 Components of risk

To help understand how risk is generated (and hence how best it may be managed) the sometimes-subtle characteristics of the two basic components of risk (probability and consequence) are explored below.

The probability of a situation with the potential to cause harm (hazard)

Probability represents the chance of an event occurring given the population of all possible events. In the context of flood risk, probability is typically used as shorthand for exceedance probability, *i.e.,* the chance that given threshold (*e.g.*, water depth) will be exceeded. Exceedance probability is always related to a given timescale. The chance that a given water level will be exceeded in a given year is referred to as the Annual Exceedance Probability (AEP), and chance it is exceeded in a given 100-year period as the '*100-year exceedance probability'*. AEP is not simply the same as the reciprocal of the 'return period in years'; a misconception often made by lay-persons and professionals alike (Box 3-1). This confusion hampers the understanding of risk and progress towards more complex interpretations. Over long timescales, for example, questions of stationarity within the statistics become increasingly important and the description of the probability of exceedance increasingly problematic. The *'chance of exceedance'* is often used in less formal terms – for example in qualitative terms (high, medium low) – but in either case the evidence used, and the time of interest must be clearly communicated; without doing so confusion and misunderstanding propagate.

Box 3-1 Communicating the chance of a flood: The use and abuse of probability, frequency and return period

To help understand the differences between these terms consider the probability of exceeding a defined flood that has an associated return period of one in one hundred years. The expected number of events that will exceed this value in any given 100 years is, on average, 1 (*i.e.,* frequency), but it is easily possible that exceeds this value may not occur at all, or else it may occur more than once. To illustrate this point, the diagram below represents ten 100-year periods and the random occurrence of values that exceed a nominal 1in100 year threshold. Each panel (a to j) contains 100 small squares each representing a single year. The shared squares illustrate those years in which the "100 year" flood was equalled or exceeded. In one of the 100 years, periods the "100 year" flood is never exceeded (panel b, e, and i) and in others it was exceeded once (panel a, d, e, g, and h). In other (panel j) the "100 year" flood was exceeded three times. It should be stressed that these patterns are all generated from the same distribution of annual floods: they just represent different possible outcomes that might be observed in any 100-year sequence.

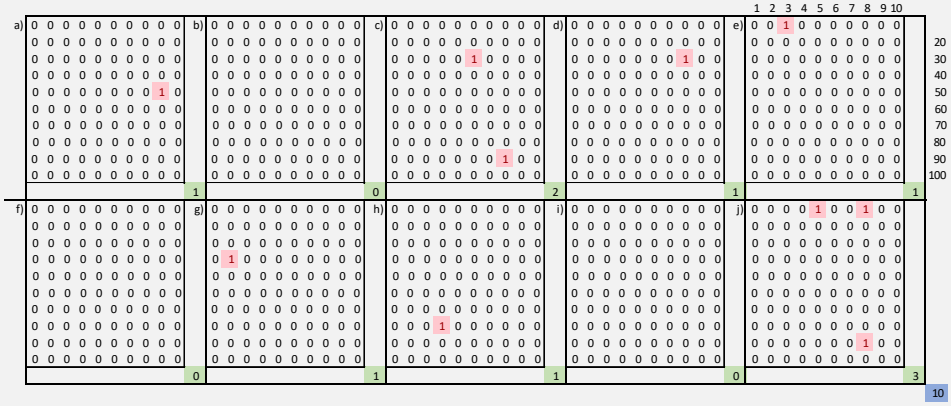


Image from Flood event simulator inspired by Rory Nathan

While from the perspective of a 'long term average' a flood with a return period of T years is likely to be equalled or exceeded once in T years is correct (the blue square), this simple interpretation often leads to confusion and misinterpretation by the layman and professional alike. Risk managers often add to the confusion by failing to recognize frequency and probability are not the same. Return period relates to the number of times, in a given timeframe, that a particular condition is likely to be equalled or exceeded on average. In this frequentist interpretation return period is the reciprocal of the annual exceedance frequency but is not a reciprocal of the annual probability of exceedance (although a reasonable approximation for higher return period >10 years). This is because *probability* defines the chance of occurrence of one event compared to the population of all events. The chance of a flood is not the same as the chance of the driving storm event: Return period typically refers to the hydraulic load or rainfall event and not the response of ultimate interest, *i.e.,* the flood. The probability of a flood occurring often considered the same as the equivalent return period of the flow; an assumption that wholly fails to capture the likely performance of the defences, temporary defences *etc.* The chance of harm (damage) occurring may be even less. The complication of a non-stationary climate makes a frequentist view difficult to interpret as within a non-stationary climate the expectation. The definition of an *exceedance probability* (or an *encounter probability*) is more readily assessed in the context of any population or period of time and hence is a more robust term under the assumption of non-stationarity.

Source: Sayers et al., 2014b and Sayers P B (2015b)

A *'situation with the potential to cause harm'* refers to the potential harm to a receptor. Flood water entering a house has the potential to cause 'harm' not the water level in the river or the wave conditions offshore. To determine the probability, it is therefore necessary to consider the initiating **source** of the hazard (for example the rainfall or coastal surge *etc.*) and the conditional probability that floodwaters reach a particular **receptor** (the ***pathway*** of the hazard from the **source** to the **receptor** of interest). To be meaningful, the assessment of probability of a flood hazard therefore must take account of the severity of the driving storm and the conditional performance of the intervening system of wetlands, river channels, nearshore morphology, dams, embankments, floodwalls, and other structures that influence the progress of flood waters towards the receptor.

The probability of exceedance of a flood hazard is influenced by several drivers of change; those that influence the 'source' of the hazard (such as climate change) and those that influence the pathway (such as changes in land use, flood defences, urban drainage and any other aspect that influences the physical geography of the landscape).

The consequences should a hazard occur (exposure and vulnerability)

Consequence can be expressed in many valid forms, either quantitatively in monetised or native terms or qualitatively by category or description (*e.g.,* USACE, 2000, Sayers *et al,* 2002a). Consequences are typically considered as harmful and therefore negative. Alternative actions may have positive outcomes for the economy, society, or ecosystem. Such *'gains'* are consequences but typically 'risk' paradigms are focused on the avoidance of harm; but as such may feed into a broader decision framework than trades 'gains' (for example biodiversity benefits) and 'losses'.

To better understand 'consequence' it can be usefully disaggregated into issues of the *vulnerability* and *exposure*, where:

- ***Exposure:*** Describes and quantifies (where possible and useful to do so) the receptors (property, people, habitats *etc.*) that may be directly exposed to a given flood hazard should it occur and those that may be indirectly exposed as impacts cascade through interconnected receptors (for example, a rail station may be directly exposed, and users of rail network further afield may be impacted by the flood indirectly). The concept of exposure is not as simple as it appears. Some receptors, such as residential properties, can be considered *"static"* whereas others, such as people and wildlife are *"dynamic"* and may or may not be at a given location at a given time. To understand the degree of exposure, a further conditional probability (the probability that a receptor will be 'present' to be exposed, directly or indirectly) influences the risk. The time of day the flood occurs (rush hour, night *etc.*) or season (holiday season *etc*.) may determine the number of people directly exposed (a consideration routinely embedded in dam safety assessments but rarely included in long-term flood risk investment planning). Exposure is therefore influenced by population change, development and spatial planning and the inherent characteristics of the infrastructure systems and way risks cascade through such systems.

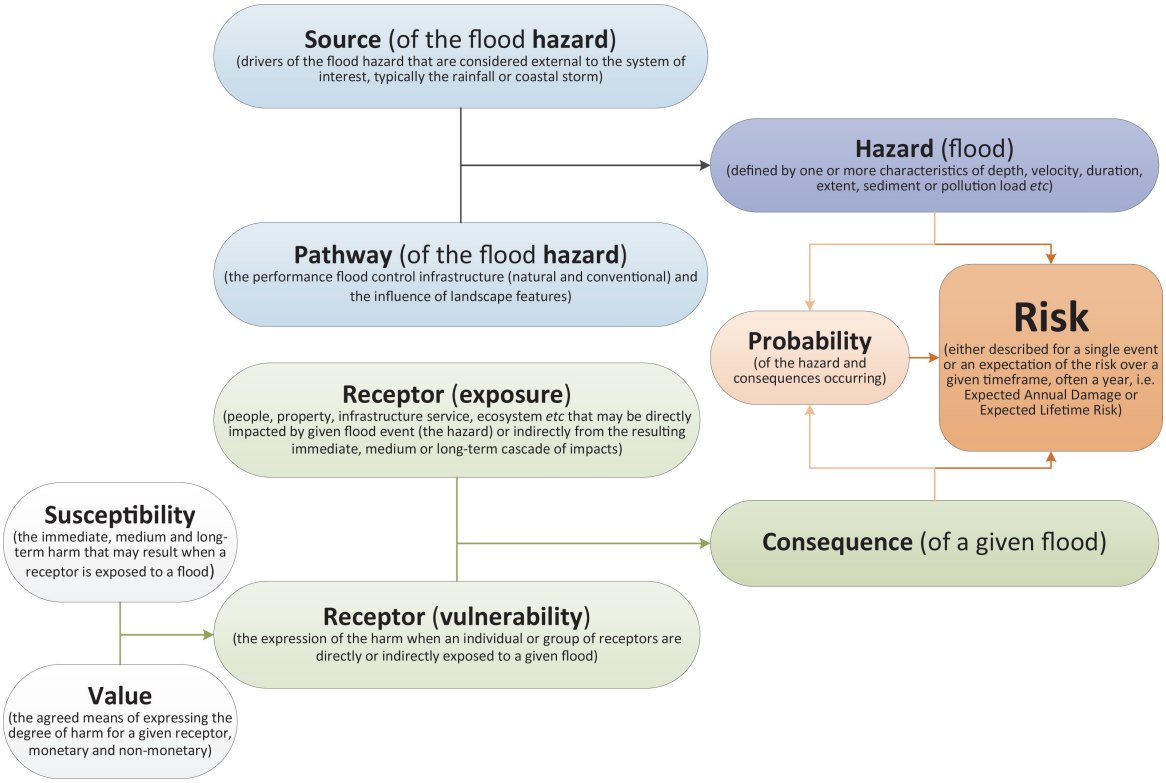
- ***Vulnerability****:* Describes the **agreed** expression of the potential harm incurred when a

receptor is directly or indirectly exposed to a flood hazard. A receptor that can autonomously recover from a flood (*e.g.,* by drawing upon their own capacity) or respond to a change (*i.e.,* reorganising their behaviour without external assistance) has little vulnerability. Taking steps to promote the ability of a receptor to recover reduces vulnerability and promotes inherent resilience traits that reduce risk. To understand *vulnerability*, two aspects are important:

Susceptibility - the tangible or intangible harm that occurs when a receptor is exposed to a flood hazard that is independent of the value system used to determine the significance of that harm. A building may incur physical damage; a wall may collapse, a carpet ruined, flora or fauna may be harmed, or an individual may suffer physical injury, loss of life or their mental health may suffer *etc.* Such impacts may be short-lived or persist for many years. The capacity to recover is embedded in the notion of susceptibility. As such, susceptibility is influenced by the receptor's capacity to recover (*e.g.,* an individual's income, education, family *etc.*, their community networks and access to post-event recovery aids such as insurance *etc.*).

Value - expresses the degree of harm incurred. The adopted value system is central to assessed risk and the recognition that some harms may be perceived as more serious than others. An attempt could be made to monetise all harm into a common currency (if so, the basis of valuation should be clear, for example a development or welfare economic basis) or harm could be kept in native parameters (*e.g.,* number of people impacted by water restrictions, or loss of lake habitat in hectares) and appropriately weighted (*e.g.,* using a structured elicitation process such as a Delphi process). Simpler approaches may provide a qualitative scale of value (*e.g.,* high, medium, or low). In most practical decision frameworks, a combination of monetisation and native parameters are used, for example, as with the DEFRA priority scoring system. This recognises that fully monetised approaches can obscure the nature of the 'risk' from the decision-making process and make explicit trade-offs (between different types of risk, people, property, economic) more difficult. Regardless of the adopted approach, the evidence on which the value is based (from expert opinion to observation) must be recorded and agreed to support decision-making (*e.g.,* Sayers *et al.,* 2016a).

These subtle components of risk are illustrated in Figure 3-9.



Source: Sayers et al., 2019, adapted from Sayers et al., 2013, 2002a

Figure 3-9 The components of (flood) risk

3.5.2 Frameworks of risk assessment

Risk always has units; these units reflect the way the probability and consequences are defined and integrated. This flexibility is both a strength and a weakness. It is strength in that it allows the framework of assessment to be tailored to the context of the decision it supports; but it is also a weakness, as it can give rise of the complexity and confusion of the communication. Within flood management, two standard frameworks of assessment are often used: *site-based frameworks and event-based frameworks*.

Local-dependence framework

The term 'Local-dependence framework' in the context of a risk assessment is used here to refer to an assessment of Expected Annual Damage (EAD) that assumes the probability of the flood hazard is fully dependent across the area of interest. The defences protecting the same floodplain, for example, are assumed to experience the same severity of load, say a 1in100 year return period water level, and the resulting flood inundation is conditional on that load. This is reasonable at a local scale (*e.g.,* a single floodplain) but becomes increasingly in error at larger scales.

A local-dependence framework typically underpins public sector risk analysis, including (i) the communication of the probability of flooding to the public (as an Annual Exceedance Probability taking account of the chance of the flood ***source*** and conditional performance of the ***pathway***) and to make the investment case for flood management actions, and (ii) to assess the national flood risk by comparing the economic efficiency of alternative

investments in flood management (*i.e.,* benefit–cost analysis typically relies upon the change in Expected Annual Damage with and without investment).

To assess national scale risks using a local-dependence framework, Expected Annual Damages (EAD) are calculated locally and aggregated. EAD is widely used as a convenient measure of the average annual damage and typically calculated using a trapezium rule to integrate the product of the probability and the damage value (to approximate the mean annual damage as the area under the probability versus damage curve):

$$EAD = \sum_i (P_{i+1} - P_i) \times \left(\frac{D_{i+1}+D_i}{2}\right) \qquad \textit{Eq. 3-2}$$

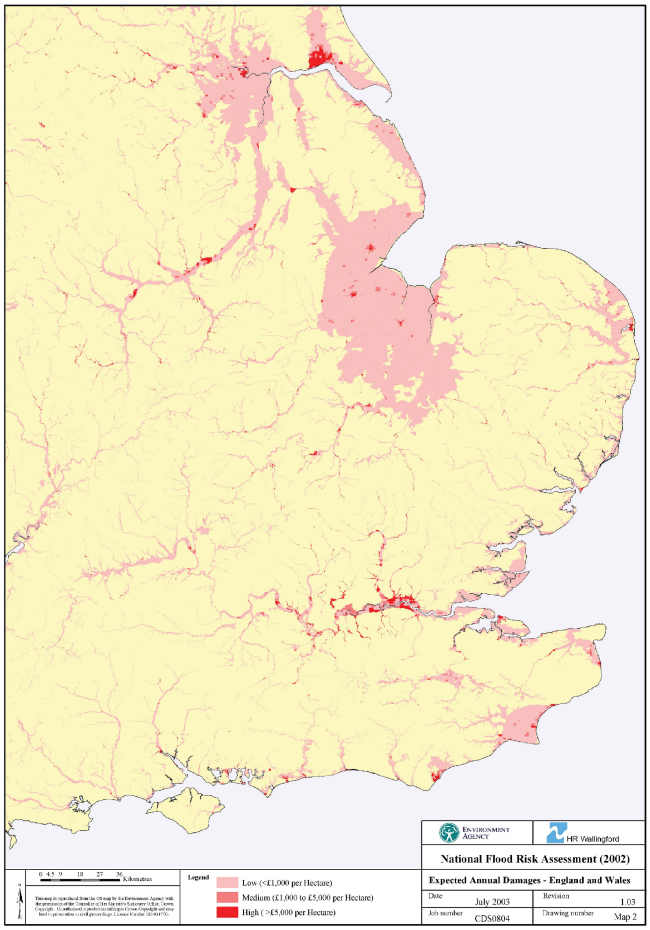
Where P is the AEP of the flood and D is the associated damage.

When annualising the damage in this way, there is an implicit assumption that the damage varies linearly between D_i and D_{i+1}. This may not be the case. The error introduced through this process (at a local scale) is readily seen to depend on the number of AEPs for which damages are available; with fewer AEPs the credibility of the assumption reduces and greater uncertainty is introduced. Analysis by McGahey and Sayers, 2006 suggested, at a local scale, 20 AEP are needed to limit the significance of the error introduced; although this can be reduced if AEP values are well chosen to reflect discontinuities in the damage response.

It is typically assumed that local assessments of Expected Annual Damages can be aggregated in space using simple addition (*i.e.,* the EAD assessed in one location can be added to the EAD elsewhere). This process of the aggregation of local risks underpins the National Flood Risk Assessment (NaFRA, Sayers *et al.,* 2003b, 2004, Gouldby *et al.,* 2008) and Climate Change Risk Assessment (Sayers *et al.,* 2015a, 2020a). This is reasonable given there is no inferred spatial or temporal coherence to the Expected Annual Damage, only that it obeys the general principle that an *aggregated* (*e.g.,* national) mean annual damage is the sum of the *local* means.

Expected Annual Damage calculated in this way offers a simple and useful view of risk but not necessarily the significance of the risk faced. An EAD value dominated by low probability/high consequence combinations is not the same 'risk' as one dominated by high probability/low consequence combinations, even though the estimated magnitude may be the same.

Understanding the 'risk profile' (*i.e.,* the relationship between damage and probability) is as important, if not more so, than simply understanding the expected value. By understanding the risk profile, risks with the same numerical value (*i.e.,* low probability/high consequence events and high probability/low consequence events) can be distinguished and management actions appropriately tailored. Although local-assessment framework can be used to provide a 'risk profile' locally they are not able to do so at an aggregated scale. This inability arises because of a lack of information on the spatial coherence of the AEP value assigned to the hazard in different locations. It would be grossly conservative to assume the 1in100 year return period damage at a national scale to be a simple sum of the 1in100 year damage at all locations. Addressing this shortcoming is the central driver of the event-based approaches (Figure 3-10).



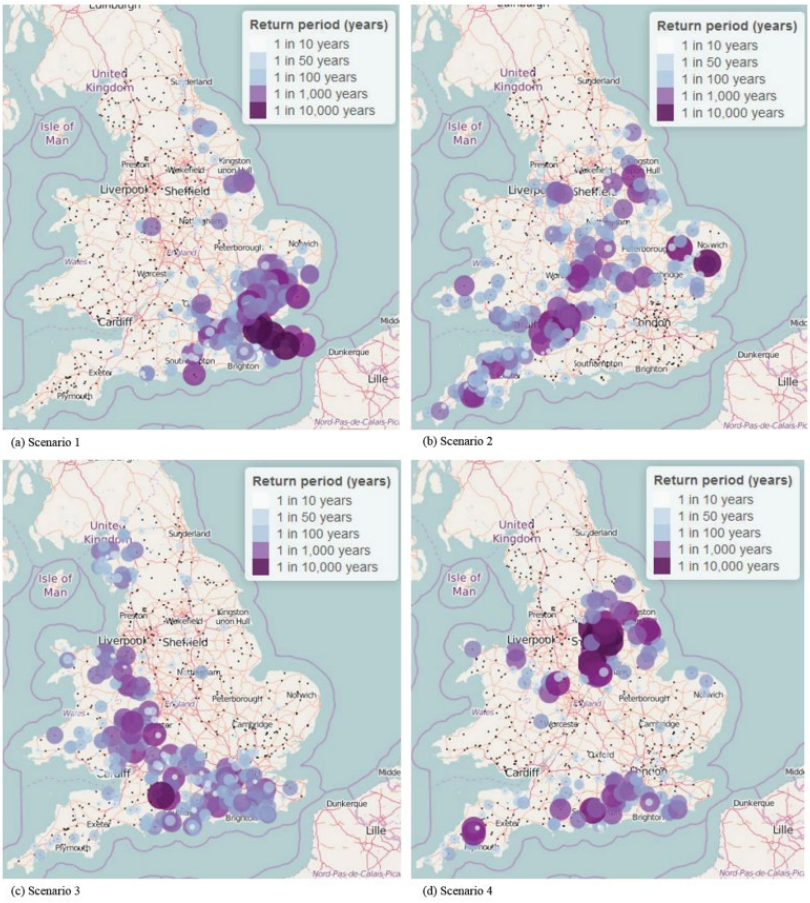
Source: Sayers et al., 2003b (the first National Flood Risk Assessment – NaFRA - in England using the RASP High Level Method (HLM), Hall et al., 2003, Sayers et al., 2004)

Figure 3-10 Spatially independence assessments of Expected Annual Damages are typical outputs from public sector national flood risk assessments

Event-based frameworks

Events such as the widespread flooding of 2007 and 2014/15 in the UK (see Chapter 2) have reinforced the early warning of Evans *et al.,* (2004a) that 'disruption can quickly lead to widespread and serious consequences' and that 'proactive measures are needed to improve resilience of (infrastructure) networks' and motivated the National Flood Resilience Review (2016) to highlight the importance of spatial coherence in driving cascading and escalating risks. An event-based framework responds to this by providing an assessment of risk based on the analysis of spatially coherent events. In turn, a spatially coherent event is defined as a set of values of some variable that are linked together spatially in some way, the most obvious connection being that they occurred simultaneously (Figure 3-11). *'Simultaneous'* does not necessarily mean at the same precise time but is typically defined in the context of *'time window'* judged to be capture the same event (*e.g.*, 16 days is proposed for rare fluvial floods in the UK by De Luca *et al.,* 2017). The intra-event or inter-event evolution of flooding is captured through the concept of temporal coherence (*i.e.,* how values of variables are connected in time). Temporal coherence exists across multiple timescales, from within-season to decadal (Hillier and Dixon, 2020) and may change in time (with climate change for example).

Event-based frameworks are typically used within the financial and reinsurance sector. This reflects the importance of understanding the probable maximum loss that an insurer expects to incur across its policy portfolio. This fundamentally requires an understanding of the 'risk profile' at scale of the policy portfolio (including national or even global scales). Catastrophe (CAT) modelling approaches were developed in the late 1980s to service this need. CAT models generate stochastic spatial 'hazard event sets' and use these to drive an assessment of damage for each event. This analysis yields a distribution of events and associated damages that can be used directly to determine an extreme distribution of the damage at any scale of aggregation (as well as an EAD). In most existing CAT models both the marginal distribution of extreme hazard variables and their dependence structure are inferred from a blend of observations and weather, and present-day climate modelling. Climate projections are rarely incorporated (an issue returned to in Chapter 8).



Source: National Risk Assessment, Defra (2007). Discs represent local return period of flows at river gauging stations.

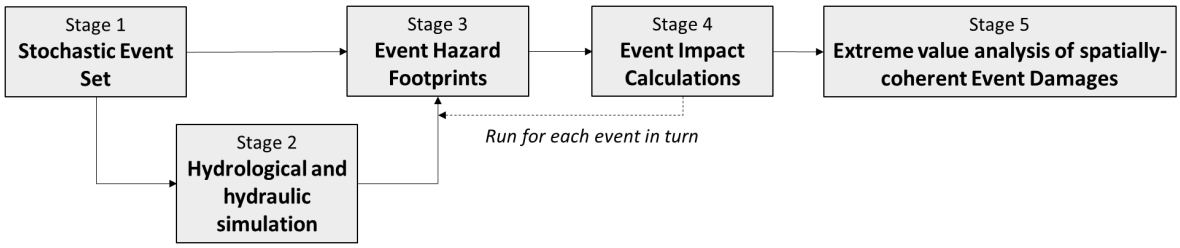
Figure 3-11 Examples of spatially coherent events as developed for the 2017 National Risk Assessment

The central advantage of an event-based framework is the rich information content it provides on the distribution of losses, and in particular, the tails of the distribution. This enables questions such as:

- What is the national 1 in 100-year flood damage?

- What is the chance that many different locations will be affected by severe flooding around the same time?
- What is the expected flood damage in November?

Whilst the local-assessment frameworks and EAD approaches underpinning existing national flood risk assessments are useful in helping prioritise investment decisions, they cannot readily answer the questions above. The central disadvantage of adopting an event-based framework is the complexity of the analysis, requiring many thousands of events to be simulated to provide a reliable estimate of risk, particularly in the tails of the distribution. In general, the more extreme or rare the impact, the longer the effective time series represented by the events needs to be to achieve a defensible probability estimate for that impact. A larger event set is needed, for example, to reliably estimate the national 1in5000 annual probability economic loss from a single flood event than the 1in5-year loss event. To simplify the analysis chain and avoid the need for computationally intensive end-to-end continuous simulation for many 1000s of possible events (including the sampling of defence performance), CAT models typically use a staged approach to the assessment (*e.g.,* Jones *et al.,* 2017). The first stage is to develop a synthetic event set of maximum river flows, defined in terms of return period, at points along the river network (or equivalent at the coast). The second stage typically provides local assessment of the flood footprints (that may be associated with each return period river flow at a local scale) that enables a rapid look-up of event hazard footprints for each event (in Stage 3). The hazard footprints can then be aggregated to identify events of interest for more detailed analysis of the associate damage in Stage 4 (taking account of the conditional performance of defences). The final stage includes an extreme value analysis based on the marginal distribution of event damages (Figure 3-12). Fully continuous simulation-based approaches, that seek to provide an end-to-end analysis within a probabilistic risk assessment framework, are emerging but remain computationally challenging (*e.g.,* Jones *et al.,* 2017).



Source: Sayers et al., 2021b

Figure 3-12 Basic stages in an event-based framework of risk assessment

In most existing CAT models both the marginal distribution of extreme hazard variables and their dependence structure are inferred from observations. Climate change is typically included through regional uplift, but more sophisticated analysis is now emerging using climate model outcomes as a pseudo-observational record and the development of empirical copulas based on those 'observations' to extend the event record (as returned to later in Chapter 8).

3.5.3 Significance of a risk

How society and individuals perceive a risk is fundamental to understanding how much effort they are prepared to invest to reduce it. Perception is influenced by many factors, and each plays a part in shaping our response to the risk faced. These issues are reflected in stakeholder preferences and their appetite for different types of risk. An environmentalist may be prepared to accept greater economic risk for environmental gain compared to a financier who may tolerate a greater risk of environmental damage for certainty of financial return. Equally, the decision-maker's general predisposition to be risk positive, risk neutral or risk averse will influence the choices made.

Understanding the significance of risk is much more than a simple question of analysis and is fundamentally associated with the degree of outrage society and individuals experience should an event occur (*e.g.,* Sandman *et al.,* 1987) or the perceived reward that may be secured by an investment. Many of the factors that influence the perception of risks are well-known and include:

- ***The perspective of whom****?* To an individual or society as a whole? Many hazards can affect whole groups of people or ecosystems (*group risk*). On the other hand, an individual may be at risk due to their location and circumstances (*individual risk*). In each case the acceptability of the risk is viewed differently.
- ***Reaction to catastrophic events and disasters*****.** There appears to be more concern about accidents involving a high number of fatalities or major disruption than many smaller events that sum to the same number of deaths (*e.g.,* Birkland, 2006). Coach crashes, air crashes and terrorist activities frequently make headlines on the national news, despite their relative rarity compared to say road accidents and the fact that the fatalities associated with the former may be less than the monthly fatalities of the later. A catastrophic flood would come into this former category. Society appears to respond to a shock factor that regards high consequence events as being more significant than more frequently occurring lower consequence events; reflecting the general perception that society does not understand probability well as consequence.
- ***Trust in risk managers*****.** Trust features strongly in how people perceive the significance of a risk. Most people have trust in their own ability to drive safely, for example, and believe accidents happen to others who are less skilled. In flood risk management the public are asked to trust in the judgement of others and hence are inclined to view any reported risk with scepticism and with either an increased or decreased significance. To build (or enhance) trust, appropriate recognition of all risks and the associated uncertainties need to be engaged and openly discussed within the information provided (Tinker and Galloway, 2009).
- ***Voluntariness/perceived gain*****.** Perception of a risk alters according to whether a person creates the risk or bears the risk, and if they gain a benefit from the risk. These perceptions are influenced by factors such as whether the risk is undertaken voluntarily (*e.g.,* rock climbing) or whether it is imposed (*e.g.,* although we all have choice regarding the place we live and often ignore available information about hazards, flood and coastal

erosion risks are often considered by much of society as imposed risks over which the individual has no control). The perceived value of the secured benefits (the joy of new habitats or direct economic benefits) can have a major influence.

- ***Ability to recover/permanent loss.*** Increasingly, perceptions of flood risks are influenced by the ability to recover from an event. In general terms society would be less willing to accept the chance of permanent loss – for example life and/or habitats. This bias is often reflected in the way both loss of life and ecosystems are embedded into the risk analysis process and the reluctance to monetise such losses, preferring to leave such losses described in their native parameters. The ability or inability of individuals and business to recover financially is a major influence. Following the floods along the Elbe (2002), in Florida and New Orleans (2005), and the 1998, 2000 and 2007 floods in the UK, the insurance industry raised public concern over the affordable provision of insurance cover and the possibility of withdrawing insurance cover from selected areas.
- ***Perception of protection.*** It is often noted that those individuals and businesses located in the floodplain but protected by flood defences (especially dykes and levees) often lose their appreciation of the residual risk. Experience in the US highlights that when individuals are located behind a levee or a flood wall, especially when that structure has been built by the federal, state or local government (a trusted organisation) and receives some form of approval and periodic inspection, the assumption is made that the risk has been eliminated or is negligible; "otherwise the government would not let people occupy the land". In communities participating in the National Flood Insurance Program in the US for example, owners of properties in the 100-year floodplain must purchase flood insurance (see Chapter 14). If the property is in an area perceived to be protected by a US Army Corps of Engineers 'certified' 100-year (or larger) levee, property owners are exempt from this mandatory purchase requirement. This process of levee accreditation can have a perverse impact with those protected by a certified levee perceiving that protection is high and therefore the risk is very low, if any. Whereas those living in a less naturally hazardous area, perhaps exposed to the 1: 10-year flood with a small uncertified levee protecting them, will perceive the risk as much greater as full insurance is mandated by government, and perhaps are more likely to take action to reduce their residual risk, even though perhaps their risk to life (given the nature of the flood wave) may be less.
- ***Perceived Inequity.*** A perception or reality of an inequitable distribution of risk and benefits because of a strategy or policy is likely to make a risk less acceptable, particularly by those with the less favourable circumstances.

3.5.4 Cascading, escalating and coherent risk

Risk analysis is increasingly applied to understand the propagation of impacts and risks through connected systems (as discussed in earlier sections).

3.5.5 Non-stationary risk

The future will be different from the past. Climate change and socio-economic development can affect the probability and associated consequences of a drought. Accepting risk as a non-

stationary phenomenon is an important concept for risk management and implies the need for continual review and adaptation as the understanding of the future changes.

3.5.6 Residual risk

Risk cannot be eliminated. It is impossible to remove all risks and it is said that there are only two types of levee; *"those that have failed and those that will".* There will always be a future flood event that will threaten and overcome the most robust of defences. State-of-the-art warning systems may fail. Communicating the residual risk is a central component of flood risk management – only through knowledge can individuals and organisations take their own measures and make their own choices regarding the acceptability of the residual risk.

3.5.7 Risk management and acceptable risks

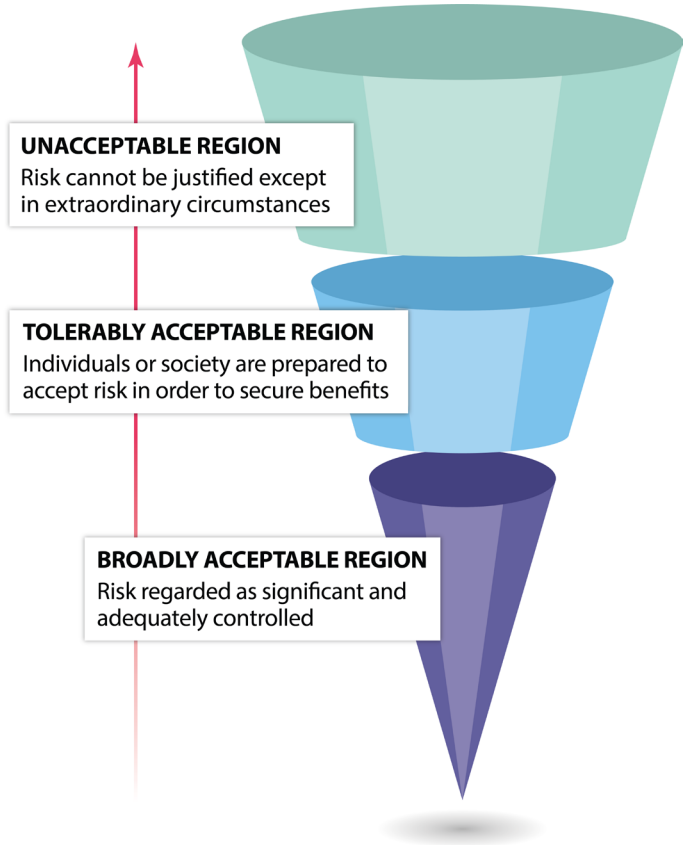
Management of risk is a topic that received increasing attention in the latter half of the twentieth century and has continued to be a dominant issue in the twenty-first century (Sayers *et al.,* 2002a). Indeed, it has been suggested for some time that risk will be the primary issue that occupies modern societies (*e.g.,* Beck, 1992). Specific areas of attention that will be familiar to all civil engineers are those associated with the management of health and safety risk (ICE 1995, Barnard 1998, Fink, 1997), construction risk (Godfrey 1996, Hall *et al.,* 2001), environmental risk (DETR, 2000) and business risk (Institute of Chartered Accountants, ICA, 1999).

Until the latter part of the twentieth century, risk management was focused on two primary issues:

- **Insurance and the financial markets**. Recognition that many unknowns influenced the success of trade led to the development of new methods that could provide insight into the risks and how best to share exposure to the expected consequences. Throughout the early part of the twentieth century, approaches became increasingly sophisticated. 'Natural disasters' [*sic*] were certainly part of these calculations, but they were primarily considered in the context of re-insuring retail insurance liabilities (*e.g.,* Sayers *et al.,* 2013).
- **Public sector and industrial safety:** The 1980s saw a catalogue of industrial disasters in the UK, including the Piper Alpha oil rig fire in the North Sea, the capsizing of the Herald of Free Enterprise, and the King's Cross underground station fire – all national tragedies that raised considerable disquiet about the management of risk. This disquiet led to the Royal Society's influential 1992 report *Risk: analysis, perception, and management* (Royal Society, 1992) that, for the first time, sought to bridge the gap between quantified and perceived risk, and to comment on the merits of risk-benefit trade-offs. Publication in 1992 signalled the emergence of a new analytic-deliberative approach to decision-making (that had been discussed previously but never marshalled into a coherent text). Up until this point, in both insurance and public sectors risk management had been deployed as a defensive approach to reassure shareholders and the public, but perhaps also to limit blame.

Increased awareness of environmental issues in the mid-twentieth century focused attention on assessing and managing 'risks' associated with the natural environment and human activity in general. The application of risk management techniques emerged in response concerns around the widespread use of chemicals in manufacturing and pharmaceutical production and the started to be applied to many sectors through the 1970s and 1980s. Professional organisations, such as the Society for Risk Analysis in the US (established in 1980), were formed to bring together academics, government, and business interests for the discussion and advancement of risk analysis.

In the UK, the Royal Society report started to influence approaches in practice, and risk management began to feature more strongly in the governance of the manufacturing industry, air travel and power generation (both hydro-electric and nuclear) covering all industrial activities that placed either workers or society at risk. The seminal paper by the Health and Safety Executive (HSE) 'Reducing risks, protecting people' (UK HSE, 2001) set out a framework enabling both the risk to individuals and society to be considered and traded against the benefits secured by investment (in a dam for example). The HSE introduced the concept that risks should be managed to a level *'As Low As Reasonably Practicable'* (ALARP) and described 'practicable' in the context of a balance of costs (described as all costs – monetary and non-monetary) and benefits (described as all benefits – both monetary and non-monetary). The HSE introduced the concepts of 'broadly acceptable risk' (that require no management effort); *'unacceptable risks'* (that must be reduced unless the costs of doing so can be demonstrated to be disproportional to the risk reduction achieved or it is not technically possible to do so); and *'tolerable risk'* (that should be reduced based on a consideration of the cost of doing so and the benefits secured). This framework is summarized in Figure 3-13 and sets out the conceptual approach of exploring *'acceptable risk'*; defined as the level of risk a society or community considers acceptable given existing social, economic, political, cultural, technical and environmental conditions and hence a means of guiding the level of investment that may be appropriate to reduce the risk (where possible).



Source: Based on HSE, 2001 (redrawn by the FAIR Consortium, 2020)

Figure 3-13 The framework of tolerable risk introduced by the HSE in the early 1990s in the UK manufacturing and process industries

3.5.8 Influence on flood management

Since the 1930-50s the concepts of risk (*e.g.,* White, 1936 and elaborated further in Chapter 4) have influenced flood management decisions. Following the major flood associated with a coastal surge in the North Sea in 1953, The Waverley Report (as introduced in Chapter 2) recommended that flood defence standards in England should reflect the land use of the protected area, noting urban areas could expect higher levels of protection than sparsely populated rural areas. In the Netherlands, following the same storm, and through the 1960s in London, the Delta Committee used rudimentary risk-based methods to help determine the design heights and performance standards for extensive new systems of flood defences. It was not until the early 1990s that the process of risk management started to become more formally and routinely used within flood management. In 1993, the UK Government published its first Project Appraisal Guidance Notes for flood and coastal erosion projects (MAFF, 1993) with the aim of improving the efficiency and effectiveness of public spending on flood management (based on an assessment of a range of probabilities and consequences as well as the whole life costs and benefits). Methods for assessing flood damage to property and disruption were established to support the consistent application of these approaches (Penning-Rowsell and Chatterton, 1977, Penning-Rowsell *et al.,* 1992, 2010 and today so-called ‘damage functions’ are available globally, JRC, 2017).

The methods of risk assessment, particularly ALARP, have been central in the evolution of approaches to dam management (*e.g.,* Hartford and Baecher, 2004; Wallis *et al.,* 2012, 2013) and in flood risk management with approaches developed through the 1990s and 2000s. In some countries, the focus remained on providing 'strong' defences but using risk-based methods to help explore national scale risks and set national safety standards and maintenance targets (*e.g.,* USACE, 1996; TAW, 2000; Sayers *et al.,* 2002a, Sayers and Meadowcroft, 2005a; Gouldby *et al.,* 2008). Other countries started to use risk-based methods routinely in the development of flood management projects and schemes at a more local scale (*e.g.,* NRC, 2000; Sayers and Meadowcroft, 2005).

In 2005, the ComRISK2 Project (an EU Interreg-funded collaboration involving many of the northern European countries bordering the North Sea) compared approaches to risk-management. The ComRISK2 analysis, for the first time, crystalised the importance of strategic approaches and, drawing upon various national documents and discussions, supported the characterisation of 'strategic risk-based planning' put forward by Sayers and Meadowcroft, 2005, namely:

- *'A proactive rather than reactive process of analysis*
- *Based upon a broad range of options – both structural and non-structural such as:*
    - *all key consequences associated with action and in-action*
    - *regulation of urban development*
    - *structural intervention*
    - *improved public preparedness*
    - *better emergency responses*
    - *insurance / compensation*
- *Encourages co-operation between stakeholders (including NGOs, Governments, and the public)*
- *Promotes long-term thinking and sustainability*
- *Provides an opportunity to undertake assessment of risks at the widest possible scale.'*

Despite these advances (or perhaps because of them) flood management has typically remained less codified than other sectors of civil engineering and hence continue to require 'risk' to be addressed in an explicit way by those involved in developing flood management interventions. It has always been acknowledged that however extreme a chosen design load, more severe conditions could be encountered (*i.e.,* designing for exceedance). It is acknowledged that absolute protection from flood hazards is impossible and that risks can only be reduced to a level that is *'as low as reasonably practicable'* (as defined by the ALARP principle introduced above). To determine what constitutes ALARP several countries, Austria, Finland, Spain, Ireland, and the Netherlands chose to debate this issue at a national scale and provide national guidelines or legal texts on the level of protection required based on a consideration of societal benefits and costs, often defining an acceptable individual risk (based on the concept of social justice through '*solidarity'*, *e.g.,* Vrijling and van Gelder, 2000, Jonkman *et al.,* 2011). Others, such as the UK, chose not to provide a national prescription of the required standard, but instead set out how government investments in flood risk management will be prioritised based on a consistent risk-informed

basis (for example as described in appraisal guidance published by the Department for Environment, Food and Rural Affairs, Defra, 2011). Such approaches tend to devolve the notion of acceptability to a more local scale and avoid the need to specify *a priori* threshold at which the risk becomes *'unacceptable*'.

A simple summary of the influence of risk-based approaches on the basis, motivations and objectives of flood management are illustrated in (Table 3-1). The boundaries between these approaches are, in practice, often blurred with many countries often adopting some form of hybrid approach (for example, in the Netherlands the management paradigm focuses on '*multiple design events'* (for defence design) leading to safety standards derived using a process of national risk assessment).

Despite risk being a well-established concept, the multiple, and sometimes subtle, dimensions of risk are often confused and continue to evolve. These important subtleties are reflected within the strategic approach promoted here and are therefore introduced below and how they link to the process and context of strategic flood risk management discussed. This is not to imply that all flood risk management approaches are based on this 'rich' interpretation of risk; many are not and, in many ways, prevent progress.

Table 3-1 A shift from flood control to flood risk management

Approach	Basis		Characteristic	Example objective
Engineering Design / Safety Standards (Traditional approach)	Probability	Historical event	To prevent flooding during a repeat of a specified historical event.	Design the flood defences to withstand the 1822 flood.
		Single design events	To prevent flooding during a storm event of a specified return period.	Design the flood defences to withstand a 1: 100-year flood.
		Multiple design events	To prevent flooding under design storms that vary according to land use/asset protected.	In highly urbanised areas design the flood defences to withstand a 1: 200-year flood. In rural areas design the flood defences to withstand a 1: 20-year flood.
	Consequence	Safety regulation	To limit the consequences of flooding during a design flood event to a specified level (safety standard) regardless of the cost.	Given the probable maximum hydrological flow ensure no individual is exposed to a chance of dying in excess of 10^{-4} and the chance of >1000 people dying is less than 10^{-7}.
Risk Management (The basis of a modern approach)	Risk	Resource optimal and multi-criteria	To implement a range of interventions that maximise benefits (across multi-criteria) and minimise whole life resource inputs.	Implement a portfolio of measures and instruments to reduce risk effectively and efficiently whilst achieving societal preferences for equity, safety, and ecosystem health. The increased resource inputs required to provide progressively greater reductions in risk should not be disproportionate to the additional benefits secured.

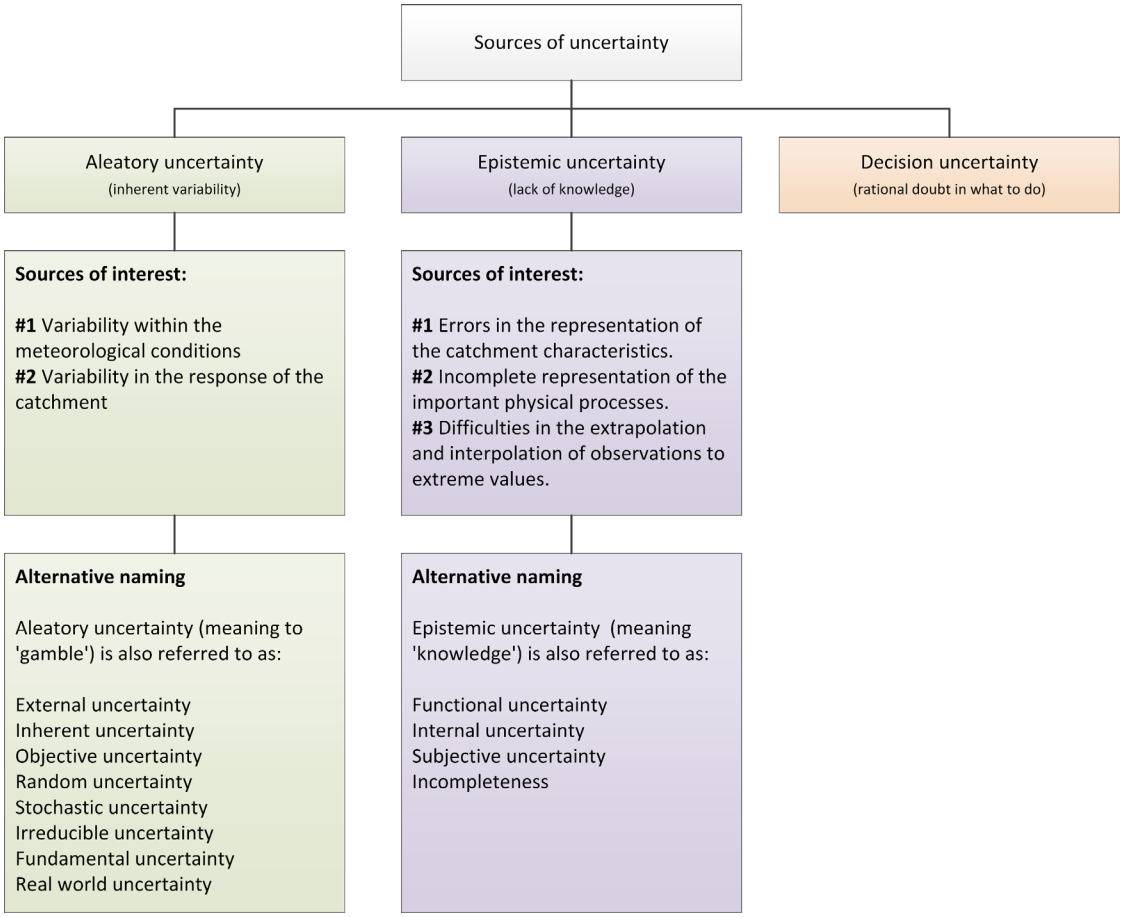
Source: Sayers et al., 2013

3.6 CONCEPTS OF UNCERTAINTY

All estimates of rainfall and flood flow contain uncertainty. Recognising this does not imply that the goal is to eliminate it – a practical and philosophical impossibility. Instead, the aim is to understand it as well as possible and judge its importance in terms of the decisions being made.

3.6.1 Components of uncertainty

Uncertainty arises from many sources (Figure 3-14). These include our lack of knowledge of the behaviour of the physical world (epistemic uncertainty), its inherent variability (aleatory uncertainty) and the complexity of our social/organisational values and objectives (decision uncertainty). Each source is elaborated below.



Source: Sayers et al., 2014b

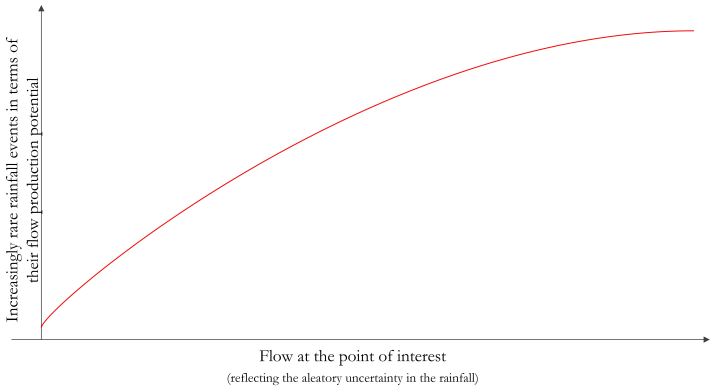
Figure 3-14 Sources of uncertainty

Aleatory uncertainties

Sometimes referred to as natural variability or irreducible uncertainties, aleatory uncertainty is associated with natural variability of storm events and the hydrological response. Engineers and scientists are used to handling the natural variability of nature's forces. It is not possible to say, for example, when a flood flow exceeding the 1in1000 AEP will next be observed at any given location in the river or at the coast. Such uncertainty reflects the stochastic nature

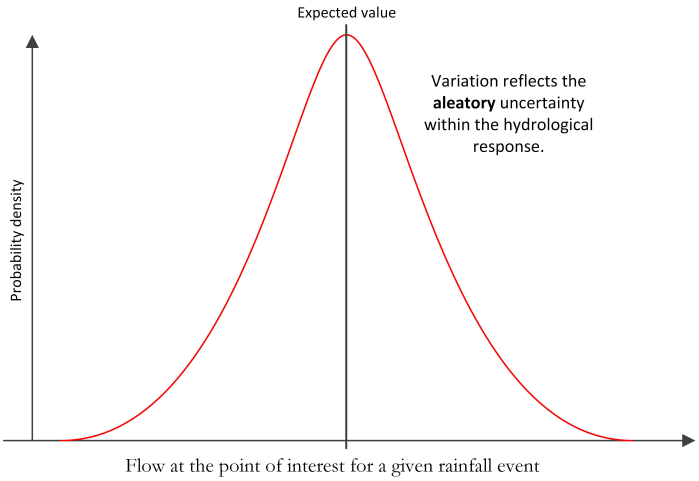
of the flood-producing processes and cannot be reduced through further research, data collection or model refinement.

Natural variability is not only present in the sequence and intensity of the driving rainfall but also in the hydrological response. For a given rainfall event the flow flood at a point will vary not only in response to the characteristics of the rainfall event (intensity, duration, spatial variation *etc.*) but also the local temperature effects influencing the micro-physics of soil wetting and drying, ice blockage *etc.* For practical purposes, additional hydrological uncertainties are likely to be considered aleatory sources, such as the morphological changes in the channel network, roughness of the floodplains, performance of control structures *etc.* Within event-based models the season of rainfall occurrence, the associated variability in catchment losses and initial reservoir level as likely to be treated as aleatory uncertainties (all of which may become sources of epistemic uncertainties within a continuous simulation model). The contribution of the aleatory uncertainty is therefore reflected in the population of rainfall events (Figure 3-15) and the hydrological response to any given event (Figure 3-16).



Source: Sayers et al., 2014b

Figure 3-15 Aleatory uncertainty – Part I: Natural variability in the severity of the meteorological drivers



Source: Sayers et al., 2014b

Figure 3-16 Aleatory uncertainty – Part II: Natural variability in the hydrological response to a given meteorological event (e.g., a range of outflows for a given PMP estimate)

Epistemic uncertainties

Epistemic uncertainties (sometimes referred to as knowledge uncertainties or reducible uncertainties) are those associated with a lack of knowledge, that could in principle be overcome. Typical epistemic uncertainties include those within input variables, model parameters as well as the model structure itself.

The epistemic uncertainty therefore reflects the uncertainty within the parameters and relationships used within the hydrological transfer functions that links inputs to outputs. Within a physically based simulation model this may require distributions to be assigned to a wide range of variables (*e.g.,* infiltration rates, evaporation, upstream blockages, *etc.*). Within a more conceptual model the number of sample variables may be much more limited. Within data-based models the uncertainties in these relationships may be expressed more explicitly.

The different components of epistemic uncertainty that typically contribute to the uncertainty in the estimation of flood flow are illustrated given in Table 3-2. These different sources are then further discussed in the following sections.

Decision uncertainty

Decision uncertainty is perhaps the only meaningful form of uncertainty as it refers to a state of rational doubt as what to do. Externalising decision uncertainty is fundamental to understanding why certain options are preferred over others. The view of the world promoted in this report asserts that uncertainty is natural and that for all important decisions there will exist to a greater or lesser extent uncertainty surrounding the selection of a course of action. This should be recognised as wholly acceptable and understanding how knowledge of uncertainty influences the preferred choice gets to the heart of our value system and the trade-offs we are prepared to make; the risks found acceptable and those that are not, the priority given to achieving social equity and fairness at the expense of the ecosystems and vice versa, and how much are we prepared to invest to reduce unknown future risks *etc.*

Table 3-2 Typical sources of epistemic uncertainty in flood flow estimates

Source	***Discussion (****Source: Adapted from Sayers et al., 2014b)*
Errors in the representation of the catchment characteristics	All measured data has errors **(measurement error**), and how these are handled and propagated through the analysis can profoundly influence the flow estimate. There are errors, for example, in rainfall depths and river flows caused by factors such as the poor siting, obstructions such as leaves, and human error in reading the measurements. Such errors tend to increase with the magnitude of the observation, and thus can have a disproportional influence on the identification of model parameters in calibration, or the derivation of rainfall frequency estimates.
	The physical feature of a catchment can all have a profound influence on flood flow generation. Changes can confound calibration of models to historic events, and how these may change in the future is unknown. Such uncertainty can undermine the ability of calibrated flood models to characterise flood flows under seen and unseen conditions.
Incomplete representation of the important physical processes	Process model uncertainties (the inability of the individual component models to faithfully represent the physical processes) arise through various means. This includes (i) through simplifications used to try and overcome known spatial heterogeneity within the characteristics (*e.g.,* using 'effective parameters') (ii) an inability to describe the response of the catchment based upon point or small scales process descriptions, and (iii) the bias within physical understanding that reflects the greater weight of evidence relevant to more frequent events and lack of evidence from extreme flood behaviour (by definition).
	The way in which the physical processes are represented within the model will contribute to uncertainty (**Model structure errors**). Understanding the contribution to uncertainty due to the chosen model structure is perhaps the most difficult challenge. For example, understanding how complete the model is and being sure that all important processes and interactions are faithfully represented is an impossible task given the extreme nature of the flows of interest (often significantly beyond what has been observed in the historic record). At such extremes the important physical processes are poorly understood and the completeness of the analysis difficult to determine.
Difficulties in the extrapolation and interpolation of observations to extreme values	Observational records are seldom of sufficient length or completeness to provide a representation of the population of potential events / situations. The shorter the record, or the more extreme the value of interest, the greater the statistical inference uncertainty. Such uncertainty is often embedded into a model through the parameter values used or the empirical relationships developed and may be opaque to the decision-maker. Calibration is often against observed data (often measured during relevant frequent events). The relationship will never fit the data perfectly and introduces error, but perhaps more challenging is whether the calibration holds true for unseen and more extreme events (**inference error**).
	The type of statistical model used to extrapolate or interpolate observations (and the assumptions made within the fitting process and selection of distribution type) can introduce uncertainty (**statistical model uncertainty**). Different statistical models may provide an equally valid fit to the data but yield a significantly different extrapolation. The difference in the extrapolation between notionally valid models – if any exist – gives an indication of the uncertainty.

3.6.2 Alternative model development philosophy

Most environmental analysis models are constructed based upon either statistical inference, deductive reasoning, or inductive reasoning. These different philosophical standpoints modify the nature of the model, the insights it provides and its ability to deal with different forms of uncertainty. A brief introduction to each is provided below.

Statistical inference

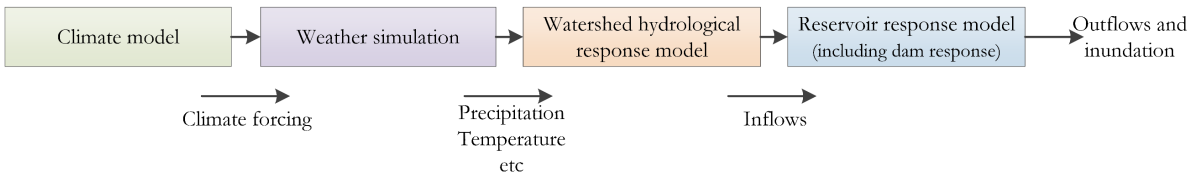
Direct observations of the variable of interest (either at-site or across a region) form the basis of the analysis. More extreme values than those observed within the record are inferred using assumptions regarding the nature of their distribution (supported by analogy to other similar locations with longer records). Although relatively simple to apply, and in uncontrolled watersheds reasonably reliable, there are several limitations:

- No ability to reflect the influence of operational control – for example direct statistical analysis of observations downstream of a dam would be meaningless due to influence of the dam on the flow record.
- No ability to explore "what-ifs" – for example climate change, urbanisation *etc.*
- Insight into uncertainty is restricted to those associated with statistical inference and statistical model choice.

Deductive reasoning

Deductive reasoning seeks to describe the hydrological system using a 'bottom-up' application of the principles of physics. This approach has dominated developments in the past decades and today physically based hydrometeorological models are widely used to estimate the way in which the important physical processes interact to deliver the flood flow at a point of interest.

Within a deductive approach the process of model development proceeds by formulating a hypothesis and testing that hypothesis against observable data. The reliability of the resulting model is reflected by how stringently observable data corroborates predictions. This approach is the basis of the majority of hydrological (and climate) models and leads to the well-recognised process of physically based simulation (Figure 3-17).



Source: Sayers et al., 2014b

Figure 3-17 Deductive reasoning underlies the well-recognised physics-based simulation models widely used today

Simulation approaches offer several advantages over statistical analysis. Perhaps the most important is their ability to reflect the inter-storm processes (through evolution of antecedent conditions) and intra-storm processes (by explicitly including the spatial coherence of the

storm, as embedded in the rainfall or flow boundaries for example). The results support a rich understanding of the drivers of extreme flows and response of the basin.

Compared to a statistical approach, physically based simulation is typically more computationally demanding and can require significantly more input data. Until recently, such approaches have been considered too complex, too data intensive and carrying too great a computational burden to be practical. Recent advances in computational power, data availability and automated software have eroded many of these difficulties and simulation approaches are starting to move centre stage as the preferred approach in many countries. This in part reflects the limited nature of observed flow records (needed for direct statistical analysis) compared to rainfall data (used to drive a simulation) that are generally longer and more abundant.

A deductive approach therefore offers several advantages, particularly the ability to:

- *Promote confidence in the results* – through a transparent approach explainable in physical terms.
- *Explore extreme responses* – by enabling forcing conditions outside of the range of the observed record to be explored (see associated limitations below).
- *Explore the influence of uncertainties* – in parameters and variables conveniently through sampling schemes (in so far as they can be meaningfully associated with probability distributions).
- *Explore "what-if" questions* – scenarios of future change can be easily incorporated and explored (land use, changed reservoir operations *etc.*).

There are several limitations of deductive approaches to be aware of, including:

- ***A potentially misleading appearance of scientific rigor and certainty*** – physics-based simulation models are necessarily based on extensions of our mental models and abstracted representations of the real world (rather than necessarily accurate representations of the real world itself). The uncertainty introduced due to the model structure (not simply the variables and parameters it contains) is therefore difficult to quantify and understand.
- ***Models become increasingly complex*** – physics-based models can range in complexity but are always a simplified representation of reality. Despite considerable literature on the problems of over parameterisation the trend over the past few decades has been towards the use of ever more detailed representations of the physics (demanding ever more computational effort) in the bid to describe the hydrological response better. Progressive reductionism, guided by a belief that physical systems can be described very well, if not exactly, based upon the well-known scientific laws (provided only that sufficient detail can be included to describe all the physical processes perceived to be important) leads inexorably to large, non-linear models (Young, 2002a). Ultimately, such a reductionist approach is not supported by our current level of physical understanding and the longstanding deterministic relationships which encapsulate it. It is widely acknowledged, for exampe, that the theoretical relationships applicable at point or small plot scale fail to

describe behaviour at a much larger, catchment, scale. The spatial heterogeneity across watersheds makes a faithful representation problematic (often requiring the introduction of 'effective parameters' that undermines the 'true' physical basis of the model). Equally, the inherent chaotic nature of some responses (and the aleatory uncertainty this introduces, see Section 7) cannot be captured properly in the deterministic representations of the physics.

- ***Lack of confidence in the performance of the system during extreme events*** – physical relationships are typically derived and confirmed in the context of frequently occurring events. It is often unclear if such relationships continue to hold true under extreme forcing (beyond the range of the observed record).

Inductive reasoning

Inductive approaches to constructing a hydrological model started to emerge as mainstream approach in the late 1980s in the form of a top-down approach. Klemeš, 1983 states that the inductive approach *'starts with trying to find a distinct conceptual node directly at the level of interest (or higher) and then look for the steps that could have led to it from a lower level'.* Thus, the inductive approach attempts to characterise the hydrological functioning of the watershed through the interpretation of the observed data at the scale of interest.

Within an inductive approach theoretical preconceptions are avoided as much as possible in the initial stages of the analysis. In particular, the model structure is not pre-specified by the modeler but, wherever possible, it is inferred directly from the observational data. Only then is the model *'interpreted in a physically meaningful manner, most often (but not always) within the context of the current scientific paradigms'* (Young, 2002b).

An inductive approach offers some attractive advantages, particularly:

- ***The model can be targeted to represent the scale of interest.*** The top-down analysis enables the model to be targeted directly at the scale of interest, hence the model can be as simple as possible without the need to reflect processes not relevant to the level. In this way, the most parametrically efficient (parsimonious) model structure for the scale of interest is proposed.
- ***The model structure emerges from the analysis.*** There is no need to prescribe the model structure *a priori*, this emerges from the analysis. By delaying the mechanistic interpretation of the model, the modeler avoids the temptation to attach too much importance to prior, subjective judgment, when formulating the model equations.
- ***Uncertainty is explicitly included.*** The relationships developed can be described directly in stochastic terms.

There are several limitations of inductive approaches to be aware of, including:

- ***Lack of confidence in the performance of the system during extreme events.*** Inductive approaches are data-led; therefore, their performance beyond the observed record is difficult to determine.

- ***Lack of ability to explore future change.*** The data-based nature of the approaches mean they are tailored to the performance of the observed system and have limited ability to explore the impact of radical changes in the watershed (*e.g.,* climate or land use).
- ***Lack of belief in a black box.*** Inductive approaches rely on an *ex-post* explanation of the physical meaning of the model relationships. This can lead to scepticism and a lack of belief in the model.

3.6.3 Decision-making under severe uncertainty

Climate and demographic change can have a profound influence on flood risk and how best to manage it. In this context, 'uncertainty' cannot be described using observational evidence to condition a probability, but the uncertainty is more profound reflecting a Keynesian interpretation:

'By uncertain knowledge, let me explain, I do not mean merely to distinguish what is known for certain from what is only probable. The game of roulette is not subject, in this sense, to uncertainty … Even the weather is only moderately uncertain. The sense in which I am using the term is that in which the prospect of a European war is uncertain, or the price of copper and the rate of interest twenty years hence, or the obsolescence of a new invention … About these matters there is no scientific basis on which to form any calculable probability whatever. We simply do not know. Nevertheless, the necessity for action and for decision compels us as practical men to do our best.' (John Maynard Keynes, 1937)

Making the right choices under this severe uncertainty is a significant challenge. Many of the choices made today will persist for several decades if not centuries, so taking a longer term, strategic view when planning flood risk management investment is critical to making the right choice. Various methods and approaches that have been applied in practice to support good decision-making under severe uncertainty, including scenario development, robust decision-making, and adaptive management (based on multi-stage interventions) and embedding adaptive capacity appropriately within the choices made. A detailed discussion of the issues and decision aids can be found in Sayers *et al.,* 2012, as summarised below:

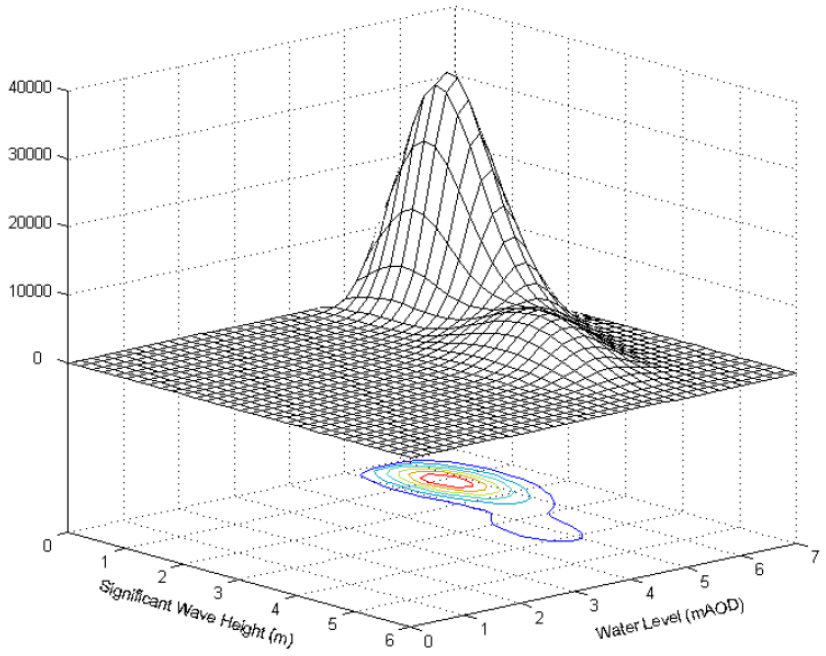
- ***Robustness and robust-satisficing.*** How to make a choice where probabilities are difficult to assign has been an ongoing subject of philosophical debate for centuries. Laplace's principle of indifference or insufficient reason involves assigning an equal probability to uncertain quantities. Yet an assignment of equal probabilities represents an exact statement about the relative likelihood of the events concerned, which is hardly a reflection of severe uncertainty. Knight (1921) recognised the situation where there is no knowledge about probabilities of uncertain events, and defined it as 'decision-making under uncertainty', in contrast to the situation when probabilities are known, which he termed 'decision-making under risk'. While there are well-established rules for how a rational decision-maker should behave when taking risk decisions (Lindley, 1990), in the case of decision-making under uncertainty there are no normative rules, although several have been proposed. Wald's maximin model (Wald, 1945) seeks to choose the option that maximises the reward given that the worst case materialises. This is a worst-case

approach and may be very conservative. More generally, a solution is thought of as being robust if it performs acceptably well irrespective of what the future holds. The approach is referred to as *'satisficing'*, a term originally introduced by Simon (1956) to describe how decision-makers seek solutions that satisfy their decision criteria rather than optimising to find the best possible performance. '*Robust satisficing'* aims to maximise the *degree of sureness* that a satisfactory outcome will result. Robust satisficing therefore asks *"are the outcomes good enough?"* and seeks to identify options that satisfy performance thresholds across multiple criteria and under all plausible future scenarios.

- ***Info-gap analysis.*** Any approach that explores option performance over a set of possible uncertain quantities relies upon definition of that set of possibilities. Info-gap analysis (Ben-Haim 2006) circumvents the need to precisely define the set of possible uncertain quantities by conducting a progressive sensitivity analysis with respect to an expanding set of possibilities.
- ***Decision trees***. Decision trees are a well-established method for analysis of sequential decision problems. They are very useful in the context of long-term planning problems, where processes of long-term change trigger particular system management decisions. Each decision point is constrained by previous actions, and each is more or less suited to different future states that may exist. The performance of each decision pathway – the set of decisions that constitute a single route through the decision tree – under each future can then be assessed against a range of future scenarios and the most robust strategy identified (either through a robust-satisficing or simialr approaches as introdcued above).
- ***Automated optimisation method****s.* Whilst the decision tree approach is intuitively appealing, the number of possible combinations and sequences of options rapidly increases, so it becomes impossibly time-consuming to exhaustively evaluate every pathway through the decision tree. To overcome this problem, automated methods to optimise flood risk management strategies have recently started to appear in the context of asset management (Sayers *et al., 2*010, 2012). The most promising methods make use of Genetic Algorithms (GAs), which have been widely used in other discrete optimisation problems, including problems with multiple objectives. The search for optimal solutions proceeds by a process that involves recombination of promising solutions with random variation to ensure that the search does not get stuck in local optima. Where multiple, and potentially conflicting, objectives are set, for example maximising net present value, minimising cost, minimising loss of life, maximising environmental gain sets of optimal solutions will be developed, each optimal with respect to single variable (for example the maximum benefit for a given level of expenditure). This set of solutions, or Pareto front, provides decisions-makers a graphical understanding of the trade-offs being made. As with any automated analysis method the outputs from the optimisation process need to be supplemented with engineering judgement. It is seldom possible to encode in the GA objective function all the considerations that infleunce a decision or design. Any solution identified therefore needs to be carefully scrutinised and, if necessary modified.
- ***Real options analysis – formally valuing flexibility.*** The theory of valuing financial options is well developed in economics. Real Options Analysis extends this theory to deal

with real-life choices, such as the decisions relevant to flood management. Keeping options open will not be cost-free. Real Options Analysis provides the theory required to estimate the financial value of mainatinng an option to *'do something*' in future. In other words, a Real Option is *"a choice that becomes available through an investment opportunity or action"* (HM Treasury 2009). Real Options Analysis has in recent years been promoted as a means of evaluating climate change adaptation decisions (Ranger *et al.,* 2010) and is increasingly recognised as applicable to flood risk management.

- ***Sensitivity analysis and visualisation.*** As with routine uncertainties the starting point for the identification of solutions robust to severe uncertainty is a process of isolating the most important uncertainties and understanding the response of decision alternatives with respect to those uncertainties. Figure 3-18 illustrates typical results from this type of analysis, based upon sampling three main sources of uncertainty (sea level rise, dyke deterioration and economic growth). Whilst a probabilistic representation of these three significant epistemic uncertainties has in this case been adopted, the approach does not integrate out the uncertainties into an expectation, but illustrates the full distribution of option performance, so decision-makers can see how performance varies over a wide range of input conditions.



Source: Sayers et al., 2012 – from Sayers et al, 2002 a plot provided by co-author Richard Dawson

Figure 3-18 Flood damage (in pounds) for an area in North Wales subject to two major sources of uncertainty – tidal level and significant wave height

Box 3-2 A cautionary note – Uncertainty is rarely (never) complete

The typical reaction when presented with an estimate of uncertainty is to believe that estimate to be a complete representation of all uncertainty. This is always not the case, due to both philosophical and practical reasons. Understanding whether the uncertainty is under- or overestimated is more problematic and as Beven (2009) points out we do not actually know.

Central to ensuring the correct 'decision' in response to the uncertainty is to clearly identify the sources of 'uncertainty' that have been included within the analysis. Equally ensuring the separate treatment of aleatory and epistemic uncertainties will promote understanding. These simple, but vital, steps are often missed leading to an ambiguity in the understanding and interpretation of 'uncertainty'; an ambiguity that is an ever-present and unresolved issue in many applications (Sayers *et al.,* 2014b).

3.6.4 Influence on flood management

'Decisions taken today will have a profound impact on the size of flood risks that future generations will need to manage. They will strongly influence the options available for managing those risks' (Foresight Future Flood Study, Evans *et al.,* 2004a, b).

Uncertainty is pervasive within flood risk assessment and in the management choices that result. To support 'good' decisions, the evidence presented must represent all important influences on the decision and be truthful about the uncertainty of the evidence presented (see earlier). Here lies a bear trap. Any presentation of uncertainty is typically viewed as 'comprehensive', yet it often reflects only a few easily described uncertainties (known unknowns). These uncertainties may lie in the data, such as errors in the measured height of flood defences, or in model components such as the assessment of defence overtopping. This dichotomy is evident in William Ruckelshaus, a former administrator of the US Environmental Protection Agency, address to US National Academy of Sciences in 1983, *"A climate of fear now dominates the discussion of environmental issues. The scientific community can help alleviate this fear by making a greater effort to explain to the public the uncertainties involved in estimates of risk"* (Ruckelshaus, 1983).

To understand, and where appropriate reduce, uncertainty in the assessed risk first relies on an unambiguous communication of the uncertainty within those estimates. This understanding helps direct effort towards data collections and method improvements that maximise the uncertainty in the assessed risks (*e.g.,* Gouldby, Sayers *et al.,* 2010). Within the decision context, recognising uncertainty in future conditions continues to mature and shape flood management. Making choices that are robust given these uncertainties (including setting out flexible plans than can be adapted as the reality of the future becomes better known) are increasingly embedded in decision-making frameworks (in support of the flood management. This includes being clear on the definition of the uncertainty, the associated sources of uncertainty and the contribution each source makes to the overall lack of sureness. Although significant progress has been made, the ability to communicate uncertainty meaningfully – in a way that reflects data, model, and crucially model-structure errors – remains difficult (Penning-Rowsell *et al.,* 2014a; Sayers *et al.,* 2016a).

3.7 SPATIAL PLANNING FRAMEWORKS

Spatial planning aims to organise the environment in which humans find themselves living in or being dependent upon. In doing so, spatial planning seeks to direct the location and distribution of land use to ensure spatial coherence in society's activities at multiple geographic scales (from a park to a town, city, region, nation and even globally). In support of this goal the process of spatial planning has evolved from its origins as a measure to control the design of individual developments to its contemporary role as (adapted from Helfer *et al.,* 2017):

- **A catalyst for investment and development.** Spatial planning choices can create opportunities for development, by incentivising the private sector investment in infrastructure and development.
- **A regulator of social wellbeing and ecosystem health.** Spatial planning has a role in providing the regulatory framework that sets out controls on development (for example, where development can take place, the degree to which it must be supported by associated investments in communications, schools or community facilities that must accompany commercial developments *etc.*).

Spatial planning is both scientific as well as an administrative discipline and is fundamentally a multi-disciplinary approach that seeks to *'balance regional development and the physical organisation of space according to an overall strategy'*.[4] As such, spatial planning is the process through which socio-economic and environmental policies are translated into development frameworks (for residential and commercial development, infrastructure networks, recreation, agricultural *etc.*) and in turn into land-use strategies that can be used to direct development in a given geographic space. Spatial planning therefore has a central role in the zonation (either nationally or locally) of land for certain purpose(s) and in setting out the regulatory controls that shape these choices; and as such as is closely related to many of the other processes (particularly basin and coastal planning) discussed here.

3.7.1 Influence on flood management

Floodplains have always been in high demand for development, a process that continues today with many of the world's most dynamic cities located in river deltas and estuaries (Bangkok, Shanghai, New York, London, New Orleans, and many others). Some development of the floodplain has been, and will continue to be, essential. In the UK it would not be sensible to forgo the development of floodplain areas in London that are already home to intensive human use (*e.g.,* Parliament and many government officers are sited within the

[4] *European Regional/Spatial Planning Charter (also referred to as the 'Torremolinos Charter'), adopted in 1983 by the European Conference of Ministers responsible for Regional Planning (CEMAT): as referenced in: http: //www.ess.co.at/spatialplanning/planning.html Accessed March 2019*

Thames tidal floodplain), for example, or to entirely retreat from the flood protected fenlands of the east coast that offer the best agricultural land in England (Sayers *et al.,* 2015c). [5] Similarly, it is not necessarily sensible for China to forgo the growth in cities such as Shanghai or Wuhan or constrain the intensification of agriculture when there is a growing population to feed; or for the Netherlands to relocate important cities and infrastructure because they are exposed to flooding. Where such development is essential, flood management is tasked with ensuring that appropriate plans and schemes are put in place to appropriately manage the associated risks.

Sometimes the need to balance the management of 'risk' and 'development' breaks down. In the United States, the federal government attempted to influence local planning decisions through the introduction of a National Flood Insurance Program in 1968 (Anderson, 1974). This offered federally subsidised flood insurance to those living in communities willing to participate in the programme. To be eligible to participate communities had to agree to control future development in their floodplain (between 1968 and 2011 more than 21,000 communities joined the programme, Galloway, 2012). In some communities, such as New Orleans, this has had the preserve outcome of encouraging a false sense of security and led to a concentration of development on the floodplain behind government 'certified levees' to access government-backed insurance; despite flood risks perhaps being lower elsewhere. Similarly, in much of the developing world *de facto* defences (often simply spoil from local dredging operations or historical agricultural levees) provide the perception of 'protection', often leading to ill-conceived and high-risk developments (Figure 3-19).

Increasingly spatial planning is seen as having an active (rather than passive) role in flood management. The increasing focus on resilience promotes a societal perspective of risk management (Sayers *et al.,* 2017a) that includes making space for flood waters (*e.g.,* by ensuring rivers remains connected with floodplains) and the natural dynamics of coasts and rivers. If well planned, such actions help reduce downstream/drift impacts and promote the environmental benefits such actions accrue. An unconstrained coast, for example, will naturally adapt to changing sea levels; retreating as they rise, advancing as they decline (Sayers *et al.,* 2017d). Few coasts are afforded this opportunity today. Squeezed between rising sea levels and landward development, there is often little room for the mangrove forests, coastal dunes, and wetlands to adapt and continue to afford this nature-based protection. Once constrained by poor planning choices, a cycle of negative feedback starts. As a coastal habitat degrades, wave attenuation weakens, its ability to trap sediment reduces and foreshores lower and steepen. Any backshore defence is soon undermined and may require significant investment to hold a given shoreline position (Figure 3-19). Spatial

[5] *Following World War II, the focus in Great Britain was on improving agricultural production and national food security (via self-sufficiency). As a result, considerable effort was directed towards land drainage in support of agriculture and the associated protection from flooding by structural means.*

planning has a central role in avoiding this downward spiral, giving room to the river, and making space for the coast to adapt. Ensuring rivers remain connected with floodplains and coastal dunes and saltmarshes are given space to respond to storms and climate change are all choices that are fundamental touchstones between spatial planning and flood management.

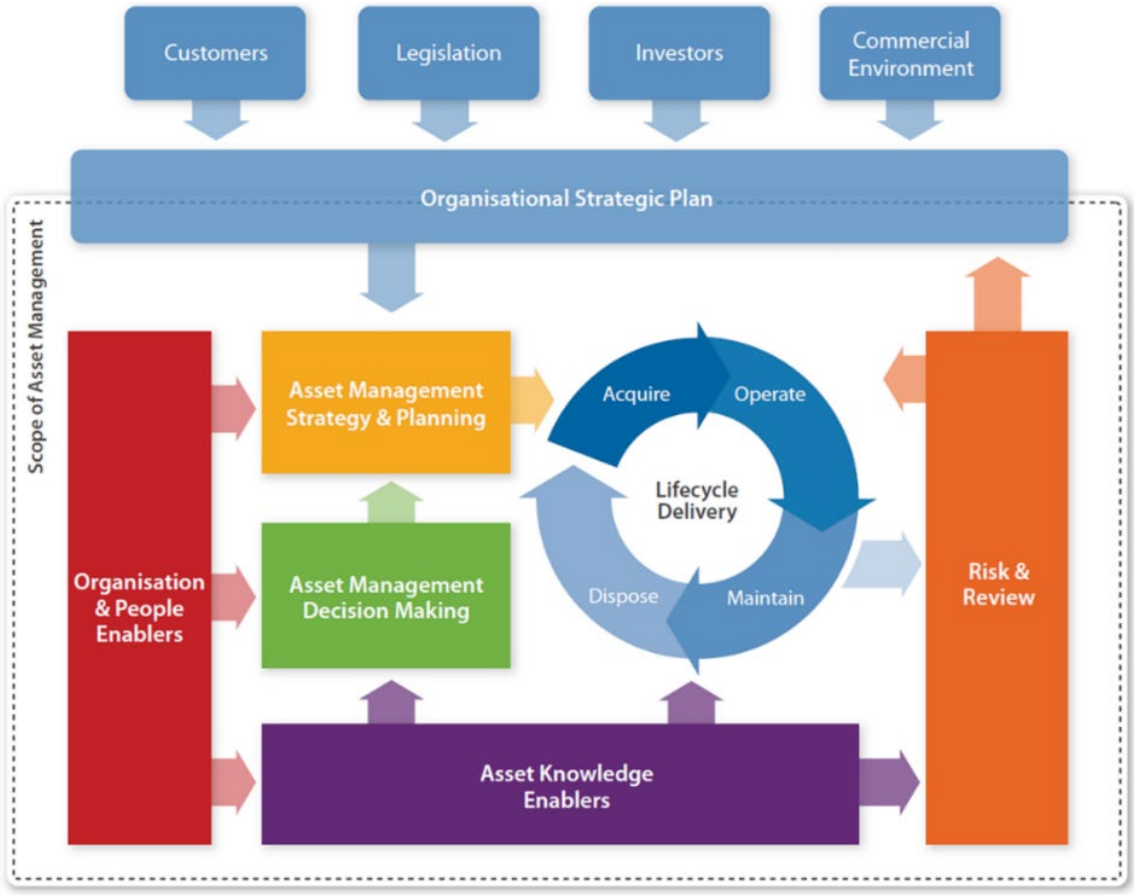


Left: Ibadan, Nigeria: Development takes place behind a de facto defence constructed of locally dredged material (Sayers) Right: Gambia: the beach is squeezed between development and the sea; unable to retreat, the beach lowers and protection is lost (Kennedy)

Figure 3-19 Spatial plan choices are inexorably linked to short and longer terms management of flood risk

3.8 ASSET MANAGEMENT

Sharing data and analysis to determine, and agree, the contribution individual assets make to the overall outcomes of interest (*e.g.,* flood risk reduction, biodiversity, water resource, carbon sequestration *etc.*) underpins deciding how best to collectively manage a complex infrastructure system with limited resources. Well-developed methods and standardised good practice already exist to support asset management (e.g. ISO, 2104; Figure 3-20) but are often applied with the implicit assumption that all assets of interest are within a single organisation. This organisational (siloed) perspective often drives an internally focused asst management process and one that can make it difficult to collaborate with others to achieve common goals.



Source: Institute of Asset Management's (IAM's) Conceptual Asset Management Model, ISO, 2014

Figure 3-20 Sustainable Water Infrastructure builds upon good practice asset management

3.8.1 Influence on flood management

The UK Government has a vision to provide *'an infrastructure network that is resilient to today's natural hazards and prepared for the future changing climate….by ensuring that an asset is located, designed, built and operated with the current and future climate in mind'* (HM Government, 2011). This goal applies equally to the wide variety of infrastructure associated with flood risk management (*i.e.,* any feature that is managed to reduce the chance of flooding) that act to 'control' flood waters and reduce the probability of flooding in most (if not all) floodplains that contain significant economic assets.

Legitimate flood infrastructure assets include local-scale features, such as houses, businesses and critical service nodes, and system-scale landscape infrastructure (including passive-built infrastructure, such as embankments, and active-built infrastructure, such as floodgates, as well as dynamic natural infrastructure from wetlands and forests to dunes and beaches. Understanding flood infrastructure through an asset management lens is at the heart developed a shared and better understanding of asset performance, both at an individual and system scale. The strategic approach advocated here builds on this movement by extending the often narrow focus on asset management to a systems perspective that includes built and natural infrastructure as legitimate assets to be managed with aim of achieving well-defined flood protection targets alongside multiple other objectives (*e.g.,* Pathirina *et al.,* 2021).

Box 3-3 Climate impacts on flood infrastructure

Climate change has the potential to impact the standard of protection flood defence assets provide as well as their condition and reliability on demand. Impacts may include increasing the rate of material degradation (*e.g.,* spalling of concrete, corrosion of steel, soil desiccation, surface cover erosion *etc.*) or changing the rate of wear and tear of mechanical components (*e.g.,* through increased 'on-demand' use). The severity of loads may change, including increased wave overtopping and flow velocities, leading accelerated damage to structural elements (*e.g.,* removal of rock armouring, toe scour, loss of surface cover).

Some infrastructure owners are starting to establish a better understanding of these impacts and how to reflect the severe uncertainties associated with climate change within infrastructure investment plans (*e.g.,* Tarrant and Sayers, 2012). For many others, climate change continues to be dealt with in a rather rudimentary fashion within the infrastructure design process (largely through the consideration of precautionary allowances applied to basic descriptions of climate loads). Little consideration is given to the impact of climate change *i.e.,* changes in rainfall, groundwater levels, coastal storms, extreme temperatures, and invasions/biological attacks on the performance of a flood asset (*e.g.,* Sayers *et al.,* 2015a). Although progress is being made much is left to do to enable infrastructure designers and planners delivering climate change-ready infrastructure, as well as highlighting opportunities that could contribute to a transformation towards adaptive infrastructure.



Left: Flood defence embankment breaches following high water levels at Corbridge in Northumberland (Courtesy of Mike Walkden 10th Jan 2005). Right: Spalling of concrete cover layer (Courtesy of the Environment Agency).



Left: Overtopping of the seawall at Samphire Hoe (Picture courtesy of the White Cliffs Country Project, taken October 1996) Right: Desiccation of the earth embankment (Courtesy of Prof Mark Dyer)

Examples of infrastructure failure and failure modes (Sayers *et al.,* 2015a)

3.9 ECOSYSTEM-BASED FRAMEWORKS

The recognition of the importance of freshwater and coastal ecosystems to human wellbeing was helped by the emergence in the 1970s and 1980s of the concepts of *'ecosystem services'* (*i.e.,* the many benefits society receives from natural systems) and *'ecosystem functions'* (*i.e.,* the functions that give rise to these ecosystem services). These concepts received little attention outside of niche environment lobbies prior to the 2005 Millennium Ecosystem Assessment (MEA, 2005). The MEA, for the first time, provided an international effort to understand the societal dependence on ecosystems and assess the consequences of ecosystem change on human wellbeing and the scientific basis for action.

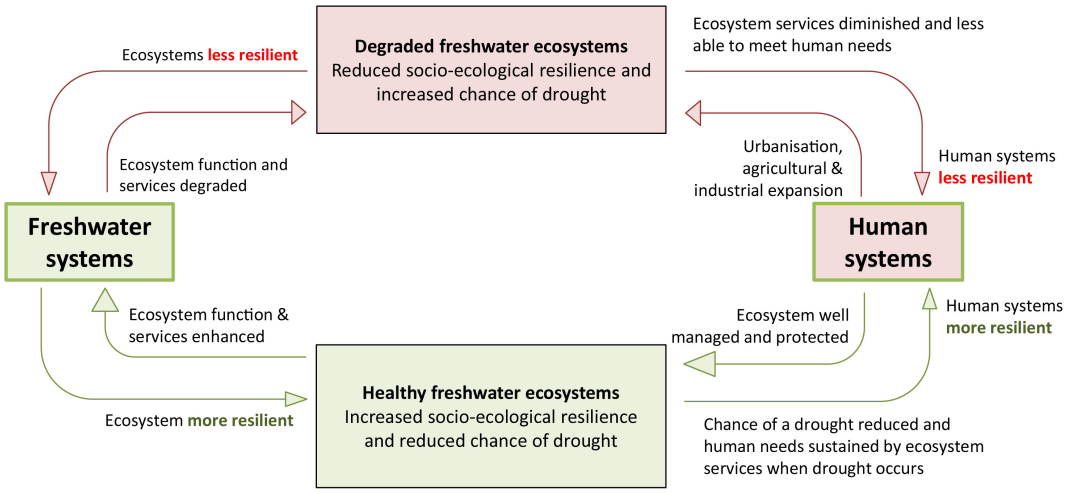
Since 2005 the notion of *'ecosystem services'* has evolved to underpin an *'ecosystems approach'*; an approach that is advocated by the UN Convention for Biodiversity (CBD[6]) and is aligned with the concepts of sustainable development. The aim of this approach is to develop *"a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way"* and has helped promote the concepts of *"ecosystems-based disaster risk reduction"* (eco-DRR) (Renaud *et al.,* 2013) and *'ecosystems-based adaptation'* (EBA) that use "*biodiversity and ecosystem services to help people adapt to the adverse effects of climate change as part of an overall adaptation strategy*" (UNISDR, 2009; PEDRR, 2011). The IPCC Special Report (IPCC, 2012) reinforces this message in stressing the value of investing in ecosystems as part of climate change adaptation strategies, and ecosystem-based adaptation has been formally endorsed by the Subsidiary Body for Scientific and Technological Advice, under the auspices of the Nairobi Work Programme of the UNFCCC (UNFCCC, 2017).

Ecosystem service approaches are often adopted in support of economic appraisal process. In these approaches, ecological variables are integrated into the decision process by assigning monetary values to functions supplied by ecosystems that are comparable to infrastructure functions such as water purification, flood risk reduction, and water storage (Seppelt *et al.,* 2011). The development and assignment of economic value to an '*ecosystem service'* is often challenging (and may be overwhelmed by other expected returns from the planned investment) and as a result such approaches have not been as widely adopted or influential as once hoped (Schröter *et al.,* 2014). As an alternative to *a priori* monetisation various trade-off approaches have emerged in recent years (*e.g.,* multi-criteria approaches, Sayers *et al.,* 2014a; Eco-Engineering Decision Scaling, Poff *et al.,* 2015). In these approaches the 'value' of the ecosystem service is described using the native parameters of the services provided enabling the trade-offs in the final choice to be visible to the decision-makers.

Despite the international recognition of the importance of ecosystems and their role in disaster-risk reduction (as promoted through implementation of the Hyogo Framework for

[6] *https: //www.cbd.int/ecosystem/sourcebook/ Accessed 08/01/2016*

Action and the Sendai Agreements, introduced earlier) and methodological advances, take-up remains stubbornly slow (Renaud *et al.,* 2013). Water management approaches in particular fail to recognise the full range of interdependencies between human systems and freshwater ecosystems, and often fail to capitalise on the potential for positive feedback between the two (Figure 3-21).



Source: Sayers et al., 2017d

Figure 3-21 Freshwater ecosystems and human systems are interdependent: Failure to recognise this linkage undermines current efforts to manage droughts and their impacts

3.9.1 Influence on flood management

Without early consideration of how best to safeguard and promote ecosystems, flood management choices can have a devastating impact on the services they provide (*e.g.,* as experienced in the Danube basin leading to significant restoration needs to improve flood protection, water quality and biodiversity (Tickner, 2013)). *'Soft path'* measures (such as land use changes, wetland storage, and floodplain reconnection *etc.*) and selective *'hard path'* measures (such as bypass channels, controlled storage *etc.*.) both offer opportunities to simultaneously manage risk and promote ecosystem services (Sayers *et al.,* 2014a, 2017d; Opperman *et al.,* 2013). Until recently little attention has been given to maintaining the beneficial relationship between floods and ecosystem services in flood management practice (although always appreciated at a local scale and in academic terms). During the middle of the nineteenth century, for example, the United States Congress passed legislation that supported the draining of wetland areas to provide room for agriculture and provided funding for flood control activities (*e.g., The Swamp and Overflowed Lands Act* of 1850 ensured that the state would be responsible for funding the attempts at developing wetlands into farmlands, Dovell, 1948). In a near complete ignorance of the ecological value of wetlands, the US Congress saw little value in these periodically inundated areas. The lack of understanding of the natural and beneficial functions of floodplains inherent in this legislation set the tone for the treatment of the floodplain environment that would continue in the US over the next century and reflected practice across much of the western world at that time (as testified by the infrastructure systems that remain; from the hidden rivers of London (Talling,

2011) to the concrete lined trapezoidal channels characteristic of many urban storm channels in the US and elsewhere).

To make gains in safeguarding and promoting ecosystems through flood management a shift in emphasis is required and good practice is emerging. To make progress, working with natural processes needs to become a central consideration – a requirement acknowledged with the recent initiative of the Environment Agency in England to promote the concepts of '*working with natural processes in flood risk management'* (Environment Agency, 2012, 2017) and the recent adoption of *"natural flood risk management"* into Scottish legislation (SEPA, 2012). The *'Building with Nature'* and the *'Room for the River'* programme in the Netherlands (introduced in Chapter 2) and *'engineering with nature'* in the US as well as more general (but similar) concepts of *'nature-based approaches'*, *'green infrastructure'* (*e.g.,* The Floods Green Guide, WWF-US, 2016)*, 'resilient by nature'* have started to move centre stage.

Legislation is starting to reflect the connection between ecosystem health and human wellbeing with an influence on flood management. In California, US the Delta Stewardship Council, created in legislation under the Delta Reform Act (2009), is mandated by the state to achieve so-called *"coequal goals"* for the Delta with the aim of *"providing a more reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem. The coequal goals shall be achieved in a manner that protects and enhances the unique cultural, recreational, natural resource, and agricultural values of the Delta as an evolving place"* (CA Water Code §85054). Improving flood protection by structural and non-structural measures is planned in the context of this broader framework (Delta Stewardship Council, 2013).

3.10 SOCIAL JUSTICE FRAMEWORKS

Social justice is increasingly promoted through international policy agendas and recognised as central to achieving sustainable and resilient futures. The Paris Climate Change Agreement made during the UN Climate Change Conference (COP21) in Paris) set ambitious targets for climate change mitigation which in effect demand transformational change in global systems of production and consumption. The UN Sustainable Development Goals and the UN-Habitat III agendas also explicitly call for transformational change and many scholarly articles highlight the importance of social justice issues under climate change such as vulnerability and its political economic determinants (Pelling 2011, Brien 2012), and the importance of a justice lens for orienting adaptation efforts in urban contexts (*e.g.,* Bulkeley *et al.,* 2013, Hughes 2013, Kind *et al.,* 2017).

'Justice' can be seen from many perspectives and a *'just'* approach is an issue of ethical debate. To act ethically implies that any action taken is motivated in the best interests of both those that act and others that may be directly or indirectly affected. An ethical approach is concerned with the wellbeing of those that benefit and those that do not as reflected through the restricted liberty principle (*i.e.,* the *'no harm principle*', John Stuart Mill, 1859) that states we are all free to act as we please as long as we do not harm others (i.e., *'Everyone has the*

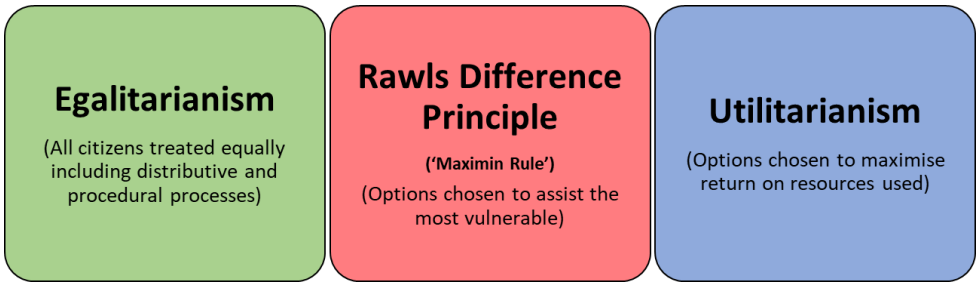
right to be safeguarded from the consequences of another person's actions' (Van Velson, 2000).

Unfortunately, many inherent conflicts exist and achieving this in practical sense can often be difficult. This does not necessarily imply an action is unethical, but it does require the decision to be legitimised through a process of *'informed consent'* (that demands all parties participate in the process based on an appreciation and understanding of the facts, implications, and consequences of an action). Those making the decision to act, have a *'moral duty'* to seek informed consent (as implied by Immanuel Kant, 1974-1804: *Critique of Pure Reason*). The only exception to the need for 'informed consent', Mill's argued, was to *'prevent harm to others'*.

In practice, issues of *'no harm'* and the meaning of *'informed consent'* are both subjective; the latter frequently used (and often inappropriately as a 'get out clause') during the 1950-80s to justify large dams and the impacts of major water transfer projects (such as the south-north water transfer scheme in China). Despite progress in recent years to make such actions more difficult to justify, a renewed focus on dam building in Africa and Asia may benefit those promoting the schemes, but whether they will have the informed consent of those impacted is questionable.

The concept of social justice recognises that ethical considerations are necessary but not sufficient to identify actions that are just. This is because 'justice' is broader than ethical consideration alone and requires a more specific framing. Various approaches offer insight here. The '*capabilities approach' (e.g.,* Sen, 2001; Nussbaum, 2009*)* to justice seeks to address the local variability in the effects and experiences of, and responses to, climate change (and by extension flood risk). Sen and Nussbaum insist that justice should not focus solely on distributive ideals, but instead on the range of capacities necessary for people to develop free and productive lives they design for themselves. The emphasis is not simply on resources but on how those resources enable individuals and communities to function. Being able to function is what is ethically significant, and injustice is found in the limitation of capabilities necessary for that functioning. Sen and Nussbaum offer differing accounts of the theory; both incorporate a broad range of justice-related concerns in their capabilities approach, including distributional equity, social recognition, and public participation.

In a practical sense, three theories of justice flow from this discussion: egalitarianism, utilitarianism, and Rawls Difference Principle (Figure 3-22). Each of these three theories of justice provide a framework basis towards one or more of the requirements of a social just approach as discussed below.



Source: Sayers et al., 2017c

Figure 3-22 Three theories of social justice as applied to flood risk management

3.10.1 Egalitarianism

Egalitarianism or rights-based theories of justice, recognise that the framework of society (its laws, institutions, policies, *etc*..) give rise to variations in the distribution of benefits and burdens across the members of that society (*e.g.,* Sen, 1992). Egalitarianism is concerned with this distribution (*distributive justice*) and seeks to ensure that all citizens have equal opportunity to have their risk managed and have equal voice in decision-making processes and governance (*procedural justice*). To translate these general propositions into more practical guidance it is useful to consider 'equality' through two rights-based lenses. Firstly, *Liberty Rights (or Privileges)* state that we all have the right to our freedom, but this places a duty upon us not to interfere with the freedom of others (*e.g.,* Thomson 1990). The second is *Welfare Rights* (or *Claim Rights*), referring to the duty of the society to provide an entitlement. For example, the right of a child (the claimant) to an education and requirement of other people (the duty bearer) to make this education accessible to that child. Hence egalitarian principles, as expressed through liberty and Welfare Rights (or Privileges and Claims as first set out by Wesley Hohfeld,1879–1918), contain both freedoms and duties (either the duty to refrain from acting or the duty to act).

3.10.2 Utilitarianism

Utilitarianism (Jeremy Benthem, 1748-1832, John Stuart Mill 1806-1873) states the action that leads to *'the best consequences is the morally preferred action',* but notes that the *'consequences'* of interest should have *intrinsic value* (*e.g.,* beauty, love, health, friendship) and not simply *instrumental value* (*e.g.,* money, that enables you buy other things). Utilitarianism provides the underpinning advocacy for a benefit-cost approach to determine the worthwhileness of an investment and is widely adopted in public sector decision-making. In practice, utilitarian approaches often default to rather narrowly defined costs and benefits (where only those benefits and costs that can be readily monetised are included). When implemented narrowly such approach is often criticised but because of its failure to include any notion of 'distributive justice' (see egalitarianism above). Applied in isolation, such an

approach would often suggest that it is preferable to maximise the collective outcome for the many to the detriment of the few, thereby prioritising efficiency over effectiveness.

3.10.3 Rawls Difference principle

John Rawls (1921-2002) developed a theory of justice in which 'fairness' plays a central role (Rawls, 1971). Rawls argues that a 'fair' approach seeks to maximise the minimum outcomes by making the choice that produces the highest payoff for the least advantaged (the so-called *'maximin rule'*). This is a powerful concept and addresses the well-known shortcoming of utilitarianism and suggests that even if considerations of efficiency indicate differently, it may be fair to spend taxpayers' money unevenly if it maximises the benefits for those who have little welfare resource. As such a Rawlsian approach focuses on the degree to which an action is effective in delivering socially just outcomes.

3.10.4 Influence on flood management

Concepts of social justice are fundamental forces that shape the strategic approach to flood risk management promoted here. The ethical framing engenders a participatory, multi-perspective, approach that involves all parties and empowers them to express, share and communicate their needs, concerns, cares, views, information, knowledges, and ideas with a view to achieving a consensus of support for the outcomes sought and the actions taken (Vojinović and Abbott, 2012). A socially just approach to flood risk management aims to satisfy all three principles (introduced above) to a lesser or greater extent (Table 3-3). How to do this continues to be explored (see Johnson *et al.,* 2007, Nada-Rajah, 2010, Penning-Rowsell, *et al.,* 2016a) and achieving demonstrably 'fair' outcomes in practice continues to be difficult to achieve (partly because the achievement of one form of justice tends to preclude the achievement of another form, Sen, 1996). In part, this may be the complexity of the challenge; but acknowledging that flood risk cannot be managed simply based on optimising narrowly defined costs and benefits is an important first step in placing social justice at the heart of the choices made and can help focus attention on deciding *"what is the right thing to do"* (Vojinović and Abbott, 2012).

Table 3-3 Social justice ("fairness" and "equity") and flood risk management

Justice principle	Rule / Criteria	Meaning for flood risk management	Potential implications for future flood risk management
Egalitarian	Rights-based approaches that seek to ensure all citizens are treated equally.	Every citizen should have an equal opportunity to have their flood risk managed.	In some countries, such as the Netherlands, the principle of "solidarity" seeks to provide a common minimum level of protection to all individuals (*e.g.,* van Alphen, 2014). The heterogeneity of the flood risk in England means that such an approach, even if achievable is likely to be grossly inefficient (Defra, 2004). Instead, a consistent decision-making process is sought, for example, enabling those at flood risk a fair chance of receiving tax funded investment.
Utilitarian	The return on investment is maximised to ensure the greatest risk reduction per unit of resource input.	Assistance provided to those members of society to which the benefits offer the greatest gain to society.	A prioritised programme of investments that provides the greatest return (reduction of risk) for each unit of resource investment. The adoption of a common approach to the assessment of benefits and costs to identify those actions that yield the greatest return (*e.g.,* Environment Agency, 2010a, Kind, 2013). Increasingly this process reflects whole-life-costs and the multi-benefits under multiple futures (although readily monetised benefits continue to dominate this process and potentially undermine the ability to maximise utility).
Rawlsian	An approach based on positive discrimination that seeks to direct resources to those least able to help themselves.	Options are chosen that target the most flood vulnerable members of society (even when greater economic returns can be found elsewhere).	The most vulnerable individuals and communities need to be identified and plans developed that specifically cater for their needs. Policy and planning processes to incorporate bias to ensure preference is given to managing flood risk for most vulnerable individuals and communities. Although many policy goals promote preferential targeting of the most vulnerable, the only formal expression of this (known to the authors) within the decision-making process is England's Flood Defence Grant-in-Aid scheme, although Scotland and Wales have more informal processes.

Source: Sayers et al., 2017c, extended from Johnson et al., 2007; Sayers et al., 2014

3.11 DISASTER RISK MANAGEMENT FRAMEWORKS

The International Strategy for Disaster Risk Reduction (ISDRR) and the associated Hyogo Framework for Action (HFA) and subsequent Sendai Framework for Disaster Risk Reduction (DRR) (Box 3-4) all reinforce the need to be better prepared for, and able to respond to, disasters (a prerequisite for the sustainable development). Therefore, although not yet fully linked with the concepts of sustainable development, Disaster Risk Reduction (DRR) and Disaster Risk Management (DRM) are certainly supportive of it.

At a national scale, various governments adopt a common framing to structure their efforts to reduce the consequences from low probability events; from extreme hurricanes to large-scale industrial accidents. Often this framing consists of a *'safety chain'* notation that considers the disaster management process as consisting of five typical stages: pro-action, prevention, preparation, repression, and recovery (*e.g.,* Jongejan *et al.,* 2012) where (i) *Pro-action* concerns risk management at its most basic level: risks can be avoided altogether by simply avoiding hazardous situations; (ii) *Prevention* concerns the reduction of risks by designing socio-technical systems in a way to ensure safe performance. But the probability of an accident, however remote, will always remain. (iii) *Preparation* involves all activities prior to an accident to improve emergency response. (iv) *Repression* is the actual response to emergencies, and (v) *Recovery* involves all activities in the post-accident phase. A similar approach is adopted by FEMA (2003) to address safety and security issues. It consists of four phases: mitigation, preparedness, response, and recovery. In real-world decision-making the notion of a *'safety chain'* does not exist in the context of a stepwise implementation and emerges as a multi-actor parallel process of decision-making and actions. As Jongejan *et al.* notes, the recognition of this reality has important implications for the assessment of risk and its management; the performance of the DRM is not as weak as its weakest link and each stage is not equal its contribution to risk management or the resources that should be devoted to it.

Box 3-4 The Hyogo Framework for Action 2005–2015 and The Sendai Framework for Disaster Risk Reduction 2015-2030

Following the 2005 World Disaster Reduction Conference the UN General Assembly endorsed a 10-year plan to make the world safer from natural hazards. The resulting Hyogo Framework for Action 2005–2015: *Building the resilience of nations and communities to disasters* (Framework for Action, 2005) sets out the principles for reducing the disaster risks, highlighting the need to:

- Ensure disaster risk reduction is a national and a local priority with a strong institutional basis for implementation.
- Identify, assess, and monitor disaster risks and improve early warning.
- Use knowledge, innovation, and education to build a culture of safety and resilience at all levels.
- Strengthen disaster preparedness to enable an effective response at all levels.

The Hyogo Framework goes on to note that in their approach to DRR local, regional, and international organisations and other actors concerned should take into consideration the key activities listed under each of these five priorities and should implement them, as appropriate, to their own circumstances and capacities.

The Sendai Framework for Disaster Risk Reduction 2015-2030 was adopted by UN Member States on 18 March 2015 at the World Congress on Disaster Risk Reduction. The Sendai Framework was the first major agreement of the post-2015 development agenda, and sets four Priority Actions (that build upon and add to the Hyogo Framework):

- Understanding disaster risk.
- Strengthening disaster risk governance to manage disaster risk.
- Investing in disaster risk reduction for resilience.
- Enhancing disaster preparedness for effective response, and to "Build Back Better" in recovery, rehabilitation, and reconstruction.

Source: Hyogo and Sendai Frameworks

3.11.1 Influence on flood management

The frameworks of disaster management are well-rehearsed in flood management. Despite the maturity of this process, the effectiveness of emergency management is always subject of intense debate post a major flood event, a debate that often focuses on a small number of common issues, including (after Sayers *et al.,* 2014a):

- **Design for exceedance.** A significant conceptual connection between the DRR and DRM agendas is the need to *plan for exceedance*, as inevitably flood defences will be overtopped/breached and drainage networks are overwhelmed (*e.g.,* Ashley *et al.,* 2007, Digman *et al.,* 2014). In such situations loss of life and injury can be significant. The effectiveness of the immediate and short-term response (*e.g.,* emergency response, through compensation and insurance mechanisms, re-establishing important services and rebuilding infrastructure *etc.*.) is critical in reducing the impact of the event and aiding recovery (*i.e.,* preventing a 'disaster').

- **Effectiveness of preparations.** Post event reviews will inevitably focus on the degree to which preparations could have been better. Often such reviews highlight common themes, including for example (Sayers *et al.,* 2014a): ***(i)*** Failure to understand the speed of onset of the flood (in response to infrastructure failures, levee breach, bridge collapse *etc.*); ***(ii)*** Failure to understand the potential for loss of life and make appropriate preparations (ranging from insufficient safe haven and evacuation planning, see Box 3-5 – although evacuation is itself a hazardous activity and is unlikely to be risk-free – to inadequate and mortuary arrangements *etc.*); ***(iii)*** Failure to stockpile sufficient emergency equipment (temporary defences, sandbags *etc.*) at appropriate locations; ***(iv)*** Unclear lines of command; ***(v)*** Poor understanding by those involved as to who does what and when; ***(vii)*** Poor communication; ***(viii)*** Poor understanding of the opposition to evacuation, and ***(ix)*** Poor prioritisation of who to assist and how.
- **Timeliness and effectiveness of warning.** Those affected by flooding commonly claim that there was insufficient warning and lack of clarity as to what they should do. One reason for this is the traditional focus on deterministic warnings (*i.e.,* a flood will occur or not), and associated concern of *'crying'wolf'* (warnings against an event that does not occur), often impedes the delivery of early warnings. In the early 1990s, for example, India's Central Water Commission conducted operational flood forecasting for several major rivers, but the results were not made public due to fear of widespread inconvenience if the (inherently uncertain) warnings turned out to be unwarranted (Sayers *et al.,* 2014a). Developing a more mature relationship between those issuing and receiving the warning in terms of the trade-off between certainty, lead time and its delivery (that focuses on enabling the recipient to take appropriate action) continues to be a focus.
- **Lack of capacity to response to very large (and widespread) emergencies:** Resources devoted to establishing a resource capability often fail to accommodate widespread or prolonged disasters. This can result in limited capacity to respond in the most significant events and authorities often rely military resources to fill the resource gap. If pre-planned and well-rehearsed this can be effective. If often called upon in a rather *ad hoc* manner with limited rehearsal the response is unlikely to be successful, or may even excersbate the impacts.
- **Under-estimation of the escalation of risks and lasting health impacts.** Numerous flood events have highlighted that emergency planning often fails to recognise: ***(i)*** the highly interconnected and mutually dependent nature of risks (see system approaches discussed later in this Chapter), and ***(ii)*** that the people and communities affected will feel the effects for many weeks, months or even years after the flood has occurred (Penning-Rowsell *et al.,* 2005, 2010). Reducing these risks involves infrastructure providers (rail, highways, telecommunications, water, power *etc.*) and health authorities (hospitals, doctors, clinics, ambulance services and other socials services) and illustrates the complexity of genuine flood risk management.
- **Moral hazard and blame.** Past decisions to develop in the floodplain can come under intense scrutiny in the aftermath of a flood. The role of insurance and taxpayer-funded

compensation for those that accepted flood risk, perhaps for commercial gain or failure to take appropriate action to reduce their own risk, acts to create a moral hazard. Providing financial support in a way that avoids rewarding those that failed to prepare and rewards those that do, whilst continuing to enable everyone to recovery as rapidly as possible is often debated, but yet to be solved. In the UK, the private floods re-insurance market fails to discount flood insurance for property owners that take measures to install flood protection products, but fire insurance is often lower for those installing appropriate alarms and doors *etc.*

Box 3-5 Lessons from Hurricane Katrina, New Orleans – Safe havens must be safe for prolonged periods

Immediately following Hurricane Katrina, New Orleans' residents who were unable to evacuate gathered at two large facilities that were out of the flood zone – the Super Dome and the Convention Center. While these structures took the people out of harm's way from flooding, the failure to provide adequate food, water, and sanitation as well as police protection created an unsatisfactory condition that led to sickness, discontent, and in some cases, crime. If a safe haven is established, planning for its use must include provision of those resources necessary to provide a safe and healthy environment for the anticipated duration of the disruption. These matters cannot be left to be dealt with during the event itself.

3.12 ADAPTATION FRAMEWORKS

In a changing world, exhibiting gross uncertainty (see earlier, Section 3.6), it makes sense to develop solutions that can be modified if the future should turn out to be different to expectations. A framework of adaptation refers to the adjustments that societies or ecosystems make to limit the negative effects of change (such as increases in heat, flood or drought arising from climate change, population change and changing societal contexts) or to take advantage of opportunities provided by these changes. Adaptation can be 'autonomous' (where the individuals and organisations recognise the need change and adjust to those changes) or 'planned' (where governance processes encourage adaptative behaviours and promote adaptation through regulation and investments procedures). Both 'planned' and 'autonomous' adaptation presents an opportunity for maladaptation – where action is taken that enhances the negative effects of future change.

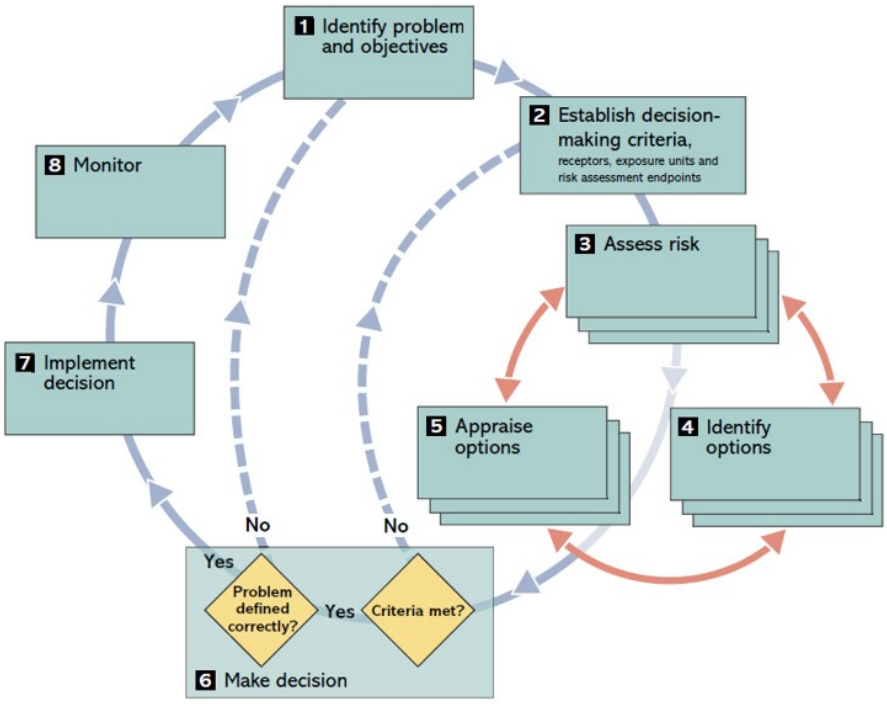
Given the future is profoundly uncertain and as a result, a rationale doubt as what to do is natural and prompted Duin & Stavleu, 2005 to note: *"If history taught us one thing, it is that it teaches us less and less. Indeed, a paradox."* And as Albert Einstein (and many others in slightly different forms) assert *"insanity is doing the same thing over and over again and expecting different result";* a reflection that resonates strongly in the context of the changing world of today and reinforces need for adaptative approach.

Recognising the future as deeply uncertain does not prevent decisions being made. Developing 'adaptive capacity' is increasingly recognised as a central response to any uncertain future (associated with climate change, development, and funding *etc.*). In turn this has promoted the move away from conventional linear models of plan development (based

upon a more certain view of the future) towards approaches that can adapt to an unknown future. Various approaches to decision-making under conditions of uncertainty have emerged to support this transition (*e.g.,* Chen and Yin, 2016; Vermeulen *et al.,* 2013, Wilby and Dessai, 2010; McGahey and Sayers, 2008; Sayers *et al.,* 2012, 2013 and 2014a,b and many others). Such approaches typically presented 'adaptation' as either (or a combination of):

- **A planning framework.** Setting out sequential decisions and roadmap of (potential) future activities.
- **A learning framework.** Setting out the process of 'adaptive management' through a learning cycle.
- **A driver of transformational change.** Focusing on the socio-institutional, governance, policy domains and the way society innovates and collaborates, and perceptions of risks evolves and the approach to decisions change.

All these framing of adaptation share common attributes – they all promote a continuous process of monitoring and action that reinvigorates the classical engineering control loop of data acquisition, decision-making, intervention, and monitoring. Consider for example the decision-making framework proposed by Willows and Connell (2003) that considers adaptation as both a planning and learning framework. This approach establishes adaptive management as a continuous process of defining objectives, assessing risks, appraising options, implementation, and monitoring (**Error! Reference source not found.**). Conditions of uncertainty and change imply a commitment to ongoing adjustment in the context of a constantly changing system and evolving set of objectives.



Source: Willows and Connell (2003)

Figure 3-23 Framework for adaptive decision-making

Recent decision-oriented adaptation approaches are framed within a "pathways" metaphor to emphasise processes change and the temporal complexity (*e.g.,* McGahey and Sayers, 2008; Ren *et al.,* 2011; Fazey *et al.,* 2016). Adaptation pathways approaches to date mostly focus on contexts with clearly identified decision-makers (for example a given infrastructure provider/utility company, or government agency) and well-defined (and unchanging) goals; as a result, they generally constrain the nature of the responses considered to those that are largely in control of the defined decision-makers and hence often fail to provide the multi-actor adaptation that may be necessary to provide a whole system response. This broader conceptualisation (recognised by Wise *et al.,* 2014 as *'pathways thinking')* is an approach that recognises interactions between sectoral adaptation plans, vested interests, and situations where values, interests, or institutions constrain societal responses to change). Designing for adaptation will often bring some additional cost and that cost will need to be justified in terms of the whole life risks in a range of uncertain futures. Various techniques are emerging as practical means of supporting this value judgement as discussed below.

3.12.1 Influence on flood management

'Decisions taken today will have a profound impact on the size of flood risks that future generations will need to manage. They will also strongly influence the options available for managing those risks' (Foresight Future Flood Study, Evans et al., 2004a, b).

Flood management has always faced the challenge of decision-making in the face of multiple uncertainties relating to the climate, the economy and society. Traditionally, this lack of forethought has often led to the need for future unplanned adaptation that takes place in response to future events (as either greater storm events are experienced, or other requirements come to the fore). This process of progressive unplanned adaptation is exemplified within the stratification of modifications clearly visible within the flood walls of the Thames Estuary (Figure 3-24). In this example, designers of the flood defence have given little thought to the uncertainty in their estimate of extreme water levels and simply 'reacted' to flood events as they have happened. In doing so, opportunities to provide less costly long-term approaches (example: perhaps by making space for the estuary or setting back tiered defences) are lost and the options available for further adaptations are constrained by past choices. This passive approach to future change is characteristic of an engineering design/safety standards approach.

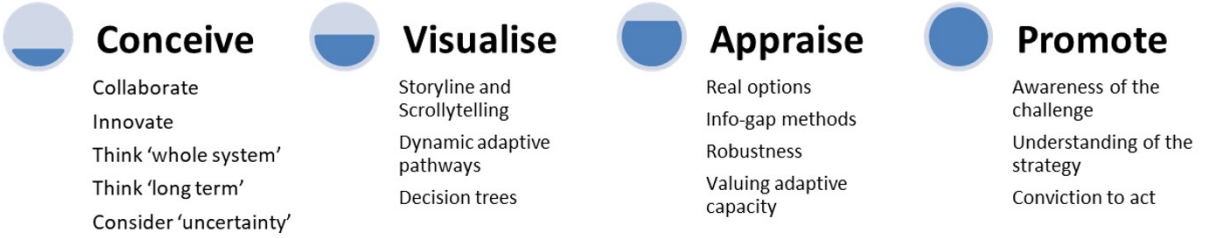


Source: Rachael Hill, Environment Agency: The Thames flood defences have evolved through a progress of unplanned reactive adaptations in response to a series of flood events

Figure 3-24 A traditional response to floods can lead to progressive reactive adaptations as along the tidal Thames, London

More recently the uncertainty has been addressed more directly, often by adopting a precautionary approach to strategy development and scheme design (often referred to as planned adaptation, *e.g.,* Brisley *et al.,* 2015). In such an approach, a single plausible worst-case view of the future is often developed and used as the basis of design (examples include precautionary allowances for sea level rise, optimism bias applied to costs *etc.*). A single linear future trajectory remains the basis of many conventional approaches and gives little or no scope for more radical changes if the future is different from that envisaged (as it inevitably will be).

The shortcomings of this approach are widely recognised (potential for lock-in to designs that are maladapted to the reality of the future and/or unnecessarily costly) and the advantages afforded by *managed adaptation* increasingly acknowledged (*e.g.,* Brisley *et al.,* 2015). A recent workshop considered how to 'make adaptation happen in practice' supported jointly by the Environment Agency and the EU INTEREG FAIR project. This included the discussion of the four ingredients needed to support planned adaptation (Figure 3-25) and the challenges and the important changes needed to make progress towards meaningful adaptation (Box 3-4).



Source: Sayers et al, 2020b (interim publication as part of the FAIR consortium)

Figure 3-25 Making adaptation happen in practice – four core ingredients

In such an approach, multiple futures are considered, and strategies developed to maximise the potential opportunity and avoid costly maladaptation. The absence of methods and tools to value adaptive approaches remains an obstacle to wider adoption. This is not to say no advances have been made; significant scientific and methodological advances have emerged in recent years (*e.g.,* Hall *et al.,* 2003a; Phillips *et al.,* 2008; McGahey and Sayers, 2008; Haasnoot *et al.,* 2012; Brisley *et al.,* 2015; Hino and Hall, 2017). Most importantly perhaps, accepting the future as unknown has several profound implications that contrast with the linear model of strategy development (based upon a more certain view of the future that is characteristic of traditional flood control decisions). This is not to imply that an adaptive approach requires more or less information on the performance of the physical and socio-economic system, simply that the uncertainty in that understanding is managed in a different way within the decision process (Table 3-4).

Table 3-4 The recognition of uncertainty has a profound impact on strategy development

Stages of strategy development	**Traditional (certain) model of strategy development and decision-making**	**Adaptive (uncertain) model of strategy development and decision-making**
Deciding what is needed	Pre-defined system of goals, objectives, and desired outcomes. Defined set of activities and resource demands.	Emerging pattern of goals, objectives, and desired outcomes. Flexible configuration of resources and priorities.
Deciding how to achieve it	Sequential process of planning, programming, and implementation. Top-down strategy development.	Continuous alignment of plans, programmes, and implementation activities with the changing world. Continuous reconciliation of the bottom-up initiatives and top-down strategies.
Understanding the external and internal influences	Stable system of decision-making. Predictable (deterministic) future change – climate, demographics, deterioration, preferences *etc.*.	Monitoring, evaluating change. Changing decision processes, strategies, and priorities. Unknown future change – climate, demographics, deterioration, preferences *etc.*.

Source: Sayers et al., 2013 adapted from Hutter and McFadden, 2009

The notion of adaptive management has influenced the way the alternative management actions are viewed and explored. This includes developing scenarios, assessing robust choices, embedding flexibility, and valuing adaptive capacity as discussed further below.

Scenario development

Scenarios can be developed as either a small number of discrete futures or a continuous spectrum of futures. Each approach has its own advantages and disadvantages in the context of supporting flood risk management policy, strategy, and engineering.

- **Discrete storylines.** A small number (up to four or five) of contrasting scenarios are developed. This approach is widespread in the field of socio-economic scenarios, where a set of narrative storylines are developed based on a small number of distinct world views. The performance of possible management actions is then assessed in the context of each discrete future and actions that perform well in a wide range of futures are identified. This approach is most useful for policy analysis which needs to be nuanced with respect to a wide range of attributes of the future, many of which may not be quantifiable. The approach is attractive in that it involves a small number of futures, so is readily communicated. It has been used in the UK Foresight Future Flooding Studies (Evans *et al.,* 2004a&b) and Schelt Estuary planning (Klijn *et al.,* 2009). In both cases, scenario analysis was used to explore high level flood risk management policies and to sucessfully influence natonal policy (for example, in England and Wales it shaped the development of *Making Space for Water*, Defra, 2005, and the subsequent *Floods and Water Management Act 2008*).
- **Continuous scenario space.** The disadvantage of the discrete storylines approach is that it deals with a relatively small number of scenarios. Moreover, the narrative basis requires further elaboration before it can be used to generate quantified inputs for decision analysis. An alternative approach, promoted most effectively by Lempert and colleagues (Lempert *et al.,* 2003) is to explore the performance of alternative policies with respect to a continuous multi-dimensional scenario space. The dimensions of this scenario space are identified to represent the main uncertain variables in a decision. Analysis of option performance with respect to this scenario space helps to identify options that perform acceptably well across a wide range of possible future conditions. This type of analysis offers advantages for engineering design in comparison to a discrete approach, as it provides the basis for quantified analysis of specific engineering alternatives and associated design characteristics (crest level *etc.*).

Robustness

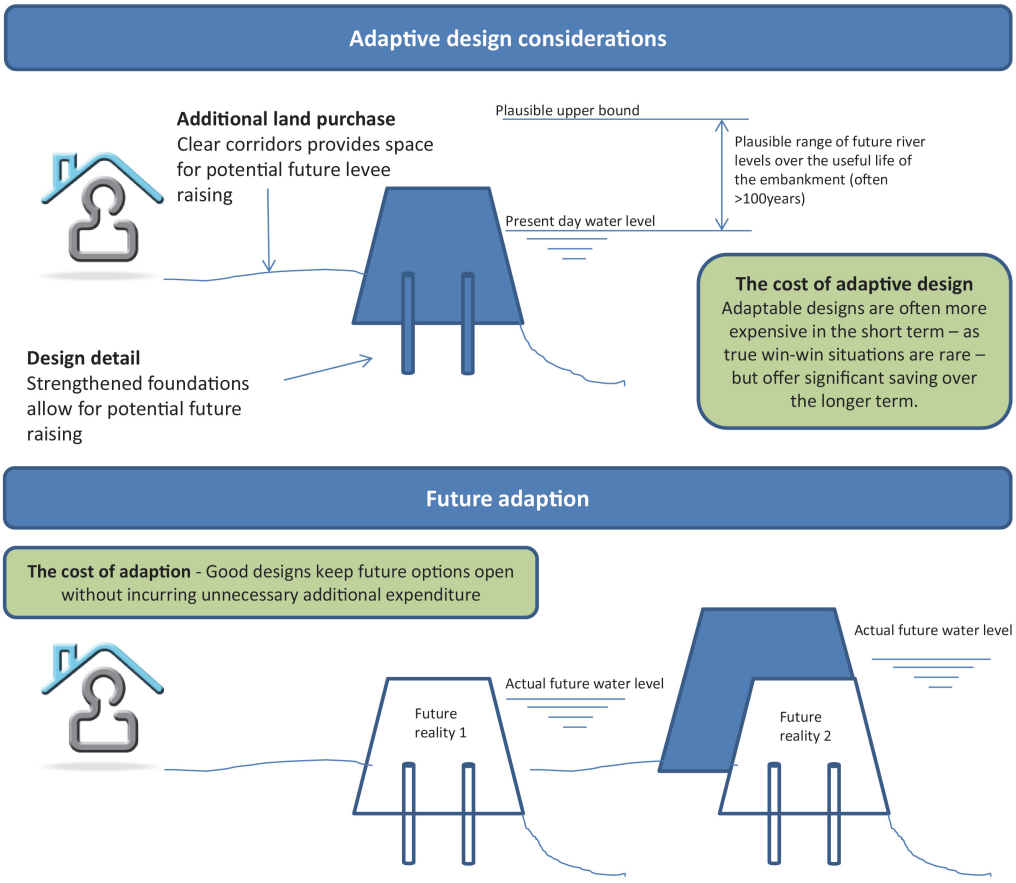
As introduced in Section 3.6.3, a solution is '*robust'* if it performs acceptably well irrespective of what the future holds. In the context of flood management choices, instead of seeking to maximise the expected value of an investment (*e.g.,* net present value), a robust approach aims to maximise the degree of sureness that a satisfactory outcome will result.. This implies and inevitable trade-off between a solution that maximises performance under an assumed set of future conditions and one that maximises the robustness with respect to a wide range of possible futures (Ben-Haim, 2006). It will often be necessary to invest more to deliver solutions that are robust. Whilst robustness is an intuitively attractive attribute, decision makers may need persuading to pay more (or sacrifice performance if some futures materialise) to provide solutions robust to uncertainty. Robustness analysis helps understand these trade-offs.

Flexibility

In a changing world it makes sense to adopt solutions that can be modified if the future should turn out to be different from expectations, and adaptive management is much easier in

systems that are flexible. Designing for planned adaptation (by which we mean designing so that a system can, if necessary, be modified in future) will often bring some additional cost and that cost will need to be justified in terms of the lifecycle performance of the design, in a range of uncertain futures. Central to this is to ensure the **strategy** itself can be changed based on monitoring and observation; avoiding including measures that foreclose future options where possible whilst promoting others that keep future choices open.

Various examples exist of an adaptable design; for example, purchasing land in the lee of an embankment to facilitate future raising or widening, or designing foundations that anticipate a heightened embankment in the future (Figure 3-26). Such options often demand greater upfront expenditure than perhaps would be the case if future change had been ignored; there are seldom true win–win situations. Flexible solutions are however likely to be more cost-effective over the longer term. Beach nourishment, for example, offers a flexible solution in that the amount of fill placed on the beach can be modified from one nourishment campaign to the next as needed, avoiding unnecessarily precaution designs (and hence cost).



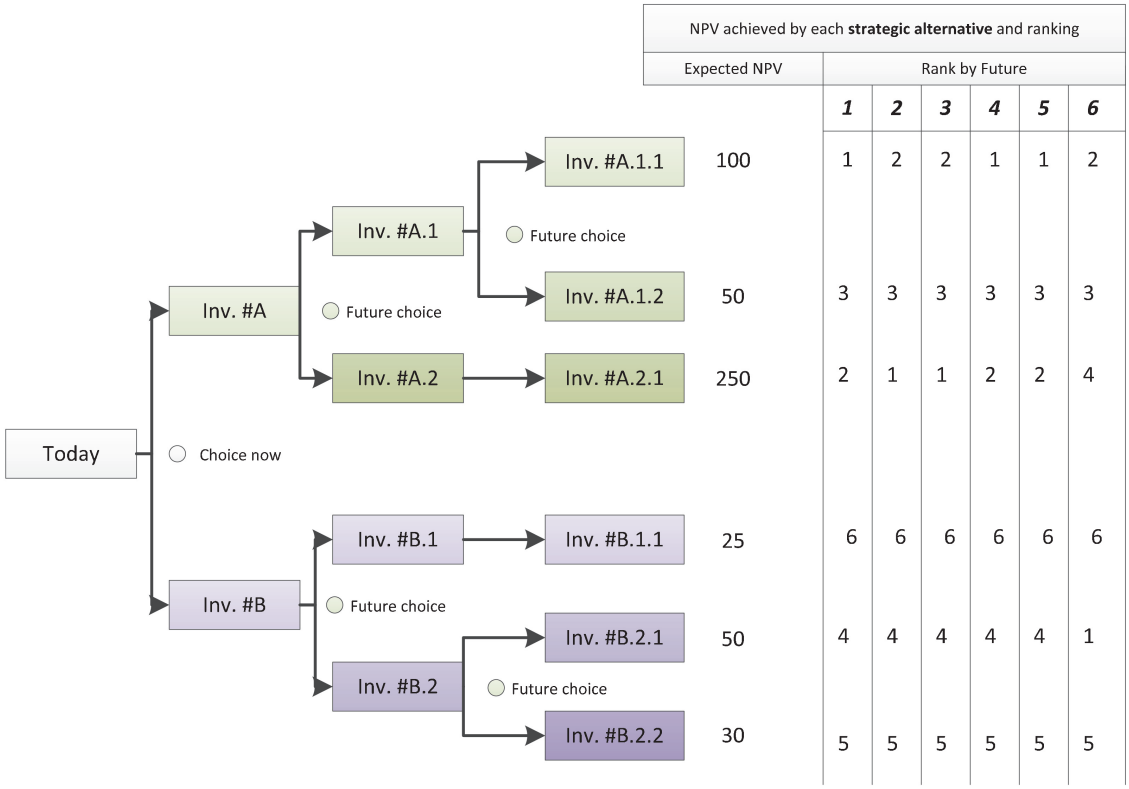
Source: Sayers et al., 2012

Figure 3-26 Adaptive design keeps future options open without incurring unnecessary additional expenditure

There is a close connection between flexibility and robustness. Flexible solutions tend to be robust to uncertainty, as they can be adapted to perform well under a wide range of possible conditions, assuming that future adaptation decisions are taken in a timely way. The methods

for robustness analysis outlined in the previous section are applicable to the analysis of flood risk management strategies that offer future choices (*i.e.,* flexibility). Various more formal techniques are starting to emerge as a practical means of constructing and analysing multi-staged decisions, including:

- ***Using decision trees to value adaptive capacity.*** Decision trees (as introdcued earlier, see Section 3.6.3) are very useful in the context of long-term planning problems, where processes of long-term change trigger particular system management decisions. Each decision point is constrained by previous actions, and each is more or less suited to different future states that may exist. The performance of each decision pathway – the set of decisions that constitutes a single route through the decision tree – under each future can then be assessed against a range of future scenarios. By taking this whole life view, flexible options are often highlighted as preferred, as they tend to perform better over a wider range of possible future conditions; this is despite the additional cost that is typically associated with flexible strategies at certain stages during the lifecycle. Analysis with decision trees provides an intuitively appealing means of developing flood management strategies and identifying those that offer maximum flexibility and do not foreclose future choices unnecessarily. Perhaps their greatest strength is their ability to identify both those actions that can be taken now, and those that should be delayed, as demonstrated through the strategic flood risk management decisions for the tidal Thames by McGahey and Sayers (2008).
- ***Real-option approaches.*** Real option analysis (introduced earlier, see Seciton 3.6.3) demands significant inputs and a degree of data and analysis that is often not practical in suport of complex real-world decision-making. More practical approaches underpin the Environment Agency on valuing adaptive capacity. By considering **altnernative strategies** and future **decsions points** flexible strategies can develop the preferred decision for today (i.e recognising the decsion that can be implemented is the one immediately at hand). Brisley, Sayers *et al.,* 2015 set out a framework of valuing adaptive capacity through multiple decision pathways, based net present value (NPV) (Figure 3-27); where the adaptive capacity is defined as the difference between the largest and small NPV outcome that remains after a practical decision point.



Source: Brisley et al., 2015 – this contribution is directly from the author

Figure 3-27 Decision tree approach to valuing adaptative capacity

3.13 RESILIENCE FRAMEWORKS

The notion of *'resilience'* has emerged in recent years as a concept in support of sustainable development. Although no blueprint is yet available as to what constitutes resilience in a practical sense, it is generally agreed to require the environmental, social, and economic functions of a human and ecological system to *'continue to function, and deliver its benefits, in the face of change, no matter the rate of change'* (Lombardi *et al.,* 2012). This builds upon notion of *'reactive resilience',* where the approach to the future is to maintain the status quo and the quest is for constancy and stability, and *'proactive resilience'*, where there is an acceptance that change is inevitable, and a resilient system is one that is capable of the necessary change (Dovers and Handmer, 1992).

Sectoral perspectives are often used to frame, and narrow, the discussion of resilience. '*Community resilience'*, as explored by Wilson, 2012 for example, reflects the local capability to plan and prepare for, respond to, and recover from adverse events and background conditions in a way that reflects the context of wider social, economic, and environmental change. The idea that by working together individuals, voluntary and community groups and other local organisations can increase the community's resilience is now well-established (UK Cabinet Office, 2011, Burchell *et al.,* 2017). These collaborative activities tend to be led by local authority emergency planners (*e.g.,* in the UK through the establishment of a Local Resilience Fora that often focus on managing short-term risks and, as a result, are less well-positioned to debate and develop more strategic solutions (Burchell

et al., 2017). Long-term community 'resilience' is more difficult to deliver and more complex to understand, including, for example, identifying (and influencing) critical nodes that will affect outcome such as household budgets and community capacity (Fazey *et al.,* 2016). *Infrastructure resilience* (*e.g.,* Guthrie and Konaris, 2012), *economic resilience* (*e.g.,* Briguglio *et al.,* 2008), city *resilience* provides a spatial lens (Lin *et al.,* 2021), *socio-economic* resilience (as explored by Hallegatte *et al.,* 2016), and *ecological resilience* (*e.g.,* Walker *et al.,* 2004, Sayers *et al.,* 2017a) adopt similar principles to focus attention on different aspects of human-natural systems. In particular, Walker introduces four aspects critical to understanding resilience: *latitude* (the maximum amount a system can be changed before losing its ability to recover); *resistance* (how resistant a system is to changed); *precariousness* (how close the current state of the system is to collapse); and *panarchy* (reliance of the individual on the health of the population, a concept built upon by Adger's (2000) definition of *'social resilience as the ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change.')*

Behavioural science perspectives advance a construct of resilience, for example McCubbin (2001) defines resilience as *'the capacity of the individual to endure and develop in the context of adverse conditions and to recognize the individual's ability to recover from adversity'.* Kaplan (2002) observes that personal resilience *'permits achieving levels of development that go beyond that which would have been reached in absence of stress'* and introduces resilience as having the ability to relate to the 'process' or the 'outcome'.

Hazard-focused perspectives of resilience are used to simplify the issue (*i.e.,* resilience to a certain type of shock or long-term change, for example heat, drought, flood *etc.*). Although it is recognised that it is not sufficient to consider resilience from the perspective of a single hazard, it is often a necessary step to challenge contemporary practice. Recognising 'resilience' as a multi-hazard endeavour can encourage a broader discussion of how to move away from the rather restricted focus on *'resistance*' and '*recovery'* to a more collective concept of resilience that involves interdisciplinary expertise and action (and develop a process of building relationships and responses across institutions, sectors, communities, and individuals, that addresses interacting systemic risks and interdependencies (*e.g.,* Hellwig, 2009; Cutter, 2010; Newman *et al.,* 2011; Twigger-Ross *et al.,* 2013, Sayers *et al.,* 2014a, Fazey *et al.,* 2016, ENSURE, 2020). This multi-hazard view is increasingly embedded in city planning contexts. Urban climate resilience, for example, is often described on three levels: **(i)** the systems of the city can survive shocks and stresses; **(ii)** the people and organisations in the city are able to accommodate these stresses via their day-to-day decision-making; and **(iii)** the city's institutional structures continue to support the capacity of people and organisations to fulfil their aims (ADB, 2014). A more specific focus on 'cities', through the Rockefeller Foundation's 100 Resilient Cities initiative is a further example of the sectoral lens that has at its core the same fundamental principles of resilience (Box 3-4). The National Development and Reform Commission, China is adopting a *'resilience'* lens to support development (Liu *et al.,* 2020).

Concepts of resilience are also progressed through international aid agendas. The United States Agency for International Development (USAID), for example, defines resilience as

'the ability of people, households, communities, countries, and systems to mitigate, adapt to, and recover from shocks and stresses in a manner that reduces chronic vulnerability and facilitates inclusive growth' (White House's Executive Order 13677 on Climate, Resilient International Development, USAID, 2015). This definition reinforces the concept that resilience covers adaptation, mitigation (reducing greenhouse gas emissions), and disaster risk reduction and places greater emphasis on the dynamic nature of systems (human and natural) and its capacity to evolve to survive, and even thrive, in the face of volatile shocks or stresses (Asian Development Bank, ADB, 2014[7]).

The foregoing highlights resilience as an emergent property of the system; and as such it cannot be measured directly. Rather the degree to which a system is resilient must be inferred through proxy metrics; the most important being one of risk. In this context a resilient society is defined here as one that exhibits *'an acceptable loss of social wellbeing, economic damage or ecosystem health when an unusual event (or combination of events) occurs – now or in the future'.* A wide range of risk metrics (individual, group, short, long term *etc.*) already exist that can be used to express the subtle and multiple dimensions of 'resilience'. Approaches exist to quantify risk and to help understand what is an '*acceptable risk*' (see earlier). Given this framing, the assessment of resilience does not require additional 'metrics' *per se*; 'risk' metrics, when considered as both 'event risks' and 'longitudinal risks' (assessed over a lifetime or longer) already provide the necessary frame of reference.

But this does not mean the framing of 'resilience' is meaningless or redundant. When considered as a management lens (as a *'process'* not an *'outcome',* the two alternative perspectives recognised by Kaplan, 2002) a 'resilience' approach is one that continues the evolution of risk management towards a whole system long-term approach. This framing is reflected in Rockefeller observable qualities of resilient city planning (Box 3-6). These are not outcomes (in the sense of a change in risk) but rather characteristics of the decision process and the actions implemented.

[7] It remains unclear if other international donors will adopt similar practice. For example, China is the world's largest infrastructure investor, and in 2015, China's state-owned development bank surpassed the World Bank in international lending (Xi Yu, 2017). Chinese developments typically aim to adopt standards of the host countries (as set out in China's Going Out Policy in 2001) and only occasionally adopt more demanding standards (as set out by the USAID for example).

Box 3-6 City Resilience Framework

Resilient cities demonstrate a range of observable qualities through their stakeholders and urban systems:

Reflective – People and institutions systematically learn from experience, with an adaptive planning mindset that accepts unpredictable outcomes. They have mechanisms to continuously modify standards based on emerging evidence, rather than seeking permanent solutions based on an assessment of today's shocks and stresses.

Robust – Robust city systems are designed and managed to withstand the impacts of extreme conditions and to avoid a catastrophic collapse of the city from the failure of a single element. A robust system anticipates system failures and makes provisions to maximise predictability and safety.

Redundant – Redundancy is to deliberately plan capacity to accommodate for increasing demand or extreme events. If one component of the system fails, other pathways or substitutable components can meet essential functional needs.

Flexible – Flexibility is a city with systems that can change, evolve, and adopt alternative strategies (in either the short or longer term) in response to changing conditions. These systems tend to favour the decentralisation of conventional infrastructure with new technologies.

Resourceful – People and institutions should invest in capacity to anticipate future urban conditions, set priorities, and mobilise and coordinate the resources (human, financial, and physical). Resourcefulness prepares a city to respond quickly to extreme events, modifying organisations or procedures as needed.

Inclusive – An inclusive approach is one that includes the consultation and engagement of communities, particularly those who are vulnerable. A city cannot build resilience in isolation of others. Resilience needs collective ownership and joint vision from various groups within the city.

Integrated – City systems, decision-making, and investments should be mutually supportive of a common outcome. Resilient system integration has evidence of systems that exist across different scales of operation. Integration requires an ongoing feedback system for collection of information and response.

Source: Arup, 2014

3.13.1 Influence on flood management

Building on the broader concepts outlined above there is an emerging consensus on the four characteristics of a flood resilient system (*e.g.,* Sayers *et al.,* 2012; Twigger-Ross *et al.,* 2014), namely:

- **Resistance (an ability to resist).** A focus on *resistance* encourages flood risk managers to reduce the chance of a flood through infrastructural responses (natural and conventional flood defences) and local infrastructure measures (*e.g.,* temporary barriers or receptor level protection) to reduce direct flood impacts and help avoid their escalation through interdependent networks at a community, regional, national and even global scale

(*e.g.,* through economies, Rinaldi *et al.,* 2001, internet communications, Hall *et al.,* 2013a; infrastructure networks, Hall *et al.,* 2013b; and ecosystems, Sayers *et al.,* 2014a). These interdependences exist at a community level too, and act to either support or undermine an individual's ability to resist an immediate loss of wellbeing (*e.g.,* due to loss of local support services, such as a doctor's surgery, or delay in receiving help due to a flooded road).

- **Recovery (the ability to bounce back).** A focus on *recovery* encourages flood risk managers to establish effective mechanisms of forecasting and warning, affordable and accessible insurance as well as the establishment of appropriate emergency service provisions that can be called upon when needed to reduce recovery times.
- **Adaptation (ability to adjust to changing conditions in a timely manner).** Limited attention has been given to the longer term, more difficult actions needed to develop the institutional, community and household agency that underpin the more broadly based concepts of societal resilience outlined above (*e.g.,* the social networks, relationships, and links between informal and formal governance structures, supporting capacity building, social learning, and organisational change). The increasing focus on climate change and the need to both *adapt* encourages flood risk managers to consider the degree to which their designs and plans may be modified to respond to future change. This includes embedding adaptive capacity within the choices made (for example, the purchase of land for future widening of a defence (or strengthening of the foundations) to enable future raising (see Figure 3-26), through to a household choosing to install property level protection measures when made aware of the flood risk they face).
- **Transformation (ability to make a step change in approach).** Numerous studies have highlighted the need for a transformation in our flood management approach towards one that adopts a whole system, risk-based and long-term perspective (Evans *et al.,* 2004a&b, Fritze *et al.,* 2008; Sayers *et al.,* 2014a, 2017a, 2021a, 2022a). Despite this, there remain few examples of radical 'transformative', with most adaptations largely incremental (but nonetheless important) adjustments to existing practices (*e.g.,* providing better protection to critical services, raising awareness, and developing evacuation plans/shelters (*e.g.,* Lumbroso *et al.,* 2008).

Adopting a 'resilience' approach is therefore an ambitious approach and one that seeks to manage a comprehensive set of short- and longer-term risks (not just flood risk) and promote capacity for future change. This implies a very substantial change. But often 'resilience' is used as a rebranding of conventional concepts and approach. The ability to 'resist' is often adopted as the primary response and unhelpfully propagates the status quo paradigm of *'flood protection'* under a different guise. The National Infrastructure Commission and draft Environment Agency Strategy for Flood and Coastal Defence promote the development of 'resilience standards'; a phrasing that tends to promulgate a narrow narrative dominated by the notion of *'resistance'.* The ability to recover is often mistakenly considered to be synonymous with 'resilience' (as shown by the attention given to forecasting, warning and emergency response in the UK Civil Contingencies Act, 2004 and National Resilience Review, HM Government, 2016); but this is only part of the resilience picture.

'Resilience' is seen here as an outcome; an emergent property of a system that exhibits the qualities outlined above. To make progress towards a resilient society relies upon the management of flood risks (including exposure, vulnerability, and hazard management). When flood management is seen in this broader 'resilience' context it reinforces the need for those involved in flood management to '*break free of the silo'* (Sayers *et al.,* 2021a), to reach out to a range of organisations, from health to infrastructure; from agriculture to conservation.

Resilience can only be discerned by observing outcomes over extended periods of time (Box 3-7). Any attempt to reflect upon a society's resilience must explicitly consider the post-event processes of recovery, adaptation and even its ability to transform. Developing measurements that provide insights into the multiple, and sometimes subtle, dimensions of flood resilience is possible but as yet do not exist. Innovative and collaborative perspectives will be important in developing metrics that provide new insights into resilience (beyond economic risk) that are sensitive to the capacity of different groups and communities to recovery (for example the Relative Economic Pain (REP) metric, Sayers *et al.,* 2017b) and recognise the inherent system vulnerabilities (tipping points within ecosystems and the infrastructure networks). A resilience perspective implies a need for a change in approach, including substantial transformative change where needed. The strategic approach promoted here seeks to support this evolution.

Box 3-7 Measuring resilience – Risk as a proxy for resilience

Resilience cannot be measured directly so tends to be quantified through proxy metrics; the most important being risk. Here a resilient society is defined as one that '*exhibits an acceptable loss (including no loss) of social wellbeing, economic prosperity, or ecosystem health over the short or longer term in response to an unusual event (or combination of events) or trend.'* This definition extends beyond the loss during the event and explicitly considers the post-event processes of recovery. This does not mean risk is a poor proxy, but flood risk must be associated with a given timeframe (*e.g.,* Sayers *et al.,* 2002b) to be meaningful in the context of 'resilience' and reflect the dependent cascade of impacts and associated probabilities over multiple timeframes (*e.g.,* intra-event, inter-event, annual, decadal, and longer).

3.14 URBAN WATER MANAGEMENT AND THE FOCUS ON CITIES

The traditional European approach to urban river management was to *'...bury them [rivers], turn them into canals, line them with concrete and build upon the (now protected) floodplains'* (Eden and Tunstall, 2006). Indeed, most urban development has historically involved transforming rivers into drains or sewers. Through the 20th century, urban river management expanded to include safeguarding people from floods and disease (Walsh *et al.,* 2005). While these remain important goals, modern approaches to urban design and river management show potential for delivery this objective alongside improved amenity and the ecological health of urban rivers (Lloyd *et al.,* 2002, *Blue-Green Dream*, Maksimović *et al.,* 2013).

This type of transition in management approach is described in a framework developed by Brown *et al.,* (2009). This framework provides the attributes of past and present hydro-social contracts[8] that reflect the evolution of the development process as cities mature and as water (inevitably) becomes more limited.

Based on a review of Australian cities, the framework describes six water management city typologies, namely:

- **Water Supply City**. Focused on providing safe and secure water supplies, usually through a centralised water supply system, for a growing urban population.
- **Sewered City** *Plus*...the development of reticulated sewerage systems to dispose of waste effluent. Examples of sewered cities first emerged in Australia in the mid to late 1880s.
- **Drained City**. *Plus*...a focus on the rapid and efficient conveyance of stormwater out of cities. Drained cities emerged in Australia after the Second World War.
- **Waterways City**. *Plus*...measures to address point source pollution, and urban planning recognises the amenity value of waterways. Such approaches commenced with the rise of environmentalism in the 1960s and 1970s.
- **Water Cycle City**. *A transition to*... urban water management based on an integrated or total water cycle approach, which involves water conservation and diverse water supplies (matched to the most appropriate uses) at a range of scales that are sensitive to the energy and nutrient cycles and ultimately contingent on protecting waterway health.
- **Water Sensitive City**. *A new state*....where environmental repair and protection, supply security, flood control, public health, amenity, liveability, and economic sustainability and all considered in urban and water management. Communities would be driven to protect intergenerational equity with regards to natural resources and ecological integrity, and to ensure resilience to climate change (Brown *et al.,* 2009).

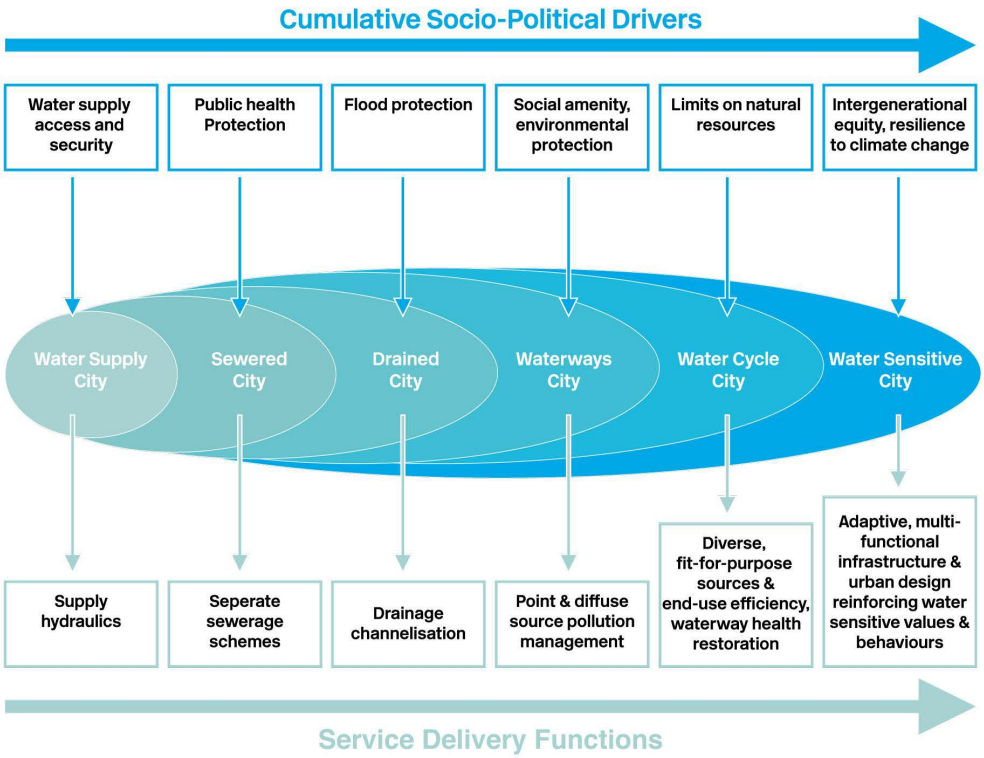
The framework recognises the different contexts that a city transitions through as it moves towards sustainable urban water condition. Each city state is linked to a range of socio-political drivers, and with those different functions that are required of the city and its waterways (Figure 3-28). The framework is designed to provide a benchmark for setting targets and measuring progress in improving urban water management. Despite significant efforts, no Australian city is regarded as fully meeting the requirements of a water cycle city, and there is currently no example anywhere in the world of a water sensitive city. While sustainable urban water management and water sensitive urban design offer alternative

[8] *A 'hydro-social contract' describes 'the pervading values and often implicit agreements between communities, governments and business on how water should be managed' (Lundqvist et al., 2001)*

approaches, urban water strategists still lack a defined vision for, and the attributes of, a sustainable water city (Brown *et al.,* 2009).

Poor practices in urban water management have been a significant contributor to the degradation of urban rivers. At the same time, implementing best practice approaches to urban water management, including retrofitting existing urban areas, is a critical tool for reducing the drivers of poor health in urban rivers.

More broadly, as populations grow and urbanisation continues to take place, cites are increasingly seen as an *'engine of change'* with peer-to-peer learning networks becoming well established (100 Resilient Cities promoted by Rockefeller and C40 Cities initiatives, representing more than 650 million people, 2018).



Source: Brown et al., 2009

Figure 3-28 Typology of different city states in transition towards water sensitivity cities management

3.14.1 Influence on flood management

The link between water sensitive urban design (WSUD) and flood risk management is conceptually well-established but unclear in practice. It is generally accepted that integrated planning and implementation is impractical. This does not mean flood management has no role in WSUD; on the contrary it does, but it is much more efficient and effective to align urban renewal, the normal processes of property and road redevelopment (Gersonius, 2012). Recognising these 'moments' of synergy can be difficult as flood issues are often considered as a constraint (to be overcome) rather than a core planning issue (Ashley *et al.,* 2012). Community focused flood management provides a means of bringing together some of these

issues but often struggles to consider the broad catchment responses (*e.g.,* McLuckie *et al.,* 2018).

3.15 SUMMARY LESSONS AND OPPORTUNITIES FOR FLOOD MANAGEMENT

The frameworks and concepts set out in this chapter have collectively influenced, and continue to influence, flood management. In response flood risk management has evolved to place a much greater emphasis on promoting multiple benefits (ecological, societal, and economic) and seek to minimise risk and maximise opportunities. In doing so, flood risk management has progressively moved away from conventional defence-led paradigms that are often characterised by the need to achieve single objectives and rely on a restricted range of management/engineering actions. In response, Sayers *et al.,* 2002b sets out several principles as prerequisites to achieving an integrated risk-based decision framework:

- **A broad definition to the flooding system, including the sources of risk and the impacts.** Arbitrary sub-division of the flooding system, for example due to geographical boundaries or administrative divisions, are avoided and a full range of possible flood sources, pathways and receptors impacts – people, economic, infrastructure disruption, ecosystem service – are considered over shorter and longer term.
- **Continuous management of system performance.** Consideration of one or a few 'design events' is replaced by consideration of a whole range of system behaviours and temporal and spatial interactions in system performance are accounted for.
- **Tiered analysis and decision-making.** The risk management process cascades from high-level policy decisions, based on outline analysis, to detailed designs and projects, which require more detailed analysis.
- **Consideration of the widest possible set of management actions that may have some impact on flood or erosion risk.** Measures to reduce the probability and measures to reduce consequence are both considered.
- **Development of integrated strategies that combine a range of flood risk management actions and implements them in a programmed way.** Management strategies are developed following consideration of both effectiveness, in terms of risk reduction, and cost with coordinated activities across stakeholder organisations.
- **Evolving with and influencing the future policy framework.** Future policy is influenced by changing management techniques.

Many of these concepts form the basis of developments in Europe (*e.g.,* Samuels *et al.,* 2010). Despite these efforts, as illustrated here progress has been slow and sporadic and many challenges remain. *'Joining up'* national, regional, and local governments to ensure the policies and regulations (and the programmes they promote) is difficult and achieving meaningful integrated action remains a significant challenge; requiring all government sectors used to working with *'regulatory instruments along vertical paths of the administrative hierarchy'* to *'cultivate more intensively forms of horizontal integration'*

(Moss, 2004). In part, this difficulty persists due to the absence of a unifying, but practical, framing. The approach promoted here shares may common features with IFRM (*e.g.,* World Meteorological Office, 2009, Walsh *et al.,* 2013). The goal of 'integration' however is recognised as potential barrier to action, and real-world problems are solved through strategic alignment and collaboration. This enables combination of bottom-up and top-down actions to take place within a common strategic framing rather than waiting of a *'perfectly'* integrated plan. The SFRM paradigm (presented in detail in the following chapters) provides the framing that is necessary, although not sufficient, to enable progress to be made.

4

FRAMEWORK OF STRATEGIC FLOOD RISK MANAGEMENT

Strategic Flood Risk Management (SFRM), as promoted here, is an approach that relies upon an adaptable portfolio of measures and policies to deliver outcomes that are socially just, contribute positively to ecosystem services and promote flood resilience. SFRM offers a practical policy and planning framework that is risk-based (*i.e.,* trades a wider set of benefits and costs over the short and long term), uses a portfolio of measures to reduce risk and promote wider opportunities (*i.e.,* avoids a narrow focus on reducing the chance of damage through the provision of 'strong' structures), and recognises adaptive management as much more than simply 'wait and see'. SFRM is implemented through a continuous process of adjustment that actively manages the changing context in which it is delivered (climate, social preferences, and investment); a characteristic that sets it apart from the linear flood defence planning paradigm based upon a narrow, and more certain, view of the future.

SFRM is a practical approach that focuses on outcomes and in doing so supports appropriately integrated planning. This sets SFRM apart from conventional 'integrated' paradigms (Integrated Coastal Zone Managed, ICZM, Integrated Water Resources Management, IWRM) that tend to focus on the process of aligning plans and the organisations. This does not mean organisational and funding alignment is ignored but is approached from the perspective of delivering multiple benefits and accepting necessary compromise to support the goals of others. In doing so, SFRM accepts there is no silver bullet to flood issues and that people and economies cannot be fully protected from flooding. It accepts flooding as an important ecosystem function and that natural infrastructure (*e.g.,* wetlands, forests *etc.*) is a legitimate flood management asset that contribute not only to ecosystem health but also to flood risk management. Perhaps most importantly, SFRM enables the inherent conflicts that inevitably exist in managing flood risk and supporting wider opportunities, to be openly debated, priorities to be set, and difficult choices to be made.

4.1 INTRODUCTION

The demand for a more strategic approach to water management, and specifically flood management, builds upon the increasing advocacy system-based approaches and the integrated action (including blending natural and built infrastructure into management choices, UN, 2015; Sayers *et al.,* 2013, 2014a, 2017d, *in press*; Speed *et al.,* 2013, 2016, *in press*; Pegram *et al.,* 2013, *in press*; Browder *et al.,* 2019).

Although ambitious, the Strategic Flood Risk Management (SFRM) as advocated here is achievable in practice. A strategic approach is stoic in its philosophy, enabling progress to be made in the complex and often messy reality of the challenges we face. SFRM promotes alignment, co-ordination, and collaboration across multiple boundaries (including political, jurisdictional, sectoral, disciplinary), but accepts 'perfect' integration is not possible. Success therefore relies upon leadership that motivates collective action and a credible assessment of risks and opportunities (to identify shared interests and agree trade-offs) and an ability to translate this evidence into shared goals and actionable investments based on good technical design.

Given this context the overarching motivation for SFRM is to support Sustainable Development (and the linked goals of water security, energy security and food security) and sits at the intersection of many planning and investment decisions. As such SFRM is in a pivotal position to be a positive force in promoting desired societal, environmental, and economy outcomes and transcend decision-making rooted in sectoral silos to provide the necessary horizontal and vertical collaboration to make progress. SFRM seeks to allow room for innovative solutions to be co-developed, co-funded and implemented in a way that supports social wellbeing, economies, and ecosystems health (*e.g.,* Sayers *et al.,* 2017a).

This chapter sets out the framework of SFRM and the underpinning characteristics.

4.2 FRAMEWORK OF SFRM

The emphasis on 'strategic' decision-making brings together information on risk (both probability and consequence) and a transparent process of trade-offs with issues of climate justice and fairness. This includes understanding issues of utility (the return on investment) as well as outcomes for the most socially vulnerable or particularly vulnerable freshwater ecosystems. This contrasts with 'standards-based' planning approaches to infrastructure that tend to focus on the need to buffer variability and seek to achieve *a priori* defined performance criteria (such as protecting a city from a 1in100-year design flood or avoiding all domestic water restrictions during a 1in500 year drought). Such criteria restrict the freedom of the infrastructure planning process and the decision-makers to develop alternative strategies that achieve the best outcomes for the resources available (*e.g.,* Sayers *et al.,* 2013). A narrow standards-based framing can unnecessarily promote 'tried and tested' designs that can be most easily linked to the required 'standards' but may provide few additional benefits when compared to more innovative options (Box 4-1).

Box 4-1 Shortcoming of a standards-based approach to infrastructure

Standards-based planning can place an unwarranted focus on 'protection' and conventional infrastructure rather than 'management' and fail to deliver maximum outcomes for people, economy and ecosystems given limited resources (a *maximost* outcome – *i.e.,* benefiting the least vulnerable the most). This lack of innovation arises because 'standards-based' infrastructure designs tend to:

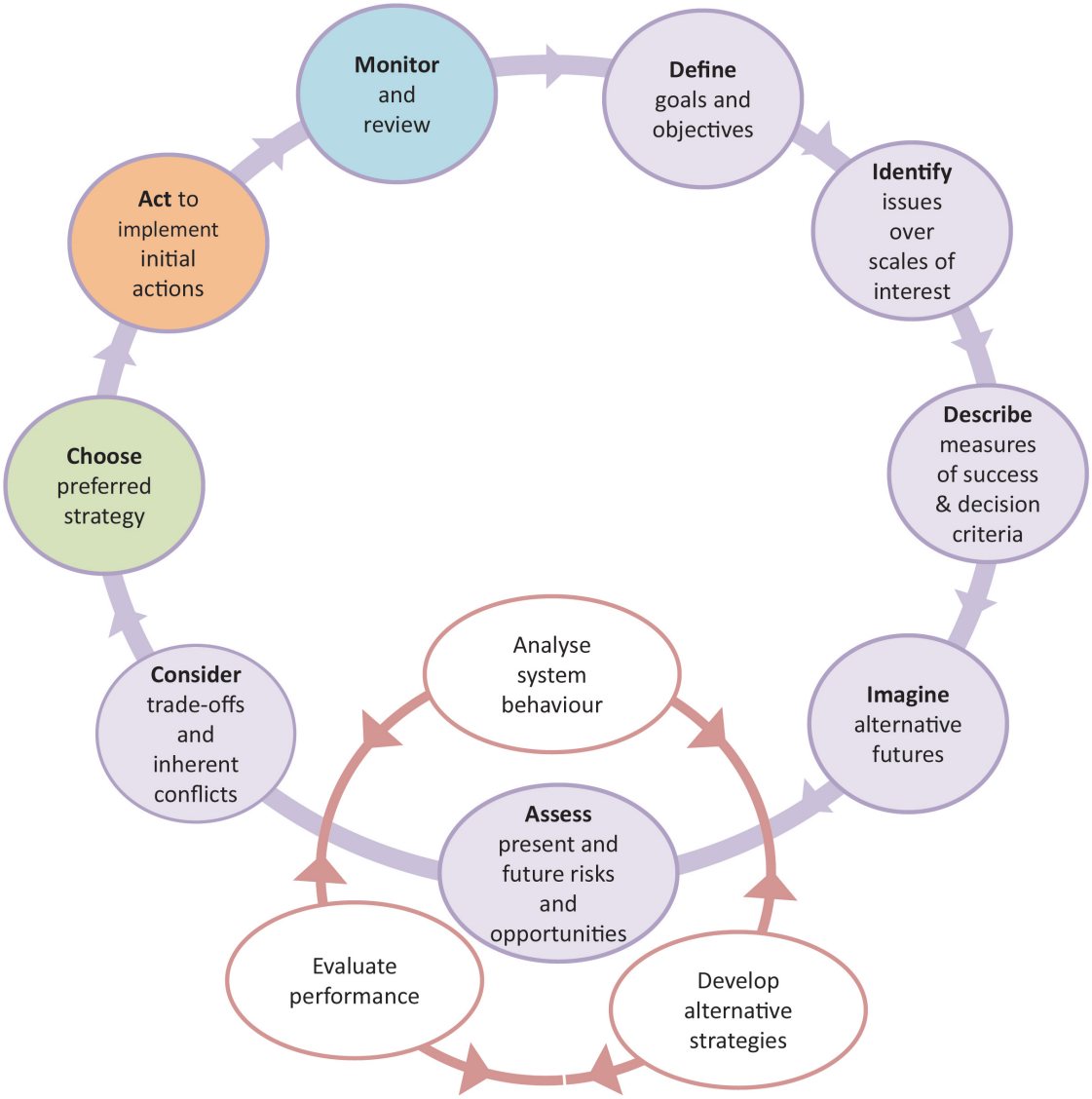
Perform only within a limited range of conditions: Stakeholders can be unsighted as to the potential impacts and trade-offs associated with events more or less extreme that the defined standard. This makes it difficult to incorporate these impacts into the decision-making process and can lead to designs that perform poorly outside of the narrow design range.

Reflect a generic context: Standards are often set within regional or national policies and as such can fail to capture locally specific issues and restrict the opportunity for local trade-offs (including the opportunities if the resources were directed differently). It may be preferable, for example, to reduce resources directed to built infrastructure and increase resources to natural infrastructure and non-structural responses as part of a portfolio of responses to manage flood risk to maintain natural functioning of rivers (*e.g.,* Sayers *et al.,* 2013).

Adopt a short-term view of the performance requirements: Standards-based approaches tend to focus on the requirements today. In doing so, the analysis tends to be dominated by short-term economic analysis that undervalues long-term natural benefits (a shortcoming that has been acknowledged for many decades, *e.g.,* Constanza, 1991)

Assume the future will be a version of the past: Standards-based approaches often lack the flexibility to incorporate future uncertainty in the decision-making process. In conditions of unknown future change the precautionary allowances that may be embedded with the chosen standard (for example, the head room allowance within a reservoir storage volume or freeboard of a flood defence) may not be suitable as the reality of the future becomes known; either too much (and resources used unnecessarily) or too small (and performance of the infrastructure compromised).

As such SFRM contrasts with a linear management model that adopts a more certain view of the future that is characteristic of traditional flood control decisions. It urges those involved to recognise the future may be different from the past and seeks to embed adaptive capacity within the choices made. This underlines the need for a continuous process of monitoring and intervention; reinvigorating the classical engineering control loop of data acquisition, decision-making, intervention, and monitoring that now reappears in contemporary thinking about adaptive management (see Chapter 3), as summarised in Figure 4-1.



Source: Sayers et al., 2013

Figure 4-1 Flood risk management takes place as a continuous cycle of planning, acting, monitoring, reviewing, and adapting

The framework of SFRM reflects the well-rehearsed adaptation cycle. Instead, the distinctive features of SFRM are not necessarily this broad framing, but rather the underpinning stoic philosophy, enabling progress to be made in the complex and often messy reality of the challenges we face. SFRM promotes alignment, co-ordination, and collaboration across multiple boundaries (including political, jurisdictional, sectoral, disciplinary), but accepts 'perfect' integration is not possible (and underpins the failure of IWRM paradigms to make significant progress). These underpinning characteristics of SFRM, and how they contrast with earlier technical (engineering focused) and unrealistic integrated (*e.g.,* IWRM) paradigms (see Chapter 2), are summarised in Table 4-1. The most important of these are elaborated below.

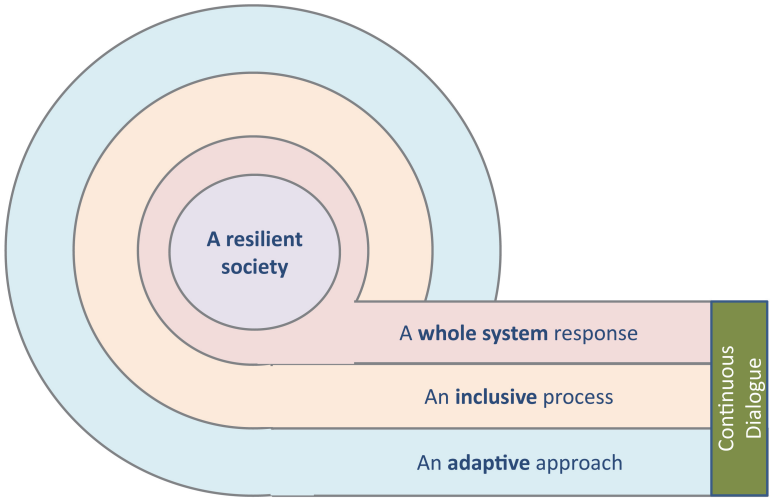
Table 4-1 The contrasting water management paradigms

Technical paradigm	**Integration paradigm**	**Strategic paradigm**
Input focus (*e.g.,* What needs to be done): Success described in terms of investments made, infrastructure built *etc.*	Process focus (*e.g.,* What needs to be done): Success described in terms of decision frameworks and planning processes.	Outcome driven (*e.g.,* What do we wish to be achieved): Success described in terms of reduced risk, biodiversity gain or other tangible social gain.
Single issue and institution focus: Considered actions from a single 'siloed' perspective or organisational remit.	Top down 'sector' centric integration: Goals promoted through policy, regulation, and sector-based master planning.	Collaborative across sectors and scales: Proactively seeks opportunities to align multiple planning processes within and beyond flood management.
Engineering driven and infrastructure focus: A process of 'predict and protect' underpins a bias to build conventional infrastructure to a priori defined standards.	Stakeholder driven (dialogue-based) and institutional focus: Prioritises changes to the system of governance through dialogue and debate, seeking consensus on requirements and who pays.	Stakeholder driven (evidence-based) whole system response: Built infrastructure seen as a 'last resort' with preference given to use of a portfolio of measures and instruments to maximise the social and environmental outcomes.
Utility focus: Preferred options chosen based on utility (return and efficiency). Little to no consideration given to the distribution of benefits and costs within society.	Procedural justice focus: Promotes the identification of winners and losers and the ensures all have an opportunity to influence the choices made.	Socially just investment: Explicit debate of trade-offs of risk, opportunity, uncertainty, and investment to selection actions based on Rawlsian principles of justice (*e.g.,* Sayers *et al.,* 2017a).
Ecosystems viewed as a competitor: Space and water for development prioritised over the environment and few safeguards applied to limit impact.	Ecosystems viewed as service provider to be safeguarded: The value of ecosystems recognised in the decision-making and actions taken to avoid significant degradation.	Ecosystems viewed as an asset to be promoted: The multiple benefits provided by natural features and processes – natural infrastructure – recognised and promoted as a legitimate component of the portfolio response and the associated benefits articulated and valued.
Project-by-project perspective and reactive to change: Based on an assumption of stationarity and designs optimised accordingly.	Ambiguous: Little guidance given to the influence of potential future change leading to linear plans with basic staged implementation.	Dynamic whole system long-term perspective that prepares for uncertain change: Accepts knowledge as uncertain and enables the strategy/response to evolve through a continuous process of adjustment, debate, and consensus.
Siloed decision-making: Primary promoters and designers drive the decision process.	Demands collaboration: Top-down planning and institutional processes seek to coerce others to align.	Facilitates collaboration: Breaks free of the silo and proceeds with a broadly based social licence.
Flooding viewed as a brake on economic growth: A focus largely placed on the assessment of economic damage and its prevention.	Flooding viewed as part of the broader role of water in development: Water is seen as a resource to be exploited/controlled with safeguards applied.	Flooding viewed as a natural process to be maintained where possible, controlled where necessary: Water is valued, including the beneficial aspects of floodplains, and recognised as central to supporting social wellbeing and healthy ecosystems.

Note: The boundaries between the paradigms will depend on their implementation in practice; those presented here are characteristic differences.

4.2.1 Outcome driven

The advantage of a strategic risk-based approach, and what above all distinguishes it from other approaches, is that it deals with outcomes; outcomes for the people, economy, and ecosystems (Sayers *et al.,* 2002a&b, 2014a). Delivering desired outcomes relies upon credible and transparent evidence on the risks reduced and benefits gained (Box 4-1). This aligns with the broader notion of resilience as an outcome (rather than a process) and the four enablers of this outcome (Figure 4-2).



'Resilience is seen as an outcome of society that is: appropriately prepared; appropriately protected; capable of adapting; capable of transforming'.

Sayers et al., 2022a

Image: Sayers at al., 2020b
Figure 4-2 SFRM supports the four enablers of resilience

Managing flood risk in this context is characterised by the need to continuously deal with uncertainty (*e.g.,* Hall *et al.,* 2003a, McGahey and Sayers, 2008, Hutter and Schanze, 2008, Sayers *et al.,* 2013, Haasnoot *et al.,* 2013). The timing and severity of a storm, the associated performance of the structures and the reaction of individuals and communities to flood events cannot be known with certainty. A risk approach enables this uncertainty to be explicitly recognised within the decision process. In turn, this supports making choices that are robust to that uncertainty. An often-held misconception is the need to remove uncertainties within data or models and that it is necessary to gather ever better data and apply increasingly sophisticated models to manage flood risk successfully. This reductionist perspective can add unnecessary complexity with limited improvement in decision meaningful knowledge (*e.g.,* Sayers *et al.,* 2010). Uncertainty is only important when it influences the choice to be made; if it does not, any additional expenditure on data or analysis is wasted. Some uncertainties, however, have a profound influence on decisions. The importance of a given uncertainty (for example on the location of vulnerable people or ecosystems due to gross uncertainties in future climate or demographics) can only be assessed in the context of a specific decision. A strategic approach to flood risk management as advocated here, provides a framework within which uncertainty can be explicitly identified and managed (for example promoting strategies that are robust to future change, performing well in all plausible futures, and capable of adapting to new information as it becomes known). By recognising uncertainty explicitly, flood risk managers can choose how to best to respond.

Box 4-2 Flood risk management outcome measures

Increasingly multiple measures are used to describe the desired outcomes from an ongoing flood risk management effort. Typically, such outcome measures include risk to economies and people as well as the risk to ecosystems. They also include societal and individual risks and reflect risk arising during a specific event, annual expectations, and long-term performance.

The most common outcome measures typically focus on the three pillars of sustainability (introduced in Chapter 3). The detail of the chosen outcome measures varies according to the decision context they relate to (national or regional governance for example) and local context of the issues. The general framework of the outcome measures will remain the same and include consideration of:

Measures of economic sustainability. These focus on the likely economic losses that could be incurred in either a single event or an annual expectation. Importantly, measures of economic sustainability link to social and ecosystems through concepts of "fairness" and "viability". Economic measures of sustainability therefore place potential losses in the context of the local and national wealth (as measured for example through the GDP) and the availability of resources to deliver flood risk management to reduce losses, now and over the longer term.

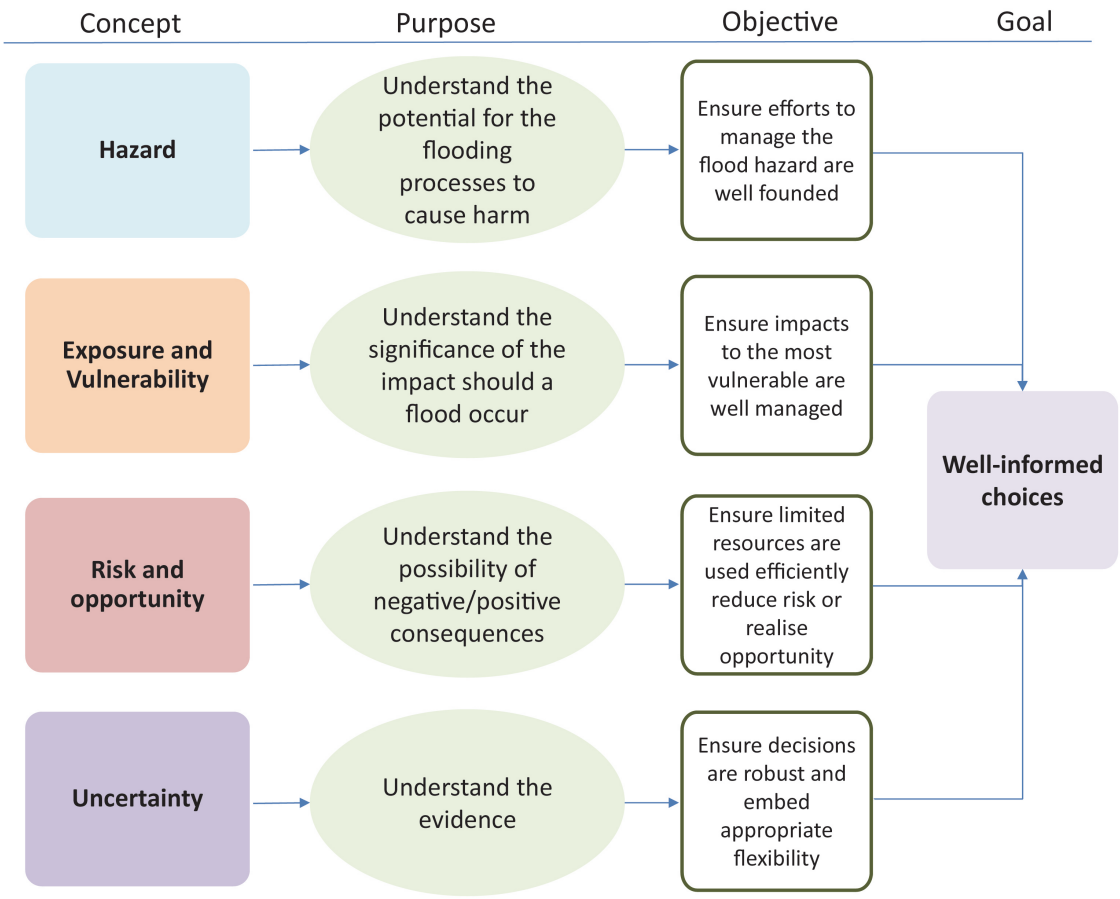
Measures of social sustainability. These focus on the impact that flooding, and its management, may have on the well-being of society and individuals and link to economic and ecosystem sustainability through "fairness" and "bearability". In providing these measures the degree to which risk management decisions consider the needs of all individuals and treat all groups fairly (with special attention to the most vulnerable) can be assessed. No single quantified definition of social justice exists, and many have developed different interpretations of what constitutes fair treatment and a just share. It is therefore important for the flood risk manager to define these in the context of a flood risk analysis and the decision-making process to be adopted.

Measures of ecological sustainability. These focus on maintaining the environment's natural qualities and characteristics and its capacity to fulfil its full range of functions, including the maintenance of biodiversity and ecosystem connectivity and function. Ecological sustainability links to economic and social wellbeing through "viability" and "bearability". These are typically measured in terms of long-term gains and losses to the ecosystem or a measure of the relationship between organisms and their environment and how this may potentially be enhanced (or impacted).

Source: Sayers et al., 2013

4.2.2 Based on evidence

Well-informed choices rely upon evidence (*e.g.,* Evans *et al.,* 2004, Chetty *et al.,* 2009, Head, 2014). For flood risk management four strands of evidence are central: (i) hazard; (ii) exposure and vulnerability; (iii) risk and opportunity, and (iv) uncertainty (Sayers, 2017 – Figure 4-3). This enables alternative courses of actions and investment choices to be compared in the round and well-informed choices to be made. The underlying principles of the concepts set out in Figure 4-3 have been previously introduced in Chapter 3 but are revisited below in terms of their role in strategic decision-making.



Source: adapted from Sayers et al., 2017a

Figure 4-3 SFRM uses an understanding of exposure, vulnerability, risk, opportunity, and uncertainty to make informed choices

Hazard

An understanding of the flood hazard that has the potential to cause harm is the foundation of all decision-making. Flood hazards are often incorrectly conflated with extreme rainfall, river flows or a coastal surge. This misunderstanding leads to a misdirection of resources. The flood hazard is the hazard that has the potential to cause harm to a receptor and hence relates to the inundation. Typically, the hazard is defined in terms of the depth, velocity, duration, and contamination of the flood water at a location. The chance of the hazard occurring reflects how the storm event is moderated through the physical geography to lead to a flood in a given location (so reflects the probability of the combination of the state of the source and pathway (introduced in Chapter 3), the so-called system state).

To develop a rich understanding of the hazard does place several additional demands on the analyst in comparison to traditional methods. These include understanding and appropriately representing:

- ***Joint extremes.*** How likely are multiple sources to occur simultaneously? For example, storm surge and local rainfall (*e.g.,* as associated with typhoon) or earthquake loading (and liquefaction of its foundations) and tsunami wave loading (*e.g.,* as experienced by

sea defences along the coast of Japan, 2011). Is a particular reservoir more likely to experience an earthquake when full?

- ***Spatial coherence of the flood events*.** How widespread is a single event likely to be? What is the chance of flooding impacting the whole region or basin (as in the recent floods in Pakistan, 2010) or will it be highly localised (associated with a thunderstorm induced mudslide or flash flood)?
- ***Temporal coherence of the flood events*.** Are certain sequences of events more or less critical than larger single events?
- ***The performance of pathway channels, defences, and other control structures*.** In many floodplains, the flood hazard is moderated by both local flood protection assets (dykes, embankments *etc.*) and remote assets (including in natural and build infrastructure in the upstream catchments or within the connected coast). Representing the performance of these assets, where they exist, and how they may change during a storm and between storms is often a central consideration in providing a credible representation of the hazard.

Exposure and vulnerability

To understand the significance of the potential impact should a flood hazard occur relies upon an understanding of the potential for negative welfare outcomes for people, loss of biodiversity, and economic damage. Understanding both **exposure** (the individuals, organisations, habitats, that may be either directly or indirectly exposed to a flood hazard) and **vulnerability** (the potential for a given receptor to experience harm when exposed to a given hazard) is central to this (as elaborated earlier in Chapter 2). To support decision-making, it is necessary to move beyond the often-used interpretation of vulnerability simply as depth v damage relationships (that has underpinned many risk assessments, from Evans *et al.,* 2004 to Hinkel *et al.,* 2019) to provide a more insightful understanding to support 'fair' decisions that manage the risks faced by the most vulnerable as well.

Evaluating a **Rawlsian** perspective of fairness (see earlier in Table 3-3) relies upon ensuring the risk faced by the most socially vulnerable is well-managed. Social vulnerability refers to the combination of the inherent characteristics of people that make those exposed to a hazard more or less likely to experience a negative welfare outcome. Social vulnerability is influenced by multiple social indicators (including bio-physical indicators such as older age groups and people with pre-existing ill-health as well as factors such as income, property tenure, access to insurance and access to support to enable adaptation, including who pays, Penning-Rowsell and Priest, 2015b). The combination of hazard, exposure and social vulnerability provides insight into spatial variation in social risk (referred to here as *Geographic Disadvantage, Lindley et al., 2011, Sayers et al., 2017b)*. Extending this understanding explores the systemic nature of disadvantage by comparing the risks faced by the most socially vulnerable with others (referred to as *Systemic Disadvantage,* Sayers *et al.,* 2017b, and arises when the risks faced by the most socially vulnerable are greater than those experienced by others within the same group). Insight into the Systemic Disadvantage supports the development of a just (*i.e.,* fair) approach to adaptation.

Issues of autonomous recovery are important considerations in understanding vulnerability. A home that is well-insured, for example, may be able to recover without the need for external intervention, or a healthy ecosystem, that has room and time to recover from the hazard event, may suffer in the short term but maybe be able to recover quickly without external aid. There are limits to this capacity, and thresholds (in terms of the frequent or severity of the hazard) that make autonomous recovery not possible. Understanding the limits of recovery can be important in supporting an appropriate response to securing the space needed for ecosystems to adapt (*resilient by nature*) and taking action to manage the hazard and provide support to aid recovery.

Risks and opportunity

A risk and opportunities lens enables the alternative courses of action (or inaction) to be compared using common economic, environmental, or people-based metrics. The choice of metric relates to the context of the decision (see examples in later chapters). The assessed risk and opportunities can be assessed to ensure resources are used efficiently (using Net Present Value, Benefit Cost Ratio or Internal Rates of Return or similar metrics) and effectively (by understanding the conditional consequence or opportunities across a range of probabilities, *i.e.,* how many people are exposed to a 1in100 year return period hazard, for example).

Uncertainty

An understanding of uncertainty provides the evidence to ensure that decisions made are appropriately robust and are likely to continue to perform as desired despite this uncertainty. Uncertainty within the analysis chain is not simply additive (as often falsely assumed within description of the uncertainty cascades, Toimil *et al.,* 2021). Often uncertainties within the analysis chain diminish when considered in terms of the contribution to the rationale doubt over how to proceed. This decision perspective enables knowledge of 'uncertainty' to be explicitly used in the decision-making process.

4.3 FOUR CORE CHARACTERISTICS OF SFRM

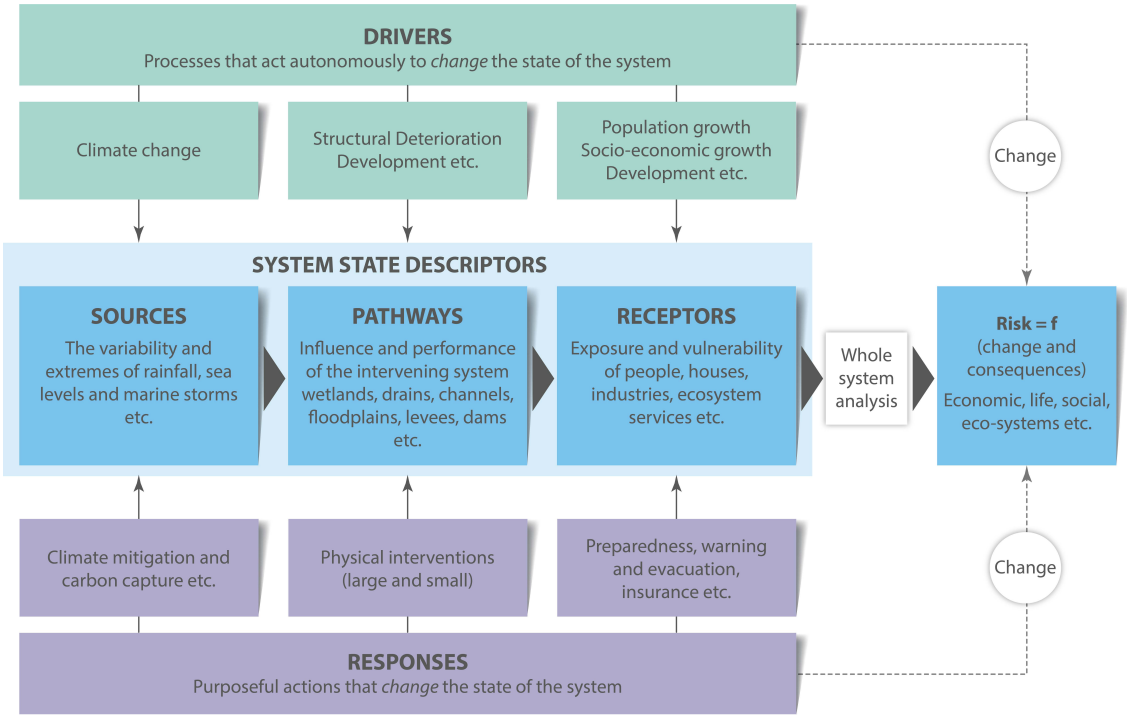
The outcome driven and evidence-based framework of SFRM underpins a planning and management process that brings together the multiple frames of influence set out in Chapter 3 to in four strategic themes:

- The adoption of a dynamic whole system long-term perspective
- The promotion of built and natural infrastructure
- The acceptance of a trade-off driven decision process
- The use of continuous, collaborative, and inclusive development process

These themes are discussed below and illustrated in practice in the following chapters.

4.3.1 Dynamic whole system long-term perspective

An appropriate understanding of the whole flood risk system (and how it responds to change) is increasingly recognised as a fundamental building block of good flood risk management (*e.g.,* Sayers *et al.,* 2002; Evans *et al.,* 2004a&b; Sayers *et al.,* 2013). The discipline that derives from adopting a whole system framework presents several advantages. Most notably it forces the systematic consideration of all aspects of the system influence risk (including the sources, pathways, and receptors – as introduced in Chapter 3) and how they may change due to (primarily) external – exogenous – drivers (such as climate change and socio-economic influences) as well as internal – endogenous – management responses (including both structural and non-structural measures). This framework of whole system thinking is shown in Figure 4-4 and discussed below.



Source: Redrawn from Sayers et al., 2014a based Evans et al, 2004a&b and Sayers et al., 2002a

Figure 4-4 A structured framework of whole system thinking based on understanding the sources, pathways, and receptors of risk

A whole system understanding of risk

Developing a meaningful whole system understanding presents a significant challenge to the analyst (*e.g.,* Dunn and Deering, 2009, Walport and Craig, 2014). The chance of harm is not, as it is often mistakenly supposed, equivalent to the chance that a particular storm event occurs but necessarily includes the full chain of events that lead to the harm. Equally, the consequence of a flood is not simply the direct material damage incurred but reflects the susceptibility of the receptors exposed to the flood, the cascade of impacts beyond those directly affected and ability of the receptors affected (either directly or indirectly) to autonomously recover in a timely manner, and the value society places on the harm incurred. To add further complication, risk systems behave stochastically; that is, they are governed by random processes.

To develop a well-founded whole system understanding of risk, therefore, consideration must be given to:

- **All-important sources, pathways and receptors and their interactions.** Flooding is usually a result of a combination of conditions, for example resulting from an extreme meteorological event, the overtopping or breach of a levee and the consequent flooding of vulnerable people or property. To be credible, and useful, the understanding of risk should be based on a consideration of all sources of risk (including a wide range of storm conditions and return periods), the pathways through which these flow (including the potential for breach, blockage, *etc.*) and the receptors directly and indirectly impacted. This comprehensive consideration contrasts with the more limited view often taken by conventional flood control approaches that optimise actions in the context of a single type or magnitude of a flood 'event'.
- **Reflect behaviour at multi temporal and spatial scales.** Flood risk management decisions operate at multiple spatial scales (from high level policy decisions at a transnational or national level through catchment or regional level and single communities and individuals). Decisions are also nested in time, ranging from policy and strategy decisions that focus on achieving long-term sustainable outcomes (for example setting management policy for a city or river basin) through to operational choices that influence actions in the short term (for example deciding to open or close a gate during a particular storm). An understanding of these interactions enables the detail of the analysis and the range of measures considered to be tailored to the decision context.
- **Reflect the whole system behaviour.** Whole-system risk-based analysis necessarily demands a modelling approach that represents all elements of the system and how they perform and interact. This adds significant computational demands, yet significant research continues to be devoted to produce ever more detailed models of single elements in the 'whole system' (featuring, for example, better representations of the hydrodynamic processes during a given flood, or the use of increasingly fine-grained terrain models to represent topographic features that may influence aspects of those processes). The results of such reductionist models are easily communicated, but they fail to support risk-based choices; for although they may simulate inundation in fine detail, they are often based on grossly simplifying assumptions regarding the location, timing, and growth of a breach (for example), the preceding storm sequences that may have weakened defences or saturated the catchment or the sediments and debris that may have blocked a culvert or changed the morphology of the watercourse.

In the acknowledgement that any model structure error has the potential to lead to an over- or under-estimate of risk (and hence misdirect resources, Penning-Rowsell *et al.,* 2016b), recent years have seen significant progress in developing more complete *'whole system'* analysis approaches (see Chapter 5). Such approaches seek to appropriately incorporate all important sources of flooding (across a full range of events), all potential receptors that may be affected (either directly or indirectly), and the performance of the intervening system of physical pathways (the land surfaces, channels, beaches, and engineered channels, defences, barriers, and pumps). A whole system approach also includes the interactions between the flood event

and society (individuals; emergency response teams; businesses and so on) and the important broader interactions between the physical, ecological, and human systems. This contrasts with the thinking that underpins conventional modelling approaches that typically focus on individual components of this 'whole system', and, consequentially, flood risk managers have tended to manage those individual components (the standard of protection afforded by an embankment for example) and not the complex reality how flood risks emerge. As such, developing a whole system understanding should not be considered an academic endeavour (although this demands scientific rigour) but as central to making the *'right choice'*; as illustrated in Box 4-3.

Box 4-3 Understanding the whole system behaviour can change choices

An understanding of the whole system behaviour is a precursor to good management. The importance of developing an appropriate understanding has been demonstrated many times through projects and real events. Some of these are discussed below.

A lack of understanding of all sources of flooding (Coultard and Frostick, 2010). The floods in the UK on 25 June 2007 occurred in the wettest month recorded in Yorkshire since 1882. Within the City of Hull, the flooding was largely due to heavy and prolonged rainfall falling on a catchment already saturated (pluvial flooding). Of the watercourses and open land drains in the area, only the Setting Dyke came out of bank. The pluvial nature of the flooding and very low surface gradients led to slow rises in flood water across the city as opposed to rapid inundation associated with point source flooding such as a breach of flood banks. In many cases, floodwaters rose beneath houses through the underfloor cavities and foundations. Under these circumstances, sandbags, although widely deployed, were of limited use and in some areas internal flooding reached a depth of 3m. The June 2007 floods came from an unexpected source: surface water flooding. This revealed a major weakness in UK flood defence strategy, which had limited capability for forecasting or warning from pluvial flooding. The disaggregated nature of the responsibilities for different kinds of flooding exacerbated the problem, with, at the time, no lead agency for the management of all sources of flooding.

A lack of understanding of system connectivity (Thorne *et al.,* 2011). Spatial interactions exist throughout the river and coastal system. It is well recognised that construction of flood defences upstream may increase water levels downstream. Similarly, structures that intentionally, or unintentionally, trap sediment can have profound implications further afield. Recognising the need for the management of coastal and river morphology as a valid component of the flood system – not simply the ecosystem – is now starting to become a central theme.

Quantitative whole system risk analysis has the power to promote a change in policy (Cheng *et al.,* 2013). Whole system models (that represent all the spatial and temporal interactions) are starting to emerge worldwide. Building on the UK Foresight future flooding studies (Evans *et al.,* 2004a, b), an analysis was made of the Taihu basin (located in the delta region of the Yangtze River in east China with a population of 36.8 million and a GDP of 1890 billion Yuan (£10bn) in 2003). The Taihu basin Foresight project involved a complete 'end-to-end' flood risk analysis, from the generation of climate and socio-economic scenarios, through hydrological, hydraulic and damage modelling to a final GIS system, the Taihu Basin Risk Assessment System (TBRAS). The TBRAS enabled all sources of the flood hazard to be simulated and a comprehensive view of the flood risk to be established as a precursor to aiding the development of resilient long-term management policies.

A whole system management response

The aspirations set out in Figure 4-4 can seldom be achieved using a single management response (*e.g.,* a flood defence) but typically requires a range of measures and instruments to be used in combination (Table 4-2). In doing so, a strategic approach encourages moving away from conventional 'linear thinking' (that considers standalone projects conceived with in a static context, Van Buuren, 2007)) to a 'systems thinking' approach that acknowledges the environment as dynamic system and working within a dynamic context.

This shift, away from single and static response to a dynamic portfolio whole system approach, has a profound influence on the way flood management is considered and implemented. This includes a change in focus away from a single design solution to a whole system management response that:

- Blends actions today with possible actions in the future (through adaptation pathways, *e.g.,* McGahey and Sayers, 2008, Haasnoot *et al.,* 2013).
- Blends conventional 'built' infrastructure measures (such as construction of dykes, levees, dams, *etc.*) to natural infrastructure measures (nature-based approaches such as wetlands *etc.*) where possible and in-combination.
- Blends natural and built infrastructure with non-structural measures (such as improved flood forecasts and warnings).
- Enables governance and planning instruments to be central supporting activities (such as land use planning, insurance, and traditional and innovative funding incentives, such as homeowner grants for flood proofing or payment for ecosystem services provided by upstream communities).

This notional complexity places a high demand on analysts, planners, and wider stakeholders. This is because it involves collective action across different government authorities and those outside government, including the public and business. This places an increasing emphasis upon effective communication and mechanisms to reach consensus without succumbing to the short-termism that is often present within the many competing views. Structured presentation of evidence is therefore central to success.

Box 4-4 Progress in implementing a portfolio response

The World Meteorological Organization (WMO) and the Global Water Partnership (GWP) issued an Overview Situation Paper on Flood Management Practices. The paper examined the results of 18 case studies of flood management carried out on rivers in Asia, Europe, North America, Africa, South America and a Pacific island that sought to determine if flood mitigation efforts in these areas were being carried out under the concept of Integrated Flood Management (IFM), which it defined as an approach that integrates land and water resources development in a river basin, within the context of Integrated Water Resources Management (IWRM). IFM includes within it flood risk management. The report noted that the flood management approaches observed in the case studies: *'show that there is ability in the countries to apply flood management measures that reduce the flood risk by avoiding increase in flood hazard, avoiding exposure and decreasing vulnerability or increasing resilience in the society against floods'.* The extent of these measures depends on the

economic development in the country, level of investment in capital and human resources. The report also notes that "moving away from concepts such as 'flood control' or 'taming the river' form a welcome departure point for IFM." In 2006, the European Network of Environmental Authorities reported *that "a holistic catchment management strategy is the only sustainable way of reducing the risk of flooding." Source: WMO, 2005*

Table 4-2 Summary of measures and instruments that form the basis of a portfolio-based flood risk management strategy

Categories of action to management risk	**Example options**
Reduce the **chance** of flooding	***Influencing the source of flood waters:*** Through, for example, storage at or close to source (inland water bodies and lagoons, reservoirs, ground water recharge, bogs, marshes, fens, Sustainable urban Drainage Systems, SuDS). Land management: Forestry/ floodplain woodland, ponds and wetlands, field scrape/infiltration trench, soil management, riparian buffer strips *etc.* ***Influencing the pathway of flood waters*** Through, for example, morphological, debris and vegetation management, wetland and washland creation as well as permanent and temporary structural defences, pumps, and barriers.
Reduce the potential **consequences** should flooding occur	***Influencing the exposure of receptors:*** Through, for example, development control and flood aware land use planning; evacuation planning including use of safe refuges and clear evacuation routes. ***Influencing the vulnerability of receptors:*** Through, for example, raising awareness and preparedness of people and business, providing post-event recovery systems (insurance and state help).
Mitigate climate and demographic change	***Influencing future climate change:*** Through, as a minimum, use of low carbon use solutions. More ambitious flood risk managers will look for solutions that sequestrate carbon through, for example, use of existing wetlands and restoration of damaged wetlands to promote natural carbon capture and storage. ***Influencing demographic change:*** Positively influencing population growth, integrating flood management with food and water resource security.

An adaptive approach based on appropriately value adaptive capacity

Flood risks do not remain constant in time. The change in response to exogenous pressures (such as climate change or socio-economic development largely beyond the influence of the flood manager) or in response to purposeful intervention (from changes in insurance regimes to levees). Many of the choices made today will also persist for several decades if not centuries, so taking a longer term, strategic view, when planning flood risk management investment is critical to making the right choice. Accepting the future as unknown, although widely recognised as important (*e.g.,* Evans *et al.,* 2004a & b, Hall and Solomatine, 2008, Bouwer *et al.,* 2010, Deloitte, 2011, Klijn *et al.,* 2004, 2015, Brisley *et al.,* 2015,

Environment Agency, 2016a), is yet to become a routine consideration within flood risk management practice. Accepting this premise has several profound implications; both in terms of the way in which strategies are developed, and the way in which infrastructure is designed.

Adaptation is a purposeful process. It includes marginal changes (raising a levee crest level in response to projected changes in sea level) to more profound transformational adaptation that challenges the status quo (for example accepting that a coastal community at risk from erosion should be set back rather than defended) and prepares the way for changes in the future (for example by purchasing land today to maintain an option for future development or strengthen the foundation of a levee today to support future raising). Adaptive management is therefore much more than simply 'wait and see' but is a purposeful approach that is inherently risk-based and, importantly, seeks to actively manage uncertainty.

4.3.2 A blended built and natural infrastructure response

Built flood defence infrastructure will continue to be an important element of SFRM but has recognised limitations. Catchment management approaches are widely promoted in flood management guidance (*e.g.,* Environment Agency, 2010; 2014, Sayers *et al.,* 2014a, Forbes*,* 2015; Sayers and Smith, 2018, Bridges *et al.,* 2015, 2018) and many policy initiatives (*e.g.,* EU Floods Directive 2007, England's 25 Year Environment Plan, Defra, 2018). River restoration, functional floodplain reconnection, upland storage and remeandering can increase hydraulic roughness and slow the speed of flood flows. This whole catchment perspective improves habitats for a range of species and associated biodiversity and contributes to the control of flood flows.

The gaps between the disciplines of engineering and ecology around water management in general, and flood management, are significant and durable. This, in part, reflects the conventional process of assessment in which ecosystem services are typically considered through the lens of an Environmental Impact Assessment (EIA); an activity often relegated near to the end of the design and planning process and often approached with the aim of mitigating or compensating for environmental damage rather than actively promoting environmental outcomes.

Despite these important initiatives, the blending of built and natural infrastructure presents many practical, as well as policy, challenges and implementation remains limited (despite advances in the acceptance of Nature Based Solutions at national policy level and some notable applications: 'room for the river', Ministry of Infrastructure and the Environment (2006), and the transition from a levees-only approach to a system approach 'flood ways' within the Mississippi, Box 4-5). In part this is due to the continued focus on traditional engineered solutions and the (often falsely) perceived certainty of performance they provide and associated lack of effective funding mechanisms for more innovative responses (Sayers *et al.,* 2017a). SFRM provides a framework to maximise the advantages of a blended approach as discussed below.

Box 4-5 Mississippi flood management – from levees only to a systems approach

Following the disastrous Mississippi River Flood of 1927, the US government determined that the previously used "levees only" policy for protection the people and property alongside the lower Mississippi River was no longer valid and that new approaches should be put into place. In the aftermath of this flood, Congress authorised the Mississippi Rivers and Tributaries Project (MR&T) to develop a new approach based on a combination of levees, upstream storage behind new dams, floodways to divert large volumes around critical areas, and periodic storage of flood waters on agricultural lands. The MR&T provides a demonstration of two principles. First, that levees alone may not be sufficient to manage floods and that some portions of the floodplain will be needed to store and convey floodwaters. Second, effective flood management requires a system-scale approach, integrating (1) floodplain management and land use; (2) levee system alignment along with levee design, construction, and maintenance; and (3) water management in reservoirs. Thus, the MR&T provides an early example of many of the characteristics of a strategic infrastructure approach, including planning and management at a system scale and the integration of multiple components, including the use of floodplains to complement built infrastructure.

The MR&T received its greatest test from a flood in 2011 and demonstrated the value of this system-scale, integrated approach. Although the 2011 flood had a greater discharge than the 1927 flood, the impacts were dramatically different. In **1927**, many levees were breached and 700,000 people were displaced from their homes and officially hundreds (and more likely thousands) of people died. In **2011**, the magnitude of the flood approached the design level, and all four floodways were put into service and successfully passed the floodwaters around the designated areas (Mississippi River Commission, 2011). No levee failed, damage and disruption were minor relative to 1927 and without any loss of life. While levees were the primary defence in 1927, in 2011 vast areas of floodplain within managed floodways helped to store and convey floodwaters, reducing the pressure on the levee system.

Subtle management of the system through in-combination interventions

The interplay between weather and landscapes across a catchment can act to amplify flood peaks at given location, increase or decrease the opportunity for groundwater recharge in an area, or influence dry season flows in a particular reach. Although spatial-temporal interaction is increasingly recognised as part of the assessment of water-related risk (*e.g.,* Jongman *et al.,* 2014, Berghuijs *et al.,* 2019), the potential to synchronise or desynchronise flows to reduce downstream risks is rarely used as a management tool. A strategic approach can help identify these relationships and provide interventions accordingly.

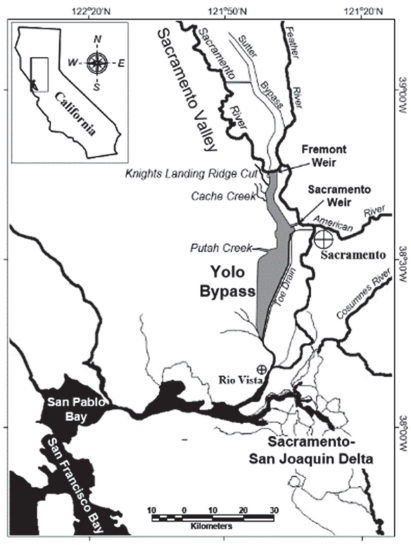
Achieving multiple objectives through in-combination interventions

Each type of action has its strengths and weaknesses; understanding these differences enables successful blended strategies to be developed. Built infrastructure, such as construction of levees, weirs and dams, inevitably reduces habitat complexity, and dampens these dynamics. A strategic perspective focuses on appropriately buffering natural variability where necessary (to protect people from flooding) but maintains a dynamic stability within the system that supports habitats and biodiversity. This includes maintaining longitudinal connectivity (between upstream and downstream reaches), lateral connectivity (between river and adjacent side channels and floodplains), and vertical connectivity (between surface water and

groundwater). Built infrastructure is often used to buffer variability (*e.g.,* in flood levels or flows) but in the absence of a strategic lens may act necessarily to reduce connectivity, between the channel and floodplain and upstream and downstream processes. This in turn reduces ecosystem productivity and the exchange of sediment and nutrients between the land and river with negative impacts on habitat and species biodiversity and reduces the system's natural capacity to contribute to improve water quality and attenuate flood flows Box 4-6). Using a blended approach where the advantages of one option compensates for the disadvantages of another to minimise risk and maximise opportunities is a central consideration within a strategic approach.

Box 4-6 Incorporating principles of ecosystem connectivity into flood management – California Central Valley and the Yolo Bypass, US

California has a Mediterranean climate, with nearly all precipitation falling between October and April with a long dry season that extends over half the year. The Central Valley is the largest watershed in California, with the south-flowing Sacramento and north-flowing San Joaquin Rivers converging in an inland Delta and draining toward the Pacific Ocean through the San Francisco Estuary. The flood management challenge is significant. A system-scale approach has been developed to replace decades of fragmented attempts at flood management; central to this is the role of the Yolo Bypass. The Yolo Bypass is a 240 km^2 leveed floodplain designed to protect Sacramento and other communities in the California Central Valley. Constructed during the 1910-30s in response to several severe floods. The bypass conveys up to 80 per cent of the Sacramento River's floodwaters during major flood events and fills completely during wet years. Below Sacramento city, the Sacramento River channel has a maximum design flow of 3,100m^3/s, which compares to the Yolo Bypass' capacity of 14,000m^3/s (Sommer *et al.,* 2001).



Left: the Yolo Bypass. Right: Comparison of growth of juvenile salmon that rear in a floodplain (right) compared to a river (left). Image Jeffres et al., 2008



While the Bypass was originally constructed to protect city from flooding whilst also maintaining land ownership in agriculture, more recently it has been recognised as valuable floodplain habitat that supports significant populations of fish and wildlife (*ibid*). Approximately one-third of the Bypass is now a non-agricultural habitat, including ponds, wetlands, grassland, and riparian forest. This means that in addition to providing effective flood protection, the land is used for agriculture during the summer, and large areas of wetlands provide critical habitat for bird and aquatic species. When the bypass floods it functions as an important spawning ground, rearing nursery, and migration corridor. Allowing the floodplain to be inundated, rather than disconnecting it from the river, has resulted in multiple environmental benefits. The biological value of the bypass for native species is particularly important since much of the historic floodplain has been lost due to development, levee construction and river channelisation. The Yolo Bypass demonstrates how carefully designed structural approaches to flood management can be adapted to sustain and support natural processes in aquatic and wetland systems.

Adaptation plus mitigation

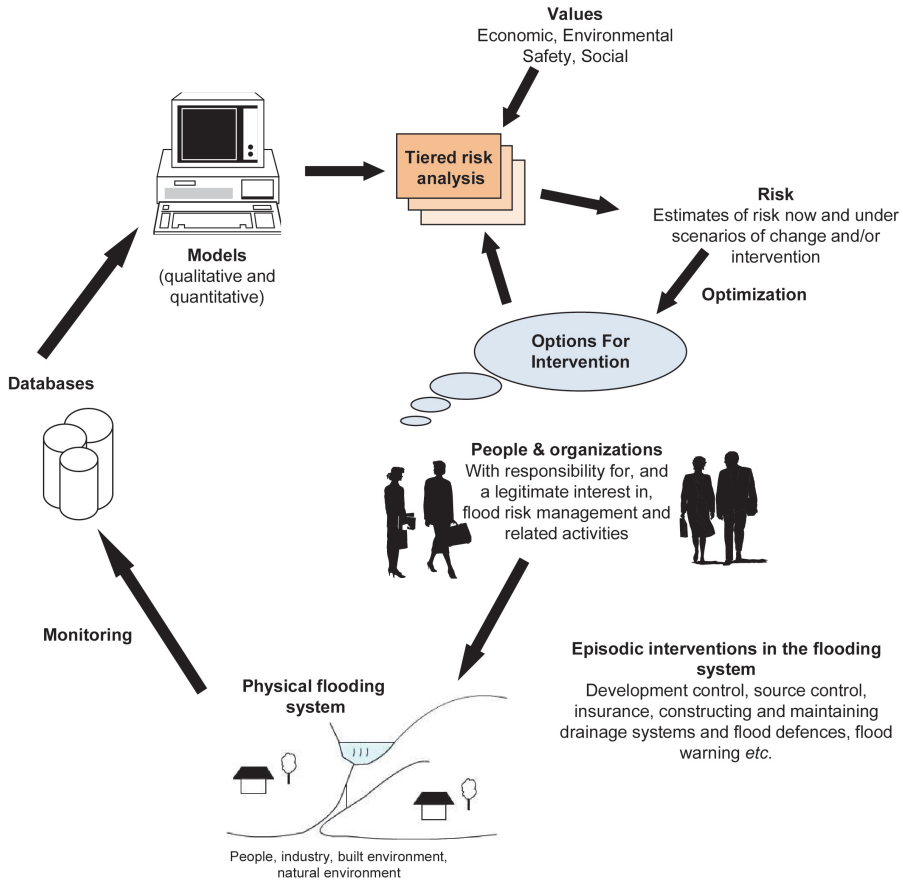
Since the late 1980s the Intergovernmental Panel on Climate Change (IPCC) has focused attention on the challenge of climate change and recognised that some degree of climate change is inevitable. Adapting to that change is one response – the focus of the approach advocated here – but a strategic approach that promotes natural infrastructure responses also can contribute to the reduction in emissions.

4.3.3 Continuous, collaborative, and inclusive

A strategic approach draws upon the influences of social justice (see Chapter 3) and seeks to develop an opportunity for positive collaboration, recognising that compromise does not always enable a win-win outcome but does enable a wider range and more supported outcomes to be delivered (Sayers *et al.,* 2022a). The provision of transparent and comprehensive evidence is only the first step and ultimately decisions are made by people. An open and participatory process of collaboration is therefore critical to deliver successful outcomes (Aarhus Convention, European Union, 1998). The evidence provided by a risk approach offers a step change in the effectiveness of the engagement process and the dialogue with communities in developing, funding, and delivering risk management.

Future conditions and priorities inevitably change in unexpected ways. Changing climates, socio-economic contexts as well as deterioration in structural defences all present the decision-maker with complex policy choices. Every time a decision is taken on a major project (such as roads, rail, hospitals, schools, new housing, flood defence and water resources infrastructure), the capacity for society to respond to future change in the medium to longer term is altered. Poor decisions can *'lock-in'* maladaptation that would poorly serve a changed future society and are very expensive to reverse.

In this changing context, uncertainty in future change presents the flood risk manager with a rational doubt as to what to do and when. The gross uncertainties, such as those associated with climate or demographic change, cannot be reduced through improved data or models. By adopting a long-term planning focus process, such an approach embeds the concept of building in the capacity to adapt. This is done in the expectation that the future will be different from the present and policies and actions will need to be changed as new knowledge becomes available. Strategic flood risk management therefore takes place as a continuous process of acting, monitoring, reviewing, and adapting (Figure 4-5). This is not to imply that physical interventions can be made incrementally through continuously modification, but they can be monitored, and their performance maintained under review to support staged modifications or transformations (including removal where necessary) recognised that physical interventions take place as discrete choices and actions.



Source: Redrawn from Hall et al., 2003a

Figure 4-5 Flood risk management as a continuous process of acting, monitoring, reviewing, and episodic action to adapt

Continuous coordination with other plans

Flood risk management plans are among many that exist within governmental structures and must be carefully coordinated with these other plans. National policies for flood risk management as well as national, basin, and local strategies must be carefully integrated with other planning efforts. Because of the time involved in developing and executing flood risk management plans, it is not unusual for parallel plans such as agriculture, navigation, and so on, to experience change. Unless there is continuous exchange of information among the different planning agencies, it is possible for efforts that once were in synchronisation to suddenly become in conflict. At each step in the flood risk management process there must be passage of information to those agencies most affected by the flood planning. Similarly, flood risk managers should not expect sectors to inform them of changes in their planning that might impact on the structure of flood risk management plans but proactively seek collaboration.

Developed a process of mutual learning

Mutual learning and an iterative process of deliberation to evolve joint priorities and actions is central to successfully managing flood risk (Box 4-7). This includes providing an effective

linkage between the *'push'* of science and the *'pull'* of practice as well as between practitioners. Peer-to-Peer learning (including City-to-City and Region, for example) provides a framework for co-evolving good practice. City-to-City learning and university collaborations are all part of this mix.

Prepare the foundations for ongoing collaboration

A strategic approach considers '*How future choices will be made?'* and *'who will make them?'*. Doing so helps lays the foundations for how plans will be maintained, reviewed, and adjusted as knowledge, preferences, stakeholders, and experiences change.

Box 4-7 Benefits of a collaboration continuous process of dialogue

Lessons on establishing a meaningful dialogue drawn from the EC Interreg Project Cloud-2-Coast Adaptation, include:

A strategic context

- Obtaining a structured understanding of the behaviour of the whole system. This also enables interactions between constituent systems to be understood, and the way flood risk may cascade and escalate through those systems.
- Making strategic choices about the management of the whole system. Adaptation 'at the edges' (*e.g.,* creating local storage) is easy; to address the hard choices (from coastal realignment to diverting rivers flows) is much more difficult, but these choices are central to dealing with (more extreme) climate change.
- Developing an integrated vision for a coastline, catchment, or city, where flood and coastal risk management is integrated into strategic spatial planning. This could for example be a vision to develop green-blue corridors between city and catchment, where the surrounding rural area serves as (excess) water storage.

A tactical context (the tactical handshake)

- Exploring opportunities to connect an adaptive plan / implementation agenda for flood and coastal risk management with the implementation agenda in other sectors, such as spatial planning or ecosystem restoration.

An operational context

- Ensuring that operational decisions to manage flood risk and beyond (in other sectors) will not be maladaptive under climate change and climate change adaptation at higher scales.
- Exploring opportunities to create or enhance social, ecological, or cultural values that may arise from multi-functional solutions.

4.3.4 Trade-off driven decisions

Trade-offs are inevitable in all decision-making; seldom do true solutions that maximum wins on all fronts exist. Trade-offs operate at multiple scales; where, when, and how to act, and with national choices around how to prioritise flood management alongside other public safety issues (for example traffic safety) as well as between local and national preferences. The basis of a trade-off analysis will typically reflect issues of:

- **Desired outcomes.** What do successful outcomes look like for people, the economy (local and national) and nature?
- **Efficiency and effectiveness.** Maximising the risk reduction for every unit of resource spent and ensuring set target outcomes are reached. Efficiency of public spend, for example, is typically the central considertation in UK public investment choices. Such an approach avoids the need to specify a threshold at which the risk becomes unacceptable but requires a framework of multi-criteria decision-making. In the Netherlands, the notion of solidarity adds a consideration of effectiveness (see Chapter 3).
- **Reversibility and flexibility.** The use of many measures, as opposed to a single major intervention, often promotes greater flexibility with individual measures more easily modified and adapted or, indeed, removed.
- **Adaptability.** Promoting measures that can be modified in response to future change through a process of planned adaptation (replacing the reactive, and occasionally maladapted, response to an extreme flood that has occurred throughout the history of flood control approaches).
- **Robustness.** Identifying combinations of measures that are likely to offer acceptable performance regardless of the reality of the future.

In responding to the challenge of finding the 'right' solution, a strategic framework as set out here guides the decision-makers to provide:

- **Innovative solutions that deliver multiple objectives.** Whilst delivering multiple objectives in practice does not come without challenges, it also offers opportunities. River restoration projects, such as those in Danube River in Europe and the Florida Everglades in the United States, not only improve endangered ecosystems, but also make a significant contribution to flood risk management efforts (providing concurrent flood damage reduction and environmental benefits). Progressive planning policies, which seek to avoid inappropriate development within the floodplain, can have a considerable influence on a community's exposure to risk.
- **Perform well against a range of criteria**. Decision-making, trade-offs, and uncertainty are inextricably linked. Understanding performance relies upon extending the assessment beyond simply economic efficiency through to indicators of social fairness and ecosystems enhancement, as well as the inclusion of indicators that reflect the robustness and resilience of the strategy.

An adaptive management approach (Sayers *et al.,* 2012, Brisley *et al.,* 2015, others) has emerged as a key change in the way long-term investments are planned and implemented. Such an approach:

- **Looks beyond historical precedents.** There is no certainty about what the future holds and increasingly a historical analogy provides limited guidance. Lack of imagination in describing the possible future change can condition actions based on current knowledge and experience.

- **Looks for solutions that perform well in multi-plausible futures – robust solutions.** To be meaningful all plausible futures and possible strategies must be considered. Judgments made too early as to the most likely strategic preference or possible future can precondition the answer in an undesirable and sub-optimal manner. Conversely, overcomplication must be avoided, including unnecessary detail or very localised options.
- **Takes a long-term view avoiding short-termism.** The planning and implementation of flood risk strategies is often biased towards quick wins. More progressive strategies that embed a longer-term view and support progressive management are often difficult to develop and implement.
- **Looks for radical solutions and challenge the status-quo.** Engineers need to be brave enough to propose new or radical solutions such as land banking, forced programme integration (e.g., energy generation and flood defence, habitat creation and flood management etc.), urban blue and green corridors, stream buffers and land management and land use controls.
- **Maximises the efficient and safe use of the sunk investments.** Much of the developed world, and developing world, has already invested significant sums in infrastructure portfolio, much of which is aging. After detailed technical evaluation of structure integrity, it may be possible and fiscally efficient to incorporate and/or adapt existing infrastructure, if such incorporation can be accomplished in a sustainable manner.

4.4 TEN GOLDEN RULES TO GUIDE STRATEGIC FLOOD RISK MANAGEMENT

This chapter has set out the building blocks of a strategic approach. These influences together with the insights from earlier chapters in combination with workshops and discussions held with the experts and practitioners from around the world (including the US, China, Europe, and Africa, from governments universities and NGOs) a small number of golden rules from emerge as the cornerstone of good ‘strategic’ flood risk management practice (although necessary conditions for progress, they may well not be sufficient in themselves). These ten golden rules reinforce our intuitive response of management of the world around us but provide a tangible guidance as discussed below and illustrated in Figure 4-6.



Illustration based on Sayers et al., 2014a

Figure 4-6 Ten Golden Rules of Strategic Flood Risk Management

4.4.1 Accept absolute protection is not possible and plan for exceedance

There will always be a 'bigger' flood. Engineering design standards, however high they are set, will be exceeded. Structural protection, by definition, provides protection against more frequent lower consequence events but often provides limited protection from low-frequency, high-consequence events. Engineered structures may also fail (breach, fail to close, *etc.*). Non-structural measures such as early warning systems or evacuation plans taken to mitigate flood consequences are also susceptible to failure. Through an acceptance of residual risks, and that some degree of failure is almost inevitable, a focus is placed upon building resilience into all aspects of the planning process (urban development planning, flood control structures, warning systems, building codes, *etc.*) and 'managing failure' rather than ignoring it. The ability to recover failed infrastructure rapidly is vital in supporting the timely return to normality. This can be supported by good design choices that avoid the need for complex planning, highly specialised skills or difficult to source materials when making a repair.

A prerequisite to avoid the rapid escalation in the severity of a flood event is to ensure critical infrastructure (*e.g.,* energy, transport, communications, and emergency services) continue to function to serve local needs and avoid disruption propagating through regional or even global networks (a central lesson from the Asian Tsunami as impacts escalated as they cascaded through global supply chains). Identifying critical components within these networks, at a range of scales, relies on an understanding of the independencies that exist, within and across sectors; an understanding that is rapidly developing (*e.g.,* Hall *et al.,* 2013) but will demand coordinated action to mainstream into practice (mainstreaming existing guidance such as CIRIA, 2010 and developing new approaches).

4.4.2 Promote some flooding as desirable

Maintaining the natural functioning of floodplain across a range of return period flows where appropriate is central to the strategic concept of management, working with rather than against natural processes where possible (*e.g.,* maintaining the functional floodplain and room for the natural dynamics of the coast, river, and surface water flows). This is not always possible and flooding needs to be constrained to protect people, property, and infrastructure. SFRM seeks to actively promote some flooding as part of a whole system solution. This recognises that ecosystems provide critical provisioning, regulating and cultural services (UN, 2005). Not taking early consideration of how best to safeguard and promote these flood management choices can have an unnecessary and devastating impact on ecosystem health (*e.g.,* as experienced in the Danube basin leading to significant restoration needs (*e.g.,* Jungwirth, *et al.,* 2002; Sayers *et al.,* 2013). A strategic approach recognises the opportunity to bring together natural flood management measures (such as land use changes, wetland storage, and floodplain reconnection *etc.*) and alongside built engineered measures (such as bypass channels, controlled storage *etc.*) to simultaneously manage risk (protecting people and property) and promote healthy ecosystems.

The synergy that exists between the needs of natural ecosystems and the need to manage flood risk to people is all too often overlooked and there remain few examples where this is actively pursued at the system scale. To make gains in safeguarding and promoting

ecosystems through flood management a shift in emphasis is required. Working with natural processes is increasingly sought as a central consideration (as evident in the development of Nature-Based Solutions in recent years that promote the concepts of working with natural processes in flood risk management).

Making room for the river and the sea, maintaining connectivity of flood flows to carrying sediments to maintain habitats as well as morphological protection in the form of deltas and wetlands are all features of a strategic systems-based approach. Structural protection and the use of conventional engineered structures, remains a valid, and significant, part of the response; but seeking innovation is needed to develop integrated actions that maximise the value of natural assets and only seek to supplement their performance where necessary (and not vice versa – *e.g.,* Sayers and Smith, 2018, Sayers *et al., in press*).

4.4.3 Understand uncertainty, risk, and vulnerability

In all but the simplest of settings, judgement or intuition cannot alone establish a meaningful understanding of present and future flood risk. Structured whole system analysis has an important role to play in managing flood risk well, addressing:

- **Uncertainty.** Despite the continued advances in risk assessments methods and the data that supports them, considerable uncertainty continues to remain. Some are irreducible (particularly those associated with how the future may develop) and need to be addressed through exploratory methods and robust decision-making (as discussed in Chapter 3 and returned to in the examples presented in later chapters). Others have the theoretical potential to be reduced but it may be impractical (or feasible) to do so. As Voltaire proposed, 'the perfect is the enemy of the good' (Voltaire, 1694-1778). The endless search for perfect knowledge (data, information, and models with which to conduct analyses) should not be a reason to delay the development of options, making choices and implementing appropriate flood management activities. The strategic flood management process proposed here promotes an approach that is iterative and adaptive, taking into account better information as it is developed and not waiting for what is likely to be unattainable information before proceeding to the next step. The uncertainty in the information should be explicit and choices made that are robust to that uncertainty (an issue that underpins the regional assessment in support of the Thames estuary 2100 plan presented later in Chapter 5).
- **Risk and resilience.** Recognising the full richness of the meaning of risk and its components includes identifying the relationship between probability and consequence and distinguishing between low-consequence / high-probability risks and high-consequence / low-probability risks (at the aggregated and local scale). This important distinction can be lost when risk is simply (and incorrectly) only considered as the product (and not a function of) probability and consequence. Taking an event-based approach where needed to understand how risks may cascade through systems and how some systems may recover, and others may not so easily. Understanding the potential magnitude of the potential consequences (people, economic and ecosystem), irrespective of the associated probability, can also be useful to help understand the significance of a

risk and help ensure steps are taking to reduce potential impacts on a 'what-if' basis when probability can only be described in qualitative terms. Approaches based upon a wide portfolio of structural and non-structural responses typically offer a degree of redundancy that promotes greater resilience than relying upon a single measure. A strategic approach promotes such a portfolio of measures, including both built and natural infrastructure measures that address the sources and pathways of flooding as legitimate flood management assets (*e.g.,* Evans *et al.,* 2004a & b). Resilient infrastructure design (including design elements robust to uncertainty) can help ensure an acceptable level of performance, is maintained when exposed to events more severe than anticipated (*i.e.,* levees should not breach when a notional design level has been exceeded, nor should their performance decay catastrophically without warning).

- **Social vulnerability.** Adopting a proactive assessment of the most socially vulnerable and ensuring their risks are understood and addressed proactively to delivery fair outcomes (in both benefits and the burden of costs) based on an inclusive process of decision-making that meaningfully engages the most vulnerable in the co-design of approaches and actions (responding to the issues of climate justice introduced earlier in Chapter 3 and illustrated through a national assessment of geographic and systemic disadvantage later in Chapter 7).

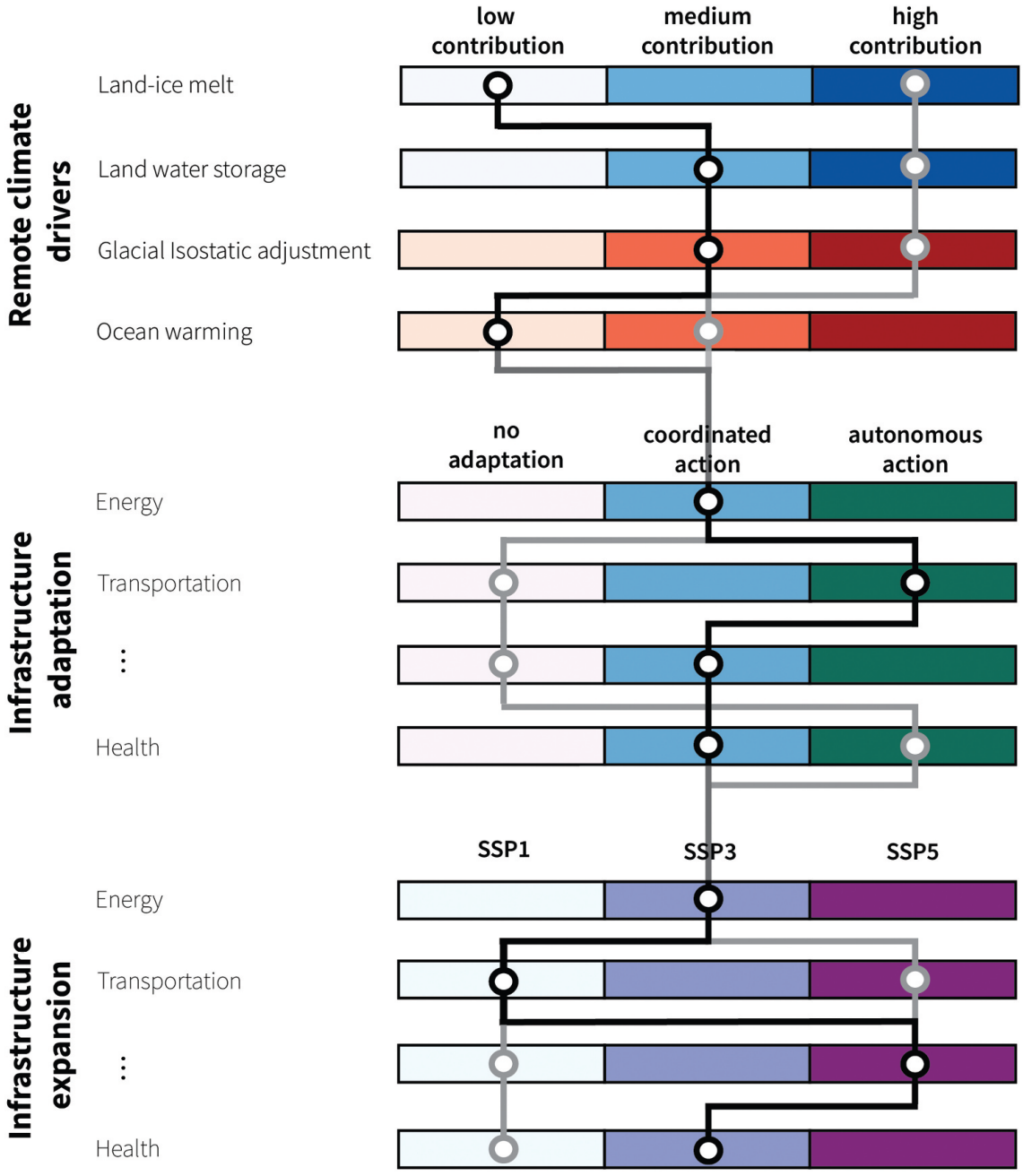
4.4.4 Recognise that the future will be different from the past

There are many ways in which climate change may unfold, how our society responds, and what our infrastructure requirements will be. There is no certainty about what the future holds and increasingly a historical analogy provides limited guidance (in terms of climate forcing but also more broadly societal expectations and preferences); in a changing world, history perhaps teaches us less and less.

In this changing context, multiple futures are plausible and the future that manifests cannot be known with certainty or meaningfully described through the notion of probability alone (*i.e.,* to say there is an *x*% chance that sea levels will have risen by *y* metres and adaptation will have happened in a given way, would be to grossly overstate our depth of understanding). Judgments made as to the most likely future can precondition the answer in an undesirable and sub-optimal manner. Conversely, overcomplication must be avoided, including unnecessary detail. Lack of imagination in describing possible future changes can also negatively condition actions based on current knowledge and experience. To identify the preferred approach, plausible futures considered to minimise the rationale doubt in the decision are being made. Storyline approaches provide a useful means of structuring alternative futures that can be used alongside or independent of probabilistic description. Stories that are conditioned by evidence from across physical, social, and political science provide a useful means of structuring the description of possible futures (Figure 4-7).

A storyline framework therefore reflects a continuum of storylines within which any number of possible future system states can be considered. Alternative futures are illustrated by the storyline pathways 1 and *n* (Figure 4-7); where each storyline embeds three aspects of the future: (i) sea level rise; (ii) effort devoted to the adaptation of coastal infrastructure; and (iii)

degree of expansion of coastal infrastructure (*i.e.,* the development of new infrastructure for energy, telecommunication, and transport services among others). These alternative pathways represent the epistemic uncertainties around how the future will evolve (including the drivers of climate change and adaptation).



Source: Koks, Sayers et al., 2022

Figure 4-7 Future system state framework: a continuum of possible futures

Developing and implementing adaptive strategies relies upon: (i) creativity in selecting innovative responses that do not foreclose future options or unnecessarily constrain future choice; (ii) responses that are effective under the widest set of plausible futures; (iii) monitoring of change in knowledge about the future, and (iv) appropriately modifying policies, strategies, and actions. Some flood risk management choices are very long-lived and

difficult to modify once made (the continued protection of London for example). Even in these contexts, how and when investments are made are either promote or reduce future flexibility. An adaptive approach does not lack clarity or a clear direction but is explicit on actions today and how future flexibility is maintained (from when to make an incremental change to raise a defence, to make a transformational change to relocate a town, Sayers *et al.,* 2022b). Embedding future flexibility can require additional resources today (*e.g.,* to strengthen foundations in preparation for future crest raising) but can provide significant future benefits. Delivering strategic flood risk management is a purposeful approach that necessarily must align operational, policy and analytical understanding (as explored by Bloemen *et al.,* 2019) and seeks to actively manage uncertainty through a well-defined and understood programme of actions that links policy, strategy, and action (Sayers *et al.,* 2021a).

Support for innovative and adaptive solutions, and how to generate the political momentum to deliver them, remains a central barrier to progress. The policy in recent years within England and Wales has been guided by the principle of *"Making Space for Water"* (Defra, 2005) and, in the Netherlands, *"Room for the River"* (Ministry of Infrastructure and the Environment, 2006). The sentiment of these policy goals is clear but often at odds with the local political and public response to a flood event (*e.g.,* for better protection from flooding), local economic development choices (*e.g.,* with continued development in the floodplain, for example), and insurance industry agreements that focus on reducing the chance of flooding. Only where it is easy to *"make space"* or *"room"* is this done. Experience in practice reinforces strategic flood management as a human endeavour and one that requires leadership and collaboration to be successful. The articulation of a strategic vision, and the adaptive pathway to achieve it, can help overcome barriers to progress.

4.4.5 Implement a system-scale portfolio of responses

Despite the increasing recognition of need for a system scale perspective, on the ground practice has often failed to change, with a continued reliance on locally promoted flood control/defence and few examples of ecosystem-led 'whole system' solutions. Strategic framing of the approach to flood risk management explicitly promotes the consideration of the widest possible set of management actions and the assessment of risk. Adopting a systems perspective helps identify solutions that may be remote from the location impacts, for example in the upstream catchment, or may enable hybrid solutions to be developed that combine conventional flood protection with exceedance measures to manage flood water before they are inevitably overflowed. A portfolio provides opportunities to use the advantages of one measure to compensate for the disadvantages of another to deliver multi-layers of safety but also multiple benefits.

A strategic framing provides the space to seek radical and portfolio-based solutions that challenge the status quo. Land banking, synergetic solutions (*e.g.,* energy generation and flood storage, habitat creation and the management of flood flows), and innovative large-scale spatial planning (use of urban blue highways, building codes *etc.*) are all legitimate elements of the response. Few places offer a blank canvas and much of the developed world, and developing world, has significant sums already invested in aging flood control structures

(dams, levees, pumps, *etc.*). These sunk investments should be utilised where possible. A strategic perspective enables the role of existing infrastructure to be challenged and incorporated, adapted or repurposed where sensible and removed where necessary.

4.4.6 Utilise limited resources efficiently and fairly to reduce risk

The criteria for assessing flood risk management strategies are no longer solely economic but involve consideration of a much broader set of outcomes, including social justice and ecosystem health. This requires strategies to be developed not only based on economic efficiency but in terms their fairness (in benefits and burdens) and ecosystem services (from carbon sequestration, biodiversity, amenity, and other desired outcomes).

Flooding, and actions taken to manage floods, are not fair *per se:* the inherent natural spatial inequality in the frequency and extent of flooding, plus the legacy of past interventions and the coverage of new ones being the cause. Every intervention to manage flood risk inevitably tends to prioritise one group or location over another, creating further inequality and unfairness. In general, it is accepted that decision-makers must seek to maximise the utility of an investment whilst ensuring that it is distributed through a just process that also protects the most vulnerable members of society. Achieving this raises several practical problems. This strategic framing places an explicit focus on how issues of equity are addressed (as in the Netherlands through the principle of 'solidarity' or through an equitable decision process as in England, see Chapter 3), utility (through directing resources to maximise risk reduction) and Rawlsian considerations to ensure the outcomes for the most socially vulnerable are prioritised.

Placing these issues within a common framework is central to a strategic approach, including the adaptation of quantified methods to reflect social vulnerability to understand how different strategies influence the outcomes for the most socially vulnerable compared to others (including for example the used of the Neighbourhood Flood Vulnerability Index (NFVI) and assessment of disadvantage illustrated later in Chapter 7). Understanding 'fairness' in this broader sense enables strategies to be developed that deliver for all.

4.4.7 Be clear on responsibilities for governance and action

A long-term view enables change to be embraced, and short-termism avoided. The planning and implementation of flood risk strategies is often biased towards 'quick wins'. More progressive strategies that embed longer term progressive management offer significantly greater opportunity to challenge the status quo and promote radical and adaptive solutions, but these are often more difficult to develop and implement. Ownership of the strategy needs to be shared with clear roles and responsibilities. This includes recognising contributions across national, regional, and local governments, private sector organisations (for example ensuring their infrastructures are well adapted) and individuals (to contribute actively to the co-design and to act where this is feasible).

Long-term strategies demand action by many stakeholders over extended periods. Buy-in to such decisions can be difficult to achieve and requires continual reinforcement and review. Often the ability to implement strategic management is undermined by independent actions.

Significant flood events, or indeed the lack of flooding, can dramatically alter the perception of the risk the floods pose. Collective memory is often short-lived, and priorities can rapidly change. Implementing a long-term plan requires long-term commitment and continuity to be successful; a goal which is often difficult to secure in practice.

Sharing of both responsibility and fiscal support of flood risk management activities ensures the full participation of leadership at all levels in the development of a common understanding of the processes being followed in the floodplain management activity. Effective flood risk management also requires that interventions be carried out on a watershed or catchment basis so that upstream-downstream, cross-river conflicts may be avoided and/or mitigated. Procedures must also be developed to provide continuous collaboration among agencies with parallel or interlocking responsibilities.

4.4.8 Communicate risk and uncertainty effectively and widely

Decision-makers and the public alike must understand the risks that they face; frequently they do not. Too often, after a flood, those affected claim that no one had told them of the risk they faced. Tools, such as risk maps, social networking, and educational processes should be used to facilitate an appropriate understanding of risk. Effective communication enables both communities and individuals to understand their responsibilities in helping manage risk, and why specific measures are necessary. Communicating the risk after a catastrophe is too late.

The mechanisms that communicate risks and strategies in a way that motivates engagement and action are necessarily vague according to the target audience and the decisions to be influenced. This may include rich descriptions of risks, hazards, exposures, and vulnerabilities as well as clarity on how to get involved and actions to take.

4.4.9 Promote stakeholder participation in the decision-making process

Implementing the strategic approach flood risk management promoted here places a high demand upon its stakeholders (including all those with a legitimate interest in the activities). It involves the collective action of a range of different government authorities and those outside government, including the public and business. This places an increasing emphasis upon effective communication and mechanisms to reach consensus without succumbing to the short-termism that may be present within the many competing views.

Strategic flood risk management is inclusive and engages meaningfully with stakeholders throughout the decision-making processes and has recourse to proper processes and resources being in place to manage this process on an ongoing basis. Success relies upon stakeholders playing an active role in developing, delivering and, increasingly, contributing to the operation of flood risk management measures in a way that promotes ‘living with floods’ rather than ‘fighting’ against them.

4.4.10 Reflect local context and coordination with other planning processes

Multiple opportunities and constraints exist. Flood management does not take place in isolation of other Sustainable Development goals. Achieving and understanding multiple (and

changing) objectives presents many challenges; objectives often conflict both in the short term and more fundamentally in terms of setting the long-term 'direction of travel'. Supporting Sustainable Development (and the necessary resilience and adaptive capacity) through a strategic approach to flood management is much more than simply maintaining the long-term integrity of flood control structures: a common misconception in many parts of the world. It also includes promoting the long-term health and resilience of the associated ecosystems, societies, and economies. This requires collaboration (and a degree of coordination) across all those involved in the policy and planning processes as well as scientists and engineers across different disciplines and the practitioners at the forefront of managing flood risk such as city planners, critical infrastructure operators, the insurance industry, local and national governments, crisis managers and first responders. The way collaboration is translated into coordinated policy objectives shapes the nature of the flood risk management that is delivered. A strategic approach does not seek perfect coordination but an understanding that collaboration fosters co-learning, the development of a shared understanding of what matters for flood risk management decisions and to where opportunities for co-development lie.

The details of any strategy will be different; reflecting the specific risks that must be faced and the framework of development that should enable this freedom of expression. Flooding issues are always context specific. As a result, all flood management plans appropriately differ in the specific combination of actions they prescribe. As the notion of resilience matures, sectoral perspectives that are often used to frame issues of risk and narrow the discussion of resilience (for example, community, infrastructure, ecosystems, or flooding resilience) are increasingly challenged. The strategic approach set out here argues that such siloed approaches offer no meaningful advance towards a resilient society. To make progress beyond the paradigm of flood risk management a radical transformation is required that broadens (not narrows) the scope of the risk management endeavour. In this context *'resilience'* is not seen as an outcome metric p*er se* but is a lens through which risk is managed and sectors of society and responses are embedded in development and investment choices (not just a conventional portfolio of flood risk management measures, including structural and non-structural). Achieving this *resilience shift* relies upon the building upon the whole system, long-term, and strategic approaches to the assessment of flood risk whilst making a substantial change in the approach to management of these risks and associated opportunities as advocated here. Although no blueprint is yet available as to how to do this in a practical sense this paper sets out the most important considerations to be addressed if progress is to be made towards strategic flood risk management that actively contributes to a resilient society.

4.5 Defining Strategic Flood Risk Management

The approach to Strategic Flood Risk Management advocated here challenges conventional practice and encourages more ambition, recognising the management of flood and coastal issues will be an area of increasing concern and how flood risk is responded to central in determining a wide range of outcomes for people, the economy and nature. The essence of the proposed approach is captured through the definition first promoted in Sayers *et al.,* 2014a (simplified here):

> ***Strategic Flood Risk Management delivers multiple outcomes for people and nature over the short and long term. The approach is inherently collaborative, inclusive, and systems-based with choices based on an understanding of risks, benefits, and uncertainties. A continuous process of review and adaptation actively manages change, incorporates new knowledge, and modifies plans and actions.***

This definition has stood the test of time and continues to have resonance as the framing of flood risk management has continued to evolve. Although not written as guidance, the whole systems approach it advocates is now widely embedded (see for example the Cloud-to-Coast, Sayers *et al.,* 2022a) and underpins the UK Climate Change Risk Assessment flood projections (Sayers *et al.,* 2015a, 2020a). In England, the Environment Agency's Flood and Coastal Defence Strategy (Environment Agency, 2019) promotes the ideas of an adaptation portfolio, whole system understanding and (at least in part) issues of fairness. The Golden Rules have also been shown to be of international interest, including in China (including translation into Mandarin by the General Institute of Water Design and Planning) and the USA (through collaborations that supported their original formulation and the principles of Corps of Engineers to move flood risk management forward in the US – personal communication Gerry Galloway) and elsewhere. The approaches promoted by the Queensland Reconstruction Authority (personal communication Graeme Millighan, QRA), Australia and across the North Sea Region (through initiatives such as FAIR, Sayers *et al.,* 2021a and Cloud-2-Coast, Sayers *et al.,* 2022a), for example, continue to take forward the concepts of fairness and whole system analysis and adaptation. Fairness is also increasingly an issue outside of the public sector; within insurance sectors Flood Re commissioned an exploration of fairness (including consideration of ethnicity) within the UK flood insurance market using the tools set out in Chapter 7 (Sayers *et al.,* 2020c).

5

SYSTEM FLOOD RISK ANALYSIS AND PLANNING FOR THE THAMES ESTUARY

London is the economic powerhouse of the UK. The current systems of flood defences were designed in the late 1960s, early 1970s and completed in the 1980s. The original designer scheduled in a major review after 30 years (around 2000, mid-way through their design life) in recognition of the potentially long lead times associated with implementing a new plan. At the start of the 2000 the fragmented nature of the flood management responsibilities within London meant that several requests had been put forward to central government for funding to improve local defences. Central government questioned the justification of the uncoordinated proposals and demanded that an estuary-wide, risk-based strategy be developed: the so-called Thames Estuary 2100 Plan (TE2100).

To incorporate risk-based decision-making and adaptability at the heart of the strategy plan, it was necessary to develop innovative tools (including enabling the application of the Risk Assessment Strategic Planning (RASP) methods (Sayers *et al.,* 2004) with the supporting developing of the Rapid Flood Spreading Method, RFSM (Mulet-Marti and Sayers, 2006) and formal introduction of fragility curves as part of a major UK study and the incorporation of adaptive decision pathways as set out in McGahey and Sayers, 2008.

Uncertainty within the climate change projections was severe, and profoundly influenced the shape of the final flood risk management plan. The gross uncertainty within these future projections led to the development of an adaptable management strategy where investment decisions are triggered by the monitoring of key variables of change. The plan recognises that there is no engineering limit to our ability to protect London from climate change (including sea level rise of up to 4m) but the preferred management approach was shown to vary with SLR. The TE2100 Plan therefore includes a process of monitoring sea level rise (and changing future projections) as a trigger raising defence, modifying the existing Barrier, or even developing a new barrage in the outer estuary.

5.1 INTRODUCTION

This chapter explores the development of the Thames Estuary flood risk adaptation management plan (the so-called Thames Estuary 2100 Plan). The TE2100 project (started in 2003 and running through to 2009 with ongoing updates since) was established to provide a long-term flood risk management strategy for the tidal Thames, London. Three primary drivers provided the motivation for the study:

- ***Climate change.*** The Thames Barrier and its associated gates were designed with a useful life of 60 years based on assumptions made about climate change in the early 1970s. In recognition of the uncertainty in these projections and the long lead time associated with implementing a major change to the Thames flood defences (estimated to be 20 to 30 years), a recommendation was made for a major mid-term review (*i.e.,* the early 2000s).
- ***Ageing of the current flood defence infrastructure.*** The linear defences throughout the estuary have been built over many years, in some cases over 300 years, and various sections were considered in need for improvement. Improving the condition of all the defences would be a significant task (estimated to require up to £4bn of investment). Central government questioned this need and the piecemeal justification provided by the Environment Agency (through local studies), and demanded a more a strategic approach, estuary-wide approach.
- ***More people living and working in the tidal floodplain.*** The development pressures along the estuary are significant. As part of the Thames Gateway initiative up to 120,000 new homes will be built within a 40km corridor between London Docklands to Southend in Essex and Sheerness in Kent, up to 75% of which could be located within the flood plain[9]. Without a well defined flood risk management strategy for the Thames, long-term development decisions could be made in the absence of appropriate strategic input by flood risk managers.

In response to these concerns, flood risk (present and future) was assessed and the strategic direction for managing these risks in the short-term (next 15 years), medium-term (the following 30 years) and long-term (to 2100) determined. This Chapter presents the context of the study (Section 5.2) and the author's contribution to the development of innovative tools (Section 5.3) and decision and planning approaches (Section 5.4) developed to support the adaptation strategy for the tidal Thames. Insights into wider considerations that influenced the Plan (beyond flood risk) are briefly explored (Section 5.5) before reflecting upon the lessons learnt from this major study and the live issues that remain (Section 5.6).

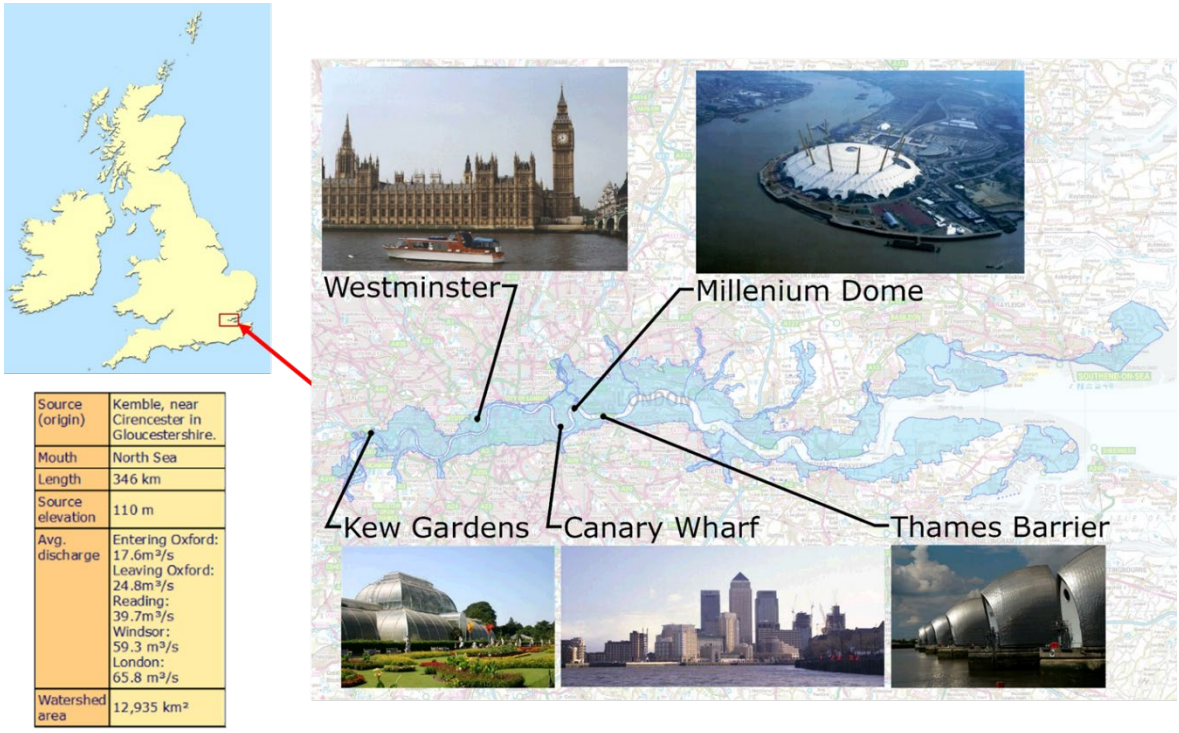
[9] *https://21stcenturychallenges.org/the-thames-gateway/ accessed June 2018*

5.2 THAMES ESTUARY IN CONTEXT

5.2.1 Setting the scene

The Thames is only 346km long but is the longest and most important river in England. The Thames Valley was probably first inhabited 400,000 years ago, with permanent settlements dating back to Neolithic times and a detailed recorded history that goes back over 2,000 years. Over this period the Thames Valley, and the Thames Estuary, has grown to become one of the most significant financial and cultural capitals of the world with a population today of around 8 million (as of the 2011 Census) with a gross domestic product (GDP) per capita of around €67,500 (Eurostat, 2017).

Today, the flood plains of the Thames Estuary are home to approximately 0.5 million homes, 1.25 million people (on any given working day), national government and ministries, around £200bn of property assets; nationally and internationally important infrastructure (including the London Underground, 16 hospitals and eight power stations); and internationally important nature conservation areas. London is also the UK's economic powerhouse, contributing around £250bn annually to the UK economy. The financial and business service sectors are central to this, and although the traditional 'square mile' of the City of London is outside of the tidal flood plain of the Thames, the commercial centre of Docklands (including the ionic Canary Wharf) is wholly within it (Tarrant and Sayers, 2012 - Figure 5-1).



Source: Background – Environment Agency (Flood Zone 3); Images open source. The ensemble image taken a presentation by the author at the American Association of Floodplain Managers conference, 2007.

Figure 5-1 A range of vital and valuable assets lie in the floodplains of the tidal Thames – the setting for the Thames Estuary case study

5.2.2 Authorities involved in management of the Thames – Past and present

In the Middle Ages, the Crown exercised general jurisdiction over the non-tidal Thames and the City of London exercised jurisdiction over the tidal Thames. Both continued to argue over ownership of the tidal river until the Thames Conservancy was formed in 1857. In 1866, the jurisdiction of the Thames Conservancy was extended to include the tidal and non-tidal reaches of the Thames. In 1909, as commerce in the tidal reaches continued to grow, the powers of the Thames Conservancy over the navigation in the tidal river were transferred to the Port of London Authority – and they continue to take the lead role in issues of navigation and port development in the tidal Thames today.

The broader management of the Thames River remained with the Thames Conservancy, which transferred to the Thames Water Authority on its creation in 1972. When Thames Water was privatised in 1990, its river management functions (including flood management) were transferred to the National Rivers Authority, which, in 1996, was subsumed into the Environment Agency – and they continue to have strategic oversight of issues that relate to river management (*e.g.,* water quality, flood risk management).

Today, the Environment Agency work closely with the Mayor of London (an elected politician), along with the London Assembly of 25 elected members along with the Greater London Authority (permanently staffed with civil servants) and many other organisations to develop and deliver strategies for London (Table 5-1).

Table 5-1 Organisations involved in flood risk management in England

Department for Environment Food and Rural Affairs (Defra)	Defra has national policy responsibility for flood and coastal erosion risk management within England and provides funding through grants to the Environment Agency and on to the local authorities.
Environment Agency	The Environment Agency has a strategic overview of all flood and erosion risk management in England and Wales. It is responsible for forecasting and mapping flood risk, providing warnings, advising on development in the floodplain, building and keeping defences in good order and taking part in emergency planning and response. The Environment Agency manages central government grants for capital projects carried out by local authorities and Internal Drainage Boards.
Local authorities	Local authorities lead in reducing risks from development in the floodplain and management of drainage and small watercourses as well as coastal erosion. They will play an increasingly important role in helping to manage the risks associated with surface water flooding. They also take the lead in emergency planning for flooding and handling the recovery of areas that have been affected by flooding.
Internal Drainage Board (IDB)	IDBs are independent bodies responsible for land drainage in areas of special drainage need. These are mostly low-lying areas that need active management of water levels.
Regional Flood Defence Committee (RFDC)	RFDCs have a duty to take an interest in all flood matters in their area. They are responsible for decisions about the annual programmes of improvement and maintenance work carried out by the Environment Agency.
Local Resilience Forums	These are the local planning forums for all emergencies, including flooding. They bring together the emergency services, Environment Agency, National Health Service and other bodies like water and energy companies. Together they plan for prevention, control, and reduction of the impact of floods on the public.
Coastal Groups	Coastal Groups provide a forum for all things at the coast. This includes data collection and the integration of coastal policies and management.
Insurance industry	The Association of British Insurers and its members are vital in providing cover and handling claims for damages caused by a flood. Under an agreement with the government, they have committed to continue insurance coverage for most properties, even some at significant risk, in return for action by government to identify and manage risks.
National Flood Forum	A registered charity providing advice to those at risk and campaigning for better protection from flooding.
Non-governmental organisations (NGOS),	Provide a strong voice in shaping flood and erosion risk management actions.
Natural England, English Heritage, and statutory consultees	Provide a strong voice in shaping flood and erosion risk management actions and are statutory consultees when flood risk or erosion risk management activities overlap/impact upon designated habitats/species or features of historical interest.

Source: Based on Tarrant and Sayers, 2012

5.2.3 Historical approach to flood defence within the Thames Estuary

Flooding has always been an important topic for London. The earliest written record of flooding along the Thames Estuary is from an Anglo-Saxon Chronicle of 1099, which recorded a flood on the *'first day of the new moon'*, and numerous floods have been recorded since then. A period of dramatic growth in the 17th and 18th centuries fuelled the largely *ad hoc* reclamation of marshes and mudflats alongside the Thames for industrial and agricultural purposes that established the outline of today's London. Frequent flood events occurred during this period with little in terms of a formal response. This changed in the 19th century in response to two exceptional record tides, the first in 1874 and second in 1875. In response Parliament acted by passing the Metropolis Management (Thames River Prevention of Floods) Amendment Act 1879 (Gilbert and Horner, 1984). The Act set a statutory level for the flood defences in London. Following the 1928 event, the last major event to flood central London, the defences were raised again; this time under the powers of a new Land Drainage Act passed in 1930. Following the devastating North Sea surge of 1953 (see Chapter 2) and 58 deaths on Canvey Island in the outer Thames Estuary, the issue of flooding gained new prominence. In 1954, the government-appointed Waverley Committee reported on the disaster and the search for new flood defence options commenced. Eventually, the government's Chief Scientist, Sir Herman Bondi, recommended in 1966 that the best solution was a *'tidal surge barrier and raising the height of the riverbank, backed up with a good system of flood warnings'*. In 1972, legislation was provided through the Thames Barrier and Flood Prevention Act to design and construct the system of River Thames tidal defences seen today.

This period, prior to the development of the Thames Barrier, was characteristic of a 'flood defence' -led management paradigm and is evident in the stratification of the tidal defences as they exist today (see Chapter 3, Figure 3-24).

5.2.4 Present-day setting flood defence system for London

Today, flood risk is managed in the estuary using a portfolio of approaches, including a formal flood defence together with non-structural measures, including forecasting and warning, spatial planning, and emergency exercises. All these elements are discussed below.

Flood defences

The flood defences put in place following the 1953 flood (and completed in the early 1980s) provide the defence system that continues to exist today (Figure 5-2). This includes the Thames Barrier at Woolwich, inaugurated by the Queen in 1983, three decades on from the 1953 floods. In addition to the Thames Barrier, this system of defences consists of five other barriers (Barking, Benfleet, Dartford, East Haven, and Fobbing Horse) and two major flood gates at the entrance to the Royal and Tilbury Docks. These barriers and gates work alongside 337km of linear flood defences (walls and embankments), which are themselves punctuated by a further 300 riparian flood gates and 400 minor moveable structures. The Barrier, its associated gates and defences were designed to protect London from the 1in1000-year combined tidal/fluvial flood event in 2030 (the highest standards of flood defence in the

UK)[10]. Although the protection afforded is generally welcome there is an increasing sense that these defences acted to separate the community from the river and, in parts, unnecessarily restrict the natural function of the river.



Source: Background map, Environment Agency (Flood Zone 3); images open source. Image ensemble from Sayers et al, 2007

Figure 5-2 The defended Thames tidal floodplain and the present-day standard of protection and primary tidal barriers

Flood forecasting and warning

Operation of the flood barriers is dependent on accurate forecast data. Developing conditions of storm surge, high tide and high fluvial flow are monitored from the control room at the Thames Barrier, which is manned 24h a day, 365 days of the year. This process has been in place since the Barrier became operational in 1982 and maintained under constant review and improvement. Looking to the future there is concern that the frequency of closure may increase so much as to make maintenance impossible (Figure 5-3).

Spatial planning control and risk management

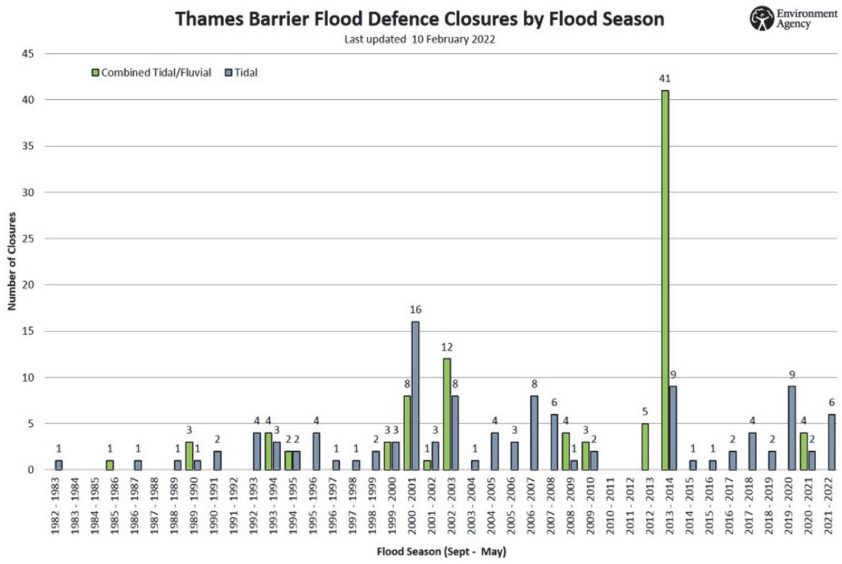
Development pressure on London's tidal flood plain is significant. It is not appropriate to attempt to prevent all new developments but rather seek to ensure any development that does

[10] The final crest level chosen during the design included a generous freeboard allowance and analysis undertaken in support of the strategy development – subject of the discussion later in this chapter – suggests the actual standard to be approximately a 1 in 10000-year return period (Sayers et al., 2007).

take place is appropriately safe and does not impact the functioning of the estuary. Planning is led by the multiple local authorities within London, working closely with the advice from the Environment Agency. The success of these measures remains the subject of discussion.

Emergency and contingency planning

Resilience forums operate to plan for and manage the potential consequences of flooding. Such planning activities include: (i) development of business continuity plans; (ii) planning for the consequence of a flood event, emergency evacuation, shelter, and clear-up operations, and (iii) providing advice to local communities on what action they can take before, during and after a flood. The ability to execute the plans is regularly tested as part of a synthesised response exercise, but in the absence of a widespread flood since 1953 their operational success remains to be confirmed.



Source: Environment Agency via Gov.uk – open source[11]

Figure 5-3 Change in closure frequency of the Thames Barrier

5.2.5 Habitat and environmental importance of the Thames Estuary

Any major engineering project in England must be accompanied by a Strategic Environmental Assessment (SEA). The SEA for the TE2100 Project highlights the importance of the Thames Estuary as a wildlife corridor. The estuary supports one of the widest variety of animals of any estuary in Europe, is one of the five most important estuarine complexes for birds in Europe (supporting over 300,000 migratory waders and wildfowl) and has diverse fish stocks (with 121 species of fish having been recorded since the 1960s, nine of which now spawn within the estuary). Large parts of the outer estuary are designated

[11] *The Thames Barrier – GOV.UK (www.gov.uk) Accessed August 2022*

wildlife sites, and support nationally and internationally important habitats and species (notably birds, but also fish, invertebrates, and marine mammals). The Thames Estuary is also intrinsically connected to the (southern) North Sea and the East Atlantic Flyway (a flyway linking a discontinuous band of arctic breeding grounds that stretch from Canada to Siberia, Russia).

5.2.6 Flood sources

Tidal flooding is not the only concern in the Thames Estuary. Fluvial flooding from the tributaries, pluvial flooding and groundwater flooding all present problems. The TE2100 project, and the remainder of this chapter, focuses on the management of tidal and fluvial flooding in the tidal estuary but, for context, the groundwater and surface water (pluvial) challenges are briefly introduced below.

Groundwater

Before the 1750s, London's water table was close to the surface. The Industrial Revolution and the associated boom in factory building in and around London created an unprecedented demand for water resources. Significant groundwater abstractions were used to meet this demand and as a result groundwater levels fell. In recent years this trend has reversed as commercial activities have changed from production to service industries and groundwater water levels have risen.

In response to the raising water levels has been limited to the approval of new abstraction licenses across the central London area, with the responsibility for developing and funding a more strategic groundwater management plan unclear.

Pluvial flooding and surface water

London lies on a layer of London Clay and other impermeable alluvial deposits and many rivers that once acted as surface drains have been culverted. As a result, runoff is now routed through underground drainage and discharged through a network of pumping stations and gravity flap values to the estuary. Heavy rain soon overwhelms the drainage network and flap value outfalls are often tide-locked. This inability to move water from the urban surface into the estuary often results in localised flooding.

Surface flood waters are also often polluted

In common with many older cities, the majority of London is served by a combined sewerage system (CSS); a single system that manages sewage and storm water flows. The network of interceptor sewers, constructed by Sir Joseph Bazalgette following the 'Great Stink' of 1858, are still the backbone of this system, Halliday, 2001). Bazalgette's design uses the City's culverted river network (such as the Fleet and the Tyburn which had already been built over before Victorian times) to convey water to interceptor sewers and then onto balancing tanks in East London. Bazalgette designed the system to overflow through discharge points into the River Thames in times of severe storms, rather than flooding streets and homes. A combination of continued development, climate change and pollution concerns led to commissioning a Thames Tideway Strategic Study Group in 2001. As a result, a major new

inceptor tunnel (7.2m in diameter, 25km long, up to 65m below ground) was selected by the Government as the preferred solution and (at the time of writing) remains under construction. The choice of this solution has not been without its critics, with many highlighting a that a more distributed '*blue-greening'* of the City would have achieved additional benefits for less (*e.g.,* Richard Ashley and past ICE President Jean Venables). The impact on tidal flooding (the focus here) is expected to be marginal.

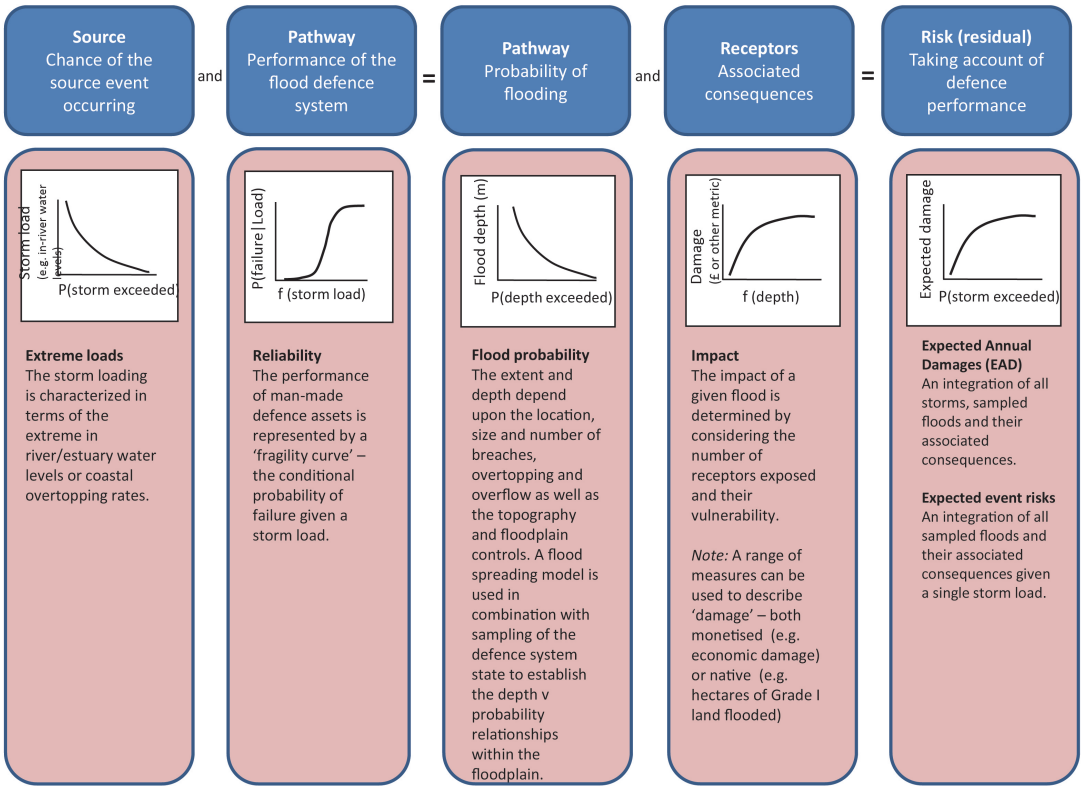
5.3 DEVELOPING SYSTEM RISK TOOLS AND TECHNIQUES FOR THE THAMES

Conventional modelling approaches were considered unable to provide the whole system risk analysis required to assess flood risk across the estuary within practical run-times and in a way that represented the performance of the extensive defence system and complex spatial variation in economic activities. In response to this challenge, the method developed to assess flood risk across the estuary evolved from the *Source-Pathway-Receptor* concept (see Chapter 3, Figure 3-8) and the RASP (Risk Assessment for Strategic Planning) analysis framework (Sayers *et al.,* 2004). The development of the RASP analysis approach and application to the Thames Estuary are the focus of this chapter (with extended detail available in Sayers *et al.,* 2004, Sayers and Meadowcroft, 2005, Hall *et al.,* 2003c, Gouldby *et al.,* 2008 and the Environment Agency led study reports 2009a,b&c).

Note:
Following completion of the TE2100 studies the RASP methods continued to develop. From 2008 the RASP HLMplus (see Table 5-2) underpinned the National Flood Risk Assessment (NaFRA) and translated into the Modelling Decision Support Framework 2 (MDSF2) software used by the Environment Agency and its consultants (*e.g.,* McGahey and Sayers, 2009, McGahey *et al.,* 2010).

5.3.1 Overview of the RASP framework

The RASP framework (Figure 5-4) brings together a full range of storm-loading conditions (*e.g.,* extreme water levels, wave heights *etc.*) with the performance of defences (represented through fragility curves, *e.g.* Casciati and Faravelli, 1991, Melchers, 1999, Shinozuka *et al.,* 2000) and an assessment of inundation and the economic consequences associated with a range of defence system states (*e.g.,* breach and non-breach).



Source: Taken from Sayers et al., 2013 that adapts an illustration in Sayers et al., 2004

Figure 5-4 Overview of the main components of the RASP High Level Method that underlies the Thames Estuary analysis

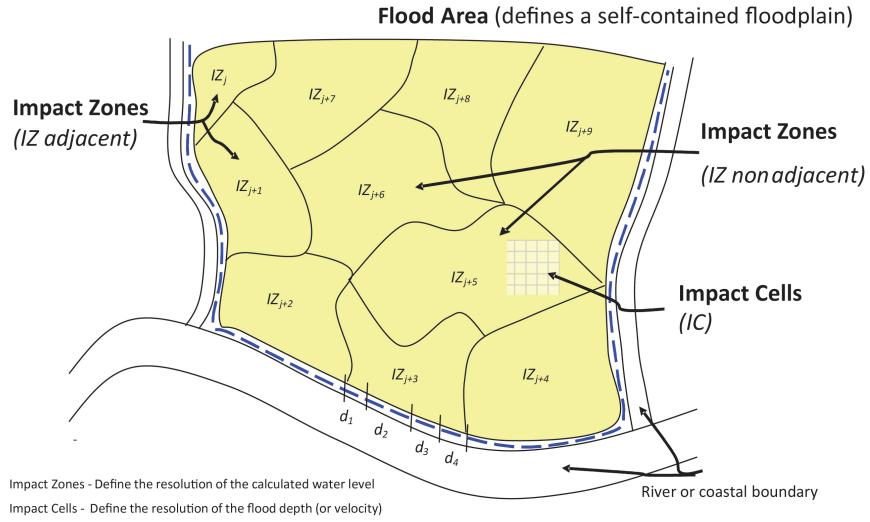
The methods used to implement this framework range in detail from the so-called RASP High Level Method (*e.g.,* Hall *et al.,* 2003c) through to a Detailed Level Method (Table 5-2). The RASP High Level Method, for example, builds a picture of risk based on an analysis of Flood Areas that are assumed to be independent, with each defence within a given Flood Area assumed to experience a dependency of load and be independent in terms of strength. More detailed RASP methods progressively relax these assumptions. Within this hierarchy of methods, a new approach was developed for the Thames, the so-called High-Level Method*plus* (HLM*plus* – *Table 5-2*). This approach is presented here in the following sections.

Table 5-2 Hierarchy of RASP methods and their principal assumptions

RASP Method	Governing Assumptions
High Level Method Initially implemented as part of the National Flood Risk Assessment (NaFRA), England in 2002 (Sayers *et al.,* 2003b) with the method described in Hall *et al.,* 2003c.	*Independence of strength – i.e.,* the behaviour of an individual asset or asset element does not influence another. *Dependence of load – i.e.,* each asset within a given defence system is assumed to be equally loaded.
High Level Method*plus* Used in support of the TE2100 studies (Gouldby, Sayers, *et al.,* 2008) and the national assessment in 2009 (Environment agency, 2009d) and within the Modelling Decision Support Framework 2 (McGahey and Sayers, *2008* – with subsequent updates)	The governing assumptions as the High-Level Method but The HLM*plus* approach introduces the Rapid Flood Spreading Method (as developed by Mulet-Marti and Sayers, 2006). This provides an improved representation of the flood area given overflow of the defence system. This enables an improved approach to the sampling of defence failure states to be incorporated and improved representation of the damages (as discussed later in this chapter). For application of the HLMplus approach in the Thames the resolution of data inputs on sources (extreme loads), pathways (including defence fragility flood and spreading) and receptors improved compared to national applications.
Intermediate Level Method Implemented as part of the RASP research, Sayers *et al.,* 2004, Dawson *et al.,* 2005 and taken forward recently in Gouldby *et al.,* 2015	*Independence of strength – i.e.,* the behaviour of an individual asset or asset element does not influence another. Relaxed assumptions and implications *Dependence of load* – this enables the spatial variation in loading during an event (for a given system state – *i.e.,* defence state and storm) to be considered. This could be supported by continuous simulation methods or joint probability analysis of discrete storms as appropriate. Relaxation this enables the feedback between river levels and the breach of a defence to be considered.
Detailed Level Method To date not implemented, progress continues (for example the inclusion of transitions within fragility analysis to relax the assumption of independence of strength	*Dependence of load* – as above. Relaxed assumptions and implications *Independence of strength* – this enables the behaviour of one asset or asset element to influence another. A breach in one location, for example, may weaken the neighbouring defence; or the modified management of a river channel may influence the downstream assets due to scour or increased loading; the construction of a groyne in one location may modify beach levels downdrift.

5.3.2 RASP High Level Method*plus* analysis approach

Figure 5-5 shows the conceptual representation of a Flood Area and presents a river channel separated from the floodplain (the Flood Area) by a series of discrete flood defences (d_1, d_2,…, d_n)). Each defence section is assumed to be independent and have a unique resistance to flood loading (reflecting, for example, different types of structure, crest levels or condition grades). The floodplain area is discretised into a series of Impact Cells (z_1, z_2,…, z_m) with the potential to be flooded by flood entering the Flood Area through any of the (n) defences.



Source: Gouldby et al., 2008 building on Mulet-Marti and Sayers, 2006

Figure 5-5 Conceptual diagram of the model backdrop of RASP High Level Method

Storm loads on a given defence (in the case of the Thames studies, in-river water levels) are defined as continuous random variables (L). The response of a defence to these loads (ultimate or serviceability limit state failure) is also defined as a continuous random variable, conditional on the load (commonly referred to as a fragility curve; a concept set out in the context of flood defences in Sayers *et al.,* 2002a and various related publications, *e.g.,* Meadowcroft and Sayers, 1998, Simm *et al.,* 2008, Allsop *et al.,* 2008).

Within a given Flood Area, the defence system is formed by a continuous boundary between the water body (*i.e.,* the estuary river and tidal rivers) and the floodplain. This continuous line includes raised and non-raised defences and makes no *a priori* assumption about the importance of any specific defence section[12].

During a flood event each defence is assumed to take one of two possible states (represented as a Bernoulli Random Variable), 'failed' or 'not failed' ($d_i, \bar{d}_i$), with the likelihood of each

[12] A concept set out in Sayers et al., 2004 and taken forward as part of the Continuous Defence Line (CDL) mapping by the Environment Agency, first published in 2018 to better support the RASP methods.

state obtained with reference to the given load (l) and the conditional probability of failure (D) given that load, $P(D_i|l)$. The number of potential defence system states (combinations of failed/not failed defences within the flood area), for a given load, is therefore 2^n. Consider an Impact Zone protected by two defences, d_1, d_2. In this case there are four defence system states: neither defence fails, both defences fail, the first defence fails and the second does not, the second defence fails and the first does not. The defence system state, derived from the failed/non-failed state of each defence section, is therefore itself also a discrete random variable (D) whose conditional probability mass function (pmf) is:

$$p_{D|L}(d\ ,l) = P\left[D = d\ \middle|L = l\right] \qquad \textit{Eq. 5.1}$$

Where

- D = Discrete random variable that represents the defence system state.
- d = A vector that comprises the state of all the defences – failed or not failed – in the defence system.
- L = Continuous random variable that represents the defence loading conditions.
- l = A vector that comprises the loads on each defence.

As introduced earlier, the RASP HLM*plus* makes the assumptions that adjacent defence strengths are independent of one another (see Table 5-2). This simplifying assumption enables the probability of any defence system state, for example, $d_1,...d_k,\overline{d}_{k+1}...\overline{d}_n$, occurring during a storm load (l), to be determined using a simple multiplication rule:

$$p_{D|L}(d,l) = P\left[D = d\middle|L = l\right] = \prod_{i=1}^{k} p(d_i|l) \prod_{i=k+1}^{n} \left[1 - p(\overline{d}_i|l)\right] \qquad \textit{Eq. 5.2}$$

The volume of flood waters (V) entering the Flood Area for a given load (l) is then a function of the defence system state and the assumed failure modes. For linear defences, a simple breach size is determined as function of the length of the defence that varies according to the severity of the load and type of defence (with wider breaches assumed for earth embankments than for concrete walls, for example). Given a crest level and a breach invert level the inflow volume into the floodplain over any given defence is then calculated using the broad-crested weir equation. Uncertainty was introduced on the various parameters influence the inflows and incorporated into a probabilistic assessment of the inflow volume (including uncertainty in crest level, dependent upon the source of that information, the breach width, and other variables as summarised in Table 5-3 as discussed further in Appendix 3 of Gouldby *et al.,* 2007).

Table 5-3 Summary of uncertainties in the assessment of inflow volumes over a given defence

Inflow volume – model input		LB – 10th percentile	UB 90th percentile	Standard Deviation or error	Distribution Type
Collected Data					
Crest Level	Basis				Normal
	A Local GPS survey	-0.01m	+0.01m	0.0078m	
	B Low Level LIDAR	-0.27m	+0.27m	0.21m	
	C Land Charge Register Drawings 1997	-0.30m	+0.30m	0.236m	
	D Statutory Defence Levels	-0.33m	+0.33m	0.261m	
	E Haskoning Defence Database	-0.37m	+0.37m	0.287m	
	F IA3 Condition Inspection Output	-0.40m	+0.40m	0.313m	
	G Version 1a Model	-0.43m	+0.43m	0.339m	
	H Thames Tidal Database	-0.47m	+0.47m	0.364m	
	I Estimation from Standard of Protection records	-0.50m	+0.50m	0.39m	
Load	Basis				Normal
	Hydraulic model results from associated studies				
	Return Period				
	1	-0.02	+0.02	0.02	
	10	-0.08	+0.08	0.06	
	100	-0.20	+0.20	0.16	
	1000	-0.45	+0.45	0.35	
	10000	-0.82	+0.82	0.64	
Ground Level	Basis				Normal
	High Level LIDAR	-0.54m	+0.54m	0.42m	
Defence Length	Basis				
	NA	NA	NA	Assumed certain	NA
Model Parameters					
Weir Equation Constant	Basis				Normal
	Physical model studies reported in the literature	-0.2	+0.2	0.16	
Breach Width Multiplier	Basis				Triangular
	Literature/Experience	-0.5 * Best Estimate	+0.5 * Best Estimate	NA	
Duration of overflow	Basis				Normal
	Studies and expert judgement.	-0.2 * Best Estimate	+0.2 * Best Estimate	NA	
Hydrograph Multiplier	Estimate	-0.05	+0.05	0.039	Normal

Note: values (bounds are given relative to best estimate or mean value). Source: Gouldby et al., 2007

The flood depth (*Y)* in any Impact Cell is therefore a function of the defence system state (and hence also a discrete random variable):

$$Y = g(D) \qquad \textit{Eq. 5.3}$$

The probability of exceeding a given flood depth (y) in a given Impact Cell and for a given loading condition (l) can then be determined as follows:

$$P(Y > y|l) = P[g(D) > y|l] \qquad \textit{Eq. 5.4}$$

In conceptual settings that enable the relationship between D to Y to be readily evaluated the solution to Equation 5.4 can be determined simply as the summation of the probability mass function (pmf) for realisations of D that yield flood depths greater than y (a region denoted as here as (A)). In this case, equation 5.4 becomes:

$$P(Y > y|l) = \sum_{A} p_{D|L}(d_s, l) \qquad \textit{Eq. 5.5}$$

In real situations the function that relates D to Y is non-trivial and requires evaluation through simulation. Methods to model flood inundation vary in complexity and accuracy, from simple spatial queries that involve no modelling of the flow physics (and need minimal information and take virtually no time to run, for example projection of in-river water levels), to models that attempt to represent the hydrodynamics of the physical processes (and require detailed input data and have high computational demands, for example including the full solution of the St Venant equations). Neither of these two extremes enable a credible evaluation of this function across a full range of defence system states.

To overcome this difficulty an innovative, fast to set up and run flood spreading model was developed (the Rapid Flood Spreading Model (RFSM), initially developed by Mulet-Marti and Sayers, 2006, discussed further below). Despite the significant runtime efficiencies provided by the RFSM (much faster than conventional flood inundation approaches, Environment Agency, 2010b), the runtime still prohibits solution of Equation (5.5) by enumeration, particularly given that the vector (d) in many Thames Flood Areas frequently exceeds 100 separate elements (*i.e.,* a defence system can comprise more than 100 defence lengths) resulting in more than 2^{100} possible defence system states, each requiring analysis for each given loading event.

A Monte Carlo simulation is used to reduce the number of system states that need to be simulated. The elements of the defence vector (D) are sampled (with reference to the defence fragility curves and loads (l)) so each sample comprises a defence system state (for example, $d_1,...d_k,\overline{d}_{k+1}...\overline{d}_n$) and an associated vector (V) comprising the volume discharged from each defence system into the floodplain given the in-river load (based on simplified overflow and breach inflow calculations as appropriate, not discussed further here but detailed in Sayers *et al.,* 2004, Sayers and Marti, 2006 with numerous subsequent advances, *e.g.,* Gouldby *et al.,* 2012).

Once sampled, the vector (V) comprises the boundary condition for the RFSM and the RFSM generates the maximum flood depth in each Impact Cell (IC) from the input flood volumes and inflow locations. The probability of exceeding a specified flood depth, given a specified loading event (l), in any Impact Cell, can then be estimated as follows:

$$P[(Y > y)|l] \approx \frac{m_{Al}}{m_l} \qquad \textit{Eq. 5.6}$$

where m_A is the number of realisations from the Monte Carlo (random) sampling process that yields a depth at ICi greater than y under loading condition l, and m_l is the total number of simulations undertaken for loading event l.

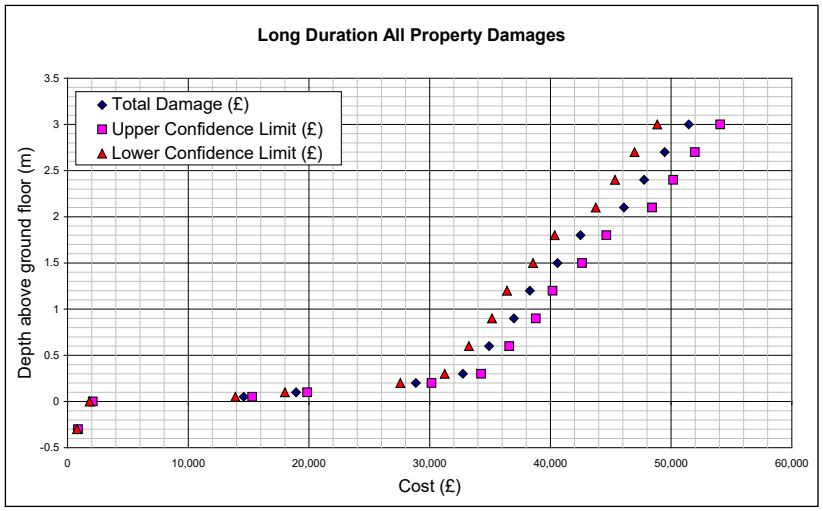
To obtain the unconditional expectation of the annual probability of exceeding y a full range of annual loading conditions must be considered. To do so, the continuous loading distributions (describing the aleatory uncertainties associated extreme water levels) are discretised into q levels of L: $l_1, l_2, l_3, \ldots. l_q$, associated with specified annual return periods.

$$P(Y > y) \approx \sum_{i=2}^{q-1}\left[p\left(L \geq \frac{l_i + l_{i+1}}{2} \right) - p\left(L \geq \frac{l_i + l_{i-1}}{2} \right) \frac{m_{Al_i}}{m_{l_i}} \right] \qquad \textit{Eq. 5.7}$$

For application to the Thames, 60 discrete loading levels are used, ranging from more frequently occurring (1in1 year return period) to much rarer (1in10000 year return period) in-river water levels (ensuring that events which exceed the notional 1: 1000-year design standard of the defences are considered[13]).

Each modelled flood event (*i.e.,* combination of the loading event and randomly sampled defence system state) results in an estimate of the flood depth for each Impact Cell. Combined with information on the receptors within each Impact Cell (primarily property type and floor area taken from the National Receptor Dataset (NRD)) the associId consequences (c) are readily found using an appropriately selected depth versus damage relationship (Figure 5-6).

[13] *Sensitivity testing suggest at least 20 loading return intervals need to be considered to avoid introducing significant error, McGahey et al., 2006.*



Source: Middlesex Multi-Coloured Manual (MCM) All Residential Property – Long Duration events (Penning-Rowsell et al., 2005)

Figure 5-6 Example depth versus damage curve used as part of the Thames analysis

The Expected Annual Damage (EAD) associated with an Impact Cell is then estimated in a similar way to the probability of flooding to a given depth. First the mean economic consequence for each loading level is established through the Monte Carlo simulation (so-called event economic damage).

$$\bar{c}_l \approx \frac{1}{m_l}\sum_{j=1}^{m_l} c_j \qquad \text{Eq. 5.8}$$

where

$\bar{c}_l =$ Mean economic consequence associated with the loading condition l in a specified Impact Cell.

The mean event economic damages are then integrated over the range of loading levels using the same discretisation procedure introduced above (equation 5.7) giving:

$$EAD_{IC} \approx \sum_{i=2}^{q-1}\left[p\left(L \geq \frac{l_i + l_{i+1}}{2} \right) - p\left(L \geq \frac{l_i + l_{i-1}}{2} \right) \bar{c}_{li} \right] \qquad \text{Eq. 5.9}$$

where EAD_{IC} is the Expected Annual Damage associated with each Impact Cell IC. These damages are then aggregated over all Impact Cells within a given Flood Areas and the estuary.

An important consideration in any implementation of a Monte Carlo simulation is to determine when sufficient simulations have been completed and a robust result established. The assessment of both the expected flood depth and economic damage for each load interval as well as the annual average provides a useful guide to this and to limit the error introduced through the sampling procedure. To do so, convergence on $\bar{c}_l$ (Eq. 5.8) is monitored for each loading interval (l). Given the quantity of interest here is the Expected Annual Damages (*i.e.,* an integration of all loading levels), convergence on each loading level may not be required

(as a specific loading level may contribute little to EAD and hence effort to seek convergence on $\bar{c}_l$ for that loading level would be wasted in the context of an assessment of EAD[14]). To overcome this issue, a practical approach is implemented that undertakes a set number of random samples (typically 500) for each loading level (*i.e.,* m_l is constant) and convergence on EAD monitored after all loading levels have been assessed (before repeating as necessary).

The RASP HLM*plus* also enables an estimate of the contribution to risk to be allocated to each defence section. This is possible because of the ability of the RFSM to link the inflow location and quantify to damage based on the relationships that exists between Impact Zones (see Figure 5-5). Given this ability, directly attributing the contribution to risk of individual defences (taking account of their unique location within the defence system, fragility, and loading) is relatively straightforward (see Gouldby *et al.,* 2008) and avoids the more indirect approaches to attribution based on, for example, sensitivity testing (*e.g.,* Dawson *et al.,* 2005).

An illustration of the various outputs from RASP as discussed in the context of the Thames application follows later in Section 5.5.

5.3.3 Rapid Flood Spreading Method (RFSM)

The conventional modelling response to support a system risk analysis would be to select a limited number of defence system states and analyse these using a hydrodynamic model[15]. Typically, little to no effort is devoted to understanding the error introduced through the non-exhaustive representation of all defence systems or the gross model structure errors that are introduced through, for example, the *a priori* selection of the 'weakest link' or assumptions regarding breach location, initiation, and growth (see Chapter 4 – validation of probabilistic models).

To avoid this limitation and enable a much larger number of system states to be explored, early versions of RASP incorporated a simple parametric inundation algorithm (as used to underpin the first National Flood Risk Assessments in 2002, Sayers *et al.,* 2003a Hall *et al.,* 2003c). This approach, although useful at the time, is not sufficiently accurate to support strategy development. The Rapid Flood Spreading Model (RFRM) was developed to fill this gap. The RFSM provides a credible, but practical, assessment of floodplain flows that is

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[14] Sensitivity analysis suggests that EAD estimates tend to be dominated by load events in the region 20 to 50 return periods. In the Thames the high defence standards mean higher return periods of are also important (McGahey et al., 2006)

[15] Typically, in this case, little to no effort is devoted to understanding the error introduced through the non-exhaustive representation of all defence systems or the gross model structure errors that are introduced through, for example, the a priori selection of the 'weakest link' or associated assumptions regarding breach location, initiation, and growth (see Chapter 4 – validation of probabilistic models).

capable of utilising high-resolution topographical data (available for much of the Thames Estuary) and easily and rapidly established at a scale of the Thames (and larger). The RFSM developed in support of the TE2100 studies is detailed in Mulet-Marti and Sayers, 2006.

Conventional inundation modelling approaches use the St.Venant equations to describe the flow (Saint-Venant, 1855, von Mises, 1945, and numerous publications since) with governing equations that can be written as (in Cartesian coordinates and neglecting diffusive terms):

$$\frac{\partial}{\partial t}[H]+\frac{\partial}{\partial x}[F]+\frac{\partial}{\partial y}[G]=[S]$$

H : *conserved variables*
F : *convective terms* $x-axis$
G : *convective terms* $y-axis$
S : *source terms*

Eq. 5.10

The capability of models based on these equations to simulate surface flows has been proven many times (*e.g.,* Environment Agency, 2010b). Within the context of developing a system analysis, providing a full solution to these equations remains difficult (without access to super or distributed computational power) and they must be simplified[16].

To provide a simplified but credible solution, consider the following formulation of the vectors in equation (5.10):

$$[H]=\begin{bmatrix} h \\ hu \\ hv \end{bmatrix} \quad [F]=\begin{bmatrix} hu \\ hu^2+0.5gh^2 \\ huv \end{bmatrix} \quad [G]=\begin{bmatrix} hv \\ huv \\ hv^2+0.5gh^2 \end{bmatrix} \quad [S]=\begin{bmatrix} R \\ g(S_{ox}-S_{fx}) \\ g(S_{oy}-S_{fy}) \end{bmatrix}$$

h: $water\ depth\ (m)$
u: $velocity\ x\ axis\ (m\ per\ s)$
v: $velocity\ y\ axis$(m per s)
g: $gravity\ acceleration\ (m/s2)$
R: $Mass\ source\ terms\ (Rain,\ sewer\ system,\ etc)$
S_o: $slope\ of\ the\ terrain$
S_f: $friction\ term$

Eq. 5.11

To avoid the overhead of representing all terms in the RFSM, the following assumptions are made:

- the inflow into the floodplain (from a given overtopping or breach event) is not inertial (*i.e.,* such as the flow generated after a sudden dam break).
- the influence of the convective terms *(F* and *G* in the above equations) can be neglected.

[16] An analytical solution of equation 5.10 for 2-D cases is not obvious (excluding some very simplified 1-D cases) and must be solved numerically, hence simplification is required.

- the main driver of the water movement is the source term (*S* in the above equation, *i.e.,* gravity and friction).

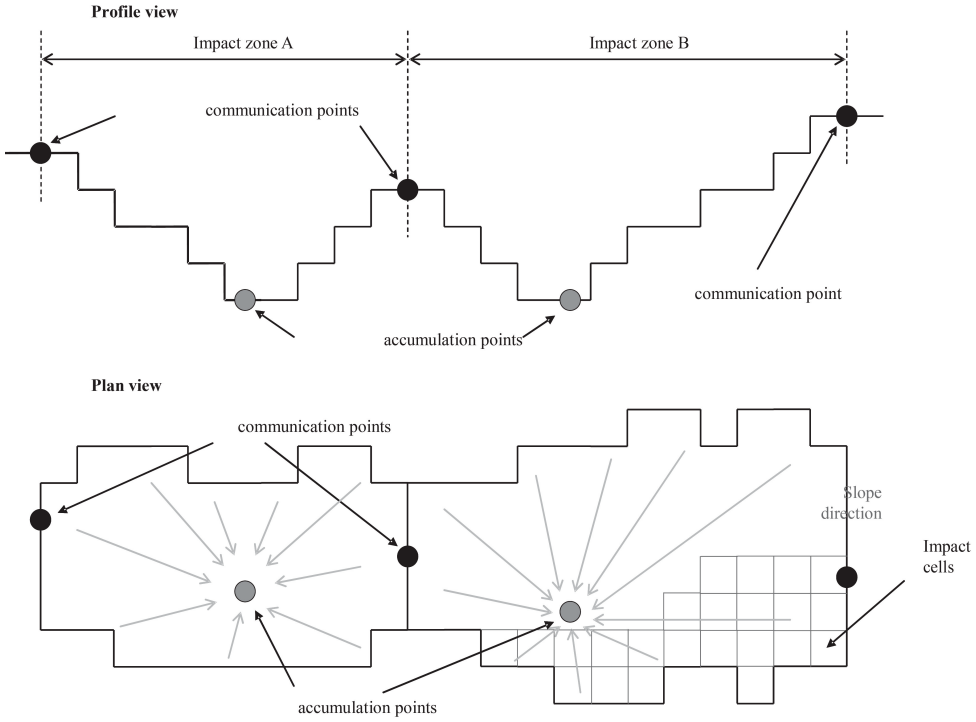
These simplifications are similar to those used to develop the early, non-inertial, versions of LISFLOOD-FP and similar models (*e.g.,* Bates and Roo, 2000), where the flow is directed by the slope and the friction of the terrain (following the Manning's or equivalent equations). Such models remain computationally demanding in the context of a system analysis. Three further simplifying assumptions therefore are made:

- ***Influence of friction can be ignored without a critical loss of accuracy:*** Based on the generally accepted view that in narrow, sloping, floodplains (such as the Thames) friction makes a small contribution to the momentum term (in comparison to the influence of slope) the influence of friction was ignored in the early version of the RFSM (as used on the Thames)[17].
- ***An understanding of temporal evolution of the flood event is not required:*** The focus of the risk assessment as part of the TE2100 studies was to support the economic appraisal and to do so does not require an understanding of temporal evolution of the flood event[18].
- ***An understanding of flood depth only:*** An estimation of the maximum flood depth in a given Impact Cell during a flood event provides a reasonable basis for the assessment of economic damages (as confirmed through the widespread use of depth versus damage relationships in flood risk assessments (*e.g.,* Penning-Rowsell *et al.,* 2005, 2010).

The RFSM calculation proceeds by spreading the inflow volumes (from each defence) into the Adjacent Impact Zones (Figure 5-5) and then to others (via communication boundaries – Figure 5-7). Flood waters accumulate in an Impact Zone (from the Accumulation Point) until water spills to the next Impact Zone. The Impact Cells provide a sub-grid representation of the Impact Zones with flood depths calculated at each Impact Cell. This enables high-resolution topographical information (available for much of the Thames floodplain) to be captured without increasing the complexity of the risk analysis or the run time of the RFSM (once the Impact Zones and rational relationships between Impact Zones have been established through a pre-process – see Mulet-Marti and Sayers, 2006 for details).

[17] *An assumption relaxed to enable the better representation of low-lying wide coastal floodplains (Lhomme et al., 2008).*

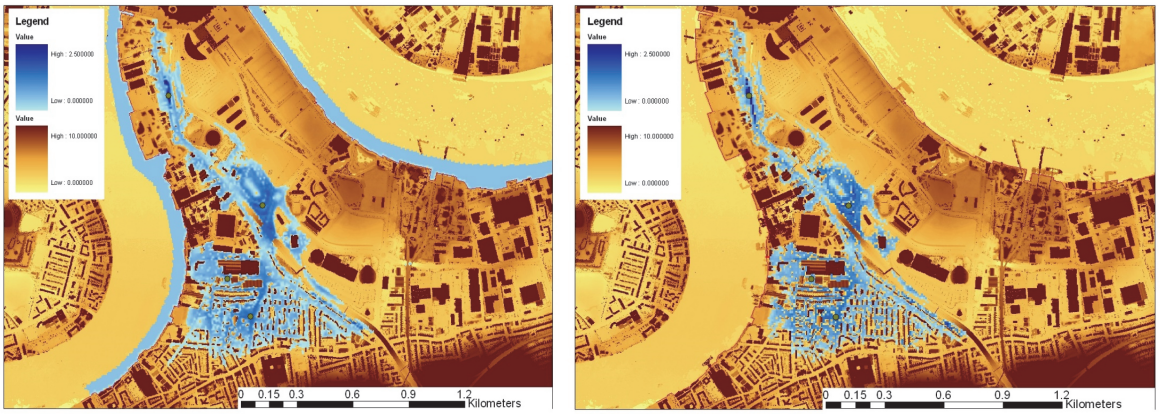
[18] *An assumption relaxed to better represent the evolution of a breach and to enable the assessment of flow velocities alongside depth in support of loss of life (Jamieson et al., 2012)*



Source: Illustration from Lhomme et al., 2008 building on Mulet-Marti and Sayers, 2006

Figure 5-7 Impact Zones provide the computational units within the RFSM with sub-grid resolution provided by the Impact Cells

The results of the RFSM compare well to more comprehensive modelling approaches in the context of the defence system and floodplains of the Thames Estuary (Figure 5-8). More extensive benchmarking of the RFSM following its application to the Thames reveals various shortcomings of the initial construction (*e.g.,* Environment Agency, 2010b) and has driven various improvements to the RFSM to enable its broader application (for example Lhomme *et al.,* 2008 and Jamieson *et al.,* 2012).



Left: Final depth TUFLOW (mAOD) Right: Final depth RFSM (mAOD). Source: Mulet-Marti and Sayers, 2006

Figure 5-8 Greenwich Embayment, Thames Estuary. Defence system state: 1 Breach. Load (notional extreme inflow)

5.3.4 Defence performance: Fragility curve assessment

High-level fragility curves (based on defence type and condition grade, from 1 – Good to 5 – Poor) form the basis of the initial set up of the Thames RASP system risk model (see Chapter 4 for an introduction to the concept of fragility). In some instances, these high-level curves have been refined based upon more detailed reliability analysis with those defence types, and in some instances individual defences, considered most critical.

In the case of the high-level analysis, two indicative failure modes have been evaluated to determine the fragility for each defence type and condition combination:

When the in-river water level is above the defence crest level

Firstly, an overtopping failure is considered. To determine the chance of failure by overtopping the following Limit State Equation is evaluated:

$$Z = q_c - q_a \qquad \textit{Eq. 5.12}$$

where:

- Z = limit state function such that $Z \leq 0$ represents system failure
- qc = critical overtopping discharge (estimated using the method of Vrouwenvelder, 2001)
- qa = calculated discharge (direct from the analysis of water level)

Secondly, a piping failure is considered. To determine the chance of failure by piping the following Limit State Equation is evaluated:

$$Z = h_c - h_a \qquad \textit{Eq. 5.13}$$

where:

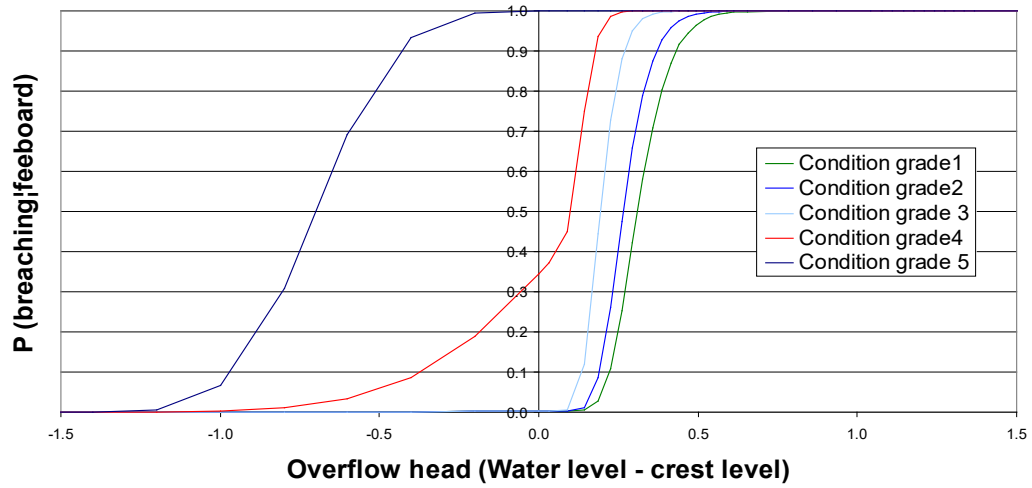
- Z = limit state variable
- hc = the critical loading-level (estimated using the method of Terzaghi, 1967)
- ha = the calculated loading-level (direct from the analysis of water level)

When the water level is below the crest level of the defence

Piping is assumed the dominant failure mode in this case and Equation 5.13 is evaluated.

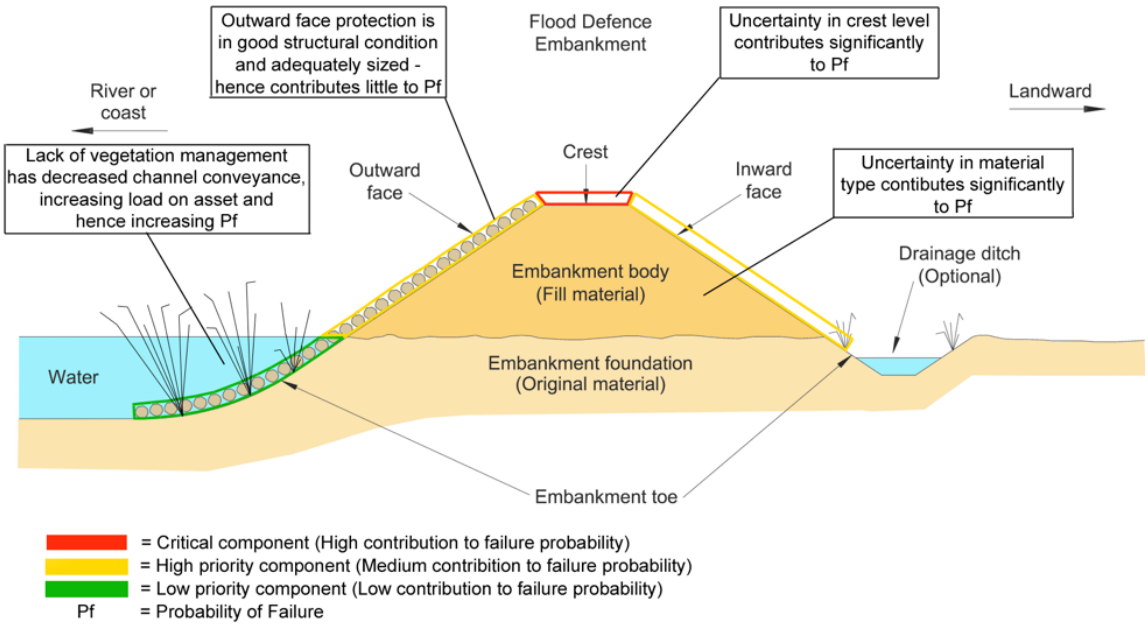
For selected defences a more detailed, multiple failure mode reliability analysis was undertaken (*e.g.,* Buijs *et al.,* 2005, 2008). Regardless of the detail of the reliability the form of the fragility curve remains unchanged (Figure 5-9). This is an important feature of the hierarchical framework provided by the RASP and enables detailed analysis on selected defences to be readily carried forward in the system risk calculation and avoids the need for a common level of analysis being applied to all defences (enabling effort to be targeted towards the most important defence assets). The detail of a progressive approach to reliability analysis as part of RASP framework is not discussed further here. Further detail is set out in Sayers *et*

al., 2004, Simm *et al.,* 2008, Sayers *et al.,* 2010 – with an illustration of the power of the analysis given in Figure 5-10.



Source: Sayers et al., 2004

Figure 5-9 Example high level fragility curve for a narrow sloping embankment given a range of Condition Grades



Source: Sayers et al., 2004

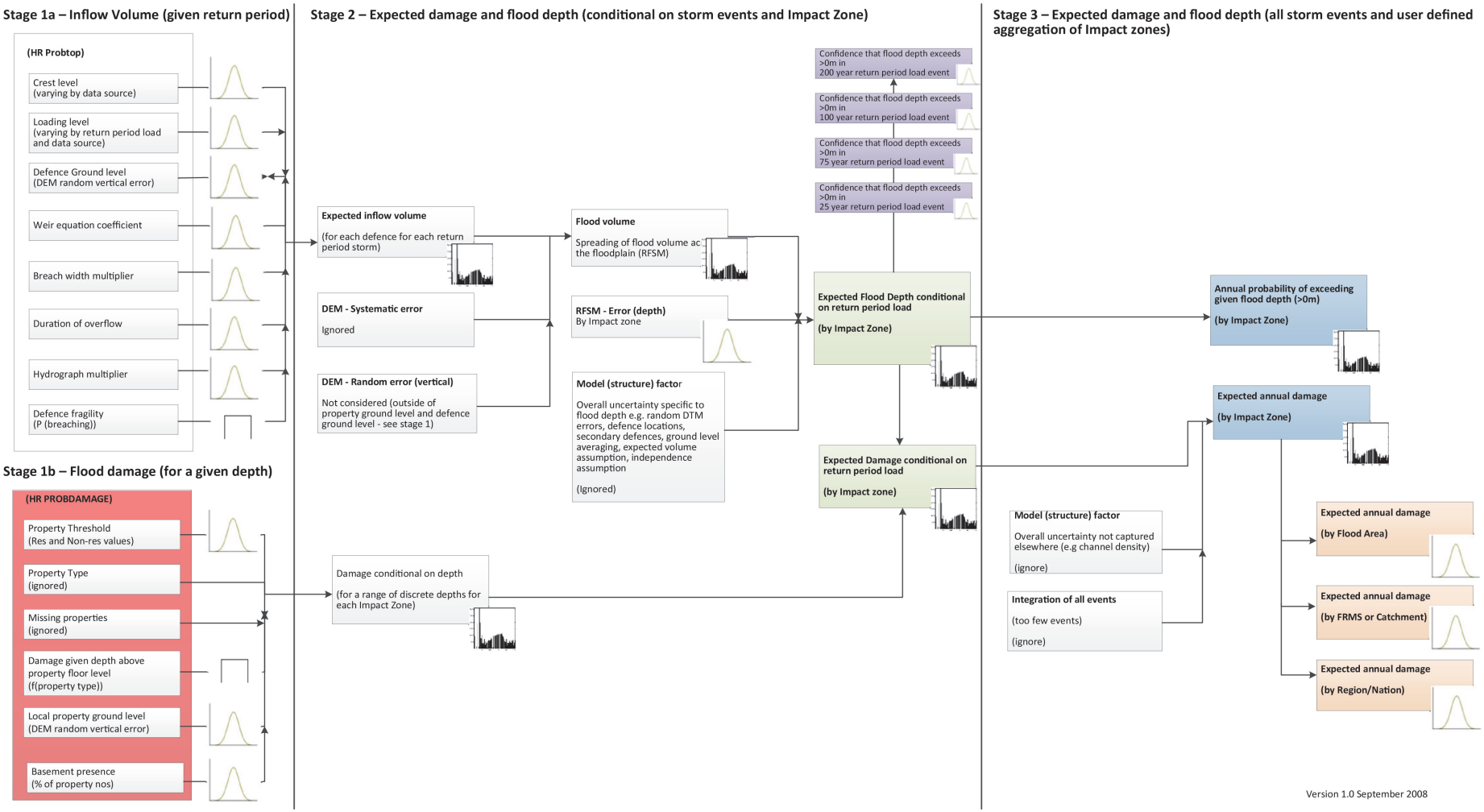
Figure 5-10 Information from reliability analysis helps target maintenance and improvement interventions

5.3.5 Handling and propagating uncertainty

In the RASP model the aleatory uncertainty is naturally integrated out in the derivation of risk that is presented as an Expected Annual Damage (or EAD). This is consistent with approaches adopted for local site-specific analyses in the UK (MAFF, 1993) and US (USACE 1996). The inclusion of epistemic uncertainties is less straightforward and requires the RASP approach to be allied with an efficient sensitivity analysis that enables the influence of individual (routine) epistemic uncertainties on the output quantity of risk to be isolated (enabling future research, development and data gathering efforts to be focused).

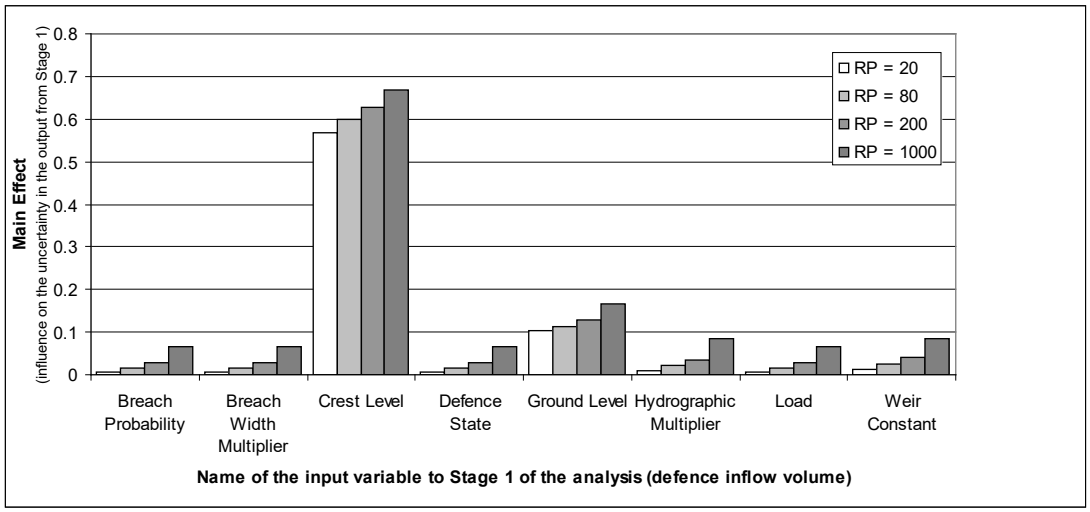
To explore the influence of epistemic uncertainties within the Thames RASP model a forward propagating Monte-Carlo method (*e.g.,* Pappenberger *et al.,* 2006) is used within the framework Variance Based Sensitivity Analysis, a generic method for establishing the relative importance of variables contributing to the output of interest (Sobol, 1993; Saltelli *et al.,* 2004). Computational runtimes have often rendered previous attempts to propagate uncertainty through complex risk models impractical. This reflects the large number of uncertain variables and parameters that must be sampled at any one time. To achieve improved computational efficiency and the transparency of the analysis, the RASP risk model is separated into *stages* – where the derived output distribution from one stage, together with new additional variables, form the input distributions to the subsequent stage. This staged process and the contributing epistemic uncertainties introduced at each stage is illustrated in Figure 5-12. Through this process, the number of variables that are sampled during any *stage* can be minimised (Gouldby *et al.,* 2010) offering benefits in terms of reduced computational time (through reduction of the variables propagated through the whole process). Using this approach, the output variance can be decomposed by allowing one input variable to vary across its range, whilst all other input variables remain fixed (the so-called Main Effect, *i.e.,* the expected amount of variance that would be removed from the total output variance, if the true value of that variable was to become known). By progressively fixing combinations of correlated variables the so-called Total Effect of a single variable can be determined. A variable with a low total effect can be frozen to any value within its range without significant impact on the output and the provision of information at intermediate stages within the overall model structure (Figure 5-12). Although such an analysis adds further computational demands to the already heavy burden of system-based risk assessment, it has significant advances over more conventional *'one-at-a-time'* approaches, namely that such approaches do not enable the sensitivity of the 'system' to be explored (Sayers *et al.,* 2014a).

Aleatory uncertainties are handled through the consideration of a range of joint storm boundary conditions (requiring the inclusion of 40 return period events from frequent to rare to limit the influence of aleatory uncertainties, McGahey *et al.,* 2008). Severe epistemic uncertainties associated with future change (*e.g.,* climate change) are not handled through the VBSA but through the exploration of alternative future scenarios in Section 5.4 below.

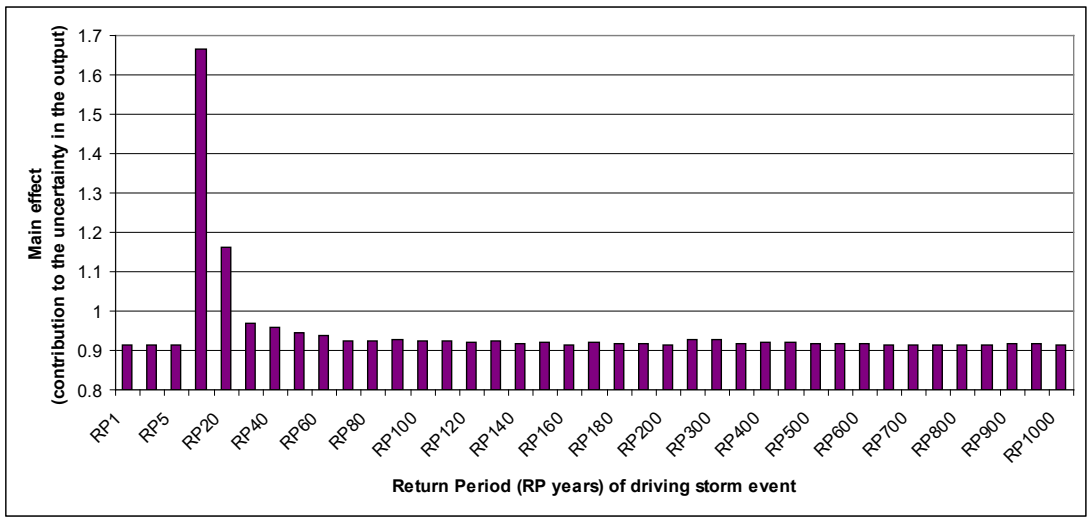


Source: The Thames Estuary IA8/10 studies lead by Sayers and published in Gouldby et al., 2010

Figure 5-11 Forward propagation of epistemic uncertainty analysis within the Thames RASP system risk



Contributions to the uncertainty in the defence overtopping volume for a given return period (RP) event (20, 80, 200, and 1000 years)



Contribution to the uncertainty in the impact zone risk by return period event
Source: Gouldby, Sayers et al., 2010

Figure 5-12 Insights from the application of a staged variance-based sensitivity analysis to the Thames RASP model

5.3.6 Supporting strategic decision-making

The basic approach to decision-making in the TE2100 broadly reflects the strategic decision-making framework set out in Chapter 4. The following sections focus on the four key steps in this process:

- Step 1 – Assess present-day performance (*using a range of risk metrics*).
- Step 2 – Determine exogenous futures (*i.e.,* establish climate and population futures).
- Step 3 – Develop strategic alternatives (*i.e., generate options*).
- Step 4 – Identify a robust and adaptable strategy *(i.e., identify the preferred strategy).*

Each step is discussed in turn below together with the support provided by the RASP system risk analysis.

5.3.7 Step 1: Assess present-day performance

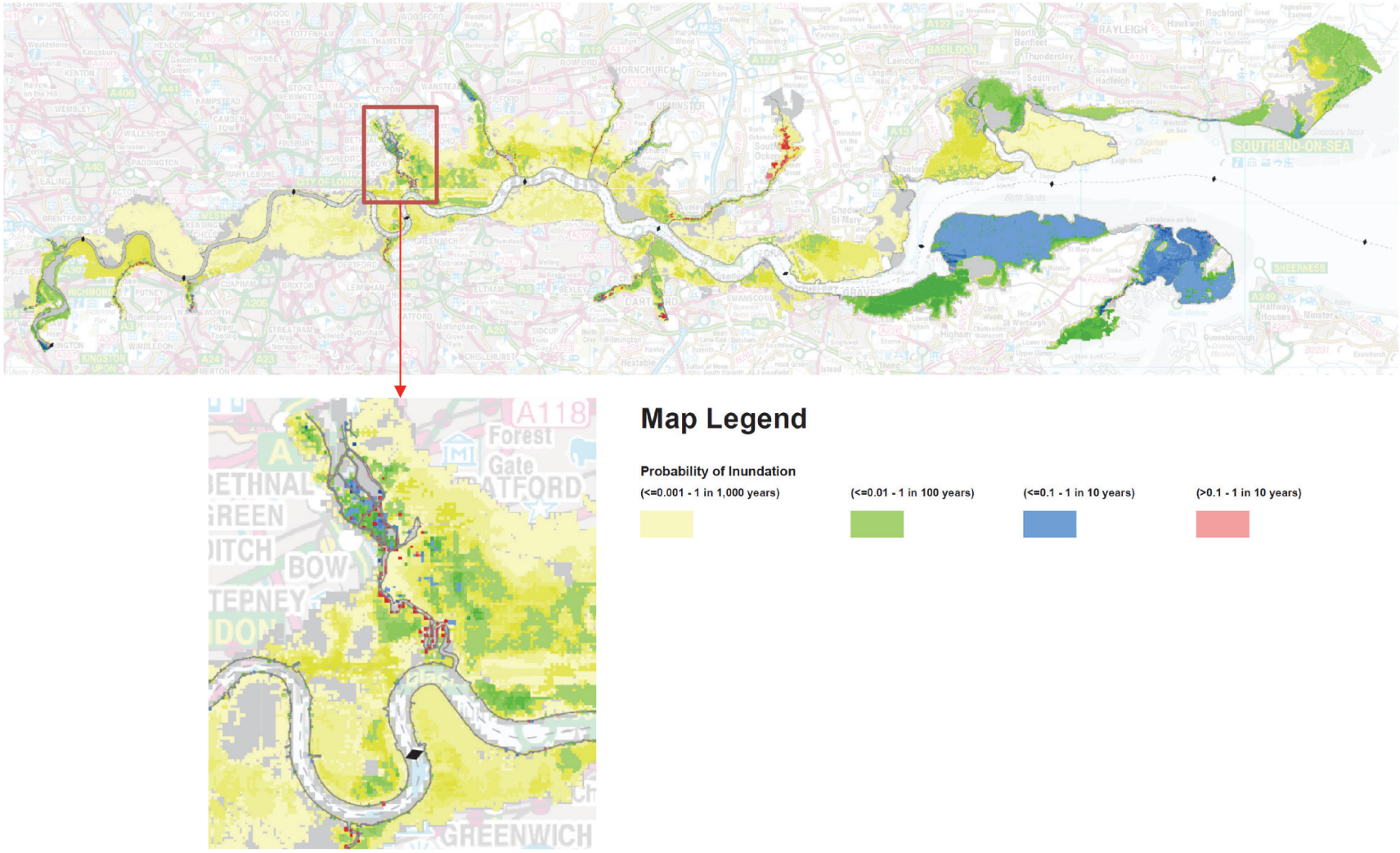
The Thames RASP model provides the engine used to support a decision-meaningful understanding of the residual risks associated with each strategic alternative. These risk perspectives include:

Spatial variation in the chance of flooding

The probabilistic integration of the sources and pathways within the RASP system risk model provides a rich insight into the spatial distribution of the chance of flooding. This analysis takes account of:

- *Sources* – 60 return period events up to and include the 1: 10000-year return period event ensuring events that exceed the notional 1: 1000-year design standard of the defences were considered. Incorporation of the spatial coherence with the tributary flows along the Thames was not considered explicitly but addressed through simplified models.
- *Pathway* – The performance of the embankments, riparian gates, and the most important barriers were all represented within the system risk model, including the probability of both serviceability (*e.g.,* overtopping without breach) and limit state failures (*e.g.,* breach).

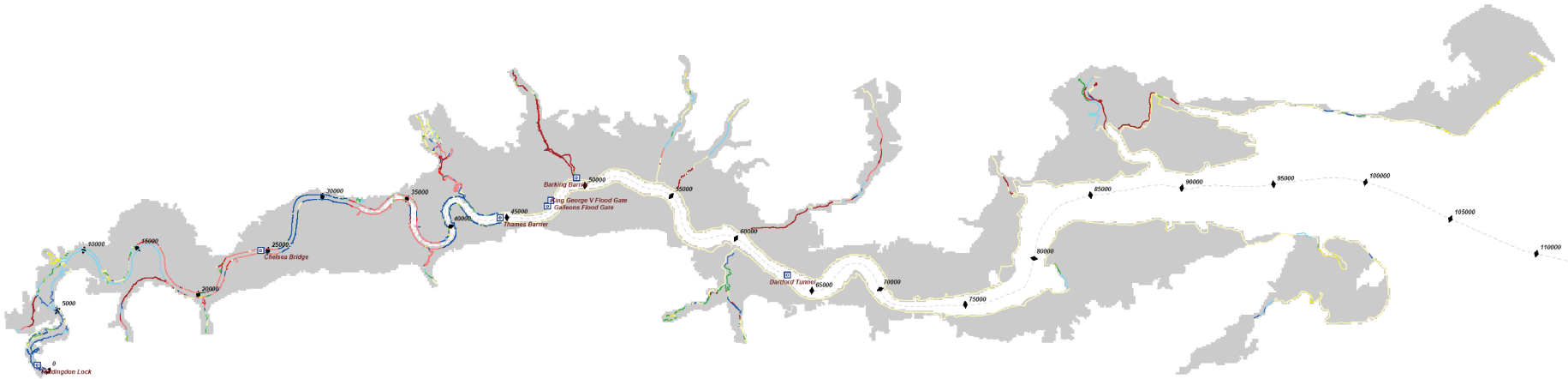
The resulting annual probability of inundation (to a flood depth exceeding 0m) under present-day conditions (and assuming the Thames Barrier to be operational) is shown in Figure 5-13. The figure shows much of the floodplain to be well protected, with the annual chance of flooding being less frequent than 1 in 1000 years on average. But the inference from this ‘hazard map’ is much more nuanced than this. The system analysis (recognising the differing standards and conditions within the defence system) produces an understanding of the probability of flooding that varies across the floodplain in a complex pattern (as illustrated in Figure 5-13); not simply the regular contours of probability offset from the estuary that typically emerge from conventional modelling assuming an absence of defences. The RASP system analysis also provides insight into the annual probability of failure that helps identify ‘weak links’ within the system (Figure 5-14) and the contribution each defence asset makes to residual risk due to serviceability limit state failure (overtopping) and ultimate limit state failure (breach) – Figure 5-15.



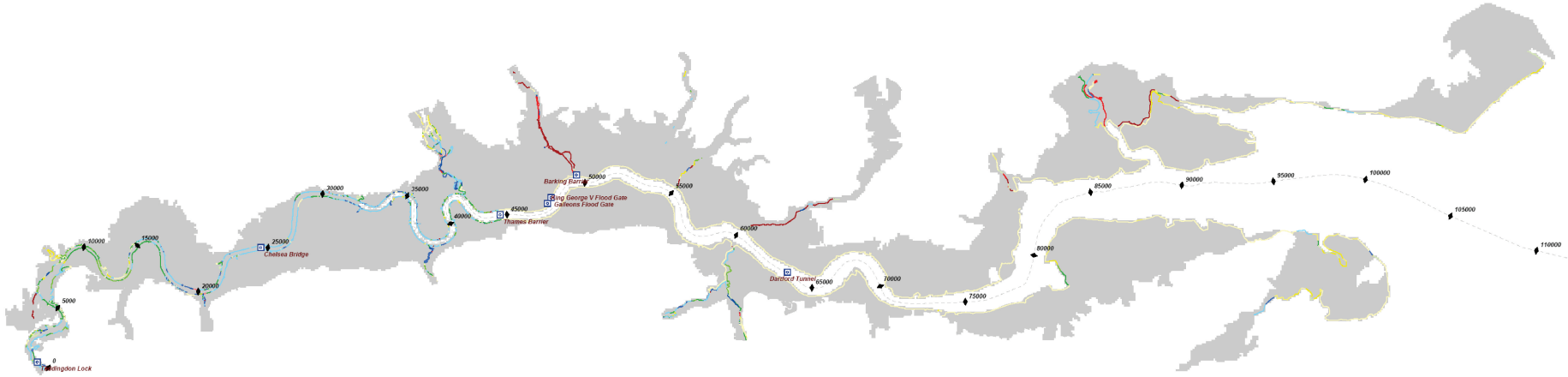
Top: Overview of spatial pattern of the probability of inundation. Bottom: A zoom in to illustrate the complex spatial pattern of the probability of inundation
Source: Gouldby, Sayers, Hassan and Panzeri, 2007

Figure 5-13 Probability of inundation within the floodplains of the Thames Estuary taking account of defence performance (Present Day)

Annual probability of serviceability failure (defence overtopping)



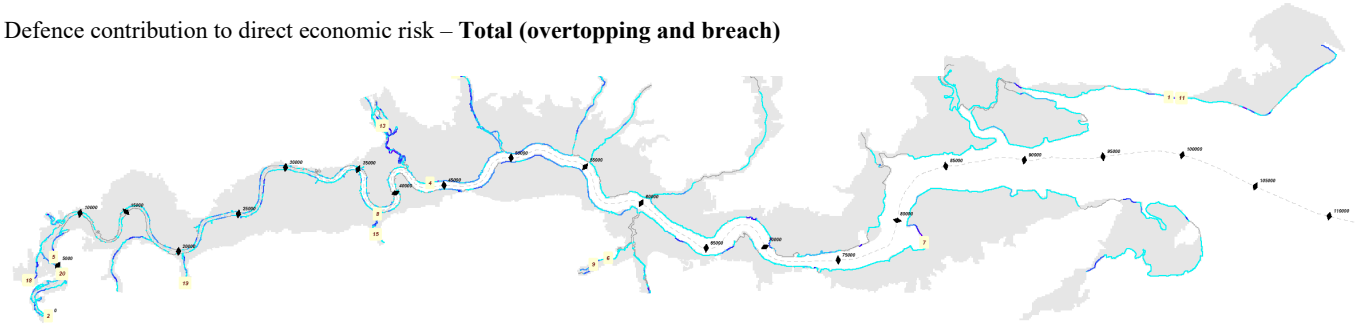
Annual probability of ultimate limit state failure (defence breach)



Source: Gouldby, Sayers, Hassan and Panzeri, 2007

Figure 5-14 Understanding the annual probability of failure to help identify 'weak links' within the system (Present Day)

Defence contribution to direct economic risk – **Total (overtopping and breach)**



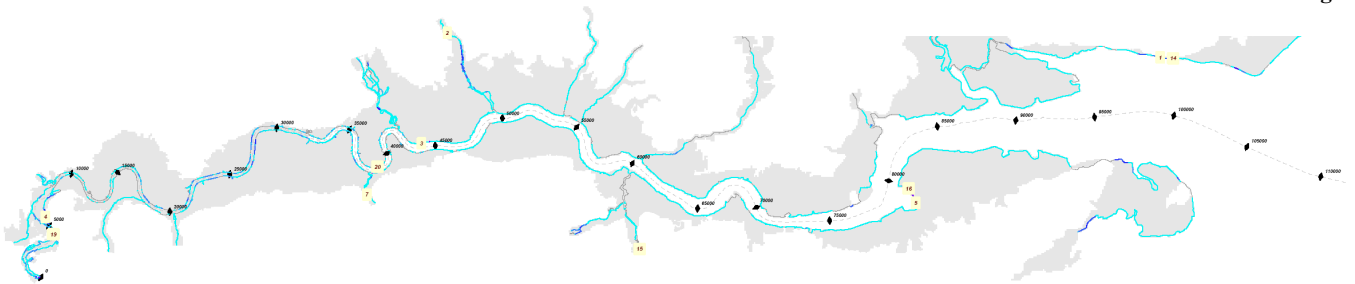
Top 20 Defence EAD contributors (Based on total contribution)

Defence UniqueID	Rank	Total Contribution	Breach Contribution	Overtop Contribution
300005043	1	£334,601	£311,041	£23,560
300000014	2	£320,896	£0	£320,896
300005266	3	£166,306	£166,306	£0
300003265	4	£147,851	£147,851	£0
300000975	5	£142,233	£141,901	£332
300000926	6	£139,721	£0	£139,721
300001596	7	£115,803	£115,803	£0
300002431	8	£106,515	£364	£106,151
300000754	9	£102,060	£3,932	£98,128
300000007	10	£98,961	£95,964	£2,997
300005019	11	£79,216	£45,124	£34,092
300000920	12	£77,339	£0	£77,339
300004585	13	£75,830	£26	£75,804
300003352	14	£74,511	£50,524	£23,987
300001681	15	£73,386	£73,386	£0
300005254	16	£67,857	£67,857	£0
300001695	17	£63,973	£63,969	£4
300000332	18	£63,328	£0	£63,328
300000318	19	£62,659	£0	£62,659
300000477	20	£62,090	£32,023	£30,066

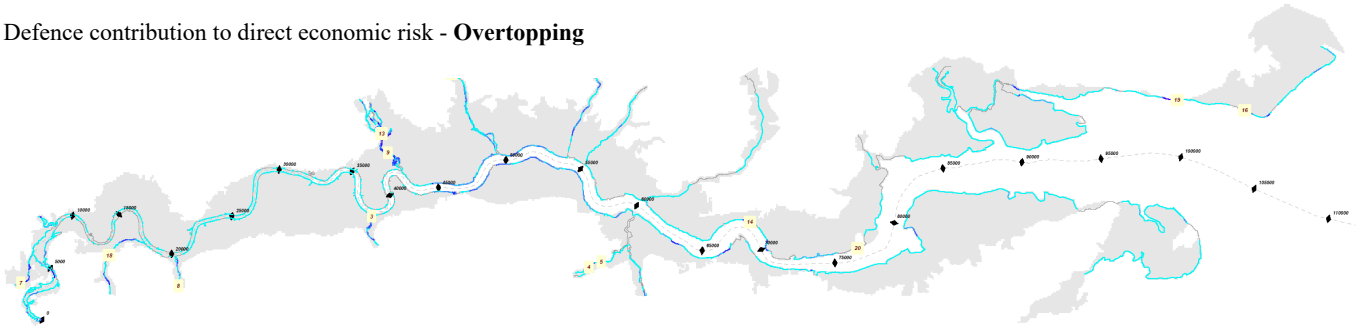
Top 20 Defence EAD contributors (Based on Breaching contribution)

Defence ID	Rank	Total Contribution	Breach Contribution	Overtop Contribution
300005043	1	£334,601	£311,041	£23,560
300005266	2	£166,306	£166,306	£0
300003265	3	£147,851	£147,851	£0
300000975	4	£142,233	£141,901	£332
300001596	5	£115,803	£115,803	£0
300000007	6	£98,961	£95,964	£2,997
300001681	7	£73,386	£73,386	£0
300005254	8	£67,857	£67,857	£0
300001695	9	£63,973	£63,969	£4
300005244	10	£54,451	£54,451	£0
300005234	11	£52,946	£52,946	£0
300005229	12	£51,595	£51,595	£0
300003352	13	£74,511	£50,524	£23,987
300005019	14	£79,216	£45,124	£34,092
300000225	15	£41,854	£39,387	£2,468
300001771	16	£44,257	£38,983	£5,274
300005230	17	£37,316	£37,316	£0
300000005	18	£42,800	£33,216	£9,584
300000477	19	£62,090	£32,023	£30,066
300002818	20	£30,850	£30,850	£0

Defence contribution to direct economic risk - **Breaching**



Defence contribution to direct economic risk - **Overtopping**



Top 20 Defence EAD contributors (Based on Overtopping contribution)

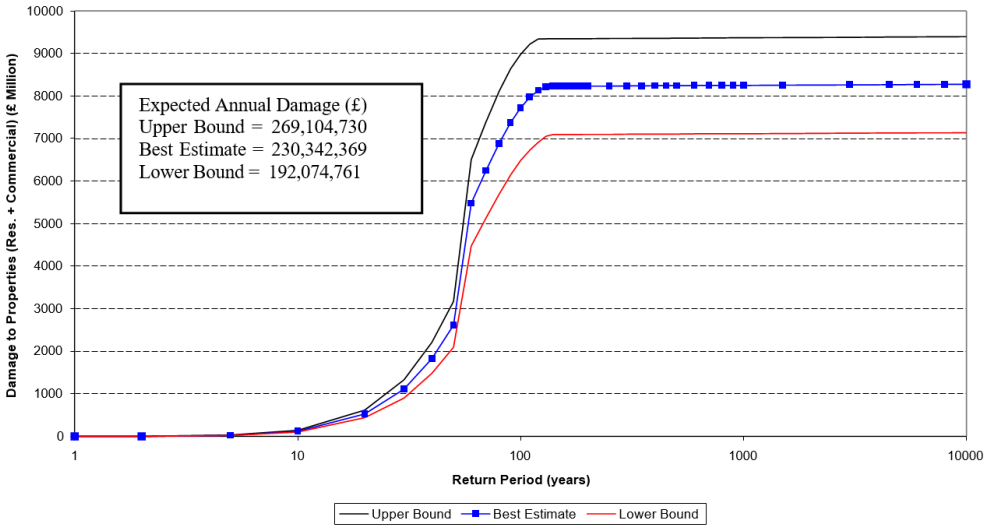
Defence ID	Rank	Total Contribution	Breach Contribution	Overtop Contribution
300000014	1	£320,896	£0	£320,896
300000926	2	£139,721	£0	£139,721
300002431	3	£106,515	£364	£106,151
300000754	4	£102,060	£3,932	£98,128
300000920	5	£77,339	£0	£77,339
300004585	6	£75,830	£26	£75,804
300000332	7	£63,328	£0	£63,328
300000318	8	£62,659	£0	£62,659
300004217	9	£57,409	£0	£57,409
300002348	10	£49,994	£14	£49,980
300002294	11	£48,808	£0	£48,808
300005267	12	£45,692	£0	£45,692
300004511	13	£45,834	£1,109	£44,724
300002207	14	£42,921	£0	£42,921
300000338	15	£40,121	£0	£40,121
300004895	16	£61,300	£21,214	£40,086
300004260	17	£36,940	£0	£36,940
300001152	18	£36,488	£0	£36,488
300005019	19	£79,216	£45,124	£34,092
300001329	20	£38,720	£6,165	£32,555

Source: Source: Gouldby, Sayers, Hassan and Panzeri, 2007

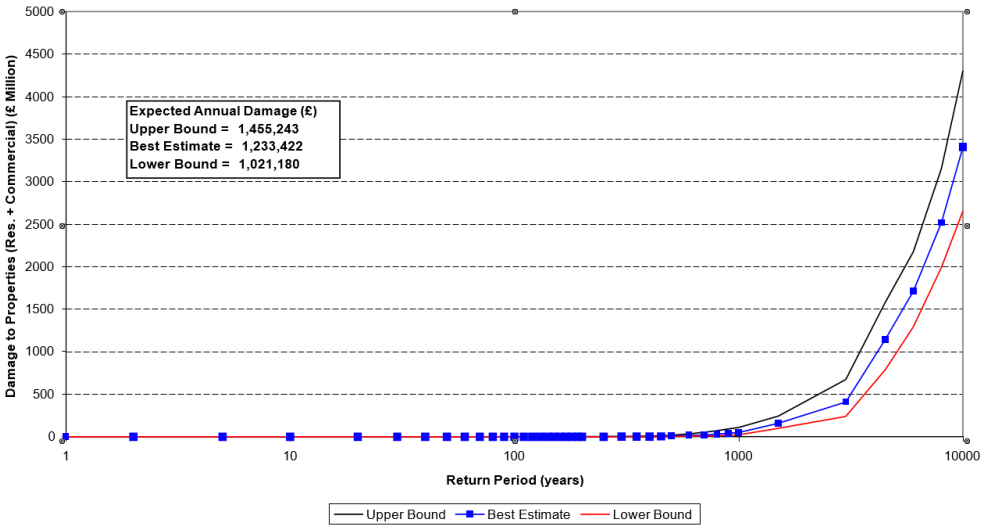
Figure 5-15 Understanding the contribution of each defence to expected annual damage (Present Day)

Economic efficiency and effectiveness

To understand the relationship between benefits and cost (*i.e.,* efficiency) and the reduction in risk achieved (*i.e.,* effectiveness) the RASP system risk model combines the probability of the flooding with the associated consequences. An example output from the RASP system model in support of the economic analysis is shown in Figure 5-16.



Damage conditional on the storm event in Bermondsey, assuming the Thames Barrier fails



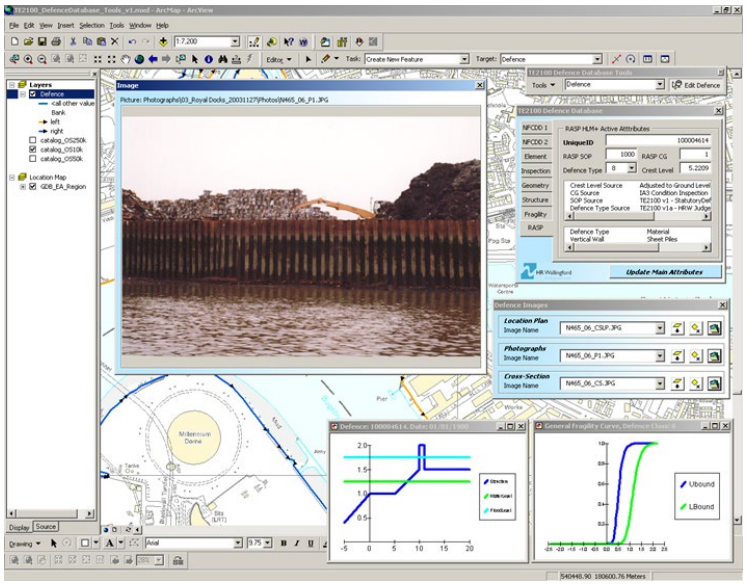
Damage conditional on the storm event in West Ham/Royal Docks, assuming the Thames Barrier works to rule. Source: Gouldby, Sayers, Hassan and Panzeri,, 2007

Figure 5-16 Economic damage conditional on the storm return in two embayments of the Thames Estuary: Present Day

Defence assets that contribute most to residual risk

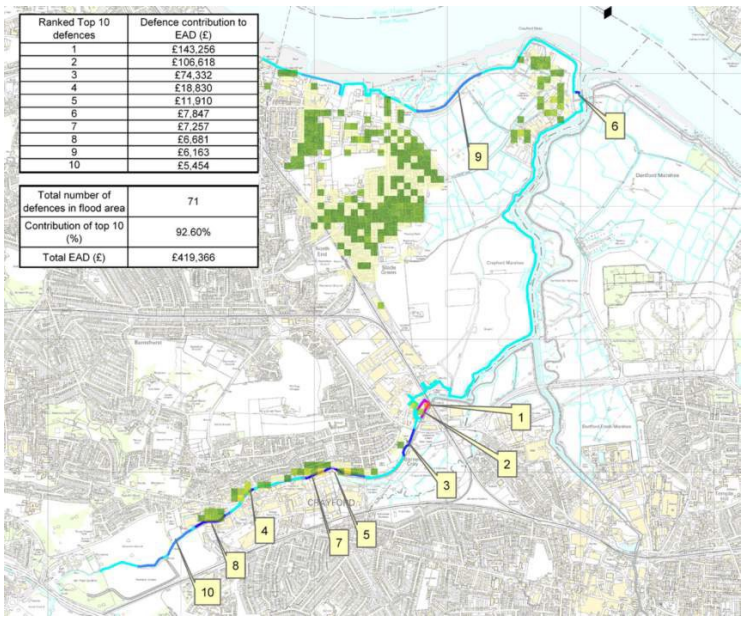
The existing defence system within the Thames Estuary is significant, seeking to ensure that maximum value from these existing assets underpins an efficient strategy. Building upon a well-constructed asset database (designed using the principles of good asset management, *e.g.,* Sayers *et al.,* 2010, and including the location, type, condition and basic geometry of each asset, Figure 5-17), the RASP system model is able to attribute the contribution to

residual risk made by each defence (Figure 5-18). The ability to attribute residual risk to defence assets is an important advance provided by the RASP system analysis, enabling those assets that contribute most to risk can be readily identified through this process (for example in Figure 5-18, more than 90% of the residual risk is attributed to just ten defences within this area).



Source: Sayers et al., 2006 with the database development led by Panzeri

Figure 5-17 A well-constructed database of the flood risk systems underlies the RASP Thames model



Source: Sayers et al., 2006

Figure 5-18 Attributing flood risk to individual defence assets – An example of area to the west of Barking Barrier

Alongside monetised impacts, social and environmental impacts form a significant component of the TE2100 planning process and are readily supported by the RASP system

analysis. Additional metrics include the **number of people exposed to flooding** (*i.e.,* the number of people at risk of injury, using the *Risk to People* methods developed by the Environment Agency, 2005); **environmental features exposed to flooding**; and **equity and fairness issues** (including a basic enhancement to the achieved benefits for properties protected in deprived neighbourhoods as determined using the Index of Multiple Deprivation, an issue returned to using more advanced methods in Chapter 7). A wide range of considerations also feature in the TE2100 planning process, including cultural heritage, and the impact on economic growth and local- and estuary-wide communities (see Environment Agency, 2009), but the RASP analysis provides only general support to these wider issues.

5.3.8 Step 2: Determine climate and population futures

Both climate change and population growth are important considerations in the Thames:

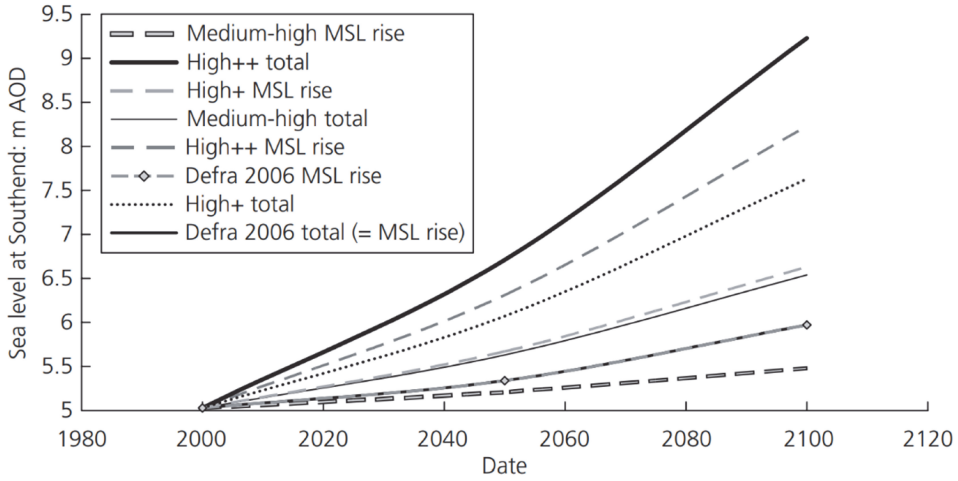
Climate change

When designed in the 1970s, the Thames Barrier and associated defences included an allowance of 8mm/year to account for the rate of change in relative sea level and was based on considerations of changes in mean sea levels and an allowance for local ground subsistence (reflecting the competing influences of a reduction in groundwater abstraction since the Industrial Revolution and a process of glacial isostatic adjustment). Since the 1970s significant advances have been made in understanding the influence of climate change in the Thames, but significant uncertainty continues to exist.

Each strategic alternative was therefore assessed against four possible climate futures. These ranged from more moderate rates of change through to more extreme assumptions, namely:

- 0.45m rise in mean sea level by 2100 (so-called Medium–High).
- 1.0m rise in mean sea level by 2100 (so-called Defra06-based on allowances outlined in Defra, 2006).
- 1.6m rise in mean sea level by 2100 (so-called High+).
- 3.2m rise in mean sea level by 2100 (so-called High++).

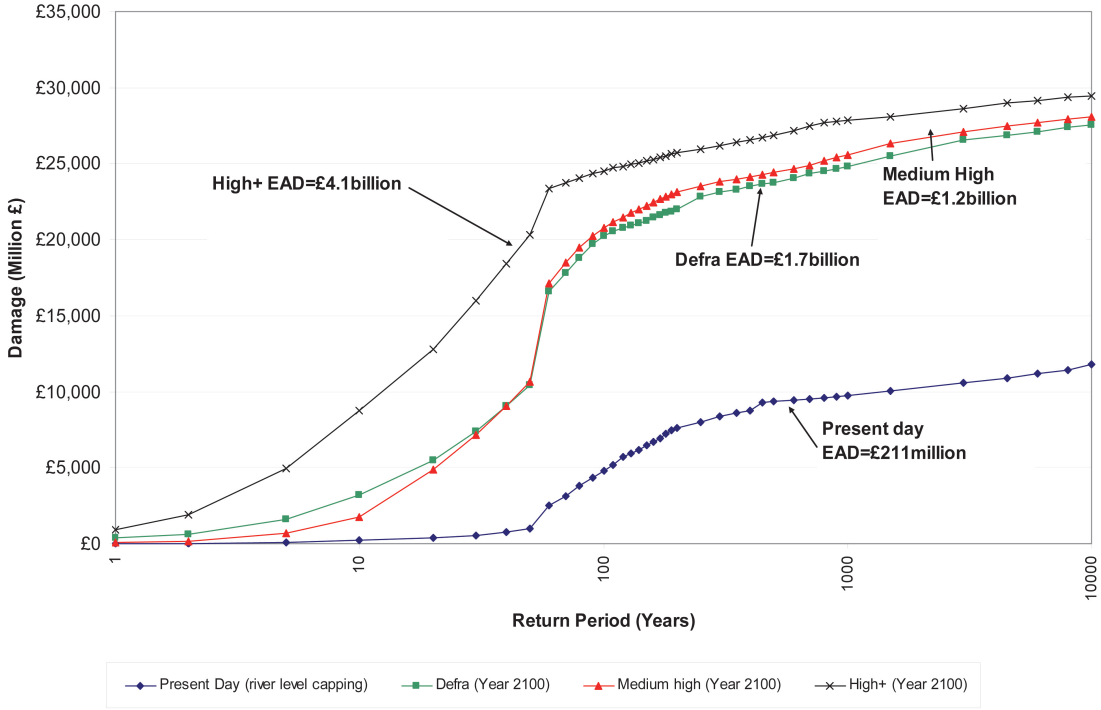
The difference in these assumptions make a significant difference to the estimated sea levels within the Thames Estuary over time, as shown in Figure 5-19.



Source: TE2100 project, Environment Agency, 2009

Figure 5-19 Projected possible future mean sea level rise and peak 1000-year surge tide level for the mouth of the Thames Estuary

The alternative estimates of climate change are material in driving a range of risk estimates (Figure 5-20). Assuming the existing system remains largely unchanged, climate change has a profound influence beyond 2030; with significant increases seen under the most pessimistic High+ scenario. The more modest climate changes suggested within the Defra guidance (at the time) also has a significant but more limited impact.



Source: Image from Sayers et al, 2007

Figure 5-20 Change in expected losses within the estuary by 2100 due to different climate scenarios, assuming the present-day system remains largely unchanged

Population growth and development

Building upon the analysis of local planning aspirations to 2030 (McFadden *et al.,* 2007) future development through to 2100 is developed based on three distinct growth assumptions:

- Low-growth future assuming no further growth
- Medium-growth future assuming a continuation of planned growth
- High-growth future assuming an acceleration in planned growth (by a factor of two).

The growth assumptions are used together with the housing occupancy rates to inform the housing development assumptions and the development distribution of new properties in the floodplain.

Note: The housing scenarios change exposure terms but have no influence on changes in run-off. In part this is reasonable, given new developments are required to incorporate approach SuDS schemes but it is an assumption that is more directly addressed as part of the national scale emulation approaches introduced later in Chapter 6.

5.3.9 Step 3: Develop and assess the performance of strategic alternatives

A reference (counter-factual) strategy was established to provide a baseline against which to judge the worthwhileness of all other strategies. The UK Treasury rules prescribe the counter-factual as a so-called *Do nothing* (or walk-away) strategy in which no further action is taken to manage or operate the flood defences.

Four strategic alternatives are then considered. Each includes a combination of actions from raising river walls, modifying the operation of existing/new flood barriers and/or flood storage areas, applying property level protection measures and so on. To bring together a coherent set of actions each strategic alternative reflects an overarching management philosophy, namely:

- ***Defence focused*:** based on '*sweating'* existing defences (*i.e.,* seeking maximum value from past investment) and acting to improve them *'just in time'*. In this case the Strategy focuses on maintaining the performance of the present-day defence system and supplementing this system with additional measures (improvements in warning or property level protection) only where and when it is essential to do so.
- ***Portfolio focused*:** based on a mix of maintaining the existing defences and creating new, set-back, defences (to make space for the river and provide additional floodplain storage, flow retention and biodiversity gains) and improved non-structural measures. Focusing on removing ageing, poorly maintained, linear defences in the outer estuary to reconnect the floodplain with the estuary. The removal of these defences provides significant habitat creation sites but their location in the outer estuary means that the reduction in extreme water levels through central London is limited.
- ***Defence focused (higher ambition)*:** based on improving existing defences and constructing new physical infrastructure to control flood waters, including a major new

outer barrier. In this case the strategic alternative is focused on delivering high standards of protection throughout the estuary in the medium and longer term.

- ***Portfolio focused (higher ambition)*:** based on seeking to maximise floodplain storage and flow retention but taking all feasible opportunities to make room for the estuary. In this case the strategic alternative focuses on developing the concepts of '*living with the estuary'*, accepting a higher residual probability of flooding and managing the residual risk with non-structural measures.

The influence of these (and other) changes can be readily conceptualised and translated into changes in the RASP system risk model using the source-pathway-receptor framing (see Chapter 4, Figure 4-4), including exogenous change (*i.e.,* external drivers of change outside of the significant influence of TE2100 plan, such as climate change and development demand as set out in Step 2 above) as well as endogenous change (*i.e.,* purposeful responses that change the state of the system, represented by the four strategic alternatives above).

Note: Further detail on the representation of changes to the flood risk system can be found in Sayers *et al.,* 2006, McGahey and Sayers, 2008 and Environment Agency, 2009. Although interesting, these are not reported here as this Chapter focuses on the structure of the RASP system risk analysis and the insights it provides beyond conventional approaches.

5.3.10 Step 4: Identifying a robust and adaptable strategy

The approach used in TE2100 followed the framework used for flood risk management as detailed in Making Space for Water (Defra, 2004). This requires that flood risk management plans are not only technically feasible but also focus on three aspects:

- protecting the wellbeing of people.
- meeting the requirements of statutory instruments such as European Directives on Birds[19] and Habitats[20] (that aim to 'protect the integrity' of internationally important nature conservation sites) and Water (that aim to 'maintain and improve the water environment'[21]); and,
- efficiency of public investment (ensuring public money is invested to ensure the greatest return across all public spending, (as defined by the HM Treasury Green Book (2003) on the investment of public money).

In addition to these guiding criteria (applied routinely to all flood and coastal investment decisions in England), the TE2100 project develops a strategy that recognises a future characterised by severe uncertainty (as detailed in Environment Agency, 2009a,b,c). In this context, no single pathway (strategic alternative) provides a uniquely preferred approach.

[19] *The Birds Directive - Environment - European Commission (europa.eu)*
[20] *The Habitats Directive - Environment - European Commission (europa.eu)*
[21] *River basin management - Water - Environment - European Commission (europa.eu)*

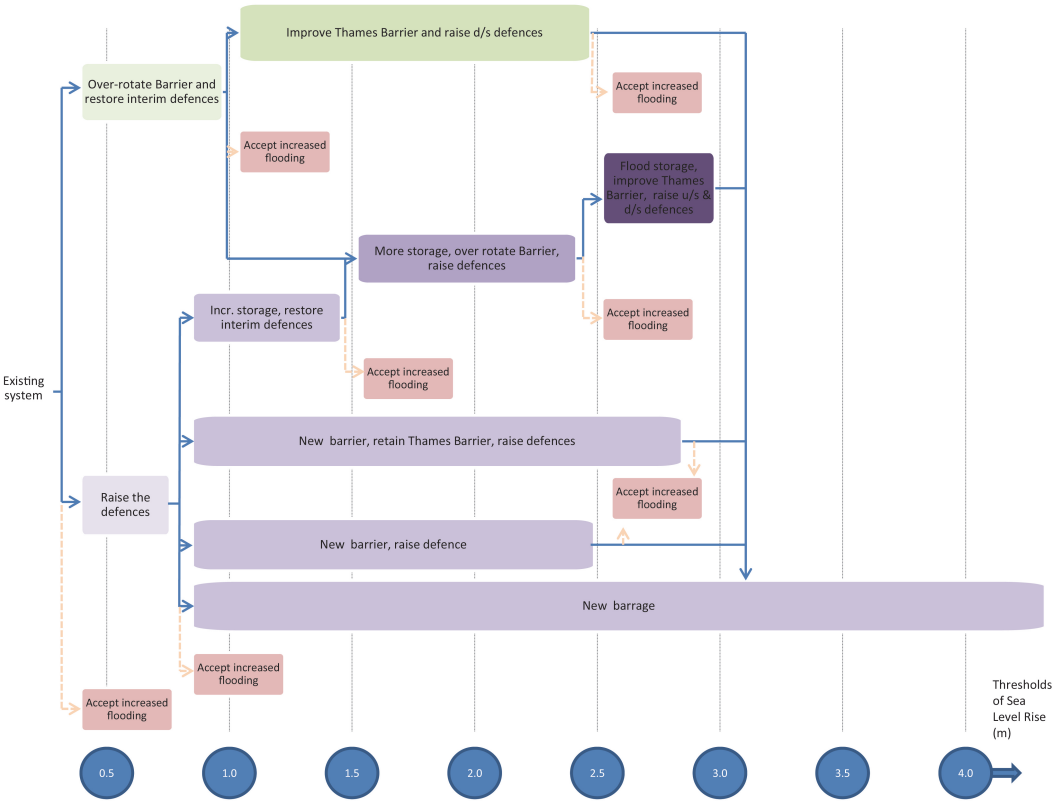
Instead, a strategy that embeds a process of adaptation based on a continuous process of review was sought.

In addition to these core selection criteria, the TE2100 project sought to develop a strategy that was adaptable to any potential future change, including climate change, to avoid expensive 'white elephant' investments while managing risk to acceptable levels. No single strategic alternative provided the preferred management strategy under all climate futures. Effort was, therefore, directed towards providing an adaptable planning framework that could be reviewed and updated as the rate of change of several key indicators became increasingly certain. The understanding of the performance of each strategic alternative under all four future scenarios is used to determine the preferred strategy by considering:

- ***Flexibility.*** Reflecting the potential for the strategy to be adapted as the reality of future change becomes clear.
- ***Robustness*** *(of the choice).* Reflecting the performance of the strategy across a range of futures, ensuring a 'no regrets' approach.

To reflect the goal of a *flexible* strategy, a strategy was developed around the concept of a decision pipeline (McGahey and Sayers 2008), that presents potential actions in the form of a decision tree. Figure 5-21 shows the decision tree developed for the Thames Estuary flood defence system, highlighting the choices to be made as sea levels rise. Depending upon the degree of sea level rise that materialises as the future unfolds, the nature of the defence system required may be distinctly different. The decision tree outlined in Figure 5-21 supported decision-makers deciding when and how to invest. It reveals that major investment to improve the defence system is not immediately required. Innovations in the operation of the Thames Barrier (through over-rotation) extends the life of the defence system, enabling potentially high regret decisions regarding the development of a major new barrier to be delayed until more is known.

To reflect the goal of robustness of choice, actions that continue to perform well no matter what future materialises were prioritised for early implementation – including continued investments in improving forecasting and warning and in spatial and emergency planning, but also in 'sweating' the existing defence system to ensure that maximum value from past investment was achieved. The TE2100 plan also includes a monitoring and continuous process of re-evaluation. The monitoring process provides the triggers (discussed in Tarrant and Sayers, 2012) for the decisions within the pipeline. If monitoring reveals that climate change is happening more quickly (or slowly) than predicted, the strategy can be reappraised as new information emerges, and options can be brought forward (or put back). Some decisions, once made, require a considerable lead time to implement. This lag time between deciding to act and delivering that action is allowed for in the plan (*e.g.,* the completion of the Thames Barrier took 30 years to plan, design and deliver). This highlights a significant decision point as SLR progresses beyond 1m (perhaps as early as 2100), to either commit to a new barrage or improve the Thames Barrier and raise downstream defences.



Source: based on Environment Agency 2009, drawing upon the decision pipelines set out in McGahey and Sayers, 2008 as part of the EU FLOODsite project

Figure 5-21 Thames Estuary 2100 Plan presented as a decision tree

5.4 WIDER ISSUES

In parallel with the development of the Strategy, the TE2100 programme reached out to a wider range of development planning processes and flood risk management activities as discussed below.

Communication and stakeholder engagement

The TE2100 project recognised the importance of engaging and involving stakeholders in the development of the strategy (spending approximately 40 per cent of its budget on communication and engagement with stakeholders, Tarrant and Sayers, 2012). The three key vehicles used for this included:

Engagement with other strategic organisations – throughout the life of the project, the TE2100 team engaged partner organisations along the estuary. The final plan draws heavily on information and suggestions made by these various groups. By actively working with the Thames Estuary Partnership (a pre-existing forum where all issues related to living and the environment within the Thames were discussed) and others, the flood risk management objectives of the TE2100 project were actively promoted in the broader context of the management of the Thames (*e.g.,* navigation, nature conservation, tourism).

Public meetings and exhibitions – the Thames Estuary is a large and diverse community. The TE2100 project sought to engage directly with the public frequently, in local borough halls or through local interest groups.

Provision of information on flood risk management – a key contributing factor to the successful communication of the project was the development of numerous graphics and maps to convey effectively the present and future risks, alternative management policies and options, and the effects of future uncertainties on the selection of those options. These graphics would often be required to distil down the complex risk of information generated using the modelling methodologies described above.

Better flood forecasting and warning

Contingency planning for the Thames is the responsibility of the emergency services, with only limited statutory connection between the development of the Thames Plan and disaster response planning (for example the flood risk manager has no power to request safe havens or specific emergency evacuation routes to be embedded in development plans). Flood hazard and risk mapping is provided by the Environment Agency and local authorities to the emergency responders and the Thames Estuary strategy adds value to this process. Prototype analysis linking the RASP system risk model to real-term forecast data provides useful insights into those that that may flood, the most likely breach locations and the most important areas to focus response effort based on risk (see the RASP outputs in Golding, 2009).

Linkage to other planning processes

Flood risk management does not stand alone and should be seen as part of a wider agenda of '*creating a better place'*[22]. But this is difficult to achieve. The TE2100 project discussed above is a risk management strategy and does not have a remit to, nor seeks to address the broader planning agenda. The opportunity for integration is clear but, in the absence of a master basin plan, the means of doing so is less clear. The TE2100 Plan provides a series of recommendations for planning authorities, including encouraging retrofitting of protection level protection measures (flood gates *etc.*) and the provision of safe havens and high-level access for evacuation as well as secondary defences around critical infrastructure. The TE2100 also encourages planner to use the detailed flood hazard and risk maps in their spatial planning decisions (including the siting, type, and layout of development).

Reinstating London's lost rivers for social and ecological gain

- During the 1700s, as the City of London grew and demand for space increased, many rivers were built over, and eventually culverted. The Mayor of London is developing a

[22] *Environment Agency: EA2025 creating a better place - GOV.UK (www.gov.uk)* – Accessed August 2022

planning agenda that seeks to build a more harmonious cohabitation of the city and nature. This goes beyond attempting to ban building in the floodplain but drives at the very heart of what is trying to be achieved through strategic, systems-based, planning. The River Quaggy (Figure 5-22) provides a good example of where a sterile urban stream has been re-naturalised providing social and ecological benefits. The Mayor of London, in association with the Environment Agency but not as part of the TE2100 team, is seeking to uncover and rehabilitate London's 'lost rivers', with the idea that their presence in the City will improve Londoners' quality of life and increase London's cachet in the global market (Figure 5-23).



Source: www.qwag.org.uk

Figure 5-22 Rehabilitation of the River Quaggy, Chinbrook Meadows, London



Source: An artist's impression of how the River Walbrook, culverted in 1800s, might look when uncovered - www.walbrookriver.org

Figure 5-23 Daylighting London's lost rivers

Developing power from a tidal barrage

- A cornerstone of the flood risk management strategy for the Thames is the Thames Barrier, the adaptation of it in the short term and, if necessary, its relocation further out into the estuary as sea levels rise. The location of a further barrier (when needed) has been made on the grounds of flood risk management benefits (reduced linear defence costs and property/people protection). During the latter stages of the development of the TE2100 Plan, the idea of developing tidal power from the Thames gathered pace. The team promoting the tidal barrage was separate to the flood risk team and working to a different agenda with little interaction between them.

An airport in the outer estuary

- During his time as the Mayor of London, Boris Johnson actively supported a new runway for London located in the middle of the outer Thames Estuary (as an alternative to the

expansion of Heathrow). Although fraught with technical and environmental problems, if this goes ahead the construction of the associated civil works would have a profound impact on the way flood risk is managed within London – yet little serious consideration is given to this within the TE2100 long-term flood risk management strategy.

5.5 CONCLUSIONS

The Thames Estuary 2100 Flood Risk Management Plan is risk-based and attempts to direct effort where best return can be achieved. The RASP system risk model provides a practical whole system risk modelling approach, a prerequisite for meaningful flood risk analysis. This is an important departure from conventional deterministic methods that focus on discrete design events (for example, a 1in10 year return period design storm) and leave out improve asset uncertainties (for example, associated with defence data and fragility, including 1st order – *i.e.,* one asset failure – and higher failures – *i.e.,* two or more asset failures – within a system of defences).

The structured system risk analysis provided by RASP does not require more data or more effort than conventional models but does require a change in mindset; in particular, recognising the trade-off between undertaking many more simulations but more broadly (using simplified inundation modelling for example as in the RFSM) compared to fewer simulations using highly detailed analysis of only one to two system states. Risk-based approaches also present a different validation challenge, as discussed in Chapter 4 and Sayers *et al.,* 2016a). Many engineers with longstanding experiencing in the Thames found the probabilistic models difficult to understand. The inability to validate probabilistic flood risk models in a similar manner to conventional deterministic hydrological models (due primarily to the lack of observation) was not easily accepted. Once accepted the RASP system model was acknowledged as providing multi and powerful insights that hitherto had not be available to decision-makers, and has since been taken forward into the Modelling Decision Support Framework (McGahey and Sayers, 2009, McGahey *et al.,* 2010, Sayers *et al.,* 2015d), the Thames Estuary Asset Management Programme (the follow-on operational implementation of the TE2100 strategy), the evolution of the National Flood Risk Assessments (Gouldby *et al.,* 2008) and, in part, into international studies (*e.g,.* Jiabi *et al.,* 2012).

In addition to demonstrating the utility of adopting a system risk approach, the Thames studies provide wider lessons around the influence of RASP system analysis, strategic planning approaches and the additional insights provided. These are discussed below together with the *'live issues and knowledge gaps'* that the analysis highlights.

5.5.1 Lessons learnt and insights from the RASP system analysis

- **The importance of taking a long-term view.** The Thames Estuary study sets out the strategic direction for managing flood risk across the estuary for the next 100 years and contains recommendations on what actions will be needed in the short (next 25 years), medium (the following 40 years) and long term (to 2100). This long-term view enables flood risk managers to challenge the status quo (a continuation of *ad hoc* maintenance of

individual defences) and promote more innovative approaches that are not constrained by present day policies and practices.

- **Maintaining a broad-scale, strategic view is vital in developing a strategy.** Many competing demands are placed on the Thames Estuary, ranging from environmental interests to commercial development. Interests are both large scale (from the development of a port with estuary-wide impacts) and local (access to the waterfront).
- **The need to deal with climate change and adopt a precautionary approach to investment.** Futures uncertainties can have a profound influence on decisions. The use of 'decision pipelines' and 'adaptive pathways' provide a structured means of dealing with future climate uncertainty. Much of the data used to develop the plan is poor (and hence uncertain, crest levels *etc.*) and future development in the floodplain could be significant. The change in sea level is potentially very large (+4 m) or relatively minor (<0.75 m) over the next 100 years. Developing a plan that is both meaningful – providing firm actions to avoid future risk – yet adaptable and avoids unnecessary investment and construction has been shown to be possible.
- **Replace and improve defences only where and when necessary.** A key finding was that the existing defence infrastructure continues to provide adequate and robust performance in most areas and could be made to 'sweat'. The risk-based analysis provided a structured and transparent means of assessing the existing defence system. This allowed decisions for major upgrades of the infrastructure to be delayed and presented an opportunity for alternative non-structural measures to be considered and programmed for implementation.
- **An effective and efficient strategy relies upon a portfolio approach.** Flood risk management influences environmental, economic, and social issues (Sayers *et al.,* 2017a). The risk to each varies throughout the estuary and the best means of managing the risk also varies. The Thames study highlights the considerable opportunities that exist to enhance the environment, improve quality of life, and reduce risk. These goals are shown not to be mutually exclusive. Developing a mix of structural, non-structural as well as estuary-wide solutions (*e.g.,* creating wetlands in the outer estuary) and local solutions (strengthening of a group of defences) was an important feature of the Thames study.

5.5.2 Live issues and knowledge gaps

- **Managing all sources of flood risk.** The TE2100 strategy is focused on flood risk from tidal surge. London and the surrounding area are subject to groundwater, fluvial and pluvial flooding. This multiple source analysis remains out of reach. Developing an integrated strategy for all forms of flooding will be an important challenge going forward.
- **Integrating flood risk management within the broader spatial, economic, and environmental planning.** London is a dynamic and growing city and flood risk is just one consideration. How best to integrate economic, environmental, and spatial plans with flood risk management plans is an issue of considerable debate. The Thames Estuary Flood Risk Management Strategy is now a statutory reference document for spatial

planning decisions; it does not dictate spatial planning nor should it but developing a closer integration will be an increasing matter of debate.

- **Influencing building regulation and control**. The TE2100 promotes avoiding development in the floodplain but recognises this is not always possible and hence emphasises the critical importance of developing the floodplain appropriately. Significant new homes are planned for the Thames Estuary floodplain. The Flood Risk Management Plan promotes the construction of flood-resilient homes where new development is planned but does not oblige planning authority and developers to take this advice.
- **Promoting, funding, and delivering multi-functional solutions.** Several opportunities exist for joining up funding streams with other initiatives being promoted by the Mayor of London to deliver multiple functional solutions with social, environmental, and economic benefits.
- **Land banking.** To maintain future adaptive capacity, the TE2100 strategy recommends the safeguarding of land for future use in flood management (storage, wetland creation and defence widening).

6

EXPLORATORY ANALYSIS OF FUTURE FLOOD RISK IN THE UK

This chapter explores future flood risk across the UK under alternative climate change, population growth and adaptation scenarios through to the 2080s using an innovative emulation model (the Future Flood Explorer). The analysis highlights significant increases in flood risk with Expected Annual Damages rising from £2bn/year today to £2.7-3.0bn in the 2080s (depending upon associated population growth) given a 2°C rise in Global Mean Surface Temperature and rising to £3.5-3.9bn given a 4°C rise.

The contribution of climate change, population, and individual adaptation measures to future changes in flood risk also disaggregated, providing insight to the most significant drivers and important responses. Climate change is the dominant influence in driving up future risk (increasing Expected Annual Damages by £4.2bn under a 2°C future and £6.9bn under a 4°C future in the absence of any adaptation) and has the greatest influence at the coast; especially when the rise in GMST exceeds 2°C (notionally 0.4m of Sea Level Rise by 2080s), with EAD rising by a further 70% under a 4°C rise in GMST (notionally 0.8m of Sea Level Rise by 2080s) compared to 2°C. For comparison, the risks associated with all other flood sources increase by ~20% between a 2 and 4°C future. Assuming a low population growth the additional impact on risk is limited, although not insignificant (adding £364m to EAD), whereas a high population growth has a much greater influence (adding ~£2.4bn to the EAD assuming a 4°C rise in GMST). By the 2080s the combination of a 4°C climate change and high population growth future drives an increase of ~£9.2bn EAD in the absence of adaptation. The future is therefore bleak in the absence of adaptation and mitigation.

Assuming a continuation of Current Levels of Adaptation, ~£7.4bn of Expected Annual Damages is offset by the 2080s (under a 4°C high population growth future) resulting in a net increase in risk of ~£1.8bn. To maintain risks at present day levels given a 4°C future, an Enhanced Whole System approach to adaptation is needed; an approach in which conventional flood defences are complemented by natural flood management, property flood resilience, better flood forecasting and warning and more effective spatial planning.

6.1 INTRODUCTION

National assessments of flood risk are widely recognised as providing important evidence to inform policy decisions (*e.g.,* Penning-Rowsell, 2014b). Such assessments have been pursued actively by the Environment Agency, England since 2002 (covering England and Wales, *e.g.,* Sayers *et al.,* 2003b, Hall *et al.,* 2003c) and their predecessors since 1998 (Deakin *et al.,* 2001), and more recently by Scottish Environment Protection Agency (SEPA) since 2011 and by the Northern Ireland Rivers Agency and the Natural resources Wales. National assessments have also undertaken in the Netherlands (*e.g.,* Jongejan and Maaskant, 2015, de Moel *et al.,* 2011) and there is a growing momentum for similar analysis elsewhere (Gaur *et al.,* 2018).

The importance attached to national risk assessment arises because of the role of a national level determination of risk in setting the pace of adaptation and shaping the policy response and resource inputs (*e.g.,* Environment Agency, 2009 and 2014; Defra, 2011, Penning-Rowsell, 2015a, 2016a), and is a prerequisite to support an adaptive approach to flood risk management. The importance of understanding future risk in the context of a range of future scenarios was perhaps first formalised as part of the seminal Foresight Future Flooding Studies (Evans *et al.,* 2004a&b). In the UK, the Climate Change Act 2008 reinforces this need and requires a UK-wide *Climate Change Risk Assessment* (CCRA – see Box 6-1) with future risks (including flood risk) to be assessed under a range of climate, socio-economic and adaptation futures.

In response to this evolving demand for large-scale flood risk analysis (reflecting a combination of probability and consequence) the supporting methods and data have progressively improved since the first formal assessment in the late 1990s (Burgess *et al.,* 2000, Deakin *et al.,* 2001, Sayers *et al.,* 2003b, Hall *et al.,* 2003c; Gouldby *et al.,* 2008). This chapter builds upon these previous assessments to provide an exploration of future flood risks through to the 2080s using the latest climate change projections (from UK Climate Programme, UKCP18, Lowe *et al.,* 2018), high-resolution projections of population growth and alternative adaptation futures. The demand for a large (but high-resolution) spatial coverage and multiple time horizons together with the number of adaptations, population and climate scenarios of interest mean conventional modelling approaches are too computationally intensive to use (a challenge recognised in Kwakkel *et al.,* 2013, Sayers *et al.,* 2016a). The Future Flood Explorer (FFE) has been specially developed to overcome these issues. First developed in 2015 and applied to the second UK CCRA2 (Sayers *et al.,* 2015) the FFE has continued to develop, with the most recent version used to underpin the latest CCRA3 (Sayers *et al.,* 2020a). The development of the FFE is presented here together with the insights from the analysis and, for the first time, an exploration of the associated benefits and costs of individual adaptation measures as part of portfolio of policy responses.

Box 1 UK Climate Change Risk Assessment

The UK Government is required under the Climate Change Act 2008 to publish a Climate Change Risk Assessment (CCRA) every five years. The Committee on Climate Change (CCC) was established to provide this assessment and review progress being made in adapting to these risks across a wide range of sectors to help guide the UK Government's priorities through the National Adaptation Programmes in England, Wales, Scotland, and Northern Ireland (these requirements do not cover the Crown Dependencies or Overseas Territories). Future flood risk is a priority risk on the UK National Risk Register and has been a central consideration in the first, second and third CCRA assessment (Ramsbottom *et al.,* 2012, Sayers *et al.,* 2015c, Sayers *et al.,* 2020a).

6.2 CONTEXT OF THE ASSESSMENT

6.2.1 Flood hazards

Three sources of flooding are considered:

- **River:** Flooding from a watercourse when water from an established river or drainage channel spills onto the floodplain (referred to here as fluvial flooding).
- **Coastal:** Flooding from the sea when tidal surge, wave action or a combination of tidal surge and waves overtop or overflow the shoreline boundary.
- **Surface water:** Flooding directly from a rainfall event prior to the generated run-off reaching an established river or drainage channel (also called pluvial flooding).

6.2.2 Future changes in drivers of risk

Exogenous change: Population and climate change projections

Exogenous change refers to those changes outside of the influence of flood risk management policy. Two drivers of exogenous change are considered:

- **Population growth:** A lower growth and a higher growth projection (based on Cambridge Econometrics, 2019). Population growth is used to drive development of residential properties. No consideration is given to the changing nature of the household goods (increased white goods for example) or economic growth that may influence the affordability of a given damage. Expansion of non-residential property and supporting municipal infrastructure (rail, roads, power *etc.*) is also excluded. Changes in income, age profile, social networks *etc.* are excluded in this analysis. These considerations are included in the assessment of the effect of social vulnerability on risk – see later – but are assumed unchanged into the future.
- **Climate change:** A 2°C and 4°C rise in Global Mean Surface Temperature (GMST) by 2100 (from the pre-industrial period).

Further detail on both the climate change and population growth projections is provided later in this Chapter.

Endogenous change: Purposeful adaptations

Endogenous change refers to changes to the flooding system that are either directly controlled or strongly influenced through policies and actions that modify flood risk. In this context a broad range of individual Adaptations Measures (AMs) are considered including those that:

- **Manage the probability of flooding:** By improving conventional flood defences, managing catchment flows (such as rural and urban storage and run-off management), or realigning the coast to improve the Standard of Protection (SoP) afforded by a defence.
- **Manage exposure to flooding:** By limiting new development on the floodplain.
- **Manage the vulnerability of those exposed to flooding:** By encouraging individuals and organisations to improve the flood resilience of their properties/assets or improving forecasting and warning (for example through awareness raising, coverage *etc.*) to enable more effective action to be taken.

Further detail on the Adaptation Measures (and how multiple measures are combined to form alternative Adaptation Strategies) is presented in Section 6.5).

6.2.3 Temporal and spatial reporting scales

Base date and reporting epochs

Two future time horizons are used: 2050s and 2080s with a base date for the analysis of October 2018.

Two primary assumptions are made in reconciling the various aspects of the analysis to this base date:

- **All data provided on present-day risks are representative of the flood risk system as of October 2018.** All the datasets provided for use in the analysis are considered to represent the state of the flood risk system as of October 2018 (despite the individual data within these datasets being derived at various times).
- **Climate change is assumed to influence flood risk from October 2018 onwards.** The climate change analysis is based on UKCP18. The analysis of these data uses several baselines: (i) for GMST, pre-industrial times are used; (ii) for changes to fluvial flows, 1960-1990; (iii) for coastal issues, 1981-2000; and (iv) for surface water and groundwater flooding the baseline is less defined and assumed to be 2018. Any change in these variables (*e.g.,* fluvial flow) between the given baseline and 2018 (the baseline of this report) is assumed to be within the observational record and included within the data provided on the present-day flood risk system.

Note:

Data provided by national leads, for example of defence standards, are assumed to represent 2018. In making this assumption it is recognised that although such events are within the observational record, industry standard statistical models applied to estimate extreme variables (such as flood flows and wave conditions) do not routinely account for non-stationarity within that record (*e.g.,* Sayers *et al.,* 2014b). On balance, this is likely to translate to an understatement of change in risk with climate change (as recent changes may not be captured in the 2018 dataset and there is emerging evidence that historical greenhouse gas emissions have already increased the probability with which recent flood events should be expected, compared with a pre-industrial climate, Kay *et al.,* 2018). Sea level data is typically detrended prior to analysis of extremes. As industry standard methods improve to incorporate non-stationarity this assumption will not be needed.

Reporting geographies

The analysis covers the UK with primary outputs reported using a mix of geographies covering one or more of the following lenses:

- **Administrative region.** Five administrative scales are used: (i) UK; (ii) National; (iii) Regional (River Basin Districts) – Figure 6-1; (iv) Local authorities; and (v) Water company (based on sewerage undertaker company boundaries).
- **Flood source.** Each source of flooding is used: (i) Coastal (including tidal); (ii) Fluvial; (iii) Surface water.
- **Settlement type.** Eight categories of urban and rural settlements are as used. These are based on the settlement types used in England and Wales and those used in Scotland and Northern Ireland have been mapped to these (Table 6-1 and Figure 6-1).
- **Social setting.** The most socially vulnerable Neighbourhoods (as defined by the highest 20 percentile of the Neighbourhood Flood Vulnerability Index (NFVI), see later in Chapter 7 for details of this index).

Table 6-1 Settlement types used in the UK

	England and Wales (ONS, 2011)	Scotland (Scottish Government, 2016)	Northern Ireland (NISRA, 2015)
Urban	Major Conurbation	Large Urban Areas	Urban
	Minor Conurbation	None	
	City and Town	Other Urban Areas	
	City and Town in a Sparse Setting	None	
Rural	Town and Fringe	Accessible Small Towns	Mixed urban/rural
	Town and Fringe in a Sparse Setting	Remote Small Towns and Very Remote Small Towns	
	Village and Dispersed	Accessible Rural Areas	Rural
	Village and Dispersed in a Sparse Setting	Remote Rural Areas and Very Remote Rural Areas	

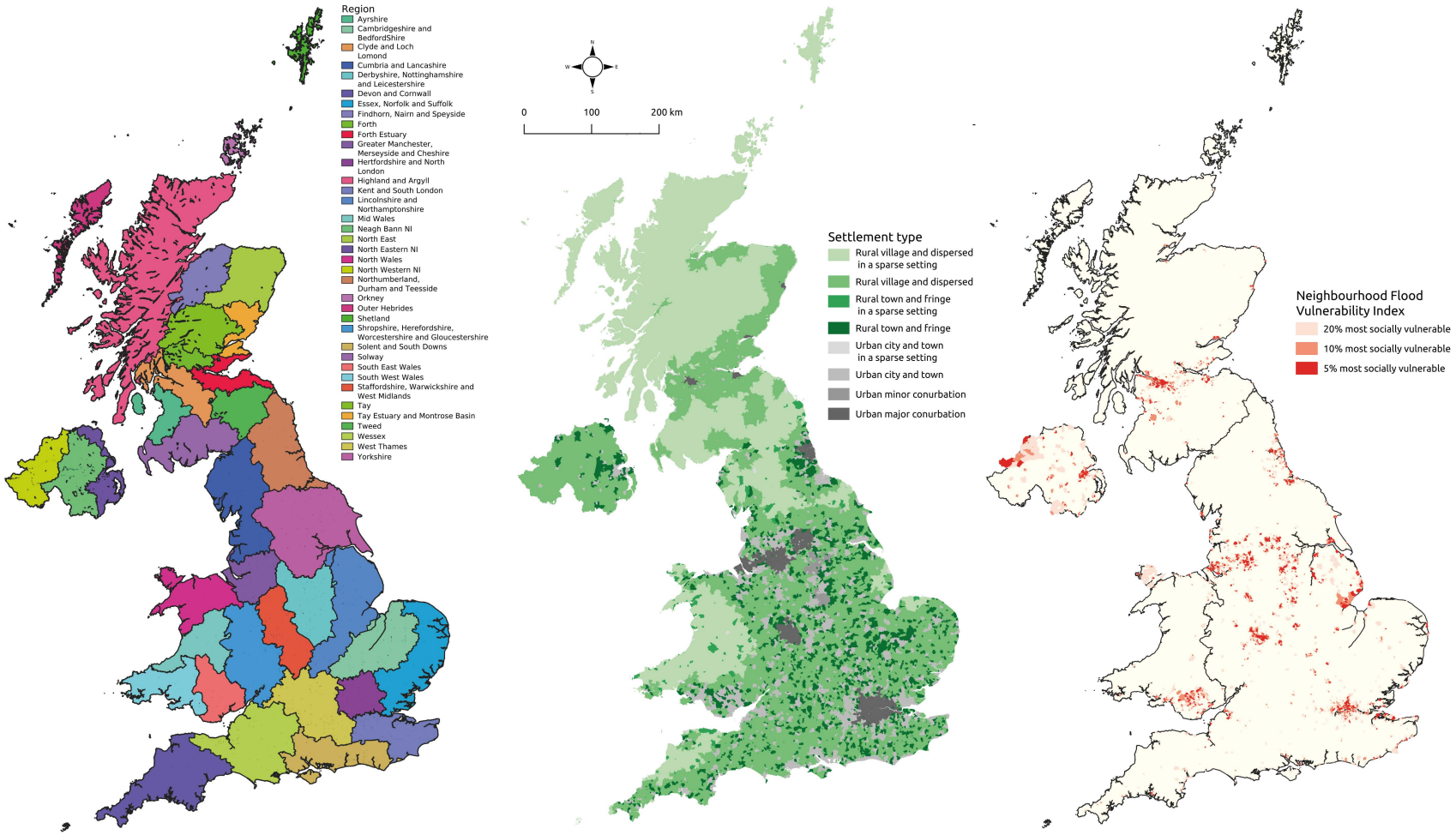
Reporting (flood hazard) bands

The lead authorities in England, Wales, Scotland, and Northern Ireland all assess flood hazards using different bands of Annual Exceedance Probability (AEP) and vary according to the source of flooding as follows:

- Significant chance of flooding
    - More likely than 1/30 AEP (an average return period of less than 30 years)
    - Between 1/30 and 1/75 AEP (an average return period of between 30 and 75 years)
- Moderate chance of flooding
    - Between 1/75 and 1/200 AEP (an average return period of between 75 and 200 years)
- Low chance of flooding
    - Between 1/200 and 1/1000 AEP (an average return period of between 200 and 1000 years)
    - Less likely than 1/1000 AEP (an average return period more than 1000 years)

Note:

The extent of the flood-prone area is assumed not changed in response to climate change: The coastal and fluvial floodplain is defined by the undefended floodplain defined as by the present-day 1in1000 year event with an allowance for climate change applied (although for different return periods and different allowances which are used in different parts of the UK).



Left: Regions; Middle: Settlement types; Right: The most socially vulnerable neighbourhoods as defined by the Neighbourhood Flood Vulnerability Index (NFVI) top 20%, 10% and 5%). The NFVI is returned to in detail in the following chapter. Source: images based on Sayers et al., 2020a

Figure 6-1 Example aggregation scales of climate risks

6.3 Analysis framework – Overview of the Future Flood Explorer

The Future Flood Explorer (FFE) initially developed in support of the UK Climate Change Risk Assessment 2 (Sayers *et al.,* 2015c) is further developed and used here (developments led by author with others, Sayers *et al.,* 2020a). The FFE enables an assessment to be made of future flood risk across the UK based on an assessment of the flood hazard, exposure and vulnerability that takes account of existing flood defences (their standard and condition) and future climate change, population growth and a portfolio of adaptation measures (including changes in flood defence standards). The FFE uses nationally recognised source, pathway and receptor data and meta modelling approaches to develop a credible emulation of the UK flood risk system that can represent future change. The high computational efficiency of the FFE allows a consistent assessment of flood risk across England, Wales, Scotland, and Northern Ireland under multiple future scenarios (*e.g.,* for this study that includes two climate change scenarios, 2°C and 4°C rise in Global Mean Surface Temperature (GMST) by 2100, low and high population projections and taking account of future adaptation.

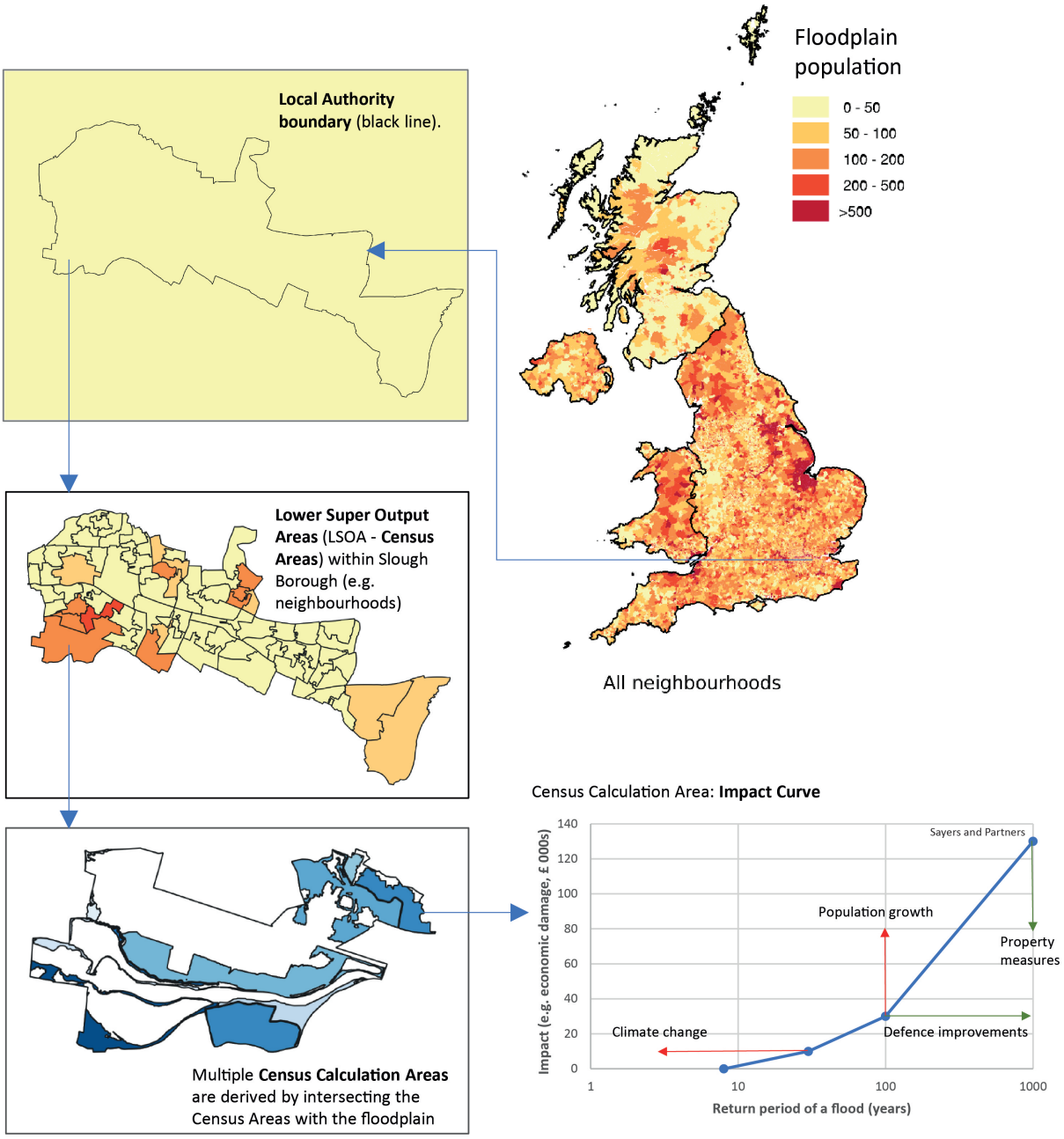
The FFE uses present-day exposure (for example, from the National Receptor Dataset in England) and the concept of a 'Neighbourhood' to aggregate socio-economic factors (such as demographics, income *etc.*). The FFE defines a Neighbourhood by census geographies (*i.e.,* Lower Super Outputs Areas (LSOAs) in England and Wales, Data Zones (DZs) in Scotland and Super Output Areas (SOAs) in Northern Ireland). The average population in each Neighbourhood varies by country: 1600 people in England, 760 in Scotland, 1600 in Wales and 2000 in Northern Ireland.

The FFE also uses hazard mapping produced by national lead authorities (for each flood source and including climate change where available – see Appendix A). This hazard data is (to different degrees) scrutinised and validated by local teams and produced for a range of return periods (from frequently occurring to very rare). The underlying spatial resolution of the available flood hazard data reflects this underlying flood data and hence varies across the UK and ranges from 2m-50m (depending upon flood source and location). These data are combined with defence datasets (both standard, condition and type) to enable the potential for breach (and how this may change with time) to be included.

The FFE assesses risk at the scale of 'Census Calculation Areas' (CCAs). The CCAs are generated within the FFE by sub-dividing each Neighbourhood using the flood hazard data into variable size polygons (yielding some 842,864 CCAs in the UK, covering fluvial, coastal, and surface water sources). This is done for all flood sources. Impact Curves for each CCA are then calculated (relating the return period of a flood event, experienced locally within the CCA, to the magnitude of the impact within the same CCA) – Figure 6-2.

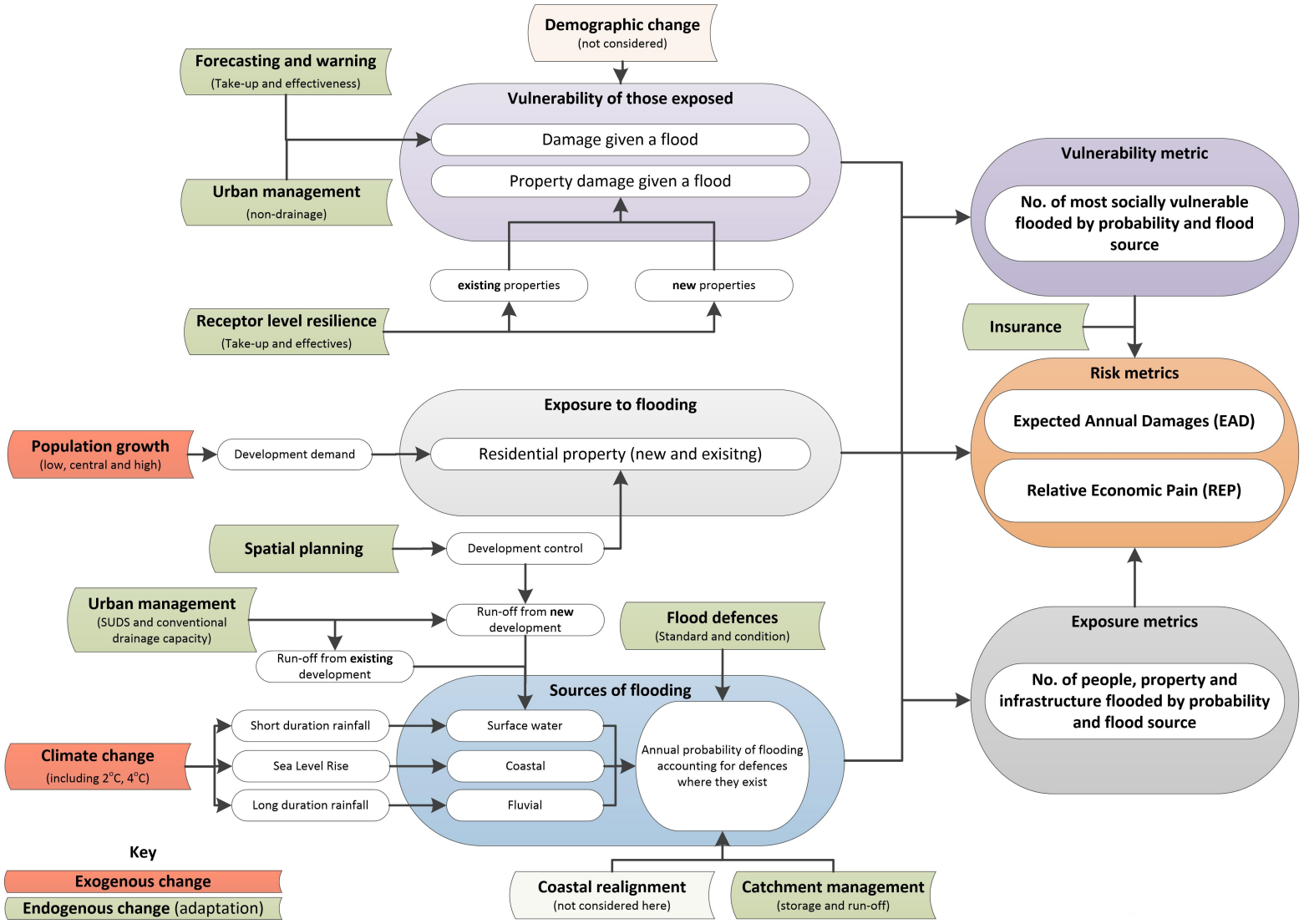
Each CCA represents an area which is broadly consistent in both its response to flooding and socio-economic characteristics. There are 842,864 CCAs in the UK, covering fluvial, coastal, surface water and groundwater flooding. Each CCA is also associated with a representative Standard of Protection (SOP, years) and Condition Grade (CG) based upon the standards and conditions of the individual defences that relate to it (Sayers *et al.,* 2015c). The FFE

manipulates the Impact Curves to quantify the influence of climate and population change as well as adaptations on flood risk (shown as an overview in Figure 6-2 with more explicitly influences shown in Figure 6-3).



Top left to bottom left: Each Local Authority contains multiple Census Areas (CA) that are in turn subdivided into Census Calculation Areas (CCAs) based on the intersection with the undefended flood plain. Source: Adapted from Sayers et al., 2015c, 2016b and 2020a

Figure 6-2 Impact curve for a Census Calculation Area used to relate return period to impact

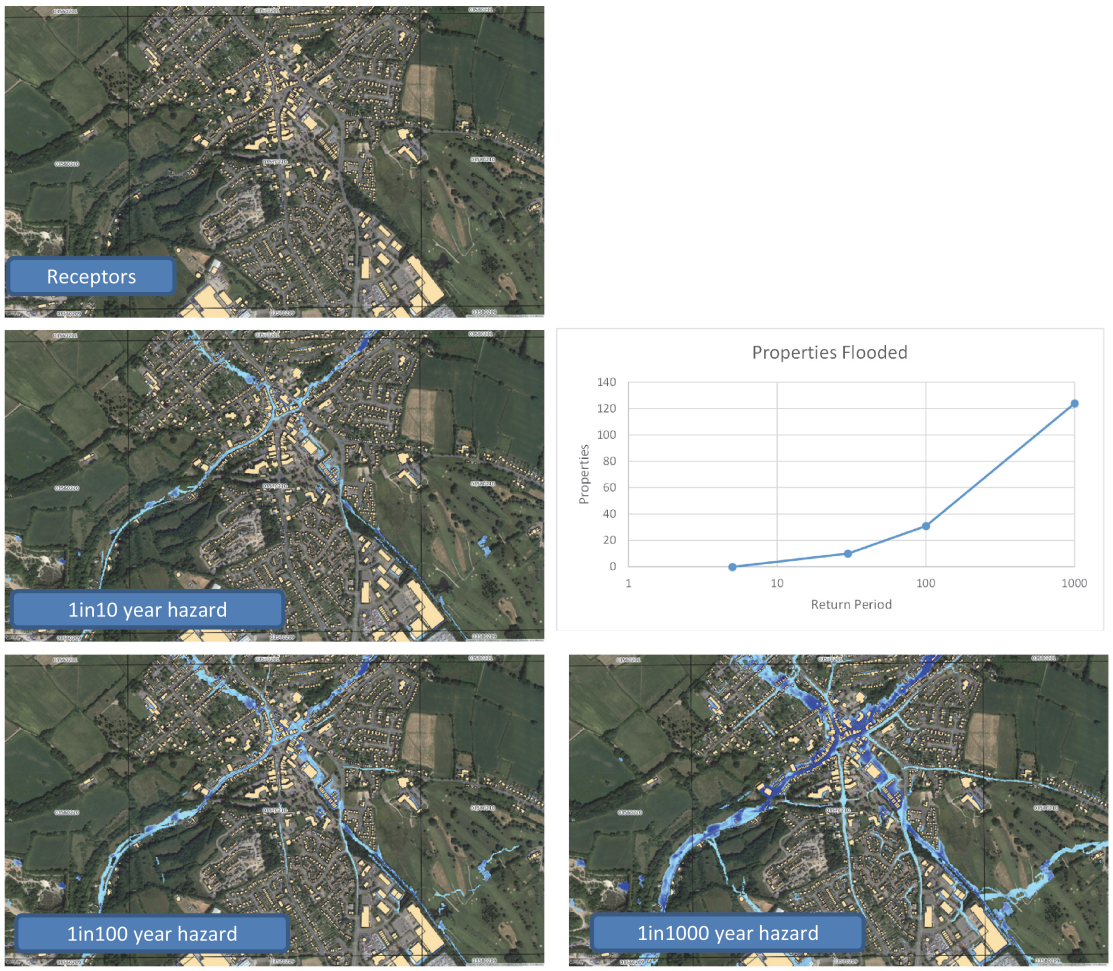


Source: Sayers et al., 2020a

Figure 6-3 Framework of the Future Flood Explorer (FFE)

6.3.1 Generating and manipulating Impact Curves

By combining the flood hazards across a range of return periods, exposure and vulnerabilities, an Impact Curve is generated for each CCA that relates the return period of a current or future flood event to the magnitude of the impact (*e.g.,* economic damage or the number of properties that would be flooded), as illustrated in Figure 6-4.

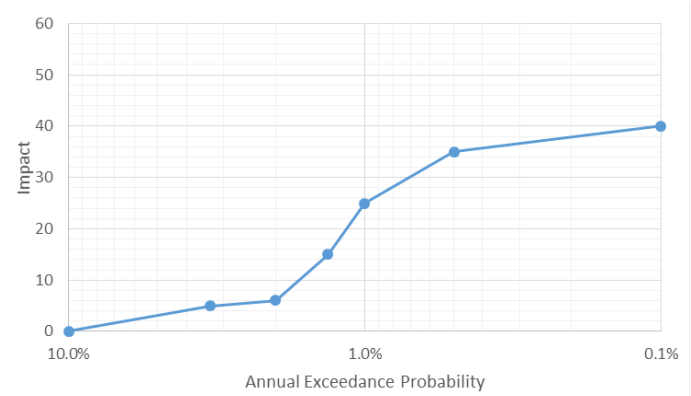


Source: Sayers et al., 2015c (Appendix F)

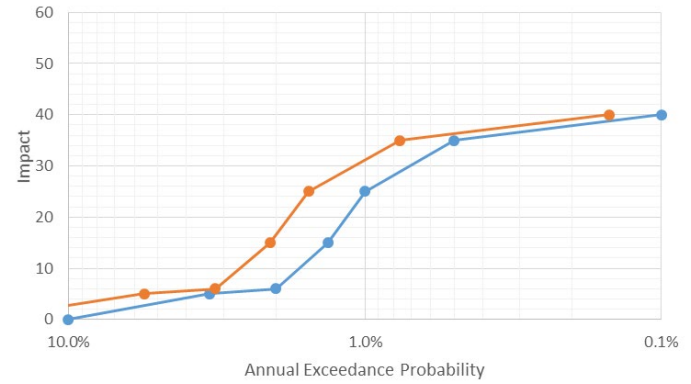
Figure 6-4 Developing present day Impact Curves for each Census Calculation Area: Overview

The Impact Curves are manipulated to quantify the influence of climate and population change and adaptations on flood risk. Figure 6-4 shows this process for an example Impact Curve, with arrows indicating how future scenarios are represented by changes to the baseline curve. To represent climate change or the influence of natural flood management, for example, the Impact Curve is moved to the left or right along the x-axis (*i.e.,* chance of flooding changes). Similarly raising of conventional flood defences shift the Impact Curve along the x-axis (in a way the represents the new standard of protection) – Figure 6-5.

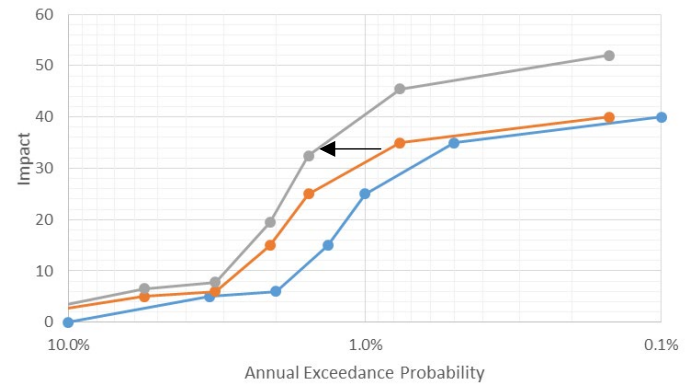
Impact curves are used to relate the **probability** of flooding to a given measure of **impact.**



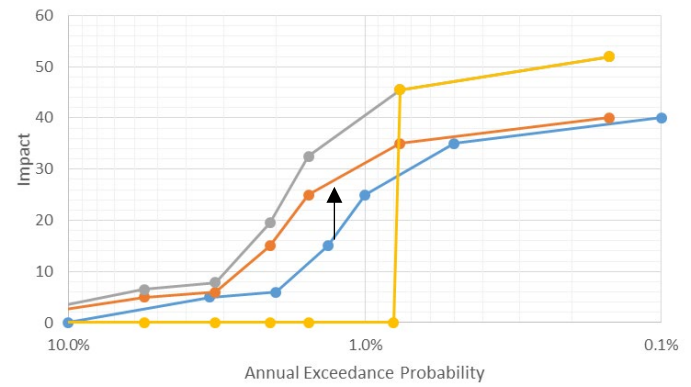
The influence of **climate change** is represented by a horizontal shift, equivalent to making each impact more likely.



The influence of **population growth** is represented by a vertical shift.



The **influence of defences** is represented by setting impacts to zero for probabilities above the standard of protection; other adaptations are represented by further shifts in the curve.



Y axis – refers to the native impact, the number of houses flooded, or agricultural land flooded. These native impacts are then converted to economic damage where appropriate (for example property damage) or left in native terms: Source. Sayers et al, 2020a (with Horritt)

Figure 6-5 The FFE manipulates each Impacts Curve to represent locally credible future change

6.4 MEASURING CHANGE: METRICS OF RISK AND EXPOSURE

The notion of *'flood resilience'* has emerged in recent years (and elaborated in Chapter 3) and is now a fundamental concept within flood management, *e.g.,* Sayers *et al.,* 2017a). In Chapter 3 a resilient society is defined as one that '*exhibits an acceptable loss (including no loss) of social wellbeing, economic prosperity, or ecosystem health over the short or longer term in response to an unusual event (or combination of events) or trend'*. This outcome-focused definition is explored here using the proxy of risk, including several vulnerability, exposure, and risk metrics. The metrics used include a combination of conventional risk metrics (as provided in CCRA2, Sayers *et al.,* 2015c) and socially focused metrics introduced by Sayers *et al.,* 2017c. The social metrics reflect the differential vulnerability of some groups and communities (as defined by the Neighbourhood Flood Vulnerability Index, NFVI, Sayers *et al.,* 2017c) and their capacity for recovery (for example the Relative Economic Pain proposed by Sayers *et al.,* 2017c and returned to in Chapter 7).

6.4.1 Metrics of flood risk

The flood risk metrics used combine hazard, exposure, and vulnerability in an *'annual expectation'* (*i.e.,* average) calculation based on an integration of annual exceedance probability consequence curve. The risk metrics are summarised in Table 6-2.

6.4.2 Metrics of exposure

Exposure is considered here as a binary term; a person, property or other receptor is either exposed to a given flood hazard or not. In assessing 'exposure' no consideration is given to the nature of hazard (*e.g.,* shallower, or deeper flooding, only the chance of the flood). Neither is consideration given to the severity of the harm that may be caused to the receptor (*e.g.,* reflecting the vulnerability of a given receptor). Therefore, exposure provides a simple metric that presents risk in native parameters (*e.g.,* number of people exposed to flooding *etc.*). The selected exposure metrics are summarised in Table 6-3.

Table 6-2 Flood risk metrics

Metric	Basic description
Economic	
Expected Annual Damage (direct damages – £): Residential and non-residential properties (separately)	The annual 'average' direct property damages in economic terms. Determined using an integration of the probability of flooding (taking account of defences and other management measures) and the associated damages.
Expected Annual Damage (total damages – £)	Direct damages plus additional indirect damages (with indirect damages assumed to be 70% of the direct (residential and non-residential) damages plus intangibles assumed to be an additional 20% of the direct (residential) damages).
Expected Annual Damage: Individual (EADi) – £	The annual 'average' total – direct and indirect – economic loss faced by an individual living within a flood-prone area. Although not representative of the risk faced by any specific individual this provides a means of comparing risks between communities.
Social	
Relative Economic Pain (REP) (dimensionless)	The 'relative pain' of the economic risks faced by those exposed to flooding (expressed as the ratio between uninsured economic damages and household income).
Social Flood Risk Index (SFRI) (z-score)	The level of social flood risk (a combination of exposure, vulnerability, and probability of flooding), at a neighbourhood scale (SFRI) and as an individual 'average' (iSFRI) – as developed in Sayers *et al.,* 2017c.

Table 6-3 Flood exposure metrics

Metric	Basic description
People (for all Neighbourhoods and the 20% most socially vulnerable Neighbourhoods as defined by NFVI)	
Exposed Population (EP)	No. of people living in flood-prone areas defined by 1in1000 year event in the absence of flood defences.
No. of People Exposed to Frequent Flooding, PEFf	No. of people exposed to flooding more frequently than 1/75 years, on average (accounting for defences and other measures that influence the chance of flooding).
Expected annual probability of flooding: Individual, EAPi	An individual's annual 'average' exposure to flooding taking account of defences and other management measures.
Property (for residential and non-residential – taking account of defences where they exist)	
Expected Annual number of residential properties flooded	The annual average number of residential properties flooded.
No. of Residential and Non-residential Properties exposed to flooding (by probability band)	No. of properties exposed to different flood frequencies (taking account of defences where they exist).
Habitats and species (taking account of defences where they exist)	
No. of hectares of most important habitats exposed to frequent flooding	No. of hectares of the most important habitats (defined as SPA, SAC & Ramsar sites) flooded more frequently than 1/30 years, on average.
Agriculture (taking account of defences where they exist)	
No. of hectares BMV land exposed to frequent flooding	No. of hectares of the Best and Most Versatile (BMV) land flooded more frequently than 1/30 years, on average.
Infrastructure (taking account of defences where they exist)	
Category A infrastructure (exposed by flood probability band)	
Water: No. of distribution and treatment sites, and Energy: No. of generation and distribution sites	Accounts for protection provided by flood defences where they exist.
Category B infrastructure (exposed by flood probability band)	
No. of railway stations, operational (licenced) landfill sites; hospitals and blue light service stations (police, ambulance, fire stations); Social support networks: No. of care homes, GP surgeries, and schools	Accounts for protection provided by flood defences where they exist.

6.5 CLIMATE AND POPULATION PROJECTIONS

6.5.1 Population growth associated increases in residential property

Two projections of population growth from Cambridge Econometrics (2019) are used here:

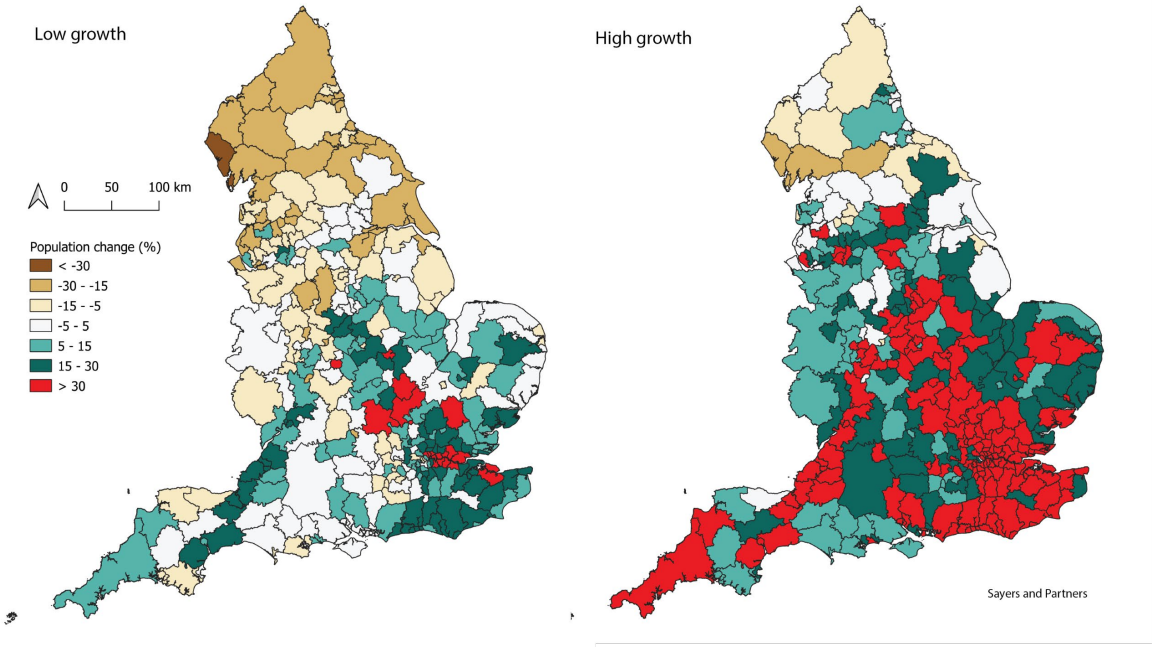
- **High growth.** Based on the ONS 'young age structure' variant of its principal population projection, the high growth projection assumes fertility rates and net migration are higher than in the central case while life expectancy is lower. The UK population grows to ~88 million in 2100, an increase of almost 27 million from 2016. The population has a younger age structure than in the central projection, with 59% of the population of working age (4% more than the central projection). The proportion of dependents aged between 0-15 is also slightly higher in the high scenario, reflecting higher birth rates.
- **Low growth.** Based on the ONS 'old age structure' variant of its principal population projection, the low growth projection assumes fertility rates and net migration are lower than in the central case while life expectancy is higher. The UK population reaches to ~68 million in 2100, an increase of just 1 million from 2016 and leads to an older age structure (with over 65s accounting for 36% of the population, compared to 29% in the central scenario).

The demand for new residential properties reflects a combination of population growth and the average household occupancy. The central projections of household occupancy at a local authority scale are taken from Cambridge Econometrics (2019) and show the average UK household size decreasing from 2.35 persons per household in 2016 to 1.96 in 2100. This change factor is applied to present-day local occupancy rates (at a Neighbourhood level) to establish a local development demand in both the high growth and low growth scenarios. No consideration is given to associated development of municipal infrastructure (railways, hospitals *etc.*). No consideration is given to the economic growth that may influence the inventory of household goods (that may yield a real term change in flood damage). It is assumed that GDP growth in general impacts all aspects of the economy equally and is therefore excluded here. These changes are summarised in Table 6-4 with the spatial pattern in England illustrated in Figure 6-6 by Local Authority.

Table 6-4 Population growth projections

Region	Current population	Future population					
	As at 2018 (millions)	Absolute values in millions of people % Change from 2018				Average household occupancy	
		Low		High			
		2050s	2080s	2050s	2080s	2050s	2080s
UK	66.47	69.51 5%	67.65 2%	79.56 20%	87.79 32%	2.14	2.00
England	56.00	59.68 7%	59.01 5%	67.67 21%	75.09 34%	2.16	2.01
Wales	3.14	2.96 -6%	2.66 -15%	3.47 10%	3.67 17%	2.11	2.00
Scotland	5.45	5.13 -6%	4.53 -17%	6.17 13%	6.59 21%	1.96	1.81
Northern Ireland	1.88	1.74 -7%	1.45 -23%	2.25 20%	2.45 30%	2.35	2.19

Source: Sayers et al, 2020a, based on data provided in Cambridge Econometrics, 2019



Left: low population growth. Right: high population growth.
Source: Sayers et al, 2022c based on data from Cambridge Econometrics, 2019

Figure 6-6 Projected population change by England Local Authority (2019 boundaries) – Present day to 2080s

The increased demand for residential property is translated into increased properties and population on the floodplain through the action of the spatial planning adaptation. Current policies, despite aiming to manage floodplain development, result in new properties being more likely to be on the floodplain than existing ones. Analysis for England shows that

between 2008 and 2014, 12% of new properties were built on fluvial or coastal floodplains (defined by the 1in1000 year return period flood area in the absence of defences where they exist), compared to 8% of existing properties. Thus, with present policies in place, an increase in properties of 10% will generate an increase of 15% on the floodplain, with equivalent uplift in property counts and damages represent in the impact curves. These uplifts are calculated at local authority level, reflecting different planning policies applied locally and the varying proportions of existing properties on the floodplain – for some local authority areas such as Hull, almost all properties are on the floodplain (an issue highlighted by Stevens *et al.,* 2010). The efficacy of planning policy in directing development away from the floodplain is reflected in different proportions of new properties on the floodplain in the different adaptation portfolios described in the next section.

A reduction in population (which occurs for some locations in the low scenario) leads to a proportionate reduction in floodplain properties and population. The FFE assumes no increase in non-residential properties or infrastructure because of population growth.

6.5.2 Climate change

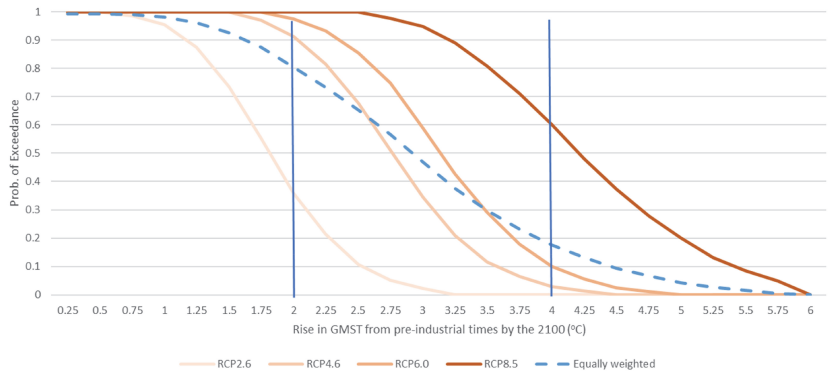
Climate scenarios are defined by the increase in Global-Mean-Surface-Temperature (GMST) reaching 2°C and 4°C in 2100 (from pre-industrial times). The way the associated changes in climate drivers are assessed under each scenario necessarily varies to reflect the available underlying data from UKCP18 and the priority given to analysis of those data within the constraints of this project as follows:

- **Rate of rise in GMST to 2100.** based on the UKCP18 Probabilistic Projections rebased to pre-industrial times.
- **Changes in peak fluvial flows.** based on the UKCP18 Probabilistic Projections and national-scale 1km flood response surfaces produced using the Grid-to-Grid hydrological model (running at a 15min time step, Bell *et al.,* 2009). The UKCP18 Probabilistic Projections (as monthly delta changes with a fitted harmonic function) are then overlaid on the flood response surfaces, to derive the change in flood flows (using the approach set out in Kay *et al.,* 2020).
- **Changes in short duration rainfall intensity** (< 6hours)**.** based on a combination of Dale *et al.,* 2015 and 2017 (that use pilot analysis from a 1.5km grid climate model, a precursor to the 2.2km UKCP18 short duration rainfall projections, Kendon *et al.,* 2014) and data used in CCRA2 (Sayers *et al.,* 2015c).
- **Changes in sea levels at the coast and in estuaries.** based on the relative Sea Level Rise (rSLR) data within the UKCP18 Marine Report (Palmer *et al.,* 2018) changes in wave overtopping are assessed. This process accounts for the offshore to nearshore wave propagation and defence overtopping response (using the approach set out in Gouldby *et al.,* 2017).

The data used and analysis under each heading are set out below.

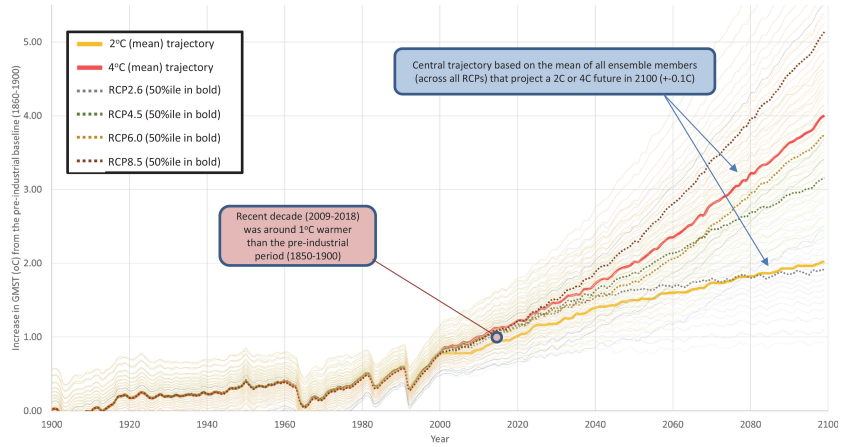
Rate of rise in GMST

Across the Representative Concentration Pathways (RCPs, as described by van Vuuren et al, 2011) many of the ensemble members from UKCP18 Probabilistic Projections show an increase in GMST of 2° or 4°C by 2100 (Figure 6-7). A mean of those members that project a rise of 2°C and 4°C (within a tolerance of +/-0.1 between 2090-2100 from a pre-industrial baseline) are used to construct a profile in the rise in GMST with time (Figure 6-8). The GMST in any year that is consistent with a 2 or 4°C rise by 2100 is then determined from this profile. This value is then used to determine the related changes in fluvial flows, sea levels *etc.* in the 2050s and 2080s (as described in the following sections).



Source: Sayers et al., 2020a based on data from the Met Office 2019 – a pre-release GMST anomaly dataset made available prior to upload to CEDA Data Archive

Figure 6-7 Rise in GMST under each RCP



Central trajectory based on a mean of all ensemble members (across all RCPs) that project a 2°C or 4°C future. After 2000 the 2 and 4°C trajectories diverge, which reflects the variation in the UKCP18 projections. There is variation in temperature for the present day (and before) because the trajectories are the modelled projections for simulations from the 1900s and not observations. Source: Sayers et al., 2020a

Figure 6-8 Rise in GMST to 2100 (from UKCP18 probabilistic projections)

Coastal flooding

Climate change variable of interest: Relative Sea Level Rise

Wave conditions around much of the UK coast are depth limited. Relative Sea Level Rise (rSLR) therefore has a dominant influence on coastal flooding (increasing both wave-driven overtopping, the chance of a breach and tidal overflow). As there is a lack of evidence of

climate-driven changes in other aspects of coastal storms, rSLR is considered here as the single driver of climate related change at the coast (an assumption also made in CCRA2, Sayers *et al.,* 2015c).

Sea level projections for the UK used here are based on the UKCP18 Marine Report (Palmer *et al.,* 2018). The UKCP18 sea level projections are based on the climate model simulations of the Coupled Model Inter-comparison Project Phase 5 (CMIP5, Taylor *et al.,* 2012). The projections include both climate drivers and the elastic response of the land to the last de-glaciation to provide relative sea level rise estimates (a main reason for spatial variations in projected mean sea level change around the UK).

The UKCP18 Marine Report (Palmer *et al.,* 2018) provides percentile values of sea level rise for three RCPs (2.6, 4.5 and 8.5). The rise in GMST and SLR estimates associated with these values are used to interpolate an assessment of rSLR given a 2 and 4°C rise in GMST in 2100 (re-based to give the rSLR relative to a 2018 baseline – as described in Sayers *et al.,* 2020a Appendix C). A detailed processing chain is used to assess the change in the Standard of Protection (SoP) afforded by a given coastal defence in response to changes in rSLR that includes issues of depth-limitation, refraction, and nearshore beach levels and defence geometry using the method set out in Gouldby *et al.,* 2017 (Figure 6-9). The central estimates from this analysis are illustrated in Figure 6-10 with the change in rSoP at a regional scale for illustration in Table 6-5.

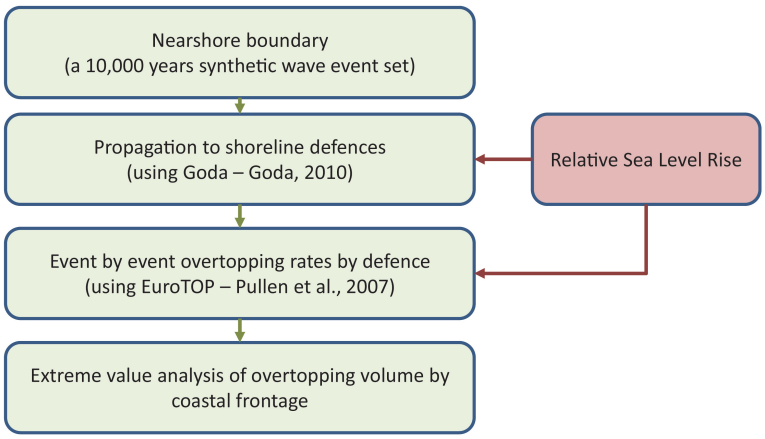
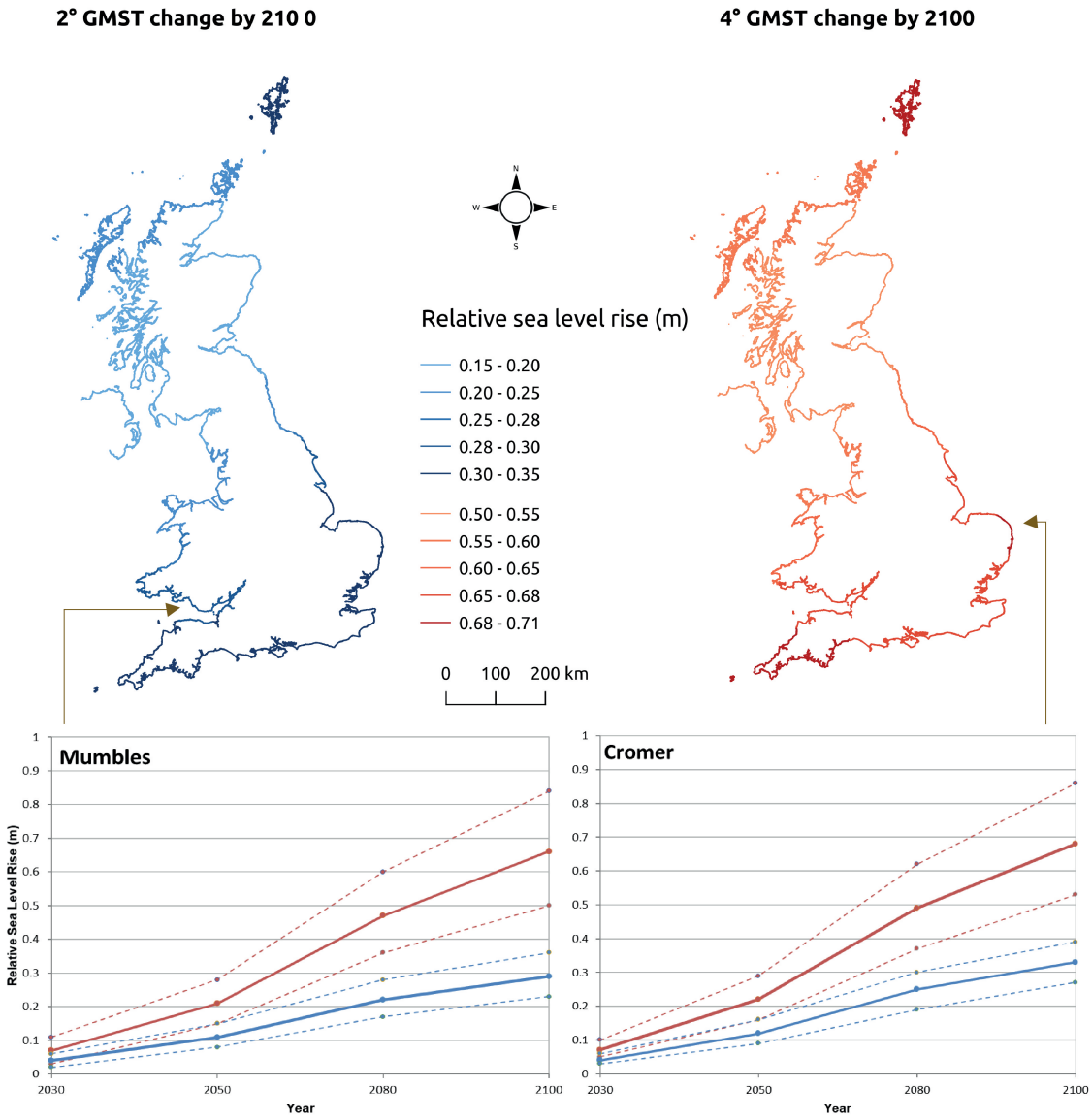


Image from Sayers et al, 2020a based on the processing chain of Gouldby et al., 2017

Figure 6-9 Assessing the impact of rSLR on coastal defence standards



Blue: 2° future. Red: 4° future. Solid lines central estimate, dashed lines present the envelope of change from the available data in Palmer et al., – 5th and 95th percentiles. Source: Sayers et al, 2020a (with Mauz and Hames)

Figure 6-10 Relative Sea level rise (2018 to 2100)

Table 6-5 Relative Sea Level Rise and impact on defence standards

	Typical values of rSLR (m) 50th percentile (10th - 90th percentiles)				Impact on Present Day Standard of Protection (Return Period - Years) of a 0.35m rSLR								
	2°		4°										
	2050	2100	2050	2100	2	5	10	20	50	100	200	500	1000
England													
01 - Scottish Border to River Tyne	0.09 (0.05-0.14)	0.27 (0.16-0.39)	0.20 (0.13-0.27)	0.65 (0.47-0.85)	0	1	3	5	12	23	44	107	202
02 - The Tyne to Flamborough Head	0.12 (0.07-0.17)	0.32 (0.22-0.44)	0.22 (0.15-0.29)	0.71 (0.53-0.9)	1	3	5	10	24	47	91	256	567
03 - Flamborough Head to Gibraltar Point	0.13 (0.09-0.18)	0.37 (0.27-0.49)	0.24 (0.17-0.31)	0.75 (0.58-0.94)	1	2	3	7	17	35	70	198	370
04 - Gibraltar Point to Hunstanton	0.13 (0.09-0.18)	0.38 (0.28-0.49)	0.24 (0.17-0.31)	0.76 (0.58-0.95)	1	3	5	8	18	32	60	145	288
05 - Hunstanton to Kelling Hard	0.14 (0.1-0.19)	0.39 (0.29-0.5)	0.25 (0.18-0.32)	0.77 (0.6-0.96)	0	2	3	7	15	28	53	128	243
06 - Kelling Hard to Lowestoft	0.14 (0.1-0.19)	0.40 (0.3-0.51)	0.25 (0.18-0.32)	0.78 (0.61-0.96)	1	2	4	9	23	42	84	232	420
07 - Lowestoft to Felixstowe	0.14 (0.1-0.19)	0.39 (0.29-0.5)	0.25 (0.18-0.32)	0.77 (0.6-0.96)	0	2	3	6	18	38	78	231	449
08 - Essex and South Suffolk	0.14 (0.09-0.2)	0.38 (0.29-0.49)	0.25 (0.17-0.32)	0.77 (0.6-0.95)	0	1	3	5	14	30	64	186	435
09 - River Medway and Swale Estuary	0.14 (0.09-0.19)	0.38 (0.28-0.49)	0.24 (0.18-0.31)	0.76 (0.59-0.95)	0	2	4	7	18	37	73	229	622
10 - Isle of Grain to South Foreland	0.14 (0.09-0.19)	0.38 (0.28-0.49)	0.24 (0.17-0.32)	0.77 (0.6-0.95)	0	1	3	6	15	31	63	162	360
11 - South Foreland to Beachy Head	0.13 (0.09-0.18)	0.38 (0.28-0.49)	0.24 (0.17-0.31)	0.76 (0.59-0.95)	1	3	5	8	17	33	64	145	288
12 - Beachy Head to Selsey Bill	0.14 (0.09-0.19)	0.38 (0.28-0.49)	0.25 (0.18-0.32)	0.76 (0.59-0.95)	1	1	2	4	11	21	40	105	215
13 - Selsey Bill to Hurst Spit	0.14 (0.09-0.19)	0.38 (0.28-0.49)	0.25 (0.18-0.32)	0.77 (0.59-0.95)	0	0	1	3	7	13	25	62	119
14 - Isle of White	0.14 (0.09-0.19)	0.38 (0.28-0.49)	0.25 (0.17-0.32)	0.77 (0.6-0.96)	0	1	2	5	10	20	40	95	185
15 - Hurst Spit to Durlston Head	0.14 (0.09-0.2)	0.38 (0.28-0.5)	0.25 (0.18-0.33)	0.77 (0.6-0.96)	1	2	3	7	18	36	70	171	331
16 - Durlston Head to Rame Head	0.14 (0.1-0.19)	0.39 (0.29-0.51)	0.25 (0.18-0.32)	0.78 (0.61-0.97)	1	2	5	9	22	41	79	197	379
17 - Rame Head to Hartland Point	0.14 (0.1-0.19)	0.40 (0.29-0.52)	0.25 (0.18-0.33)	0.79 (0.61-0.99)	1	2	4	8	19	37	72	176	351
18 - Hartland Point to Anchor Head	0.13 (0.09-0.18)	0.37 (0.27-0.49)	0.24 (0.17-0.31)	0.76 (0.58-0.96)	1	2	3	6	14	26	50	123	265
19 - Anchor Head to Lavernock Point	0.13 (0.09-0.18)	0.37 (0.27-0.48)	0.24 (0.17-0.31)	0.76 (0.58-0.95)	0	2	4	7	17	33	70	190	369
22 - Great Ormes Head to Scotland	0.1 (0.06-0.15)	0.28 (0.18-0.4)	0.21 (0.14-0.28)	0.67 (0.49-0.86)	0	1	3	6	15	30	55	135	249
Wales													
19 - Anchor Head to Lavernock Point	0.13 (0.09-0.18)	0.37 (0.27-0.48)	0.24 (0.17-0.31)	0.76 (0.58-0.95)	0	1	3	5	12	23	47	129	278
20 - Lavernock Point to St Ann's Head	0.13 (0.08-0.18)	0.36 (0.26-0.48)	0.24 (0.17-0.31)	0.75 (0.57-0.95)	0	1	2	4	9	18	35	86	175
21 - St Ann's Head to Gread Ormes Head	0.11 (0.07-0.16)	0.32 (0.21-0.44)	0.22 (0.15-0.29)	0.7 (0.52-0.9)	0	1	2	5	13	24	46	111	212
22 - Great Ormes Head to Scotland	0.1 (0.06-0.15)	0.28 (0.18-0.4)	0.21 (0.14-0.28)	0.67 (0.49-0.86)	0	1	3	5	14	28	51	126	225
Scotland													
East	0.08 (0.04-0.13)	0.23 (0.12-0.36)	0.19 (0.12-0.26)	0.62 (0.43-0.82)	0	1	1	3	8	16	32	79	158
North	0.11 (0.07-0.16)	0.29 (0.17-0.42)	0.22 (0.15-0.29)	0.67 (0.48-0.88)	1	1	2	5	12	23	44	105	207
North-West	0.11 (0.07-0.16)	0.29 (0.17-0.42)	0.22 (0.15-0.29)	0.67 (0.48-0.88)									
West	0.08 (0.04-0.13)	0.23 (0.12-0.35)	0.19 (0.12-0.26)	0.61 (0.42-0.81)	0	1	3	5	14	27	51	126	225
Northern Ireland													
Northern Ireland	0.08 (0.04-0.13)	0.24 (0.13-0.36)	0.19 (0.12-0.26)	0.62 (0.43-0.82)	0	1	3	5	14	28	51	126	225

Note: The 50th percentile values shown as used in the analysis of risk presented later in the report.

Example: For a defence in SMP 22 (Wales) with a current SoP of 1: 50, the standard would reduce to 1: 14 years.

Fluvial flooding: Changes in peak flood flows and changes in standard of protection

Climate change influences fluvial flood risk through changes in flood flows that in turn change in-river levels (and hence standard of protection). The approach is discussed in outline below with more detail in Rudd *et al.,* 2022.

Assessing changes in peak fluvial flows

The UKCP18 Probabilistic Projections that reach a 2 or 4°C rise in GMST **in or before** 2100 (from a pre-industrial baseline) are used in assessing the change in fluvial flows. This 'time-sampling' approach (James *et al.,* 2017) maximises the number of ensemble members that are used to assess the change for a given rise in GMST. The selected combinations of ensemble members and time slices are used to derive changes in peak flows on a 1km grid using the flood response surface approach, set out in Kay *et al.,* 2020, 2021) – an approach that uses a national-scale grid-based hydrological model, Grid-to-Grid. This process leads to percentile changes in return period peak flood flows on a 1km grid that correspond to each required GMST change (Sayers *et al.,* 2020a and expanded in Rudd *et al.,* 2022).

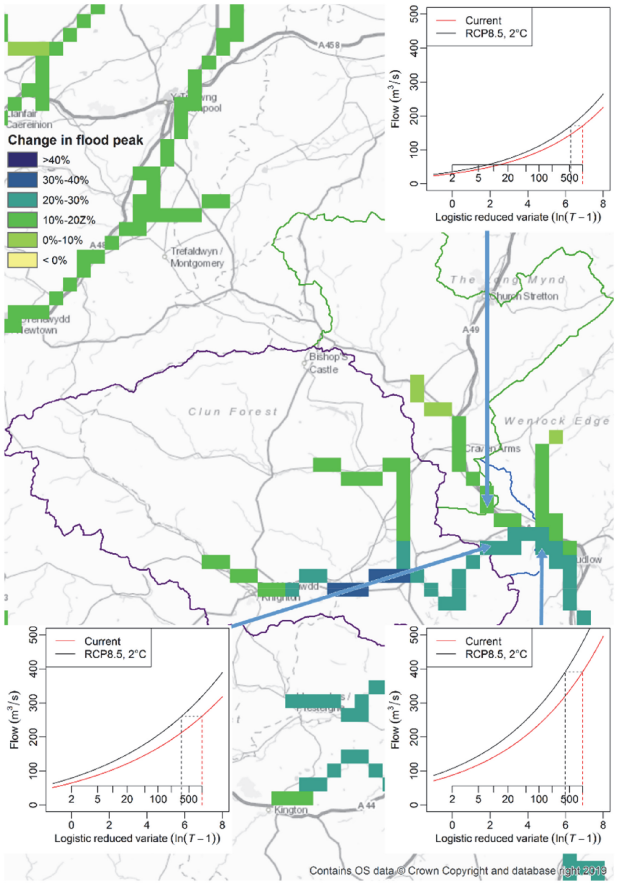
Assessing the impact on extreme river levels

Changes in peak fluvial flow are translated to a change in water levels (the effective storm loading on a defence where it exists) through application of the Flood Estimation Handbook (FEH) statistical method (Kjeldsen *et al.,* 2008) to each 1km grid (based on catchment descriptors from the most appropriate 50m FEH pixel). The FEH flood frequency curve for each grid point is used to estimate the change in the return period of the current T-year flood corresponding to a set of percentage changes in flow, as illustrated in Table 6-6. This processing chain (climate change, hydrological response, and extreme value response) enables the local context of the response to climate change to be captured and leads to highly spatially differentiated (credible) changes. Two tributaries immediately upstream of a confluence, for example, can be quite different in their physical geography. These differences mean that two nearby locations can have different responses to a change in rainfall and the flood flows. Figure 6-11 illustrates this by plotting the flood frequency curves for two points upstream and one point downstream of a confluence of the rivers Teme and Corve near Ludlow, Shropshire. This figure shows how the change in return period in response to climate change – at one location the 1000-year flood reduces to 341-year flood flow whilst at another, close by point, to the 533-year flood flow. How this change manifests in terms of a flood hazard will reflect the local defences (if present) and their standards and conditions (a consideration that adds further spatial differentiation).

Table 6-6 Fluvial flooding: Relating percentage changes in peak flow to changes in return period

ID: 30243	Current Return Period (years)					
% change in peak flow	2	10	50	100	200	1000
	Revised return period (years) given a change in peak flow					
-20%	4.8	33	173	346	690	3419
-10%	2.9	18	90	180	359	1788
-5%	2.4	13	67	133	266	1327
0%	2	10	50	100	200	1000
5%	1.7	7.8	38	76	152	764
10%	1.6	6.2	30	59	118	590
20%	1.3	4.1	18	36	72	364
30%	1.2	2.9	12	23	46	233
40%	1.1	2.2	8.1	16	31	154
50%	1.1	1.8	5.8	11	21	105

In this example a 10% increase in peak flow (+10%) would reduce the return period of a present-day 1: 100-year flow to 1: 59 years. Source: Sayers et al., 2020a (with Stewart and Kay)



Example flood frequency plots for three nearby locations with differently shaped baseline curves, showing how different changes in return period can result from different changes in flow peak, especially for the baseline 1000-year return period flood. From Sayers et al., 2020a (with Kay and Stewart)

Figure 6-11 Local physical geographies have a considerable influence on changes in flood flows under climate change

Surface water flooding

Changes in short duration rainfall

Surface water flooding primarily responds to intense short duration rainfall (defined here as sub-daily rainfall of less than 6 hours duration). It has long been known that climate models are relatively poor at simulating short duration precipitation extremes (Fowler and Ekström, 2009; Flato *et al.,* 2013, Chan *et al.,* 2014; Kendon *et al.,* 2012 and 2014). This is primarily due to the relatively coarse resolution of climate models to date and their inability to capture important processes, such as convection. Recent developments in kilometre-scale climate modelling are, for the first-time, promising credible projections of changes in sub-daily rainfall (Kendon *et al.,*2014, Kendon *et al.,*2019). The reliability of such estimates is yet to be fully explored but they generally support the underlying principle of the Clausius–Clapeyron relationship (that predicts an increase in the water holding capacity of air of approximately 7% per degree Celsius rise in temperature) and associated empirical evidence that demonstrates temperature change is a significant driver of changes in rainfall intensity (Dale *et al.,* 2015).

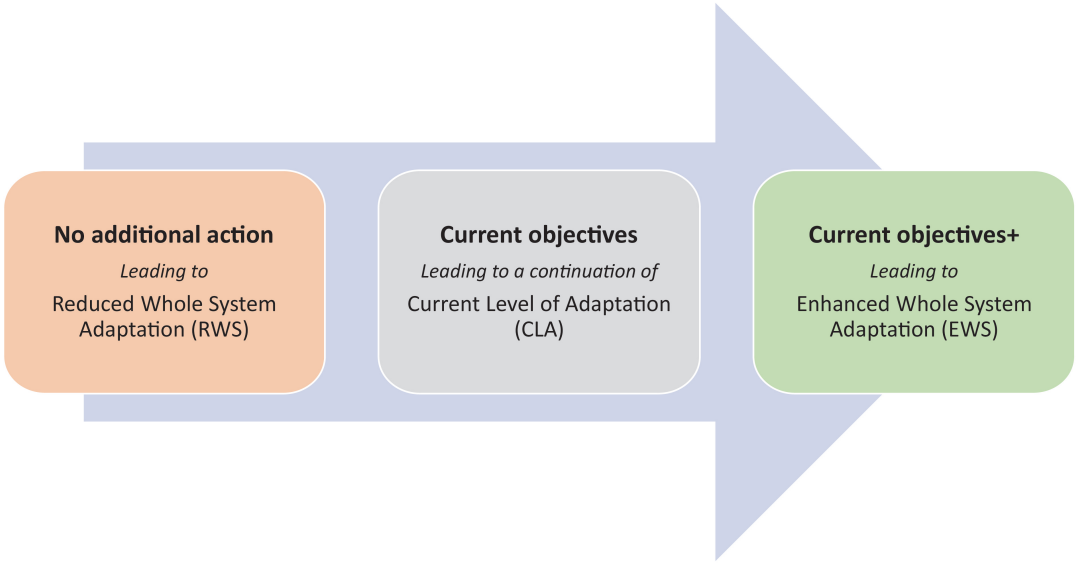
The development of finer-grid models remains in its infancy and data from the Met Office UKCP 2.2km climate model (Kendon *et al.,* 2019) is yet to be mined. A combination of evidence is therefore used here to estimate the change in short duration rainfall intensity, including the Environment Agency guidance on climate allowances (Environment Agency, 2016d, despite its basis on UKCP09 and its well-known inability to represent convective storms) and the more recent estimates within Dale *et al.,* 2017 (based on 1.5km a precursor to the 2.2km UKCP18 short duration rainfall projections, Kendon *et al.,* 2014).

6.6 ADAPTATION MEASURES AND ALTERNATIVE ADAPTATION PORTFOLIOS

It is widely recognised that flood risk is best managed through a portfolio of measures implemented through a continuous process of adjustment (*e.g.,* Evans *et al.,*2004a&b, Sayers *et al.,* 2014). The need for a 'portfolio of responses' is reflected in much of the UK flood risk management and the policies that influence its delivery (*e.g.,* Scottish Government, 2019; Environment Agency, 2019 and 2020, HM Government, 2018). The portfolio approach is also reflected here with nine individual Adaptation Measures (AMs) combined into three alternative Adaptation Portfolios (AP) that represent different levels of policy ambition.

Alternative adaptation portfolios

Three alternative Adaptation Portfolios (AP) are considered (Figure 6-12). Each represents a whole system approach that builds upon the CCRA2 (Sayers *et al.,* 2015c). The guiding philosophy behind each AP is discussed below. The detail settings (*i.e.,* how they are translated in model parameters in the FFE is given in Appendix B).



Source: Sayers et al., 2020a

Figure 6-12 Three alternative Adaptation Portfolio scenarios

- **No additional action: Leading to Reduced Whole System (RWS) Adaptation.** The 'no additional action' adaptation assumes investment in conventional defences fails to keep pace with climate change; there is limited take up of catchment-based or urban run-off measures; pressure for development and economic growth lead to continued new development on the floodplain; receptor (property) level flood resilience (PFR) continues to experience limited take-up amongst existing properties. There are several plausible reasons that may lead to such a situation. Other threats may become increasingly dominant in public funded priorities (translating to a reduction in the willingness to pay for flood risk management) or our collective capacity to promote and deliver flood risk management may wane as political and social capital is directed towards other priority issues. As a result, the condition of defences reduces the change of failure increases under load.
- **Current objectives: Leading to a continuation of Current Levels of Adaptation (CLA).** The *'current objectives'* policy response used here assumes flood risk management policies continue to be implemented as in the recent past whilst taking on board anticipated changes that are likely to result from recent changes in policy, such as the 25 Year Environment Plan and the National Planning Policy Framework in England, continued evolution of TAN15 in Wales, and National Planning Framework No. 4 in Scotland. These and similar documents are likely to encourage greater uptake of Natural Flood Management (NFM) and property flood resilience (PFR) measures than achieved in recent years and continue to encourage greater investment in FRM. This means in

major urban contributions, for example, defence standards are maintained as the climate changes, whereas in more rural areas that are typically protected by lower present-day standards they reduce.

- **Current Objectives+: Leading to an Enhanced Whole System adaptation (EWS):** The *'current objectives+'* scenario goes beyond the current implementation of policy to represent an 'Enhanced Whole System' (EWS) approach to adaptation. In this case, investment in flood defence increases (including in more socially disadvantaged neighbourhoods) and land use planning policy is more successful in restricting development in the floodplain than currently achieved or anticipated. Awareness raising and a strengthening of building regulations and planning controls encourage greater receptor level resilience. Forecasting and warning systems develop with increased levels of sophistication, targeting those at risk more accurately than has been possible to date. Opportunities for more integrated planning and implementation are sought (*e.g.,* Ministry of Housing, Communities & Local Government - MHCLG, 2019, Welsh Government - WG, 2018) and, together with increasing momentum towards a 'net zero' emissions future, nature-based solutions are increasingly promoted, and greater resilience delivered.

6.6.1 Individual Adaptation Measures

Nine individual Adaptation Measures (AMs) that address the three components of risk (set out earlier in Chapter 4) are considered. Three levels of implementation are considered for each:

- **Lower-level ambition.** assuming the measure is implemented less effectively than in the recent past (used to create the Reduced Whole System (RWS) adaptation future).
- **Current level of ambition.** assuming the measure continues to be implemented as effectively as experienced in the recent past (used to create the Current Level of Adaptation (CLA) future).
- **Higher level of ambition.** assuming the measure is implemented more effectively than in the recent past (used to create the 'Enhanced Whole System (EWS) adaptation future).

The FFE enables the implementation and effectiveness of each AM to be differentiated by its context. Existing and new flood defences standards vary by the type of settlement they protect; the effectiveness of natural flood management reflects the scale of the opportunity to implement such measures within the catchment; urban drainage capacity can be varied by wastewater company; spatial planning by local authority; and the uptake of property level resilience measures, the ability to respond to flood warning and access to affordable insurance at Census Calculation Area (CCA) scale.

The settings used for each AM under each level of ambition are summarised in Table 6-7.

Table 6-7 Summary of individual adaptation measures

	Defences	Shoreline management	Catchment management	Urban management	Spatial planning	Property flood resilience (PFR)	Forecasting and warning	Insurance
Reduced Whole System	Protection standards fail to keep pace with climate change and reduce from present-day to 75% of their existing standards. Where present-day standards are very low (<1in25years) they reduce further. Where present-day standards are very high (>1in500 years) these are maintained.	Shoreline management policies remain largely unchanged from today with little active realignment of the coast.	NFM plays a more limited role than it does today as other land use priorities take precedence (such as pressures on food security). NFM potential is assumed to be constrained, with only 10% BMV Class 2 and 15% of BMV Class 3 contributing to NFM (where potential exits) by the 2080s.	Retrofitting of SuDS in existing urban areas stops and implementation in new development drops to ~30% (around half the rate of take up today). Conventional drainage capacities also reduce (to 10mm/hr).	The proportion of new development built in the fluvial and coastal floodplains increases (to an average of 9% in Scotland and 15% elsewhere). Development in the most socially vulnerable neighbourhoods remains 1.5 percentage points higher than elsewhere.	*Existing households:* Take-up is limited (reaching only 5% by 2080s). *New development:* Planning regulations are less effective, and only 50% are flood resilient. Limited take-up by non-residential properties and infrastructure providers outside of fluvial and coastal floodplains exposed to frequent flooding continues. Take-up in significant risk areas and amongst Cat A providers continues to grow but slowly – reaching ~30% by 2080s.	Differences are relatively narrow (compared to other measures) across the adaptation portfolios. This reflects the significant advances over the past 50 years and the more evolutionary advances expected in the future (reflects behavioural constraints as well as technological ones). By the 2080s, 77-87% of properties in coastal areas successfully receiving and acting upon a warning compared to 53-60% in fluvial areas and 13-15% in surface water flood-prone areas by 2080s under the three portfolios. In the most socially vulnerable neighbourhoods, the effectiveness of warning is much less – around half as effective in coastal and surface water areas. The differential is more marked in fluvial areas, around a fifth as effective. The reduction in damage given action is assumed to be 14% in all cases. Although regional differences exist, common values are applied across the UK. In Scotland take-up is less than in England. This may be because in Scotland the process is based on 'opting in' and in England is based on 'opting out'.	After Flood Re ends in 2039 insurance penetration reduces significantly from that of today – dropping from around 75% today to 53% from the 2050s. In the most socially vulnerable neighbourhoods, the reduction is from ~40% today to ~30% from the 2050s.
Current Level of Adaptation	Protection standards continue to be maintained where the present-day standards are high (typically more than 1in75 years). Elsewhere standards fall with climate change to 75% of their present-day value before action is taken. Where present-day standards are >1in100 years these are maintained.	Some realignment takes place through the implementation of 'no active intervention' and 'realignment' policies. This helps limit the impact of sea level rise on coastal overtopping (although the impact on defence standards is small).	In the short term NFM implementation remains limited to pilot locations and a small number of frontrunner locations. These provide evidence for further projects, but implementation for the full potential of NFM remains limited (with 20% BMV 2 and 30% BMV 3 contributing by the 2080s)	Retrofitting of SuDS continues in a limited way (~5% by area). The incorporation of SuDS in new developments remains high in Wales and Scotland (~70%) with less take-up in England and Northern Ireland (~50%). Conventional drainage capacities are maintained (at 12mm/hr).	The proportion of new development built in the fluvial and coastal floodplains continues as today (*i.e.,* an average of 6% in Scotland and 12% elsewhere and slightly higher in the most socially vulnerable neighbourhoods).	*Existing households:* Take-up continues to grow slowly reaching 20% by 2080s). *New development:* Planning regulations are effective in ensuring 80% are flood resilient. Take-up by non-residential properties and infrastructure providers continues to grow reaching 50% by 2080s in fluvial and coastal floodplains exposed to frequent flooding. Take-up amongst Cat A providers continues to grow, to around 50% by 2080s.		Transitional arrangements are assumed to enable present-day penetration to continue in both adaptation portfolios. (~76% of properties exposed to flooding more frequently than 1in75 years assumed to have insurance). In the socially vulnerable locations penetration is assumed to remain around 40%.
Enhanced Whole System	In addition to the actions taken above, protection standards are raised to a minimum of 1in100 years in urban conurbations (major and minor). This includes building defences in currently undefended areas. A 1in75 year standard is maintained in urban and rural towns with highest standards of protection today.	Polices are largely implemented as set out within SMPs – including transitions to no active intervention and managed realignment; although the impact on standards remains limited.	The success of the pilot studies, a stronger evidence base, changes in land stewardship payment schemes and demand for NFM co-benefits (including in support of diversity and 'net zero' targets) drive an increase in the uptake of NFM potential (with 30% BMV 2 and 50% BMV 3 contributing by the 2080s).	The use of SuDS in both new and existing developments increases (to around 80% and 30% respectively by the 2080s – slightly more in Scotland and Wales). Conventional drainage capacities also increase in major urban areas (to 15mm/hr).	The proportion of new development built in the fluvial and coastal floodplains decreases (to an average of 3% in Scotland and 9% elsewhere by the 2050s). Differential development rates in socially vulnerable neighbourhoods also comes to end.	Compared to CLA, there is an increase in take-up amongst existing residential properties resulting in 95% of all new developments including flood resilient measures. Take-up in by non-residential properties and Cat A providers in areas at significant risk continues to grow but slowly – reaching ~60% by 2080s. In surface water flood-prone areas take up by Cat A providers increases to ~40%.		

Source: Sayers et al., 2020a

6.7 HOW FUTURE FLOOD RISKS MAY CHANGE

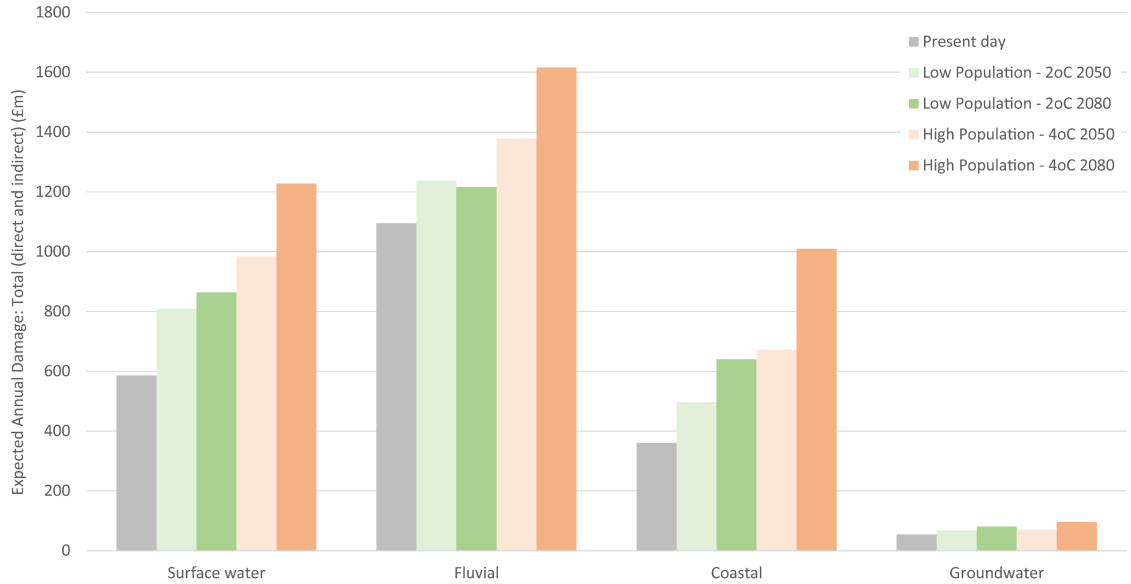
A summary overview of the most important findings from the analysis are presented below (and discussed in detail in Sayers *et al.,* 2020a).

6.7.1 How might flood risk change in the future assuming no change in approach?

Assuming a continuation of Current Levels of Adaptation, Expected Annual Damages (EAD, including direct economic damage to residential and non-residential properties and associated indirect damages) are set to increase from present-day levels. Under a 2°C future EAD rises from £2bn today to £2.7-3.0bn in the 2080s (depending upon associated population growth). Under a 4°C future risks rise to between £3.5-3.9bn.

6.7.2 What is the relative importance of different flood hazards on future flood risk?

Fluvial flood risk is dominant today when looking at the UK as a whole and remains so in the future; rising from an EAD of ~£1.1bn today to between ~£1.2bn (2°C low population growth) and ~£1.6bn 4°C high population growth) by the 2080s assuming a continuation of Current Levels of Adaptation. The increase in fluvial flood risk is proportionally less than for either coastal or surface water flooding. Surface water and coastal risks more than double under a 4°C high population growth future (surface water risks rising from ~£0.6bn to ~£1.2bn by the 2080s and coastal risks increasing from ~£0.4bn to ~£1.0bn) – Figure 6-13.



Source: Sayers et al., 2020a

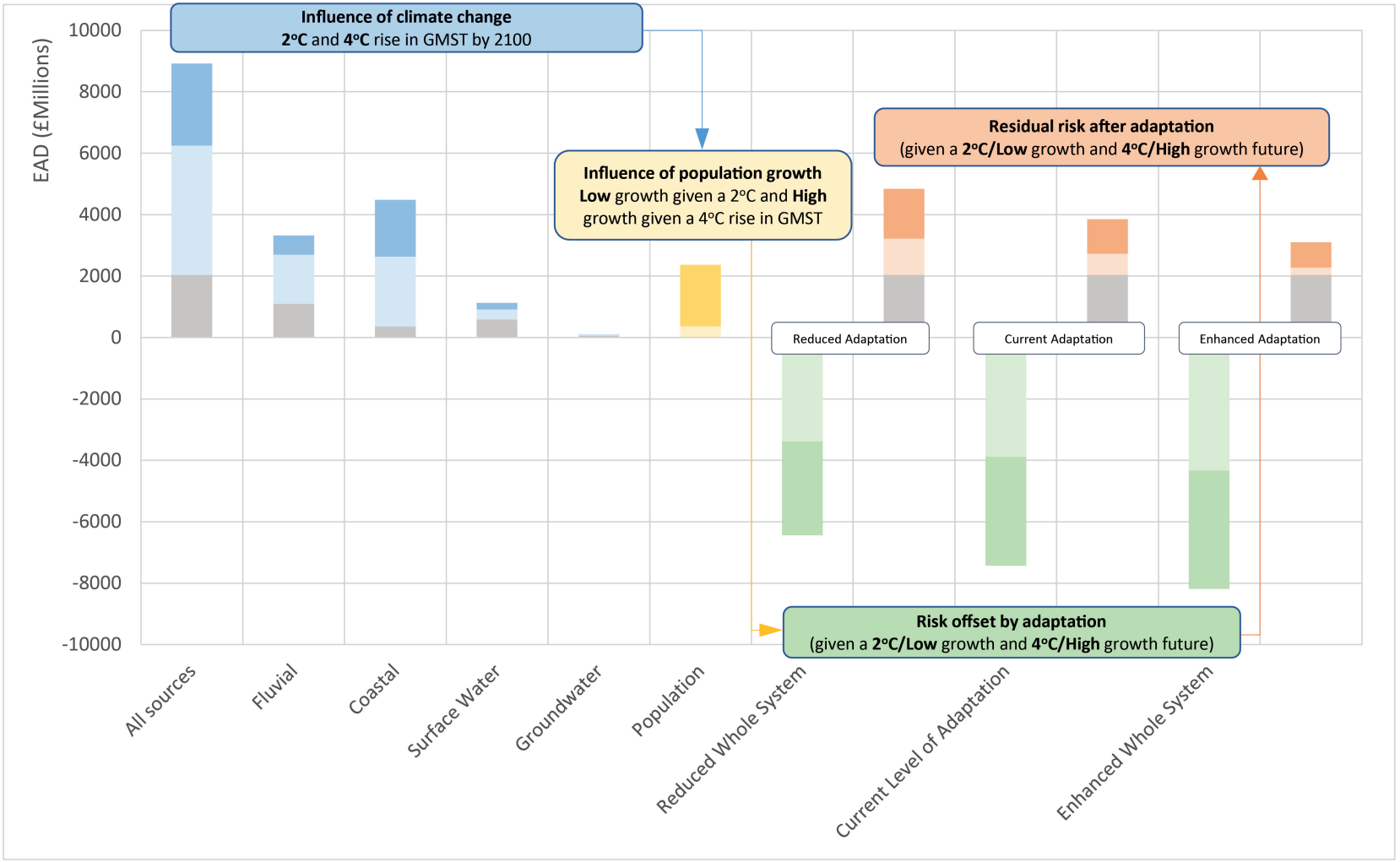
Figure 6-13 Expected Annual Damages (Total) – By Flood Source assuming a continuation of current levels of adaptation

6.7.3 What is the relative influence of climate change, population, and adaptation on future flood risk?

Climate change is the dominant influence in driving up future risk (increasing Expected Annual Damages EAD – direct and indirect – by £4.2bn under a 2°C future and £6.9bn under a 4°C future in the absence of any adaptation, Figure 6-14). The influence of climate change is greatest at the coast; especially when the rise in GMST exceeds 2°C, with EAD rising by a further 70% under a 4°C rise in GMST compared to 2°C. For comparison, the risks associated with all other flood sources increase by ~20% between a 2 and 4°C future. Assuming a low population growth the additional impact on risk is limited (although not insignificant, adding £364m to EAD), whereas a high population growth future has a much greater influence (adding ~£2.4bn to the EAD assuming a 4°C rise in GMST). By the 2080s the combination of a 4°C climate change and high population growth future drives an increase of ~£9.2bn EAD in the absence of adaptation. The future is therefore bleak in the absence of adaptation and mitigation.

All three adaptation portfolios limit this increase. A continuation of Current Levels of Adaptation offsets ~£7.4bn of Expected Annual Damages in the 2080s (under a 4°C high population growth future) resulting in a net increase in risk of ~£1.8bn. An Enhanced Whole System (EWS) approach to adaptation offsets ~£8.2bn of EAD (total) in the same scenario; limiting the net increase in risk to ~£1.1bn. This reflects the significance of the challenge of maintain present day flood risk levels through adaptation alone – but mitigation and transformation changes (including perhaps relocation) will be important. A Reduced Whole System (RWS) approach offsets much less (~£6.4bn); consequently, the net increase in risk is much greater (~£2.8bn)

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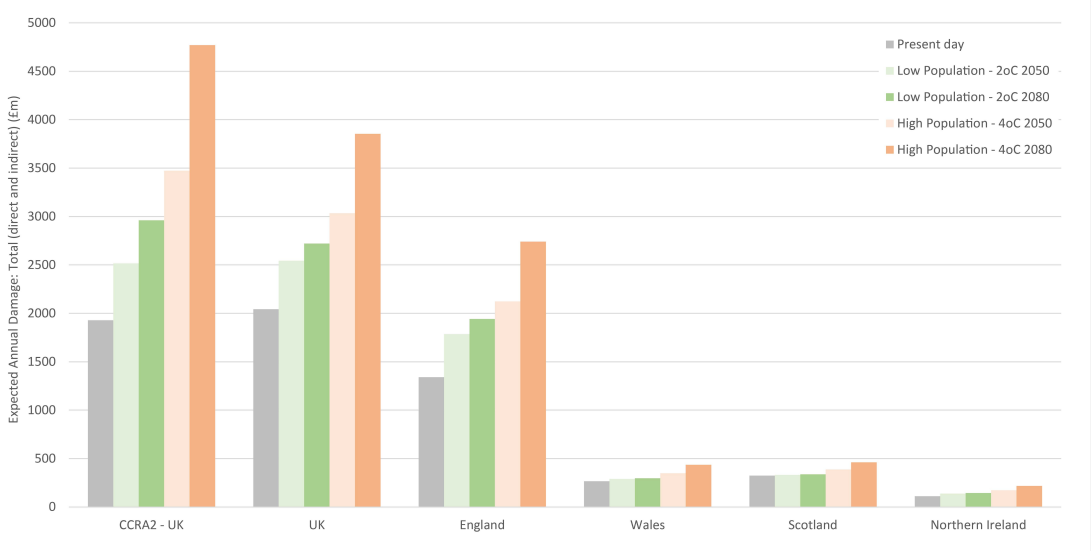


Blue *– refers to the increase risk due to each source assuming no further adaptation;* ***Yellow*** *– refers to the increase in risk due to population growth;* ***Green*** *– refers to the benefit of adaptation and* ***Orange*** *the residual risk; Positive values represent present-day and the increase in that risk because of climate change, population growth and adaptation (individually and collectively) by the 2080s; Negative values show the reduction in risk achieved by applying the three adaptation portfolios.*
Source: Sayers et al., 2020a, based on results from the Future Flood Explorer

Figure 6-14 Drivers of changes in risk by 2080s – Expected Annual Damage (total)

6.7.4 How might the spatial pattern of flood risk change?

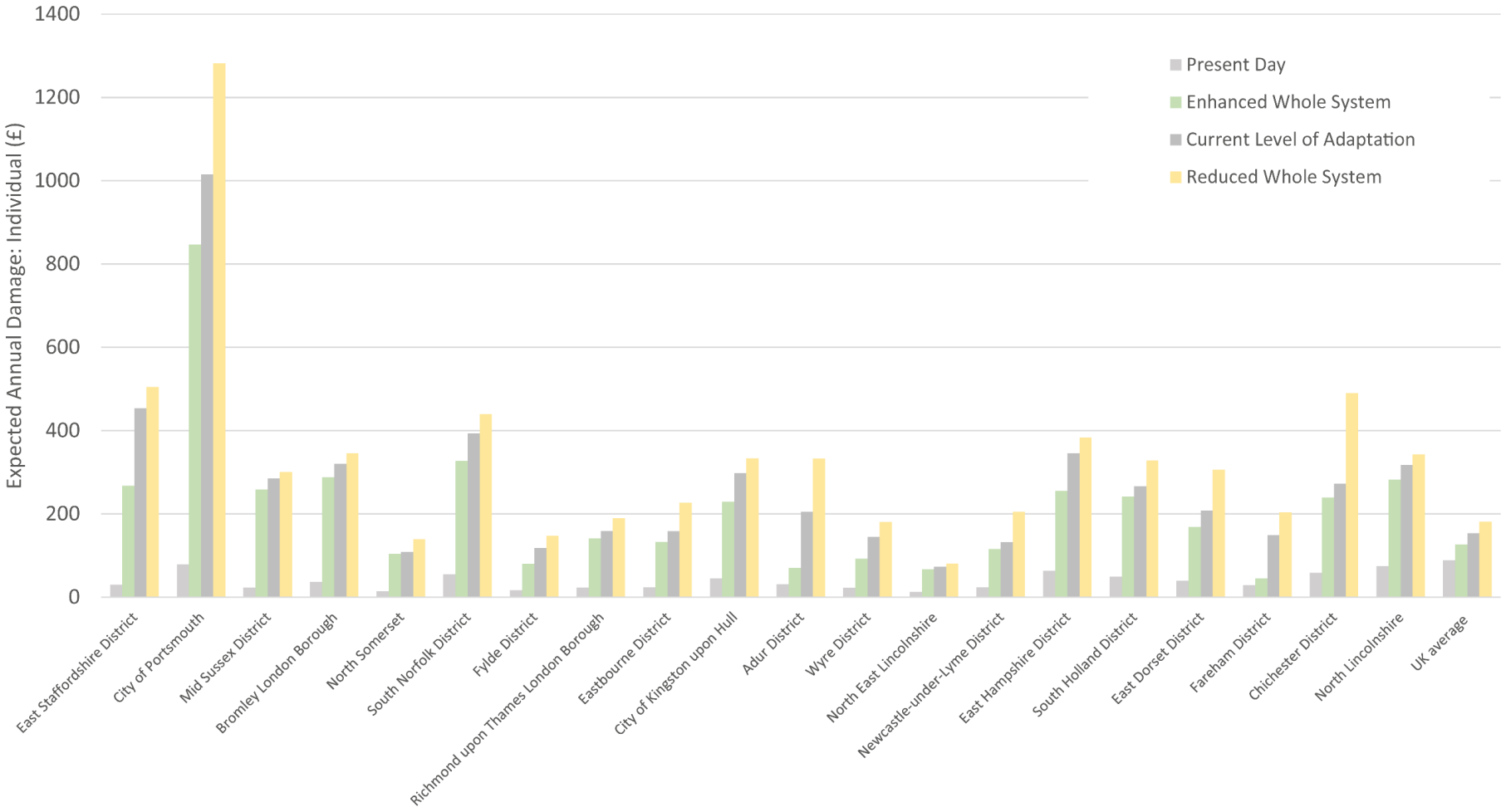
Flood risk varies across the UK today and this variation persists into the future. Most of the present-day and future flood risk is in England (Figure 6-15). Under a 4°C (high population) future the rapid rise in risk from today to the 2050s continues through to the 2080s. This is particularly the case in England where, for example, under a 4°C (High population) EAD (total) increases from £1.3bn today to £2.2bn by the 2050s and reaches £3.0bn by 2080s. When risks are normalised by the flood exposed population (*i.e.,* the average Expected Annual Damage per individual, EADi) a different picture of the distribution of risk emerges. Those living in the flood-prone areas in Northern Ireland, Scotland, and Wales, on average, are exposed to a higher Expected Annual Damage than those living in England (Northern Ireland £506, Scotland £450, Wales £316, and England £109 EAD per person by the 2080s under a 4°C high population growth future).



Source: Sayers et al., 2020a

Figure 6-15 CLA – Expected Annual Damages (Total) – By Country

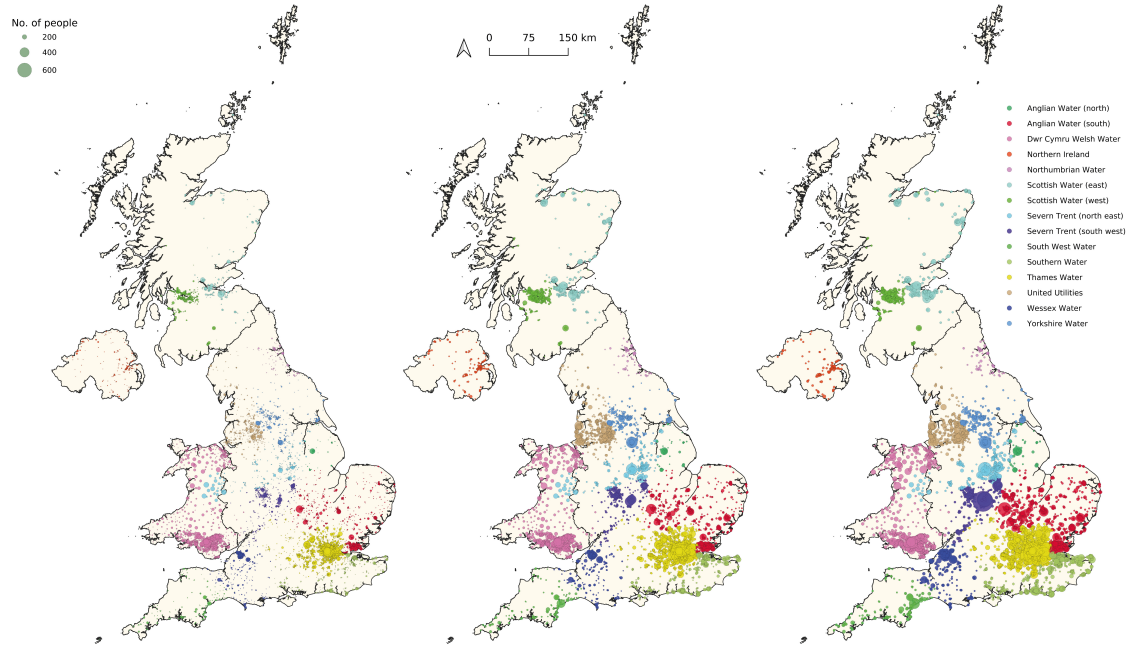
Many of the Local Authorities with the largest future risk are in coastal areas, including the top two of Hull and the City of Portsmouth (Figure 6-16). In some locations the influence of climate change on flood risk is much less, including fluvial authorities experiencing decreased peak flows.



Source: Sayers et al., 2020a

Figure 6-16 Local Authorities with the largest Expected Annual Damage (total) by Local Authority in 2080s (ranked)

The influence of climate change on exposure to surface water flooding also varies across the UK (Figure 6-17). This changing pattern of surface water flooding, assuming a continuation of Current Levels of Adaptation, is illustrated below.



Left: Present-day. Middle: 4°C High Population Growth 2050s Right: 4°C High Population Growth 2080s. Note: Only the 20% of neighbourhoods with the highest exposure shown. Source: Sayers et al., 2020a

Figure 6-17 Number of people exposed to surface water flooding more frequently than 1in30 years (on average)

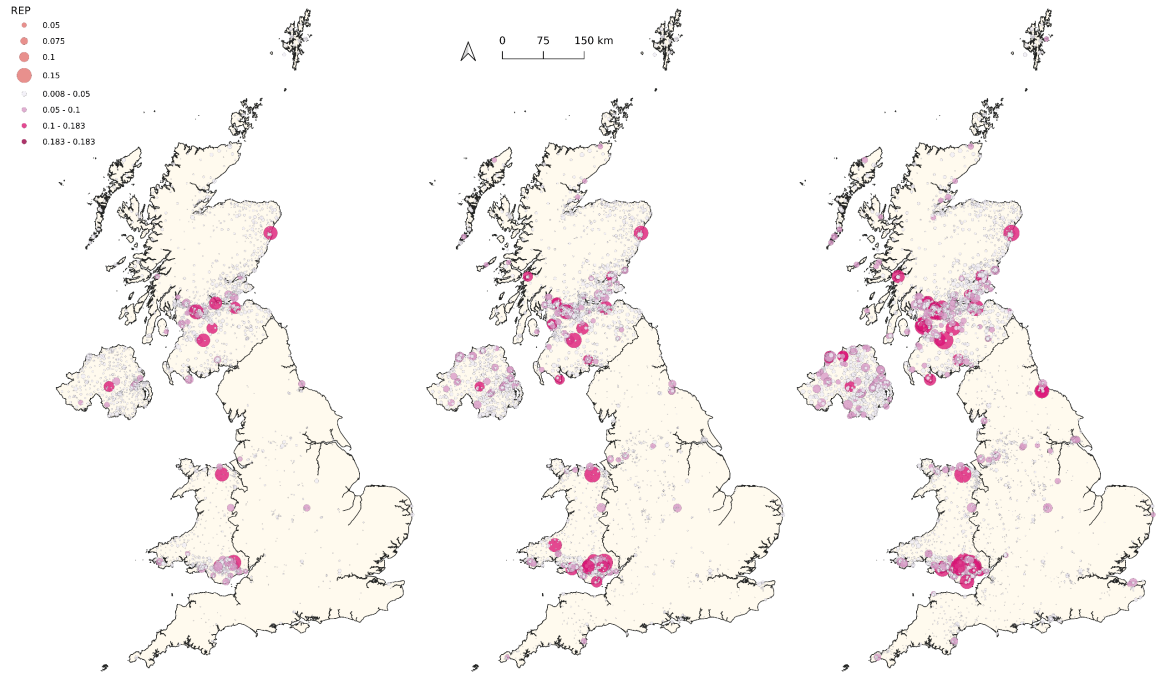
6.7.5 How might the socio-economic distribution of flood risk change?

In many rural towns and villages and smaller urban cities and towns the most socially vulnerable[23] are, on average, exposed to greater flood risk. In *rural towns and fringes in sparse setting* the present-day Expected Annual Damage is ~£150 per person (for those living in a flood-prone area) but almost double this (~£280 per person) in the most socially vulnerable neighbourhoods (on average). In the future the most socially vulnerable, particularly in *urban cities and towns* experience disproportional increases in risk with the EAD per person increasing by a factor of 2.5 on average but by 2.8 in the most socially vulnerable neighbourhoods. Although similar values, the EAD per person experienced by the most vulnerability is higher than others (rather than lower); this difference becomes more significant when income and access to insurance is included (returned to below). When considered at an aggregated national scale, the most socially vulnerable experience flood

[23] *As defined by the 20% most socially vulnerable neighbourhoods according to the Neighbourhood Flood Vulnerability Index, NFVI.*

disadvantage in Northern Ireland, Wales, and Scotland; this is the case today and in the future.

When considered through the lens of Relative Economic Pain (*i.e.,* the ratio of uninsured loss to income) the differential between the risk faced by the more and less socially vulnerable is significant (Figure 6-18). This reflects in part lower income, but also levels of insurance take-up; an issue that will need to be addressed in the transition planning as Flood Re comes to an end in 2039.



Left: Present-day; Middle: 4°C High Population Growth 2050s; Right: 4°C High Population Growth 2080s. REP = Relative Economic pain (the ratio of uninsured loss to income) – Scaled by size and colour. Source: Sayers et al., 2020a

Figure 6-18 Relative Economic Pain (REP) assuming a continuation of Current Level of Adaptation: All sources of flooding

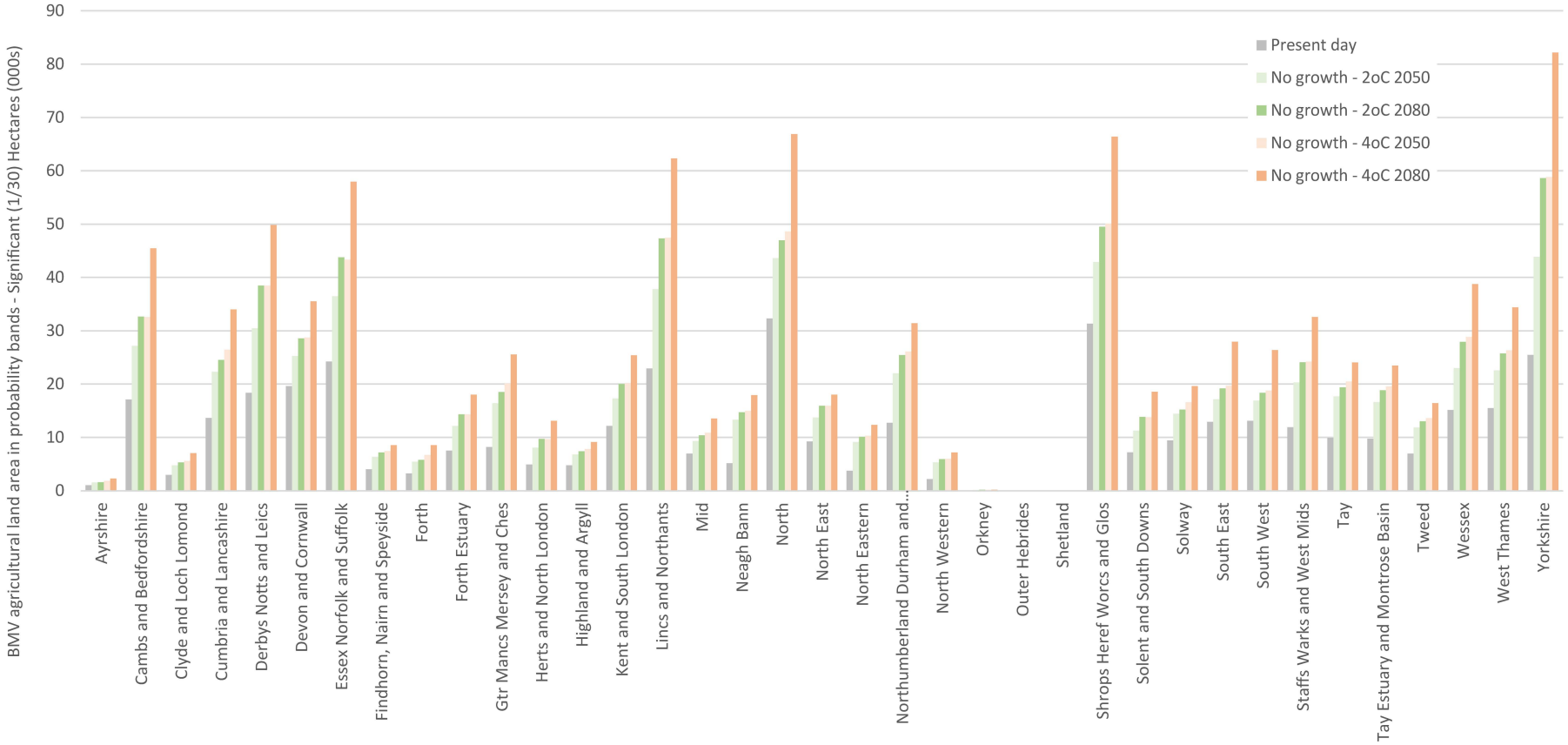
6.7.6 How might the flooding of agriculture and habitats change?

The changing nature of habitats and the impact of climate change on agricultural damage responds to multiple variables not explicitly considered here (changes in the seasonality, salinity, chosen crops, local land management practice *etc.*). There is an increase in exposure of agricultural land (Best and Most Versatile land) to frequent flooding (30-year return period or more frequent). The largest increases are projected in the agricultural heartlands of Lancashire and Northamptonshire as well as Bedfordshire, Cambridgeshire, and Yorkshire. Flooding may also impact agriculture in more marginal locations that have little (or no) Best and Most Versatile land (Figure 6-19). The impact on these more marginal lands (and associated activities and communities) is not considered here.

6.7.7 How might climate change impact infrastructure?

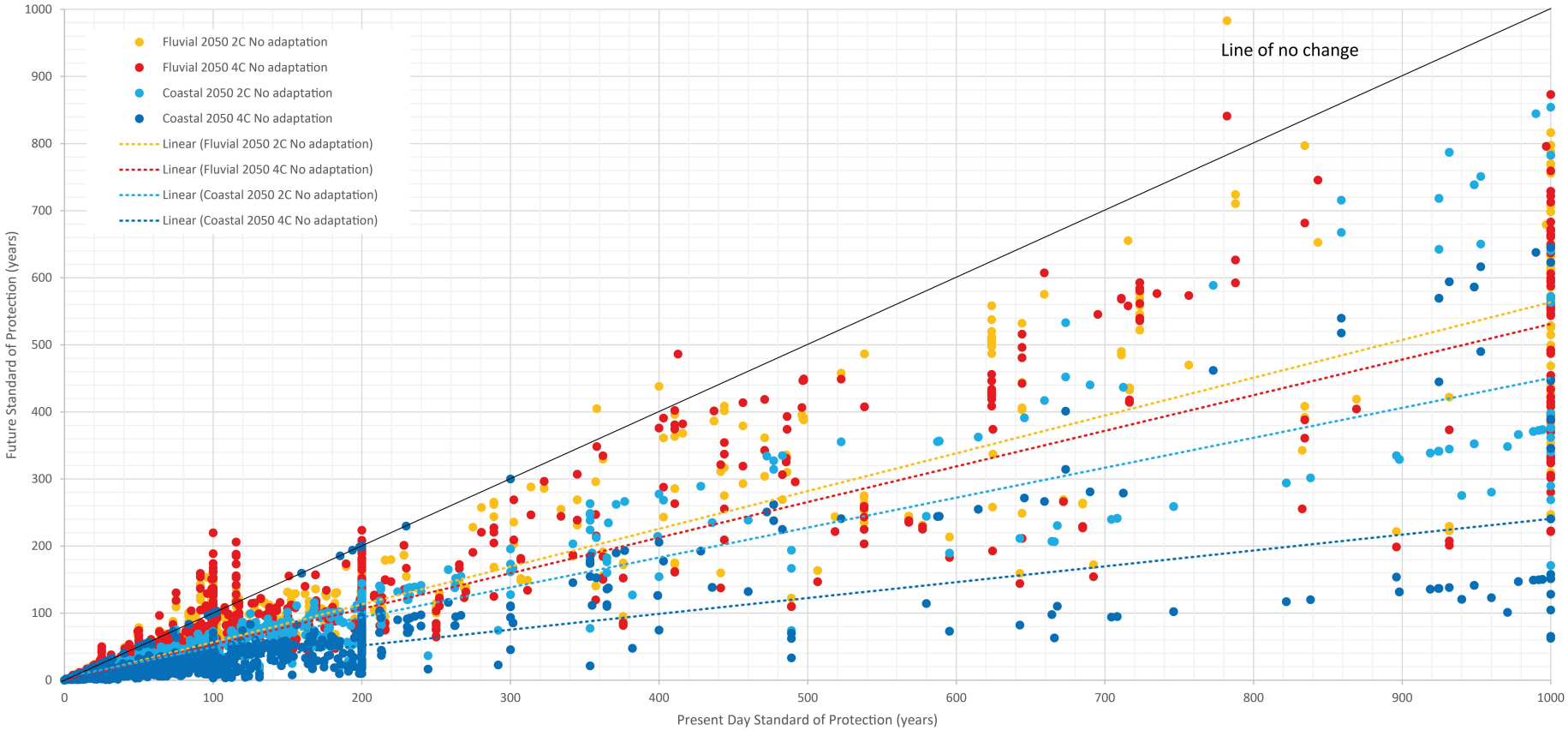
A significant increase in exposure of both Category A (including water treatment, energy, and communication infrastructure sites) and Category B (including railway stations, landfill sites, hospitals and blue light services, care homes, GP surgeries, and schools) is projected across the UK. The results highlight concentration of infrastructure risks in many metropolitan regions (such as Greater Manchester) and significant number of Category A infrastructure sites exposed to frequent flooding. These results are likely to be an underestimate (as no effort is made to include the growth in infrastructure provision that is likely to accompany population growth or explicit consideration of the impact of critical infrastructure network failures).

Climate change also impacts the standard of protection afforded by flood defences (Figure 6-20). In the absence of any further adaptation the reduction in the standard of protection provided is significant. This reduction is most marked at the coast (see below). The impact of climate change on fluvial defences is more mixed with some areas experiencing an effective increase the standard of protection as peak flood flows reduce (reflecting the complex spatial pattern of future changes in peaks flows).



By CCRA Region (short names used on chart for reasons of space). Source: Sayers et al., 2020a

Figure 6-19 Changing exposure of Best and Most Versatile Land to frequent flooding (1in30 years or more frequent): Assuming a continuation of Current Level of Adaptation



x-axis represents the present-day representative standard of protection (for each fluvial and coastal neighbourhood). y-axis presents the future standard by the 2050s under a 2 and 4°C climate future.

Figure 6-20 Impact of climate change on defence standards: 2050s assuming no adaptation

6.7.8 What types of risks appear to be the hardest to manage?

Flood risk responds to climate change and population growth but also adaptation. But there are more subtle aspects to the changes. In some Local Authorities the increase in risk is more sensitive to the adaptation choice than in others, with opportunities for adaptation in many smaller Local Authorities and islands more limited (*e.g.,* due to the lack of available land outside of the floodplain for new development). Some larger Local Authorities also have little choice but to develop on the floodplain, particularly many estuary and coastal towns and cities such as Hull.

Under a 4°C high population growth future, coastal flood risks increase under all three adaptation approaches considered here, including the Enhanced Whole System approach (that continues to see coastal flood risks increase from an EAD of £361m today to £793m by the 2080s). This is a particularly important finding given the greater risk to life and livelihoods often associated with coastal than for other sources of flooding. This also reinforces the difficulty of managing coastal risks as sea levels rise through flood risk management measures alone. Long-term integrated development planning will be needed to support communities if coastal risks are to be managed in the context of 4°C future.

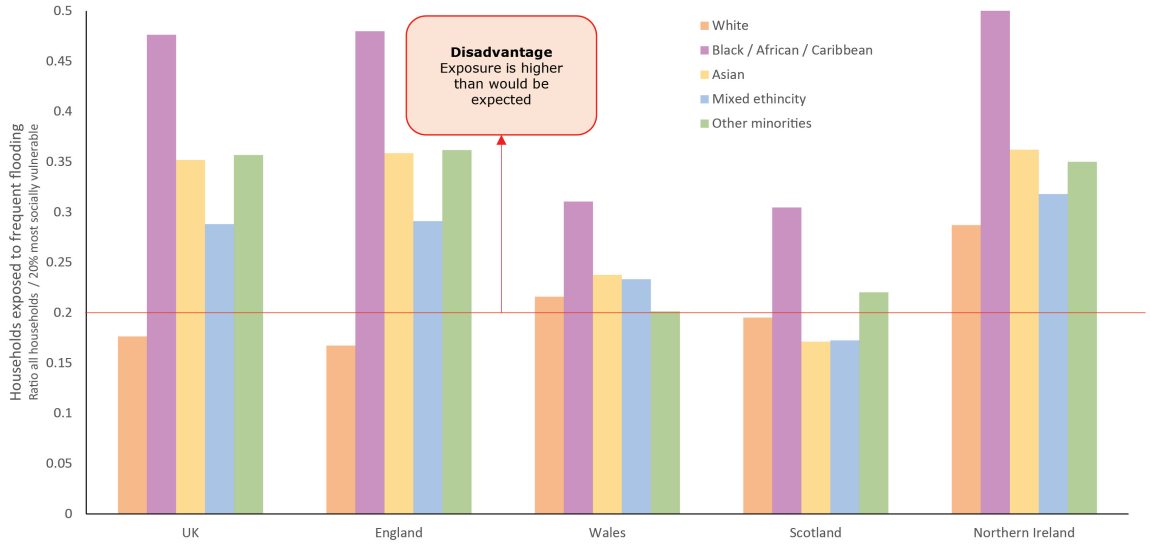
Surface water flood risks also increase rapidly (rising from £587m[24] today to £1.1bn by the 2080s under 4°C high population growth future associated with an Enhanced Whole System approach to adaptation). Increasing the capacity of conventional drainage infrastructure and retrofitting Sustainable Urban Drainage Systems (SuDS) in existing neighbourhoods can be costly and presents multiple challenges. Addressing these challenges will require integrated management actions across multiple organisations.

6.7.9 Disproportionate flood exposure amongst ethnic minority groups

Sayers *et al.,* 2020a extends the assessment of geographic flood disadvantage and systemic flood disadvantage to consider flood disadvantage experienced by the most socially vulnerable and within Black and Other Minority Ethnic Groups. The analysis uses the Future Flood Explorer together with additional Census and income distributional data to explore the present and future flood risk. The analysis highlights the most socially vulnerable (defined as the 20% most vulnerable defined using the Neighbourhood Flood Vulnerability Index, NFVI Sayers *et al.,* 2017c) experience disadvantages, with the most significant disadvantage experienced by socially vulnerable Black, Africa and Caribbean Groups (Figure 6-21). In response, a central recommendation advance is to better address disadvantage amongst the most socially vulnerable and ethnic minorities more directly within flood risk management decision-making, including public investments, grant processes and insurance. This finding echoes the insights from the analysis for the JRF in 2017 (Sayers *et al.,* 2017c) that suggested

[24] *The assessment of present-day surface water flood risks is less maturity that either coastal or fluvial flooding and hence less certain.*

a lack of capacity within the most socially vulnerable communities restricts access to investment and may act as a brake on reducing flood risk and redevelopment (*ibid*). Joined-up development pathways offer opportunities to stimulate local incomes and reduce flood disadvantage.

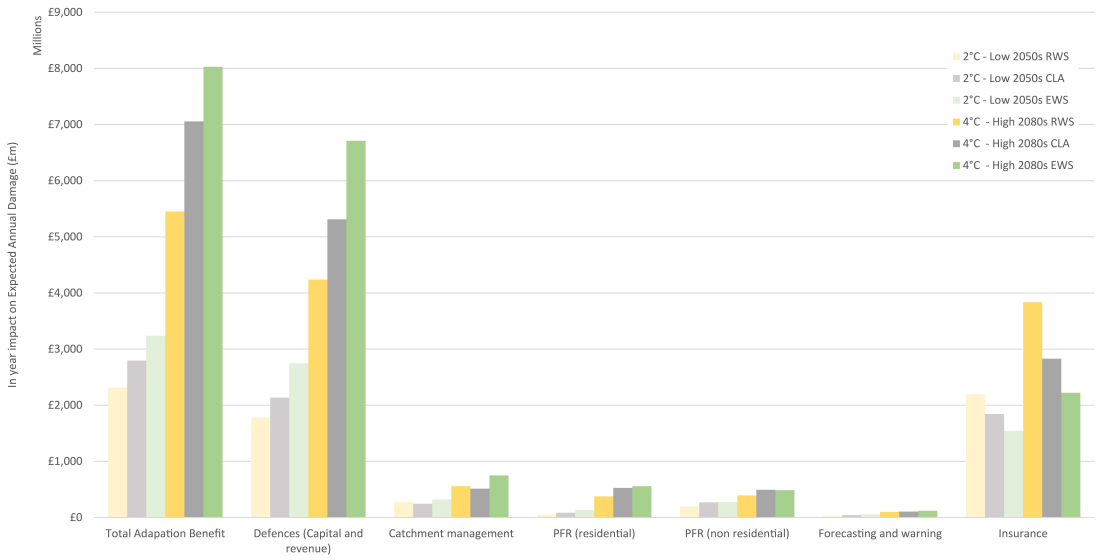


Black, Asian and Minority Ethnicities are more likely to be exposed to frequent flooding (surface water, fluvial and coastal). The disadvantage is most significant amongst Black ethnic groups. Source: Sayers et al., 2020c

Figure 6-21 Flood disadvantage – A comparison across ethnicity

6.7.10 What action is needed?

Under all adaptation futures considered here risks rise (see earlier). The increase in risk is least under an Enhanced Whole System to adaptation. Across all alternative portfolios conventional flood defences (both capital and revenue investment) remain the most important management measure (Figure 6-22). Catchment management (natural flood management), property flood resilience (both residential and non-residential take-up) are also significant in reducing EAD (reflecting their ability to contribute to the management of more frequently occurring events). Flood forecasting and warning provide an underpinning response across all portfolios (but the full benefits associated with saving lives and minimising wider disruption are not included here). Effective spatial planning remains the only measure of avoiding increases in flood exposure due to development. Making greater space for water, through avoiding developing in the functional floodplain, provides a central response where this is possible. Developing our understanding of the performance of more innovative approaches (such as catchment management) will be important in realising their potential in practice. The residual risk covered by insurance reduces (despite wider take-up) with more ambitious adaptation portfolios, reflecting the reduction in risk due to other measures.



Impact of adaptation expressed through a reduction in Expected Annual Damages compared to no adaptation. Source: Sayers et al., 2020a

Figure 6-22 Adaptation benefit: Disaggregated contributions

Optimisation of investment in managing surface flood risk

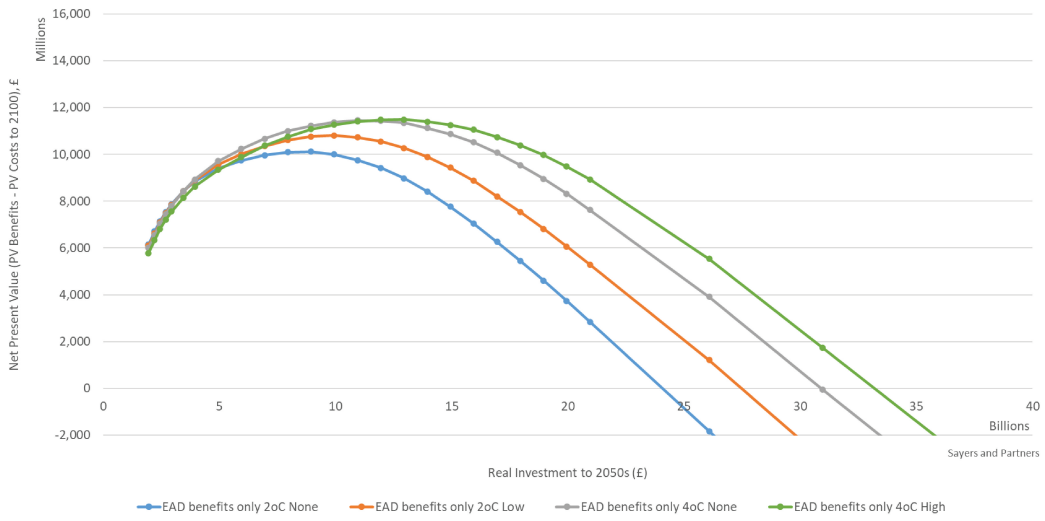
Further analysis of adaptation costs associated with surface water flooding provides a national scale optimisation of the investment in managing surface water flood risks through to the 2050s (Sayers *et al.,* 2022c). This analysis, completed for the National Infrastructure Commission, England considers a range of individual adaptation measures, namely:

- **Source measures.** To slow the flow: Adaptation measures that influence the source of flood waters act to slow the production of run-off during a storm (by slowing the flow through infiltration or storage, or both). This, in turn, reduces the flood hazard. SuDS are considered here as the primary 'source' adaptation. There are many SuDS options that can be applied at a range of scales. For the purposes of the assessment SuDS measures are grouped into three categories:
    - New build
    - Retrofit infiltration.
    - Retrofit storage.
- **Below ground pathway measures.** To convey the flow: Adaptation measures that convey run-off away from an area also influence the flood hazard. These measures are predominantly represented by the piped drainage network.
- **Exceedance measures.** To manage residual flood water: Surface water flooding occurs *en route* to the infrastructure put in place to manage it and the peak intensity of a storm can often overwhelm even well-designed infrastructure (Fratini *et al.,* 2012). Designing for exceedance (when the collective capacity of the source and below ground pathway measures are exceeded) is central to sound management of the surface water (Digman *et al.,* 2014). This includes, for example, taking measures to guide surface water flows to

minimise impacts (referred to here as surface pathways) and/or to take measures to reduce impacts given a receptor is flooded (*e.g.,* property level measures).

The cost of implementing each adaptation measure (*e.g.,* piped drainage, new build SuDS *etc.*) is assessed using a series of top-down cost functions based on the estimate of the properties protected (as described in Sayers *et al.,* 2022c). This enables the cost of each adaptation to be rapidly, but credibly, assessed in the FFE. Decision rules then used allocate a given scale of national investment, maximising the return on that investment by picking the best combination of measures at any given location focusing on benefits derived from avoided property related flood damage.

The return on investment in adaptation (as expressed through Net Present Value, NPV) rises sharply up to a real investment (*i.e.,* not discounted) through to the 2050s to around ~£5bn regardless of the climate and population future (Figure 6-23). The real investment yielding maximum return (defined by the peak NPV) does vary with the future scenarios, ranging from ~£9bn assuming a 2°C, no population change future (slightly higher than a continuation of present-day expenditure, equivalent to a spend of ~£8.2bn), increasing to ~£13bn assuming a 4°C, high population growth future. The peak of NPV return is much flatter in the case of the 4°C high population growth, with limited reduction in NPV as spends increase to ~£20bn. Although initial research with significant opportunity to be extended to all sources of flooding and all aspects of adaptation has been used by the NIC to make the case for increased investment in adaptation.



Assessment presented based on economic damage reduction only. Source: Sayers et al., 2022c

Figure 6-23 National return on investment – Maximised Net Present Value

6.8 CONCLUSIONS

The innovative analysis provided by the Future Flood Explorer enables a consistent UK-wide assessment of future flood risk taking account the four sources of flooding, population growth and adaptation. The FFE has been shown to be a practical and credible approach that is fast to run enabling multiple futures to be explored. The analysis presented here uses the latest climate projections from UKCP18, population projections from Cambridge Econometrics and the detailed consideration of alternative adaptation policy portfolios. The analysis brings together high-resolution changes in peak fluvial flows, sea level rise and intense rainfall together with alternative portfolios of adaptation, providing a step change in the UK's national understanding of future flood risk and the role of alternative adaptation measures as part of that portfolio.

The highlights from the analysis are summarised below.

Changing risk

Climate change is the dominant influence in driving up future risk (increasing Expected Annual Damages by £4.2bn under a 2°C future and £6.9bn under a 4°C future in the absence of any adaptation). The influence of climate change is greatest at the coast; especially when the rise in GMST exceeds 2°C (notionally 0.4m of Sea Level Rise by 2080s), with EAD rising by a further 70% under a 4°C rise in GMST (notionally 0.8m of Sea Level Rise by 2080s) compared to 2°C. For comparison, the risks associated with all other flood sources increase by ~20% between a 2 and 4°C future. Assuming a low population growth the additional impact on risk is limited (although not insignificant, adding £364m to EAD), whereas a high population growth future has a much greater influence (adding ~£2.4bn to the EAD assuming a 4°C rise in GMST). By the 2080s the combination of a 4°C climate change and high population growth future drives an increase of ~£9.2bn EAD in the absence of adaptation. The future is therefore bleak in the absence of adaptation and mitigation.

Adaptation limits the increase in risk: Assuming a continuation of a Current Levels of Adaptation, ~£7.4bn of Expected Annual Damages is offset by the 2080s (under a 4°C high population growth future) resulting in a net increase in risk of ~£1.8bn. To maintain risks at present day levels given a 4°C future, an Enhanced Whole System approach to adaptation is needed; an approach in which conventional flood defences are complemented by natural flood management, property flood resilience, better flood forecasting and warning and most importantly effective spatial planning (that where possible make greater space for water).

Sources of flood risk

Fluvial flooding contributes the greatest to economic damages now and in the future but the relative contribution of both surface water and coastal flooding increases. Coastal and surface water risks both increase more markedly with climate change than fluvial flooding, with coastal flood risk increasing most rapidly.

Risk for infrastructure and flood defences

Category A and B infrastructures see a large increase in exposure driven by surface water and fluvial and coastal flood sources. The reduction in the standard of protection afforded by defences, in the absence of adaptation, is most marked at the coast. In fluvial settings most defences experience a reduction in standard, but in some areas climate change acts to increase the effective standard provided. This reflects the complex spatial pattern of future changes in peaks flows, that in some case (particularly under the 4°C future) reduce.

Risk for habitats and agriculture

The changing nature of habitats and the impact of climate change on agricultural damage responds to multiple variables not explicitly considered here (changes in the seasonality, salinity, chosen crops, local land management practice *etc.*). There is an increase in exposure of agricultural land (Best and Most Versatile land) to frequent flooding (1in30 years return period or more frequent). The largest increases are projected in the agricultural heartlands of Lancashire and Northamptonshire as well as Bedfordshire, Cambridgeshire, and Yorkshire. Flooding may also impact agriculture in more marginal locations that have little (or no) Best and Most Versatile land. The impact on these more marginal lands (and associated activities and communities) is not considered here.

Systemic flood disadvantage

The most socially vulnerable experience disproportionate flood risks today and in some settings their disadvantage increases in the future, including ethic minority groups (with the greatest disadvantage experienced by Black groups). Addressing this issue presents significant adaptation challenge but will be central to 'levelling up' the flood management response and 'levelling down' flood risks across the UK. Preferential weighing within investment approaches to flood risk management will continue be necessary (such as within the Partnership Funding rules used by Defra) but may not be sufficient. To be successful, joined-up investment in economic development and flood risk management will be required. When considered through the lens of Relative Economic Pain (returned to later in more detail in Chapter 7) the difference between the risk faced by the more and less socially vulnerable is significant. This reflects in part low-income levels, but also levels of insurance take-up; an issue that will need to be address in the transition planning for Flood Re.

A strong case for an enhanced approach to adaptation

By adopting an Enhanced Whole System approach to adaptation, flood risks are projected to change:

- ***Increase in risks are more limited.*** With an EWS approach to adaptation, increases in future flood risks are significantly reduced when compared to continuing the Current Level of Adaptation (CLA); Expected Annual Damages (direct and indirect) rise to £3.1bn by the 2080s under a 4°C high population growth future. This is £0.8bn less than under the CLA assumption.

- ***Systemic disadvantage is reduced.*** An adaptation portfolio of enhanced responses reduces risk in both rural and urban settings, including for the most socially vulnerable. This is most notable in smaller *urban cities and towns* with the rise in Expected Annual Damages per person lessened from £189 (under an CLA approach) to £162 by the 2080s in a 4°C high population growth future.

Under all adaptation portfolios considered here, including this enhanced approach, risks rise under a 2 and 4°C climate future. To maintain present-day risk levels constant to the end of the century, continued innovation in adaptation approaches will be required. This may include, alongside more investment in flood defences and local adaptation measures, greater effort towards making space for coastal and river dynamics within local and large-scale planning and development choices (including coastal realignment) as well as more integrated actions to address the increase in surface water flood risk.

Spatial planning approaches

The only adaptation response that acts to directly mitigate the influence of population growth is spatial planning; but spatial planning is always context specific. Many Local Authorities cannot avoid development in the floodplain whilst others have much more flexibility. The national planning framework needs to recognise this reality more directly and help locations that must build on the floodplain to do so in the context of a long-term plan to reduce risk and maintain safety. In some areas this may be by enforcing property level measures (for example in areas prone to fluvial flooding) but in coastal areas this is likely to mean a commitment to maintain appropriate long-term protection (together with an acceleration in cost that is likely to follow) or implement managed retreat (an adaptation option not explicitly considered here). Indecision today has the potential to lock-in risk for future generations.

Coastal and estuarine areas

Many estuary and coastal urban areas are unable to avoid floodplain development. Coupled with relative sea level rise (rSLR) this leads to a major increase in coastal flood risk (the fastest growing of all hazards). Exposure to flood risk can be managed by (i) avoiding locating new development in flood-prone areas (where this is possible), and/or (ii) realigning the urban landscape to reduce the number of people and properties that occupy floodable land (this could include localised land raising). Realignment at the coast presents significant challenge not explicitly addressed within the Climate Change Risk Assessment but is increasingly a significant aspect of the transformational adaptation that may be needed in some locations (*e.g.,* Sayers *et al.,* 2022b).

River catchments

Catchment management provides a meaningful contribution to economic risk reduction. Investment in catchment management provides significant returns when combined with conventional flood defences (as here) across the UK. Associated analysis suggests the Benefit to Cost Ratio (BCR) of the catchment management measures is strong across all portfolios (Sayers *et al.,* 2020a). The BCR reduces as the scale of adaptation ambition increases (as expected) but is always greater than ~20. This reflects the comparatively low cost and an

ability to meaningfully contribute to the management of more frequently occurring flood events that often drive Expected Annual Damages (based on economic benefits alone, noting that catchment management approaches also offer a wide range of co-benefits not considered here). The knowledge on the long-term performance of catchment management (and Natural Flood Management) is limited compared to the performance of conventional flood defences or planning measures. This lack of comparable knowledge should not be a barrier to appropriate use as a legitimate component of a portfolio response given the wide range of associated benefits but should be addressed.

A twin-track approach – adaptation and mitigation

The increase in risk is greatest under a 4°C future with the estimates of risk diverging significantly from a 2°C future from the 2050s (for example raising from ~£2bn today to ~£2.7bn under a 2°C rise by the 2050s and reaching ~£3.9bn under a 4°C rise by the 2080s assuming high population growth and a continuation of Current Level of Adaptation). This highlights the importance of a *'twin-track'* approach focused on both adaptation and mitigation (to reduce greenhouse gas emissions) if flood risk is to be managed. Given a 4°C climate future, transformational adaptation objectives may be required in some aspects of spatial and development planning, particularly at the coast (including relocation or much greater levels of investment not considered here) if present-day risk levels are to be maintained or reduced.

Future development suggestions

The analysis and approaches set out here are used to explore future issues in more detail in the following chapters that focus on a more in-depth national assessment of social vulnerability and the transformational adaptation challenge at the coast. The analysis also highlights the importance of future research to extend the analysis to more directly include costs to trade off the benefits and costs of alternative actions in more detail and across a full range of adaptations. This will include optimising actions not only in space and by adaptation portfolio, but also in time, considering when to invest as well as how. Further validation and application outside of the UK would also provide useful and exciting advances.

7

FLOOD VULNERABILITY, RISK, AND DISADVANTAGE IN THE UK

An understanding of the flood risk faced by the most socially vulnerable communities is a prerequisite to delivering a "fair" approach to prioritising flood risk management efforts within national policy and funding structures. Achieving this in practice raises three central questions. The first is social, what are the inherent characteristics of a community that influence its vulnerability to a flood should it occur; the second is geographic, where are the most socially vulnerable communities located and what is their current exposure to flooding; and the third is systemic; how the risk experienced by the most vulnerable communities compares to the risk experienced by the less vulnerable communities. The UK Future Flood Explorer (set out in the preceding chapter) is developed to identify those neighbourhoods at greatest disadvantage now and in the future and assesses the degree to which current flood risk management policy can be considered successful in delivering socially just outcomes. To support the quantitative comparison of the flood risks faced by more and less socially vulnerable three new indices are elaborated: the Neighbourhood Flood Vulnerability Index (NFVI), Relative Economic Pain (REP), and the Social Flood Risk Index (SFRI).

The analysis highlights three key messages. First, it reinforces and emphasises the importance of using social vulnerability to inform our understanding of flood risk and formulating a fair management response. Second, it shows that the most socially vulnerable experience systemic flood disadvantage (experiencing risk that is greater than the average). Third, the strong spatial concentration of disadvantage with ten local authorities accounting for fifty percent of the most socially vulnerable living in flood-prone areas, and high levels of disadvantage in coastal areas, economically struggling cities, and dispersed rural communities. In response to these findings the chapter advocates an approach to flood risk management that emphasises Rawlsian principles (see Chapter 3) of preferentially targeting risk reduction for the most socially vulnerable and avoiding a process of prioritisation based upon strict utilitarian (*i.e.,* cost effectiveness) or purely egalitarian (*i.e.,* equal treatment) principles. The chapter concludes by presenting recommendations to support this transition, ranging from the use of more meaningful metrics that reflect outcomes for the most socially vulnerable to more joined-up planning processes.

7.1 INTRODUCTION

Developing a better understanding of social vulnerability is a prerequisite for delivering a fair approach to prioritising flood risk management (FRM) efforts. Such an approach emphasises Rawlsian principles of preferentially targeting risk reduction for the most socially vulnerable and avoids a process of prioritisation based upon strict utilitarian or purely egalitarian principles (as discussed in Chapter 3) and is recognised as a central component of a strategic approach to flood risk management (as set out earlier in Chapter 4).

Social vulnerability in the context of floods relates to how flooding impacts on, and creates losses in, people's wellbeing (Tapsell *et al.,* 2002, Lindley *et al.,* 2011, England and Knox, 2015, Sayers *et al.,* 2017a). Delivering socially just FRM thus requires three central questions to be addressed. The first relates to the factors that influence social vulnerability. The second focuses on the geographic nature of flood disadvantage to identify those communities where high levels of social vulnerability combine with many people exposed to flooding (referred to here as **geographic flood disadvantage**). The third relates to the systemic nature of flood disadvantage and the ability to assess the degree to which FRM policy (and its implementation in practice) can be considered successful in delivering socially just outcomes (as expressed by the comparative risks faced by the most socially vulnerable communities when compared to the average and referred to here as **systemic flood disadvantage**).

This chapter explores the geographic and systemic aspects of flood disadvantage today and how these may change in in response to climate change (assuming the underlying social characteristics remain unchanged) with the aim of identifying policy gaps and recommending policy changes to improve flood resilience in the most socially vulnerable communities across the UK. In doing so, the influences of changes exogenous to FRM (*e.g.,* climate change and population growth) and influences that are largely endogenous to FRM (*e.g.,* FRM policy and its broader impacts on issues such as insurance) are considered. Both present-day and future flood disadvantage are explored through a quantified analysis at a UK scale (using and extending the Future Flood Explorer (FFE) set out in Chapter 6).

7.1.1 Why assess 'fairness' of flood risk management at a national scale

National assessments of flood risk are recognised as providing important evidence to inform policy decisions (as discussed in Chapter 6). Chapter 6 suggests that in a +4°C climate future (an extreme but plausible assumption) flood risk is likely to increase despite ongoing efforts to adapt and encourage the adoption of an *'enhanced whole systems'* approach to adaptation. The evidence provided to national policymakers often includes very limited insight into either geographic or systemic flood disadvantage. The UK Climate Change Risk Assessment (the CCRA discussed in earlier in Chapter 6) mentions social vulnerability but says little about future flood disadvantage or the policy responses that may be needed to specifically target socially vulnerable communities.

7.1.2 The changing context of flood risk management and its potential implications for social justice

A strategic approach to FRM does not simply focus on a narrow definition of economic risk but seeks to deliver broader social and ecosystem resilience (*e.g.,* Sayers *et al.,* 2014, 2017a) and takes decisions based on an understanding of the risks, uncertainties, and vulnerabilities. The UK national Flood Resilience Community Pathfinders Scheme (2013-15), for example, sought to stimulate approaches to community FRM that better enable communities to move towards greater resilience to flooding (Defra, 2013). An early review of this programme highlighted some of the difficulties in understanding what is meant by resilience and how this understanding shapes the nature of the solutions proposed, noting *'the way resilience is framed will lead to different actions and emphases'* (Twigger-Ross *et al.,* 2014). The relationship between social vulnerability and resilience also emerged as a central message from this review, with the suggestion that community networks (between individuals and more formal organisations) play a central role in both.

The political framework within which SFRM is delivered is also changing in many parts of the world. In the UK for example, the ongoing process of devolution (*i.e.,* to Scotland and to Wales but also to cities, such as Manchester) has the potential to alter the powers and competencies at a local and national scale and hence the way issues of social justice are embedded in FRM investment decisions.

7.2 METHOD OF ASSESSMENT

Flood hazards and the associated impact on the people and communities exposed to them vary across the UK. The process of identifying, and if necessary, addressing disproportionality in the risk faced by the most socially vulnerable is therefore a central component of a just approach to climate adaptation. To explore the degree to which SFRM in the UK can be considered socially just, the analysis seeks to understand both the geographic and systemic nature of flood disadvantage and identify those neighbourhoods at greatest flood disadvantage now and in the future across the UK (as published in Sayers *et al,* 2017c).

To identify the groups most likely to face flood disadvantage the analysis links to the analysis presented in the previous chapter to include a greater focus on **social vulnerability**. Here social vulnerability is used to refer to the combination of social characteristics of people and communities that determine their propensity for harm. Social vulnerability therefore reflects the inherent characteristics of the people and communities in which they live that would – if they were to be exposed to a hazard – make them more or less likely to experience a negative welfare outcome. There are many factors that contribute to social vulnerability, including bio-physical indicators such as older age groups and people with pre-existing ill-health as well as factors such as income, property tenure, access to insurance and access to support to enable adaptation. Multiple indicators are therefore used here to assess a relative measure of social vulnerability at the scale of a 'neighbourhood' (defined as in Chapter 6) using a range of indicators (expanded in the next section). People and communities may be classified as

socially vulnerable even if they are never exposed to a hazard – it is a measure of their potential to experience harm.

To identify those communities that face the greatest flood disadvantage the assessment of risk is viewed through two lenses (a 'spatial' lens and a 'social' lens – Figure 7-1) to identify:

- **Geographic disadvantage** (defined by Sayers *et al.,* 2017c). This considers the risk faced by each neighbourhood, based on social vulnerability and flood exposure within that neighbourhood. Those neighbourhoods with the greatest risk face the greatest 'geographic disadvantage.' To provide insight into how these risks are distributed, the risks at a neighbourhood scale are aggregated according to country (England, Wales, Scotland, and Northern Ireland), flood source (coastal, fluvial, and surface water flooding), urban and rural settings and selected city regions as well as between different ethnic groups.
- **Systemic disadvantage** (defined by Sayers *et al.,* 2017c). Systemic disadvantage arises when the risks faced by the most socially vulnerable are greater than those experienced by the less vulnerable. To assess the degree of systemic disadvantage the risks faced by the 20% most socially vulnerable neighbourhoods within any of the four groupings (see above, *i.e.,* within the same local authority, settlement type, flood source or ethnic group) are compared with the risks faced by the less vulnerable within the same group. This comparison of the risks faced within each of the four groupings helps to ensure the outcomes for the most socially vulnerable are appropriately supported, *e.g.,* are central to the informing of a just (*i.e.,* fair) approach to adaptation (Rawls, 1971).

Further elaboration of the assessment approach is provided when appropriate throughout the report and in the supporting appendices.

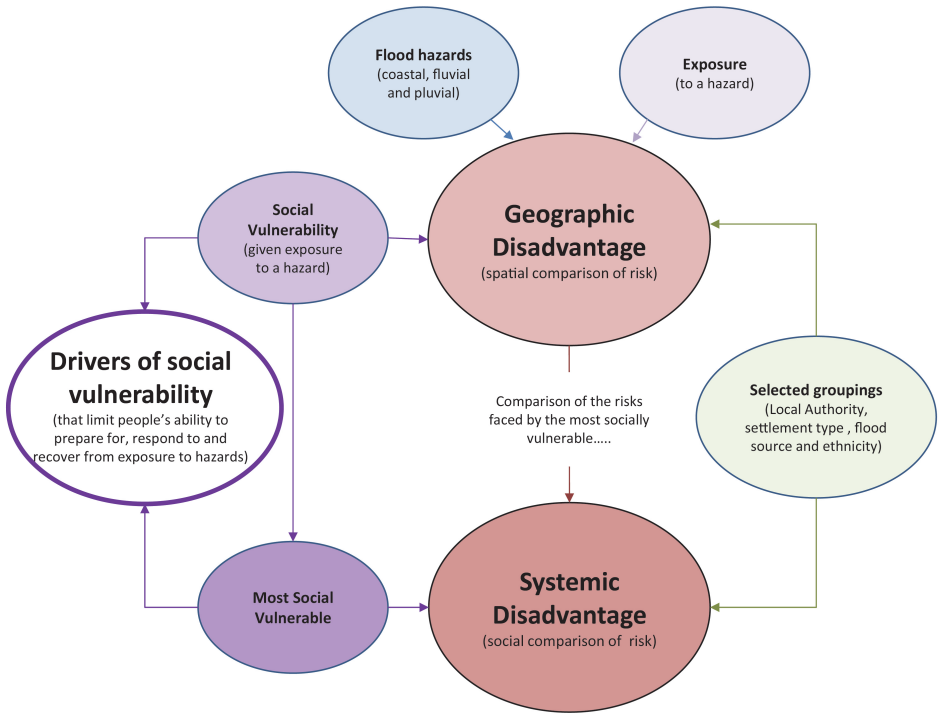


Figure 7-1 The process of geographic and systemic disadvantage assessment

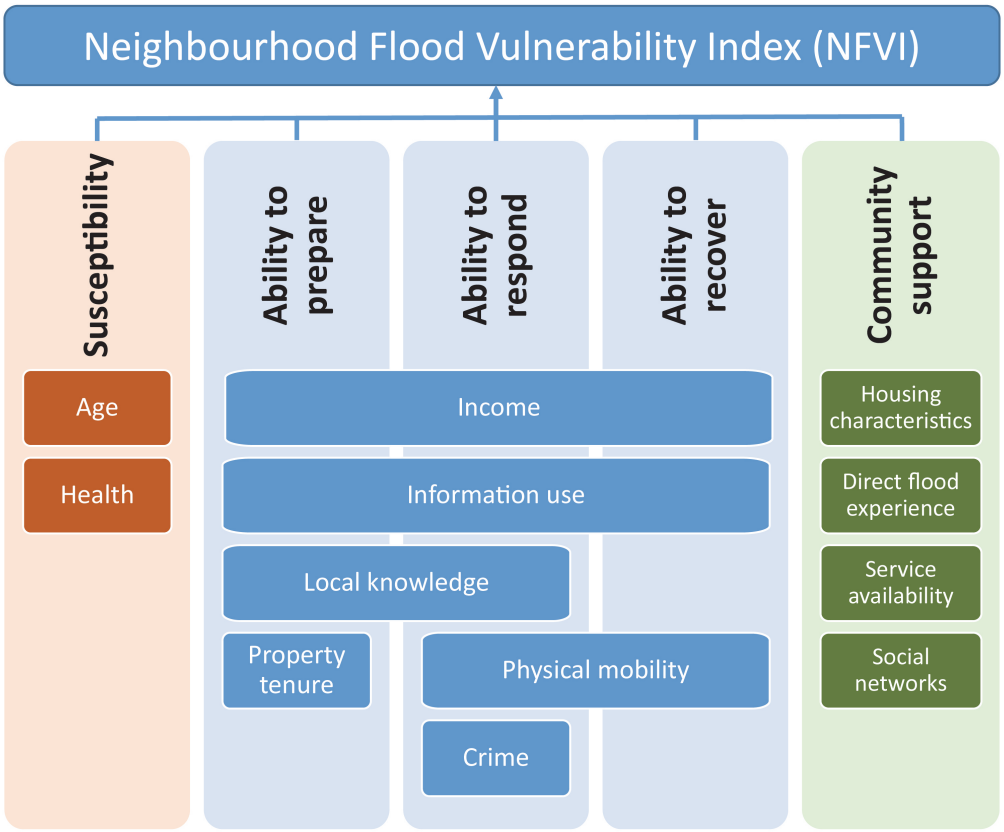
7.2.1 The characterisation of flood social vulnerability

UK FRM policy typically considers social vulnerability through the lens of deprivation (as indicated by the Index of Multiple Deprivation, DCLG, 2015) and this view provides the basis of the analysis presented in the CCRA (Sayers *et al.,* 2015c). A focus on deprivation does not necessarily reflect a community's vulnerability to a flood (although flood vulnerability is significantly influenced by income deprivation, as demonstrated by Tapsell *et al.,* 2002). To overcome this shortcoming and building on the characterisation of flood vulnerability advanced by Lindley *et al.,* (2011) and Kazmierczak *et al.,* (2015), a new measure is introduced here: the Neighbourhood Flood Vulnerability Index (NFVI). The NFVI expresses the neighbourhood's characteristics that influence the potential to experience a loss of wellbeing when exposed to a flood and over which flood management policy has limited or no control. In doing so, the NFVI builds upon previous studies (Tapsell *et al.,* 2002; Lindley *et al.,* 2011; Twigger-Ross *et al.,* 2014; Kazmierczak *et al.,* 2015) and requires consideration of five characteristics to provide a single vulnerability index at a neighbourhood scale, namely:

- **Susceptibility.** Susceptibility describes the predisposition of an individual to experience a loss of wellbeing when exposed to a flood. It is widely evidenced that the dominant characteristics that influence susceptibility to harm relate to the age (the old and very young) and health of the individuals exposed.
- **Ability of an individual to prepare for a flood.** Preparedness reflects the actions taken by an individual during normal conditions (*i.e.,* in the absence of a forecast or actual flood) that are likely to reduce the harm they suffer when a future flood occurs. Although an area of continued research, an individual's ability to prepare is influenced by their income, capacity to act, local knowledge and property tenure.
- **Ability of an individual to respond to a flood.** The underlying reasons why some individuals act more effectively in the run up to and during a flood is an area of continued research. There is broad agreement that an individual's ability to respond is influenced by their income, capacity to access and use formal and informal information, local knowledge, and physical mobility.
- **Ability of an individual to recover from a flood.** Many flood events have highlighted the length of time it can take for individuals and communities to recover from a flood. The degree to which an individual can aid their own recovery is influenced by several factors, particularly their income, capacity to use information, and physical mobility.
- **The ability of the community to support individuals.** The availability and quality of services provided by health and emergency services as well as broader care and social services are all important social facilities that have a real influence on the severity of harm caused by a flood. Despite a lack of quantified evidence, there is also strong anecdotal evidence that community support networks can help ameliorate vulnerability by providing support to affected groups and flood management policy is increasingly recognising the value of community networks (for example by supporting the national Flood Community Resilience Pathfinders schemes, Defra, 2012, 2015). As such, the

presence or absence of community support is legitimately considered here as a component of vulnerability. A formal representation of community cohesion and its influence on flood vulnerability is not available. In recognition of the importance of community support, but in the absence of more detailed insights, four indicators are considered to gauge the nature of this support: housing characteristics, the collective experience of past floods, the likely availability of community services in a flood (including emergency service providers, schools, GPs, care homes) and the social networks that exist. This is recognised as very much a first step and further research will be required to better quantify supportive community contexts.

Each characteristic of the Neighbourhood Flood Vulnerability Index (NFVI) is assessed based upon one or more of twelve indicators (the horizontal elements shown Figure 7-2) that are, in turn, based upon one or more variables (Table 7-1).



Source: Sayers et al., 2017c

Figure 7-2 Neighbourhood Flood Vulnerability Index

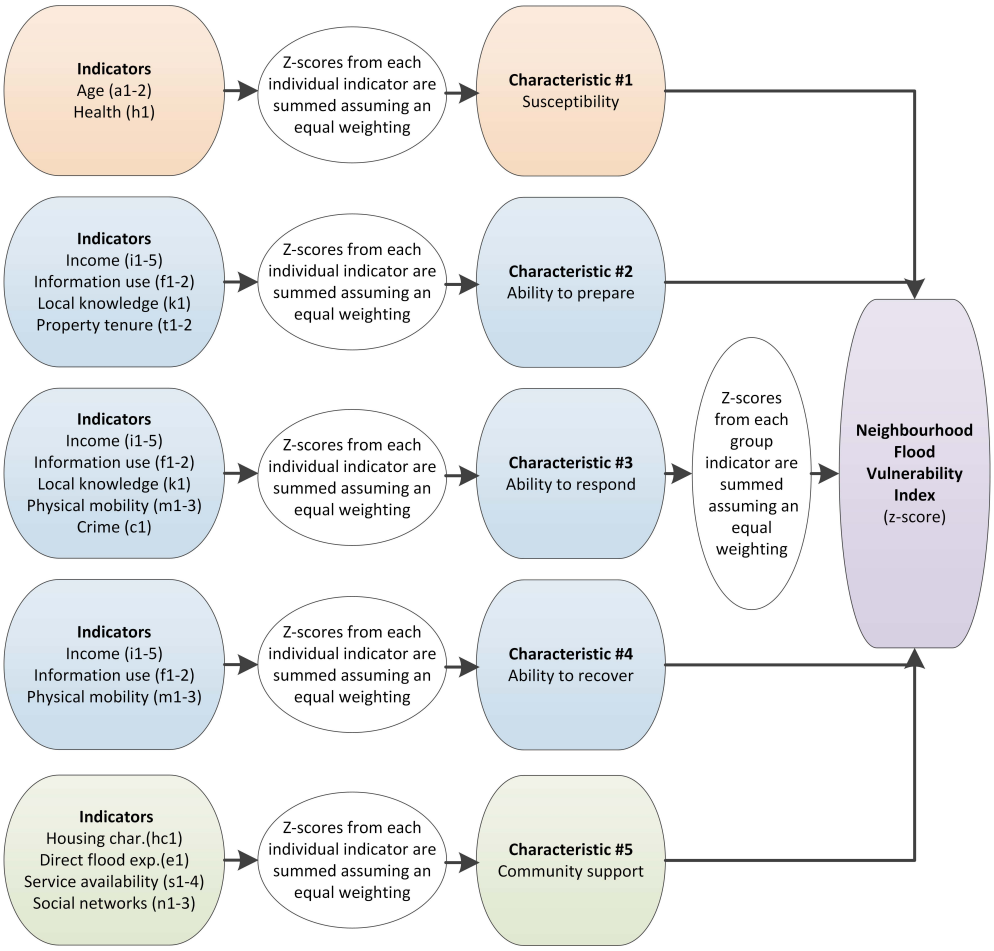
Each indicator is normalised to a z score (derived by subtracting the mean value and dividing by the standard deviation). If a variable is already in the form of a rank (*e.g.,* as is the Index of Multiple Deprivation), the equivalent z score is determined by assuming the rank is drawn from a normal distribution and calculating the number of standard deviations from the mean associated with that rank. The resulting z scores are then equally weighted to estimate each of the five characteristics (Susceptibility; Ability to Prepare; *etc.*). The only exceptions to this are the supporting variables associate with 'direct flood experience' and 'primary school-aged children' (Table 7-1; e1 and n3). These variables act to reduce social vulnerability (*e.g.,*

those with experience know how to cope better than those without; families with schoolchildren tend to have more local contacts (Tapsell *et al.,* 2002; Twigger-Ross *et al.,* 2014), and hence a negative weighting is applied (to reduce rather than increase the relative vulnerability of one neighbourhood compared to another). The resulting values for each characteristic or indicator are then themselves transformed into a z score, and summed, with equal weighting. The final z score is calculated based on these results and used as the NFVI (Figure 7-3).

Table 7-1 Neighbourhood Flood Vulnerability Index: Indicators and supporting variables

Indicator	**Supporting variables**	
Age	a1	Young children (% people under 5 years)
	a2	Older people (% people over 75 years)
Health	h1	Disability / people in ill-health (% people whose day-to-day activities are limited)
	h2	Households with at least one person with long-term limiting illness (%)
Income	i1	Unemployed (% unemployed)
	i2	Long-term unemployed (% who are long-term unemployed or who have never worked)
	i3	Low-income occupations (% in routine or semi-routine occupations)
	i4	Households with dependent children and no adults in employment (%)
	i5	People income deprived (%)
Information use	f1	Recent arrivals to UK (% people with <1-year residency coming from outside UK)
	f2	Level of proficiency in English
Local knowledge	k1	New migrants from outside the local area (%)
Tenure	t1	Private renters (% Households)
	t2	Social renters (% households renting from social landlords)
Physical mobility	m1	High levels of disability (% disabled)
	m2	People living in medical and care establishments (%)
	m3	Lack of private transport (% households with no car or van)
Crime	c1	High levels of crime
Housing characteristics	hc1	Caravan or other mobile or temporary structures in all households (%)
Direct flood experience	e1	No. of properties exposed to significant flood risk (%) (acts to reduce social vulnerability)
Service availability	s1	Emergency services exposed to flooding (%)
	s2	Care homes exposed to flooding (%)
	s3	GP surgeries exposed to flooding (%)
	s4	Schools exposed to flooding (%)
Social networks (non-flood)	n1	Single-pensioner households (%)
	n2	Lone-parent households with dependent children (%)
	n3	Children of primary school age (4-11) in the population (%) (acts to reduce social vulnerability)

Note: A discussion for the rationale of the inclusion of each indicator is given in Appendix C. Source: Sayers et al., 2017c



Source: Sayers et al., 2017c

Figure 7-3 Calculation of the Neighbourhood Flood Vulnerability Index (NFVI)

7.2.2 The differential support for adaptation

In the context of a national analysis, the effectiveness of individual adaptation measures is often considered to be independent of the vulnerability of those at risk (as for example within the CCRA, Sayers *et al.,* 2015c). The lack of differentiation results in a lack of insight into the social distribution of risk and climate change and adaptation choices may influence this distribution. Despite some funding mechanisms that explicitly prioritises investment in deprived areas (Defra, 2011) and an acknowledged need to target action towards the most socially vulnerable (see Chapter 3), there is some evidence to suggest that the most vulnerable neighbourhoods are less well protected than others (England and Knox, 2015). There is also anecdotal evidence to suggest that in inner-city areas (where urban flooding and drainage is significant) a differential in the retrofitting of Sustainable urban Drainage System (SuDS) measures may exist. This is reflected in the analysis here by assuming no retrofitting takes place in more vulnerable communities (compared to 10% elsewhere, ASC, 2014).

Spatial planning and development control are also important FRM measures that influence how population growth translates to development and future exposure. Analysis of new residential developments (in England only) in the period 2008-2014 undertaken here suggests that the percentage of new properties built within the fluvial and coastal floodplain is around

14 per cent in the most vulnerable areas (defined by the top 20 per cent of neighbourhoods by NFVI) and 11 per cent in less vulnerable areas (Sayers *et al.,* 2017b). This differential in current planning outcomes is assumed to persist into the future and is therefore carried forward into the analysis presented here.

Property level protection measures (PLP), warning services and insurance also all provide important FRM contributions, but all three can be difficult for the most vulnerable to access. Regarding property level measures, evidence suggests that the uptake by the most vulnerable in existing developments is likely to be significantly lower than in the population as whole (National Flood Forum, 2012). There may be multiple reasons for this including:

- property level measures can be expensive which may rule out installation for people on low incomes (National Flood Forum, 2012).
- the process of applying for a grant is bureaucratic and cumbersome (National Flood Forum, 2016).
- grants may be insufficient to encourage take-up by the most vulnerable (based on evidence from the case studies undertaken in this research).
- tenants in rented accommodation have a reduced ability and incentive to install property level protection measures; and
- developing an awareness of flood risk within transient communities may be more difficult.

In combination, these barriers mean it is likely that the retrofitting of PLP measures in the most vulnerable neighbourhoods will be significantly less than elsewhere, and this differential is carried forward into our analysis. There is little evidence that would suggest the uptake of such measures within new developments is any different in more and less vulnerable neighbourhoods. There is also some evidence to suggest that social vulnerability influences a community's ability to respond to a warning (Thrush *et al.,* 2005). In part, this is already reflected in the NFVI (: f1, f2, k1) but social vulnerability can also influence the effectiveness of such measures due to, for example:

- ***Barriers to receiving the warning.*** many households (particularly low-income households) are no longer choosing to maintain a telephone landline but instead rely upon mobile technologies (see Money.co.uk (2017)). This can create complications in trying to contact households to convey flood warnings, largely because there is no published list of mobile phone numbers as there is for landlines. Loss of power during a flood can also prevent communication, as mobile telephones (and cordless landlines) require power to charge batteries (Pitt, 2007). Transient and travelling communities may also be difficult to reach.
- ***Accessing the content of warnings.*** Minority ethnic groups for whom English or Welsh is not their first language may be less able to respond (Thrush *et al.,* 2005).

- ***Awareness of the need to be 'flood aware'.*** One of the factors that has been shown to have the greatest impact on levels of "awareness" is lack of previous flooding experience (Thrush *et al.,* 2005).

In combination, these challenges are assumed to lead to lower rates of uptake of warning services and the action taken in response to the warnings to be less effective at reducing economic damage in the most vulnerable neighbourhoods when compared to less vulnerable neighbourhoods.

Private insurance underpins FRM policies in the UK. This is one of the few FRM policies whose measures are universally applied across the UK (National Flood Forum, 2012). Penetration is uneven. Based on the government's Household Expenditure Survey and evidence from its own members, the Association of British Insurers (ABI) estimate that the uptake of insurance in the UK is such that 93 per cent of all homeowners have buildings insurance that covers the structure of their home, but this falls to 85 per cent of the poorest 10 per cent of households purchasing their own property. The differential in contents insurance is much greater. Some 75 per cent of all households have contents insurance, but less than half of the poorest 10 per cent of households and even fewer who are tenants have this protection. This prompted Watkiss *et al.,* 2015 to note that *"while most owner occupiers have building insurance, there are much lower levels of contents insurance among tenants, with many in the lowest income decile having no insurance at all".*

Since April 2016 Flood Re has created a pool into which all insurers contribute to subsidise the insurance premiums of those at greatest risk (Defra, 2014a). Householders purchasing flood insurance will not know whether they are in this pool or not, since they will deal with their conventional insurance company, but that company will cede the policy and the liability for claims to the Flood Re pool if the cost of insurance exceeds certain thresholds and certain eligibility criteria are met (excluding properties built after 1st January 2009). The result is intended to make flood insurance affordable, including for example capped premiums linked to Council Tax bandings[25]. In high-risk areas, it is unclear whether Flood Re has been successful in improving insurance uptake in the most vulnerable neighbourhoods and it does nothing to assist the uninsured. It is also the case that Flood Re has a life of only twenty-five years after which flood insurance will become fully risk reflective. Watkiss *et al.,* 2016 discusses how this transition to market prices will, in the longer term, lead to substantially higher premiums for those at risk, and those at most risk will pay much more than at present. This transition to an actuarial accounting process could further discourage the most vulnerable from accessing insurance.

To establish a credible representation of the role of insurance, and how it may be more or less effective in the most vulnerable neighbourhoods, several issues have necessarily been

[25] http: //www.floodre.co.uk/industry/how-it-works/eligibility/ Accessed March 2021

considered and partially modelled. First, regarding uptake by income, there is a marked difference in penetration levels with different levels of disposable income such that there is a 47.5 per cent difference between the lowest and highest income deciles (ONS, 2015). Secondly, insurance has lower levels of penetration across households in rented accommodation (ONS, 2015) – although local authorities and housing associations would typically be responsible for any structural repairs following a flood, and in the private rented sector the landlord will be responsible for structural repairs. Therefore, the insurance position of the landlord is what is critical in terms of structural repair. This is not considered further here.

To overcome the lack of insight into the risks faced by the most socially vulnerable that accounts for the differential support for adaptation and in the capacity to adapt, the analysis presented implements the portfolio of adaptation measures (presented in Chapter 6) but differentiates the effectiveness of individual FRM adaptation measures based on neighbourhood vulnerability (where there is evidence to do so).

7.2.3 Linking risk and vulnerability metrics

- As Cutter *et al.,* (2010) in the USA and Walker and Burningham (2011) have shown, the way in which flood risk, vulnerability and resilience are measured is crucial to the way they are understood and managed. Several risk metrics are considered, including three new metrics. The first, the **Neighbourhood Flood Vulnerability Index** (NFVI – as introduced above). The second combines the NFVI with an understanding of the probability and exposure to flooding and is referred to as the **Social Flood Risk Index** (SFRI). The SFRI enables those areas where the largest number of the most socially vulnerable people are most frequently exposed to flooding (defined here using a return period, on average, of 1 in 75 years or more frequent) to be identified. The SFRI therefore directly supports an understanding of geographic flood disadvantage (defined earlier) and is estimated at both a neighbourhood scale and as an individual 'average' as follows:
- ***Social flood risk index*** (SFRI) helps identify those areas where many vulnerable people, as defined by the NFVI, are exposed to flooding, and is calculated as the product of the NFVI and the annual expected number of people flooded as follows:

$$\text{SFRI} = \langle \text{Annual expectation of the number of people flooding} \rangle \times \text{NFVI} \quad \textit{Eq 7-1}$$

- ***Social flood risk index: Individual*** (iSFRI) helps identify those neighbourhoods where the vulnerability of those exposed is high (even when only a few may be exposed) and is calculated simply by dividing the SFRI by the neighbourhood floodplain population.

The third new metric is **Relative Economic Pain** *(REP)* (introduced in chapter 6 but expanded here) that enables recognition of the varying coping capacity between more affluent and low-income families. This metric captures the relationship between uninsured damages and household income: the larger the former in relation to the latter, the greater the REP. The REP builds upon previous research touching on issues of outrage (Evans *et al.,* 2004a, b; Sayers *et al.,* 2017c) to express the 'relative pain' of a risk and is defined here as the

uninsured loss (represented by one minus the insurance penetration) times the EAD on the floodplain, divided by total income on the floodplain:

$$REP = \frac{(1-I)\times EAD}{Income} \qquad Eq.\ 7\text{-}2$$

where

I = percentage of the loss covered by insurance,

EAD = Expected Annual Damages (£), and

Income = household annual income (£).

Four local case studies (in Boston, Cumbria, Blaenau and in York, the last undertaken in association with Robotham, 2016) have been used to ground truth the estimates of social vulnerability and social flood risk. These discussions provided confidence that the relative distribution of social vulnerability was indeed locally representative (Sayers *et al.,* 2017c).

7.3 INSURANCE PENETRATION

The impact of flooding on social wellbeing is fundamentally influenced by access to insurance. In turn, insurance penetration is known to vary by:

- **Income** (those on lower incomes are much less likely to have insurance)
- **Tenure** (those living in rented accommodation – particularly social housing – are much less likely to have insurance)
- **Experience of flooding** (there is some limited evidence that direct experience of a flood increases the take-up of insurance)

The evidence for each, disaggregated by ethnicity where possible, is introduced below. The spatial understanding of income, tenure and ethnicity developed using this evidence is taken forward in the analysis set out in the following chapters.

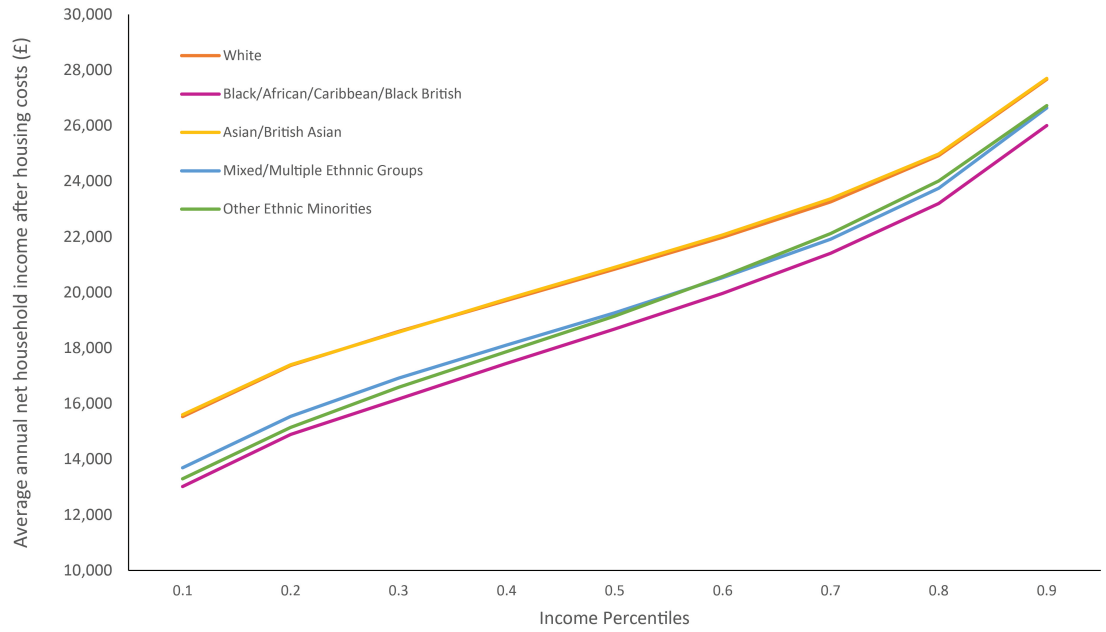
7.3.1 Income and ethnicity

Household income (after housing costs) is known to be an important driver of access to flood insurance (Table 7-2). Income is also a central consideration in social vulnerability and known to vary by ethnicity with, on average, household incomes for Black, Mixed and Other ethnic minorities significantly lower than either White or Asian households (Figure 7-4).

Table 7-2 Insurance by income (decile) in the UK

	Structure		Contents		Structure & Contents	
	£	%	£	%	£	%
Lowest 10%	152	29	125	43	266	26
Second Decile	163	42	129	62	278	39
Third Decile	178	53	146	70	309	48
Fourth Decile	171	57	147	75	305	55
Fifth Decile	197	63	155	77	332	57
Sixth Decile	206	71	172	83	368	64
Seventh Decile	200	75	163	86	352	69
Eighth Decile	214	77	175	87	372	69
Ninth Decile	222	82	186	90	393	76
Highest 10%	300	85	248	92	526	79

Source: ABI, 2018



Source: UK Census data, ONS (2011)

Figure 7-4 Net household income by ethnicity

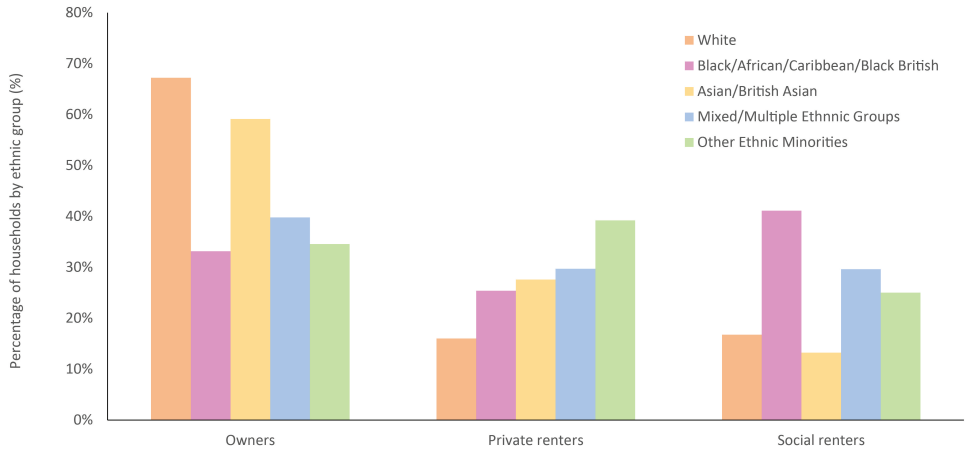
7.3.2 Tenure and ethnicity

Tenure significantly influences insurance take-up, and those in private or social rented accommodation are much less likely than homeowners to have flood insurance (as reported in Sayers *et al.,* 2017c and evidenced in data published by the ABI, Table 7-3). Direct primary data remains limited. Evidence from Census data (ONS, 2011) and national statistics suggests tenure exhibits a strong differential by ethnicity, with Black, Mixed and Other minorities much more likely to live in rented accommodation. Most noticeably Black households are significantly over-represented in social housing (Figure 7-5).

Table 7-3 Insurance penetration by tenure in the UK (ABI, 2018)

		Structure		Contents		Structure and Contents	
		£	%	£	%	£	%
Rented Unfurnished							
	Local Authority	*	*	142	40.6	*	*
	Housing Association	*	*	135	41.1	*	*
	Other	*	*	191	47.1	1	286.1
Rented Furnished		*	*	177	24.0	1	590.1
Owner Occupied							
	Being Purchased	219	93.5	178	93.5	*	*
	Owned Outright	202	93.5	164	94.7	*	*
Rent Free		*	*	162	66.0	*	*

Source: ABI, 2018, Table 11



Source: Sayers et al., 2020c

Figure 7-5 Property tenure by ethnicity

7.3.3 Direct flood experience

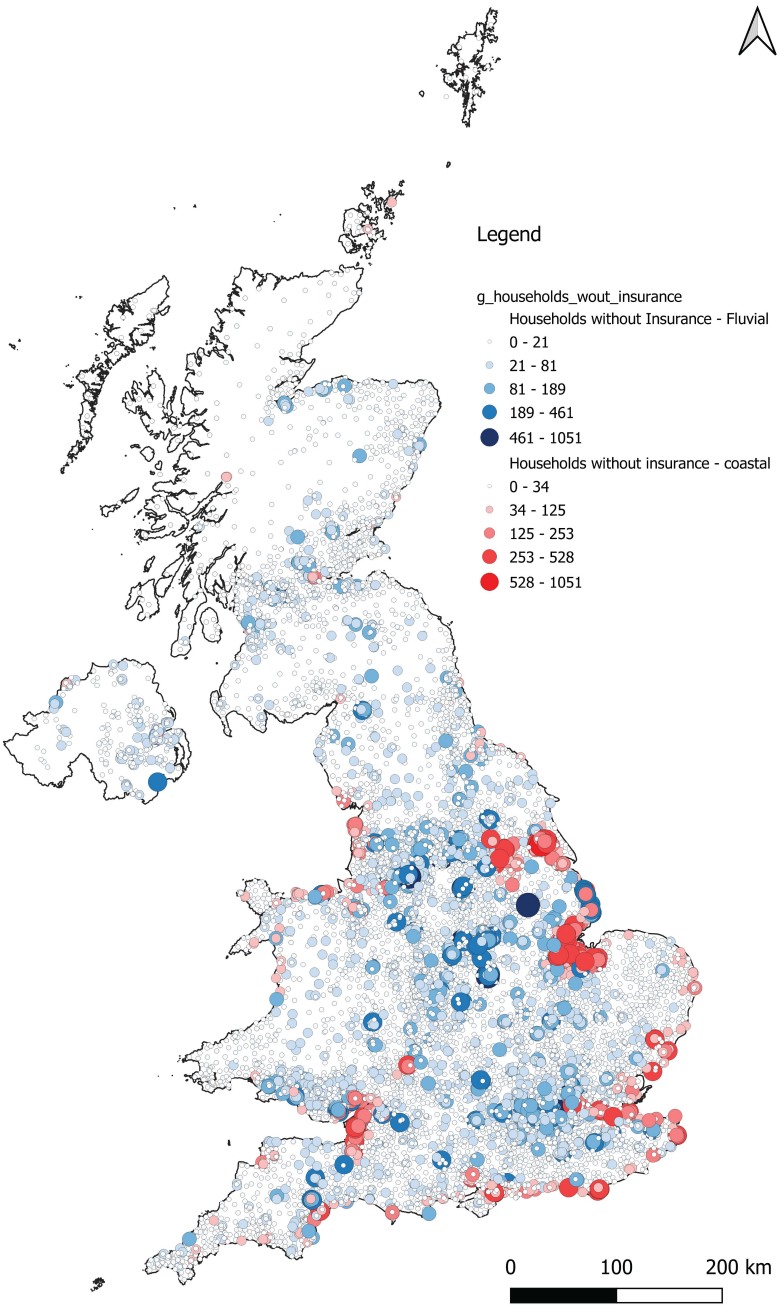
Evidence from the summer 2007 floods in England suggests that 76% of household losses (building and contents) were covered by insurance (Chatterton *et al.,* 2010). This is higher than would be expected based on the median value of 57% (Table 7-3) suggesting that those living in flood-prone areas may have a higher-than-average take-up[26]. It is therefore assumed here that for those living in less socially vulnerable neighbourhoods the take-up of insurance is, on average, 76% (as Chatterton found, rather than the non-flood specific values presented by the ABI in Table 7-3). A lower value of 38% is used for those living in the most socially vulnerable neighbourhoods without direct experience of flooding (towards the low end of the values presented in Table 7-3) rising marginally to 45% where there is direct experience of flooding (reflecting a weak influence on uptake).

7.3.4 Spatial distribution of households without insurance

An estimate of those households living in the fluvial and coastal floodplain that may not have insurance (structure and contents) is presented in Figure 7-6. This analysis, based on the assumptions set out in the previous sections, suggests that of the 1.4 million households exposed to significant flooding (today) on the fluvial and coastal floodplain, 0.45 million may be without insurance (*i.e.,* 32% of all households). Those Local Authorities where the largest number of uninsured households have been estimated for each source of flooding surface water, fluvial and coastal flooding are illustrated in Figure 7-7. The modelled estimate is broadly consistent with EA surveys post-event (such as Chatterton *et al.,* 2010), take-up rates

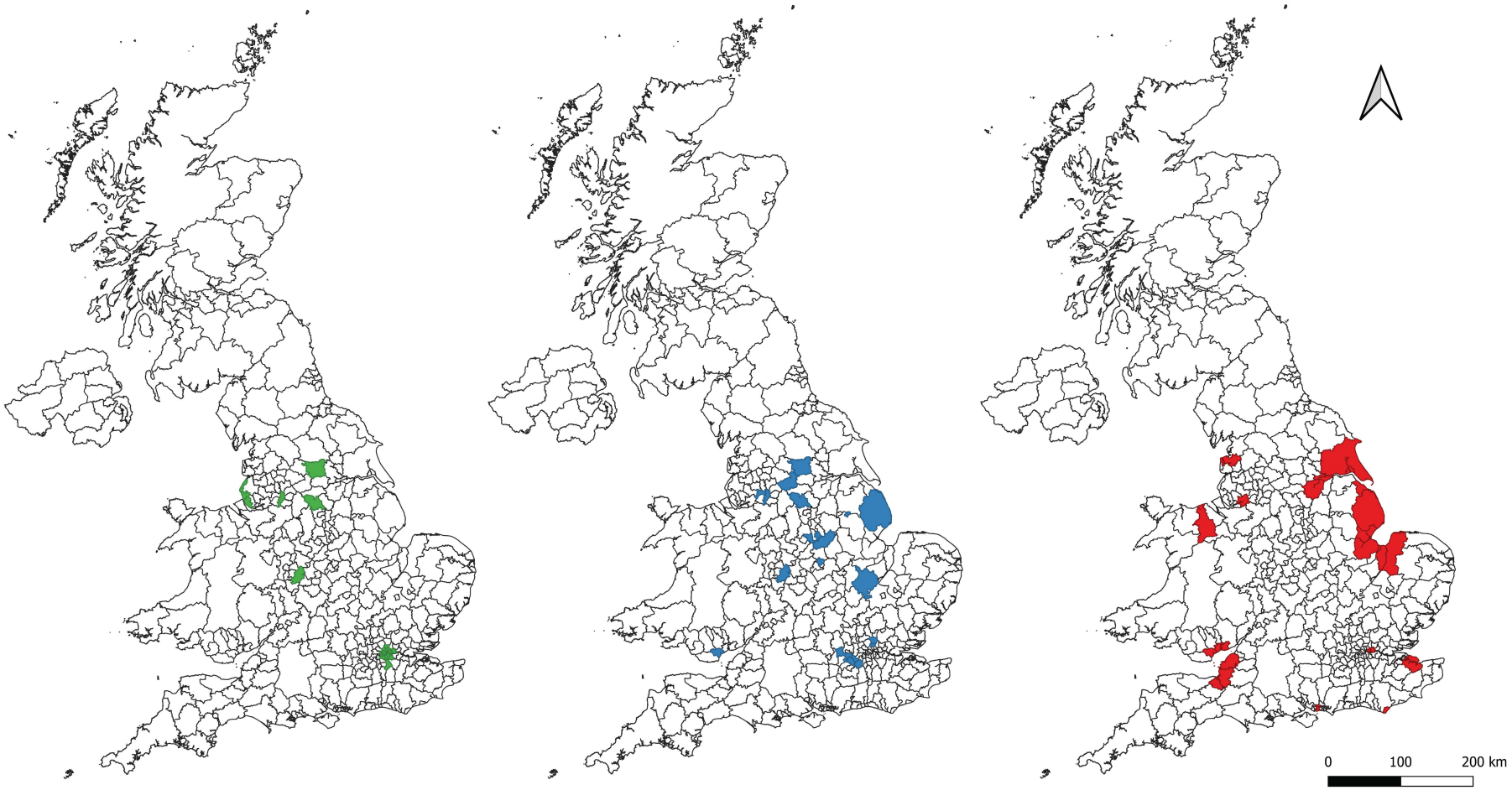
[26] Although widely considered to be important, and suggested by the findings of Chatterton, little primary research has been carried out on the influence of exposure to previous flooding on insurance take-up. Kates (1962) shows that direct experience triggers response, but that is not quite as direct as to say it triggers insurance.

published by the ABI (2018) and the findings of the Blanc Review (Blanc, 2020); although no publication provides an equivalent analysis.



Fluvial floodplains (blue) and on coastal flood plains (red) scaled by the number of properties without insurance. Surface water flooding is excluded given that the widespread nature of surface water hazards would mask the patterns within the map. Source: Sayers et al., 2020c.

Figure 7-6 Households without flood insurance



Left: Surface water; Middle: Fluvial; Right: Coastal flood sources. The maps above are based on a model estimate and not primary survey results.

Figure 7-7 Local Authorities with the greatest number of uninsured households (estimated)

7.4 PRESENT AND FUTURE FLOOD DISADVANTAGE

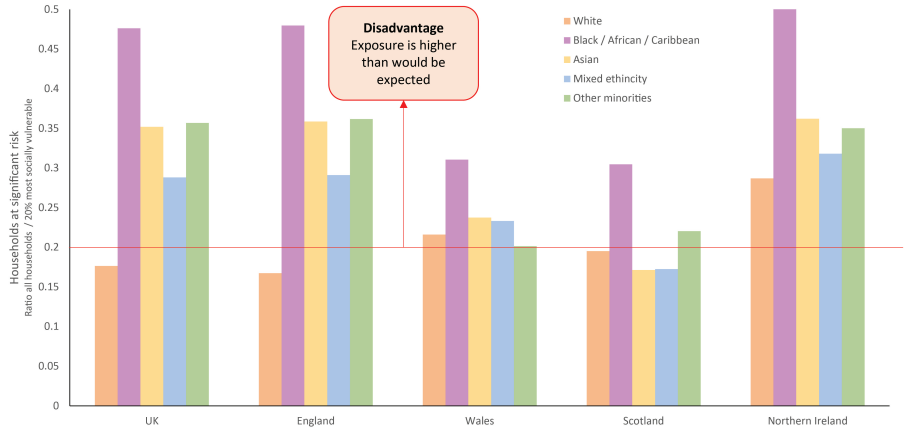
Three risk metrics are used here to provide a perspective on flood disadvantage:

- Number of people exposed to frequent flooding (one in 75-year return period or more frequent)
- Expected Annual Damage (direct contents and structural damage of residential homes, EADr)
- Relative Economic Pain (REP, Sayers *et al.,* 2017c).

The insights provided by each metric are discussed below.

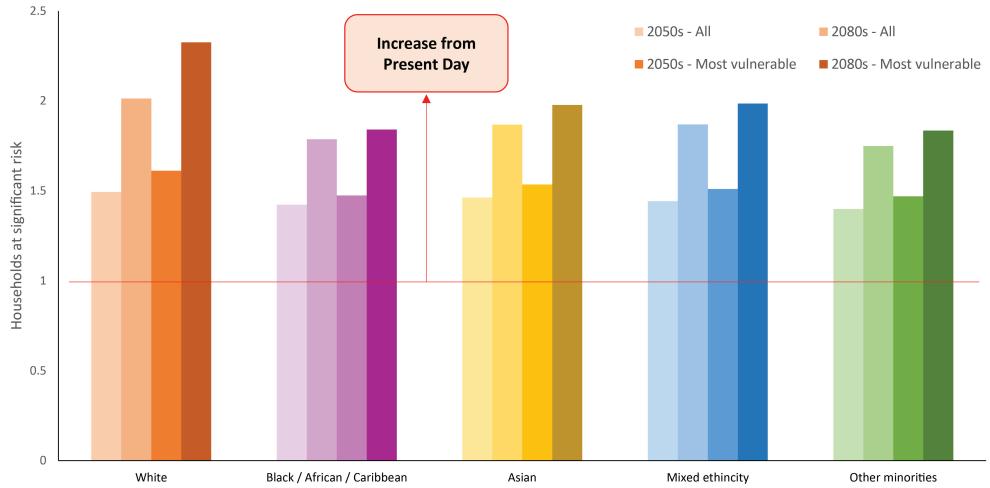
7.4.1 Households exposed to frequent flooding

This metric focuses on the number of households exposed to flooding with a one in 75-year return period or more frequent (on average). A comparison of the present-day number of households exposed to frequent flooding in all neighbourhoods and those in the 20% most socially vulnerable neighbourhoods shows significant disadvantage for many BAME groups across the UK (Figure 7-8). The disadvantage is most stark amongst the Black, African and Caribbean groups, with near to 50% of all households exposed to frequent flooding found within the 20% most socially vulnerable neighbourhoods. Assuming a continuation of current levels of adaptation, climate change increases the exposure for all groups (Figure 7-9). This is particularly the case at the coast and in areas prone to surface water flooding (Figure 7-10).



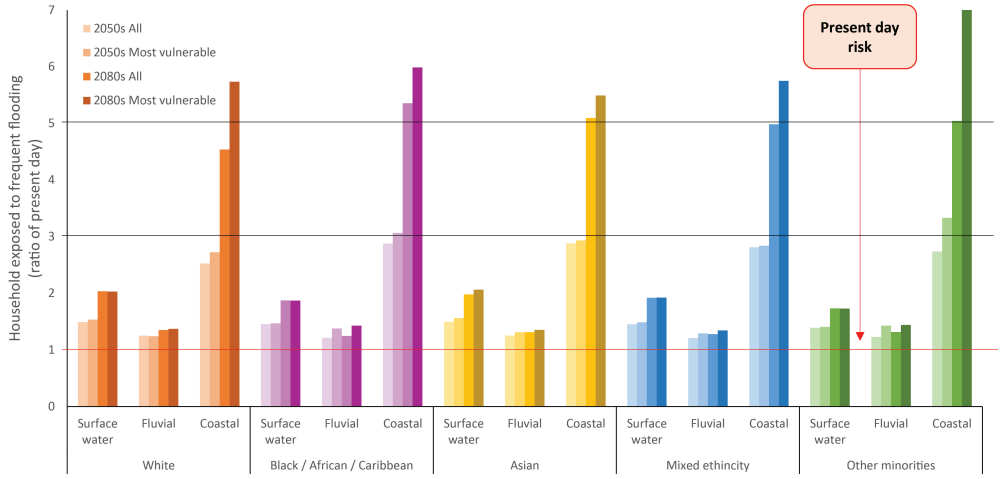
The y-axis shows the ratio between all households and those in 20% most socially vulnerable neighbourhoods. In the absence of bias, 20% of the households would be expected to be in 20% of the neighbourhoods (when aggregated at large scales as here). Frequent flooding refers to one in 75-year return period or more frequent.

Figure 7-8 Present Day – No. of households exposed to frequent flooding



The y-axis shows the ratio between present day and future exposure (in the 2050s and 2080s), with the lighter shading the change in exposure in all neighbourhoods and the darker shading for the 20% most socially vulnerable. Each group of bars reads as 2050s all, then 2050 most vulnerable and then 2080s all and 2080 most vulnerable. Source: Sayers et al., 2020c

Figure 7-9 Proportional future increase in the number of households exposed to frequent flooding compared to present day



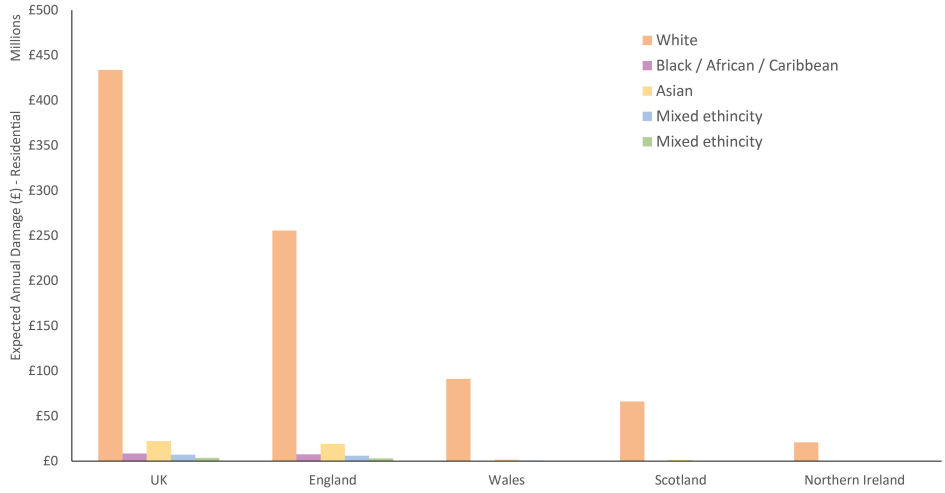
Future risk in the 2050s (2°C) and 2080s (4°C) assuming a continuation of current levels of adaptation are presented relative to present-day risk. Source: Sayers et al., 2020c

Figure 7-10 Proportional future increase in the number of households exposed to frequent flooding compared to present day: By flood source and ethnicity

7.4.2 Expected Annual Damage: Residential

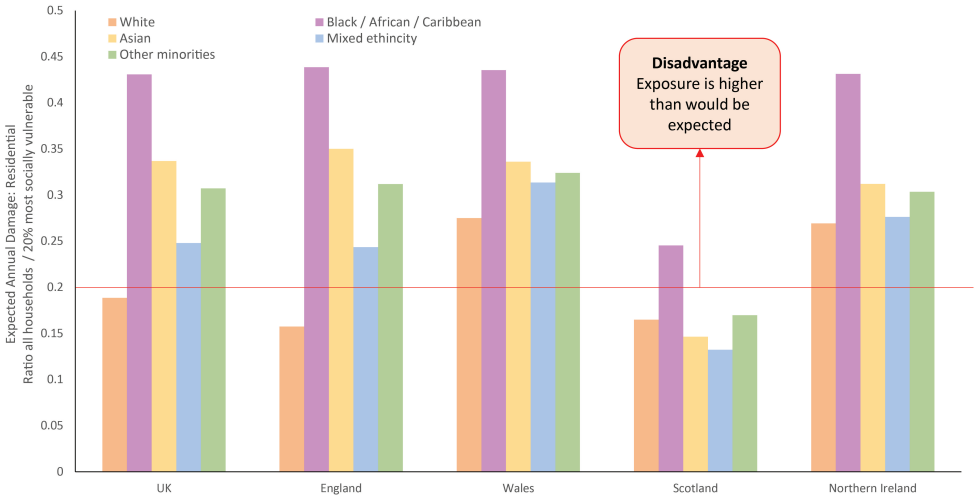
This metric provides the conventional view of risk in direct (national) economic terms. The assessment of Expected Annual Damage (EAD) combines the annual probability of a property (residential) being flooded and the associated direct economic damages (using the same method as CCRA3, Sayers *et al.,* 2020a). When disaggregated by ethnicity White ethnic groups dominate the national aggregations of risk (Figure 7-12). This is as expected given the much larger number of White households across the UK (87.2% of the population identifying as White in the 2011 United Kingdom census).

When a social vulnerability perspective is introduced, ethnic minorities (particularly Black ethnic groups) experience disproportionally larger risk than would be expected in the absence of bias (Figure 7-12).



Source: Sayers et al., 2020c

Figure 7-11 Present Day – Expected Annual Damage (Residential) – By ethnicity



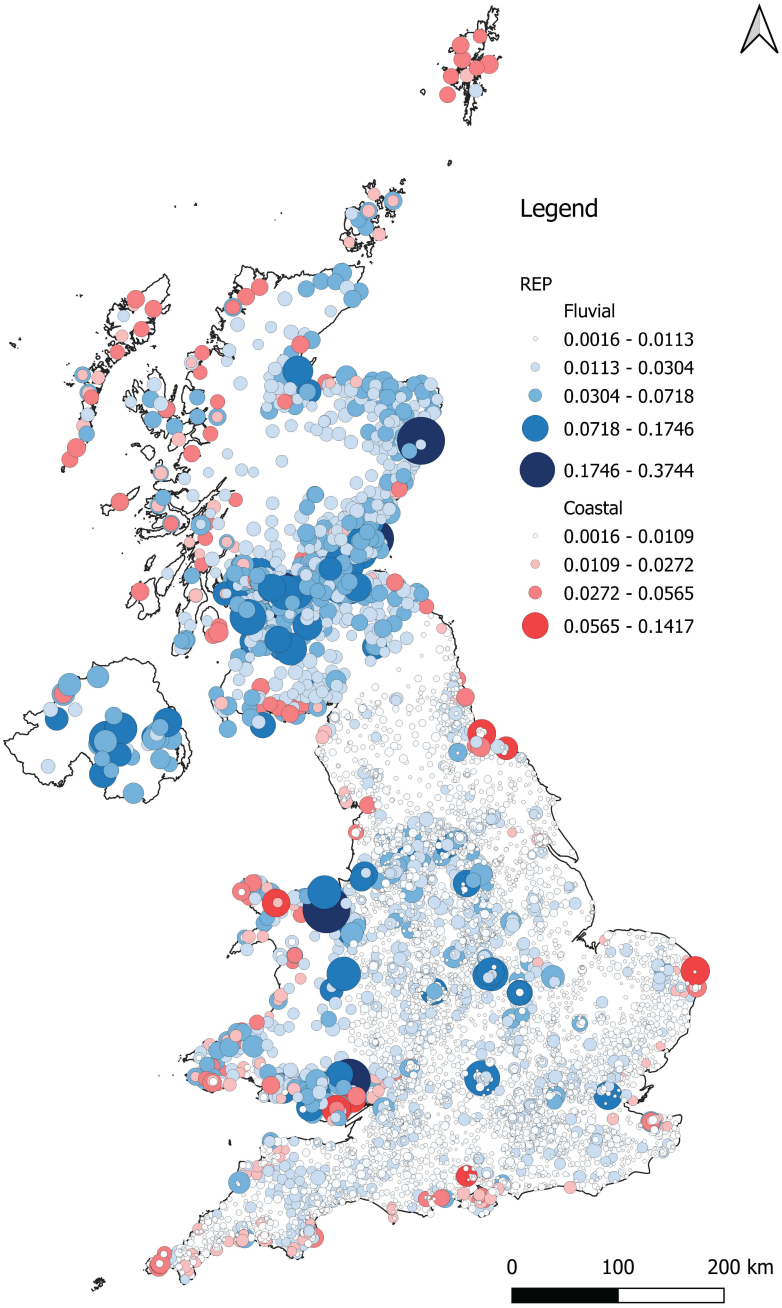
The y-axis shows the ratio between all households and those in 20% most socially vulnerable neighbourhoods. In the absence of bias, 20% of the households would be expected to be in 20% of the neighbourhoods (when aggregated at large scales as here).
Source: Sayers et al., 2020c

Figure 7-12 Present Day – Ratio in Expected Annual Damage (Residential) between the most social vulnerability neighbourhoods and others differentiated by ethnicity

7.5 Relative Economic Pain

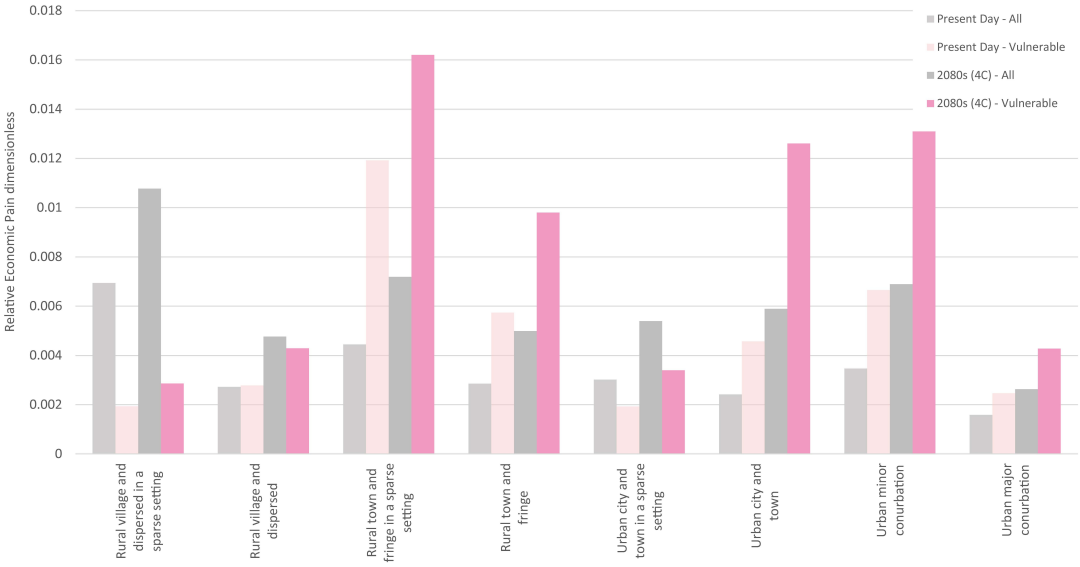
Relative Economic Pain, the REP, is defined as the ratio of uninsured loss to income (Sayers *et al.,* 2017c). The REP varies across the UK (Figure 7-13) and provides insight into the significance of flooding for different households and is a central perspective to explore flood disadvantage. When considered through the lens of Relative Economic Pain the differential between the risk faced by the more and less socially vulnerable is stark (Figure 7-14). The

REP metric also highlights how systemic disadvantage is exacerbated by climate change (Figure 7-15). On average, the disadvantage is significantly greater in Wales, Scotland, and Northern Ireland than in England, although all countries have disadvantaged communities. These findings reinforce previous findings (Sayers *et al.,* 2017c, 2020a) that also highlight the disadvantage experienced by many coastal and estuary communities as well as many isolated rural towns and smaller urban towns and conurbations.



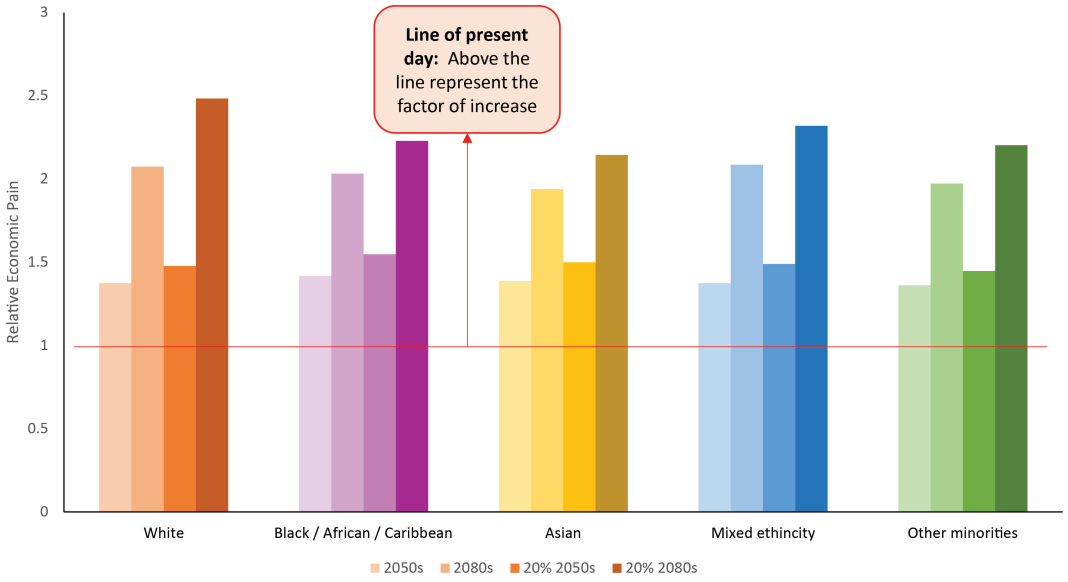
Those neighbourhoods experiencing the highest Relative Economic Pain. Red – coastal floodplains; Blue – fluvial flooding. Given the widespread nature of the surface water flooding it is excluded here. Source: Sayers et al., 2020c

Figure 7-13 Present day – Relative Economic Pain



Source: The UK Climate Change Risk Assessment, Sayers et al., 2020a

Figure 7-14 Present and Future – Relative Economic Pain – By settlement type and social vulnerability

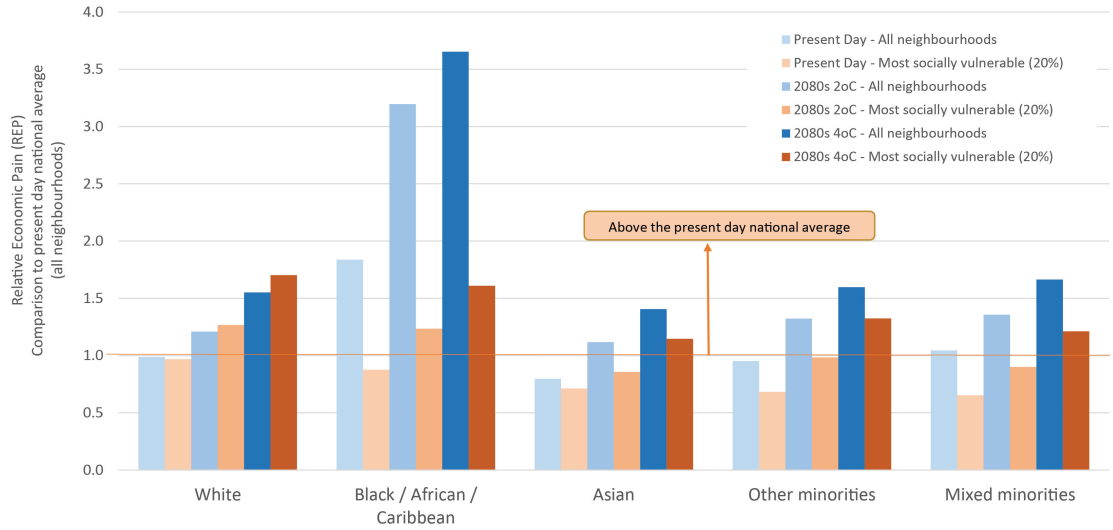


Future risk in the 2050s (2°C) and 2080s (4°C) assuming a continuation of current levels of adaptation are presented relative to present-day risk. Source: Sayers et al., 2020c

Figure 7-15 Future – Relative Economic Pain: By flood source and ethnicity

Further analysis of the relationship between ethnicity, social vulnerability, and flood risk in Scotland (Sayers *et al.,* in press b) confirms Black ethnic groups regardless of social vulnerability, on average, experience much higher levels of risk compared to others (with present-day flood risk, defined using the REP, around 1.8 times higher within the Black ethnic groups compared the national average across Scotland). When comparing the risks faced by the most socially vulnerable within each ethnic group, the most socially vulnerable White groups are most disadvantaged, experiencing a present-day REP similar to the average

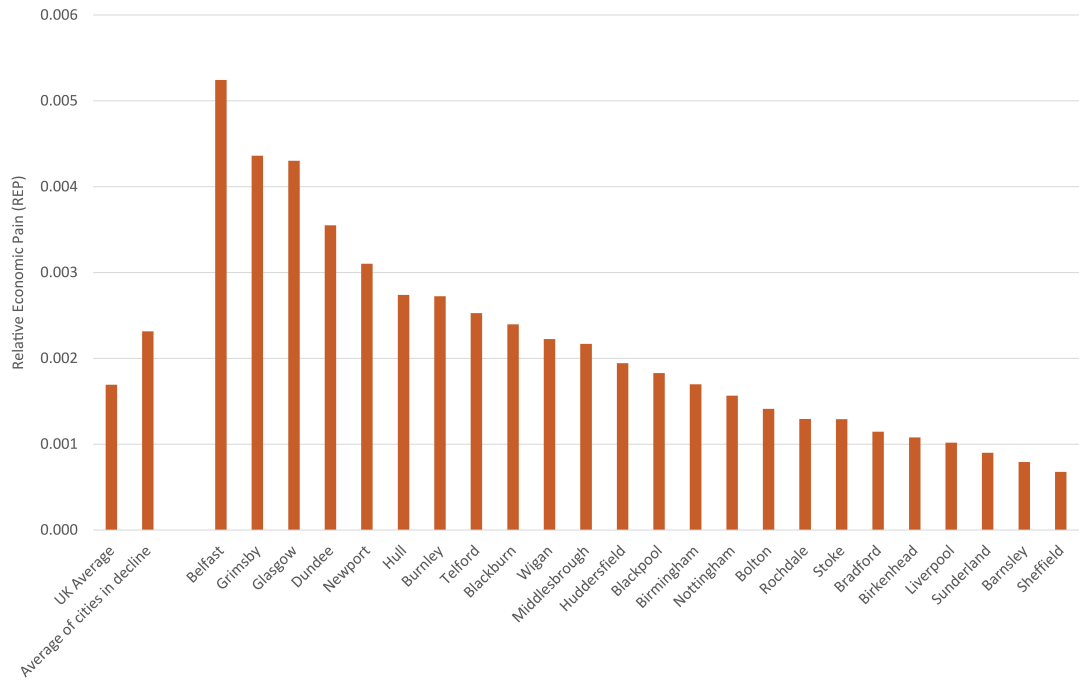
for White ethnic groups and higher REP under climate change (Figure 7-16). The broader social and economic drivers for these issues are difficult to determine but reflect similar issues within the analysis here. Both Black and the most socially vulnerable White groups are more likely than others to be living in socially rented accommodation and are more likely to experience constrained household incomes. These influences lead to both Black groups and the most socially vulnerable White groups experiencing higher levels of REP compared to others.



A value of one indicates the Relative Economic Pain (REP) is equal to the present-day national average in Scotland. A value greater than one indicates the REP is higher than the present-day average by the given factor (i.e., a value of 1.5 indicates the REP is 1.5 times the present-day value). Source: Sayers et al., in press b

Figure 7-16 Relative Economic Pain of flooding in Scotland – By ethnicity

Sixteen of the 24 city regions classed as in relative economic decline (as defined by Pike *et al.,* 2016) experience levels of flood disadvantage above the UK average. This reflects a combination of influences but from the perspective of the analysis here, is driven by higher-than-average levels of social vulnerability (as determined by the NFVI) and a greater than average number of people exposed to a frequent flood (in Glasgow, for example, those living in the floodplain are almost twice as likely to experience frequent flooding than the UK average). When income and insurance penetration are considered, the REP associated with flooding is significantly higher in these sixteen cities, reflecting the lower levels of income (on average) and lower levels of insurance (Figure 7-17).



Source: Sayers et al., 2017c

Figure 7-17 City regions in Relative Decline in the UK: Relative Economic Pain of flooding

7.6 CONCLUSIONS

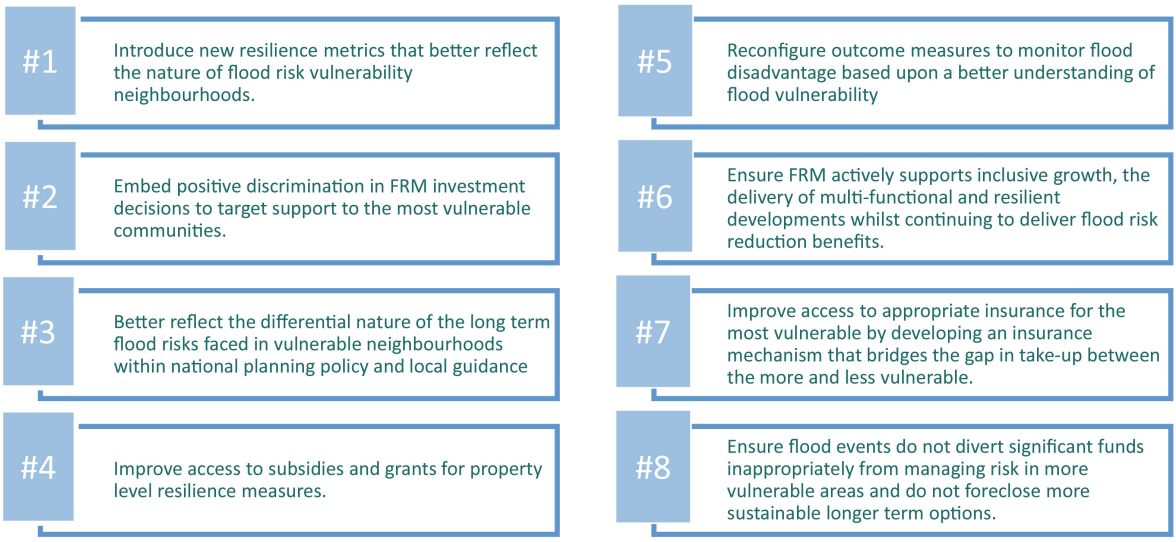
This analysis shows that:

- Providing a quantified description of social vulnerability and the risks faced by the most socially vulnerable provides new insights into issues of disadvantage. This includes using the Neighbourhood Flood Vulnerability Index (NFVI) and Relative Economic Pain (REP) as developed here.
- The most socially vulnerable are disadvantaged by present-day flooding and often the disadvantage increases with climate change.
- Those living in social rented accommodation are more likely to be on lower incomes and are less likely to have flood insurance. This combination increases the 'Relative Economic Pain' experienced when flooded.
- Flood disadvantage exists across all sources to some extent but is most acute at the coast.
- Flood disadvantage exists across all ethnicities, but Black and Other Minority Ethnic Groups are more likely to have lower incomes and more likely to be in rented accommodation; these two factors lead to significantly lower levels of flood insurance and higher levels of disadvantage.
- Those living in rural towns and smaller urban settlements often experience more frequent flooding. The geographic disadvantage is exacerbated by lower levels of income and hence higher levels of Relative Economic Pain.

Policy gaps and recommendations

Two important policy findings emerge from the analysis: (i) the distribution of flood risk today suggests that, in general, vulnerable neighbourhoods have fared no differently compared to less vulnerable neighbourhoods and, in some instances, are at greater risk today, and (ii) the distribution of flood risk in the future suggests the largest increases in flood risk will, in many instances, be experienced by those areas which are currently most vulnerable. This does not imply that the current policy framework is wholly inadequate; there are many good examples of the progressive policy statements across the UK that acknowledge the need to reduce flood risk for vulnerable communities and often refer to prioritising vulnerable groups. Despite these high-level aims a new approach is needed that requires FRM policy to better support broader socio-economic goals (including inclusive and sustainable growth). Doing so will require a stronger Rawlsian approach to positive discrimination (in support of the most vulnerable) to be adopted alongside utilitarian and egalitarian goals.

Seven policy recommendations are made to aid this transition (Figure 7-18). Perhaps central to these is that the analysis suggested that a lack of capacity within the most socially vulnerable communities restricts access to investment and may act as a brake on reducing flood risk and redevelopment. The 'levelling up agenda' (of the Conservative Government, 2022) and regional development pathways both offer opportunities to stimulate local incomes and reduce flood disadvantage. The insights also highlighted systemic barriers to the access of post flood-event grants, including the need for associated 'top-up funding' and difficulties in mobilising landlords to act. The process of grant and community support needed to 'build back better' after a flood should be reviewed in this context. This includes the approach to Property Flood Resilience, and the policy mechanisms needed to ensure it takes account of, and targets, the most socially vulnerable and recognises the challenges faced by most disadvantaged ethnicities.



Source: Sayers et al., 2017c

Figure 7-18 Policy recommendations arising from the analysis

8

CLIMATE EVENT-BASED ASSESSMENT FLOOD RISK

Widespread, spatially coherent flood events can cause severe damage and disruption. Climate change has the potential to change the severity and frequency of such events. Despite this, climate change risk assessments of future fluvial flood risk typically give little to no consideration to potential changes in the spatial structure. To understand the significance of this gap, spatially coherent climate model simulations are coupled with a national hydrological model and a statistical Empirical Copula to develop a set of present and future fluvial flood events. The event sets are used to drive an assessment of flood risk that incorporates local uncertainties in the climate change-driven increases of local flows whilst preserving the spatial structure of the event and takes account of existing flood defences adaptation policies.

The research finds that the future spatial structure of widespread fluvial flood events may be different from today and that such changes have the potential to materially increase projected changes in risk when compared to conventional approaches to climate change risk assessment that ignore them. Excluding changes in the spatial structure of future events may mean projections of future expected annual damages from fluvial flood risk are underestimated by a factor of ~1.5. The event-based approach is shown to provide useful insights beyond expected values, provide new insights into the extreme distribution of single event damage, damage seasons, and damage years of fluvial flood risks across Great Britain. The results suggest the 1-in-100-year winter flood may increase from £1.3bn to £2.1bn and the 1-in-100-year single event damage may rise from £1.1bn today to £1.7bn by the 2080s given a 4°C rise in Global Mean Surface Temperature, assuming current adaptation policies continue and in the absence of population growth. In combination, the findings suggest a much greater emphasis is needed on spatial 'flood events' if future risk is to be understood and adaptation responses appropriately framed.

8.1 INTRODUCTION

Spatially coherent events occur when multiple connected locations are affected by the same or different hazards within a limited time window. Spatially compounding events occur when spatial inter-connectiveness (either through geography, supply chains or infrastructure networks) exacerbates the impacts beyond those that would be anticipated based on an isolated site analysis. Flood hazards are often coherent at regional (or even larger) spatial scales and have the potential to drive spatially compounding impacts (such as those frequently experienced in Pakistan, including in 2022, in Queensland in 2010/11, and across the UK in 1947 and 1953). Recent widespread flood events in the UK (including 2007 (Marsh and Hannaford, 2007) and 2014/15 (Met Office, 2014)) have reinforced the early warning of Evans *et al.,* 2004a,b that *'disruption can quickly lead to widespread and serious consequences'* and that *'proactive measures are needed to improve resilience of (infrastructure) networks'* and motivated the National Flood Resilience Review (HM Government, 2016) to highlight the importance of spatial coherence in driving cascading and escalating risks (for example through infrastructure networks, Pant *et al.,* 2016). Nonetheless the public sector understanding of risk continues to largely ignore spatial correlations in present-day climate, despite research on present-day widespread events (Environment Agency, 2011. Lamb *et al.,* 2010), and remains unsighted on how the spatial structure of flood events may change with climate change. In parallel the private sector is increasingly placing a greater emphasis on understanding risk into the future, taking account of climate and adaptation scenarios. This includes increased regulatory interest in the resilience of financial institutions to present and future climate-related risks (for example, as recognised in the Bank of England Climate Stress Test, Bank of England, 2022) and reflects the recognition that re-insurance and lending (particularly mortgage lending) exposes the risk-taker (lender or re-insurer) to the influence of climate change (*e.g.,* CISL, 2019; Westcott *et al.,* 2020).

The coming together of climate risk assessment needs within the public and private sectors provides the motivation for this paper. The flood risk assessment method and application set out brings together the advantages of the conventional public and private sector analysis for the first time into an event-based national scale climate change flood risk assessment that represents the potential changing spatial structure of fluvial flood events in the future. The approach set out can support multiple scenarios of adaptation and socio-economic change (a prerequisite for public sector applications) and can determine event-based risks today and in future climates (a prerequisite for private sector financial and re-insurance applications and public sector understanding of network resilience).

8.2 OVERVIEW OF ALTERNATIVE RISK FRAMEWORKS

The importance of understanding flood risk and how it may change in the future is now well established as the cornerstone of good decision-making and has underpinned the analysis in previous Chapters (6 and 7). An understanding of present and future Expected Annual Damage (EAD) and other annualised risk metrics have been a central consideration in such assessments and associated national adaptation investment planning (such as those presented in earlier chapters). Other frameworks of risk analysis existing, most notably Catastrophe (CAT) Models, often form the basis of present-day risk assessments within the insurance and financial sectors. CAT models rely upon stochastic event sets to determine a risk profile (the damage conditional on an annual probability of exceedance) as well as expected annual losses across their asset portfolio. Issues of climate change and adaptation have, until recently, played a less central role.

Within this chapter the 'local-dependence framework' applied in the preceding chapters are replaced with an 'event-based framework' with the difference between the two elaborated below.

8.2.1 Local-dependence framework

The term *local-dependence framework* is used here to refer to an assessment that assumes the probability of the flood hazard to be fully dependent across the area of interest. In approach any defences protecting the same floodplain are assumed to experience the same severity of load, say a 100-year return period in-river water level, at the same time. The probability of flood inundation (taking account of the conditional probability of a defence failing or being overtopped) is then determined based on that assumption. This assumption may be reasonable at a local scale (*e.g.,* a small floodplain) but becomes increasingly in error at larger scales.

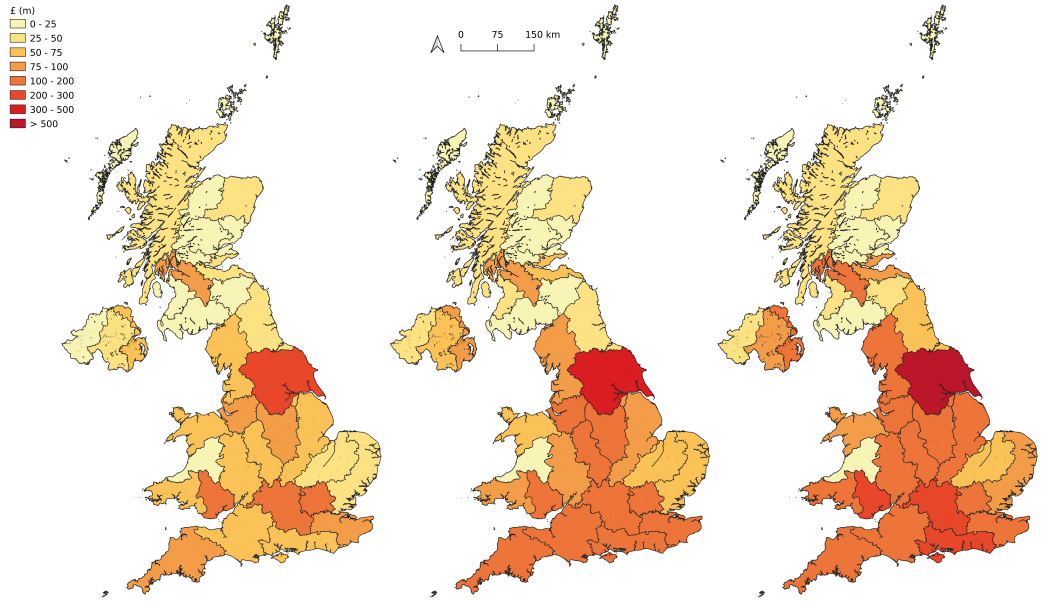
A local-dependence framework typically underpins public sector risk analysis. This includes both the communication of the probability of flooding, the assessment of risk, and adaptation policy. The communication of the probability of flooding, for example, is typically provided through local flood maps that express the Annual Exceedance Probability (AEP) of inundation for a given depth or velocity. Equally, the national case for investment in flood management relies upon a similar assessment, focused on determining the change in probability of flooding at a location and associated reduction in damage given an investment (say, in defences) to determine a change in Expected Annual Damage (EAD), where EAD is routinely determined as (Hall *et al.,* 2003c):

$$\boldsymbol{EAD = \sum_i (P_{i+1} - P_i) \times \left(\frac{D_{i+1}+D_i}{2}\right)} \qquad \textit{Eq. 8-1}$$

where P_i is the AEP of the load i and D_i is the associated damage.

When computing annual damage this way, there is an implicit assumption that the damage varies linearly between D_i and D_{i+1}. The error introduced through this process

(at a local scale) is readily seen to depend on the number of values of AEP for which damages are available; with fewer values, credibility of the assumption reduces, and greater uncertainty is introduced (McGahey and Sayers, 2006). It is also typically assumed that local assessments of EAD can be spatially aggregated through simple addition. This assumption underpins the National Flood Risk Assessment (NaFRA) in England (Hall *et al.,* 2003c; Gouldby *et al.,* 2008) and the flood projections with the UK Climate Change Risk Assessment (Sayers *et al.,* 2020a). This is reasonable given there is no inferred spatial or temporal coherence to the expected annual damage, only that it obeys the general principle that an *aggregated* mean annual damage is the sum of the local means. A typical output from this type of analysis is illustrated in Figure 8-1.



Left: Present-day; Middle: 4°C High Population Growth 2050s; Right: 4°C High Population Growth 2080s. Assuming current adaptation policies continue to be implemented. Source: Sayers et al., 2020a.

Figure 8-1 Expected Annual Damages (GBP): Present and Future – UK

Expected Annual Damage calculated in this way offers a simple and useful view of risk. As introduced in Chapter 4, EAD does not provide a full picture of the significance of the risk faced. Understanding the 'risk profile' (*i.e.,* the relationship between damage and probability) is as important, if not more so, than simply understanding the expected value. By understanding the risk profile, risks with the same numerical value (*i.e.,* low-probability/high-consequence events and high-probability/low-consequence events) can be distinguished and management actions appropriately tailored.

Local-assessment frameworks can be used to provide a local 'risk profile' but these cannot be aggregated to a regional or national scale. This inability reflects the lack of information on the spatial coherence of the AEP assigned to the hazard in different locations. It would be grossly conservative to assume the 100-year return period storm load occurs at all locations simultaneously and that the 1-in-100-year national damage is

simply the sum of the 1-in-100 year damage at all locations. Equally, assuming independence between all locations may dramatically underestimate the likely size of the more severe events (de Luca *et al.,* 2017). Addressing this shortcoming is the central driver of 'event-based' frameworks used extensively in private sector assessments of risk.

8.2.2 Event-based frameworks

An *event-based framework* is used here to refer to an assessment of risk derived from a spatially coherent event set. A spatially coherent event is defined as a set of values of some variable that are linked together spatially in some way, the most obvious connection being that they impact multiple locations *'at the same time'*. In the context of flooding this does not necessarily mean at the same precise time but is typically defined in the context of *'time window'* that reflects the persistence of flood hazard (this is typically used) or the persistence of the potential impacts (increasingly considered in the context of temporal compounding events, *e.g.,* Villarini *et al.,* 2010, Kendon and McGarthy, 2015; Barton *et al.,* 2016, Zscheischler *et al.,* 2020, Sayers, 2013, *in press c*).

Event-based frameworks are typically used within the financial and re-insurance sectors to explore the probable maximum loss that may incur during a single event across a spatially disparate asset portfolio. This relies on an understanding of the 'risk profile' at the spatial scale of the asset portfolio (a scale that may extend to national or even global scales). Catastrophe (CAT) modelling approaches were developed in the late 1980s to service this need. CAT models generate stochastic spatial *'hazard event sets'* and use these to drive an assessment of damage for each event that can then be used to determine an extreme distribution of the damage at any scale of aggregation (as well as an EAD, typically referred to in financial sectors as the Annual Average Loss where the 'average' referred to is the expected, arithmetic mean, value). In most existing CAT models both the marginal distribution of the extreme hazard variables and their dependence structure are inferred from a blend of observations, weather modelling, and present-day climate modelling. Climate projections are rarely incorporated beyond the application of local uplifts (*e.g.,* increasing river flow, rainfall, or mean sea levels to reflect climate change, see for example the Bank of England, 2022).

Extending an event-based risk assessment framework to include climate change has several advantages. By better understanding the distribution of losses today and how these may change an event-based framework provides insights into questions that can help shape the adaptation response:

- What is the national 100-year flood damage today and how might this change in the future?
- What is the chance that many different locations will be affected by severe flooding around the same time (*i.e.,* spatially compounding events)?

- What is the expected flood damage in winter compared to summer, and how is this distribution influenced by climate change?

Whilst the local-assessment frameworks underpinning existing national flood risk assessments are useful in helping prioritise investment decisions, they provide limited insight to the questions above. A disadvantage of adopting an event-based framework is the complexity of the analysis, requiring many thousands of events to be simulated to provide a reliable estimate of risk. This is particularly the case for if extreme, very rare, damage events, are to be captured. In general, the more extreme the impact of interest, the greater the number of events that must be sampled and assessed to achieve a defensible probability estimate for that impact. This is problematic if the aleatoric uncertainty in estimates of national economic losses from single flood events for both extreme (1-in-5000 year) and common (1-in-5 year) events are to be limited.

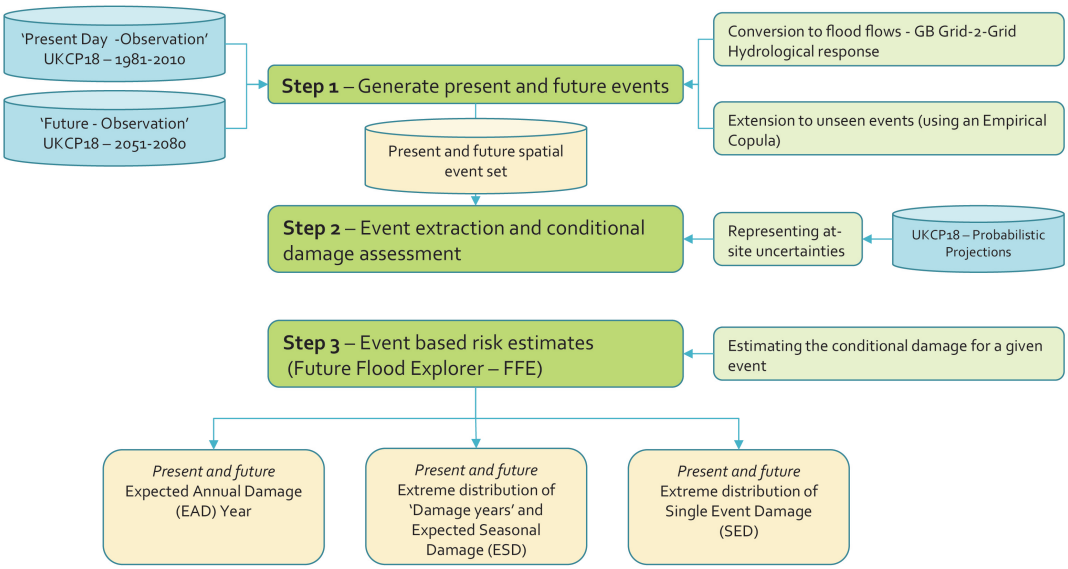
8.2.3 Towards continuous simulation approaches

Continuous simulation-based approaches seek to provide an end-to-end analysis chain of the risk system of interest (including all the sources, pathways and receptors of interest, Sayers *et al.,* 2002a). Continuous simulation approaches that operate within a probabilistic risk assessment framework are emerging but remain computationally challenging (*e.g.,* Mitchell-Wallace *et al.,* 2017). These challenges are being overcome in the context of relatively well-conditioned problems (such as water resources, Jenkins *et al.,* 2021) and hydrological flood simulations and simplified risk assessments (*e.g.,* Smith *et al.,* 2014). Such approaches do not yet offer the capability to undertake credible large-scale risk assessments for systems exhibiting more complex source-pathway-receptor relationships and adaption investment choices (such as those explored in Sayers *et al.,* 2020a using a local-dependence framework). This reflects difficulties in representing the complexity of the interactions within a conventional physics-based model chain and the associated computational expense (at least in the short term).

Given this context, to make progress, spatial event-based approaches are likely to be used increasingly to provide the richness of insights across both private and public sector decision-making whilst maintaining a practical form of analysis. An approach to achieving this that explores the potential influence of the changing spatial structure of storm events in response to climate change (a hitherto unexplored influence) is set out below.

8.3 EVENT-BASED CLIMATE CHANGE RISK ASSESSMENT FOR GREAT BRITAIN

The framework used to support an event-based risk assessment of present and future fluvial flood risk across Great Britain reflects the typical event-based assessment structure but with a significant additional component: the changing spatial structure that may exist in response to climate change. This framework (developed by the author in collaboration with Griffin, Stewart, Carr and Kay) is illustrated in Figure 8 2 and the method of implementation elaborated below.



Source: Sayers et al, in press d

Figure 8-2 Framework of the Event-based Climate Change Risk Assessment – Fluvial Risk

8.3.1 Step 1 – Generate present and future events

The UKCP18 Regional projections (baseline and future projections, Lowe *et al.,* 2018) are used to drive a national-scale hydrological model (Grid-to-Grid, or G2G; Bell *et al.,* 2009). G2G runs on a 1km grid and uses a timeseries of precipitation, temperature, and potential evaporation (PE) from the 12km Regional Climate Model (RCM) to generate a spatially coherent gridded flow series across Great Britain (GB, Kay, 2021a). The baseline results represent the period 1981-2010 and the future projections 2051-2080. The future RCM projections assume RCP8.5 emissions provide outputs for a 12-member perturbed parameter ensemble (PPE). In addition to flood flows the G2G provides an indication of the potential inundation extent (assuming an absence of defences or other flood control structures where they exist).

The G2G simulations are used here as pseudo-observations from which potential widespread flood events are identified. To do so, it is assumed that an 'at-site flood event' occurs when the flow at a site exceeds the flow expected on two days or less per year (on average). This corresponds to a daily probability of exceedance (PoE) of

~0.56%, and, assuming a Poisson approximation, an annual probability of exceedance of ~86.4%, based on a 360-day model year. A widespread 'spatial flood event' occurs when more than 0.1% grid-cells (~20km^2) exceed their threshold '*at the same time'* (defined as a window of 14 days, to avoid the inclusion of consecutive but spatially independent events, Griffin *et al.,* 2022a).

Various methods exist to translate a set of observed events into a simulated spatial event set that includes events unseen in the observed record (*e.g.,* Heffernan and Tawn, 2004; Wyncoll and Gouldby*,* 2013; Tawn *et al.,* 2018). In these methods, analysis proceeds by fitting a probability distribution to peak flow data at Location B conditional on the flow at Location A being above a threshold and being the most extreme value within the domain (the conditional distribution). Unseen events are then typically generated by:

- Selecting Location A within the domain as the most extreme flow for an event.
- Using the at-site distribution at A to determine the peak flow.
- Using the conditional distribution to determine the flow at Location B conditional on the flow at A.
- Together, flows at A and B provide simulated peak flows for a complete event.

The approach used here follows this process and generates new events on a national scale using an Empirical Copula (EC) method (Segers *et al.,* 2017). The use of an EC provides a fast and efficient way to generate widespread flooding events for the whole of Great Britain for all available ensemble members (Griffin *et al.,* 2022b). The approach also preserves the season of each observed and unseen event, a useful insight used later to determine changes in seasonal risk at a national scale.

8.3.2 Step 2 – Incorporate local uncertainties and assign a warming level

The future is profoundly uncertain. To provide an assessment of future risk that is coherent requires the future of interest to be defined. Here three assumptions are made. The first relates to climate change and considers two futures, a 2°C and 4°C rise in Global Mean Surface Temperature (GMST), by 2100 compared to pre-industrial times. Making this assumption enables each individual RCM ensemble member (and the associated events generated in Step 1) to be associated with future scenario using their nominal rise in GMST relative to pre-industrial, derived from the global model in which each RCM ensemble member is nested (Table 8-1).

Table 8-1 Summary of RCM ensemble members. Rise in GMST up to 2050-2080 relative to pre-industrial levels (1850-1900) associated with each RCM (Lowe et al., 2018), and average events per year per RCM ensemble member

RCM ensemble member	Rise in GMST from pre-industrial to 2100 (°C)	Mean G2G-modelled events per year (1980-2010)	Mean G2G-modelled events per year (2050-2080)
1	4.19	20	19
4	4.49	20	24
5	4.02	20	20
6	4.16	18	20
7	4.11	20	22
8	3.82	20	20
9	4.64	20	21
10	3.97	20	20
11	4.14	23	24
12	3.98	19	20
13	4.16	20	19
15	3.82	20	22

To improve the understanding of the influence of climate change on river flow at a given location within a given spatial event, the results from Step 1 are adjusted locally to use detailed at-site analysis. The at-site analysis uses a combination of the UKCP18 Probabilistic Projections and a version of the G2G that includes a wide range of hydrological uncertainties (as set out in Chapter 6). Although Probabilistic Projections are not spatially coherent, they are consistent with the RCM PPE results whilst taking account of a wider range of uncertainties than reflected in the 12 RCM ensemble members. Combined within inclusion of local hydrological uncertainties, this supports an improved estimate of the local changes in flows within the context of each spatial event (from Step 1). This process also provides an opportunity to determine the local uplifts for present day (assuming mean global temperature increase in 1980-2010 relative to 1850-1900 of 0.7°C, Met Office HadCRUTv5.0.1.0 observations, Morice *et al.,* 2021) and for each climate future of interest (either 2°C or 4°C as set out above).

8.3.3 Step 3 – Assess damages conditional on each event

The hazard events (defined by in-river water levels from Step 2) are used to drive a risk assessment. An evolution of the Future Flood Explorer (FFE, Sayers *et al.,* 2015c, 2020a) is used here to provide this estimate. The FFE uses the data produced by national leads (such flood defence crest levels and conditions, flood hazard data and receptor datasets) to develop an understanding of present risks and manipulates that understanding through meta modelling approaches to assess how these change in

response to climate change, population growth, and adaptation. The FFE relies on the development and manipulation of Impact Curves (IC) assessed at the scale of 'Census Calculation Areas' (defined using the intersection of river and Lower Super Output Area census boundaries, yielding 842,864 CCAs for the UK) and takes account of the Standard of Protection and Condition Grade of the individual defences that relate to each one (as discussed earlier in Chapter 6). To support the event-based implementation IC are aggregated to each river node within the G2G model to further enhance computational efficiency (reducing the number of Impact Curves by a factor of 100). Although there is no loss of fidelity in the outputs, this aggregation does reduce the ease with which adaptation and population assumptions can be controlled at a local scale. For the focus of the present study, on the influence of spatial event, a simple no population growth future assumption is made (reasonable given the UK Shared Socio-Economic Pathways show both increases and decreases, Merkle *et al.,* 2022). It is assumed that adaptation polices continues as in the recent past (as defined by the continuation of Current Levels of Adaptation set out in Sayers *et al.,* (2020) and includes a portfolio of responses, catchment management, Sustainable Urban Drainage, forecasting and warning as well as conventional defences).

The assessment of damage used here focuses on direct damage to residential properties. This reflects the dominant category of damage within public sector decision-making) but is recognised as a subset of losses incurred during real-world flood events (including loss of wellbeing, non-residential property impacts as well as disruption to supply chains, energy, communities and transport networks and many others). The focus on residential property provides a well-understood focus with well-established methods to translate exposure to a flood event to economic damage. These methods are reused here with some adjustment to enable their use within an event-based framework. This has been done by reconfiguring the Weighted Annual Average Damage (WAAD) relationship (Chatterton *et al.,* 2010, used widely in the UK to support national assessments, *e.g.,* Environment Agency, 2009; Sayers *et al.,* 2020a) to provide a Weighted Event-based Average Damage (WEAD) function. The WEAD has been developed by factoring out the probability of the event embedded within the WAAD calculation.

8.3.4 Step 4 – Determine risk metrics

The results from Step 3 are used to derive a range of risk metrics, including extreme distributions of single 'event damages', 'damage years', and 'season damages', as well as the mean 'damage year'. The approach to each is set out below.

8.3.5 'Event damage' – Extreme values

Event damage refers to the damage incurred during a single event drawn from the event set associated with a given time slice and climate future. Given it is highly likely that

more than one event will be associated with each year (as determined in Step 1), the return period (in years) of single event is determined used the binomial approximation:

$$\frac{1}{T_D} = 1 - (1 - POE)^{N_{av}} \qquad \textit{Eq. 8-2}$$

where N_{av} is the average number of events per year for a given RCM and time slice. It computes the probability that, if there were N_{av} events in a year, at least one of them would have a probability of exceedance of less than POE. The return period (in years) is determined simply as the inverse of the POE. This is recognised as an approximation but is considered reasonable for return periods greater than five years (Sayers *et al.,* 2015c).

8.3.6 'Damage Year' – Expected and extremes values

To estimate the 'damage year', the G2G-modelled events (Step 1) are used to determine the average number of events per year (N_{av}), for both the present and future climates (Table 8-1). It is assumed that each event occurs independently, and that the full distribution is adequately represented by a Poisson distribution to allow the number of events in each simulated year (N_y) to be determined, where the probability of $N_y = k$ for k=0, 1, 2, … is given by Equation 8-3.

$$P[N_y = k] = \frac{e^{(-N_{av})k} \times (N_{av})^k}{k!} \qquad \textit{Eq. 8-3}$$

To determine an extreme distribution of the 'damage years' (for example the 1-in-5 damage year), damage associated with many event years drawn from a given time slice (present or future) and climate future are estimated using the FFE and the results ranked in descending order of damage. The probability of exceedance for the nth largest event (PoE_n) is then approximated as:

$$PoE_n = \frac{n}{N_{ey} + 1} \qquad \textit{Eq. 8-4}$$

where N_{ey} is the number of event years sampled.

A return period in years of a given value 'damage year' is assumed to be the reciprocal of PoE (as above). The damage incurred during each event can be undertaken aggregated at any spatial scale of interest; national, regional, or more locally (assuming the event set is sufficiently complete to be meaningful at the aggregation of interest). This enables the extreme value 'damage years' to be determined for any region within the model domain. This provides a means for tailoring to outputs to be most useful for a given decision use (e.g., for England only or a local authority).

The sampled number of events for each year are then drawn from each RCM ensemble member (that relates to the climate future of interest) in turn and the conditional damage for each assessed using the FFE. The expected 'damage year' is then simply determined

as the arithmetic mean of the damages summed for each 'year' and equivalent the Expected Annual Damage estimated using local- dependence approaches.

8.3.7 'Damage season' – Extreme value summer and winter seasons

Season damage represents the damage incurred during events sampled from a given season. The link between the climate model and the G2G simulations enables the number of events in each season to be recorded. Based on these 'observations' the probability distribution of the events by season can be determined for each RCM ensemble member (*i.e.,* $p_{DJF,}, p_{MAM}, p_{JJA}, p_{SON}$), where:

- DJF = December, January, February (Winter)
- MAM = March, April, May (Spring)
- JJA = June, July, August (Summer)
- SON = September, October, November (Autumn)

This allows the number of events per season ($N_{DJF}, N_{MAM}, N_{JJA}, N_{SON}$) to be sampled for each simulated year (with N_y events). This is done by drawing once from the multinomial distribution (Eq.3) and returning the number of events per season for a given year. This is under the condition that $n_D + n_M + n_J + n_S = N_Y$, otherwise the probability is zero.

$$P\left[N_{DJF} = n_D, N_{MAM} = n_M, N_{JJA} = n_J, N_{SON} = n_S\right] = \frac{N_Y!}{n_D! n_M! n_J! n_S!} p_{DJF}^{n_D}\, p_{MAM}^{n_M}\, p_{JJA}^{n_J}\, p_{SON}^{n_S}$$

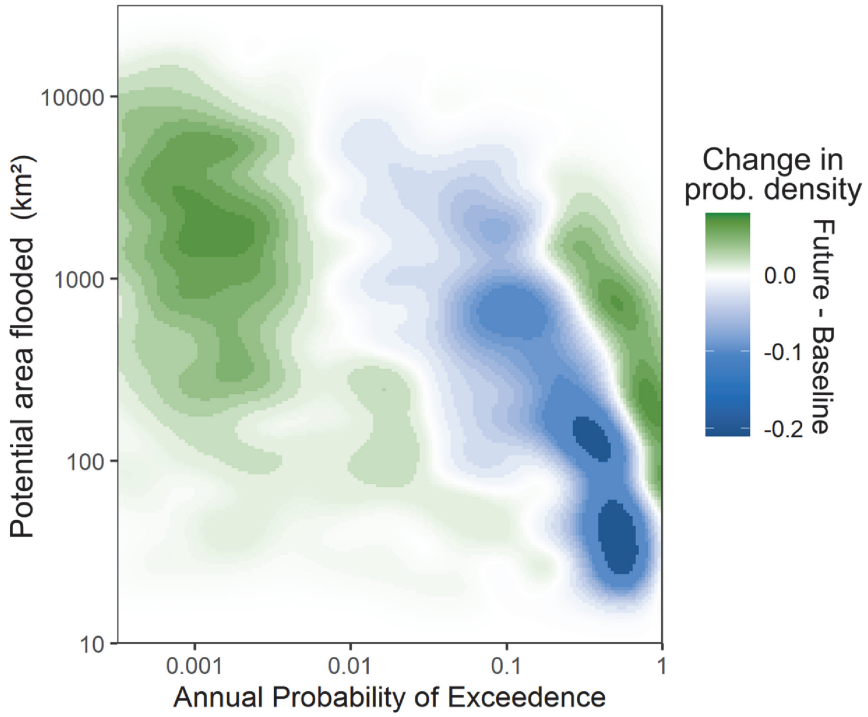
Eq. 8-5

The damage associated with each event drawn from a given season and time slice (present or future) are estimated using the FFE. The damage for each event within each season within a given year is summed to provide a *damage-season*, with return periods calculated as for damage years.

8.4 RESULTS – EVENT-BASED CLIMATE CHANGE RISK ASSESSMENT FOR GREAT BRITAIN

8.4.1 Event damages

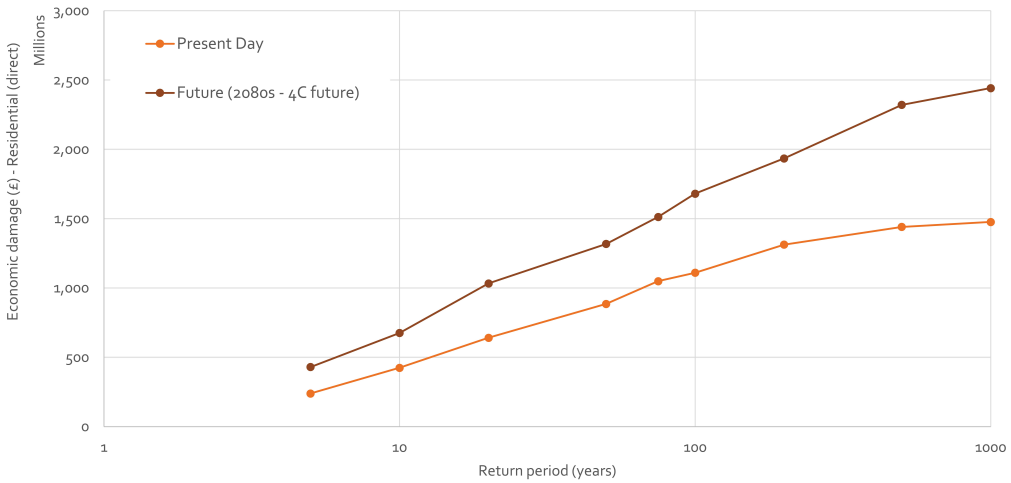
The analysis suggests climate change is driving a change in the structure of widespread flood events. A comparison of the distributions of the baseline and future events highlights an increase in widespread events that include very extreme flows (PoE of < 0.01) as well as widespread events that are formed by much more frequent events (Figure 8-3). The comparison shows the difference in the national scale results from across all RCM ensemble members (based on the event sets generated using the Empirical Copula set out in Step 1).



Positive values (green) indicate more events of this type in the future, negative values (blue) indicate less events of this type in the future. Source: Sayers et al., in press d

Figure 8-3 Heatmap showing the difference in probability density between baseline and future time slices.

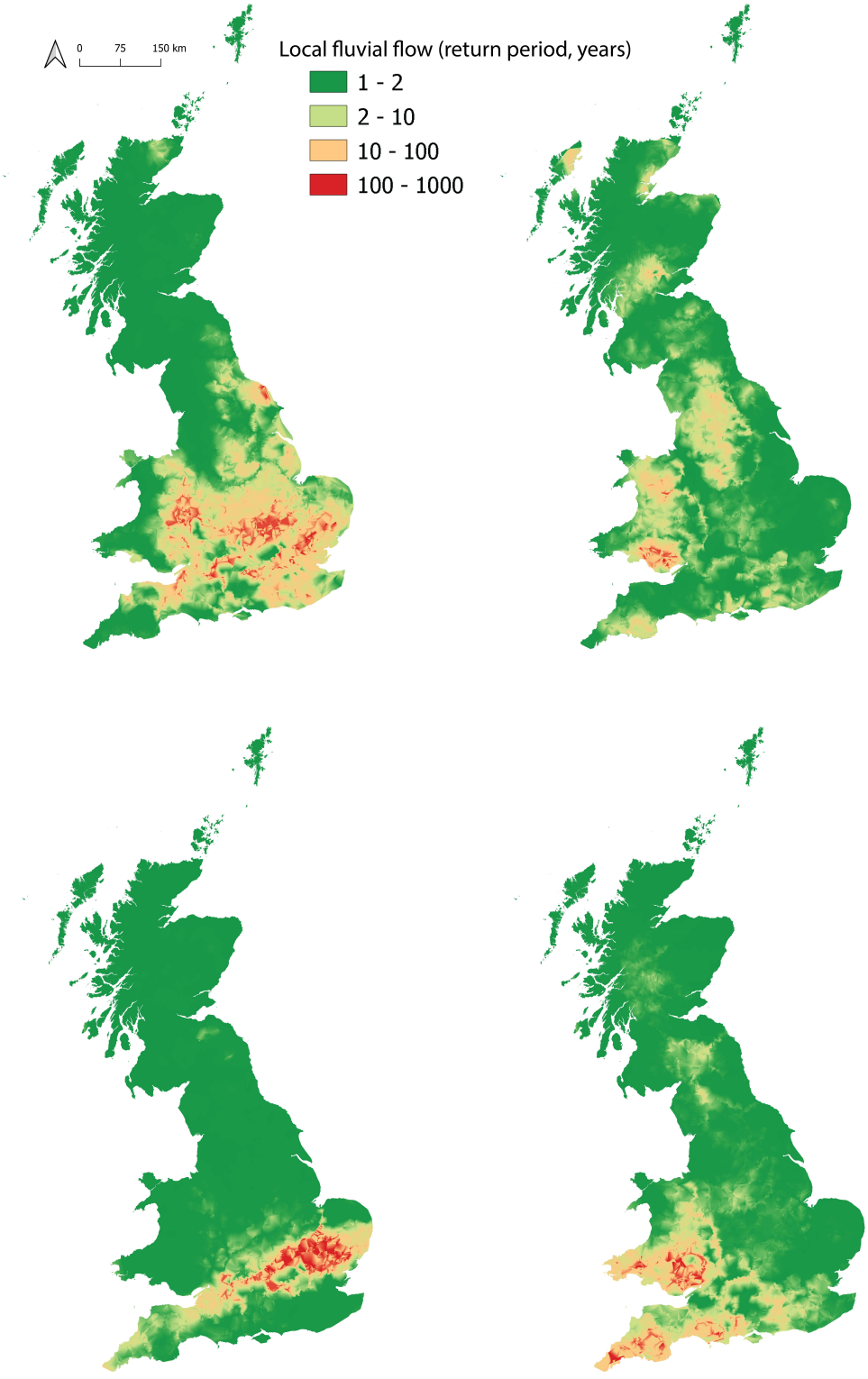
The changing structure of the hazard events combined with local increases in flows translate to a significant change in the extreme distribution of fluvial damage associated with single events (Figure 8-4). The comparison of the damage distribution associated with individual events in the present and future time periods shows a marked increase in damages for events with the same return period in the future (given a 4°C rise in GMST by 2100, no change in population and a continuation of current adaptation policy). The scale of the change increases as the return period of the event increases. This suggests the most damaging events experienced today are likely to become more frequent, and in the future damages from extreme individual events are likely to be much greater than those experienced today. The 1-in-100-year single event damage, for example, is projected to increase from £1.1bn to £1.7bn by the 2080s.



Present and future time slices based on a 4°C increase (by 2100), no population growth, and assuming a continuation of the current level of adaptation. Source: Sayers et al., in press d

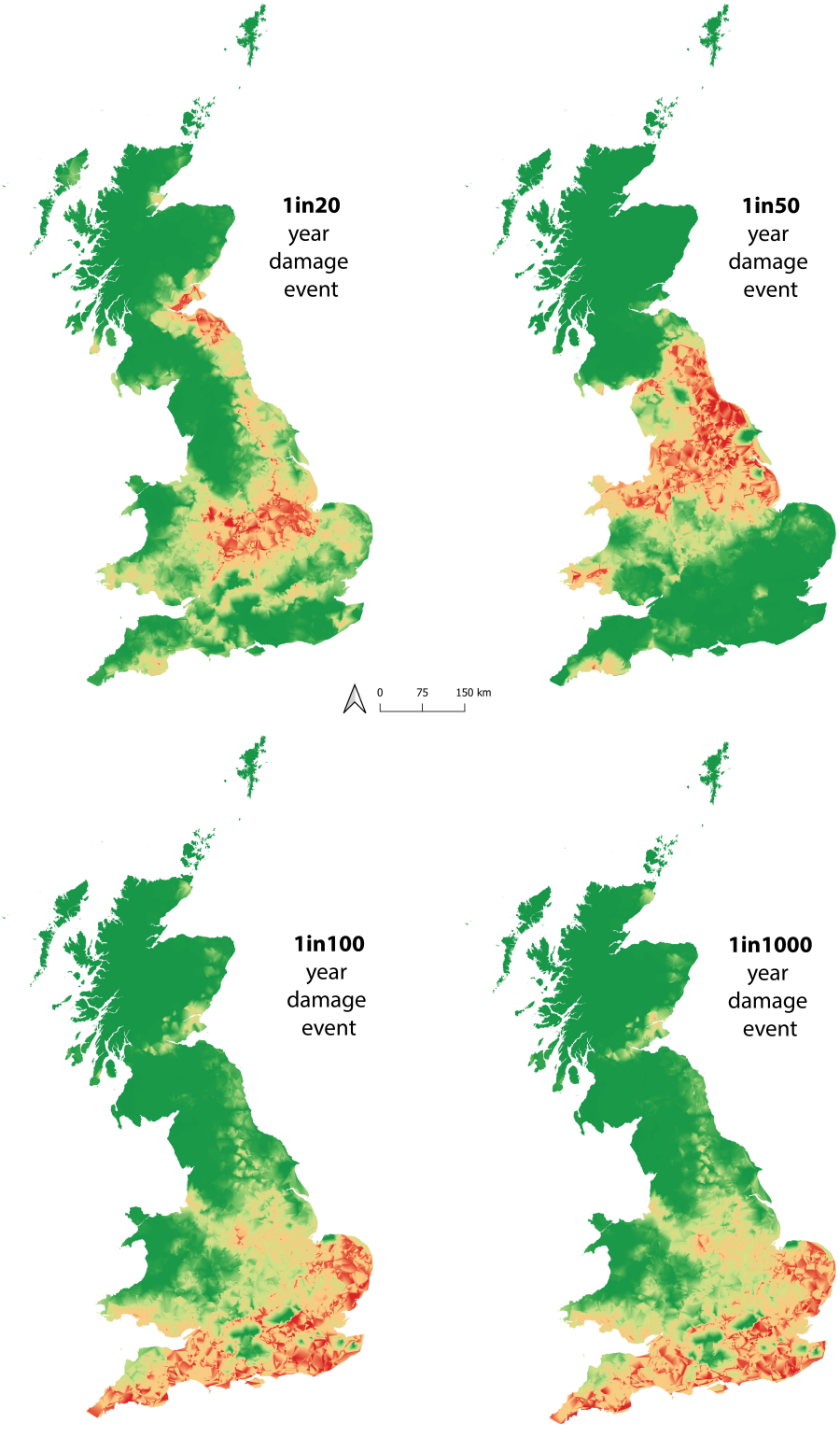
Figure 8-4 Single event direct residential property damage by return period

There is a one-to-many relationship between a given return period 'event damage' and the possible events that may generate an equivalent damage. There may be hundreds or even thousands of events that could generate damage equivalent to the 1-in-10 year 'event damage' (Figure 8-5). The event could be, for example, more widespread with more modest return period flows or more concentrated with higher flows in locations where the floodplain properties may be poorly protected. The number of events capable of generating a given return period 'event damage' reduces as the return period increases. This reflects the need for each a smaller spatial event in which high fluvial flows coincide with areas of higher exposure and possibly lower defence standards (areas in southern England outside of London), or a much larger spatial event that impacts areas with more moderate exposure and standards. These conditions are met by an increasingly smaller subset of events as the return period of the event damage increases. Example events associated with increasingly larger return period damages are illustrated in Figure 8-6 (noting that these are illustrative and alternative events exist for each).



Return period of flood flows shown in years. Source: Sayers et al, in press d

Figure 8-5 Example events yielding an equivalent 1-in-10 year damage year for the baseline period

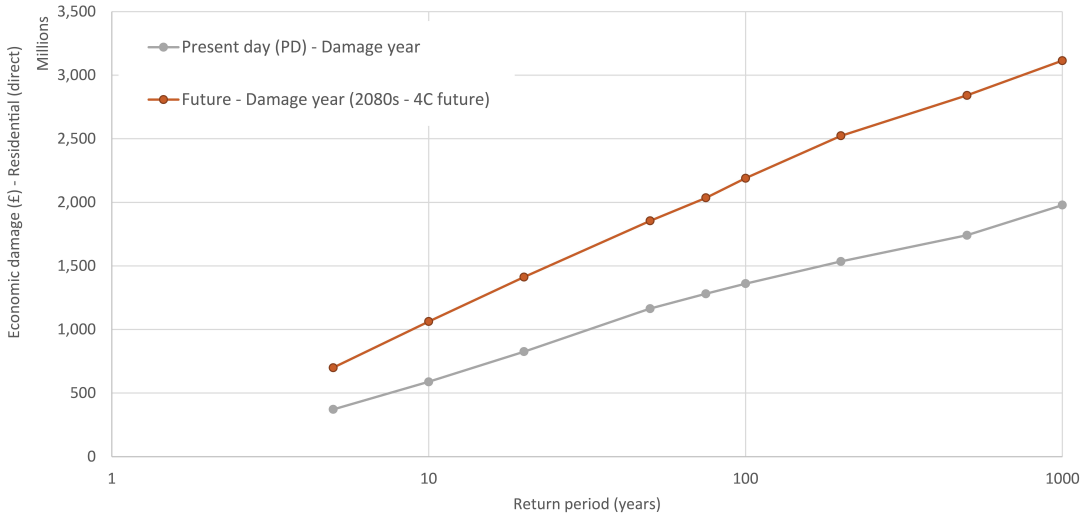


(Top left) 20-year return period, (top right) 50 years, (bottom left) 100 years, (bottom right) 1000 years. Source: Sayers et al, in press d

Figure 8-6 Example events yielding progressively more extreme fluvial event damages for four return periods for the present-day period.

8.4.2 Damage years

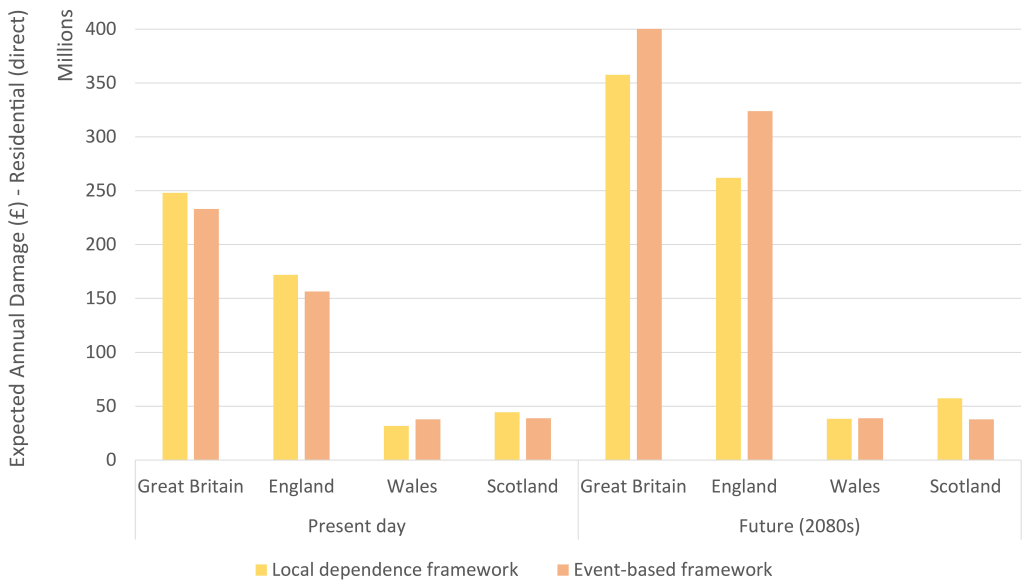
The distribution of 'damage years' provides an insight into the changing national risk profile that is not visible using local return period-based approaches. The analysis suggests a significant increase in frequency in experiencing extreme damage during a year by the 2080s given a 4°C climate future (Figure 8-7). The present day 1-in-100 year 'damage year' is projected become ~20 year 'damage year' and projects significant increases in the 1-in-100 year 'damage year', increasing from ~£1.3bn to ~2.1bn. In very rare years, say the 1000-year 'damage year' the damage incurred could rise by ~60% (from ~£2bn to ~£3.1bn of direct residential damage).



Showing a 4°C increase, no population growth, and current level of adaptation. Source: Sayers et al, in press d

Figure 8-7 National fluvial damage year by return period for present and future

Insights such as those presented in Figure 8-7 cannot be determined using local-dependence frameworks, but it is not only the richness of the information that is of interest here. The results also suggest that excluding the changing spatial structure of widespread events can lead to a systematic underestimation of the influence of climate change on risk. The published UK Climate Change Risk Assessment flood projections (set out in Chapter 6 based on Sayers *et al.,* 2020a) uses a local-dependence framework together with same underlying data on the present-day flood risk systems (the flood hazard maps, flood defences and residential properties *etc.*) as well as the same analysis model as used here but within an event-based framework. A comparison of the Expected Annual Damage from UK CCRA3 and the equivalent metric here (the mean 'damage year') reveals interesting similarities and important differences (Figure 8-8). The underlying risk model – the Future Flood Explorer – and the data on flood defences and receptors is the same in both the CCRA3 and the analysis here. The calculation of the annual expectation of damage is necessarily different in the event-based approach compared to the local-dependence framework (as discussed earlier). The damage function is also modified in form but not content, from the WAAD to the WEAD.



Present refers to the present day (~2018). Future refers to the 2080s given a 4°C rise in GMST, no population growth and a continuation of current levels of adaptation. Source: Sayers et al, in press d

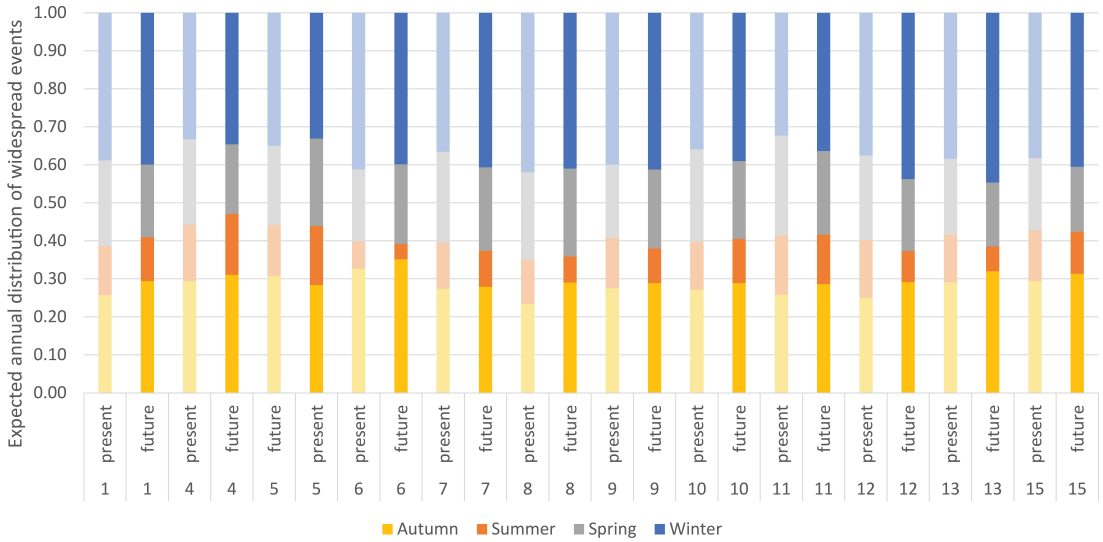
Figure 8-8 Comparison of event-based and local-dependence-based estimates of Expected Annual Damages from fluvial flooding for Great Britain, split by period and region

For the present period, it is not necessarily expected that the results would be the same in the two approaches. Although few changes are made in the underlying risk model, the way the EAD is calculated does necessarily change (the spatial aggregation of the results of local estimates using *Equation 8-1* to the event-based estimate using *Equation 8-3*). This change may yield some variation in the estimate without implying an error in one or both approaches. The closeness of present-day estimates here supports the assumption that the spatial aggregation of EAD (determined using a local-dependence framework) is reasonable and the adoption of an event-based approach introduces slight variation at this aggregated scale (as expected).

The difference in future risk is more interesting. The variation in the projected future risk suggests that conventional approaches (that fail to reflect the changing spatial structure of widespread events) may understate the increase (at least in the context of fluvial flooding as discussed here). The analysis undertaken for the CCRA3 projects a national increase in fluvial flood risk of 44% by the 2080s given a 4°C climate future, no population growth, and a continuation of current levels of adaptation. Given the same scenario, the analysis here suggests an increase of 60%. This suggests representing changes in the spatial structure of future events is important; without doing so the impact of climate change on future risk may be underestimated by a factor of ~1.5.

8.4.3 Damage season

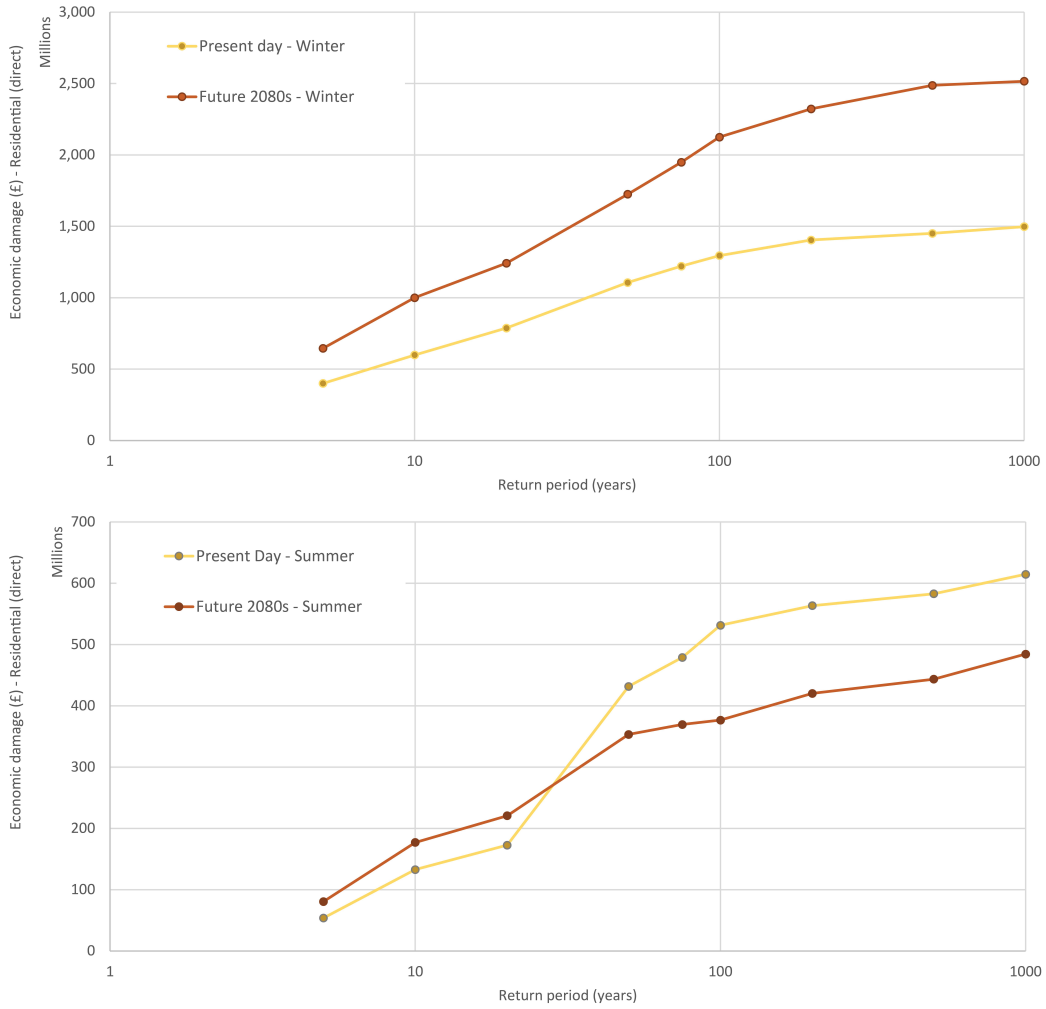
Figure 8-9 shows the relative frequencies of different seasonal events across the two time periods and ensemble members. In general, widespread flood events during winter become more common in the future, and summer events less common. There is some variance between ensemble members, but this trend is common across most ensemble members.



Source: Sayers et al, in press d

Figure 8-9 Distribution of seasonal events – Present and future

The expected 'season damage' during winter is also projected to increase as reflected in an increase in both frequent and very rare winter seasons (Figure 8-10, *top*); with the 1-in-10 year winter 'season damage' increasing from ~£0.6bn to ~£1.0bn (by 2080s given a 4°C climate future) and the in 1-in-100 year return period winter 'season damage' increasing from £1.3bn to £2.1bn. In the summer a more complex story emerges, with the damage associated with more frequently occurring summer seasons increasing (up to the 50-year return period season), but the damage associated with rare summer seasons decreasing with climate change (Figure 8-10, *bottom*).

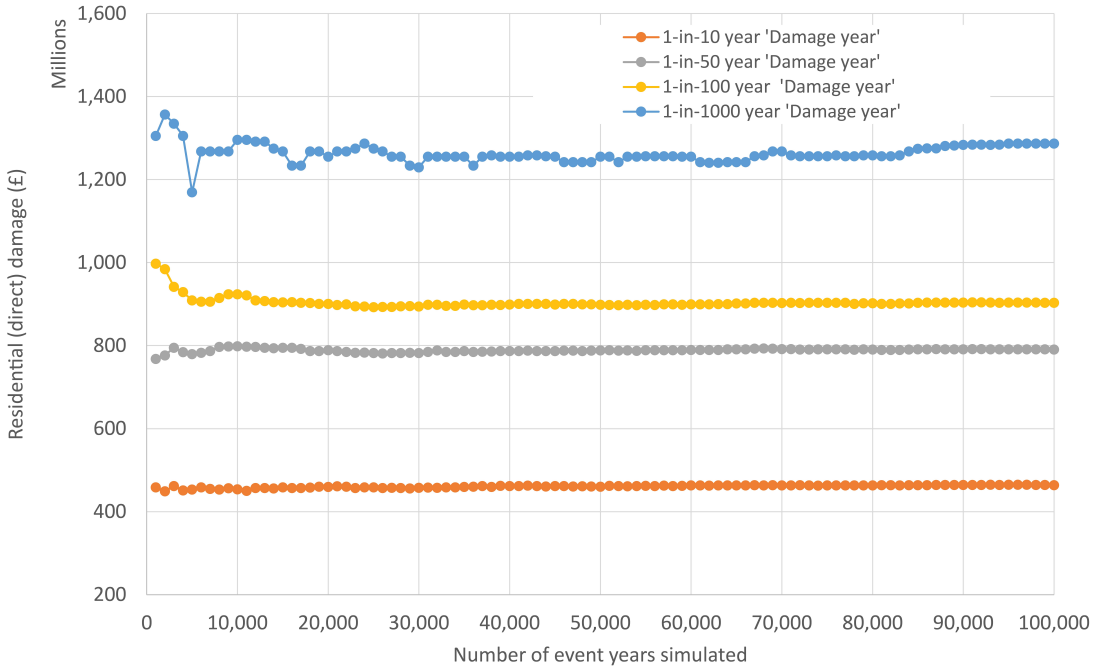


Based on direct residential property damage given a 4°C climate future, no population growth, and current level of adaptation. Source: Sayers et al, in press d

Figure 8-10 Present and future 'season damage' for winter and summer

8.4.4 Challenge of convergence

The computation effort needed to achieve convergence of the 'damage year' estimates increase with rarity (return period) of the damage year of interest (Figure 8-11). Convergence of the 1-in-10 year *'damage year'* occurs within 10,000 event year samples (*i.e.,* ~200,000 simulated events in the FFE), whereas the 1-in-1000 year 'damage year' fails to converge even after 100,000 event years (~2,000,000 simulated events). This is intuitively credible, as one would expect ten times fewer 1-in-1000 year 'damage years' to be observed than 1-in-100 year 'damage years', so it is expected that convergence would take on the order of ten times longer. The variation in mean 1-in-1000 year 'damage year' after ~50,000 event years continues to change (*i.e.,* after 1,000,000 simulated events) but can considered to have converged from a practical perspective at this point.



Residential direct damages only for Great Britain using present-day event set. Source: Sayers et al, in press d

Figure 8-11 Convergence of the damage year by return period for Great Britain

8.5 Discussion

The work in this paper suggests that future spatial structure of widespread fluvial flood events may be different from today. Such changes have the potential to materially increase projected increases in risk when compared to conventional approaches to climate change risk assessment that ignore them. The analysis presented here suggests this difference could be significant and that excluding changes in the spatial structure of future events may mean the increase in fluvial flood risk is underestimated by a factor of ~1.5. This is the central finding of the research and suggests a much greater emphasis on understand the changing structure of 'flood events' is needed (recognising that the analysis here is based on a single GCM driving a single RCM and then the twelve ensemble members used to drive one national-scale hydrological model).

Adopting an event-based approach to climate change risk assessment supports more subtle insights into the influence of climate change on fluvial flood risk in Great Britain than have hitherto been possible. The ability to explore changes in single event damages, seasonal damages, and yearly damages (including both expected values and changes in the extreme distribution of risk) provides a rich evidence base to support better adaptation choices. Understanding the spatial nature of events is a prerequisite to understanding how infrastructure networks, emergency response provision, and any other connection may be influenced as impacts cascade, and potentially escalate, through multiple location experiencing flooding 'at the same time'; an understanding

that is central to developing resilience within connected systems. These insights are not possible with a local return period-based analysis.

The transition to event-based climate risk assessment is a natural evolution of existing approaches; it requires highly efficient damage simulations and models capable of exploring multiple climate futures (via different RCM ensemble members) as well as alternative adaptation portfolios and socio-economic change. Some models do exist to support this (for example, the Future Flood Explorer as used here) but these will need to continue to be developed to address increasingly complex adaptation questions. It is now generally accepted, for example, that the notion of a single 'design' storm is not necessarily an appropriate basis for planning (the *'single design storm is dead',* Sayers *et al.,* 2015a). Temporally compounding events, driven by storm sequences and clusters, are important over multiple timescales.

Capturing the temporally compounding influence of a series of events remains difficult both with the present climate and how they may change in the future. The insights here in the changing 'season damage' also provide some insight. There is a projected increase in winter damage across all return periods, for example, 1-in-100-year winter 'season damage' is projected to increase from £1.3bn to £2.1bn. In the summer a more complex story emerges, with the damage associated with more frequently occurring summer seasons increasing (up to the 50-year return period season), but the damage associated with rare summer seasons decreasing with climate change.

The analysis presented here provides an initial analysis with multiple further strands of activity to explore. This inclusion of multiple sources of flooding (coastal and pluvial for example alongside fluvial flooding considered here), the extension to temporal sequence and the exploration of the influence of alternative GCM, RCMs and hydrological models on the findings are all obvious development areas. The analysis has obvious links to assessment of connected infrastructure as well as climate stress tests within the financial sector where coherent (in time and space) risks are important considerations. Adaptation actions performance in the context of real flood events are inherently spatial. Exploring alternative adaptations within the event-based risk assessment framework offers multiple opportunities to represent changes in the receptor profile during the year, for example to reflect summer and winter property occupancy or vary agricultural damages depending on the season and understand how adaptation influences risk at different scales.

The challenge of validating probabilistic risk assessment remains. This is central but the progress towards representing real events provides a useful foundation for observational comparisons and the improvements in the data and modelling analysis that would no doubt result.

9

CONCLUSION: TOWARDS A STRATEGIC APPROACH

The global focus on flood risk management continues to increase, yet the annual average damage caused by flooding also continues to increase (Swiss Re, 2022). A new approach to flood management is needed. This includes ensuring flood risk management is aligned with important and parallel socio-economic policies and supporting governance systems. It also promotes the use of a portfolio of measures (including natural and built infrastructure responses alongside broader actions) to deliver multiple outcomes for people and nature over the short and long term.

How flood events have shaped the evolution of flood management, and how they continue to illustrate some of the challenges that remain, has been explored. To help address these residual issues, influential concepts and methods from inside and outside of flood management have been discussed and woven into a framework of Strategic Flood Risk Management (SFRM). Exploratory tools to support this strategic approach have been developed and applied in a series of national scale assessments. The tools have been shown to be practical and the insights useful, including quantified insights to support socially just adaptation. A small number of 'Golden Rules' to enable the implementation on SFRM emerge from the research. These are discussed and presented alongside the demonstration of the assessment tools and illustrations.

The research is not complete. Continued advances in science, practice, and policy will be needed more than ever as society grapples with its future. Some of the most important of these knowledge gaps are discussed in final chapter (Chapter 10).

9.1 INTRODUCTION

This thesis has shown how modern flood risk management has emerged over the past decades in response to lessons learnt from flood events and advances in science and engineering. This process of change continues at an accelerated pace as the need for a more strategic approach is increasingly acknowledged. Such an approach recognises that there is seldom a single solution to managing flood challenges and promotes the use of a portfolio of measures and instruments (Evans *et al.,* 2004a&b, Klijn, e*t al.,* 2012, Sayers *et al.,* 2014, van Herk e*t al.,* 2015). The UK Climate Change Risk Assessment reinforces this finding and calls for an enhanced whole system approach to flood risk management (Sayers *et al.,* 2015c, 2020a). Such an approach is defined as one that brings together actions to manage the sources and pathways of the flood waters (including use of conventional built flood defences in support of natural infrastructure); to reduce exposure to flooding when it occurs (through better spatial planning); and, to reduce the vulnerability of those receptors that may be exposed (by improving flood forecasts and warnings as well as policy instruments, insurance, and homeowner grants for flood proofing).

There is also a recognition that the criteria for assessing flood risk management activities should involve consideration of a much broader set of outcomes, moving beyond readily defined direct economic impacts. This includes outcomes for the most socially vulnerable (*e.g.,* Sayers *et al.,* 2017a), ecosystem services (*e.g.*, WWF, 2011, SEPA, 2012, Environment Agency, 2014), and economic opportunities (*e.g.,* Pike *et al.,* 2016, Sayers *et al.,* 2017c). Equally, an increasing recognition of non-stationarity within the flood system (climate, geomorphological and socio-economic change) forces an explicit consideration of a full range of plausible ways in which flood risk may shift in the future. This includes moving beyond the use of simple climate uplifts (*e.g.,* in flow or sea levels) to consider how climate change may influence flood risk in more subtle ways. This includes changes in the temporal sequences that may influence defence fragility (e.g., changing drought and flood patterns, Sayers *et al.,* 2015c) or changing the spatial (widespread) structure of flood events (e.g., Sayers *et al., in press d*).

This thesis combines the exploration of theoretical frameworks (such as system risk, adaptation, and justice) with the development of supporting tools (such as the Future Flood Explorer, FFE) and new metrics (such as the Neighbourhood Flood Vulnerability Index, NFVI, Sayers *et al.,* 2017c). Through a series of national scale assessments, the system-based approaches developed here have been shown to provide new insights to help shape policy and practice of SFRM. These assessments consider multiple climate and population scenarios as well as alternative whole system adaptation responses that encourage a move away from the narrow defence led *'implement and maintain'* philosophy of conventional flood defence approaches.

9.2 OBJECTIVES MET?

The overarching aim of the thesis is to set out a strategic system-based approach to the analysis and management of flood risk that delivers longer term resilience, ecosystem health and promotes social wellbeing. In Chapter 1, this broad aim is translated into a series of objectives. These objectives are revisited below with a brief critique of the advances made.

9.2.1 Objective #1

Provide a perspective on the evolution of flood management, to ensure past lessons provide the foundation of the approaches presented.

Chapter 2 reviews the evolution of flood management. This historical perspective reveals progress to have been painfully slow with sporadic lessons repeatedly 'learnt' in response to major events. The 1917 floods on the Mississippi River, for example, highlighted the need for basin scale planning; a goal that remains difficult to achieve today. More recently the 2015/16 flooding in England highlighting the importance of understanding the resilience of infrastructure networks; an issue that remains a challenge today. Although rather sporadic, this largely heuristic approach is shown to have yielded some important advances, from the importance of forecasting and warning (a central lesson from the 1953 floods across the North Sea), to acceptance that defences fail, and the need for environmental and social safeguards. The importance of good governance has been a lesson repeatedly taught (and a central lesson that Integrated Water Resource Management (IWRM) seeks to respond to).

The review of recent floods illustrates challenges persist, including:

- How to deliver appropriate (practical) integration of flood management and other activities, including planning and social policy
- How to work with natural processes to promote multiple benefits and still deliver appropriate certainty of flood management.
- How to provide long-term solutions capable of responding to a deeply uncertain future.

Overall, the review past events highlights the folly of reactive responses. Actively reactively in the aftermath of flood can simply reinforce existing problems and fail to reset the direction towards a more resilient future. Breaking this hydro-illogical cycle (an apt phrase borrowed from Donald Wilhite) is the challenge that underline the need for a new more strategic approach.

9.2.2 Objective #2

Ensure emerging approaches and frameworks from outside conventional flood management are appropriately considered and the opportunities they provide grasped.

Chapter 3 explores a wide range of frameworks from across disciplines and sectors both within and outside of flood management. These are used to shape the approach advocated here, including the understanding of risk and resilience, the philosophy of 'fairness', the concepts of Sustainable Development, adaptation, and many others. How these frameworks and concepts have influenced, and continue to influence, flood management is discussed. Taken in-combination, flood risk management has evolved to place a much greater emphasis on managing risk and promoting multiple benefits and opportunities (ecological, societal, and economic). In doing so, flood risk management has progressively moved away from conventional *defence-led* paradigms (often characterised by single objectives) towards the use of a portfolio of measures that balance multiple objectives. This direction of travel underpins the SFRM approach advocated here (see #3 below).

9.2.3 Objective #3

Present the framework of Strategic Flood Risk Management (SFRM) and distil a small number of 'Golden Rules' that guide this approach.

Chapter 4 sets out Strategic Flood Risk Management (SFRM) as an approach that relies upon an adaptable portfolio of measures and policies to deliver outcomes that are socially just, contribute positively to ecosystem services and promote flood resilience. SFRM offers a practical policy and planning framework that is risk-based and avoids a narrow focus on reducing the chance of damage through the provision of 'strong' structures. The recognises adaptive management as much more than simply 'wait and see' enabling a transparent trade-off benefits and costs over the short and long term. The practical focus of SFRM sets it apart from conventional 'integrated' paradigms that fail to capture the reality of complex planning processes and motivations. SFRM accepts there is no silver bullet to flood issues and that people and economies cannot be fully protected from flooding. Instead, a broad definition of the flooding system is promoted, including the sources, pathways, and receptors of risk (the SPR framework introduced to flood management in Sayers *et al.,* 2002a) with management actions prioritised based on an understanding of risk and opportunity over the short and longer term.

The small number of Golden Rules distilled in 2014 by the author and colleagues to guide the implementation of SFRM are revisited in Chapter 4. They are found to remain relevant and readily elaborated to today's context. They have also been used in practice. The approaches promoted by Queensland Reconstruction Authority, Australia in response to the many floods in 2010/11, for example, drew inspiration from these rules (personal communication Graeme Millighan, QRA). In China they have been translated into Mandarin by the General Institute of Water Design and Planning, and in

the US they have helped the Corps of Engineers move flood risk management forward (personal communication Gerry Galloway). Within Europe, the Golden Rules underpin various North Sea Region programmes such as FAIR (FAIR, 2020) and C5a (Cloud-to-Coast, Sayers *et al.,* 2021a). Within the UK they have shaped the approach to the UK Climate Change Risk Assessment flood projections and the called for an 'enhanced whole system' approach (Sayers *et al.,* 2015c, 2020a).

9.2.4 Objective #4

Present supporting methods that enhance a system-based approach to SFRM and illustrate their utility through example applications at national and regional scales.

Chapters 5 to 8 demonstrate the practicality of large-scale quantified system-based risk assessment and the exploration of alternative futures (in climate, population, and adaptation).

Chapter 5 focuses on a regional application of the RASP method in support of the Thames Estuary 2100 studies, London (*e.g.,* Sayers *et al.,* 2004, 2006, Gouldby *et al.,* 2008).

Chapter 6 presents a national scale assessment of how flood risk may change given different futures. A highly efficient exploratory modelling approach is developed and enacted in the Future Flood Explorer (FFE) to support the assessment (Sayers *et al.,* 2015c, 2020a). The FFE is shown to be capable of exploring how flood risks may evolve in response to alternative climate, population, and adaptation futures.

Chapter 7 extends the national assessment to provide new quantified insights into issues of social justice. The ability to provide a quantified understanding of the risks faced by the most socially vulnerable compared to the less vulnerable (using the Neighbourhood Flood Vulnerability metric, as defined by Sayers *et al.,* 2017c) highlights, for the first time, the systemic flood disadvantage within the UK and the individual factors that influence social vulnerability.

Chapter 8 revisits the national assessment using an event-based approach to climate change risk assessment rather than the local-dependence framework used in Chapters 6 and 7. This national analysis illustrates, again for the first time, the influence of climate change on the spatial structure of flood events, suggesting a local dependence framework (that ignores the change in spatial structure) could underestimate the change in flood by as much as 50% (Sayers *et al., in press d*).

9.2.5 Objective #5

Identify priority knowledge gaps and areas of further research.

The strategic approach advocated here is not the last word. Continued innovation in the concepts, analysis methods and decision approaches as well as further demonstration in real-world case studies will continue to be needed. Four priority areas are identified for the focus of further research. These are presented in the final chapter.

10

FURTHER RESEARCH

Many (perhaps all) aspects of the research presented here could be improved and evolved. Of those, four priority areas for further research and development emerge from the thesis. These are set out below.

10.1 Towards a 'whole' system analysis of risk and opportunity

The system analysis methods developed here provide a useful first step but are not yet a 'whole' system assessment. As flood risk management moves to be part of a broader planning framework the demands of the system analysis are also set to expand.

Bringing together multiple strands of understanding will be central to developing a 'rich' understanding of risk (to people, the economy, and nature) and the opportunities alternative management approaches offer. This will include spanning scales of time and space, crossing disciplines and sectors (infrastructure, nature, development etc.), as well as involving professional and lived experiences. Doing so remains a significant challenge, but developing a more complete understanding of system behaviour is a prerequisite to better management

Achieving this will necessarily require collaboration been disciplines, technology, and those with lived experience of the issues. Developing the semantics, data, and methods to enable such a 'whole system' without losing practicality and utility in their ability to support policy and action will be a significant next step.

10.2 Advances in knowledge: Sources, pathways, and receptors

An understanding of flood risk relies upon our understanding of the associated sources, pathways, and receptors. Improving our understanding of the performance of built defences (particularly how they deteriorate under the influence of complex load sequences) and natural infrastructure (in a comparable way to built infrastructure) will be an important advance to help develop solutions that combine the two. Improving our understanding of the short- and longer-term impact of flooding on a wider range of receptors (including physical and mental health issues as well as economic damage and the environmental harm) will be needed to ensure strategies are well founded. This will include maximising the use of natural infrastructure to promote healthy ecosystems, improving our ability to differentiate impacts across different social groups (building on the NFVI), and developing a better understanding of how impacts cascade and escalate in space and time through receptor networks.

Maximising the use of blended observations from formal and informal, remote, and in-situ data streams presents a significant opportunity to a better understand the social and physical world around us and how the impacts of flooding manifest. We are only just beginning to realise the potential from Machine Learning (and data science techniques) in helping us better understand the insights from the myriad and disparate data sources in a meaningful way. Continuing to connect social, ecological, engineering and science will be a significant area of research in the coming years.

10.3 ADVANCES IN FAIRNESS AND INCLUSION IN THE DECISION PROCESS

Central to any decision to intervene in natural processes is a consideration of risk and opportunity, how these are influenced by future change, and the whole life cost of acting. Improving our ability to explore the future and identify who benefits and who pays given different choices will be needed to ensure fair outcomes and to encourage decision-makers to invest now in adaptive capacity. Doing so will require advanced analytics (building upon approaches such as valuing adaptive capacity and dynamic pathways) and engagement to co-design solutions. Improved approaches to collaboration and communication that provide a clear and accessible, but not 'dumbed' down, representation of risk is also needed. This will be necessary to support meaningful a co-design process and to successfully influence decision-making and funding.

10.4 ADVANCES IN THE WAY WE TEACH

Creativity will be at the heart of progress towards SFRM. The assessment, identification and development of innovative strategic designs involves ingenuity coupled with an intimate understanding of the performance of design alternatives, in particular context and locations. This is not something that can be readily taught via the lens of a single discipline. As geography, engineering, architecture, planning, and computer science increasingly merge within flood management teaching and professional bodies will need to find a way to reflect this without losing the depth of knowledge that is needed to ensure domain expertise remains.

APPENDIX A
SUPPORTING DATA SETS

A.1 Hazard: Coastal, fluvial, surface water and groundwater flooding

The input data sets relating to present and, where available, future coastal, fluvial, surface water and groundwater hazards are summarised in Table A1-1 together with the supporting ancillary data in Table A1-2.

Table A1-1 Hazard data: All sources of flooding

Flood Hazard Data				
Country	**Fluvial**	**Coastal**	**Surface Water**	**Groundwater**
England	Including the performance of defences: State of the Nation – Environment Agency Product: Risk of Flooding from Rivers and the Sea – Detailed (50m resolution). March 2018 Excluding defences: England Flood Risk Map for Planning (Flood Zones) for 0.1% (FZ 3), 1% (FZ 2). January 2019 Note: FZ3 plus a buffer of 100m fluvial and 500m coast used to define the floodplain with a notional 1in5000 return period assigned.		As used in CCRA2 (Sayers *et al.,* 2015c) based on uFMfSW (updated Flood Map for Surface Water), 2m resolution grid for 0.1%, 1% and 3.3% probabilities. Note: 1in1000 year used to define the limit of the floodplain	From CCRA2 (Sayers *et al.,* 2015c, MacDonald *et al.,* 2008)
Wales	National Flood Risk Assessment (Natural Resources Wales). Resolution 2m resampled to 20m (Received February 2019). Excluding defences: All three sources for six present day return periods, 10, 30, 75, 100, 200, 1000 years (20m resolution). Note: The 1in1000 with climate change (upper) used to define the floodplain (assumed notionally to be 1in5000)			As above
Scotland	SEPA national fluvial flood maps (April 2018). Variable resolution: 5m/10m/20m Including defences Assumed to perform perfectly to their standard of protection – 10, 30, 50-, 100-, 200- and 1000-year return period and 200 year plus climate change by 2080 Excluding defences 1in1000 year (note that defences that feature in the underlying DTM have not been removed as part of the SEPA analysis) Note: The 1in1000 undefended plus a buffer of 100m is used to define the limit of the floodplain (notional return period of 1in5000)	SEPA national coastal map (February 2019) Variable resolution: 5m/10m/20m Including defences Excluding the influence of waves, and defences assumed to perform perfectly to their standard of protection – 10, 30, 50-, 100-, 200- and 1000-year return period Excluding defences The 1in10000 still water level (present day) is used to define the limit of the undefended floodplain	SEPA national and regional surface water studies (regional analysis used where available). Resolution variable. Return periods available are 10, 30, 50, 100 and 200 year. Assumed drainage capacity of 1in5 years (for regional analysis) and 12mm/hr (national analysis). Note: Here adaptation influences present day drainage from a baseline of 12mm/yr Note: 1in200 is assumed to define the surface water boundary extent	As above

Table continued…

Northern Ireland	Flood Maps (NI) – Floodplain Rivers – Premium (LPS / DfI Rivers – Flooding: Product 5). Including defences Assumed to perform perfectly – Present day 2,5,10,25,50,75,100,200 and 1000 return period flows; Climate Change 100 yr return period flow (19th Dec 2018). *Excluding defences* Undefended flood map, extent for 1in100 year return period (present day) Note: The 1in100 undefended is used to define the limit of the floodplain	Flood Maps (NI) – Floodplain Tidal – Premium (LPS / DfI Rivers Flooding: Product 6). Including defences Assumed to perform perfectly – Present day 10,50,75,100, 200 and 1000 return period flows; Climate change 200 yr Return period (19th Dec 2018) *Excluding defences* Undefended flood map, extent for 1in200 year return period (present day) Note: The 1in200 undefended is used to define the limit of the floodplain	Flood Maps (NI) – Surface Water (LPS / DfI Rivers Flooding Product 3). Contains All NI - I200, I200CC, depths and extents. With I30 + I1000 data added to Product. (19th Dec 2018) Note: The 1in1000 present day is used to define the limit of flood extent	As in CCRA2 (Sayers *et al.,* 2015c)

Table A1-2 Ancillary data

Ancillary data		
Country	**River and Coastal Assets**	**River centreline and coastline**
England	Continuous Defence Line (CDL), March 2018: Location Condition Grade Standard of Protection RASP Type	Embedded in CDL (so no longer used here)
Wales	Data extracted from AMX by Chris Powell 29th November 2018. Location, Condition Grade, Standard of protection, RASP Type	Via the NRW Ordnance Survey Mastermap
Scotland	Inland (river) defences: From SEPA – January 2019 and infilled as necessary using the CCRA2 datasets Coastal defences From Dynamic coast Scotland (July 2018 type and location only) – Standards and condition from CCRA2 (based on SFDAD v1_1, February 2015) Spatial data Location Condition Grade Standard of Protection SEPA highlight these data continue to evolve and has known inaccuracies but represents the best available and is assumed corrected here.	River centreline – (DRN for Scotland – as used in CCRA2 based on May 2015) Coastline (from dynamic coast – NCCA_SCOTLAND_MHWS_MODERN, Oct 2018 infilled with CCRA2 dataset based on OS MM Jan 2015)
Northern Ireland	Flood Defences from the asset register / database (March 2019) Spatial data Location Condition Grade Standard of Protection Areas benefiting from defences (February 2019)	Enhanced River Centreline dataset (LPS / DfI Rivers Flooding Product 8) – Detailed River Network (received February 2019) Coastline (received February 2019)

A.2 Property: Residential and non-residential

The datasets used to support the property-based risk metrics are listed in Table A2-1

Table A2-1 Property-related metrics and data sources.

Data sources				
Type	**England**	**Wales**	**Scotland**	**Northern Ireland**
Property residential Property non-residential	National Receptor Dataset (as used in State of Nation 2018)	National Receptor Dataset (NRD,2018 – draft final)	Receptor data as used in 2018 NFRA (based on OS address base plus) – 28 Nov 2018	OSNI Fusion Largescale Buildings (Dec 2018) and POINTER datasets
Proportion of basements	Defined using Census datasets (Sayers, *et al.,* 2017) Scotland: from Receptor datasets			
Economic damages residential	WAAD (Weighted Annual Average Damages) tables per property from Multi-Coloured Manual (MCM – September 2015) with an uplift to present day (using ONS GDP growth) and to account for basements (1.5* probability of being present)			
Economic damages non-residential	Floor areas from footprint in OS Mastermap/OSNI Large Scale Vector WAAD tables per unit floor area from MCM (September 2015) with an uplift to present day (2019).			
Indirect and intangible economic damages	Indirect damages are assumed 70% of the direct residential damages, disaggregated as follows: 11% uplift to account for indirect losses associated with emergency services and provision of temporary accommodation (applied to residential losses only); 16% uplift to account for indirect losses for risk to life and physical injury; 43% uplift to account for indirect losses for impacts on infrastructure, transport, schools, and leisure. This value is broadly confirmed by a review of the winter 2015 and 2016 floods by the Environment Agency (2018) that infers the following contributions: Temporary accommodation (the costs of temporary accommodation) – 3% Vehicle damage (physical damage to vehicles) – 3%; Loss of life and physical injury – 15% (based on 2007 floods); Emergency services (additional costs (for example, overtime) incurred by the emergency services (fire, police, and ambulance services) – 0.5%; Local authorities (damages to public buildings, public spaces and additional costs faced by local authorities such as recovery grants) – 10% ; Transport (costs of repairs and induced losses from disrupted journeys for road and rail) – 20%; Utilities (costs for repairs and induced losses caused by loss and/or interrupted utility services for water and electricity) – 5%. Flood risk management infrastructure and service (cost of repairs to flood defence assets and additional service costs including staff and contractor overtime and materials) – Not included here Other losses including tourism, heritage, and wildlife sites: damage to physical assets and, where possible to determine, indirect impacts on the wider economy – 5% Intangible damages are considered here to refer to mental health impacts, assessed through a proxy of the additional costs associated treatment and the economic impact of absenteeism from work *etc.* The uplift applied is 20% of direct (residential) damages. An issue increasingly recognised and supported by surveys, for example Waite *et al.,* 2017.			

A.3 People (present and future projections): Number, vulnerability, and household occupancy

The datasets used to support the people-based risk metrics are listed in Table A3-1

Table A3-1 People-related metrics and data sources

Metric	Data sources			
	England	**Wales**	**Scotland**	**Northern Ireland**
Population distribution	Present day: Census 2011 *Future:* UK, country and local authority areas based on data by Cambridge Econometrics (2019) for the CCC, from the ONS population projections (2016). Providing yearly projections for alternative projections. Received February 2019.			
Household occupancy	*Present day:* Variation at a neighbourhood scale based on 2011 Census (household size) *Future: Modification from present day* based on data from Cambridge Econometrics (2019) for the CCC, derived from the ONS population projections (2016). Received February 2019. Implemented here as multiplier to the neighbourhood Census 2011 occupancy.			
Social vulnerability	Neighbourhood Flood Vulnerability Index, 2016 (Sayers *et al.,* 2017c, as used in the analysis for the JRF, Lower Super Output Areas in England, Wales and Northern Ireland and Data Zones in Scotland, based on the 2011 census). This remains unchanged with time for the analysis here.			

A.4 Natural capital

The sources of the data used to determine the location of Special Protection Areas (SPA), Special Areas of Conservation (SAC) and Ramsar sites are summarised in the below. These locations and extents are all assumed unchanged with time.

Table A4-1 Natural environment data

Focus	Description
Special Protection Areas (SPAs)	For England and Wales as used in CCRA2 Downloaded from Joint Nature Conservation Council (JNCC) – 17/11/2014. For Scotland downloaded from https: //gateway.snh.gov.uk/natural-spaces/ 20/6/2019. For Northern Ireland downloaded from Open Data NI – 24/02/2019.
Special Areas of Conservation (SACs)	For England and Wales as used in CCRA2 downloaded from Joint Nature Conservation Council (JNCC) – 17/11/2014. For Scotland downloaded from https: //gateway.snh.gov.uk/natural-spaces/ 20/6/2019. For Northern Ireland downloaded from Open Data NI – 24/02/2019.
Ramsar	For England and Wales as used in CCRA2 downloaded from Joint Nature Conservation Council (JNCC) – 02/01/2015. For Scotland downloaded from https: //gateway.snh.gov.uk/natural-spaces/ 20/6/2019. For Northern Ireland downloaded from Open Data NI – 24/02/2019.

A.5 Agriculture

The sources of data used to determine the location of the Best and Most Versatile Land (BMV) and Not-Best and Most Versatile land are unchanged from the CCRA2 (Sayers *et al.,* 2015c) and are follows:

- **England** – the Strategic Land Cover Map developed by Natural England, where 'best and most versatile' agricultural land taken as ALC Grades 1, 2 and 3a.
- **Wales** – DEFRA's Agricultural Land Classification (ALC), 1988 is used, with Grades 1-3 used to identified BMV land (Grade 3a is also included in BMV description but this is not included in the ALC, hence Grades 1-3 will be used).
- **Scotland** – the Macaulay Land Use Research Institute's Land Capability Classification for Agriculture is used (based upon the ALC 1981 and LCM2007), with Classes 1-3 (including 3.1) identified as BMV land.
- **Northern Ireland** – the Agri-Food and Biosciences Institute agricultural land classification map is used with classes 2 and 3A identified as BMV (there is no class 1 land in Northern Ireland).

These are assumed unchanged into the future.

Note:

Extensive areas of the UK's agricultural land have subsurface field drains (tiles or pipes) to improve drainage. These are not typically accounted for in the surface flood assessments (in any detail).

A.6 Infrastructure networks and systems

The data sources used to support 'important infrastructure' risk metrics are listed below.

Table A6-1– Infrastructure risk metrics and data sources

<table>
<tr><th rowspan="2">Metric</th><th rowspan="2">Basic description</th><th colspan="4">Data sources</th></tr>
<tr><th>England</th><th>Wales</th><th>Scotland</th><th>Northern Ireland</th></tr>
<tr><td rowspan="2">Water</td><td>Water distribution</td><td>OS MasterMap, 2014</td><td>NRD 2014</td><td rowspan="2">Scottish Property Data Set (SPDS)[27]</td><td rowspan="2">NIW Corporate Asset Register (CAR) – List of Facilities (15/12/2014)[28]</td></tr>
<tr><td>Wastewater treatment (major sites only)</td><td colspan="2">As CCRA2 Wastewater treatment works (ASC, 2014)</td></tr>
<tr><td rowspan="2">Energy</td><td>Power stations (generation)</td><td colspan="2">Power stations as geo-coded for CCRA1, Ramsbottom et al., 2012</td><td>As in CCRA2 Scottish Property Data Set (SPDS)[2]</td><td rowspan="2">As CCRA2 – based on Northern Ireland Electricity dataset</td></tr>
<tr><td>Sub-stations (transmission/distribution) Major sites only > 5000 customers)</td><td colspan="3">Distribution substations: from Energy Network Association (minimum 5000 customers) (as CCRA2, Sayers et al.,2015c)</td></tr>
<tr><td>Transport</td><td>Railway stations and length (km) of major roads and railway track</td><td>Roadways from NRD, with 'major' defined (SoN 2018). As CCRA2 From Network Rail</td><td>As England</td><td>A dataset provided by SEPA: Rail data from network rail and the OS. Roads data from transport Scotland</td><td>Acquired 24/2/2019 from OpenDataNI portal</td></tr>
<tr><td>Waste</td><td>Operational (and licenced) landfill sites)</td><td colspan="2">As CCRA2 – From Environment Agency 'Permitted Waste Sites – Authorised Landfill Site Boundaries' – 2015 (current only used)</td><td>As CCRA2 datasets provided by SEPA. (dated 2011). (current only)</td><td>Acquired 24/2/2019 from OpenDataNI portal</td></tr>
</table>

[27] *SEPA have noted that this dataset is known to be incomplete/unsuitable for identifying individual infrastructure assets.*

[28] *known to be incomplete.*

Table A6-2– Infrastructure networks and systems cont.

Metric	Basic description	Data sources			
		England	Wales	Scotland	Northern Ireland
Emergency Services	Blue light service stations (police, ambulance, fire stations)	Blue light services: As CCRA2 – OSMM: Emergency Services locations (October 2013)			Blue light services: Acquired 24/2/2019 from OpenDataNI portal
	Hospitals	Hospitals: As CCRA2 – Health and Social Care Information Centre (2012/13) – from CCC 2014		Hospitals: – 2018 NFRA receptors (Hospital)	Hospitals: Acquired 24/2/2019 from NINIS
Social support networks: Number of care homes, GP surgeries, and schools exposed to flooding (by flood probability band, reported separately)	Care Homes	As CCRA2 – Care Quality Commission: Registered care homes (November 2013) (downloaded 28/10/14 – England only)	From National Receptor Database (NRD), (2018)	2018 NFRA receptors Hospice Medical Care Accommodation	Acquired 24/2/2019 from the Regulation and Quality Improvement (RQIA) portal.
	GP surgeries	As CCRA2 – From Public Health England	From National Receptor Database (NRD), (2018)	2018 NFRA receptors	Acquired 24/2/2019 from OpenDataNI portal
	Schools	From National Receptor Database (NRD), (2018)	From National Receptor Database (NRD), (2018)	2018 NFRA receptors Non-state and state (CE)	As CCRA2 As latest data 2016 on OpenDataNI portal

A.7 Spatial structure of reporting and analysis

Several spatial units are used in the analysis. This is set out below.

Table A7-1 Spatial structure of reporting and analysis

Data sources				
Unit	England	Wales	Scotland	Northern Ireland
Regions	River Basin Districts (England – cycle2)			
Local Authorities	Local_Authority_Districts_December_2015 as defined by ONS and used in the population projections by Cambridge Econometrics			As used in JRF, Sayers *et al.,* 2017c – Council districts, 2016
Water companies	Water drainage boundaries (provided by the 21st Century Drainage Project, 2018)		No further subdivision beyond country level	No further subdivision beyond country level
Flood source	Fluvial, coastal, surface water and groundwater – see earlier tables for sources.			
Settlement type	Settlement types are defined by ONS using a combination of metrics (as set out by Bibby and Brindley, 2013). UK wide categories approach as used in JRF, Sayers *et al.,* 2017c and subsequently the NIC analysis, Sayers *et al.,* 2018			
Economic setting	As used in JRF, cities in decline, Sayers *et al.,* 2017c			
Neighbourhoods	Lower super-output Area (2011 census)	Lower super-output Area (2011 census)	Data Zones (2011 Census)	Lower-super output areas (2011 Census)

A.8 Climate change

The sources of data used in determining future climates are set out in Table A8-1. The methods applied to these are set out in Appendix C.

Table A8-1 Sources of climate change data

Climate change indicator	England and Wales	Scotland	Northern Ireland
Coastal floods Changes in coastal overtopping as a function of relative sea level rise	New analysis here: based on probabilistic projections from UKCP18 then transferred through offshore to nearshore, nearshore to overtopping analysis to determine a change in overtopping rates and hence a change in standard of protection. For Scotland, Wales, and Northern Ireland the response to local rSLR projections on overtopping have been developed using analogous responses from England. See Main Report for discussion. Data from England is used as proxy responses for elsewhere in the UK.		
Fluvial floods Changes in return period of extreme river levels as a function of changes in peak river flows	New analysis here: based on probabilistic projections from UKCP18 then translated through a hydrological analysis (at 1km grid) and local FEH analysis (50m) to determine the change in extreme water levels. See Main Report for discussion.		
Surface water floods Changes in intensity of short duration rainfall	Taken from a combination of sources – CCRA2 (UKWIR, 2015a&b) – updated with Dale *et al.,* 2015 – Dale *et al.,* 2017 and discussions. Note: UKCP18 2.2km outputs unavailable at time of writing and will not be used here. See Main Report for discussion.		
Groundwater floods Changes in groundwater flooding	As used in CCRA2- Sayers *et al.,* 2015c, based on BGS – Groundwater Susceptibility Model but updated with changes in fluvial flooding here.		

A.9 References

See main reference list.

APPENDIX B
INDIVIDUAL ADAPTATION MEASURES

B.1 Introduction

Nine individual Adaptation Measures (AMs) that address the three components of risk (set out in Chapter 6 of the Main report) are considered (Figure B1-10-1) with each Adaptation Measure assigned three levels of ambition as follows:

- **Current:** assuming the measure continues to be implemented as effectively as experienced in the recent past (*i.e.,* achieving the same outcomes as in recent years). This links to the 'current objectives' portfolio (Current Level of Adaptation – CLA)
- **Higher:** assuming the measure is implemented more effectively than in the recent past. This links to the 'current objectives+' portfolio (Enhanced Whole System adaptation – EWS)
- **Lower**: assuming the measure is implemented less effectively than in the recent past. This links to the 'no further action' portfolio (Reduced Whole System adaptation – RWS)

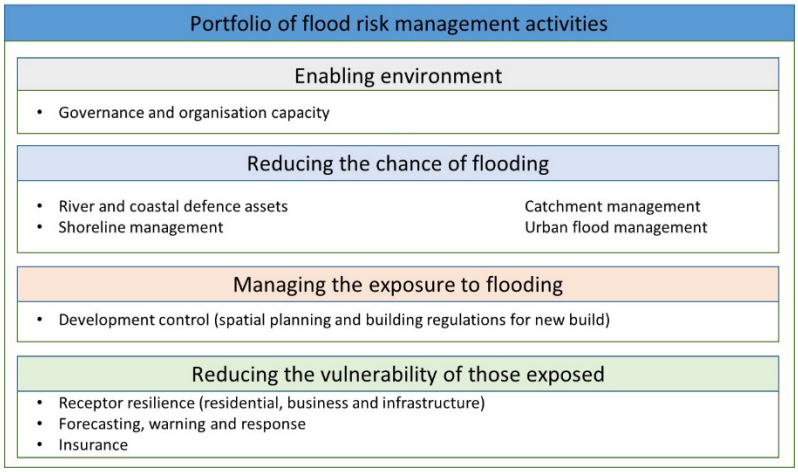


Figure B1-1 Portfolio of individual Adaptation Measures

The evidence used to determine the degree of effectiveness builds on analysis for CCRA2 (Sayers *et al.,* 2015c), the JRF (Sayers *et al.,* 2017c) and the NIC (Sayers *et al.,* 2018) together with discussion of adaptation measures with national flood lead stakeholders.

Notes:

A consistent representation of each measure is used throughout the UK unless there is compelling evidence to do otherwise (*e.g.,* for example as is the case for the implementation of SuDS) and differential implementation is possible within the context of the project resources.

Characterisation of social flood vulnerability. The Neighbourhood Flood Vulnerability Index (NFVI, introduced in the Main Report) is used to better differentiate future risk by more and less socially vulnerable communities and, where appropriate, differentiate the effectiveness of individual adaptation measures. Where a lever is differentiated by NFVI this is highlighted.

B.2 Coastal and river flood defence and control infrastructure

Under a **current level of ambition**, it is assumed that protection standards and condition grades continue to be maintained where the present-day standards are high (typically more than 1in75 years - Figure B2-1). Elsewhere standards fall. A **higher level of ambition** sees defence standards maintained to a minimum of 1in100 years in urban conurbations (major and minor); including areas that are currently undefended. A **lower level of ambition** sees investment failing to keep pace with climate change and asset condition and standards of protection are assumed to reduce from present-day in all settings, excluding urban conurbations (major and minor).

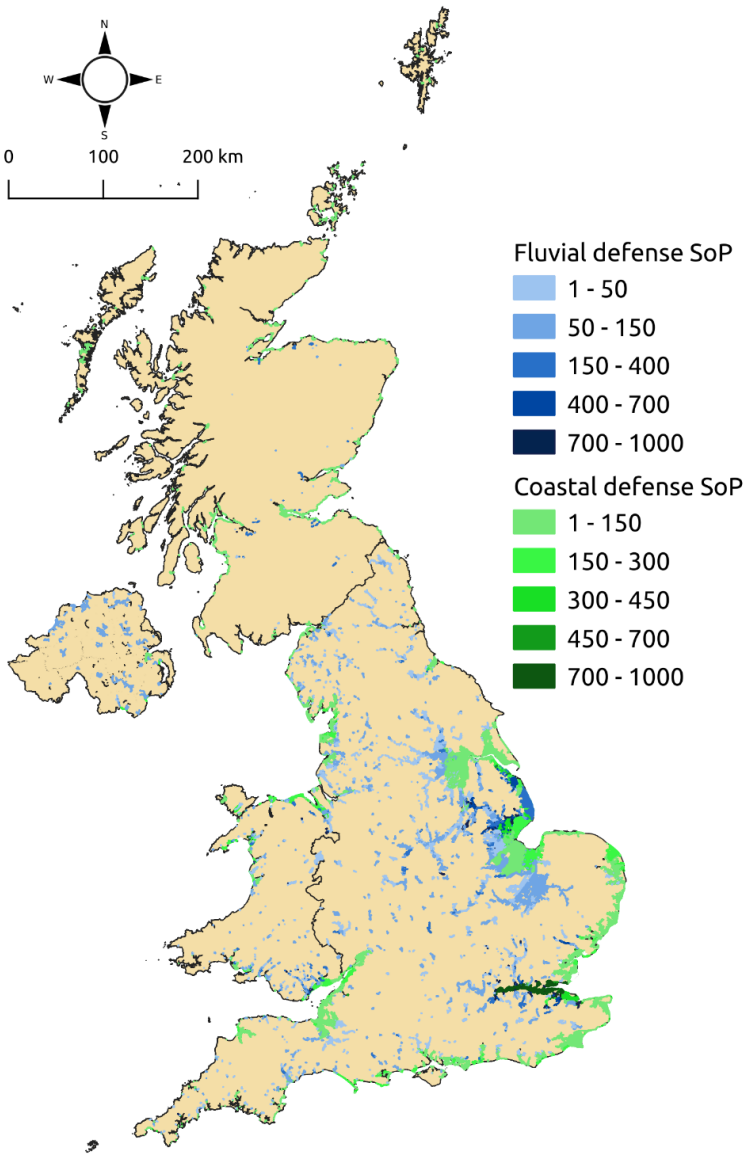


Figure B2-1 Present-day representative defence standards of protection (rSOP, years)

Representation within the FFE

Within the FFE, defence standards and conditions reduce (or, in some locations, increase) with climate change until a minimum standard is reached (defined as a percentage of the present-day standard) at which point it is raised to a new standard (again defined as a percentage of the present-day standard). This process is illustrated in Figure B2-2. This assessment operates at an aggregated scale based on the representative standard of protection afforded to an area and the associated representation condition grade of the defences (rCg – reflecting the condition of the defence and hence its chance of breach under load). The settings applied to both the rSOP and rCg within the lower, central, and higher adaptation future are summarised in

Table B2-10-1. These are based on previous studies (*e.g.,* reflecting the NIC finding of the likely efficiency of protecting large urban areas with raised defences within a higher adaptation future) and review by policy leads.

Note:

The FFE has been significantly improved for CCRA3 compared to CCRA2. Primarily this includes improved defence datasets in England and Wales (although gaps remain) and greater control on where and how flood defences are implemented in each adaptation future. In Scotland and Northern Ireland the flood defence data is much less complete.

CCRA3 continues to adopt a scenario approach to defence improvements rather than a direct benefit/cost assumption to investment in defences.

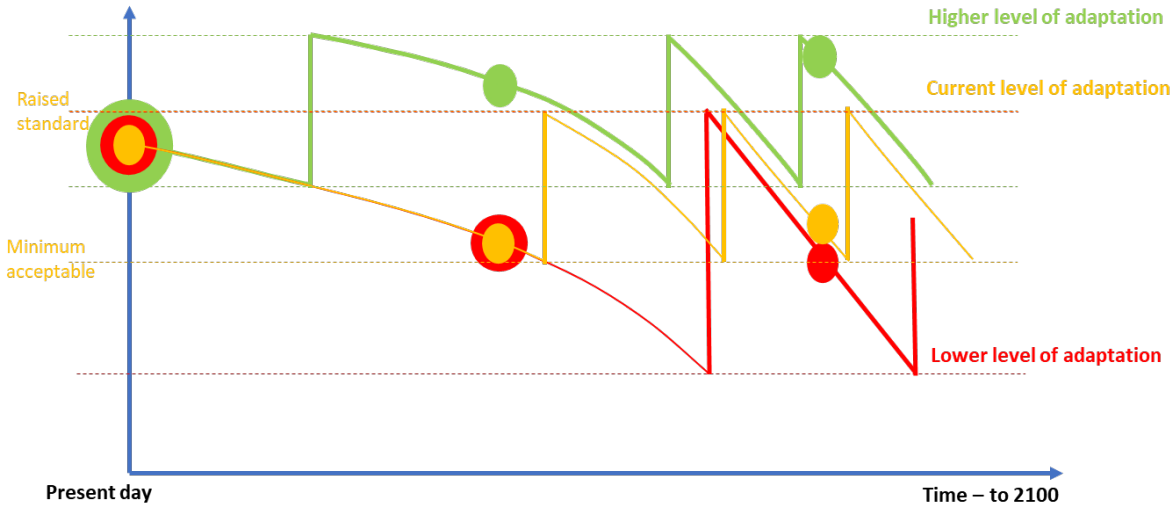


Figure B2-2 The representation of defence standards

Table B2-10-1 Adaptation measure: Flood defence and control infrastructure

Future changes in standard of protection as a function of settlement type and present-day standards (values show the allowable future standard as a proportion of the present-day standard). This is a summary of the settings – more detail can be provided on request.

	Lower				Current				Higher			
Present day standard (years)	U	R	U	R	U	R	U	R	U	R	U	R
0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
25	0.5	0.5	0.5	0.5	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
50	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	1	0.75	1	0.75
100	0.75	0.75	0.75	0.75	1	1	1	1	1	1	1	1
500	1	1	1	1	1	1	1	1	1	1	1	1
1000	1	1	1	1	1	1	1	1	1	1	1	1
Minimum standards												
	None				100	in urban majors (where present-day defences exist)			100	in urban majors (all areas including present day undefended)		
									75	in urban towns and cities (where significant defences already exist))		
									75	in those rural towns that have the highest present-day standards		

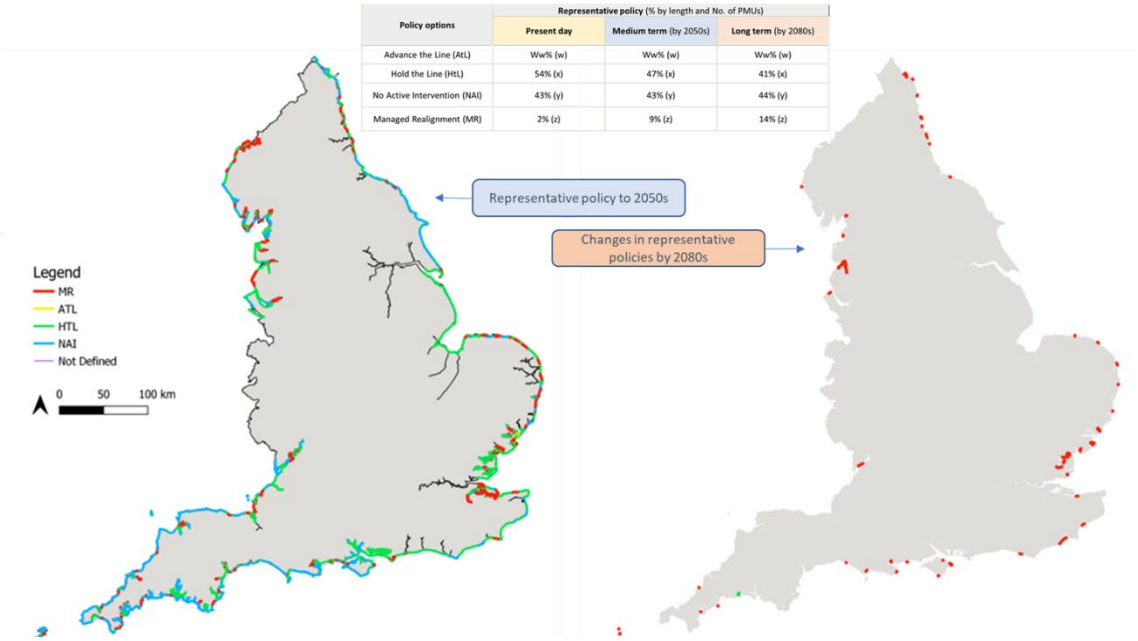
U = Urban, R = Rural areas

Future changes in condition grade (an indicator of the potential for infrastructure to fail)

rCg today	Change in Condition Grade (Cg)		
	Lower	Current	Higher
1	1	1	1
2	2	2	2
3	4	3	3
4	5	4	3
5	6	6	6

B.3 Shoreline management

Under the **current level of ambition** realignment continues to be limited, with only 5% of frontages designed as Managed Realignment within Shoreline Management Plans (SMPs) implemented by the 2020s rising to 40% by 2080s (Figure B3-1). This is based on an analysis of SMP policies in England (CCC, 2018, Sayers, 2018) and by inference elsewhere. This impacts the morphology of coast and protection afforded by the beach fronting the defences. Within the analysis a higher degree of MR has a marginal improvement on the standard of defences within a given SMP region. A **higher level of ambition** sees these issues resolved and policies largely implemented as set out within shoreline plans (facilitated, for example, by changes to compensation rules, or through other means). A **lower level of ambition** sees MR become more difficult and little realignment is achieved (as in the recent past).



MR = Managed Realignment, ATL – Advance the Line, HTL – Hold the Line, NAI – No active Intervention. Left: Mid term (by 2050s) and right: Long term (by 2100). Source: Sayers et al., 2022b

Figure B3-1 Shoreline regional definitions

Representation within the FFE

Within the FFE, realignment influences the standard of protection afforded. It is assumed that realignment provides a buffer to the backshore defences and contributes sediment to the nearshore and enables a more natural pattern of drift. These morphological processes help maintain beach performance and they improve the effective standard afforded by flood defences where they exist. This linkage is difficult to represent at a localised scale here. Instead, it is assumed to influence the standards regionally (*e.g.,* within the SMP area). In the absence of a more refined analysis or strong evidence, it is assumed here that this connection is relatively weak and varies by storm return period (with a greater impact on more frequent storms and less on more extreme storms) – see Table B3-1.

Note: CCRA3 refines the spatial scale on the assessment of realignment to reflect the aspirations in individual SMP areas. The representation of impact of realignment on coastal defence standards within the FFE remains unchanged from CCRA2.

Table B3-1 Adaptation measure: Summary of coastal realignment

% implementation of statement realignment policies (L = Low, C = Current, H = High)

Adaptation measure	2020s			2050s			2080s		
	L	C	H	L	C	H	L	C	H
% Implementation of realignment policies/opportunities									
Across the UK	2%	5%	20%	2%	20%	50%	2%	40%	100%

Proportion of coastline with managed under a policy of no active intervention or managed realignment (or equivalent) given the 'current' level of adaptation ambition

% coastline realigned in recent years (based on England 1990-2016)	***Proportion of coast managed under a no active interventionl or managed realignment policy***		
	2020s	*2050s*	*2080s*
2%	*5%*	*20%*	*40%*
England			
01 - Scottish Border to River Tyne	0.05	0.20	0.28
02 - The Tyne to Flamborough Head	0.05	0.07	0.07
03 - Flamborough Head to Gibraltar Point	0.03	0.00	0.00
04 - Gibraltar Point to Hunstanton	0.00	0.00	0.00
05 - Hunstanton to Kelling Hard	0.05	0.20	0.30
06 - Kelling Hard to Lowestoft	0.05	0.20	0.40
07 - Lowestoft to Felixstowe	0.05	0.20	0.25
08 - Essex and South Suffolk	0.05	0.15	0.14
09 - River Medway and Swale Estuary	0.05	0.20	0.30
10 - Isle of Grain to South Foreland	0.04	0.20	0.30
11 - South Foreland to Beachy Head	0.05	0.08	0.19
12 - Beachy Head to Selsey Bill	0.05	0.10	0.15
13 - Selsey Bill to Hurst Spit	0.02	0.02	0.01
14 - Isle of White	0.00	0.01	0.03
15 - Hurst Spit to Durlston Head	0.05	0.17	0.18
16 - Durlston Head to Rame Head	0.05	0.09	0.07
17 - Rame Head to Hartland Point	0.05	0.12	0.11
18 - Hartland Point to Anchor Head	0.03	0.10	0.08
19 - Anchor Head to Lavernock Point	0.05	0.14	0.16
22 - Great Ormes Head to Scotland	0.05	0.20	0.21
Wales			
19 - Anchor Head to Lavernock Point	0.05	0.14	0.16
20 - Lavernock Point to St Ann's Head	0.03	0.10	0.08
21 - St Ann's Head to Gread Ormes Head	0.05	0.12	0.11
22 - Great Ormes Head to Scotland	0.05	0.20	0.21
Scotland			
East	0.06	0.06	0.06
North	0.06	0.06	0.06
North-west	0.06	0.06	0.06
Northern Ireland			
Northern Ireland	0.06	0.06	0.06

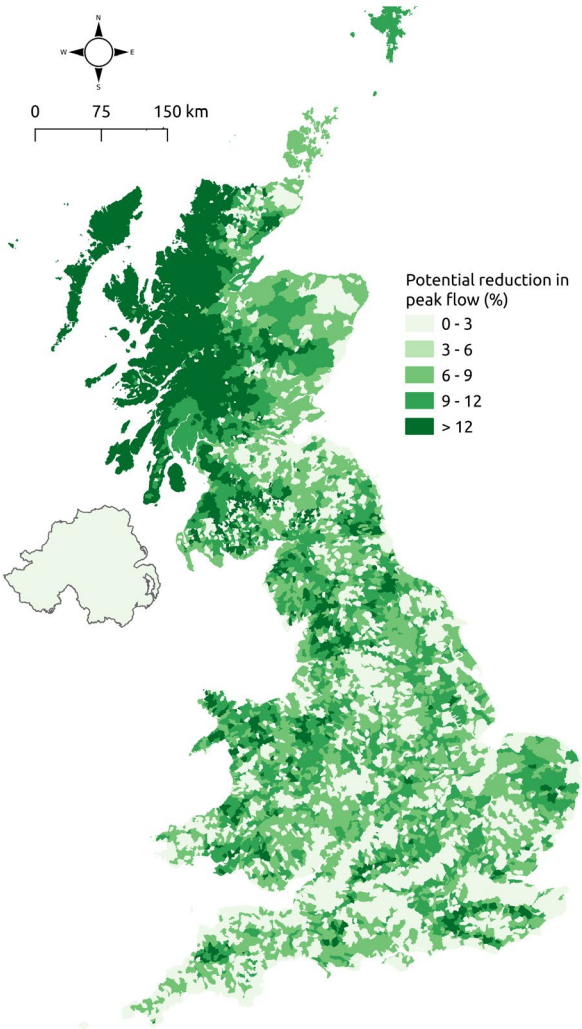
% of the climate change-induced reduction in the standard of protection avoided for each additional 2% of the coast realignment

rSOP today in coastal areas only (years)	**All adaptation futures**		
	2020s	2050s	2080s
5	2%	2%	2%
50	2%	2%	2%
100	1%	1%	1%
200	0%	0%	0%

In Scotland and Northern Ireland much of the coast comes under a no active intervention policy with little managed realignment. Therefore, a single of 6% is used.

B.4 Catchment management

The **current level of ambition** sees NFM implementation remain limited. The emerging Environmental Land Management (ELM) incentives in England and similar schemes elsewhere may make it easier to pay land managers for environmental outcomes. These developments are assumed in this report to promote the implementation of NFM beyond flood management and lead to greater take-up under a **higher level of ambition** (delivering multiple biodiversity and wellbeing benefits alongside flow management). The impact of this higher level of ambition is illustrated in Figure B4-1. Conversely, a **lower level of ambition** may see NFM play a more limited role than it does today (reflecting for example, other priorities such as pressures on food security).



Source: Sayers and Partners (based on various sources of opportunity including analysis by JBA Trust for England and Wales). The combined impact of woodland and surface storage features on flood flows assuming a higher level of adaptation. It has not been possible to include the available data for Northern Ireland as part of this project and values in NI are assumed to be an average of the GB values.

Figure B4-1 Natural flood management – Percentage reduction in peak flow (1in10 year return period)

To reflect the influence of catchment management, three aspects are considered:

- **Catchment potential:** The impact on flood flows is highest in those catchments with the greatest potential (as defined, broadly, by the available mapping from national leads) and reduces in those catchments with moderate or low potential. This potential is assumed here to be defined by the proportion of the catchment area considered to represent an NFM opportunity. This potential remains unchanged across all adaptation futures. In those catchments with the highest potential the impact on the flow is highest.
- **Scale of NFM ambition:** The degree to which the potential opportunity for NFM is translated to on-the-ground measures will, in part, vary according to the opportunity for alternative uses of the land. In catchments with a high proportion of the Best and Most Versatile (BMV) land there is likely to be a lower opportunity to use NFM than elsewhere because of competition from other productive uses of the land. A limit is therefore placed on the percentage of each class of BMV land that can be used for NFM purposes.
- I**mpact across different return period flows:** The change in flood flows is assumed to be the function of the catchment area used for NFM (a combination of the above two aspects) and their effectiveness. It is assumed here that the maximum reduction in flow that can be achieved by NFM (if all potential opportunities within a catchment are taken up) is 10% during a 1in50 year event and up to twice this in the 2-year event. These maximum values remain unchanged across the adaptation futures (as they represent maximum potential).

Note: The approach extends the method recently used in the National Infrastructure Assessment (Sayers *et al.,* 2018). The confidence in the performance of NFM measures to reduce downstream flood flows remains an area of active research. An improved understanding is expected in coming years as three ongoing NERC programmes develop new evidence, and the results of pilot studies are analysed (from across Wales, Scotland, and England). This does not imply a lack of confidence in catchment measures – they are accepted as beneficial, but it remains difficult to determine by how much.

Table B4-1 Adaptation measure: Catchment management

Impact on flow is highest in those catchments with the highest potential

Catchment potential: 1:50 year event reduction in peak	***Percentage reduction in peak runoff by this year***			
	Present day	*2020s*	*2050s*	*2080s*
Run-off management features				
15% highest NFM woodland potential by catchment area	*0%*	*3%*	*6%*	*8%*
15-30% highest NFM woodland potential by catchment area	*0%*	*3%*	*5%*	*6%*
30-80% highest NFM woodland potential by catchment area	*0%*	*2%*	*3%*	*3%*
20%lowest NFM woodland potential by catchment area	*0%*	*0%*	*0%*	*0%*
Temporary storage features				
30% highest NFM storage potential by catchment area	*0%*	*2%*	*3%*	*5%*
30-80% highest NFM storage potential by catchment area	*0%*	*2%*	*2%*	*2%*
20%lowest NFM storage potential by catchment area	*0%*	*0%*	*0%*	*0%*
In-combination				
Combined impact - 50 year	*0%*	*5%*	*9%*	*13%*
If larger than 10% flag	*8%*	*6%*	*8%*	*10%*

The opportunity that is realised is controlled by the scale of the ambition for converting BMV land

Associated scale of NFM woodland ambition: BMV land use (% of BMV class land used)									
Epoch	**Lower**			**Current**			**Higher**		
	BMV class 1	BMV class 2	BMV class 3	BMV class 1	BMV class 2	BMV class 3	BMV class 1	BMV class 2	BMV class 3
2020s	0%	0%	5%	0%	0%	5%	0%	0%	5%
2050s	0%	5%	8%	0%	10%	15%	0%	20%	30%
2080s	0%	10%	15%	0%	20%	30%	0%	30%	50%

Variation in impact on reduction in peak flows with return period (as a function of the impact on the 1in50 year flows)

Return period (years)	**Factor on flow reduction by return period**
2	2
10	1.5
30	1.25
50	1
100	0.5
1000	0.1

B.5 Urban management

The **current level of ambition** sees conventional drainage capacities unchanged (assumed to be 12mm/hr[29]) and the take-up of SuDS within new development continuing at around 50% (England), higher in Scotland and Wales less in Northern Ireland. Retrofit is less, at around 5% (by area)[30]. **Higher level of ambition** increases the take-up of SuDS in response to greater integration of planning and investment resources and the incentive for delivering net biodiversity gain. Conventional drainage capacity is also improved in major urban settlements, increasing to 15mm/hr by the 2080s. With a **lower level of ambition** take-up of SuDS reduces (due to less controlled development) and the capacity of conventional drainage reduces (to 10mm/hr). Across all portfolios, other surface water management actions are assumed to reduce economic damages by around 5% in all but the most socially vulnerable neighbourhoods.

Representation within the FFE

'Urban management' is represented in the FFE through three mechanisms:

- **Take-up of Sustainable Urban Drainage Systems (SuDS) in new developments and retrofitting to existing developments:** From a narrow flood perspective, SuDS reduce surface water run-off and hence the chance of surface water flooding. A review of the application and effectiveness of planning policy for SuDS in England since 2014 (Ministry of Housing, Communities and Local Government, 2018) found that almost 90% of sampled approved planning applications explicitly stated that '*SuDS would feature in the proposed development'* and in Scotland it is anticipated that it would be a 100% *except for single dwellings and those discharging directly to the coast.* It is not known if these conditions were implemented or those implemented will be maintained over the coming century. It is also recognised that permitted developments (patios, driveways, extensions) are excluded from this process and unlikely to incorporate SuDS. Under current adaptation it is assumed that take-up is most across Wales and Scotland (~70%) and England (~50%) for new developments and 5% retrofit across GB. Take-up is less in Northern Ireland (reflecting existing legislation and approaches). Under a higher adaptation future

[29] *As assumed within the Environment Agency surface water hazard mapping.*

[30] *A review of the application and effectiveness of planning policy for SuDS in England since 2014 (Ministry of Housing, Communities and Local Government, 2018) found that almost 90% of sampled approved planning applications explicitly stated that 'SuDS would feature in the proposed development'. It is not known if these conditions were implemented or those implemented will be maintained over the coming century. It is also recognised that permitted developments (patios, driveways, extensions) are excluded from this process and unlikely to incorporate SuDS.*

significant increases in take-up are possible through greater integration of planning and investment resources and the incentive for delivering net biodiversity gain.

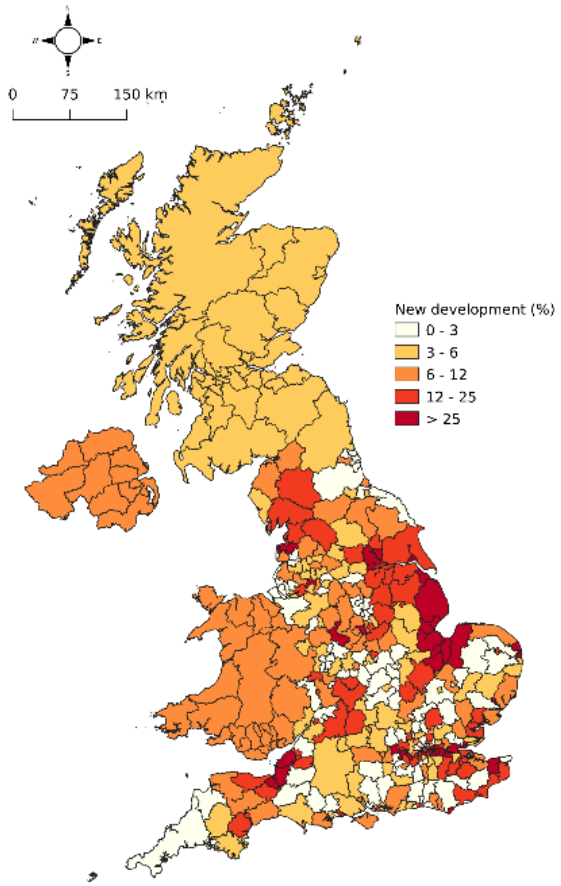
- **Increase in capacity of conventional drainage network:** Surface water hazard mapping typically includes an assumption regarding the capacity of the drainage network (12mm/hr in England for example); investment (or lack of investment) by water companies can act to increase (or reduce) this capacity. Under a current adaptation future, it is assumed there is no change in present day capacity. Under a higher adaptation future it is assumed there is an increase in the investment in urban areas and drainage capacity increases to 15mm/hr (in major and minor urban areas). Conversely, in a lower adaptation future the value reduces to 10mm/year due lack of investment in upgrading networks to account for development and deterioration.
- **Other surface water management measures** (such as gully clearance, preferential surface routing of the flood flows, *etc.*)**:** These may form part of surface water management planning in addition to SuDS and reduce the damage. Across all futures it is assumed these actions reduce damages by 5% but are ineffective in reducing damages in the most vulnerable neighbourhoods.

Table B5-1 Urban management: Adaptation summary

	2020s			2050s			2080s		
Adaptation measure	*Lower*	*Current*	*Higher*	*Lower*	*Current*	*Higher*	*Lower*	*Current*	*Higher*
#1 Take-up of SUDS in new developments and retrofitting to existing developments									
England									
Existing developments @ significant risk	*0%*	*5%*	*10%*	*0%*	*5%*	*30%*	*0%*	*5%*	*30%*
New developments	*30%*	*50%*	*60%*	*30%*	*50%*	*75%*	*30%*	*50%*	*80%*
Scotland and Wales									
Existing developments @ significant risk	*0%*	*5%*	*10%*	*0%*	*5%*	*30%*	*0%*	*5%*	*30%*
New developments	*30%*	*70%*	*85%*	*30%*	*70%*	*85%*	*30%*	*70%*	*85%*
Northern Ireland									
Existing developments @ significant risk	*0%*	*0%*	*10%*	*0%*	*0%*	*30%*	*0%*	*0%*	*30%*
New developments	*10%*	*15%*	*15%*	*10%*	*15%*	*25%*	*10%*	*15%*	*25%*
#2 Increase in capacity of conventional drainage network (mm/hr)									
Major and minor urban settings	10	12	12	10	12	15	10	12	15
Elsewhere	10	12	12	10	12	12	10	12	12
#3 Other surface water management measures (% reduction in direct economic damage achieved)									
All neighbourhoods	5%	5%	5%	5%	5%	5%	5%	5%	5%
20% most socially vulnerability (by NFVI)	0%	0%	0%	0%	0%	0%	0%	0%	0%

B.6 Spatial planning (Development control)

Under the **current level of ambition**, the percentage of new development built on the floodplain continues as in the recent past and varies across the UK as illustrated in Figure B6-1. Under the lower level of ambition, a greater proportion of the new development is built on the floodplain (assumed here to be 3 percentage points more than the current proportion of development). A higher level of ambition sees less development on the floodplain (3 percentage points less). This small differentiation reflects the long-lived nature of the existing planning rules that seek to limit floodplain development and hence significant variation from current level is unlikely. Where new development does take place on the floodplain it is assumed that building regulations and planning conditions (such as appropriately designed raised floor levels that continue to provide accessibility and safe egress) ensure flood damage to and from any new development is minimised. This aspect is covered under the receptor (property) level measures discussed later.



Source: Multiple – Environment Agency, 2019 and discussion with Scottish Government. In the absence of quantified data in Wales and Northern Ireland (NI), the UK average has been assumed. It is noted that lead authorities in both Wales and NI expect the number to be lower than the UK average.

Figure B6-1 Proportion of new development built on the floodplain in the recent past

Representation within the FFE

Spatial planning influences the risk calculation within the FFE through two opposing forces:

- **Development pressure due to population growth:** This drives a change (*i.e.,* an increase, a decrease is not considered here) in the demand for residential properties. The location of new development is then determined by spatial planning settings.
- **Increase in urban footprint:** The change (increase) in urban growth drives an increase in urban run-off (an increase that is moderated by the uptake of SuDS – see earlier adaptation lever).

Table B6-1 Adaptation measure: Changes in the national average floodplain development

	2020s			2050s			2080s		
	Lower	Current	Higher	Lower	Current	Higher	Lower	Current	Higher
% of all new development in flood prone areas - All neighbourhoods (fluvial and coastal only)									
England	12%	12%	12%	15%	12%	9%	15%	12%	9%
Wales	12%	12%	12%	15%	12%	9%	15%	12%	9%
Scotland	6%	6%	6%	9%	6%	3%	9%	6%	3%
Northern Ireland	12%	12%	12%	15%	12%	9%	15%	12%	9%
% of all new development in flood prone areas - 20% most socially vulnerable (fluvial and coastal only)									
Increase on above	1.5%	1.5%	1.5%	1.5%	1.5%	0.0%	1.5%	1.5%	0.0%

Note:

The representation of development control in the FFE is significantly improved since CCRA2. The approach now takes account of the updated population projections (including the projected household occupancy – see earlier) and includes an ability to control the proportion of new development being built on the floodplain by Local Authority where available (*i.e.,* England and Scotland). Relocation is not considered: the impact of active relocation of coastal communities (for example) on risk is not considered here. This would be possible to include and should be carried forward to future assessment.

B.7 Receptor (property – new and existing – and infrastructure) level measures

Residential properties

Under the **current level of ambition** ~80% of new developments and ~5-10% of existing properties in high-risk areas take up PFR measures. Under a **lower level of ambition** this reduces (by around half) and under a **higher level of ambition** take-up increases (by up to 15 percentage points to 95%).

Non-residential properties and infrastructure

Under the **current level of ambition** around 80% of infrastructure exposed to fluvial or coastal flooding will have implemented local measures by 2080s and 50% of those exposed to surface water only. Under a **lower level of ambition** this reduces (to 50% and 20% respectively). In a **higher level of ambition** future take-up increases (to 95% and 65%).

Representation in the FFE: Residential properties

The FFE reflects two aspects of residential property flood resilience (PFR)

- **% uptake of PFR measures by householders:** differentiating the take-up according to the location of the property (on or off the fluvial / coastal floodplain) and between the most socially vulnerable and less vulnerable neighbourhoods (based on evidence presented, Sayers *et al.,* 2015a and 2016b). Changes in uptake may reflect incentives provided by insurers, for example those that may be applied through Flood Re and any transitional arrangements that may come into force after 2039. Although there are several unknowns related to how any incentives may change behaviour it is assumed here that they (or similar incentives) would be successful in increasing uptake within the higher (EWS) future.
- **Effectiveness of PFR in reducing damage:** differentiating the reduction of the damage according to the return period of the flood event (given evidence suggesting retrofit measures are likely to be more effective at reducing damages in more frequent events (and shallower depths) and less so in more extreme events (with greater depths). For new developments it is assumed that designs are modified to ensure flood damage is limited (for example by raising floor levels) for events equal to or more frequent than the 1: 100-year event.

Table B7-1 Adaptation measure: PFR: Residential

% uptake of PFR measures (residential)

	2030s			2050s			2080s		
	Lower	Current	Higher	Lower	Current	Higher	Lower	Current	Higher
All households									
Off floodplain fluvial / coastal floodplain (including surface water only areas)									
New properties (% take up)	0%	5%	5%	5%	10%	20%	10%	15%	30%
Existing properties – % take up in Low to moderate probability areas	0%	0%	0%	1%	2%	5%	3%	5%	8%
On fluvial / coastal floodplain									
New properties (% take up regardless of the probability of flooding)	50%	80%	95%	50%	80%	95%	50%	80%	95%
Existing properties – % take up in High probability areas	0%	5%	8%	3%	7%	10%	5%	10%	15%
Existing properties – % take up in Low to moderate probability areas	0%	0%	0%	0%	0%	2%	0%	0%	5%
20% most vulnerable neighbourhoods (by NFVI)									
Existing properties – % take up in High probability areas	0%	1%	2%	0%	1%	5%	0%	1%	5%
Existing properties – % take up in Low to moderate probability areas	0%	0%	0%	0%	0%	5%	0%	0%	5%

% uptake of PFR measures (non-residential)

	2030s			2050s			2080s		
	Lower	Current	Higher	Lower	Current	Higher	Lower	Current	Higher
Off floodplain fluvial / coastal floodplain (including surface water only areas)									
% uptake for non-residential and Category B infrastructure in High probability areas	0%	2%	2%	2%	3%	7%	3%	5%	10%
% uptake for Category A infrastructure providers (irrespective of flood prob.)	0%	5%	5%	5%	10%	20%	10%	15%	30%
On fluvial / coastal floodplain									
% uptake for non-residential and Category B infrastructure in High probability areas	15%	25%	40%	30%	50%	60%	30%	50%	60%
% uptake for non-residential properties and Category B infrastructure in Moderate and Low probability areas	4%	6%	10%	8%	13%	15%	8%	13%	15%
% uptake for Category A infrastructure providers (irrespective of flood prob.)	15%	25%	40%	30%	50%	60%	30%	50%	60%

Table B7-2 Adaptation measure: PFR: Reduction in damage

Severity of event (years)	Res - All neighbourhoods			Non-Res - All neighbourhoods		
	Reduction in damage					
	Coastal	Fluvial	Surface water	Coastal	Fluvial	Surface water
No protection	0%	0%	0%	0%	0%	0%
2	100%	100%	0%	100%	100%	0%
5	100%	100%	0%	100%	100%	0%
10	100%	100%	0%	100%	100%	0%
25	80%	80%	0%	100%	100%	0%
50	50%	50%	0%	50%	50%	0%
100	25%	25%	0%	10%	10%	0%
>200	0%	0%	0%	0%	0%	0%

Severity refers to the return period of the flood event. No protection is used to highlight that in the absence of PFR the damage to the property is not moderated by PFR.

B.8 Forecasting and warning

The effectiveness of forecasting and warning is applied consistently across the UK (despite known differences) and considers the reduction in damage reflecting multiple issues:

- **The take-up of warning services is greatest in coastal areas:** This reflects the heightened perception of risk (Parker, 1991; Parker *et al.,* 2007), the maturity of the flood warning system since it was implemented after the 1953 event and the forecasting challenge that may exist in rapid response catchments. Numerous events have been tracked since this time, and warnings to the communities affected have become better publicised and more targeted because of this experience.
- **Surface water flood forecasting:** Effective forecasting and warning of surface water flooding (capable of reducing direct damages) remains limited but efforts to improve this (by *e.g.,* the Met Office, Environment Agency *etc.*) are under development.
- **The effectiveness, in terms of reduction in damage, increases with return period of the event:** It is assumed here that more extreme events are more foreseeable in terms of providing a longer lead time, and hence greater opportunity to act, that is typically associated with more extreme events (Parker, 1991). It is a recognised simplification and may not be the case in rapid catchments. The ability of warnings to reduce damage during flash flood events (*e.g.,* in Boscastle in 2004) is typically very low despite the rarity of the event, but in many fluvial and coastal storm events a higher return period (often associated with longer lead times) increases the opportunity for people to take risk reducing actions, such as in Tewkesbury in 2007. This is counterbalanced by the increased likelihood that those that have previously experienced flooding, or live in a high-risk area, are more likely to act on a warning (although the evidence for this is mixed).
- **The absence of community networks:** In the most vulnerable neighbourhoods (as defined by the NFVI – see earlier) informal community networks can be much reduced (RSPB, 2014, Sayers *et al.,* 2017c).
- **Ability to respond:** Not everyone is able to respond as easily to warnings as others. A limited physical mobility, for example, may impact an individual's ability to deploy flood protection measures at home, such as flood gates (Defra, 2014b).

All these aspects are represented in FFE and vary across the adaptation scenarios. Under the **current level of ambition,** it is assumed that by the 2050s, 53% of households in fluvial floodplains successfully receive and act upon a warning reducing their damage by ~12% in a large event. Those acting upon a warning reduces to 13% in surface water

areas and rises to 77% in coastal areas[31]. In the most socially vulnerable neighbourhoods those acting upon a warning is assumed to be significantly less (14% in fluvial floodplains for example). Under a **higher level of ambition**, take-up increases in all areas (to around 87% in coastal areas for example) and is assumed to reduce under a **lower level of ambition** (to around 68% in coastal areas for example).

Note:

Rapid response catchments: The ability to provide forecasts to reduce impacts in fluvial flooding in 'flashy' catchments is not differentiated here from other fluvial floods; a shortcoming that may overstate the capability of forecasting and warning in Scotland and Wales in particular.

Role of prior flood experience: This is often associated with higher levels of action and people in areas which flood reasonably frequently are more likely to have prior experience of a flood. This matches anecdotal evidence from the 2015/16 floods where some people were very surprised to discover they lived in an area of flood risk. This awareness is countered by the shorter lead time that is typically associated with more frequent events. This combination of issues should be considered in more detail for future assessments.

Representation within the FFE

The ability of forecasting and warning to reduce economic damage relies on the success of a chain of activities (for example see Environment Agency, 2015). These aspects are reflected within the FFE through the following considerations (Table B8-1): (a) **% properties that successfully receive and act upon a warning, that in turn is defined as an aggregate four user controls**: this is determined based on four aspects (i) % coverage of the flood warning service (residential); (ii) % take-up of residential properties; (iii) % of those that receive a warning when signed up; (iv) % of those that take appropriate action and the actions taken are effective; (b) **% reduction in direct residential property damages:** % reduction in the estimated damages.

[31] *In Scotland only around 25% of those living in coastal and fluvial areas sign up to a warning and hence these values are likely to overstate the importance of forecasting and warning in Scotland. Personal communication with SEPA – Flood Warning Target Area data – dated October 2018.*

Table B8-1 Adaptation measure: Flood Forecasting and warning

All households

	Present day	2020s			2050s			2080s		
		Lower	Current	Higher	Lower	Current	Higher	Lower	Current	Higher
% properties that successfully receive and act upon a warning										
Coastal areas	43%	51%	58%	66%	68%	77%	87%	77%	77%	87%
Fluvial areas	26%	32%	37%	43%	45%	53%	60%	53%	53%	60%
Surface water areas	6%	8%	9%	11%	11%	13%	15%	13%	13%	15%
% reduction in DIRECT damages given appropriate action taken										
All sources and across all return periods	10%	10%	10%	10%	12%	12%	12%	14%	14%	14%

20% most socially vulnerable neighbourhoods (by NFVI)

	Present day	2020s			2050s			2080s		
		Lower	Current	Higher	Lower	Current	Higher	Lower	Current	Higher
% properties that successfully receive and act upon a warning										
Coastal areas	6%	12%	17%	23%	28%	38%	49%	38%	38%	49%
Fluvial areas	0%	2%	4%	6%	9%	14%	20%	14%	14%	20%
Surface water areas	0%	1%	1%	1%	2%	4%	5%	4%	4%	5%
% reduction in DIRECT damages given appropriate action taken										
All sources and across all return periods	10%	10%	10%	10%	12%	12%	12%	14%	14%	14%

B.9 Insurance

An estimate of those households living in the fluvial and coastal floodplain that may not have insurance (structure and contents) is presented in Figure 7-6. This analysis – undertaken for Flood Re (Sayers eta l, 2020) – suggests that of the 1.4 million households exposed to significant flooding (today) on the fluvial and coastal floodplain, 0.45 million may be without insurance (*i.e.,* 32% of all households). This modelled estimate is broadly consistent with EA surveys post-event (such as Chatterton *et al.,* 2010), take-up rates published by the ABI (2018) and the findings of the Blanc Review (Blanc, 2020), although no publication provides an equivalent analysis. Insurance take-up is therefore uneven, and this is reflected in the FFE. Variation under the **current** and **higher level of ambition** is relatively small (compared to other measures) with around 76% of properties exposed to flooding more frequently than 1in75 years assumed to have insurance. A much lower level of insurance is assumed in the socially vulnerable locations (20%). Under the **lower level of ambition** insurance penetration is assumed to reduce assuming the market fails to fully adjust to full actuarial pricing mechanisms in the absence of Flood Re – with penetration falling by half against tenants in socially vulnerable neighbourhoods and significantly elsewhere.

Representation of adaptation in the FFE

Within the FFE, flood insurance acts to reduce the number households suffering an uninsured loss. Where flood insurance is in place it is assumed that households can cover the full economic loss caused by the flood (excesses or other constraints on what can and cannot be claimed, and the difference between economic and financial losses are not considered). The central issue considered is therefore penetration. To determine these values consideration has been given to:

- **Penetration of insurance:** evidence from the summer 2007 floods in England suggests that 76 per cent of household losses (building and contents) are covered by insurance (see Table B9-1, Chatterton *et al.,* 2010). We assume here that this is indicative of the penetration in all other neighbourhoods other than those that are the most vulnerable. In the most vulnerable neighbourhoods we assume there is a lower penetration of insurance (see table below).
- **Tenure of the property:** Evidence suggests that tenants are more likely than homeowners to have little or no flood insurance, and are often very significantly underinsured (ABI, 2010; ONS, 2015). Approximately 40 per cent of those in some form of rented accommodation take-up flood insurance (The Poverty Site, undated).
- **Low income:** Only one in three adults earning between £150-250 per week has home contents insurance compared with around 70 per cent of those on more than £600 per week (2015 Family Expenditure Survey, now called the Living Costs and Food Survey (ONS, 2015)). Around 55 per cent of households within the bottom 10 per cent by income have no flood insurance (ABI, 2010).

- **Direct experience of flooding:** It is unclear if direct experience of flooding affects the propensity to insure. Kates (1962) shows that direct experience triggers response, but that is not quite as direct as to say it triggers insurance. To reflect this relationship, it is assumed here that in areas prone to more frequent flooding the awareness of the risk faced is higher (and those living there are, on average, more likely to have been flooded previously. This translates to higher take-up rates in areas prone to more frequent flooding (although marginal).
- **Surface water flood areas:** Insurance does not consider the source of flooding at all. It is all included, but awareness of surface water risk is much less than fluvial or coastal risks.
- **The move towards actuarial pricing after Flood Re:** The evidence presented above predates the introduction of Flood Re. Flood Re may have a positive impact on penetration but as yet this is unknown. Within the current objectives adaptation portfolio, no adjustment is made to take account of Flood Re and no adjustment is made to reflect its proposed cessation in 2039. In the lower adaptation future (no additional action) it is assumed that no mechanism is put in place to replace Flood Re and insurance penetration significantly reduces.

In combination, these influences are translated into the specific changes within the FFE as below.

Table B9-1 Adaptation measure: Insurance penetration

% penetration of insurance (residential properties)

Example for those at significant chance of flooding (1in75 years): Coastal	Present day	2020s			2050s			2080s		
		RWS	CLA	EWS	RWS	CLA	EWS	RWS	CLA	EWS
Homeowners - contents										
All households	76%	76%	76%	76%	53%	76%	76%	53%	76%	76%
Low household income (20%ile)										
No history of flooding	38%	38%	38%	38%	27%	38%	38%	27%	38%	38%
Direct experience of flooding in the area	45%	45%	45%	45%	32%	45%	45%	25%	45%	50%
Tenants (Social and private) - contents										
All households	76%	76%	76%	76%	38%	76%	76%	38%	76%	76%
Low household income (20%ile)										
No history of flooding	20%	20%	20%	20%	10%	20%	25%	10%	20%	38%
Direct experience of flooding in the area	32%	32%	32%	32%	16%	32%	35%	16%	32%	50%

B.10 Governance and organisational arrangements

No standalone representation of the influence of governance and organisational arrangement is included here. Governance capacity does not feature in the settings used for each other lever and in differentiating the values used in each Adaptation Portfolio. Further assessments should consider more subtle influences of governance.

Representation of adaptation in the FFE

No effort is made here to quantify the influence of governance and institutional capacity on flood risk within the FFE (although research is emerging to explore this more quantified relationship within the EC Funded Cloud-2-Coast adaptation project[32]). Governance arrangements that deliver the above are a prerequisite to achieving the current or higher adaptation outcomes in practice.

B.12 References

See main reference list.

[32] https: //northsearegion.eu/c5a/about/

APPENDIX C SOCIAL VULNERABILITY INDICATORS

C.1 Social vulnerability indicators

The rationale for the inclusion of the various indicators of social vulnerability are discussed in the tables below. Given the overlap between indicators that influence flood vulnerability and vulnerability to other climate hazards these are also discussed. Further discussion can be found in the various supporting references cited with the flood related indicators presented and discussed in Sayers *et al.,* 2017c.

Table C-1 Social vulnerability indicators

Domain	Indicator	Rationale	Summary metric
Age	Young Children	Young children are more susceptible to harm from a range of environmental hazards. There is extensive evidence from analyses of past events and wider academic research. Young children and babies | Climate Just	% people under 5 years old
	Older Adults	Not all older people are socially vulnerable. Older people may be more likely to experience detrimental physical impacts during periods of high temperatures, *e.g.,* due to inhibited ability for thermo-regulation and dehydration. This may exacerbate existing ill-health. Similar evidence exists with respect to poor air quality, with the potential for poor air quality and high temperatures to be experienced concurrently. Older people | Climate Just	% people over 75 years old
Health	People in long-term ill-health	The long-term sick are more vulnerable to flooding; the flood they experienced often making their pre-existing condition worse either as a one-off 'hit' or accelerating its adverse trajectory (discussed in Sayers *et al.,* 2017c).	% people whose day-to-day activities are limited
	Households with members in ill-health	Flooding may prevent the use of complex home-based health care systems, for example home dialysis, due to direct flood damage or to loss of power (discussed in Sayers *et al.,* 2017c).	% households with at least one person with long-term limiting illness
	Emergency hospital admissions	Some conditions and illnesses (or the medicine used to treat them) make people more sensitive to the effects of air pollution and high temperatures, *e.g.,* dehydration, ability to sweat and exacerbate symptoms, *e.g.,* cardiovascular disease. Some illnesses are associated with acute symptoms and hospital admissions, while others might not be People in poor health | Climate Just	Emergency stays in hospital (index)
	Disability and Ill-health		Comparative illness factor (index)

Table continued…

	Mood and Anxiety Disorders	Some mental health disorders affect people's ability to self-regulate to avoid environmental hazards or recognise and take effective precautions against symptoms caused or aggravated by environmental hazards. In some cases, medicines used may also increase susceptibility to effects, *e.g.,* of heat stress (Page *et al.,* 2012).[33] People in poor health | Climate Just	Population prescribed drugs for anxiety, depression, or psychosis
	Medical and Care Residents	People living in medical and care establishments may have greater dependencies because of health-related factors. People in poor health | Climate Just	% Living in medical and care establishments
	Low birthweight	Babies with low birthweight are susceptible to a range of health effects which can be exacerbated by exposure to high temperatures and poor air quality. Furthermore heat, air quality and other environmental stressors are also a cause of low birthweight due to impacts on pregnant women (Dadvand *et al.,* 2014).[34]	Proportion of live singleton births of low birth weight
Income	Unemployment	Low-income households are less likely to have the capacity to fully prepare for future floods (through insurance and property level measures). The NFVI uses a combination of income metrics to represent this important influence. The indices used to assess social vulnerability to high temperatures and poor air quality also use a range of income factors (see following section).	% unemployed
	Long-term unemployment		% long-term unemployed or who have never worked
	Low-income occupations		% in routine or semi-routine occupations
	Households with dependent children and no adults in employment		% Households with dependent children and no adults in employment

[33] Page, L, Hajat, S, Kovats S, and Howard, LM (2012). Temperature-related deaths in people with psychosis, dementia, and substance misuse. Br J Psychiatry 200(6): 485-490.

[34] Dadvand, P; Ostro, B; Figueras, F; Foraster, M; Basagaña, X; Valentín, A; Martinez, D; Beelen, R; Cirach, M; Hoek, G; Jerrett, M; Brunekreef, B; Nieuwenhuijsen, M (2014) Residential Proximity to Major Roads and Term Low Birth Weight, Epidemiology: Vol 25 - Iss 4 - p 518-525 doi: 10.1097/EDE.0000000000000107

Table continued…

	Employment Deprivation	People on low incomes have reduced adaptive capacity to high temperatures and poor air quality, *e.g.,* have fewer choices in terms of goods and services, and they may also suffer lower self-esteem, engage less with others (*e.g.,* via support networks) and experience higher levels of stress and anxiety. Employment deprivation is a distinctive measure of lower income which accounts for the proportion of working age people who are involuntarily excluded from paid employment, due to lack of opportunities, ill-health and disability or caring responsibilities. People on low incomes | Climate Just	Score
	Income Deprivation	Income deprivation is a direct measure of people who are expected to be negatively impacted due to unemployment or who have low earnings. There are a range of associations between income and other factors which reduce adaptive capacity to high temperatures and poor air quality, some of which cannot be directly measured at neighbourhood level such as engagement with public organisations People on low incomes | Climate Just	Score
	Average Household Income	Average household income is included as a relative measure of resources that households may have to support adaptation to high temperatures and poor air quality, for instance ability to adapt homes, access to private transport *etc.* People on low incomes | Climate Just	Pounds
Information use	Recent arrivals	Higher proportions of people recently arrived from outside an area indicate a higher vulnerability as they are more likely to have difficulty obtaining and using information and guidance provided to the public.	% people with <1 yr residency coming from outside UK

Table continued…

	English Proficiency	Relatively poor proficiency in English restricts people's ability to prepare for, respond to and recover from events with the capacity to cause harm because it restricts knowledge of and access to information and support services.	% people who do not speak English well
Local knowledge	Population Transience	In places with high amounts of population turnover there is the potential for higher vulnerability due to lack of knowledge of hazards, health and support services and social networks. Such areas are more likely to be characterised by rented accommodation and in some cases insecure employment. These factors affect the capacity for preparing for, responding to, and recovering from environmental hazards like high temperatures.	% HHs which appear to have changed occupier (2012-2020) [35]
	New migrants	People who have recently moved into an area may lack awareness of local flood risk provided through family and community clues.	
Tenure	Social renting	Social renters are less able to prepare for extreme weather events, for example due to inability to modify their homes to prepare for heatwaves or account for poor air quality. Property maintenance and adaptation is normally the responsibility of the property owner although in the case of some social tenants social renting may also provide opportunities for adaptation. Tenants in social housing are likely to have a range of other characteristics which increase vulnerability Tenants in social or private rented housing: who are we concerned about? | Climate Just	% social rented households

[35] *CDRC Residential Mobility Index | CDRC Data https: //data.cdrc.ac.uk/dataset/cdrc-residential-mobility-index*

Table continued…

Tenure	Private renting	Private renters represent a very broad group and not all are equally socially vulnerable. On average, private renters are less able to prepare for extreme weather events, for example due to inability to modify their homes to prepare for heatwaves or account for poor air quality. Property maintenance and adaptation such as insultation and ventilation is normally the responsibility of the property owner. Renters may also be more transient and therefore less familiar with local neighbourhoods, environmental hazards, and sources of support Tenants in social or private rented housing: who are we concerned about? | Climate Just	% private rented households (historical reference)
Direct flood experience	Households exposed to significant risk	A large body of research shows that those with experience of flooding are less vulnerable in subsequent events as they have more knowledge as to what to do and how to respond. Flood experience has often been shown to be a key factor in level of willingness to take preventative action against future floods and respond seriously to warnings.	

Table continued…

Crime	Crime Rates	People living in high crime (or perceived high crime) areas may have reduced adaptive capacity during high temperature events due to an unwillingness to leave windows open at night. There is also a connection between crime and income, and income and security measures. Who are we concerned about? | Climate Just	Crime rate per 10,000 population
Mobility	Disability and Ill-health	People with disabilities or poor health are more likely to have reduced mobility and/or be reliant on others to assist them during extreme events, *e.g.,* if they have symptoms of heat stress or acute adverse effects due to poor air quality. Even if people are relatively independent in normal times, there may be additional pressures if infrastructure is impacted, *e.g.,* power cuts, internet, or mobile networks. People with low personal mobility | Climate Just	Comparative illness factor (index)
	Medical and Care Residents	People living in medical and care establishments may have greater dependencies because of health-related factors. As well as making people generally more susceptible to negative effects, there are also more likely to be low mobility and additional needs in relation to responding to and recovering from environmental stresses like high temperatures and poor air quality. People with low personal mobility | Climate Just	% living in medical and care establishments
	Private Transport ownership	People with access to private transport have increased adaptive capacity as they have more flexibility to cope with impacts which may result from extreme events and environmental hazards, for instance helping immediate family or the local community access health or other support services, or handling changes due to transport problems during periods of extreme heat.	% households with no car or van

Table continued…

	Accessibility by bus	In areas with low public transport provision, it may be more difficult for people to cope during and after events like heatwaves, or if immediate family is affected by symptoms aggravated by poor air quality. More physically isolated areas may also be associated with other factors which increase vulnerability (Preston *et al.,* 2014[36]).	Bus accessibility
Social network	Single Pensioner Households	Socially isolated people may have restricted adaptive capacity because of a lower ability to seek and receive help if negatively affected by heat or poor air quality. For instance, a sample of approximately half of 919 people who died at home during the 2003 heatwave in Paris showed that 92% of them lived alone and social service records for 383 indicated that a quarter had no social ties (Poumadère *et al.,* 2005).[37] Other studies have shown that those with social ties have lower risk of death, were more likely to take remedial measures and to have support networks for recovery. Single pensioner households may be particularly vulnerable due to a greater chance of other factors such as older age and ill-health, all other things being equal. People who are socially isolated | Climate Just	% single pensioner households

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Table continued…

	Primary School networks	Social ties are generally greater in some sub-sections of society meaning that information and support networks developed as part of everyday life vary. People with primary school children are one such group since connections between children and between parents of young children (*e.g.,* through school-related activities) are likely to be stronger on average (Kazmierczak *et al.,* 2015). [38] During and after extreme events trusted social networks may enable greater adaptive capacity, *e.g.,* through information sharing, support and sharing resources.	% children not of primary school age
	Civil Organisations	The presence of charities and other voluntary organisations in an area is one indicator of social networks and civil society. Such networks facilitate greater social engagement and participation which provide more potential for information, sharing of resources and wider support. People in neighbourhoods with these networks are less likely to be socially isolated, and people who are socially or physically isolated may also benefit because of activities of these organisations.	Per capita rate of registered local civil organisations (Rutherford and Brook, 2018) [39]
	Single Adult Households	Living alone is not necessarily an indicator of social isolation, there are several reasons why single adult households may be more vulnerable, including because of the potential for poorer social networks especially following traumatic life events. Furthermore, people in single households may have fewer resources and more precarity.	% single adult households
	Lone parent households	These households face practical difficulties in responding to a flood where children are dependent on them as there is less direct within-the-family support.	% lone-parent households with dependent children

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Table continued…

Health Service access	Accessibility of Pharmacies and Hospitals and Surgeries	People living in areas which are more physically isolated from health services are less likely to be able to access health services, medical help, or medicines quickly if experiencing heat stress or the effects of poor air quality. They are also less likely to use such services (Ensor, 2004).[40] Fortunately, more physically isolated areas tend to have cooler temperatures and better air quality, although residents may be affected by relatively low temperatures compared to people adapted to warmer environments. This situation is reflected in the differences with heat health warning thresholds across the UK.	Accessibility of Pharmacies (Daras *et al.,* 2019)41
	Travel time to GP surgery (public transport)		Travel time to GP surgery (public transport) (mins)
Service availability	Emergency services, care homes exposed to flooding	Various studies highlight the link between the degree of support provided by institutional (such as the police, the fire brigade, ambulances, and local authority social care) and community support networks and the vulnerability of the individuals in those communities. These linkages are discussed in Sayers *et al.,* 2017c.	% of emergency services and care homes exposed to flooding
	GP and schools exposed to flooding		% no. of GP surgeries and schools exposed to flooding
Housing characteristics	Overcrowding	Densely populated locations and overcrowded households are indicators of where temperatures may be elevated indoors. There is also evidence for poorer health in residents living in crowded accommodation (Public Health Scotland, 2021).[42]	% of people in over-crowded households

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Table continued…

	High-Rise Flat indicator	High-rise flats are well known to be associated with elevated temperatures during heatwave events (Taylor *et al.,* 2015).[43] Analyses of past events demonstrate increased mortality in these building types. Modelling suggests that the degree of enhanced exposure depends on a range of factors such as building orientation, insulation, ventilation and building use (DCLG, 2012). [44]	Count of flats without gardens (Proxy for high-rise flats) Office of National Statistics Source: Ordnance Survey Open Greenspace
	Smoking Behaviour	Maternal smoking is an indicator of the potential for smoking behaviour within the home which may leads to poor indoor air quality.	% mothers current or former smokers
	Indoor sources	Sources of indoor air pollution, such as solid fuel burning, can give rise to elevated air pollution within the home. Domestic and commercial black carbon emissions are taken as a proxy indicator of a range of air pollutants associated with solid fuel use.	Per HH Domestic/Commercial black Carbon emissions (t/a total / HH total) National Atmospheric Emissions Inventory[45]

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Table continued…

Physical Environment	Urban Cover	Urban land covers are associated with higher temperatures because of the Urban Heat Island effect, especially during heatwave conditions (low wind speed, high solar radiation, and low cloud cover) (Levermore *et al.,* 2018).[46] The effect is particularly marked in larger urban areas due to urban structures which prevent re-radiation of stored heat, albedo and thermal capacity of urban structures and waste heat from human activities (Smith *et al.,* 2009). [47] Changes in urban cover overtime also exert an influence on temperature trends as has been shown for Glasgow (Emmanuel and Krüger (2012).[48] Neighbourhoods without much greenspace | Climate Just	% urban land cover Land Cover Map (2019)
Physical Environment	Lack of private greenspace	Vegetated cover around individual dwellings has the potential to provide cooling through shading and evapotranspiration, thus cooling the local areas around where people live. This assumes private spaces are vegetated. In Manchester, the average garden is about 50% vegetation and 17% trees (Baker *et al.,* 2018). [49]Modelling studies have shown both local cooling effects from vegetation and increased temperatures if vegetation is removed. (Skelhorn *et al.,* 2014).[50] Private greenspace may also offer residents better adaptive capacity during hot weather.	Lack of private greenspace (% dwellings without gardens) Office of National Statistics Source: Ordnance Survey Open Greenspace

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Physical Environment	Lack of community greenspace	Urban parks have been shown to be on average 1°C cooler than built-up areas and larger parks have a greater cooling effect due to shading and evapotranspiration (Bowler *et al.,* 2010).[51] This impact can be particularly important in larger and denser urban areas where the cooling effect has an influence on surrounding areas. This effect can be reduced or even reversed in some cases, *e.g.,* dried grass areas. Neighbourhoods without much greenspace | Climate Just	Median combined size of parks and public gardens and playing fields within 1,000m radius (m^2) Office of National Statistics Source: Ordnance Survey Open Greenspace

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LIST OF ACRONYMS

AEP	Annual Exceedance Probability
ALARP	As Low As Reasonably Practicable
ASC	Adaptation Sub-Committee
BCR	Benefit Cost Ratio
CA	Calculation Area
CBD	United Nations Convention for Biodiversity
CCA	Census Calculation Area
CCC	Committee on Climate Change
CCRA	Climate Change Risk Assessment
CDF	Comparative Disadvantage Factor
CLA	Current Level of Adaptation
Defra	Department of Food and Rural Affairs
DZ	Data Zone (census polygon used in Scotland)
DRR	Disaster Risk Reduction
DRM	Disaster Risk Management
EAD	Expected Annual Damages
EADi	Expected Annual Damages: Individual
EAP	Expected Annual number of People flooded
EAPi	Expected Annual number of People flooded: Individual
EC	European Commission
EIA	Environmental Impact Assessment
FDGiA	Flood Defence Grant-in-Aid (England)
FRM	Flood Risk Management
FFE	Future Flood Explorer
GMT	Global Mean Temperature
GFD	Geographic Flood Disadvantage
HFA	Hyogo Framework for Action
iBCR	Incremental Benefit Cost Ratio
ICZM	Integrated Coastal Zone Management
IFRM	Integrated Flood Risk Management
IMD	Index of Multiple Deprivation
IPCC	Inter-governmental Panel on Climate Change
ISDR	International Strategy for Disaster Risk Reductions
JRF	Joseph Rowntree Foundation
LEP	Local Enterprise Partnerships
LSOA	Lower Super Output Area (census polygon used in England and Wales)
LTIS	Long Term Investment Scenarios
MEA	Millennium Ecosystem Assessment
MSOA	Middle Layer Super Output Areas
NFVI	Neighbourhood Flood Vulnerability Index
ONS	Office of National Statistics

PEFf	Number of People Exposed to Frequent Flooding (1: 75 years or more frequent, on average)
RASP	Risk Assessment for Strategic Planning
RBD	River Basin District
REP	Relative Economic Pain
RIBAMOD	River Basin Modelling, Management and Flood Mitigation
SDG	Sustainable Development Goals
SEPA	Scottish Environment Protection Agency
SFD	Systemic Flood Disadvantage
SFRI	Social Flood Risk Index
SFRM	Strategic Flood Risk Management
SOA	Super Output Area (census polygon used in Northern Ireland)
SoP	Standard of Protection
TCPA	Town and Country Planning Association
UNFCCC	UN Framework Convention on Climate Change
USACE	US Army Corps of Engineers
WFD	Water Framework Directive (EC)
WMO	World Meteorological Office

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GLOSSARY

The following definitions are drawn from Sayers *et al.,* 2013, 15, 16 and focus on some of the important aspects associated with Strategic Flood Risk Management. The underlining sources reflect a variety of international publications and workshop discussions and have been adapted for specific use here, including definitions provided by the following organisations and projects:

- ADRC Asian Disaster Reduction Center (in UNU)
- DEFRA Department for Food Environment and Rural Affairs (England and Wales)
- Environment Agency (England and Wales)
- FEMA US Federal Emergency Management Agency
- FLOODsite – EC Integrated Project
- ICOLD International Commission of Large Dams
- UNESCO – IHE UNESCO-Institute for Water Education
- UNU – EHS UN University – Institute for Environment and Human Security
- USGS US Geological Survey
- WHO UN World Health Organisation

Adaptability	The ability to modify a particular measure (structural or non-structural) or instrument (policy or regulation) as the reality of the future becomes known or future projections change.
Adaptation	The ongoing adjustment in natural, engineered, or human systems in response to actual or changing expectations in climate or other drivers of risk. Adaptation may be either autonomous (and achieved through natural change) or planned (and achieved through purposefully adaptation planning; replacing the reactive adaptation often seen in response to an extreme flood that has invariably been characteristic of traditional flood control approaches).
Adaptation pathway	An approach to presenting multiple alternative future strategies (including a portfolio of measures through time) , that can be assessed given uncertainty in future conditions and present day knowledge to determine the preferred course of action today and identify future decisions points.
Afflux	The increase in water surface elevation in a watercourse due to the presence of a constriction in flow (for example arising from a structure

	such as a bridge or culvert), relative to that which would exist without the constriction in place.
Alternative	When making a choice, the decision-maker selects from available alternatives (and holds options for future selection).
Asset management	Systematic and coordinated activities through which an organisation manages its assets and asset systems.
Biodiversity	Biodiversity is a measure of the health of ecosystems – can be readily destroyed or enhanced by management choices. Biodiversity is commonly used in the totality of genes, species, and ecosystems of a region – in context this may refer to a single river reach through to a river basin and even a network of basins. Biodiversity provides a unified describes of the traditional three levels at which biological variety, namely species diversity, ecosystem diversity, genetic diversity – all of which are important considerations in flood risk management.
Capacity	The combination of all the strengths, attributes, and resources available within a community, society or organisation that can be used to achieve agreed goals.
Catchment (River)	The area of land surface that drains to a given point in the river system.
Consequence	An impact such as economic, social, or environmental damage/improvement that may result from a flood. Consequence can be expressed in many valid forms, either quantitatively by qualitatively by category (*e.g.,* High, Medium, Low) or description. The magnitude of the consequence will be influenced by the inherent vulnerability of the receptor and the value society places upon the harm caused and may be expressed in monetarised form, the native form of the impact (*e.g.,* hectares of habitat lost) or in more abstract units.
Control (flow)	A means of modifying (typically limiting) the peak flow to the downstream system.
Conveyance (flow)	The process by which water (or effluent within a sewer system) is transferred from one location to another.
Coping capacity	The ability to which people, organisations, and systems, using available skills and resources, are able to face and manage adverse conditions, emergencies, or disasters.
Debris	Solid natural and anthropogenic material, carried through a watercourse by the flow, that has the potential to increase flood risk (either through the blockage (at bridges and culverts) or through collision with people and buildings). Debris can range significantly in size – from large woody material and shopping trolleys through to individual leaves and bags. In natural channels, and outside of the urban areas, natural vegetation is a positive and important contributor to biodiversity – in their settings such material should not be termed debris. Typically, inorganic sediments are also excluded from the term debris.

Deterministic approach	An approach that adopts precise, single values for all variables and parameters within a precisely defined model, giving a single value output.
Disaster	A serious disruption of the functioning of a community or society causing widespread consequences (including human, material, economic or environmental losses) which exceed the ability of the affected community to cope using its own resources.
Effectiveness	The risk is reduced as expected/desired. In general effectiveness is increased by adopting a portfolio approach where the advantages of one option to compensate for the disadvantages of another to minimise risk and maximise opportunities.
Efficiency	Requires avoiding wasting resources of time, effort, money, environmental capital *etc.* In general efficiency management seeks to develop measures that are synergistic such that the sum effect is greater than the individual parts. In more specific terms, resources are said to be used inefficiently when it would be possible, by using them differently, to make at least one person or community better off without making any other person or community off. Conversely, resources are used efficiently when it is impossible, by using them differently, to make any one person or community better off without making at least one person or community worse off.
Encounter probability	The chance of exceeding a given threshold of a selected variable within a given time.
Environmental Impact Assessment (EIA)	A systematic assessment of possible positive and negative impacts that a proposed project may have on the environment, considering all natural, social, and economic aspects. The purpose of the assessment is to ensure that decision-makers consider the ensuing environmental impacts prior to major decisions being taken and commitments made.
Exposure	The people, property, habitats, networks, and other receptors (see below) that may be flooded and thereby subject to potential harm/losses.
Failure	Failure can be either an ultimate limit state or a serviceability limit state failure (the *failure class*). Several *failure modes* will be related to each failure class. For breach it may be considered an ultimate limit state failure. One possible associated failure mode could be erosion of the downstream face of an embankment leading to breach. Various pre-processes, *failure mechanisms,* may lead to this failure mode.
Flexibility	The ability of a given management strategy to be changed as the reality of the future unfolds and / or projections of the future change.
Flood	The temporary covering by water of land not normally covered by water. The nature of the flood can vary significant depending on the driving source, for example coastal floods (storm surge, wave overtopping and tsunamis), fluvial floods (caused by rainfall – such floods can range from long raise lowland floods to rapid onset flash floods), *pluvial floods* (caused by rainfall directly on the urban area),

	and groundwater floods. The principles of flood risk management are common to all types of floods, but the specific tools and available management options may vary.
Flood Control	Measures taken to modify the behaviour of the flood wave and reduce the probability of flooding in some areas and increase the probability of flooding others. Typically, these are structural measures, either on a large scale (*e.g.,* barriers and levees) or on a small local scale (*e.g.,* run-off attenuation).
Floodplain	The generally flat areas adjacent to a watercourse or the sea where water flows in time of flood or would flow but for the presence of structures and other flood controls. The limits of floodplain are notionally infinite and are therefore defined by the maximum flood extent (based on the worst case or with or without flood control) resulting from a given return period storm.
Floodplain maps (flood)	Maps that typically indicate the geographical areas which could be covered by a flood (during a given return period storm or extreme event) in the absence of control structures. The maps may be complemented with: type of flood, the water depths or water level and where appropriate flow velocity, often simplified hazard categories.
Fragility (curve)	The relationship between the conditional probability of failure (for example the chance of a breached levee) and a given loading condition (for example the water level in the river). The fragility curve provides a graphical representation of this relationship over a range of loading conditions.
Hazard (Flood)	The potential for inundation that threatens life, health, property, and/or natural floodplain resources and functions. The flood hazard is comprised of three elements: severity (depth, velocity, duration, and extent of flooding), probability of occurrence, and speed of onset.
Hazard zoning (flood)	Delineation of areas with different possibilities and limitations for investments and development, based on flood hazard.
Individual Risk	The risk faced by a particular individual (as distinct from societal – or group – risk discussed below).
Integrated Flood Risk Management (IFRM)	An approach to dealing with flood risk that explicitly recognises the interconnection of flood management actions within broader water resources management and land use planning; the value of coordinating across geographic and agency boundaries; the need to evaluate opportunities and potential impacts from a system perspective; and the importance of environmental stewardship and sustainability.
Mitigation	Measures and instruments, including any process, activity, or design to avoid, reduce, remedy, or compensate for adverse impacts of a given activity, development, or other decision.
Non-structural measures	Any measure not involving physical construction that uses knowledge, practice, or agreement to reduce risks and impacts, through policies and laws, public awareness raising, training and education.

Option	When holding an option, the opportunity to choose between alternative (see previous) actions in the future remains. The option-holder can delay making the final decision, rather than having to make it now.
Outcome measures	Measures used to express, in quantified terms, the desirable outcomes that are considered important. This might include the reduction in annual expected lives lost, economic risk reduced, biodiversity gained *etc.*
Overflow	Flow over a structure, such as a flood embankment or sea wall, by a progressive increase in water level.
Overtopping	Periodic flow over a structure, such as a flood embankment or sea wall, through wave action.
Pathway (of the risk)	The connection between a particular initiating event (source of the risk – see below) and the receptor that may be harmed or experience loss (*e.g.,* a property – see below). The pathway, for example, may consist of the upland land surfaces, the river channel, the levees, and the flood plain between an upstream inflow boundary (the source) and a particular house (the receptor).
Policy and regulatory instruments	Policies and regulations provide the principles and rules that guide the framework within which flood risk management strategies are developed, decisions made and, in some instances, delivered on the ground.
Portfolio approach	A management approach to reducing risk that relies upon the implementation of a wide range of options, in space and in time. Within a portfolio approach the aim is to develop a strategy consisting of a range of activities where the advantages of one measure or instrument compensates for the disadvantages of another, and synergies provided by combinations of options are exploited (*e.g.,* wetland creation and support, flood warning).
Predictive models	*Understanding* cause-effect relationships – either through quantitative or qualitative models – forms the bedrock of predictive capability. These can be based on reductionist or complex system approaches. Increasingly models based solely on past observations are unable to provide meaningful predictive tools. It is not meaningful, for example, to conduct a statistical analysis of the release from a reservoir, or indeed of the flow in a heavily regulated river.
Probability	The probability is a measure of the degree of the belief that a flood will occur within a given time frame (annual, lifetime *etc.*) or during a given event. This measure has a value between zero (impossibility) and 1.0 (certainty). There are two main interpretations: *(1) Statistical frequency* – The outcome of a repetitive experiment of some kind like flipping coins. It also includes the idea of population variability. Such a number is called an "objective" probability because it exists in the real world and is in principle measurable by experiment.

	(2) Subjective probability – Quantified measure of belief, judgement, or confidence in the likelihood of an outcome, obtained by considering all available information honestly, fairly, and with a minimum of bias. Subjective probability is affected by the state of understanding of a process, judgement regarding an evaluation, or the quality and quantity of information. It may change over time as the state of knowledge changes. Many "probabilities" of interest to the flood manager/analyst are subjective and cannot therefore be formally validated by observation.
Probability of flooding	The chance of a particular part of the floodplain experiencing flooding after taking account of the performance of any associated flood control infrastructure (including both failure and non-failure possibilities). The chance of flooding must be linked explicitly to an associated reference timescale (annual or lifetime probability for example) and a specific characteristic(s) of the flood (depth, duration, or velocity for example). The probability of flooding is not simply related to the return period of the driving storm.
Receptor	The entity that may be harmed by a flood. In the event of heavy rainfall (the source) flood water may propagate across the flood plain (the pathway) and inundate, for example, a house (the receptor) that may suffer material damage (the harm, consequence).
Residual risk	The risk that remains after accounting for the performance of all flood risk management actions (*i.e.,* measures to reduce the chance of flooding and those taken to reduce vulnerability or improve resilience). To avoid confusion, the date at which the residual risk has been assessed should be communicated. Typically, the stated residual risk of relevance to the public is associated with the present day. For planners understanding how the residual risk varies in time due to climate or other changes is crucial.
Resilience	The ability of an individual, community, city, or nation to resist, absorb or recover from a shock (*e.g.,* an extreme flood), and/or successfully adapt to adversity or a change in conditions (*e.g.,* climate change, economy downturn) in a timely and efficient manner and transform to a new state.
Resilient design	Resilient design fosters innovative approaches to the design, construction and operation of buildings and infrastructures that are resilient to climate-related (and other) hazards. Adopting an integrated approach incorporates resilience as one of the primary goals during building design. In addition to protecting the lives of building occupants, buildings that are designed for resilience can absorb and rapidly recover from a disruptive event. Continuity of operations is a major focus.
Return Period	A statistical measure denoting the average recurrence interval that a particular event (*e.g.,* an in-river water level, or wave overtopping volume) of a given magnitude is exceeded (when considered over an

	extended period). While it is true that a 10-year event will, on average, be exceeded once within any 10-year period, the chance of encountering such an event in the next 10 years is approximately 65% – the so-called encounter probability.
Risk	The combination of the chance of a particular event (*e.g.,* the flood hazard), with the impact that the event would cause if it occurred. Risk therefore has two components – the chance (or probability) of an event occurring and the impact (or consequence) associated with that event. The consequence of an event may be either desirable or undesirable. Within this context the probability is typically related to the 'hazard' (the occurrence of a flood of given depth for example) and the consequence reflect the exposure and the vulnerability of those exposed (*e.g.,* Sayers *et al.,* 2014). The assessment of the risk is typically framed giving consideration to the behaviour of the sources-pathways and receptors (as defined here). Given flood risk management is concerned with protecting society and hence a risk is typically concerned with the likelihood of an undesirable consequence and our ability to manage it. (Note: Opportunities for positive gains should also be sought but recorded as "opportunity gains" and not risks).
Risk evaluation (Flood)	The process of examining and judging the significance of risk estimated through the process of risk analysis. The risk evaluation stage is the point at which values (societal, regulatory, legal and owners) and value judgements enter the decision process, explicitly or implicitly. Within risk evaluation consideration is given to the significance of the estimated risks and the associated social, environmental, economic, and other consequences together with an understanding of the investment needed to reduce the risk to develop an appropriate flood risk management strategy.
Risk identification (Flood)	A qualitative process of determining what could go wrong, why, and how.
Risk reduction (Flood)	A selective application of options (both structural and non-structural) to reduce either likelihood of a flood or its adverse consequences, or both.
Risk-based or Risk-informed decision-making	An approach to decision-making that supplements information on risk (both probability and consequence) with subjective trade-offs and issues of equity and opportunity gains. (In some countries a more restricted definition of risk-based is used and relates to a decision made only through consideration of benefits and costs).
Risk (tolerable)	The level of risk a society or community considers tolerable given existing social, economic, political, cultural, technical, and environmental conditions. An understanding of tolerable risk helps guide the level of investment that may be appropriate to reduce the risk (where possible).
Risk Maps	Maps that combine information on probability and consequences to spatially differentiate risk. The mapped risk is often expressed in terms

	expected annual risk (integrating all possible storm events and possible system responses that may occur in a year) or event risks (*i.e.,* the expected damages associated within a specified storm event). Risk maps typically display: (i) Numbers of potentially deaths or serious injuries; (ii) Economic damages (national or financial) (iii) Secondary impacts – for example arising from accidental pollution caused by flooding, loss of power to non-flooded properties *etc.*
Robustness	The degree to the outcome of a given choice continues to perform as desired (acceptably) across a range of possible future scenarios.
Societal concerns	Concerns engendered by those hazards which have the potential to impact on society if realised. The evaluation of a risk will reflect the degree of societal concern.
Societal risk	Widespread or large-scale consequences arising from the realisation of an extreme hazard, the implication being that the consequence would be on such a scale as to provoke a socio/political response, and/or that the risk provokes public discussion and is effectively regulated by society through its political processes and regulatory mechanisms. Such large risks are typically unevenly distributed, as are their attendant benefits. The construction of a dam, for example, may increase the risk to those close by but provide a benefit to those remote from the dam, or an action/decision may harm a future generation more than the present one (for example tying a future generation into a poor, and expensive, planning decision). The distribution and balancing of such major costs and benefits is a classic function of Government, subject to public discussion. The results of such a debate shape the evaluation of risk and the nature of the management policies and approach adopted.
Source (of risk)	The event(s) that is/are considered to initiate a potential flood (for example, heavy rainfall, strong winds, surge, or even human error/ attack – accidental opening of a gate or aircraft collision into a dam *etc.*).
Stakeholder	Any one person or group of people with a legitimate interest in the decisions being made.
Strategic Flood Risk Management (SFRM)	Strategic Flood Risk Management delivers multiple outcomes for people and nature over the short and long term. The approach is inherently collaborative, inclusive, and systems-based with choices based on an understanding of risks, benefits, and uncertainties. A continuous process of review and adaptation actively manages change, incorporates new knowledge, and modifies plans and actions.
Structural measures	Any physical construction to reduce the chance or severity of the flood waters reaching a receptor (see above). Structural measures range from large-scale infrastructure responses, such as barriers and levees, through to local responses to improve the resistance and resilience of individual homes or critical installations.

Sustainability	First defined as 'development which meets the needs of the present without compromising the ability of future generations to meet their own needs,' sustainability is a simple yet powerful concept. It emphasises the inter-linkages between economic development, environmental health, and social wellbeing – not as three separate objectives but one. Agenda 21 reinforces the notion of integration and stresses the need to move away from sector-centred ways of working to new approaches that involve cross-sectoral coordination and integration. Broad public participation in decision-making as a fundamental prerequisite for achieving sustainable development is also emphasised. Flood risk management is inextricably linked with issues of sustainability. Not only does flood risk management impact the physical environment, through the development of control structures and spatial planning measures, but also provides opportunities for, and constrains upon, human and natural activities in the long term.
System (flood risk)	In the broadest terms, the social and physical domain within which risks arise and are managed. An understanding of the way a system behaves and the mechanisms by which it may fail, is an essential aspect of understanding risk. This is true for an operational system like flood warning, as well as for a more physical system, such as a series of flood defences protecting a floodplain, and, importantly, the system.
Tolerable risk	The degree of residual risk that society is prepared to tolerate to secure certain net benefits (*e.g.,* environmental improvement, power generation, urban development, limited expenditure on flood management *etc.*). Tolerable risk varies from situation to situation and is not negligible or something we might ignore. The associated residual risks must be kept under review and reduced further where appropriate.
Unacceptable risk	A level of risk that cannot be justified except in extraordinary circumstances. Typically, where the continuation of the risk has been authorised by government or a regulator in the wider interests of society, and either further reduction of risk is simply not possible (for example all levees and dams, regardless of their design and maintenance regimes, have some, albeit small, chance of failure) or the resources required to reduce the risk are disproportional to the additional benefits secured.
Uncertainty (routine)	Any prediction/inference (timing of a storm, data, model, or decision) that is not accompanied with complete sureness, whether described by a probability distribution. Uncertainty can be attributed to (i) the inherent variability in natural properties and events (aleatory uncertainties), and (ii) incomplete knowledge of the variables, parameters, and model structures (both quantitative and qualitative models) (epistemic uncertainties).
Uncertainty (deep)	A profound and rationale doubt about what choice to make. This underlying uncertainty (in the data and modelling) cannot be eliminated through further investigation. The doubt can only be addressed through the exploration and the identified of the preferred choice, based on

	stated preferences (from low regret, robust, precautionary, or other decision frameworks).
Vulnerability	A combination of the inherent susceptibility of a particular group, people, property and or natural feature to experience damage during a flood event and societies preferred means of valuing the harm experienced. The vulnerability of a property, for example, is expressed through a flood depth to economic damage relationship, the vulnerability of an individual may be expressed through a relationship between flood depth/velocity and the chance of dying or being seriously injured. Vulnerability may therefore be modified through actions that reduce a receptor's susceptibility to experience harm (improved speed of recovery after a flood for example).
Watershed	A general description for a drainage basin, sub-basin, or catchment.
Wetland	A permanently moist and seasonally flooded area whose formation has been dominated by water, whose physical characteristics are largely controlled water, and which supports a rich and diverse ecosystem that is specifically adapted to the prevailing, hydrological regime.

About the Author

Paul is a Chartered Engineer and specialises in the strategic management of the water environment and its associated risks and opportunities. Paul graduated in Civil Engineering from Brighton in 1991 with a first-class honours degree. Studying under John Moffett and Prof. Andrew Chadwick (authors of a leading undergraduate text on hydraulic engineering) laid the foundation for his chosen career. In 1991 Paul joined the Hydraulics Research Wallingford and left his position as the Director of Flood and Water Management in 2010 to establish Sayers and Partners.

Paul has over thirty years national and international experience in all aspects of flood and coastal risk management (including providing leading contributions to the seminal Foresight Future Flooding studies in early 2000). Paul's international experience covers Africa, Asia, Europe, Australia, and North America.

Paul has enjoyed various visiting associations during this time, with the Environmental Change Institute, University of Oxford, UK; Tyndall Centre at the University of East Anglia, UK; and IHE-UNESCO in the Netherlands. Paul has had a longstanding association with WWF (providing strategic advice on water issues) and continues to be a member of the Expert Panel on Nuclear Safety (coastal hazards) within the Office of Nuclear Regulation, and is a longstanding advisor to joint Defra and Environment Agency research programme.

The development and application of risk-based strategic approaches that deliver positive outcomes for people and nature have formed a red thread throughout his career. This continues to be the case.

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Throughout history flood management practice has evolved in response to flood events. This heuristic approach has yielded some incremental advances, but flood risks continue to increase. A new approach is needed.

This thesis sets out a more strategic approach to flood management and demonstrates its application at national and regional scales (for the UK and the Thames estuary). Strategic Flood Risk Management (SFRM) is presented as an approach that adopts a systems perspective and relies upon an adaptable portfolio of measures to deliver outcomes for people, economies, and nature. Supporting tools are developed, including a hierarchy of highly efficient exploratory modelling approaches capable of exploring how flood risks may change in response to climate change, population growth, and alternative adaptation policies. New risk metrics are presented, including the Neighbourhood Flood Vulnerability Index (NFVI), and shown to provide new quantified insights into social vulnerability and systemic disadvantage across the UK.

The exploratory tools, metrics and framework are shown to have influenced long term policy and planning in the UK and elsewhere, with the Golden Rules of SFRM set out in the early years of the thesis revisited and shown to have lasting relevance.

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