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Tidal Thames in London:
Flood Risk and Adaptation Planning

Climate Risk and Resilience in China (CRR)

Project Overview

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Introduction

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 and techniques to assess the performance of different management strategies under future scenarios. 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. This case study summarizes the context of the Thames, the analysis of risk (hazard exposure and vulnerability) and the resulting adaptation strategy.

1. Overview

This case study explores the background to 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 ran through to 2009 with ongoing updates since) was established to develop for a long-term tidal strategy for the Thames, London (and in response to three primary drivers:

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 however would be a significant task (estimated to require upto £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. For example, 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[1]. It was increasingly clear that the lack of a clear flood risk management strategy for the Thames could lead to long-term development decisions being made in the absence of appropriate strategic input by flood risk managers.

In response to these concerns, a detailed assessment of flood risk (present and future) and set out 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) was undertaken. The context of this study is presented together with the adaptation strategy and the approach to monitoring and financing the actions.

Thames River (© unsplash / Shane Rounce)

2. Thames Estuary in Context

2.1 Setting the scene

The Thames is only 346 km 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 2011 Census) with a gross domestic product (GDP) per capita of around 67,500 Euro[2].

Today, the flood plains of the Thames estuary are home to approximately 0.5million homes, 1.25million people (on any given working day), national government and ministries, around £200billion 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 £250billion 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. (**Figure 1** [3]).

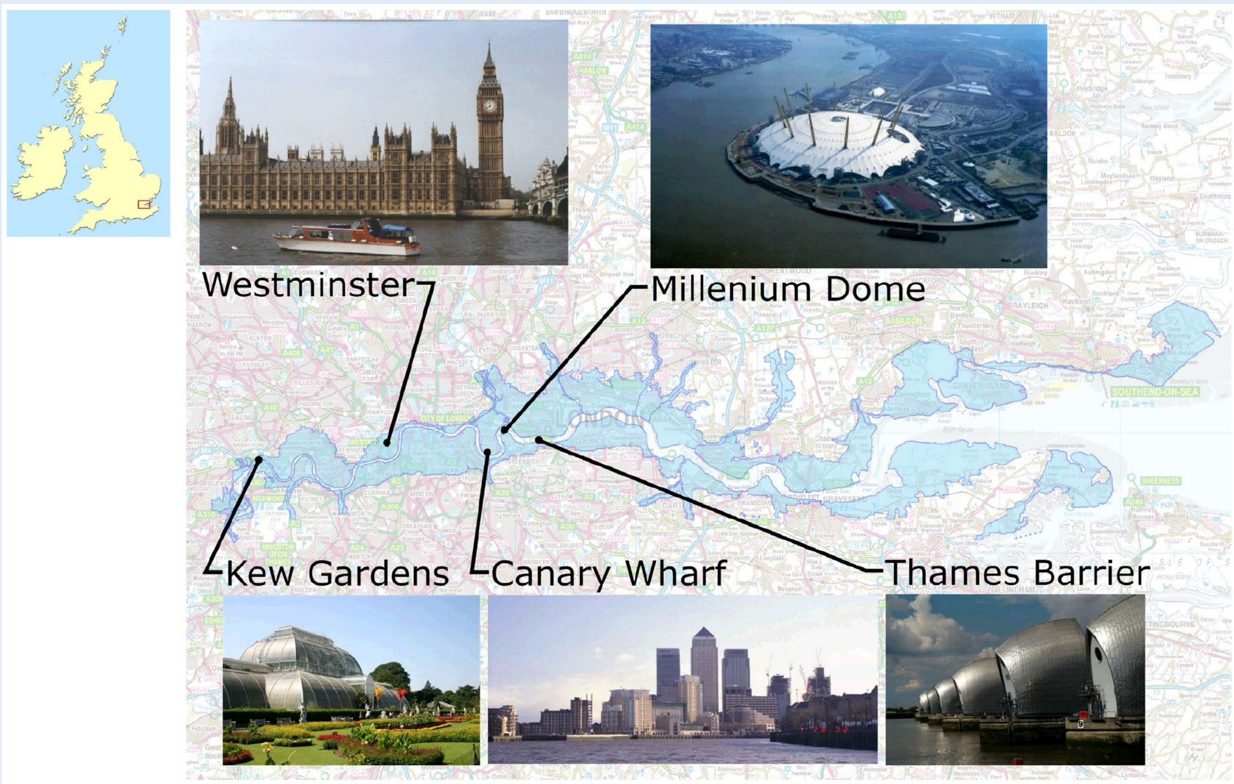


Figure 1: A range of vital and valuable assets lie in the floodplains of the tidal Thames – the setting for the Thames estuary case study
Source: Background map, Environment Agency (Flood Zone 3); images open source

2.2 Authorities involved in the management of the Thames – past and present

Several organisations are involved in flood management in the UK (**Table 1**) with the Environment Agency having strategic oversight of all flood issues across England. Within London and the Thames estuary the Environment Agency work closely with the Mayor of London (an elected politician), along with the London Assembly of 25 elected members, to contribute to the strategic development of London. The Greater London Authority (permanently staffed with civil servants) supports the work of the Mayor and the Assembly, helping them develop and deliver strategies for London.

Table 1: Organisations responsible for flood and erosion 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.
Various non-governmental organisations (NGOS), e.g. WWF, RSPB	Provide a strong voice in shaping flood and erosion risk management actions.
Natural England, English Heritage and other 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.

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 during this period with little in terms of a formal response. This change in the 19th century, following two exceptional record tides of 1874 and 1875. In response Parliament acted by passing the Metropolis Management (Thames River Prevention of Floods) Amendment Act 1879 [4]. 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 (**Figure 2**). Following the devastating North Sea surge of 1953[5] and 58 deaths on Canvey Island in the outer Thames Estuary, the issue of flooding gained new prominence. It took until 1972 before legislation was provided (through the Thames Barrier and Flood Prevention Act) to design and construct the system of River Thames tidal defences seen today.

2.4 The flood defence system in London today

The flood defence system in London today results from the various decisions of the past (as set out in the previous section). Today however there is a greater emphasis on managing flood risk in the estuary using a portfolio of approaches, including a formal flood defence together with nonstructural measures, including forecasting and warning, spatial planning and emergency exercises. All these elements are discussed below.

Flood defence: 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 3**). 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,

Figure 2: Historically a flood defence approach has led to "reactive" raising of the defences in response to major events – Courtesy Thames Estuary 2100 Project.

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 1 in 1000 -year combined tidal/fluvial flood event in the year 2030 (the highest standards of flood defence in the UK)[①]. 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.

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, 365days 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 however there is concern that the frequency of closure may increase so much as to make maintenance impossible (**Figure 4**).

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 development but rather seek to ensure any development that does 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 remain 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 are regularly stress-tested as part of synthesised response, but in the absence of a widespread flood since 1953 there operational success remains to be confirmed.

[①]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 discussed later in this chapter - suggests the actual standard to be approximately a 1 in 10000-year return period

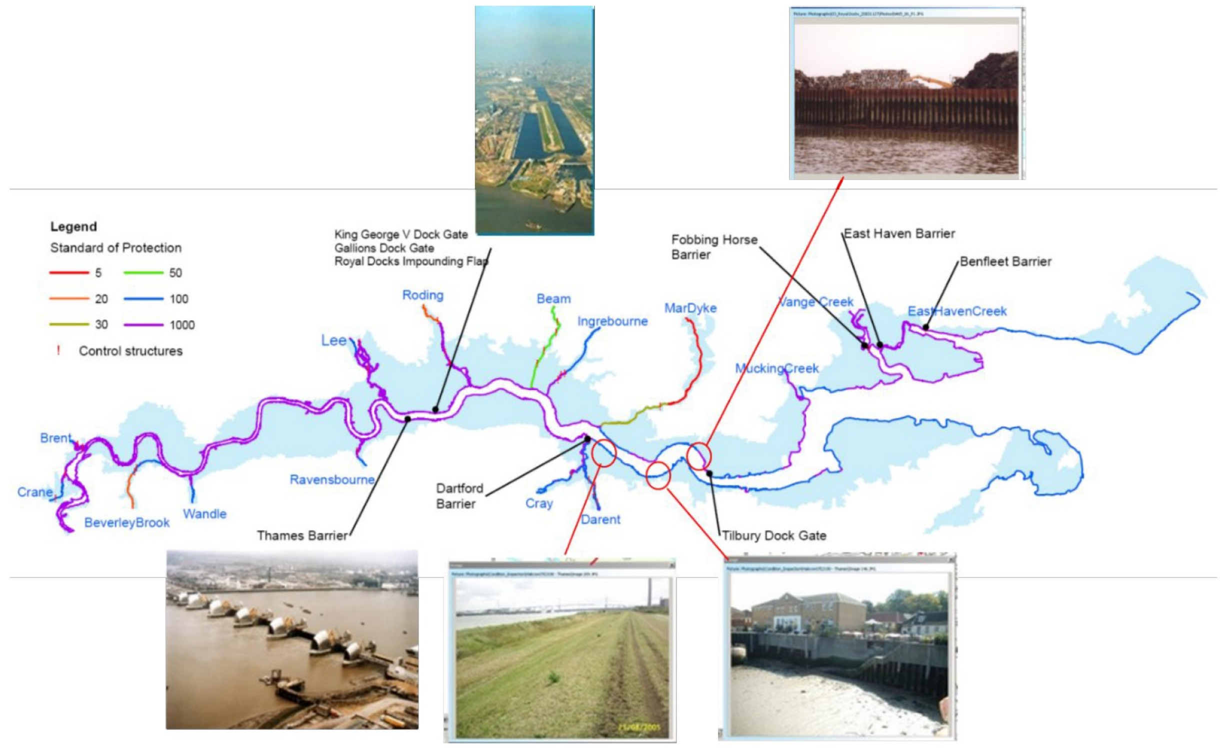


Figure 3: The defended Thames tidal floodplain and the present-day standard of protection and primary tidal barriers
Source: Background map, Environment Agency (Flood Zone 3); images open source

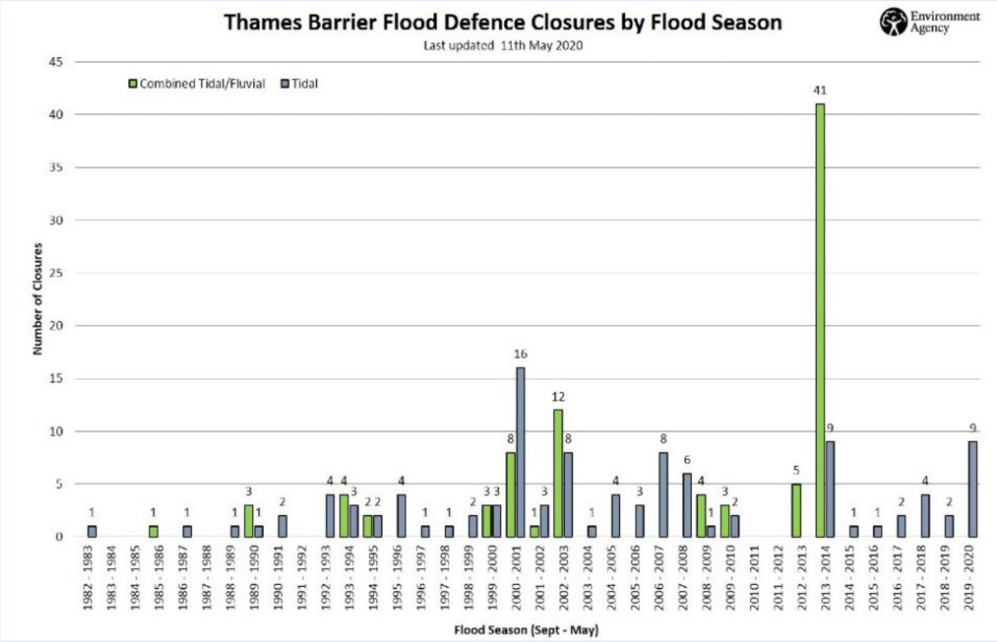


Figure 4: Change in closure frequency of the Thames Barrier
Source: Environment Agency open source

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[7]. 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 have been recorded since the 1960s, nine of which now spawn within the estuary) – **Figure 5**. Large parts of the outer estuary are designated wildlife sites, and support nationally and internationally important habitats and species (notably birds, but also fish, invertebrates and marine mammals). Thames estuary is also intrinsically connected to the (southern) North Sea and the east Atlantic fly-way (a flyway linking a discontinuous band of arctic breeding grounds that stretch from Canada to Siberia, Russia).

Figure 5: Thames Estuary supports significant biodiversity and provides an important habitat
Left: Courtesy Andy Wallace, Environment Agency, Right: Environment Agency, 2006
Right: Green areas indicate natural marshland in the Thames floodplain and example grazing marsh in the outer estuary

2.6 Flood sources (hazards)

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 Environment Agency provides a strategic overview of all flood issues, however, developing and delivering integrated solutions; due in part to the technical challenges of doing so and in part due to the division of responsibilities over different sources of flood water in England (not discussed further here). The TE2100 projects, and the remainder of this chapter, therefore 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 placed an unprecedented demand on 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.

The response to the raising water levels has been the approval of new abstraction licenses across the central London area however the responsibility for developing and funding a more strategic groundwater management plan is unclear and limited progress has been made.

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 localized 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[8]. 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. In times of severe storms, Bazalgette designed the system to overflow through discharge points into the River Thames, rather than flooding streets and homes. A combination of continued development, climate change and pollution concerns lead to a commissioning of the Thames Tideway Strategic Study Group in 2001. As a result, a major new inceptor tunnel (7.2m diameter, 25km-long tunnel, up to 65m below ground) was selected by Government as the preferred solution and the (at the time of writing) is under construction. The choice of solution, however, has not been without its critiques; with many highlighting a that a more distributed 'blue-greening' of the City would have achieved additional benefits for less (e.g. Prof Richard Ashley and past ICE President Jean Venables). The impact on tidal flooding (the focus here) is expected to be marginal.

3. System Risk Analysis: Tools and Techniques for the Thames

From the outset it was clear that conventional modelling approaches would not be able to provide the whole system risk analysis required to assess flood risk across the Estuary within practical runtimes 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 evolves from the Source-Pathway-Receptor concept (**Figure 6**) and the RASP (Risk Assessment for Strategic Planning) probabilistic analysis method that implements the Source-Pathway-Receptor framework[9][10][11] ②. The probabilistic integration of the sources-pathways and receptors includes considerations 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 where all represented within the system risk model; including the probability both serviceability (e.g. overtopping without breach) and limit state failures (e.g. breach).

- **Receptors** – A wide range of simple to quantify impacts are considered, with primary risk metrics based on direct economic damages (based on residential and commercial property damages)[14]. Wider considerations, such as risk to environmental, people and business disruption were also included but using methods and techniques less well advanced and largely based on expert elicitation.

The RASP model enables risk to be tracked in the floodplain and then attributed back to the corresponding failed or overtopped flood defence lengths. This functionality was used to highlight where future improvements could be made. **Figure 7** shows the probability of inundation in the Thames Estuary under the present-day conditions assuming the

②Following completion of the TE2100 studies the RASP methods continued develop. From 2008 the RASP HLM*plus* underpinned the National Flood risk Assessment (NaFRA) and translated into the Modelling Decision Support Framework 2 (MDSF2) software now widely used by the Environment Agency and its consultants

Thames Barrier is fully operations and the wall and embankments are in the current condition. The majority of the floodplain has a lower than a 1:1000 year probability of inundation, which is as expected given the current level of defence. Certain hotspots can be seen of the tidal tributaries and in the outer estuary where defence standards are lower.

Once established the system risk model was then used to explore the influence of future change on the estimate of present day risk in a structured manner, including:

- **Changes in the source terms** – Changes in climate, both in mean sea level, fluvial flows and potentially extreme surges are only important issues to explore. The system models provided a framework that made exploring the impact of such change relatively straight forward.
- **Changes in the pathways** – Modification to the barriers and defences, either through raising, strengthening or repositioning, flood proofing of properties or more ambitious modification of the floodplain topography are considered modification to the pathway within the system model, and there individual influence on risk isolated.
- **Changes to the receptors** – Modification to the ensure the number or location of the people or property in the floodplain, or changes to their vulnerability (perhaps through enhanced warning or better preparedness) were reflected in the system model through changes to the quantified receptor damage functions.

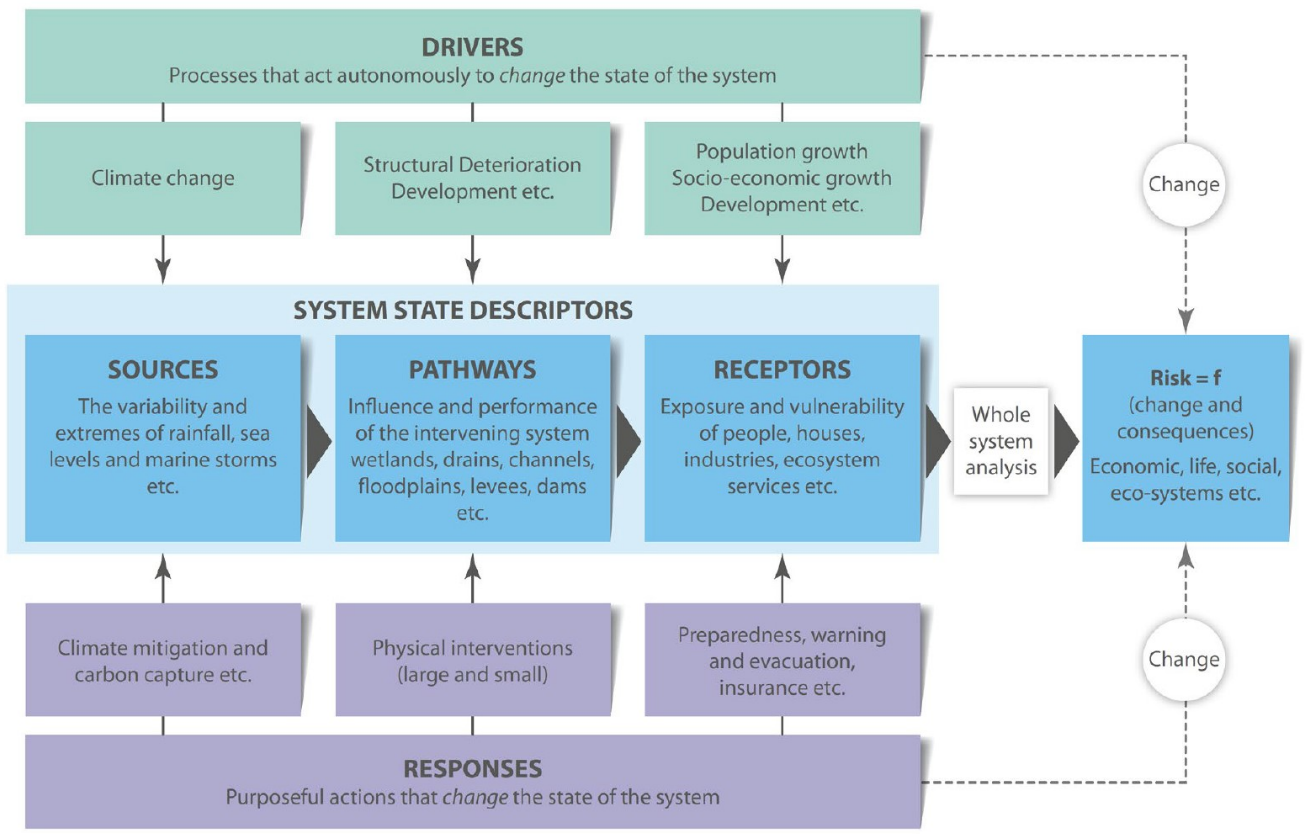


Figure 6: The risk analysis for the Thames Estuary is based on analysis is based on the source-pathway-receptor framework [9]

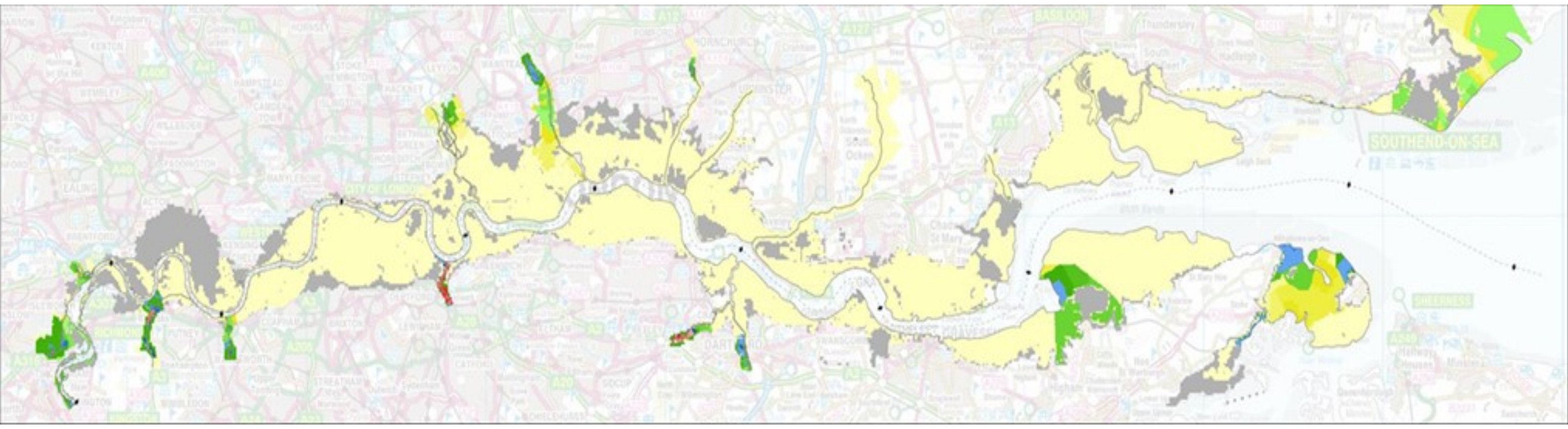


Figure 7: Probability of Inundation along the Thames Estuary under present-day conditions[3]

4. Supporting Adaptive Decision-Making

The approach to decision-making in the TE2100 adopts a long-term strategic framework focused on four key steps:

- Step 1 – Assess performance present day performance (using a range of risk metrics).
- Step 2 – Determine exogenous futures (i.e. establish alternative 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 discussion in turn below together.

4.1 Step 1: Assess present-day performance

No single metric provides a comprehensive understanding of risk. Instead, several multiple metrics are 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: Figure 7, for example, shows the annual probability of inundation (to a flood depth exceeding 0m) under present-day conditions (and assuming the Thames Barrier to be operational). The figure shows much of the flood plain 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 (**Figure 8**).

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 probability of the flooding with the associated consequences (exposure and vulnerability terms). An example output from the analysis showing the direct economic damage to residential and commercial properties against the annual exceedance probability (expressed in return period for ease) is shown in **Figure 9**.

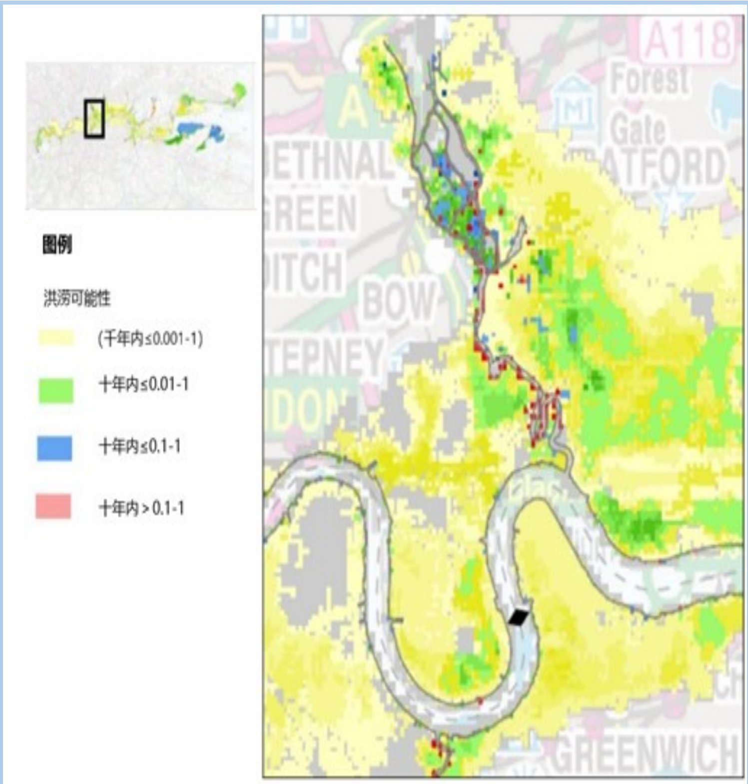


Figure 8: Probability of inundation along the Thames Estuary under present-day conditions (a selected view)[15]

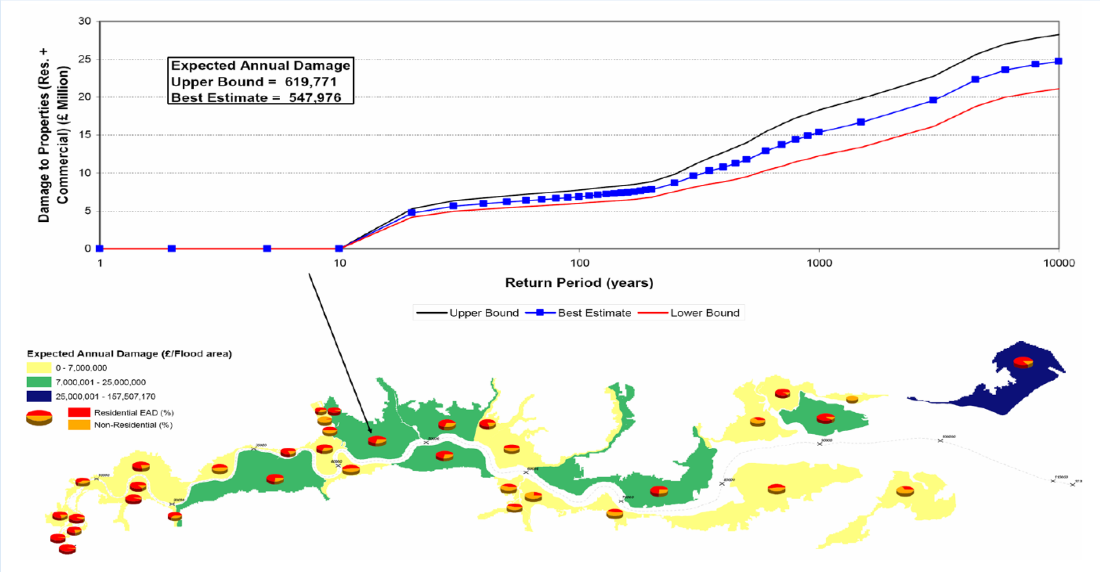


Figure 9 Example of economic risk profile and Expected Annual Damages in the Thames Estuary: Present Day[16]
Top - The chart shows how the risk increases with storm return period (so-called 'event risk') for the West Ham/ Royal Docks Flood Area).
Bottom - The chart shows the Expected Annual Damage (£)

Defences asset that contribute most to residual risk: The existing defence system within the Thames Estuary is significant, maximising value from these existing assets underpins an efficient strategy. A well-constructed asset database (designed using the principles of good asset management, e.g. Sayers et al., 2010[17]) together with risk system model is enables those assets that contribute most to risk to be readily identified through this process (for example in the **Figure 10**, more than 90% of the residual risk is attributed to just ten defences).

Alongside monetised impacts, social and environmental impacts form a significant component of the TE2100 planning process. For example, number of people exposed to flooding (i.e. the number of people at risk of injury); environmental feature exposed flooding (using a range of criteria); and, equity and fairness issues (including a basic enhance to the achieved benefits for properties protected in deprived neighbourhoods as determined using the Index of Multiple Deprivation). 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.

4.2 Step 2: Determine exogenous 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, however significant uncertainty continues to exist. Depending on assumptions regarding future global emissions and, critically, the response of the polar ice caps and glaciers, there is a significant variation in future projections of relative sea level rise (rSLR) in the Thames, including standardised projections (**Figure 11**).

Given this uncertainty, and the profound influence alternative

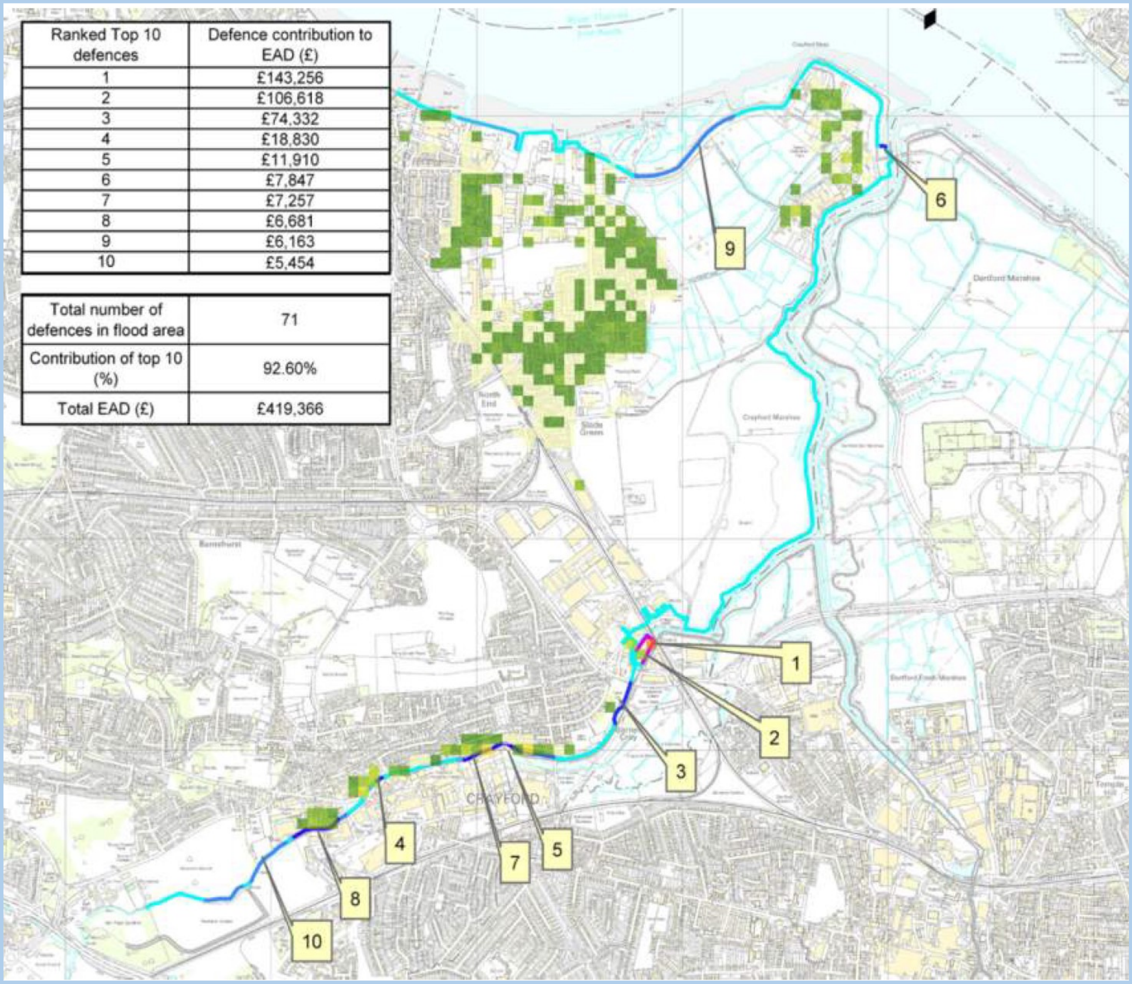


Figure 10: Attributing flood risk to individual defence assets[15]

estimates of rSLR have on the performance of different management strategies, the TE2100 programme uses four climate change scenarios to assess the performance of alternative strategies, namely:

- Low – a 0.5m rise in mean sea level by 2100.
- Medium–high – a 1.5m rise in mean sea level by 2100.
- High+ – a 2.7m rise in mean sea level by 2100.
- High++ – a 2.2m rise in mean sea level by 2100.

Population growth and development: Building upon the analysis of local planning aspirations to 2030 future development through to 2100 are developed based on three distinct growth assumptions:

- Low growth future assuming no further growth
- Medium growth further 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 development the distribution of new properties in the floodplain.

These projections are shown in **Figure 12**, with further detail provided in McGahey and Sayers, 2008[13].

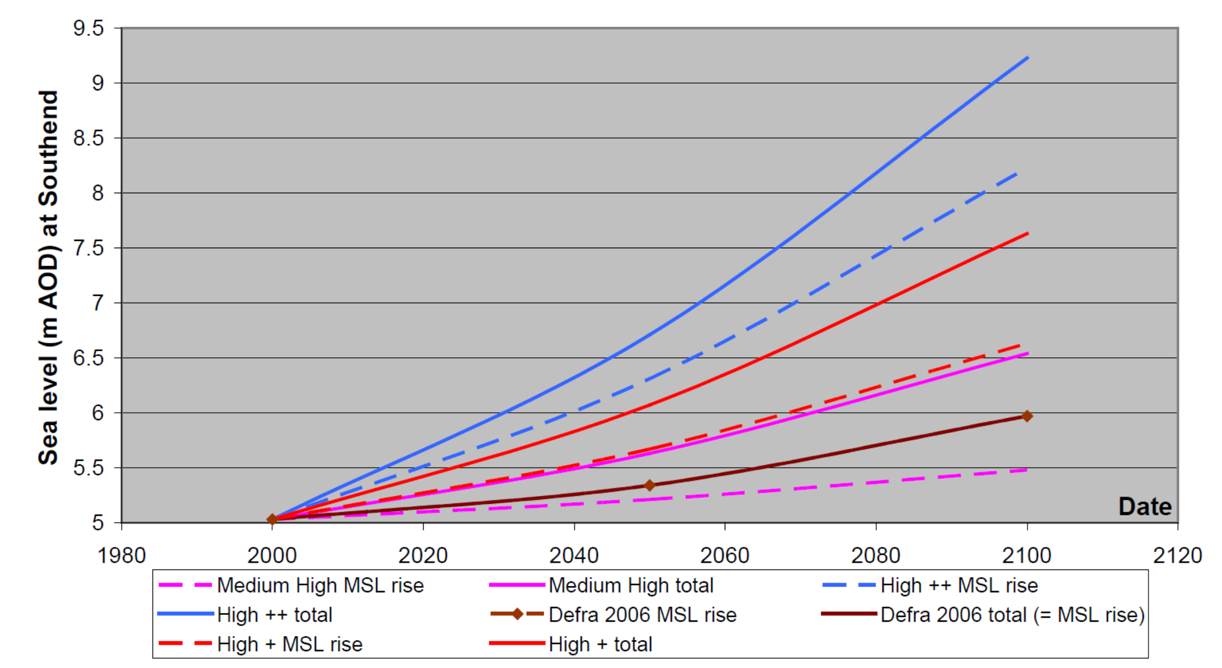
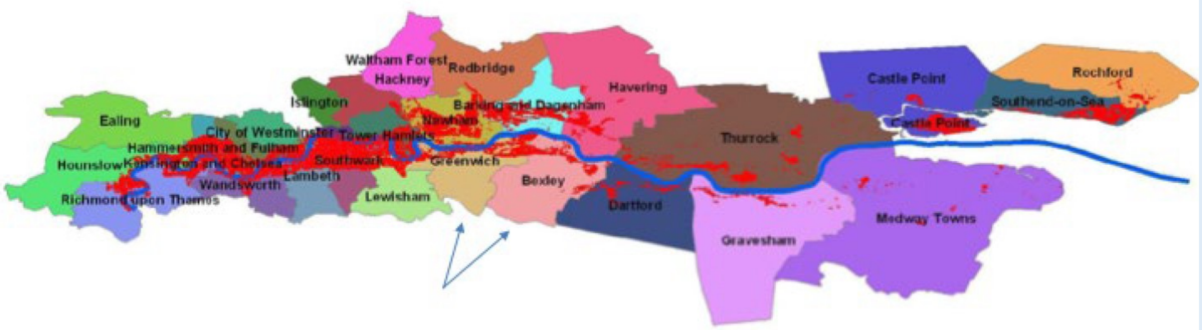
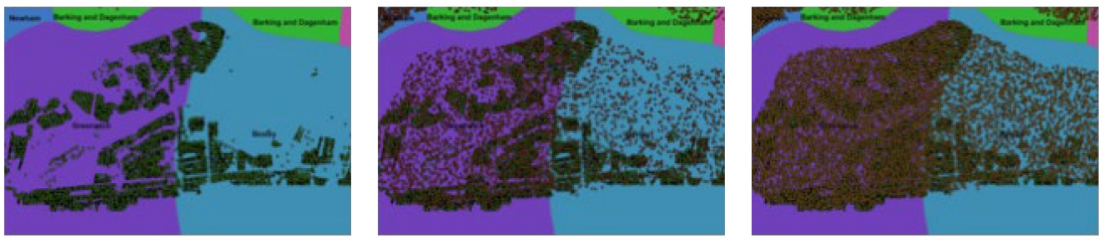


Figure 11: The influence of sea-level rise on 1000-year water level in the outer Thames Estuary



Existing houses in floodplain of the Thames Estuary (and Borough boundaries)



Medium projection housing growth (a) present day, (b) 2040s and (c) 2100s (Greenwich and Bexley Boroughs)

Figure 12: Translation of long-term housing projections to property development in the floodplain[13]

4.3 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 aging, 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 mean 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 a 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 developing the concepts of 'living with the estuary', accepting a higher residual probability of flooding and managing the residual risk with non-structural measures.

4.4 Step 4: Identifying a robust and adaptable strategy

Guidance set out by the UK Government requires that flood risk management plans focus on three aspects: **(i) protecting the well-being of people; (ii) meeting the requirements of statutory instruments such as European Directives on birds and habitats** (that aim to 'protect the integrity' of internationally important nature conservation sites) and water (that aim to 'maintain and improve the water environment'); and, **(iii) efficiency of public investment** (ensuring public money is invested to ensure the greatest return across all public spending). The TE2100 project develops a strategy that recognises a future characterized by severe uncertainty. In this context, no single pathway (strategic alternative) provides a uniquely preferred approach in addressing all of these issues. Instead, a strategy that embeds a process of adaptation based on a continuous process of review was sought.

To reflect this goal of an adaptable strategy, a flexible strategy was developed around the concept of a decision pipeline or adaptative pathway[13], that presents potential actions in the form of a decision tree. **Figure 13** 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. In particular 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.

The TE2100 plan also includes a monitoring and continuous process of re-evaluation[18][19][20]. The monitoring process provides the triggers[2] for the decisions within the pipeline. For example, if monitoring reveals that climate change is happening more quickly (or slowly) than predicted, the strategy can be reappraised in light of the new information, 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).

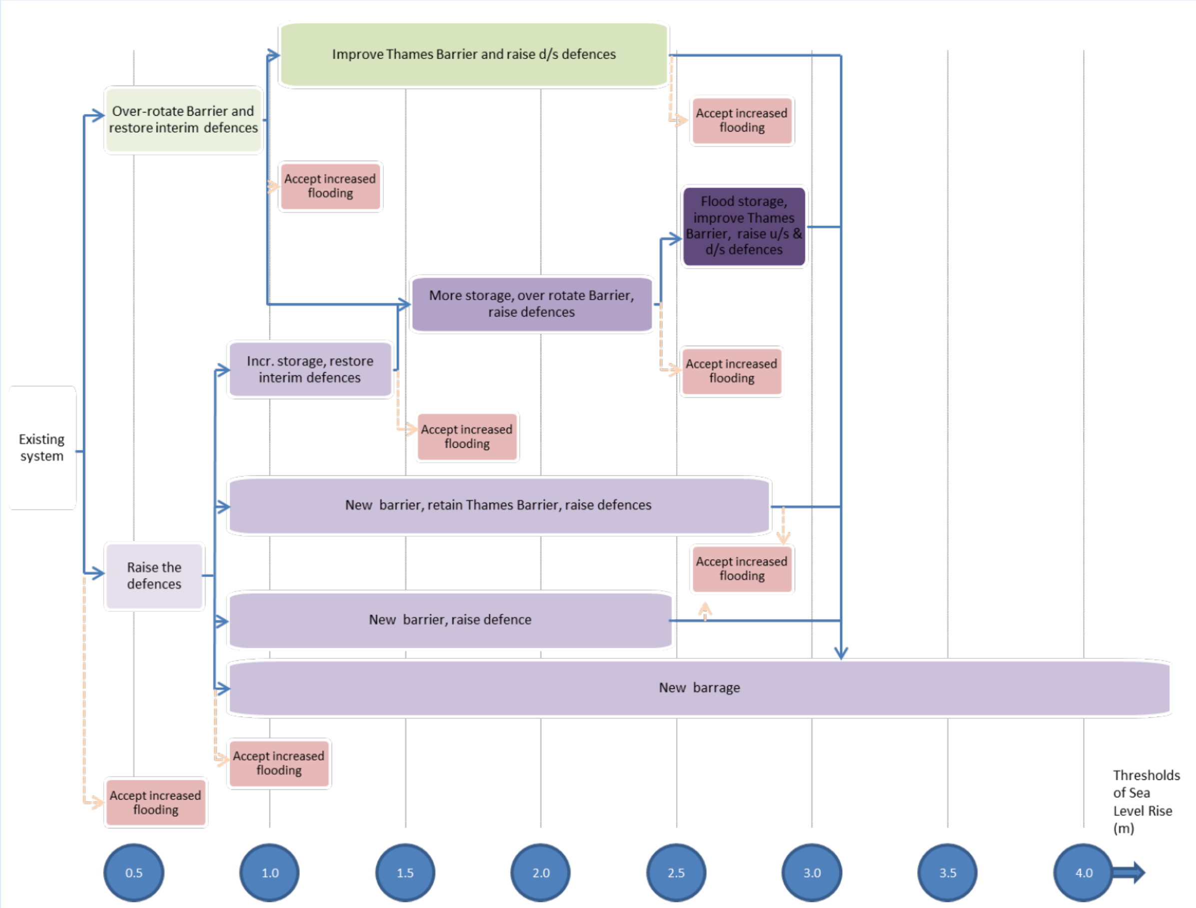


Figure 13: Thames Estuary 2100 Plan presented as a decision tree[21]

5. 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, including:

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[3]).

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).

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 (reinforced and explored further recently in Sayers et al, 2021[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 encourage planners to use the detailed flood hazard and risk maps in their spatial planning decisions (including the siting, type and layout of development).

Figure 14: Rehabilitation of the River Quaggy, Chinbrook Meadows, London[23]

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 river were built over, and eventually culverted. The Major of London is developing a 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 14**) provides a good example of where a sterile urban stream has been re-naturalised providing social and ecological benefits.

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 idea of developing tidal power from the Thames has gathered pace in recent years but is still a concept.

6. Conclusions

The Thames Estuary Flood Risk Management Plan provides several lessons and live issues that remain. These are briefly summaries below.

6.1 Lessons learnt

- **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 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 upon 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[5].** Flood risk management influences environmental, economic and social issues. 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.

6.2 Live issues

- **Managing all sources of flood risk.** The TE2100 strategy is focused on flood risk from tidal surge. London and the surrounding area is subject to groundwater, fluvial and pluvial flooding. 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 emphasizes 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 Major 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). This incurs opportunity costs but buys adaptive capacity.

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