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Flood Standards of Protection and Risk Management Activities

Final Report

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A report produced for the National Infrastructure Commission

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Revision History

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28 February 2018	-	Tom Bradbury, Matt Crossman (NIC), Mike Steel (EA)
21 May 2018	Addresses comments provided in relation to previous version - explanation of how response and recovery included, new section providing step by step functioning of tool, more explanation of settlement types.	Tom Bradbury, Matt Crossman (NIC), Mike Steel (EA)
5 June 2018	Further detail on justification for cost approaches and updated results	Tom Bradbury, Matt Crossman (NIC), Mike Steel (EA)
3 July 2018	Minor changes to wording, reinstatement of upper and lower metrics rather than just extremes, formatting and references	Tom Bradbury, Matt Crossman (NIC), Mike Steel (EA)

Contract

This report describes work commissioned by Brooke Engel, on behalf of the National Infrastructure Commission, by a letter dated 8 November 2017. The National Infrastructure Commission's representative for the contract was Tom Bradbury. Rob Lamb, Rachel Brisley, Neil Hunter, Sam Wingfield, Sarah Warren and Paul Mattingley of JBA Consulting, and Paul Sayers of Sayers and Partners carried out this work. Prof. Julien Harou of the University of Manchester contributed to the discussions of optimisation that maybe progressed in the future.

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Purpose

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Executive Summary

Long-term Flood and Coastal Risk Management (FCRM) infrastructure investment need is currently assessed through the Environment Agency's Long-Term Investment Scenarios (LTIS). The risk and expenditure tools behind LTIS are complex and embed an automated process to maximise the Net Present Value. This complexity limits their utility for high level user-driven 'what-if' analysis. The tools outlined in this report therefore respond to the National Infrastructure Commission's (NIC) requirement for an independent and easy to use tool to enable more accessible analysis of 'what-if' scenarios.

However, the number of adaptation, population and climate scenarios, and multiple sources of flooding (coastal, fluvial, surface water) and risk metrics of interest mean that traditional modelling approaches are too computationally intensive to explore all combinations (a challenge recognised in Kwakkel et al, 2013). Instead, the approach adopted links the UK Future Flood Explorer (FFE, Sayers et al, 2015, 17) alongside high-level functional relationships linking individual adaptation options (defence raising, natural flood management, property level measures etc.) to cost.

The UK FFE provides an emulation of the UK flood risk system that embeds nationally recognized source, pathway and receptor data to construct an emulation of the present-day flood risk system and to explore the future change in flood risk. It is capable of exploring the impact of future change on a range of risk metrics. The FFE allows alternative epochs, climate change futures and alternative Adaptation Scenarios to be assessed with limited runtime overhead. The evidence based high-level cost functions are used alongside the FFE to enable a national scale evaluation of investment outcomes by developing and implementing a simple 'exploratory' toolset capable of estimating the cost of implementing alternative Standards of Protection and other risk management activities and the associated change in flood risk. The toolset developed here (referred to as the NIC Analytics Tool) enables the NIC to self-explore the costs and benefits associated with alternative adaptation approaches aiming to achieve a range of Standards of Protection.

The methods, data and assumptions employed reflect the high-level nature of the analysis and are set out in this short report alongside illustrative results from the tool. Although the validation of national scale risks models is conceptually and practically difficult, estimates of present-day expenditure compare well to reality (recognising present day expenditure is itself difficult to define) and estimates of future expenditure given a focus on providing a high standard of protection to major urban areas compares reasonably with an equivalent LTIS scenario based on protecting Core Cities (Environment Agency, 2014), although this comparison is only approximate. These comparisons, together with explicable model behaviours, provide confidence that, in the context of the high-level project commissioned by the NIC, the toolset meets the requirements of the project Terms of Reference (set out in Appendix A). Further refinement and improvement is however possible, and we encourage further studies to build upon the foundations set out in this study.

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Abbreviations

ASC ... Adaptation Sub-Committee
BMV ... Best and Most Versatile (land)
CCRA ... Climate Change Risk Assessment
CDL ... Continuous Defence Line
EA ... Environment Agency
EAD ... Expected Annual Damages
EED ... Expected Event Damages
FCRM ... Flood and Coastal Risk Management
FIP ... Forward Investment Programme
FRM ... Flood Risk Management
FFE ... Future Flood Explorer
FFW ... Forecasting and Flood Warning
LPA ... Local Planning Authority
LTIS ... Long-Term Investment Scenarios
MTP ... Medium term plan
NFM ... Natural Flood Management
NIA ... National Infrastructure Assessment
NIC ... National Infrastructure Commission
NPV ... Net Present Value
NRA ... National Risk Assessment
ONS ... Office for National Statistics
PLP ... Property Level Protection
RLR ... Receptor Level Resilience

rSoP .... representative Standard of Protection
SPL .... Sayers and Partners Limited
SMP .... Shoreline Management Plan
SoP .... Standard of Protection
SUDS .... Sustainable Urban Drainage Systems
WAAD .... Weighted Average Annual Damages
WwNP .... Working with Natural Processes

1 Background

1.1 Context

The National Infrastructure Commission (NIC) produced the UK's first National Infrastructure Assessment (NIA) in 2018 to assess major infrastructure needs over the next 30 years. The modelling annex to the Interim NIA[1] (published October 2017) included investment requirements for multiple sectors, but not flood risk management (FRM). This study will help fill this gap.

It is recognised that long-term Flood and Coastal Risk Management (FCRM) infrastructure investment need is currently assessed through the Environment Agency's Long-Term Investment Scenarios (LTIS), which is an approach focused on identifying a level of investment in FCRM that maximises net present value (NPV). The risk and expenditure tools behind LTIS are complex to run; this limits their utility for high level user-driven 'what-if' analysis. The tool outlined in this report therefore responds to the NIC requirement for an independent, and easy to use, tool to enable more accessible analysis of 'what-if' scenarios.

The aims of the project translate into three core requirements (the original Terms of Reference are provided in Appendix A)

1. Enable a national scale assessment of the costs and benefits of adopting differing standards of protection (SoP), by estimating:

- The cost of implementing alternative defence-led adaptation scenarios and other risk management activities (differentiated by settlement type or other simple criteria).
- The associated change in flood risk expressed using a small range of metrics that are well understood by the FCRM industry including Expected Annual Damages (EAD)[2] , and the number of properties exposed to flooding across a range of annual exceedance probabilities (AEP)[3] and flood sources (coastal, fluvial and surface water).

2. Support the evaluation of national investment outcomes by developing and implementing a simple 'exploratory' toolset:

- The toolset developed here (referred to as the NIC Analytics Tool and provided to the NIC as the key deliverable from this study) enables the NIC user to explore the costs and benefits associated with alternative adaptation approaches. This NIC Analytics Tool uses the UK Future Flood Explorer (FFE, Sayers et al, 2015) to estimate future changes in risk and links this with a high-level costing approach.

3. Provide a short report describing the method, key data and assumptions to enable users to the tool to adjust adaptation levers and assess the corresponding effect on flood risk:

- This report responds to this requirement and sets out the purpose of the NIC Analytics Tool, how it has been assembled, the key assumptions on which it is based and the outputs that it can produce. This report is not intended to be a user guide but instead guidance on its use has been provided throughout its development to the NIC (the most efficient modus operandi given the ambitious nature of the study in terms of timescales, budget and content).

1.2 Core assumptions

In delivering the core requirements several assumptions have been agreed with the NIC:

- The geographic focus is England
- The estimates of costs and benefits should focus on the 2020s to 2050s, taking account of alternative population, climate change and adaptation scenarios
- Simple interpolation is to be applied to enable a cost stream to be developed and presented as in-year cash values (non-discounted) and Present Values using discount rates controlled by the user.

1 National Infrastructure Assessment (2017) Congestion, Capacity, Carbon: Priorities for National Infrastructure - Consultation on a National Infrastructure Assessment
2 The average flood damages computed over many years
3 The probability of a flood event occurring in any year

The analysis considers surface water, fluvial and coastal flood sources. Groundwater flooding and flood risks arising from reservoirs are outside the scope of this project. This is because of the relatively lower importance of groundwater flooding at a national scale when compared with fluvial, coastal and surface water (see Sayers et al., 2015). Reservoir management is delivered under the Reservoirs Act and not included here. Coastal erosion is also not included.

2 Methodology

2.1 Overview of approach

The approach builds on the FFE, developed by Sayers and Partners (SPL) and used to inform the 2017 Climate Change Risk Assessment[4] (CCRA) and the national assessment of flood disadvantage (funded by the Joseph Rowntree Foundation, Sayers et al, 2017)[5]. It also builds on the spatially-coherent extreme flood hazard models developed by JBA and applied for the 2017 National Risk Assessment (NRA)[6]. These elements are combined with an investment layer. The detail of the existing approaches is set out in the references cited above and is not repeated here.

The overall approach is outlined in Figure 2-1 and discussed in the following sections.

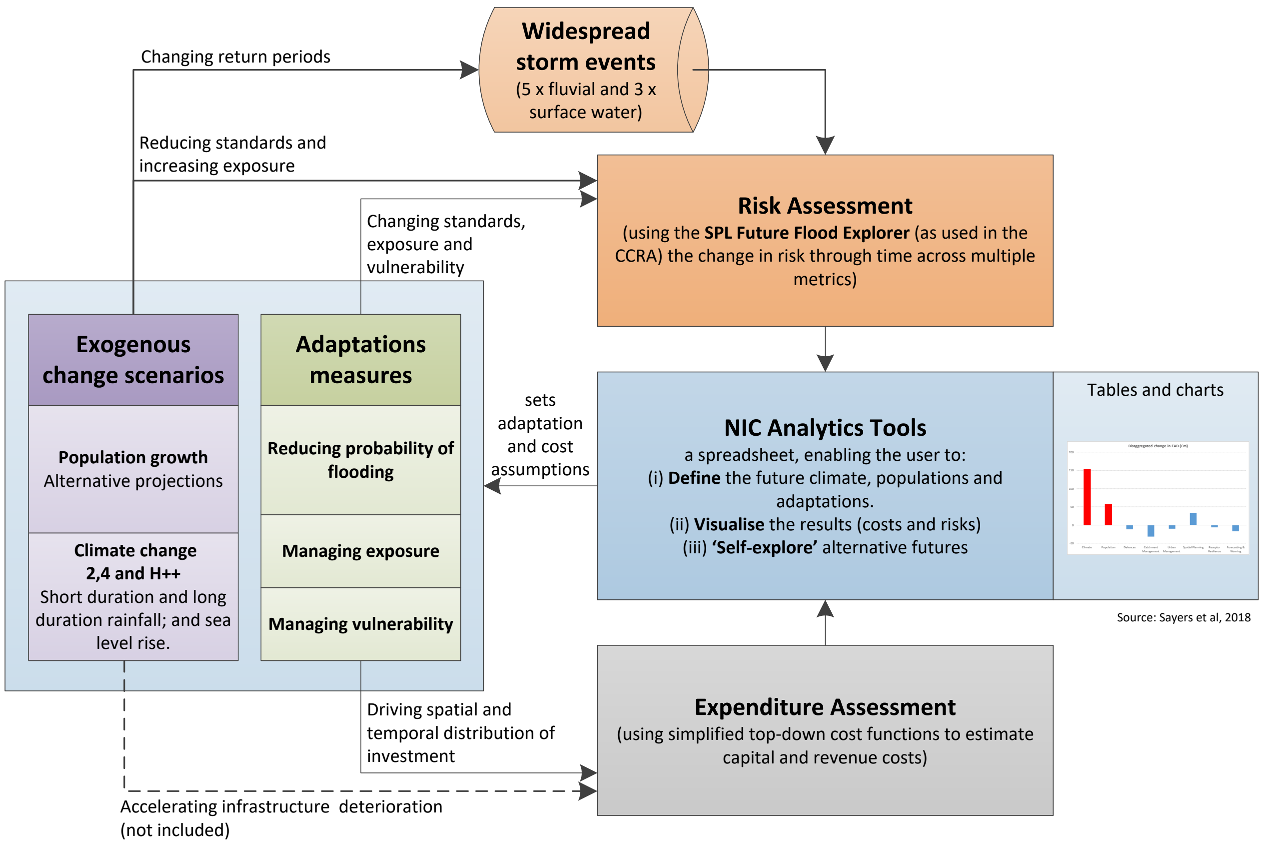


Figure 2-1: Outline of the overall approach

The analysis framework outlined above includes:

- **Consideration of the flood hazard:** the probability of flooding arising from three sources are considered - fluvial (river), coastal and surface water (pluvial).
- **Consideration of flood exposure:** two aspects of exposure are considered - residential and non-residential property.

4 Sayers, P.B., Horritt, M. S., Penning-Rowsell, E., and McKenzie, A. (2015). Climate Change Risk Assessment 2017: Projections of future flood risk in the UK. Pages 125. Sayers and Partners LLP report for the Committee on Climate Change.

5
Sayers, P.B., Horritt, M., Penning Rowsell, E., and Fieth, J. (2017). Present and future flood vulnerability, risk and disadvantage: A UK scale ass essment. A report for the Joseph Rowntree Foundation published by Sayers and Partners LLP.

666 Wood, E., Lamb, R., Warren, S., Hunter, N., Tawn, J., Allan, R., and Laeger, S. (2016). Development of large scale inland flood scenarios for disaster response planning based on spatial/temporal conditional probability analysis. E3S Web of Conferences, 7, [01003]. DOI: 10.1051/e3sconf/20160701003 (http://dx.doi.org/10.1051/e3sconf/20160701003).

- **Consideration of flood vulnerability:** vulnerability is considered through the lens of economic damage (direct and indirect).
- **External future change:** two drivers of external change (i.e. drivers of change considered largely outside of influence of FRM policy) are considered here - climate change and population growth.
- **Future management responses:** seven purposeful actions taken to directly control or strongly influence future flood risk are considered. These reflect a broad range of FCRM responses (as advocated by various documents: Making Space for Water (Defra, 2005); Working with Natural Processes (Environment Agency, 2010b, 2014b); Delivering Sustainable Flood Risk Management (Scottish Government, 2011); CCRA Future Flooding Report (Sayers et al., 2015)) and controlled by the user through over 200 user set variables.

2.2 Overview of the supporting risk analysis method

The spatial coverage of the analysis and the number of adaptation, population and climate scenarios of interest (as well as the multiple epochs, flood sources and risk metrics to be considered) mean that conventional modelling approaches are too computationally intensive to explore all combinations (a challenge recognised in Kwakkel and Pruyt, 2013). Instead, the approach uses the FFE that uses available data on flood hazard, exposure and vulnerability to develop a credible representation of the behaviour of the UK flood risk system that can then be used to assess present day flood risks (for a range of metrics) and the change in risk given a range of influences such as climate change, population growth and adaptation, including actions to manage the probability of flooding as well as those that influence exposure and vulnerability.

The high computational efficiency of the FFE allows a consistent assessment of flood risk under the multiple user determined scenarios.

Building upon these base studies, the FFE has been combined with a high level adaptation costing method to assess the costs of alternative adaptation scenarios through to the 2050s and a set of widespread events. Fundamental aspects of the underlying risk modelling used in the FFE are introduced below.

2.2.1 Reporting scales

FFE outputs are not directly provided at the Census Calculation Areas (CCA) scale but aggregated to larger areas that are more amenable for comparison and provide more robust insights. The chosen levels of aggregation for this study are:

- England
- ONS Regions
- ONS Settlement types
- Local Authorities (i.e. Districts, Unitary Authorities and London Boroughs).

These units are briefly explained below.

ONS Regions

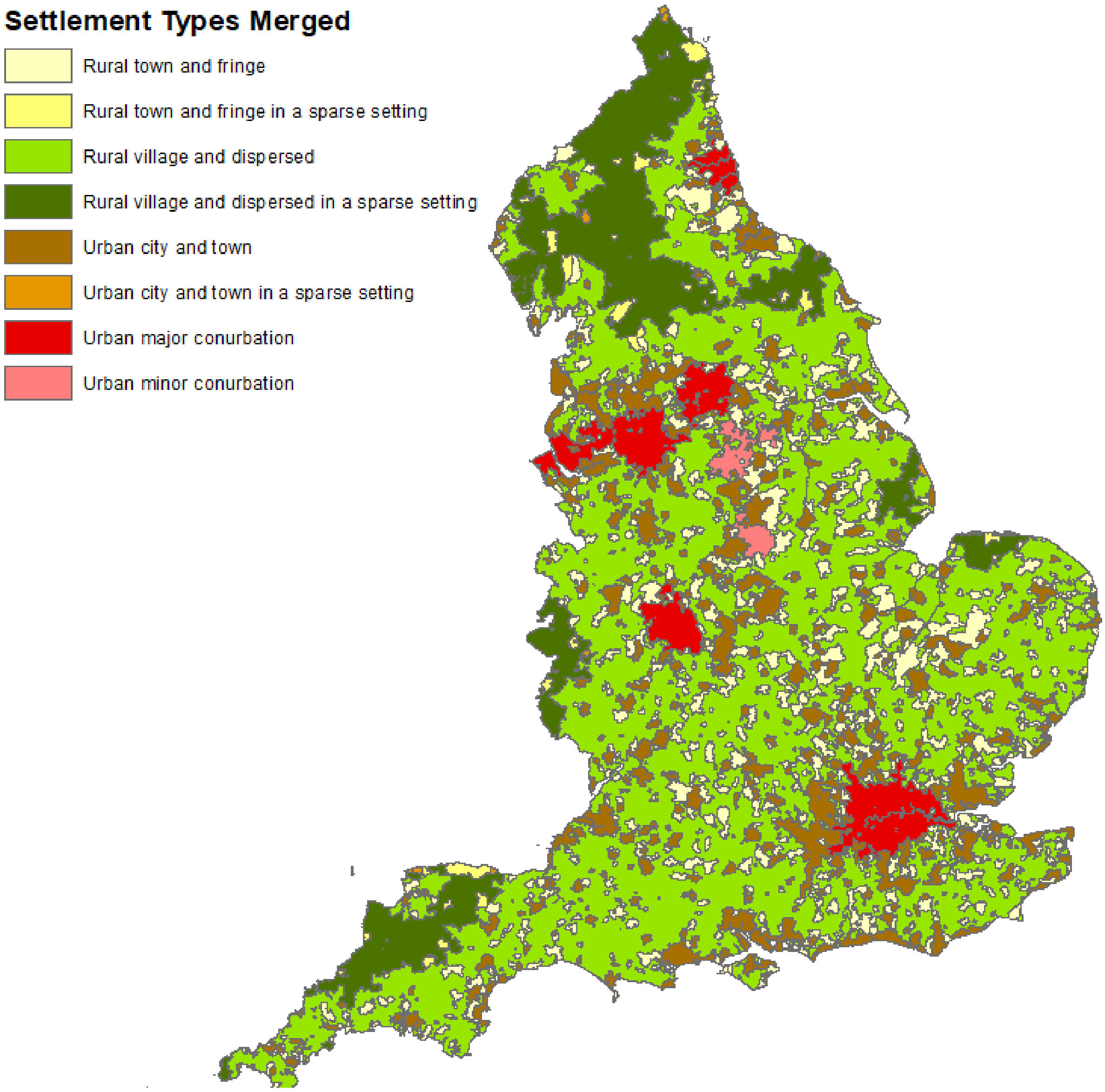
The nine Government offices for the regions (GOR), in existence Jan 1999 to March 2011 and now simply referred to as 'regions' (as agreed by the Regional and Geography Committee), are set out by the ONS[7] and used here. They comprise:

- East Midlands
- East of England
- London
- North East
- North West
- South East
- South West
- West Midlands
- Yorkshire and The Humber

7 https://www.ons.gov.uk/methodology/geography/ukgeographies/administrativegeography/england

2.2.1.1 Settlement types

Settlement types are defined by ONS using a combination of metrics (as set out by Bibby and Brindley, 2013). These eight categories are mapped in Figure 2-2 and their relative importance in terms of the number of properties exposed to flooding shown in Table 2-1.



Source: ONS

Figure 2-2: ONS Settlement type: Spatial illustration

Table 2-1: Number of residential properties within the fluvial and coastal floodplain by settlement type

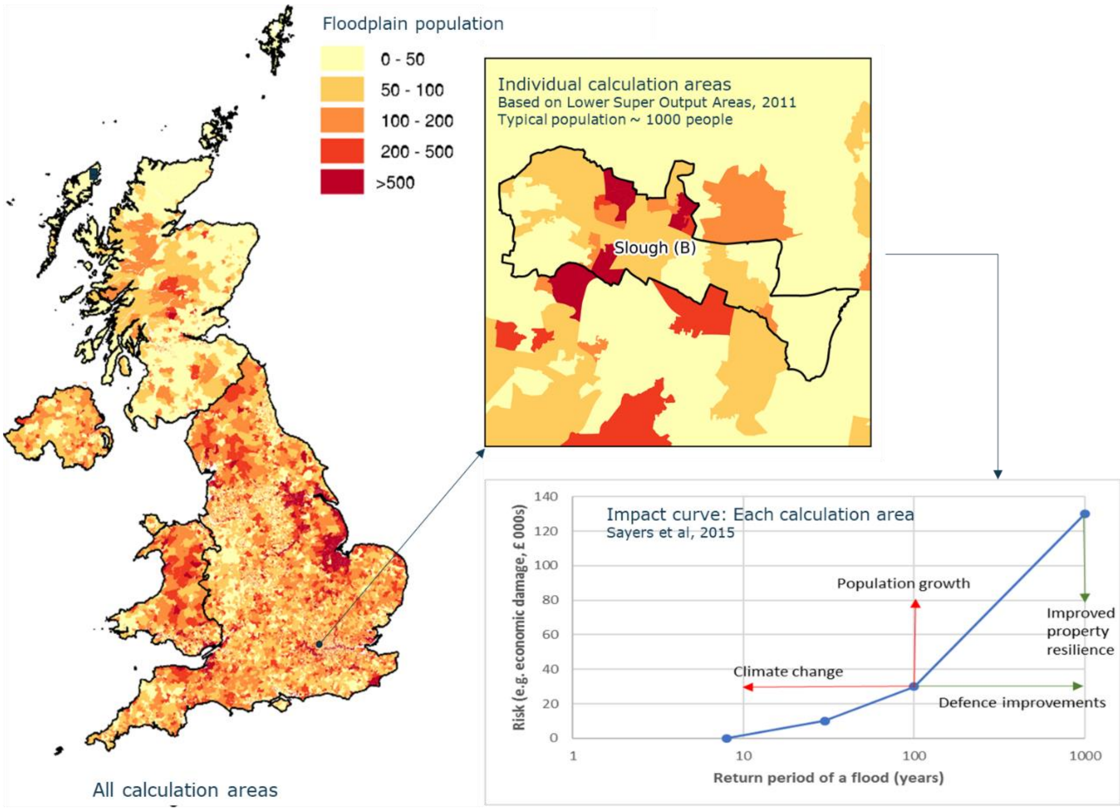
Settlement type (as defined by Bibby and Brindley, 2013)	Total residential properties exposed to fluvial and coastal flooding assuming the absence of defences (0.1% AEP)
Urban major conurbation	465,000
Urban minor conurbation	70,000
Urban city and town	900,000
Urban city and town in a sparse setting	15,000
Rural town and fringe	200,000
Rural town and fringe in a sparse setting	10,000
Rural village and dispersed	255,000
Rural village and dispersed in a sparse setting	30,000

2.2.2 Overview of the Future Flood Explorer (risk analysis tool)

The FFE provides an emulation of the national flood risk system that uses nationally recognized source, pathway and receptor data to explore the future change in flood risk. It is capable of exploring the impact of future change on a range of risk metrics

The underlying spatial resolution of the available flood hazard data reflects the underlying flood data from the Environment Agency (notionally 50m x 50m grid cells, nationwide). The available data on exposure is based on residential point datasets and hence has an apparent resolution of a single property. This does not, however, mean the results are credible at these scales. The concept of the 'neighbourhood' is therefore used as a small, but appropriately aggregated, spatial unit to bring together flood hazard and exposure. Neighbourhoods correspond to Lower-level Super Output Areas (LSOAs) for England. The average population in a neighbourhood is approximately 1600. The FFE calculation operates at this scale, referred to as a 'CCA. There are approximately 600,000 CCAs in England, covering fluvial, coastal and surface water sources. A schematisation of the CCA for a small region is shown in Figure 2-3.

For each CCA, an Impact Curve is generated relating 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). The Impact Curves are then manipulated to quantify the influence of climate and population change as well as adaptations on flood risk. Figure 2-3 shows an example impact curve for a CCA, with arrows indicating how future scenarios are represented by changes to the baseline curve. For example, to represent climate change the Impact Curve is moved to the left along the return period axis. The raising of flood defences, however, would act to reduce risk by shifting the Impact Curve in the opposite direction. The resulting change is then used as input to the assessment of the cost of affecting that change (i.e. increasing the number of properties protected to a given standard).



Source: Adapted from Sayers et al, 2015, 2016

Figure 2-3: Impact curve: Example relationship return period vs. impact used within the FFE (Sayers et al, 2015, 2017)

2.3 Overview of the cost analysis

The cost of implementing user-set adaptations are assessed using a series of evidence-based top-down cost functions that link a change in risk to cost.

Five cost functions have been developed relating to five primary categories of adaptation:

- **Flood defences** - three aspects are considered in relation to defence costs: capital costs associated with raising the standard of protection afforded to an area, the capital maintenance costs of maintaining standards of protection and the revenue costs associated with day to day maintenance.
- **Catchment management -** two aspects are considered in relation to the costs of catchment management (NFM): capital and revenue costs of woodland (run-off) based measures and the capital and revenue costs of storage-based measures.
- **Urban management** - two aspects are considered; the capital cost associated with the take-up of SUDS in new and existing developments (as a proxy for all other urban drainage measures) and reduction in damages due to other surface water management measures (such as preferential surface routing of the flood flows, urban storage etc); revenue costs of maintaining these measures.
- **Receptor level resilience** - two aspects are considered; capital costs of implementing RLR in new build properties and retrofitting to existing properties; revenue cost of maintaining RLR measures.
- **Forecasting and warning:** two aspects are considered: capital costs associated with improving the service and the revenue costs associated with the delivery of the service.

2.4 Validity of approach

2.4.1 Risk analysis

The validation of any analysis of flood risk is difficult. In part this is because flood events are rare and flood systems (the climate, the defences, the socio-economic setting etc.) are always changing. It is difficult, if not impossible, to determine the accuracy of an estimate of risk through comparison with measured data alone (Sayers et al., 2016). The validity of any analysis therefore relies upon assumptions and limitations being acknowledged (as highlighted throughout the report and the papers it is based upon) and gaining confidence that the analysis is credible at the scales of interest (in this case a national high-level appraisal) and in the context of the objectives of the analysis (and exploration of the future risks and costs). To provide appropriate confidence in the analysis presented here, two important aspects are discussed below:

- **Credibility of the input data:** it is considered that the input data used by the FFE (including, but not limited to, flood hazard, defence standards and conditions, property, census data) is credible at the scales of interest and in the context of the study objectives. Importantly the FFE used here is based upon the latest State of the Nation analysis (Environment Agency, 2018), the Continuous Defence Line (provided March 2018) and the latest National Receptor Dataset (provided March 2018). The datasets are understood to be significant improvements on 2014 datasets used as part of the CCRA (Sayers et al, 2015). Note: considerable effort was directed towards validating the FFE against the equivalent LTIS and the NaFRA datasets in 2014, it has not been possible to repeat this here and equally the State of the Nation has not had the same level of scrutiny as previous NaFRA datasets (simply due to the short time it has been available). Despite these caveats the latest datasets are included as they provide the most up to date information available.
- **The skill of the FFE as an emulator:** to provide valid estimates the FFE must provide a faithful reproduction of the underlying data. To provide confidence that this is the case the results of the FFE have been previously compared to standalone estimates of the number of properties at significant risk and the EAD (as produced, for example, by Environment Agency's National Flood Risk Assessment), confirming the ability of the FFE to produce known results (Sayers et al., 2015).

2.4.2 Cost analysis

All cost inputs have been obtained from reliable sources such as the Environment Agency's FIP or MTP, published research documents, other published investment information etc.; these are all fully referenced in Section 6. We have worked closely with Environment Agency representatives throughout to ensure the credibility of input information and existing costs.

2.4.3 The credibility of new results

To provide confidence in the functioning of the model and the results it generates, the following approaches have been adopted throughout the project

- **Engagement with the client group:** progressive drafts of the analysis have been scrutinised as they have emerged by the NIC and the wider client group in the Environment Agency. This process has provided useful challenges and gives confidence that the results reflect collective experience.
- **External scrutiny:** the overall approach was presented at a meeting of the Flooding Round Table held in February 2018. This was organised by the NIC and attended by the consultant's project team as well as representatives from the NIC secretariat, HM Treasury, Defra, Environment Agency, local authorities and key FCRM experts. The meeting provided an opportunity to discuss the approach with both FCRM professionals and high-level policy and decision makers.
- **Internal validation process:** as this is a rapid high-level project, validation has focused on the functionality of the tool and ensuring that the process of estimating future risks and costs is clear and faithfully reproduced. This has involved user testing within the team (including in collaboration with the National Infrastructure Commission and Environment Agency) on an individual and group basis as well as sense checking inputs and results. A note on QA is provided as Appendix 2.

3 External change scenarios: climate change and population growth

3.1 Climate projections

The two climate projections established to inform the CCRA 2017 (Sayers et al, 2015)[8] are re-used here without modification or update, namely:

- 2ºC increase in global mean temperature by the 2080s from the pre-industrial baseline
- 4ºC increase in global temperature by the 2080s from the pre-industrial baseline

  Each climate projection includes spatially varying changes in:

  - Short duration, intense rainfall (<6hrs): driving changes in surface water flooding
  - Longer duration rainfall events: driving changes in extreme river flows
  - Sea level rise: driving changes in the standard of coastal defences (derived using results from the Coastal Vulnerability 2075 studies).

3.2 Impact of climate change on defence standards

The influence of climate change on the present day Standard of Protection is illustrated in Figure 3-1. The variation highlighted in the figure reflects the spatial variation in the impact of climate change on river flows, sea level rise as well as the sensitivity of a particular river or coastal defence to those changes (e.g. Sutherland et al, Sayers et al, 2015).

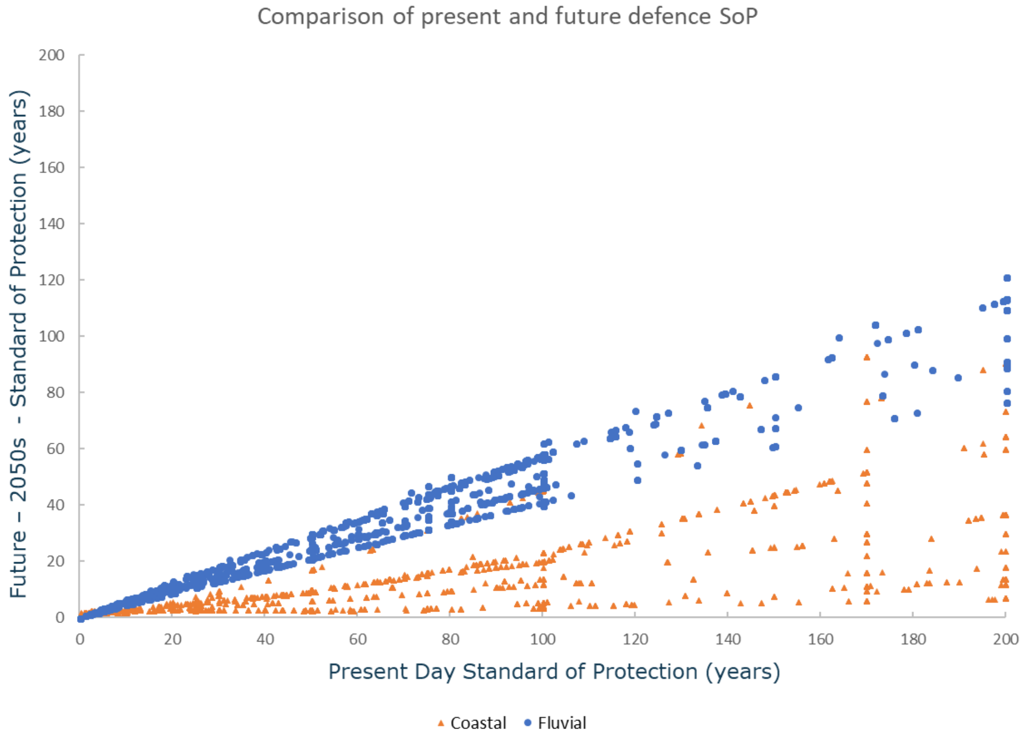


Figure 3-1: Influence of climate change on defence standard (4ºC Future)

Note: More detail on the climate scenarios can be found in Sayers et al., 2015: Appendix Climate Change Projections[9].

8 https://www.theccc.org.uk/wp-content/uploads/2015/10/Appendix-B-Population-growth-projections-Final-06Oct2015.pdf
9 https://www.theccc.org.uk/wp-content/uploads/2015/10/Appendix-C-Climate-change-projections-Final-06Oct2015.pdf

3.2.1 Main assumptions

Three primary assumptions are made:

- The climate change analysis used to inform the CCRA 2017 remains fit for purpose. Information on future climate continues to evolve and should be updated as new intelligence is published such as the UKCP18 projections that are to be published later this year.
- Flood defence maintenance is effective at maintaining flood defence (i.e. there is no deterioration in condition grades through time) due to climate change. Climate change, however, acts to increase the costs of such activities (with higher costs associated with higher rates of climate change).
- The two warming scenarios (+2°C and +4°C) provide a sufficiently wide range to support a robust understanding of the uncertain impacts of climate change.

3.3 Population projections

The population projections, provided by the NIC, form the basis of future change. The two selected by the NIC for consideration here are

- B - low migration (based on a low migration national projection, ONS, 2014)
- C - high fertility (based on a high fertility subnational experimental projection, ONS, 2014).

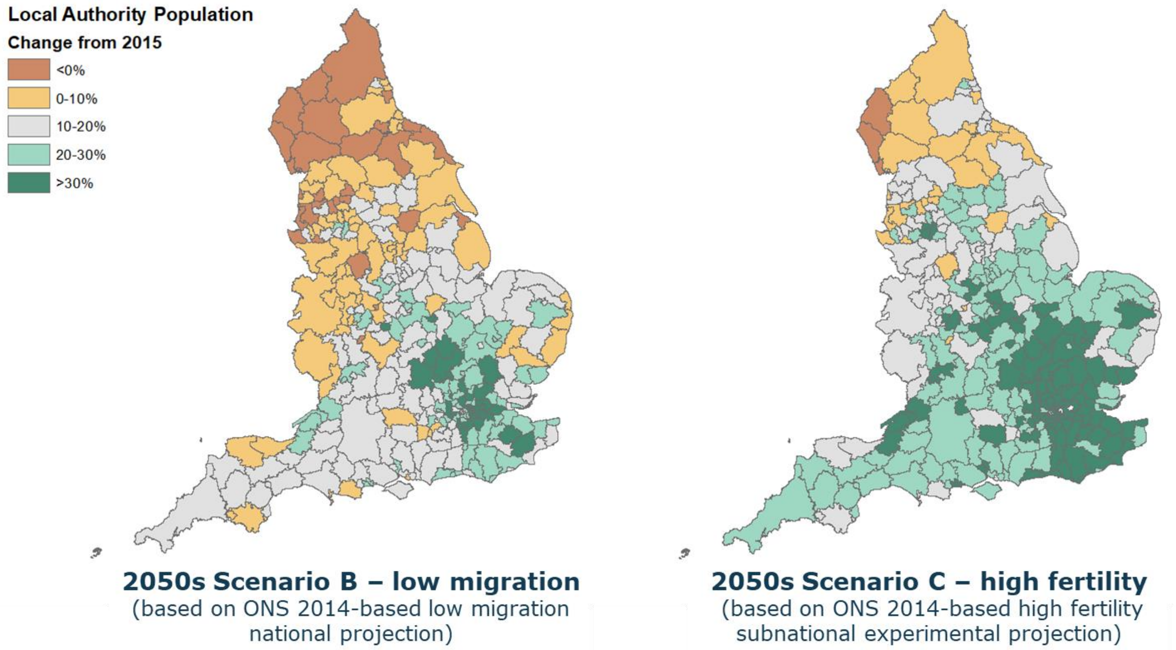


Figure 3-2: Population growth scenarios

3.3.1 Main assumptions

- It is assumed that population change drives an increase in residential housing only. The number of new properties is assumed to reflect the population growth can be calculated assuming a continuation of existing local occupancy rates.
- Non-residential properties and other infrastructure services are unaffected by population growth.

4 Adaptation measures

Effective Flood Risk Management (FRM) is widely recognised as based on a portfolio of responses (Evans et al, 2004, Sayers et al, 2014). This is reflected here within the range of adaptation measures and their characterisation within the FFE. This range of adaptations is illustrated in Figure 4-1 and discussed in turn below.

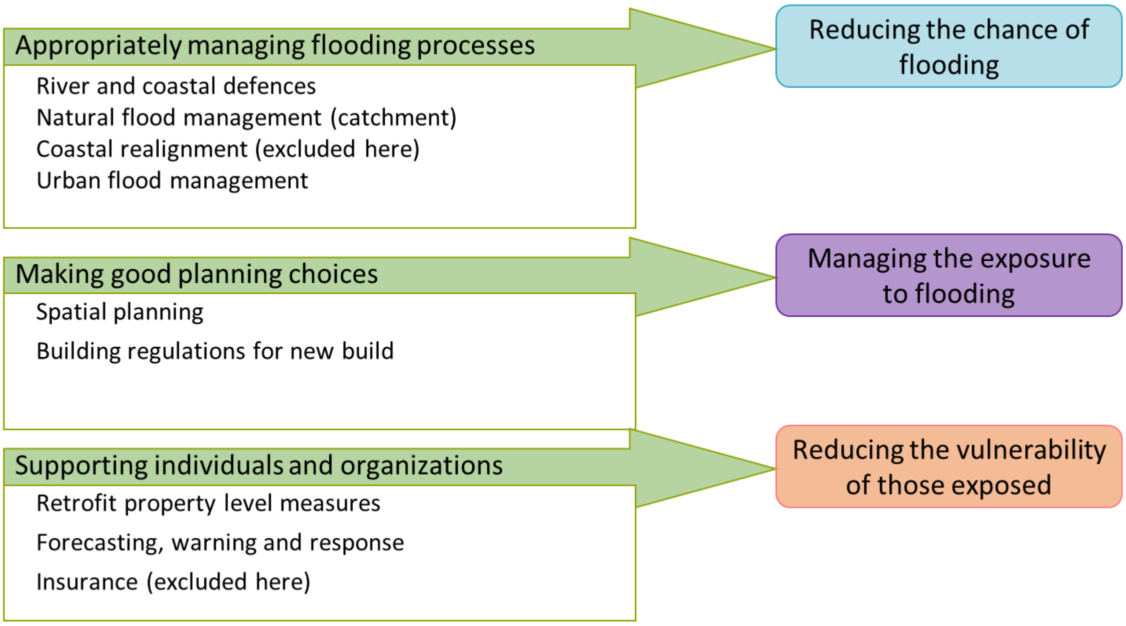


Figure 4-1: Portfolio of adaptation responses (Source: Adapted from Sayers et al., 2017)

Note: Important caveats on the representation of adaptations and future change

Actions outside of FRM: although an increase in residential properties is assumed to occur alongside population growth, no consideration is given to broader developments that would be needed to reflect or support that growth (i.e. new schools, hospitals etc.) nor the actions taken by those providers to safeguard their services during a flood.

Local context is important: the applicability and effectiveness of a given mix of adaptations will reflect the local context within which they are applied. This local context is in part embedded within the description of the individual adaptation measures. For example, the degree to which climate change reduces the Standard of Protection provided to an area reflects the present-day standard in that area. This means that parts of the floodplain protected to a higher standard today continue to have more effort devoted to them in the future. The consideration of specific local constraints and opportunities that will determine the feasibility of specific adaptation measures at a local level is, however, out of scope.

4.1 Coastal and river flood defence infrastructure

4.1.1 Context

Flood defences are the primary response to flooding across the UK and various studies confirm they are likely to continue to play a significant (but not sufficient) role in the future (e.g. Evans et al., 2004a, b; Sayers et al., 2015a). Other interventions will also be required and whilst the majority of investment in FRM is directed towards the maintenance and improvement of defences, it is important to note that many schemes are multi-faceted with defences being the primary management measure, but often supported by other approaches such as SUDS, NFM and RLR. The Environment Agency's Long Term Investment Scenarios (LTIS) (Environment Agency, 2014), are primarily based on the on-going provision of defence infrastructure, and the political response to the 2013/14 Winter floods (Defra, 2016) led to the allocation of new government funds for flood alleviation schemes. Similarly, a review of Shoreline Management Plans (SMPs) (England and Wales only) highlighted a policy of 'hold the line' in the majority of coastal areas (ASC, 2013).

4.1.2 Representation within the FFE

The FFE incorporates the performance of defences by considering the:

- **Representative Standard of Protection (rSoP) of an area:** this expresses the degree of protection afforded by flood defences, that is, the return period (in years) of the storm event that would overtop the defences assuming they remain structurally intact. The rSoP is calculated as a length weighted average of the individual defences that combine to protect a risk calculation area (where a 'risk calculation area' is defined by a Census Lower Support Output Area, Sayers et al., 2017). The distribution of the present-day rSOP is illustrated in Figure 4-2 (based on 2015 data).
- **Representative Condition of those defences (rCg):** the Environment Agency uses a grading system to express the condition of a defence (Condition Grade, Cg, of 1 represents as-built condition and Cg 5 is in very poor condition, with Cg 3 generally considered the minimum acceptable condition). The representative condition of the defences that combine to protect an area is calculated as a length weighted average of the condition grade of each individual defence protecting that area.

Future change in the rSOP is determined through a two-step process:

- **Step 1:** The change in rSOP given climate future and under the assumption of no adaptation. For example, if the crest of a defence remains at the same level the rSOP may fall from say 1 in 100 years to 1 in 10 years due to climate change increasing the probability (i.e. reducing the return period) of flood loading exceeding the physical crest height of the defence in the future.
- **Step 2:** The influence of adaptation. For example, say the user sets the future standard to be 200 years, the future SOP of the defence in the example above would be considered to need raising (as its standard is below the user set target of 1 in 200) and raised to 1 in 200 years.

  In setting the adaptation ambition the user can select either:

  - Minimum rSOP (as a return period, in years),
  - or a combination of the
    - minimum allowable representative standard of protection (as a % of the present-day standard), and,
    - raised representative standard when minimum exceeded (as a % of the present-day standard).

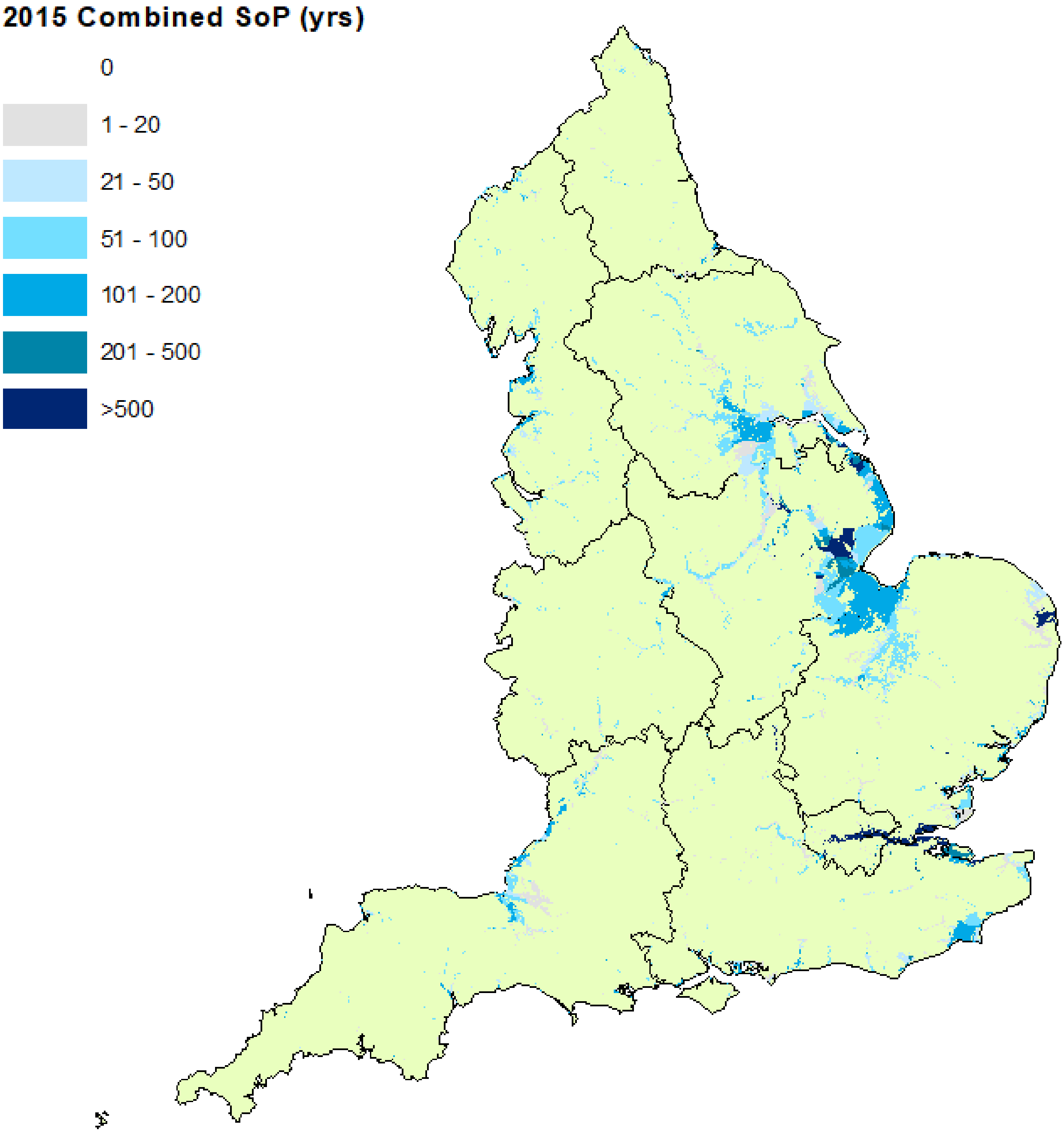
The highest standard based on the above is then carried forward to the analysis.

To provide further control to user, the defence settings can be differentiated according to the eight ONS settlement types (introduced earlier), and by the present-day defence standards.

The user is also able to set the defence Condition Grade associated with the management of both new and existing defences. This is important as it controls the chance of defence failure.

4.1.3 Main assumptions

- A weighted average of rSOP is a reasonable proxy for the performance of the individual defence assets that provide protection to an area.
- The base defence datasets have been updated with the recently published Continuous Defence Line (CDL) to improve the representation of defence standards, conditions and completeness of the existing defence system. The approach to including the CDL in the FFE and a comparison of CDL and pre-CDL defence standards and condition grades is provided in Annex A.
- Risk and cost estimates assume the existing cohort of defences continues (at a raised or reduced standard) and new defences built where no defences currently exist.
- The default assumption is no change for present Condition Grades between 1-4 (one being good) and the abandonment of Cg 5 defences. If a defence is raised or newly constructed where previously no defence existed it is assumed that the condition grade is equal to 1.



Source: Future Flood Explorer, Sayers et al, 2015

Figure 4-2: Present day defence standards (representative standards shown)

4.2 Management of shoreline process and coastal realignment

4.2.1 Context

Around half of all sea defences in England are protected and buffered against waves and storm surges by coastal habitats (ASC, 2013). As sea levels rise, beaches and coastal habitats will reduce in width as they are squeezed between the fixed backshore structures and the high-water mark (so-called 'coastal squeeze'). In recognition of the increasing cost of 'Hold the Line' and the environmental and downdrift gains that may be accrued by 'retreating the line' (so called Managed Realignment), Shoreline Management Plans (SMPs) in England have a combined intention to realign some 9 per cent of the coastline by 2030, rising to 14 per cent by 2060 (ASC, 2013). However, the current rate of managed realignment since 2000 (in England) would need to increase five-fold, to around 30km a year, to meet this intent.

4.2.2 Representation within the FFE

Managed realignment is typically not about improving the SOP but is more usually associated with reducing costs or gaining habitats (or other benefits). As agreed with the NIC, coastal realignment is not considered here.

4.3 Catchment management

4.3.1 Context

In recent years, the concept of Natural Flood Management (NFM) has been increasingly recognised as a legitimate supporting measure in FRM. Indeed, NFM practices (including upland storage, the management of run-off from agriculture, floodplain/river restoration, riparian tree planting etc.) are now widely promoted within various policy and guidance documents, such as Working with Natural Processes (EA, 2010; 2014), Strategic Flood Management (WWF), Natural Flood Management (OST, 2011), 'Living with rivers and the sea' (Rivers Agency, 2008) and Slowing the Flow (Forest Research, Pickering, Yorkshire).

The desire to promote such solutions (and the multiple benefits they provide) however has not yet been matched by 'on the ground' take up. This is despite most Catchment Flood Management Plans across England and Wales including policy options for managing runoff and storage (available at Environment Agency, 2009). In part this is due to the lack of scientific evidence regarding the performance of nature-based solutions, particularly during more extreme flood events and over large areas (Dadson et al., 2016).

Nevertheless, experience is being gained on the effectiveness of these measures. Example pilot studies include at Pontbren; Parrett; Hooder; Pickering, Yorkshire; Elwy catchment, Wales; Clwyd catchment, Wales (Dadson et al., 2016). In this last case, modelling based analysis showed that if implemented across the catchment, improved land management could reduce peak flows by up to 25 per cent in the summer and eight per cent in winter. This was based over a number of years reflecting a range of event probabilities.

There is no direct evidence that this intervention measure reflects the vulnerability of the affected community. However, such approaches tend to focus on rural areas where the benefits of maintaining defence lines are low and the opportunity to make a significant difference to downstream flood peaks are often high.

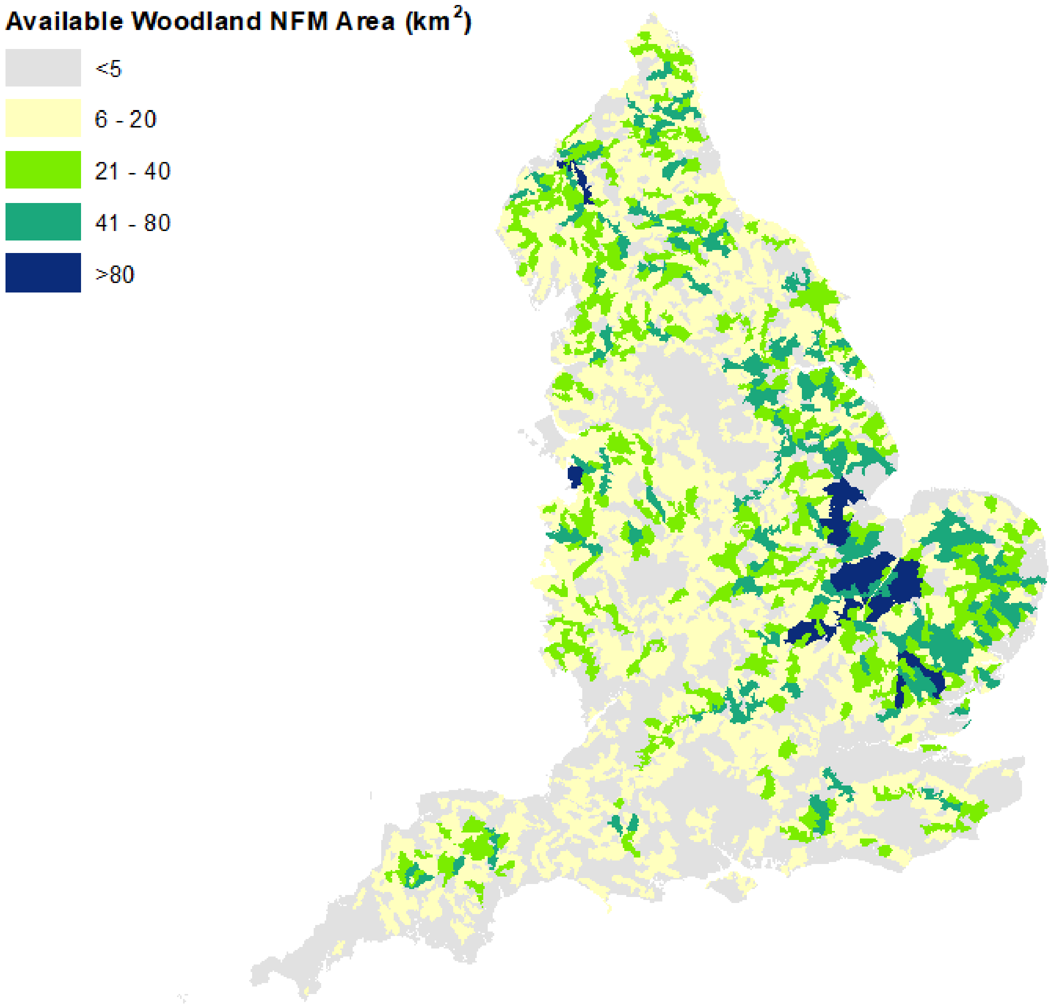
4.3.2 Representation within the FFE

Given that many management policies across the UK promote the role of NFM in some form, the continuation of Current Levels of Adaptation (CLA) scenario presented in the CCRA (informed by Sayers et al., 2015) has been advanced here to take account of new mapping of areas with potential for enhanced NFM (sometimes referred to as 'opportunity maps') recently published by the Environment Agency, and the supporting analysis used in that study (led by Hankin et al of JBA).

In controlling the influence of catchment management within the FFE, the user has three controls:

- **#1 Catchment potential:** The impact of catchment management measures is widely accepted to be limited during more severe flood events. The analysis of evidence presented in the CCRA (informed by Sayers et al., 2015) suggests the reduction is unlikely to exceed 10% in total. This credible maximum is used to guide the user in setting the upper-bound reductions in peak river flow that may be achievable in catchments with the highest potential for catchment management, moderate potential and lower potential (as defined by the proportion of the catchment area considered to represent an NFM opportunity). In setting these values the opportunity for (i) temporary storage features and (ii) rural run-off management measures (Figure 4-4) is considered separately.
- **#2 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 (Figure 4-5) there is likely to be a lower opportunity to use NFM than elsewhere because of competition from other productive uses of the land. The user is therefore given the ability to control the degree to which different classes of BMV land are used to support catchment management measures.
- **#3 Enhanced impact on lower return flows:** The user can control the potential for managing peak flood flows during the 1 in 100 year event according to the relative degree of practical opportunity for NFM within a

catchment (taking account of the points above) The impact of catchment measures on more frequently occurring flood flows is likely to be higher than in the 100-year return period event, and the user can control this by applying a multiplier to the reduction achieved during the 100-year return period.



Source: Hankin et al

Figure 4-3: Environment Agency NFM Opportunity Maps: Run-off management (woodlands etc.)

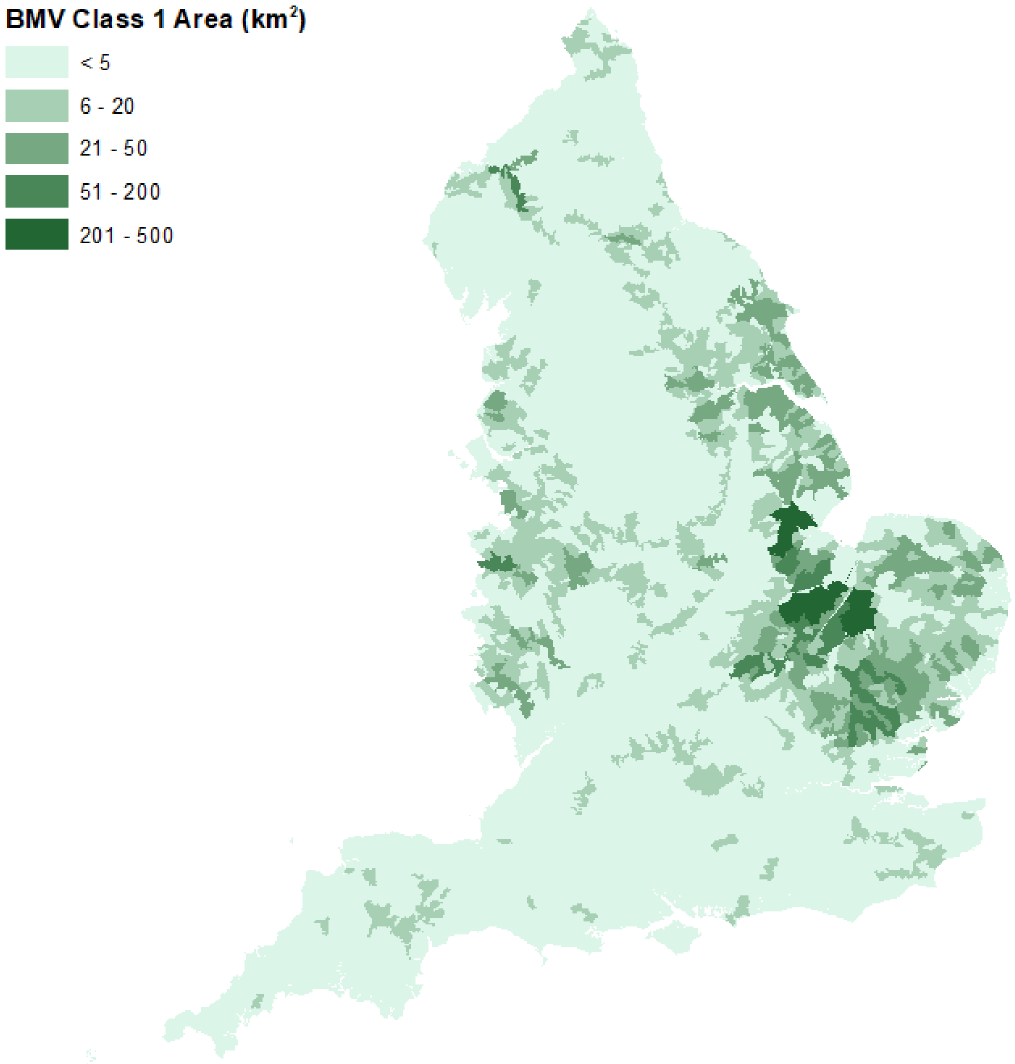


Figure 4-4: Natural England: Best and Most Versatile land (Natural England)

4.3.3 Main assumptions

- The potential for NFM is likely to be constrained by alternative land uses - and hence, there will be fewer NFM opportunities in catchments with the most BMV land.
- There is limited quantified evidence on the impact of catchment management currently available but a reasonable maximum value during the 1:100 year flood event is 10%.

4.4 Urban management

4.4.1 Context

Widespread flooding across England in 2007 damaged 55,000 properties, with much of the damage resulting from drains and sewers being overwhelmed by heavy rain (Environment Agency, 2007). This highlights that traditional piped sewer systems cannot readily be adapted to deal with increased rainfall, particularly in dense, urban areas. Half of the national sewer network in England is reported to be currently at or beyond capacity (RSPB, 2014). There are a range of responses to help surface water flooding, the most common of which is the promotion of Sustainable Drainage Systems (SUDS) (through urban storage, green space, green roofs, soakaways, permeable paving, ponds and swales with the aim to slow down and store flood water) as well as considering the separation of foul and surface water sewers, preferential flood routing (to urban storage areas) and the deployment of temporary or demountable flood defences.

4.4.2 Representation within the FFE

Urban management is used here to refer to the influence of surface water management activities on the surface water flood hazard and its impacts. Two aspects are considered:

- Changes in surface water run-off due to SUDS take-up (in new developments) and retrofitting (to existing developments).
- Reduction in damages due to other surface water management measures (such as gully clearance, preferential surface routing of the flood flows, etc.) that may form part of a Surface Water Management Plan in addition to SUDS.

The representation of each aspect within the FFE is discussed in turn below.

4.4.3 Urban flood hazard: Changes in surface water run-off due to SUDS take-up

The influence of SUDS is represented through a modification to the rainfall-run-off processes (Sayers et al., 2015). Within the FFE, the runoff from short duration rainfall events is controlled by the weighted sum of the runoff calculated from the urban areas (assumed to be dominated by impermeable surfaces) and non-urban (rural) area (permeable) within the calculation area. In doing so, the run-off is estimated by weighting the proportion of the area that is urbanised, namely:

$$Runoff = \frac{Runoff_{Urban}A_{Urban} + Runoff_{Rural}A_{Rural}}{A_{Total}}$$

SUDS, which aim to mimic the equivalent greenfield runoff signature, are represented as a modification to the proportion of the calculation area that can be considered to produce 'urban runoff' (u). Figure 4-5 shows how the urban extent (u) then controls the extent to which a calculation area behaves in an urban or rural way.

New developments that include SUDS do not change the runoff characteristics of an area (as it is assumed that the new properties mimic greenfield runoff), whereas new developments that exclude SUDS will increase the urban area generating runoff in line with the increase in property numbers.

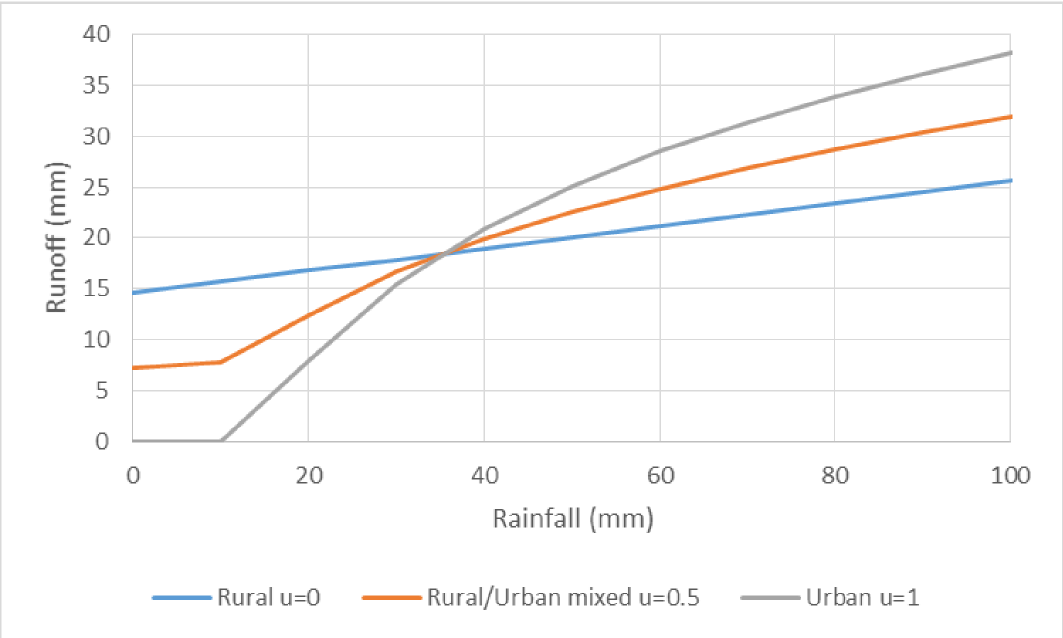


Figure 4-5: Rainfall – runoff relationship for different levels of urbanisation as parameterised by u (Sayers et al,

2015)

The user controls the SUDS adaptation by setting:

- Take-up of SUDS in new development as a percentage of the projected new development areas (that varies according to the population growth scenarios and the spatial planning adaptation lever - see later)
- Retrofitting of SUDS in existing urban areas (as a percentage of the urban area subject to surface water flooding).

4.4.4 Urban flood damage: Reduction in risk from measures to manage urban surface water run-off (excluding SUDS)

In addition to the focus on managing the chance of surface water flooding, the tool provides the user the ability to include other FRM efforts to manage surface water flooding by reducing the impact of surface water flooding rather than its probability. This is a simplifying assumption because many measures (such as preferential flow routing, culvert and gully management etc.) act to influence flood flows rather than directly reducing damages. Such influences are, however, highly context specific.

The user is able to control the reduction in damage experienced by those properties exposed to frequent flooding (i.e. an annual probability of 1:30 or more frequent) and more in-frequent flooding separately within the tool (by setting a percentage reduction factor in adaptation settings).

4.4.5 Main assumptions

- Surface water management activities have no impact on fluvial or coastal flooding.
- In developing the approach to surface water flood risk management, we have excluded broader water company focused efforts to improve the capacity of sewer / piped drainage networks.
- The cost of SUDS provides an appropriate proxy for upgrades to the capacity of sewer and piped drainage networks. This is, of course a simplification, and a key recommendation for improvement in future developments (for example in-combination with the 21st Century Drainage initiative).

4.5 Spatial planning: Managing future development

4.5.1 Context

Analysis by the Adaptation Sub-Committee (ASC) to the Committee on Climate Change (CCC) found that around 21,000 homes were built in the floodplain (defined as Flood Zones 2 or 3) every year (on average) between 2001 and 2014 in England (ASC, 2015). The ASC's analysis estimates that 73 per cent of residential development in coastal and fluvial floodplain in England takes place in areas with a low chance of flooding (i.e. areas with between a 1-in-100 and 1-in-1000 annual chance of flooding). However, 27 per cent of floodplain development since 2001 (68,000 new homes) has taken place in areas subject to flooding more frequently than 1-in-100-year return period on average. Around 23,000 new homes (9 per cent of floodplain development) have been built in areas with a high chance of flooding, subject to flooding more frequently than 1-in-30-year return period on average. Development in areas with a higher chance of flooding appears to be mostly in more sparsely populated locations. This may be because community-level flood defences are more difficult to justify on cost-benefit terms in these more rural areas.

4.5.2 Representation within the FFE

Development in the floodplain within the FFE reflects the balance of two opposing forces:

- Development pressure due to population growth (from the NIA projections)
- Effectiveness of development management in preventing development taking place on the floodplain (the spatial planning lever in the FFE).

These two issues impact flood risk estimated by the FFE in two ways:

- A change (increase) in the number of residential properties in the floodplain
- A change (increase) in the urban run-off (but this depends upon the uptake of SUDS in new developments - see earlier adaptation lever).

The user can control the effectiveness of the spatial planning adaptation within the FFE by setting the % of all new developments built in the floodplain across England (12% is the default value based on analysis of data from 2008-14, as discussed in Sayers et al, 2015).

4.5.3 Main assumptions

- Population growth drives residential development only (i.e. there is no increase in associated non-residential properties).
- The representation of the spatial planning lever uniformly across England is reasonable.

4.6 Receptor level resilience

4.6.1 Context

Properties can be made more resilient or resistant to flooding (referred to here in the combined sense of Receptor Level Resilience, RLR). These measures can, if appropriately implemented, lessen the damage incurred during flood events and reduce reinstatement costs.

Several policy measures encourage individual property owners to protect themselves and their property from flooding. The Environment Agency's Flood & Coastal Erosion Risk Management Strategy (Environment Agency, 2011) and Defra's partnership funding (Defra, 2011) policies encourage local communities to contribute towards their risk reduction, not least by implementing RLR measures. Local authority enforced Building Regulations have been strengthened in recent years to promote RLR measures (e.g. Defra, 2007a; CIRIA, 2010), and subsides and grants are often made available for those in flood affected areas to install certain RLR measures. At the same time, the availability of these measures is increasing from a wide range of companies, including installing 'kitemarked' devices for preventing the ingress of flood waters into properties (Environment Agency, undated; National Flood Forum, 2012) and installing fixtures and fittings that are less susceptible to flood damage should a property be flooded (e.g. plastic kitchen fittings).

There are, however, counteracting tendencies to such trends. Property owners are often reluctant to implement risk-reducing measures which demonstrate to the wider public that their properties are at risk (such as external flood gates, see Harries, 2008; 2012) so the implementation of RLR measures is not 'plain sailing'. Furthermore, RLR measures are only likely be an efficient response where the frequency of flood events is high (Defra, 2014b), and are only likely to be effective when the external flood depth is less than 600mm (Defra, 2007a). They also often rely upon neighbourhoods acting to prevent flood waters propagating through party walls and shared roof spaces. At flood depths greater than this, or in the absence of the collective action that may be necessary, it is likely that resistance measure (i.e. external flood boards and similar products) will be overtopped or will be of insufficient strength to withstand the loading of large depths of the flood water. Additionally, not all measures implemented will be successful. An evaluation of post-installation effectiveness commissioned by Defra concluded that (Defra, 2014b):

'Of the 11 Environment Agency responses received, 6 schemes had been tested and Property Level Protection measures deployed but only 4 provided further detail. The information provided showed that for 79 per cent of properties, Property Level Protection measures either prevented flood water ingress or served to reduce the impact and level of flooding experienced, whilst 21 per cent found that it made no difference at all.'

Nevertheless, under current planning policy all new properties built in the fluvial and coastal floodplain are likely to include resilience measures and there are low cost resilience measures that help people recover more quickly which are fairly cost neutral (and therefore potentially more likely to be approved by insurers (Rose et al., 2016). Outside of the coast and fluvial floodplain it is unlikely that planning authorities will impose such conditions.

4.6.2 Representation within the FFE

The FFE enables the user to control both take-up and impact as follows:

- % uptake of RLR measures: the user can differentiate the take-up according to the location of the property (on or off the fluvial / coastal floodplain - given evidence suggesting uptake away from the fluvial and coastal floodplain is low, Sayers et al, 2015).)
- Effectiveness of RLR in reducing damage: the user can control the percentage reduction of the damage according to the return period of the flood event (given evidence suggests that such measures are likely to be effective at reducing damages in more frequent events (and shallower depths) and less so in more extreme events (with greater depths), Sayers et al, 2015). The user can set values separately for new and existing developments, enabling development management rules (e.g. floor levels of any new development to be above the 100-year flood level by setting a 100% reduction in damage for events equal to or more frequent than the 1:100 year event).

4.6.3 Main assumptions

No significant assumptions beyond those associated with the effectiveness (and costs) of RLR in reducing damages are included. In doing so, it is noteworthy that damage is estimated using the Weighted Annual Average Damage (WAAD) calculation. The WAAD figure gives an indicative estimate of direct costs to residential properties, non-residential properties and agriculture. It includes the benefit offered to residential and non-residential properties by flood protection schemes but does not include the benefit from flood warning schemes. This figure has recognised deficiencies, that have been highlighted by current work that JBA is undertaking in reviewing the LTIS RLR approach for Flood Re, but it is assumed here (as in LTIS and elsewhere) that WAAD is reasonable.

4.7 Forecasting and warning

4.7.1 Context

Flood awareness is essential for reducing vulnerability of individuals and communities. Improving awareness can promote autonomous or planned behavioural responses by those concerned, and the forecasting of floods and providing warnings to communities is essential for enhancing this awareness.

Communities and individuals who receive these warnings are better able to prepare and respond by taking damage-reducing actions, better able to develop strategies to minimise the impact of the flood on their families and property, and thereby in a better position to hasten recovery, given that losses will be reduced, and injury and loss of life will hopefully be prevented.

This ability to respond is fundamentally affected by the timeliness of reliable warnings, the clarity of message and encouragement to act, and the ability of those involved to take action to help themselves or others (for example, older people with physical disabilities are less likely to be physically able to move valuable possessions to safety but can be prioritised to receive assistance from voluntary services). Good forecasting and warning is therefore necessary to reduce the impacts of a flood, but it is not sufficient. Ultimately, it is the ability of people to respond to this information which makes the difference and therefore incidence management has an important role in complementing flood forecasting and warning activities.

4.7.2 Representation within the FFE

Forecasting and warning is represented in the FFE through two variables:

- **% properties that successfully receive and act upon a warning, that in turn is defined as an aggregate four user controls (differentiated by social vulnerability and flood source):**
  - % coverage of the flood warning service (residential)
  - % take up of residential properties
  - Reliability and availability: the % who receive a warning when signed up
  - % who take appropriate action and the actions taken are effective
- **% reduction in direct residential property damages (implemented as a % reduction in the estimated WAAD value):**
  - the user controls this by setting the percentage reduction by the severity of the flood event (as evidence suggests forecasting and warning can be more effective when the lead time is longer, assumed here to infer a more extreme event, Sayers et al, 2015) and by socially vulnerability.

4.7.3 Main assumptions

No significant assumptions beyond those associated with the effectiveness of the forecasting, warning, response chain in reducing damages; both of which can be controlled by the user.

4.8 Insurance

4.8.1 Context

Flood insurance is generally only compulsory in the UK for those purchasing their property with a mortgage. Other householders are free to purchase or not to purchase flood insurance, which is bundled in with domestic insurance against fire, theft, subsidence, etc. Flood insurance is available in the UK for domestic properties built since 1 January 2009 via the Flood Re scheme and businesses through private insurance companies and aims to compensate victims for the flood damage that they incur, therefore enhancing recovery after flood events (and reducing vulnerability of residents).

4.8.2 Representation within the FFE

The FFE can represent the impact of flood insurance - including the differential access to insurance of the most vulnerable groups (Sayers et al, 2017). An insurance lever, however, has not been included here given the focus on infrastructure investment but could be included in future through a further enhancement and would need to be included for as part of any FRM policy development.

5 Risk Assessment

5.1 Translating the adaptation futures to a change in risk

The risk analysis uses the FFE to assess the change in risk by the 2050s given user selected climate, population and adaptation settings (as described in the previous sections). The FFE can report a wide range of risk metrics and a sub-set of these are used here, namely:

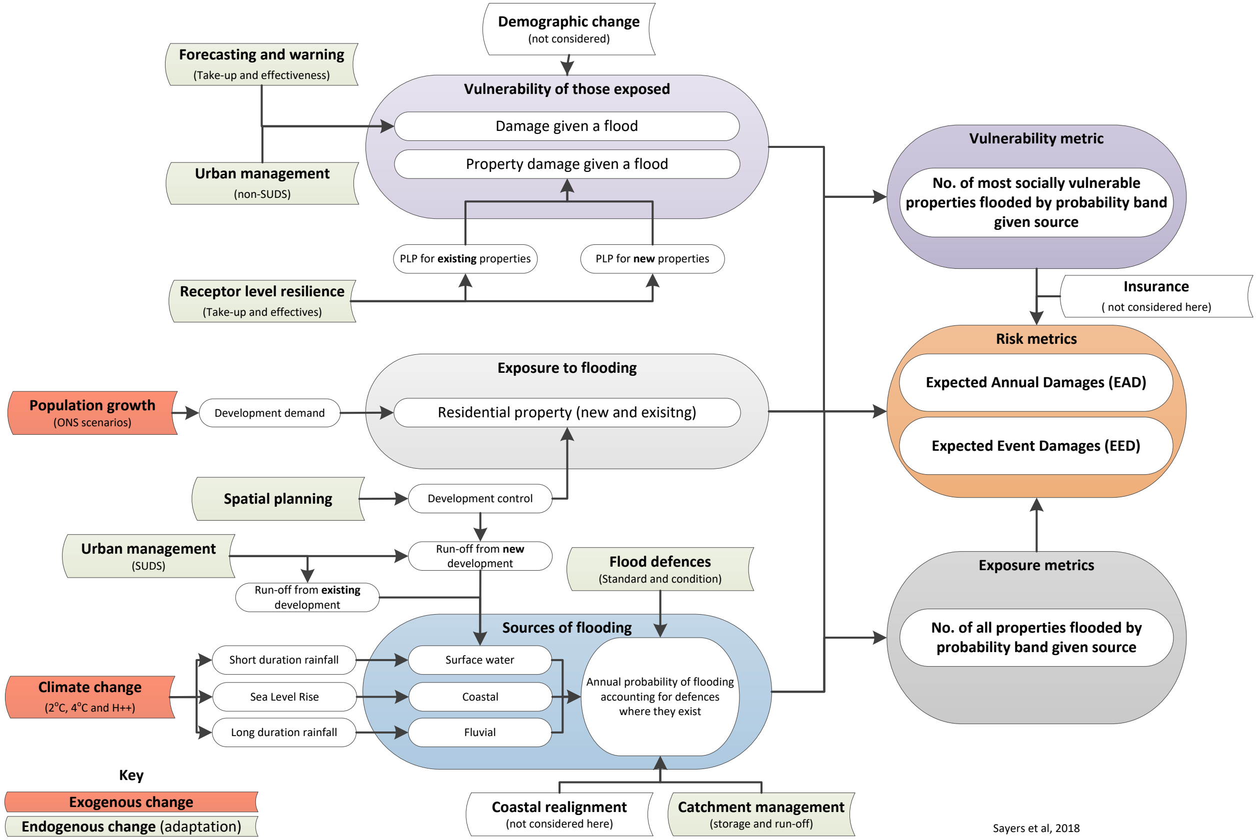
- Expected Annual Damages (EAD) for residential and non-residential properties, which is defined as an integration of the annual probability of flooding and associated damages. EAD can be used as a basis for quantifying risk that considers a wide range of potential flood events, accounting both for their different likelihoods and their different consequences.
- Expected Annual Damages (EED) or scenario event damages for residential and non-residential properties, which are defined as the damages conditional on a single, extreme, spatially-coherent flood event. Four inland flood events and two surface water events are considered. These events represent plausible, but stretching, extreme widespread flood scenarios, as modelled by JBA in work for the Environment Agency to develop the inland flooding scenarios within the 2017 National Risk Assessment[10], see Figure 5-1. Each has a probability of occurrence assessed to be, approximately, in a range between 1 in 200 and 1 in 20 within the next five years .The event damages reflect a statistical expectation of the resilience of defences, conditional on each assumed scenario. The event damages offer an alternative perspective to EAD by allowing the effects of proposed adaptations to be tested against particular extreme scenarios, which may reveal features such as clusters of high damages that are averaged out within the EAD.

In estimating the economic damages, direct damages are estimated using the Weighted Annual Average Damage (WAAD) methods. Indirect damages are assumed to be 70% of the direct damages (i.e. the total damage reported is 1.7 x the direct damage). The basis for the 1.7 factor is set out in Sayers et al, 2017 and includes the following aspects (and based on the 2014 LTIS report):

- 11% indirect losses associated with emergency services and provision of temporary accommodation; this is applied to residential losses only in accordance with the method adopted in LTIS
- 16% for risk to life and physical injury
- 43% for impacts on infrastructure, transport, schools and leisure

The factor of 1.7 excludes broader mental health, an issue that is increasingly recognised and subject to achieve research (e.g. on-going Environment Agency led research into the economic benefits of FCRM investment on recreation, tourism and health and a longitudinal study by Public Health England into the long-term impacts of flooding on mental health, reported in BMC Public Health). To enable an exploration of the influence of in-direct damage factors, the user can modify this setting within the tool (via the run parameter settings).

10 Wood, E., Lamb, R., Warren, S., Hunter, N., Tawn, J., Allan, R., and Laeger, S. (2016). Development of large scale inland flood scenarios for disaster response planning based on spatial/temporal conditional probability analysis. E3S Web of Conferences, 7, [01003]. DOI: 10.1051/e3sconf/20160701003 (http://dx.doi.org/10.1051/e3sconf/20160701003).



Source: Adapted from Sayers et al, 2015

Figure 5-2: Future Flood Explorer: Risk analysis framework

6 Cost assessment and functions

6.1 Introduction

The cost assessment estimates the investment required to implement the user-set adaptations. This is done via user-defined discount rates and a series of high-level cost functions that link the adaptations, and associated change in risk, to cost. This approach is embedded within the NIC Analytics Toolset and presented for each adaptation lever as well as an overall investment. Figure 6-1 sets out a summary of the cost functions associated with each adaptation measure with more detail provided below.

6.1.1 Cash values, discounting, efficiency saving and inflation

The spend profiles for the different scenarios show the undiscounted annual costs required to achieve the desired SoP. However, we have also provided Present Value, discounted costs for the whole of the assessment period so that the economic case (value for money, BCR) for the total spend compared to the benefits can be understood. These costs have been discounted over 100 years using the discount rate specified by the Treasury. Discounting is used to convert all costs and benefits into Present Values by multiplying the discount factor by the costs that occur in that year. The standard Treasury discount rates (taken from HM Treasury, March 2018 update, The Green Book) are shown in Table 6-1 below.

Table 6-1: Discount rates

Discount Rate (%)	Year
3.50%	0-30
3.00%	31-75
2.50%	76-125
2.00%	126-200
1.50%	>= 201

An efficiency saving rate and a rate for differential inflation in the construction sector are also represented as in-year rates and can be defined alongside the discount rate by the user.

6.1.2 Public private split

The main source of funding for FCRM is Environment Agency Grant in Aid (GiA) that requires external funding contributions (from the public and private sectors). As the costs have largely been derived from the Environment Agency's Forward Investment Programme (FIP) that sets out the amount of Grant in Aid and external contributions, it has been possible to identify the split between public and private funding that currently support FCRM. Future funding requirements are based on the same proportional split between public and private sector funding as with the present day. This split varies by adaptation measure; where evidence exists, the user is able to modify this value.

Table 6-2: Public-private split by adaptation measure

	All sources	Defences	Coastal Catchment management	Urban management	Spatial planning	RLR (existing)	RLR (new)	Insurance	Additional items	
Capital										
Public %	95%	95%	95%	89%	100%	80%	0%	100 %	0%	0%
Private %	5%	5%	5%	11%	0%	20%	100%	0%	100%	100 %
Revenue										
Public %	100%	100%	95%	89%	100%	20%	0%	100 %	0%	100 %
Private %	0%	0%	5%	11%	0%	80%	100%	0%	100%	0%

6.1.3 Overview of costing method

The overall approach for the cost functions is set out in Figure 6-1 - each step is then explained in more detail throughout the remainder of the Section.

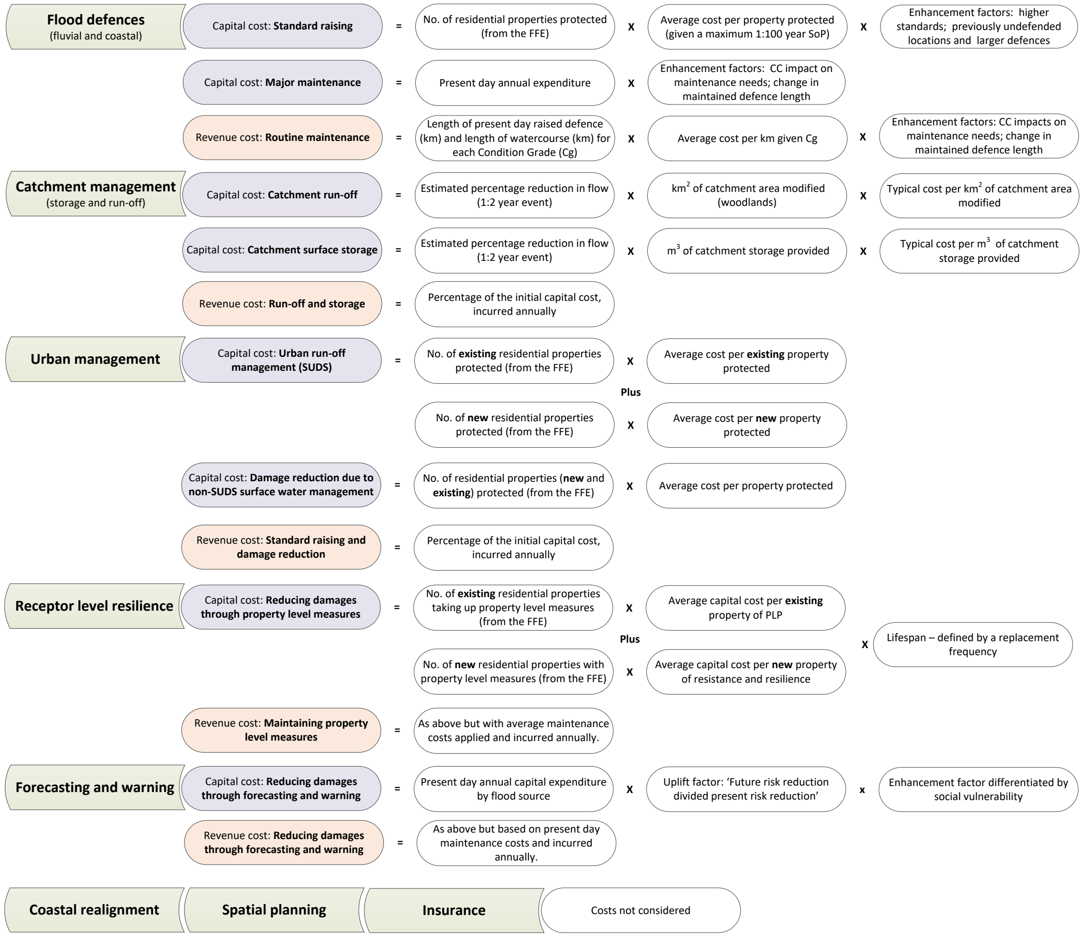


Figure 6-1: Summary of cost functions

6.1.4 Main assumptions

Each cost function relies upon a credible understanding of present day expenditure and return for that expenditure. The available data is assumed reasonable for this purpose as it is based on actual data from the Environment Agency's Investment Programme or published sources as detailed in the following sections. Data sources have been discussed and agreed with Environment Agency representatives as appropriate for this use.

6.2 Flood defences: Capital costs of raising defence standards

6.2.1 Cost function

If adaptation is needed to raise the SoP of a given defence (determined by the user set defence standards and projected future standard given no defence focused adaptation determined by the FFE after accounting for climate change) the capital cost of raising the SoP is calculated as follows:

Capital cost: **Standard raising** = No. of residential properties protected (from the FFE) x Average cost per property protected (given a maximum 1:100 year SoP) x Enhancement factors: higher standards; previously undefended locations and larger defences

The evidence and analysis used to support this function are discussed below.

6.2.2 Evidence base and analysis approach

6.2.2.1 Number of properties protected

The number of residential properties protected is defined here as:

- The number of *number of floodable properties in a given calculation area (*defined by the FFE and introduced earlier).
    - *subtract*
- *The Expected Annual no. of Properties* flooded (estimated by the FFE as integration of the probability of flooding against the number of property flooded curve). This changes given the combination of with climate, population and adaptation selected.

6.2.2.2 Average cost per property protected

The average cost per property protected is based on evidence of recent scheme costs and differentiated by settlement type

The average cost of protecting a single residential property has been assessed using information on projected expenditure in the Environment Agency's six-year Forward Investment Programme (FIP, covering 2016-2021), and actual costs through analysis of the Environment Agency's previous Medium-Term Plan (MTP) dating back to 2010 (covering 2010-2015). Using the FIP as the data source means relying on the evidence of schemes that are in development and averaging how much it costs to protect a property. The advantage is that using real data from a high number of schemes will give a realistic cost, accurate enough to use at a national and regional level. There will be variations in scheme costs based on defence type and length. However, this information is not readily available in the FIP and would add further complexity and reduce the accuracy of the overall averages used.

Before using the raw data from the FIP to estimate this cost, the following steps were taken to clean and adapt it to the objectives of this project:

- **Removing erosion, groundwater and reservoir removes 243 of the total 3549 entries:** this is because the tool does not include these sources.
- **Removing schemes where OM2 (properties moved from one risk band to a lower probability risk band) is 0 removes 942:** because the estimate of the average cost per property relies on a non-zero estimate of cost and number of properties protected.
- **Removing schemes that have a start or end SOP of 0% takes away 399:** these schemes could not be used to show the costs of improving the standard. This includes erroneous entries and environmental schemes.
- **Removed five that have no Total Project Expenditure (TPE) entry:** as it would not be possible to obtain an average cost per property from these schemes.

- **Removing ten records that have spurious resulting SoPs (e.g. 1 in 2 annual exceedance probability):** these schemes could not be used to show the costs of improving the standard.
- **Removing records that suggest a cost per property protected of more than a £200k per property:** these are likely to be erroneous or outliers and have been removed.
- **Removing records categorised as CM (capital maintenance) but do not raise the defence standard:** for example, act only to replace mechanical and electrical components and should therefore not be included in the cost estimations - identified within the records via key words of ‘pump', 'sluice' and/or 'gate’ and applied judgement where necessary.

From the remaining records the following have then been used in the development of the cost functions:

- **Schemes categorised as DEF (defence):** these are considered representative of costs of new schemes that raise the SoP.
- **Schemes categorised as CM (capital maintenance):** that act to increase the SoP.

Figure 6-3 illustrates the results and highlights the significant spread in the per property estimates and the lack of a significant trend with the end standard provided. This supports the use of a single average value for any scheme providing a target standard of 1in100 years or less (see Table 6-3). The targets standards above 1in100 a cost enhancement is used (see below)

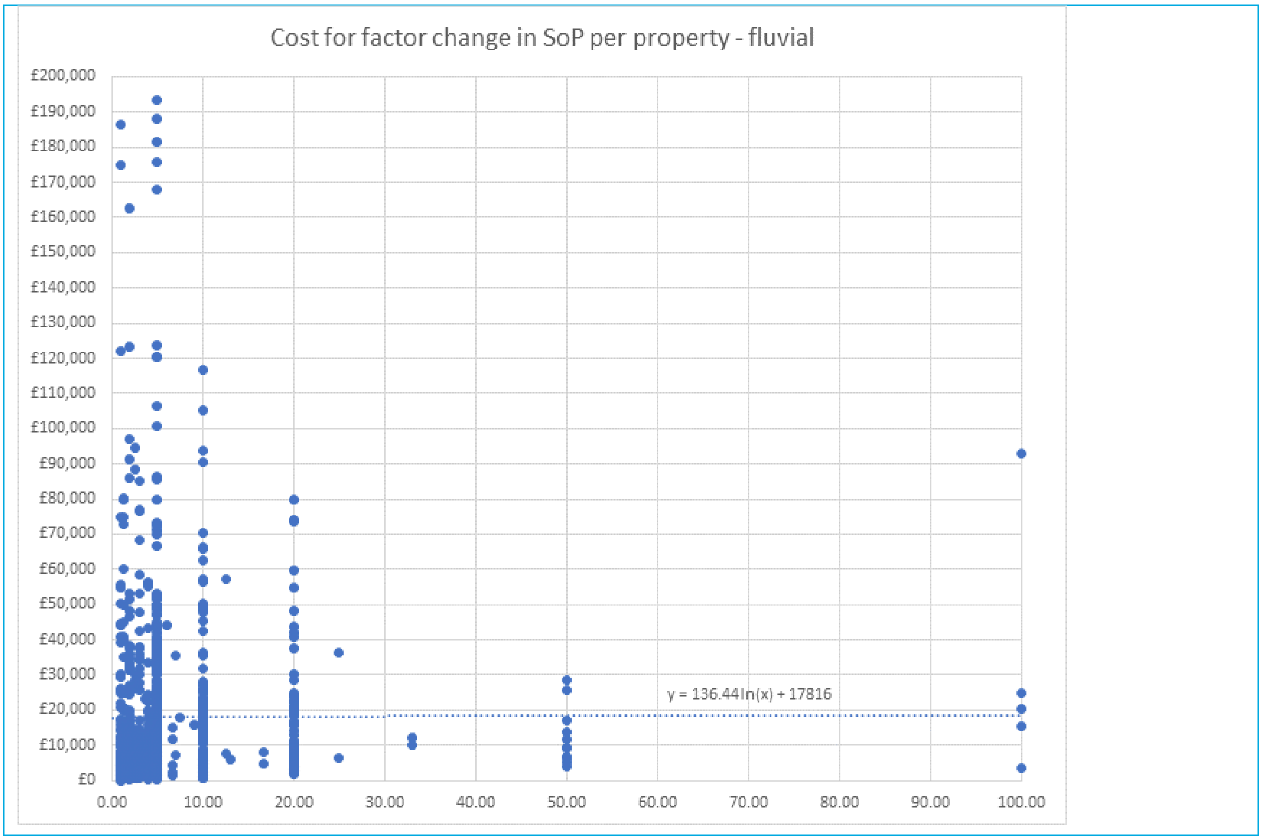


Figure 6-2: Cost for factor change in SoP

	Average		Lower		Upper	
Settlement Type	Coastal defences	Fluvial defences	Coastal defences	Fluvial defences	Coastal defences	Fluvial defences
	(£)	(£)	(£)	(£)	(£)	(£)
Urban major conurbation	9597	15866	3465	3217	11570	23411
Urban minor conurbation	9597	15866	3465	3217	11570	23411
Urban city and town	19673	18225	2285	3968	30697	27893
Urban city and town in a sparse setting	19673	18225	2285	3968	30697	27893
Rural town and fringe	17649	19424	2297	4417	31140	31612
Rural town and fringe in a sparse setting	17649	19424	2297	4417	31140	31612
Rural village and dispersed	26548	17609	1991	5341	58053	26427
Rural village and dispersed in a sparse setting	26548	17609	1991	5341	58053	26427

Table 6-3: Cost ranges for coastal and fluvial defences

(NB: upper and lower refers to 90% (upper) and 10% (lower) percentiles)

Note: Length of defence is not available in the MTP and FIP datasets - only the number of properties protected, hence a length term is not included here.

6.2.3 Enhancement to account for high user set standards

A review of 27 Project Appraisal Reports for schemes included in the FIP found nine considered schemes with SoPs higher than 1 in100 years. A review of detailed Project Appraisal Reports (PARs) written in support of these nine schemes suggests the typical Benefit Cost Ratios (BCRs) are lower than lower standard schemes and hence the cost per property protected is higher. This evidence (although limited) has been used to help set default value enhancement factors for schemes that provides a 1:200, 1:300 and 1:1000 year SoP ((see Table 6-4 below). Given the uncertainty in the supporting the sensitivity to these factors can be explored by the user.

Table 6-4: Cost enhancement factors: Accounting for an increased cost in provided higher standards of protection

Cost enhancement factors	
SOP after <=	Enhancement factor
100	1
200	1.20
300	1.40
1000	1.75

6.2.4 Enhancement to account for the need for larger defences

Providing protection for future storms is likely to require physically larger defences than today. Existing protection costs are assumed to implicitly reflect the costs of providing protections under a 2°C future (reflecting the minimum demands of existing guidance) but under more extreme climate futures a higher cost per property protected is anticipated. These is however limited quantified evidence to support the degree to which costs are likely to increase. A default enhancement factor has therefore been set based on judgement but is available to be modified by the user to explore sensitivity to this factor. The default enhancement is summarised in Table 6-5.

Table 6-5: Cost enhancement factors: accounting for larger defences

	2°C	4°C
Cost enhancement factors to take account of larger defences in the future	1.00	1.20

6.2.5 Enhancement to account for defence construction in previously undefended areas

The cost of providing a defence in areas that have, to date, been undefended is likely to cost significantly more to defend than indicated by analysis of the current investment programme (as these are, by definition, likely to reflect the most cost-efficient schemes). An cost enhancement is therefore applied to previously undefended areas that reflects the settlement type and user set standard of protection.

To calculate the cost enhancement is it assumed that, on average, the length of defence needed to provide protection to a given standard will be proportionally the same in the previously undefended area as it is in an equivalent defended area.

For example, consider the user setting the standard of protection to be 1 in 100 years in an urban conurbation that is currently undefended. First, the proportion of raised defences (by length) in areas that already experience a standard of protection of 1 in 100 years is estimated (for example 50%). It is then assumed that proportion of the currently undefended watercourse length will need to be raised.

The number of properties protected per km of the proposed raised defences is then compared to the equivalent value for that settlement type and user set standard of protection. The ratio between the two provides an initial enhancement factor that is then moderated to account for local efficiency saving (that will no doubt be possible to minimise the defence costs). This efficiency factor is difficult to determine, however through comparison of national results between the LTIS Core Cities and a degree of judgement, this is reduced by a factor of 5.

By way of illustration:

- If on average it costs £10 to protect one property when, on average, the defence protects 100 properties per km
    - then
- It will cost £100 to protect one property when, on average, the defence protects 10 properties per km.
- This is then adjusted to take account of the opportunity for local efficiencies to give a cost of £20 per property

6.3 Flood defences: Capital cost of major maintenance

6.3.1 Approach in summary

The cost of improving the representative Standard of Protection provided to an area is estimated as follows:

Capital cost: **Major maintenance** = Present day annual expenditure x Enhancement factors: CC impact on maintenance needs; change in maintained defence length

The evidence and analysis used to support this function are discussed below.

6.3.2 Evidence base and analysis approach

The maintenance costs are raised by the anticipated increase in defence length, where the increase in defence length is estimated by comparison to analogous present-day areas. For example, if the user sets currently undefended areas to a SoP of 1 in 100 years it is assumed that the proportion of defending length required is similar to existing areas with a 1 in 100 SoP in the same settlement type.

- The cost per property protected is based on the remaining schemes from the investment programme (see above). The average cost per property protected was estimated using the TPE divided by OM2 (number of properties at reduced risk).
- The data were analysed against four settlement types by combining the eight in Table 4-1 to four: village, town, city, conurbation.
- The data were then analysed against tidal or fluvial flooding source. Tidal flooding is classed as 'River Flooding (Tidal)' but Coastal Erosion schemes are outside of the scope of this commission so were excluded. In addition, 'Surface Runoff' schemes were excluded as they are assessed in Urban Management, see section 6.5.

6.3.3 Enhancement to account for the impact of climate change on revenue costs

This enhancement is related to the potential impact of a more significant impact of climate change on climate maintenance. Example enhancement factors have been included, but this function is user defined. A value of '1' assumes revenue is constant (for a given km of defences into the future (i.e. climate change increase the need for revenue), negative value that it decreases and positive that it increases

Table 6-6: Climate change enhancement for revenue costs

Epoch	2°C	4°C
2020s	1.00	1.10
2050s	1.25	1.38
2080s	1.50	1.65

6.3.4 Enhancement to account for the change in the managed length of defences

Through the analytics toolset the user is able to raise defences in previously undefended areas. In this case, the capital maintenance costs are raised by the anticipated increase in defence length, where the increase in defence length is estimated by comparison to analogous present-day areas. For example, if the user sets currently undefended areas to a standard of protection of 1 in 100 it is assumed that the proportion of defending length required is similar to exist areas with a 1 in 100 standard of protection in the same settlement type.

6.4 Flood defence: revenue costs

6.4.1 Approach in summary

Revenue costs for flood defences cover day to day maintenance. Two issues are considered: the revenue costs of maintaining raised defences to a target Condition grade (Cg) and the revenue costs of maintaining watercourses to a target Cg and is estimated as follows:

Revenue cost: **Routine maintenance** = Length of present day raised defence (km) and length of watercourse (km) for each Condition Grade (Cg) x Average cost per km given Cg x Enhancement factors: CC impacts on maintenance needs; change in maintained defence length

The evidence and analysis used to support this function are discussed below.

6.4.2 Evidence base and analysis

Base data

Evidence on revenue costs provided by the Environment Agency (December 2018) covered total revenue maintenance funding from 2013 to 2018. The dataset includes the cost, benefits, and length of raised defence and watercourse within each flood system together with data relating to the SoP and Cg of assets within those systems.

Length of present day raised defences and cost of maintenance

After removing outliers, the evidence provided by the Environment Agency was used to determine an average cost associated with maintaining a km of raised defence within a system with a particular target condition grade (i.e. Cg = 1 to 5) - see Table 6-7. The results of these analysis are summarised in Table 6-8 and 6-9. Significant variation exists in these numbers but at a national scale the trend within these average values appears sensible.

Table 6-7: Present day (2017) length of raised defence and length of watercourse by condition grade

Length of raised defence (km)	Length of watercourse (km)	Cg
112	1578	1
1222	2163	2
6280	25795	3
143	594	4
16	79	5

Table 6-8: Costs associated with maintaining a km of raised defence with target condition grades

	Cost per km (£)		
Cg	**Average**	**Lower**	**Upper**
1	16,097	7,123	22,236
2	16,097	7,123	22,236
3	7,725	2,648	14,904
4	1,653	1,061	3,477
5	1,653	1,061	3,477

Table 6-9: Raised defence maintenance costs per km

Cost per km (£)	
Cg	Average
1	16,097
2	16,097
3	7,725
4	1,653
5	1,653

Length of present day water course and cost of maintenance

Using the same data as above the analysis has been repeated for the cost of maintaining associated water courses. The results are shown in Tables 6-10 and 6-11.

Table 6-10: Present day length of water course: By system condition grade and cost

	Cost per km (£)		
Cg	**Average**	**Lower**	**Upper**
1	1,307	490	3,057
2	1,307	490	3,057
3	422	81	1,253
4	285	265	701
5	285	265	701

Table 6-11: Watercourse maintenance costs per km

	Cost per km (£)
Cg	Average
1	1,307
2	1,307
3	422
4	285
5	285

6.4.3 Enhancement to account for climate change impacts on maintenance costs

An enhancement factor has been included to account for the potential impact that future climate change could have on maintenance costs as increased maintenance is required as a result of the effects of more intense rainstorms and sea level rise of FRM infrastructure.

Table 6-12: Enhancement to maintenance costs per km to account for climate change

Epoch	2^oC	4^oC
2020s	1.00	1.10
2050s	1.25	1.38
2080s	1.50	1.65

A value of '1' assumes maintenance is constant (for a given km of defences) into the future (i.e. climate change increase the need for capital maintenance), negative values that it decreases and positive that it increases.

6.4.4 Enhancement to account of a change in length of raised defences

The same approach as applied to Capital maintenance costs is applied here to enhance the revenue cost related to changes in the lengths of defences and watercourses.

Table 6-13: Change of length of raised defences and watercourses

Epoch	Raised defences	Watercourses
2020s	1.05	0.96
2050s	1.05	0.96
2080s	1.05	0.96

6.5 Coastal realignment: Capital costs

6.5.1 Approach in summary

Coastal realignment and coastal erosion schemes are not included within the study (sea defence schemes are of course included through defences costs). The Adaptation Sub-Committee of the Committee on Climate Change has commissioned research to assess the economics of coastal change management in England and to determine potential adaptation pathways for a sample of exposed communities. This may provide additional insights that are useful to the aims of this study but and could be used to update the tool in the future.

6.6 Catchment management: Capital costs

6.6.1 Approach in summary

Two key issues are considered in relation to the costs of catchment management (NFM): capital and revenue costs of woodland (run-off) based measures and the capital and revenue costs of storage-based measures.as follows:

Capital cost: **Catchment run-off** = Estimated percentage reduction in flow (1:2 year event) x km^2 of catchment area modified (woodlands) x Typical cost per km^2 of catchment area modified

And

Capital cost: **Catchment surface storage** = Estimated percentage reduction in flow (1:2 year event) x m^3 of catchment storage provided x Typical cost per m^3 of catchment storage provided

The evidence and analysis used to support this function are discussed below.

6.6.2 Evidence base and analysis

Two issues are considered here:

- the capital and revenue (ongoing cost) of NFM woodland (run-off) based measures
- the capital and revenue (ongoing cost) of NFM storage based measures.

Evidence on costs builds on those provided within the Working with Natural Process Evidence Base (Defra, 2017), particularly the following insights:

- Woodland based measures can be approximated by the area (km^2) with the cost increasing as the desired reduction in flow increases (£1-2,000 per ha ($0.01km^2$)). Costs are identified per % change in peak flow achieved (2 year return period event) per km^2 of catchment area modified for NFM (woodland).
- Storage based measures can be approximated by the volume stored where this is identified as the area (km^2) x 1 km, with the cost increasing as the desired reduction in flow increases - £10-£15 / m^3 (very approx.) capital plus maintenance and sediment removal etc.). Costs are identified per % change in peak flow achieved (2 year return period event) per m^3 of catchment area modified for NFM (storage).

The tables below show examples of costs per change in peak flow for woodland improved (Table 6-14) and NFM flood storage (Table 6-15). Only the first few percentages have been shown here.

Table 6-14: Cost of change in peak flow following woodland creation

	Capital costs	Revenue costs
% change in peak flow	**£ (per km²) of woodland improved / provided**	**£ (per km²) of woodland improved / provided**
2 year storm event	Average	Average
0%	0	0
1%	3000	90

Table 6-15: Cost of change in peak flow from natural flood storage

	Capital costs	Revenue costs
% change in peak flow	**£ (per m³) of storage provided**	**£ (per m³) of storage provided**
2 year storm event	Average	Average
0%	0	0
1%	10	0

6.7 Catchment management: Revenue costs

6.7.1 Approach in summary

Due to the lack of available evidence regarding the revenue costs of catchment management, we have assumed that these would be 3% of the capital costs incurred each year, as follows:

Revenue cost: **Run-off and storage** = Percentage of the initial capital cost, incurred annually

The sensitivity to this value can be explored by the user modifying this value.

6.8 Urban management: Capital costs

6.8.1 Approach in summary

Two issues are considered to estimate the costs associated with urban management; the modification of the effective urban extent due to SUDS take-up in new developments and retrofit in existing developments and wider efforts to manage urban surface water run-off (excluding SUDS).

Capital cost: **Urban run-off management (SUDS)** = No. of **existing** residential properties protected (from the FFE) x Average cost per **existing** property protected

Plus

No. of **new** residential properties protected (from the FFE) x Average cost per **new** property protected

Capital cost: **Damage reduction due to non-SUDS surface water management** = No. of residential properties (**new** and **existing**) protected (from the FFE) x Average cost per property protected

Note: Costs of conventional drainage improvements, such as pipe networks, are excluded (as both difficult to estimate and these are primarily private water company expenditure that is difficult to obtain due to commercial sensitivity).

6.8.2 Evidence base and analysis

Base evidence

The costs data contained within the EA's Forward Investment Programme has been used to establish a typical SUDS cost - however the information is highly bundled and may include SUDS measures within a package of different interventions and may include major infrastructure replacement e.g. new surface water sewers.

Average cost of protecting a property

The evidence presented from the MTP data has been used to determine the average cost of property protection to a property through a SUDS scheme. This cost is also used as proxy for other forms of delivering surface water management.

Table 6-16: Cost (£) pre property protected or damage reduced from urban management

Type of urban management		Average Per property cost (£)
Retrofit SUDS schemes = Average cost per property protected		7000
SUDS new development = Average cost per property protected		4000
Non-SUDS - Average cost per property	≥3.3% (i.e. more frequent than 1:30 years)	7000
Non-SUDS - Average cost per property	<3.3% (i.e. less frequent than 1:30 years)	7000

6.9 Urban management: Revenue

Revenue costs are assumed to be 2% of the initial capital cost based on a whole life PV of between 1-5% - with the majority for SUDS ~1% and larger but fewer schemes ~4%. This is based on analysis of the FIP and MTPs.

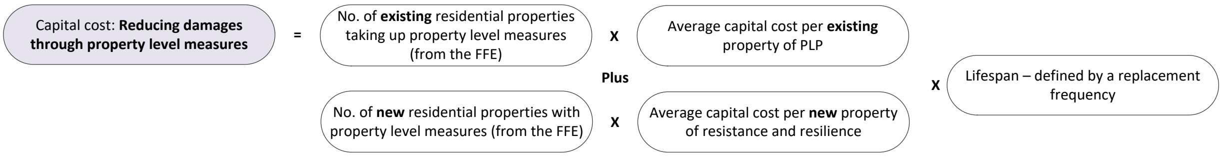
6.10 Spatial planning: Capital costs and revenue

Spatial planning costs are not considered here.

6.11 Receptor resilience: Capital costs

6.11.1 Approach in summary

Capital cost: reducing damages through property level measures is calculated as follows:



The evidence and analysis used to support this function are discussed below.

6.11.2 Evidence base and analysis

Several sources are used to identify potential average costs for improving resistance and resilience of individual properties. These are:

- Average costs of PLP schemes in the EA Forward Investment Programme
- LTIS: Additional Analysis – Topic 5 technical report, Property level resistance and resilience (CH2M 2017)
- Assessing the Flood Risk Management Benefits of PLP (JBA, 2014)
- Indicative Prices for home flood protection products (Dublin Flood Forum 2013)
- Establishing the Cost Effectiveness of Property Flood Protection (JBA, 2012)
- Assessing the Economic Case for Property Level Measures in England (Royal Haskoning DVH 2012)
- Research to identify potential low-regrets adaptation options to climate change in the residential buildings sector (Davis Langdon, 2011)
- Flood Resilient Homes (ABI, 2010)
- Lamond, J., Rose, C., Mis, N. and Joseph, R. (2018) Evidence review for property flood resilience phase 2 report. Project Report. Flood Re, London. Available from: http://eprints.uwe.ac.uk/35489

The LTIS costs were similar to others and the most recently produced and therefore used as the basis for the average costs for Receptor resilience.

The take up of RLR can be set by the user as part of the adaptation settings and recommended take up factors are provided for each measure within suggested RLR packages, based on the LTIS work referenced above.

Capital cost of installation: Existing properties

The current costs for a range of measures are set out below. These relate to RLR measures being installed in existing properties that are at risk of flooding.

Table 6-17: Capital costs for RLR in existing properties

Capital cost (upfront)	Average	Proportion implemented
A: Passive resistance	£6,546	40%
B: Active resistance	£4,159	30%
C: Resilience without resilient flooring	£12,390	10%
D: Resilience with resilient flooring	£17,839	10%
E: Passive resistance and resilience with resilient	£22,997	5%

flooring		
F: Active resistance and resilience without resilient flooring	£15,161	5%

Capital cost of installation: New properties

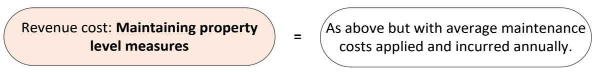
New properties should not be developed in areas at flood risk as detailed in the National Planning Policy Framework, 2012 and the sequential test it sets out. However, it also includes an Exception test wherein development can take place on the flood plain where there is no other suitable land or for overwhelming regeneration reasons. Where planning applications are submitted for development in the flood plain, these need to be supported by flood risk assessments setting out how flood risk will be managed through floor levels, safe access and egress and, where required, resilience measures - these minimise the impact of flooding rather than prevent it occurring and therefore comprise measures such as waterproof finishes, raised sockets etc.

Table 6-18: Capital costs for RLR in new properties

Cost type	**Average**	**Take up (lower than for existing as only a small proportion will require RLR)**
Capital cost (property protected average) - £	£2270	13%
Annual cost (property protected average)	£25	

6.12 Receptor level: Revenue

6.12.1 Approach in summary



6.12.2 Evidence base and analysis

The annual maintenance costs and proportion of take up have been taken from LTIS.

Table 6-19: Annual maintenance costs

Annual maintenance costs	**Average**	**Proportion implemented**
Annual maintenance cost for Package A	£155	40%
Annual maintenance cost for Package B	£83	30%
Annual maintenance cost for Package C	£0	10%
Annual maintenance cost for Package D	£0	10%
Annual maintenance cost for Package E	£155	5%
Annual maintenance cost for Package F	£83	5%

6.13 Forecasting and warning: capital costs

6.13.1 Approach in summary

The cost of reducing damages through forecasting and warning is calculated as follows:

Capital cost: **Reducing damages through forecasting and warning** = Present day annual capital expenditure by flood source x Uplift factor: 'Future risk reduction divided present risk reduction' x Enhancement factor differentiated by social vulnerability

The evidence and analysis used to support this function are discussed below.

6.13.2 Evidence base and analysis

GiA costs were identified for 2015/16 and 2016/17 from the Environment Agency MTP and overall delivery costs are taken from the Flood Incident Management Plan provided by the Environment Agency assuming that 50% of the total spend is invested in coastal flood management, 40% fluvial and 10% surface water.

Uplift on present day expenditure

It is assumed that the present day spends at a national level can be uplifted to estimate the future spend based on the expectation of improvement in the service.

The cost function is therefore expressed as the future expectation of risk reduction divided by the present expectation of risk reduction to the power of the enhancement factor. The expectation of risk reduction is taken from the user set adaptations and used to uplift the costs of the service. The differentiation of the service costs by flood source is then determined by proportion (Table 6-20). There is limited evidence to support these so users have the ability to define this proportion.

Table 6-20: Split of the flood forecasting cost across flood sources

Flood sources	% Split of the cost
Coastal flooding	
Capital	50%
Revenue	50%
Fluvial flooding	
Capital	40%
Revenue	40%
Surface water flooding	
Capital	10%
Revenue	10%

6.14 Forecasting and warning: Revenue

6.14.1 Approach in summary

Revenue cost: Reducing damages through forecasting and warning

- Based on present day maintenance costs and incurred annually.

6.14.2 Evidence and analysis

The Environment Agency provided information from its Flood Incident Management Plan regarding existing capital revenue costs across sources of flooding. The costs here are assumed to be repeated on a 10 year cycle.

Table 6-21: Revenue expenditure in total and proportion by flood source

Expenditure type	**Cost (£)**
All sources	
Capital	16,350,000
Revenue	27,300,000
Coastal flooding	
Capital	50% of spend
Revenue	50% of spend
Fluvial flooding	
Capital	40% of spend
Revenue	40% of spend
Surface water flooding	
Capital	10% of spend
Revenue	10% of spend

6.15 Other costs

6.15.1 Insurance

Insurance costs are not considered within the tool.

6.15.2 Exceptional costs

Exceptional items of expenditure that may be required in the future, for example replacing the Thames Barrier or installing a new radar system are excluded here. The cost of recovery from major flood events in the form of payments from the Bellwin scheme - these are included within the present day expenditure and projected forward in a straight line trajectory - are however included.

7 Validation and Quality Assurance

7.1 Validation of the cost estimates

The QA process does not explicit refer to the accuracy of the risks. The accuracy of NaFRA has been actively debated for over 15 years and is difficult to determine. Projections of costs given climate and population are even more problematic. Although formal validation is outside the scope of this study (and an achieve and ongoing research agenda) we have considered the credibility of the cost estimates in two important contexts - present day and future estimate. These are discussed below.

7.1.1 Present day costs

Under an assumption of a continuation of current levels of adaptation the costs (given a 2ºC / Low population future – i.e. least change from present day conditions) the expenditure estimates in the short term should be similar to present day. The results show this is borne out reasonably well (assuming a continuation of the current levels of adaptation and comparing the results for 2018 with to present day expenditure - see table 7-1).

The 4ºC future brings costs forward significantly in the model, as expected, but it is difficult to link this to a reasonable objective comparator.

Table 7-1: Comparison of total current expenditure - Environment Agency and NIC Analytics Tool

	EA Budget*	Estimated here	Comment
Capital totals	£544,650,000	£516,590,689	
Flood risk: Public contributions	£424,000,000	£431,213,290	EA spend based on average 2016-21 and from 2018 estimated here assuming CLA 2c Pop B
Flood risk: Private contributions	£65,000,000	£29,727,399	EA PF income based on the average from FCERM programme** (2015-2021) and 2018 estimated here assuming CLA 2c Pop B
Erosion management, groundwater and reservoir	£55,650,000	£55,650,000	Not assessed here - EA value used directly and included as part of analysis under 'Additional expenditure'
Revenue tools	£313,477,210	£313,477,210	
Flood risk: Public contributions	£123,534,875	£123,534,875	EA spend based on asset, FFW and SUDS revenue spends and infills here - estimate and actuals taken from 2018 estimated here assuming CLA 2c Pop B
Flood risk: Private contributions	£3,506,414	£3,506,414	EA spend assumed to be equal to the estimate here - estimated based on CLA 2c PoP B 2018
Revenue items not explictly modelled here			
Local service costs (non-asset)	£78,544,680	£78,544,680	Not assessed here - EA value used directly and included as part of analysis under 'Additional expenditure'
National EA central services	£41,000,000	£41,000,000	Not assessed here - EA value used directly and included as part of analysis under 'Additional expenditure'
Other expenditure (IDBs and LA revenues etc)	£60,057,224	£60,057,224	Not assessed here - EA value used directly and included as part of analysis under 'Additional expenditure'
Extra-ordinary expenditure (Bellwin average)	£6,834,017	£6,834,017	Not assessed here - EA value used directly and included as part of analysis under 'Additional expenditure'
Other central services	All included above	All included above	
Total	**£858,127,210**	**£830,067,899**	

7.1.2 Future costs

It is very difficult to know if a future estimate is 'right' (in fact, a philosophical and practically impossibility), but we can gain some confidence by comparing different models. For example, the LTIS explores a scenario of defending the core cities to a high standard. We have completed a similar (but not precisely the same, due to different model set ups) run here that assumes all Major Urban Conurbations are protected to 1/1000 (including previously undefended areas). The results show a reasonable comparison:

- LTIS suggests a PV of £24/25bn (to 2100), which we assume includes capital and revenue defence costs.
- The equivalent projection in this study is run 2050s_CLA_2c_PopB_Defences195, which results in estimated PV capital defence raising (£26bn) and revenue (£4bn) = £30bn total.
- Given the large number of properties currently undefended in major conurbations (~25% of the total in their floodplains), the estimate of £30bn seems reasonable in comparison with the LTIS core cities scenario.

7.2 Validity of the risk estimates

The FFE has been previously validated through extensive discussion as part of the CCRA. The extension here to include the latest State of the Nation and CDL datasets have also been reviewed, but given the time constrains of the project not with the same vigour as in the CCRA. Nonetheless the structure of the FFE remains unchanged and it is reasonable to expect the same performance and this is borne in comparison with both present day and the observed sensitivity to adaptation settings.

7.2.1 Present day damages

Present day damages:

- Total annual damages from the FFE: £704m
- From State of the Nation briefing document: £664m.

7.2.2 Properties at risk

Table 7-2: Properties at risk

Band	Probability range	FFE	SoN
High	> 1:30	198,000	126,000
Med	1:100 - 1:30	515,000	482,000
Low	1:1000 - 1:100	943,000	823,000
Very low	<1:1000	37,900	539,000

- The numbers in High to Low bands broadly agree; differences occur because of the different way defence fragility is represented in the FFE that affects the probability of inundation assigned to each property.
- Another difference arises from the treatment of properties in the Very Low band that are excluded from the FFE analysis as being outside the floodplain. Some properties within the floodplain are assigned this very low probability of inundation because they are protected by very good defences.
- Another difference is that the FFE does some double counting of properties at risk from fluvial and coastal sources that are not distinguished in the State of the Nation data.

7.2.3 Future risk

The primary purpose of the FFE is to explore alternative futures and the change in risks between these futures (and not to estimate present day risks per se). The results - presented later - highlight that behaviours appear credible in the context of the study here.

8 National investment analytics tool

A single spreadsheet controlled tool has been developed that enables alternative investment strategies to be explored using simplified investment analysis set out above and then supported by the risk assessment provided by the FFE.

The NIC Analytics Toolset consists of six steps and supporting analysis (Figure 7-1). Progress through this framework is controlled via the 'NIC - Flood analytics - 1 Run and parameter settings' spreadsheet.

Each step is introduced briefly below.

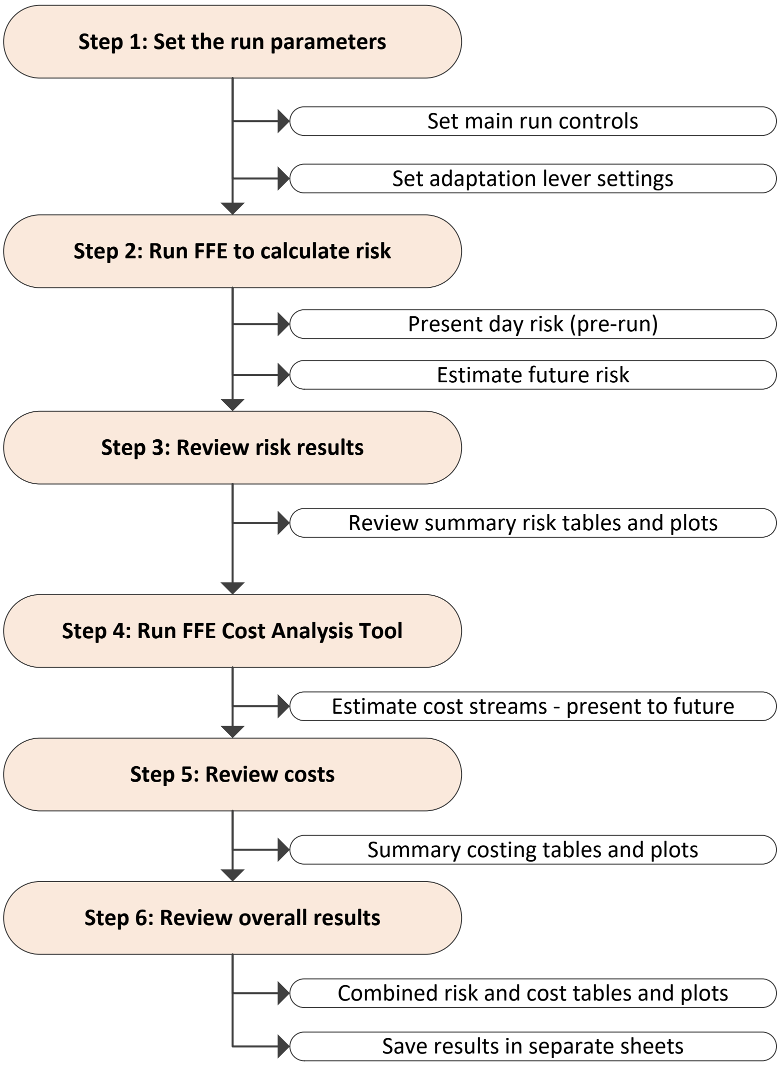


Figure 8-1 NIC Analytics toolset - overview of framework of analysis

8.1 Step 1: Set the run parameters

In this first set the user sets the general control parameters for the run including:

- Climate scenario
- Population scenario
- Sets each adaptation lever.

And switches on or off outputs including:

- Expected Annual Damages
- Expected Event Damages

- Costs.

8.2 Step 2: Run FFE to calculate risk

In this second step the user initiates the Future Flood Explorer via a spreadsheet macro in the control spreadsheet (NIC - Flood analytics - 1 Run and parameter settings).

8.3 Step 3: Review risk results

In this third step the user is asked to review the results from the risk analysis, providing an opportunity to confirm the adaptation settings used are reasonable and the results appear credible. Exploratory results undertaken in the development of this report are provided in Annex X.

8.4 Step 4: Run FFE Cost Analysis Tool

In the fourth step, the user initiatives the calculation of costs. In addition to the cost functions embedded into the tool the user is able to set:

- Test Discount Rate
- A year on year efficiency savings rate
- A year on year differential inflation rate
- Anticipated public and private investment split for each adaptation.

The user is also able to review the assumptions of present day expenditure that are assumed to represent expenditure in 2015.

8.5 Step 5: Review costs

In the fifth step the user is able to review the cost results. This includes a breakdown of expenditure by:

- Public and private sources
- Capital and revenue spend
- All adaptation and the individual adaptation
- Cash costs (present day and 2050s) and Present Value.

8.6 Step 6: Review overall results

In the final step the user is able to review the results from both the costs and risk analysis. If appropriate the user must then save the analysis.

Following finalisation of the model and final runs, we will include results here. For example:

- Cost profile - alternative adaptations under a 2C, low population future
- Cost profile - alternative adaptations under a 4C, high population future
- Annual average spend - alternative adaptations under a 2C/low population and 4C/high population future
- Annual average spend - alternative adaptations under a 2C/low population and 4C/high population future.

8.7 Main additional assumptions

The user is an expert user: specific user guidance is not provided nor are detailed descriptions published elsewhere repeated here. The tool will respond to user inputs.

9 Potential future improvements

Throughout this report, we have set out a series of improvements that could be applied to the tool in future to improve its functionality and remit. These are summarised here for completeness:

9.1 Improved representation of climate projections

Two priority enhancements are suggested for future development of the toolset:

- Update the coastal analysis using coastal overtopping analysis developed as part of the State of the Nation analysis (already available at the time of writing) to better represent the impact of sea level rise coastal defence standards
- Update the projections with latest UKCP projections (UKCP18) as they become available.

9.2 Improved representation of population projections

The priority enhancements for future updates include:

- Better representation of the type of residential development and the associated deviation from existing occupancies and ground floor dwellings (move to high rise etc).
- The representation of the impact of population growth on non-residential property and supporting infrastructure development.
- Consideration of demographic change as well as basic changes in population numbers.

9.3 Improved representation of coastal and river defence infrastructure

We suggest that the influence of changes in maintenance effort (and targeting) and climate change on condition grade could be included.

9.4 Improved representation of shoreline processes and coastal realignment

Shoreline management is a significant long-term challenge and should be included in future updates. The Adaptation Sub-Committee to the Committee on Climate Change has commissioned research to assess the economics of coastal change management in England and to determine potential adaptation pathways for a sample of exposed communities. Potentially this could be used in the future to support the representation of coastal realignment and other shoreline management activities outside of defence standards within the NIC Analytical Tool presented here.

9.5 Improved representation of catchment management

Two priority enhancement should be considered for future updates:

- Multiple benefits: Catchment management measures provide a wide range of benefits. Capturing these is central to the case for such measures. The rather narrowly focused metrics used here fail to capture these broader (and equally important) benefits.
- Improved representation of the impact on flood flows and risk: as demonstrated in the 2016 Defra Cumbria Modelling Competition (Sayers and Horritt, 2016), it is possible to use the NFM opportunity maps together with a national hydrological model to understand how flood flows reduce through the catchment and use this to more robustly establish the associated risk reduction. This would however require time and some supporting research to ensure its credibility (but would provide much improved insights in the medium term).

9.6 Improved representation of urban management

- Include the ability for the user to modify the urban management setting according to the settlement types introduced earlier (to be consistent with the defence lever)
- Refine the definition of the other 'surface water management activities' and their representation in the analysis
- Work with the 21st Century drainage team to update the analysis to represent the influence of spatial differences in urban drainage capacity.
- Develop a options paper setting out a hierarchy of improvement options
- Consider including a representation of the cost of piped drainage adaptation (see section 4) - although initial discussions with the 21st Century project team suggest SUDS costs are a reasonable proxy to this.

9.7 Improved representation of spatial planning

Better represent the reality of the differential opportunity to avoid floodplain development by Local Planning Authority (LPA) and recast the representation of the spatial planning adaptation to be differentiated by LPA. This is likely to have a significant impact on the assessment (and spatial distribution) of future risk as we know this assumption of the same proportion of floodplain development everywhere will overestimate the change in risk in some areas and in others, significantly under estimate it.

9.8 Improved representation of receptor level resilience

Differentiate the representation of the take-up and effectiveness of PLP according to socially vulnerable groups. This is an important consideration (and differentiator) as highlighted by the JRF studies (Sayers et al, 2017).

9.9 Improved representation of forecasting and warning

Flood forecasting plays a central role in operational response (including pumps, barriers, gates etc) and increasingly in the deployment of temporary defences. A quick win enhancement would be to include a better representation of temporary defences. The representation of temporary defences is included implicitly within the urban management lever, and hence applied uniformly nationwide with no ability to disaggregate the impact of temporary defences or their cost. Given the focus on such defences, recent analysis by the Environment Agency on locations that are potential suitable for temporary measures could be used to provide a geographically differentiated representation of temporary defences. The method of implementation should enable the user to control the extent to which these 'potential' sites are implemented and hence the benefit/cost of investing in temporary defences. This would add significantly to the credibility of analysis in comparison to the current representation.

9.10 Improved representation of insurance

It would be possible to include an insurance lever that reflects differentials in take-up and effectiveness according to income and past flood experience (as done for the research for the JRF, Sayers et al, 2017). This would provide evidence to explore questions such as: (i) is Flood Re value for money? (ii) Can insurance trade-off expenditure on flood defences and other responses?

9.11 Improved representation of risk assessment

The priority updates to the FFE largely mirror those set out in the previous chapter that focus on improving the underlying input data, namely:

- Inclusion of extreme coastal events: to complement the fluvial and surface water events already included
- Joint probability of flood sources
- Greater spatial differentiation of the adaptation levers
- Other updates to include the most recent datasets on residential properties and infrastructure assets (hospitals, power etc) could also be considered alongside developments focused method updates to include infrastructure network risks.
- Some data improvements have been made during the study. Two versions have been developed, one based on the flood risk data available from the Environment Agency in 2015 (and the CCRA analysis, Sayers et al, 2015) and one with updated data from the State of the Nation (published in March 2018). This latter data has not had the scrutiny of the previous data and the given timescales and budget it has not been possible to undertake the same level of validation and inter-comparisons completed from the CCRA between the FFE and the National Flood Risk data.

9.12 Improved decision optimisation

In addition to those set out above, an additional enhancement is proposed here that provided an overarching optimisation layer. The optimisation engine would apply the FFE based on a user-selected decision optimisation formulation and identify a recommended portfolio of flood control actions, in the case of formulation 3, a Pareto-approximate set of interventions. This is a significant, but potentially very powerful variation that will required a staged development process, including (for example): (i) Inception, (ii) Formalise the optimisation formulations d (iii) tool development.

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A Project Terms of Reference

A.1 Details of the services

A.1.1 1. Description of the work:

Objective

To assess the costs of different standards of flood protection and other risk management activities across England. It is expected that standards of flood protection will be differentiated by settlement size, housing density or a similar parameter.

The Environment Agency and National Infrastructure Commission (NIC) are working collaboratively. We would like a complementary model to the Long Term Investment Scenarios (LTIS), by looking at investment need using a different methodology. We would like a simpler, transparent methodology that estimates the trade-off between different flood management investment levels, and the standards of protection and other risk management activities that can be obtained for those different levels.

By way of background, the NIC's remit is in line with UK government competence, respecting devolved responsibilities. Flood risk responsibility is devolved so this work will only relate to England. Central to the NIC's role is the National Infrastructure Assessment – an assessment of major infrastructure needs on a 30-year time horizon. The quality of the evidence base underpinning the NIC's recommendations is a key consideration. The NIC must be able to demonstrate its recommendations are consistent with, and set out how they can be accommodated within, gross public investment in economic infrastructure of between 1.0% and 1.2% of GDP in each year between 2020 and 2050. The NIC also has an economic remit. When making recommendations the NIC should include a transparent assessment of the impact on costs to businesses, consumers, public bodies and other end users of infrastructure that would arise from implementing a proposal. The NIC's objectives include sustainable economic growth across the UK, the UK's international competitiveness and improving quality of life.

Outcome Specification

We want to understand the balance between different levels of flood investment and the protection that might be achieved between 2021 (the end of the current investment programme) and 2050. The analysis required will be finalised by the successful provider, EA and NIC through an inception phase – see appendix.

The EA has an existing model, LTIS, used to estimate long-term optimal flood and coastal risk management investment need for England. It estimates the net present value (NPV) for different levels of annual investment, and then finds the maximum NPV. LTIS 2014 estimated the optimum to be between £660m to £1bn per year, with a central estimate of about £850m. The EA is undertaking a work programme to build on and enhance the LTIS 2014 analysis. In contrast, we wish to understand the trade-offs between costs and standards of protection across a range of different values, to be able to inform comparisons between spend on flood risk management and on other infrastructure sectors, within the limits set by its fiscal remit. This includes consideration of how standards of flood protection might vary by settlement type but be set at a similar level within settlements of a given type (such as size, housing density or a similar parameter).

The Consultant should focus on the trade-off between standards of protection, other flood risk management activities and spend. E.g. what would it cost to protect 99% of properties in major cities up to a 0.5% or 1% annual chance of flooding (1:200 or 1:100) and 1% or 3.3% in smaller cities. Conversely, if flood spend was £800m/1bn/1.2bn per year, what standards of protection could be achievable up to 2050. This should cover all flood sources: rivers, sea, surface water, to a similar level of detail. The Consultant should estimate the benefits of the different standards of protection, in terms of the different types and numbers of properties protected as well as estimates of the benefits per property from improved protection.

It should enable consideration of a range of risk management activities: e.g. protection, spatial planning, flood incident management, property level resilience. The Consultant should cover all types of expenditure, including private and public sources. Distinguishing between capital and resource spend is essential, since the NIC's fiscal remit is defined in terms of public capital expenditure. Risk areas should be estimated quantitatively e.g. what is the land used for: how much infrastructure is present, how many residential properties, socially-deprived residential, agriculture. This will enable users of the model to transparently adjust damage value parameters, for different types of land use.

The Consultant should seek validation through information such as shoreline management plans, catchment flood management plans, local flood risk strategies, case studies. Quality assurance should be undertaken per best practice outlined in the Aqua Book. Results should be presented in the most simple, transparent form possible, this is likely to be a spreadsheet, to allow further analysis and adjustment of parameters. The Consultant should produce a report, that will be published, setting out methodology, data and key findings.

The Consultant shall complete the model such that it proves value for money to the Employer and results in economic efficiencies. The Consultant shall maximise positive environmental outcomes.

All costs and benefits should be presented in current values so that we can use the analysis to form a view on potential infrastructure investment programmes and will discount costs and benefits as appropriate.

The services specifically excludes the following:

a) Recommendations

b) General discussion about flood risk

c) Wales, Scotland and N. Ireland; unless lessons can be learned from their approaches.

2. Drawings, site information or reports already available

a) Environment Agency maps and data

3. Constraints on how the Consultant provides the services

The contract will be let to a single supplier, or supplier with subcontracting arrangements, that demonstrates they have the range of expertise required to complete all aspects of the work.

4. Services and other things provided by the Employer

a) The Environment Agency aims to provide flood risk data/maps.

Table A-1: Production and Delivery Table

Milestone	Description	Timeframe
1	Project inception meeting	By 6 November 2017
2	Plan within 3 working days of inception meeting, setting-out key milestones and dates for deliverables, risks and how these will be managed.	By 9 November 2017
3	Interim findings to be provided	By mid-January 2017
4	Results and final draft of final report to be submitted	By 28 February 2018

B Incorporating the Continuous Defence Line Processing into the FFE

This note sets out briefly the processing undertaken to incorporate CDL into the FFE.

The aims_subtype attribute is used to decide which features are taken forward in the analysis as laid out in the table below.

Table B-1: Defence attributes taken forward from the CDL

aims_subtype	Include in fluvial	Include in coastal
barrier_beach	No	Yes
beach	No	Yes
bridge_abutment	No	No
complex_culvert	No	No
demountable_defence	Yes	Yes
dunes	No	Yes
embankment	Yes	Yes
flood_gate	Yes	Yes
high_ground	No	No
NULL	No	No
simple_culvert	No	No
wall	Yes	Yes

The individual asset attributes current_sop (and if missing the design_sop) are sampled to the calculation areas as used in the CCRA, buffered to 3m, to try to ensure that the CDL lies within the polygon rather than falling outside its edge. The length weighted mean of current_sop (and if missing the design_sop) are used, ignoring NULLs.

For defended calculation areas (i.e. those with some defences to be included as in the table above), where a non-NULL current_sop is available for a calculation area, this is used.

If a non-NULL current_sop is not available, a non-NULL design_sop is used.

If neither current_sop or design_sop is non-NULL, then an average from other defended areas (weighted by residential property count) is assigned.

Condition grade is sampled to the calculation areas using length weighted averaging of the non-NULL overall_condition attribute.

Any NULL condition grades for defended areas are replaced with a residential property count weighted average (as for SoP). This is only necessary for a few tens of calculation areas, representing very little risk.

A Coastal CC Type is assigned to each individual asset within the CDL polyline, using the values in the table above. The beach, wall and embankment values correspond to the return period – SLR lookup tables for which climate change is defined. The beach/wall/embankment flag is then sampled to each coastal calculation area, by choosing the one that represents the longest length of defence.

The SoP, condition grade etc for each CCRA calculation area are sampled to the Census Calculation Areas (CCAs) which it covers for use in the FFE.

The length of raised defences and total length of shoreline intersecting with each CCA is calculated and written out, for use in the costing tool.

Finally the values sampled to CCAs are filtered to remove outliers; these are where CG<1 and SoP<1.

Results comparing the previous and new SoPs and CGs are shown in the plots below. They show a reasonable correlation between previous and new values; but with significant scatter.

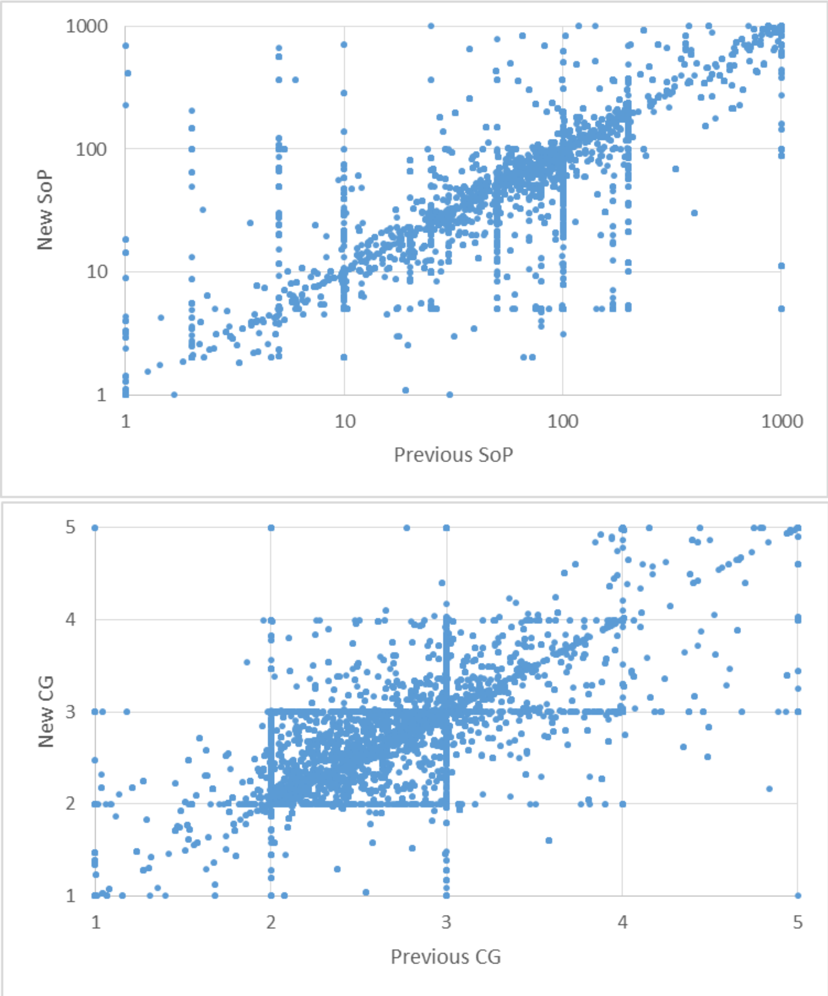


Figure B-1: Comparison of Standard of Protection and Condition Grade - Pre-CDL and Post-CDL

C Validation Process

C.1 Introduction and caveats

The commission was to produce a high level national scale tool (easier and faster to run than LTIS to enable alternative investments to be explored rapidly). The concept was to use a different methodology that could estimate England flood spend over 30 years, focusing on the trade-off between standards of protection and spend.

Expected outputs are the tool and supporting report on the evidence and approaches used in the tool (not a report on the application or results). The tool provided enables bespoke highly innovative broad scale analysis, focused on delivering results within a short timescale.

QA in the context of this rapid high level project has focused on the functionality of the tool and ensuring that the process of estimating future risks and costs is clear and faithfully reproduced.

C.2 Process

As the tool is bespoke for this project and has been developed iteratively in conjunction with the NIC, a formal standardised process for QA that would apply to commercial software based on the development of detailed specifications, unit tests and user acceptance testing, has not been possible or appropriate (it would have been too costly in this context of the project). Instead, we have focused on user testing within the team (including in collaboration with NIC and EA) on an individual and group basis as well as sense checking inputs and results.

C.3 QA queries and responses

C.3.1 Are the user inputs mapped correctly to the analysis engine?

There are many user controlled variables (adaptation and cost). Senior software staff have developed the tools and follow in-house version control process. Observed responses of the model have highlighted particular issues and these have been reviewed and addressed as they have raised:

- Insensitivity to the urban planning lever: Checked and corrected – tests highlight now responsive
- Insensitivity of cost to undefended areas: Checked and improved – tests highlight now responsive
- Insensitivity of different standards in undefended areas: checked and improved – tests highlight now responsive

C.3.2 Does the analysis provide the same result each time it is run with the same input?

Example control files have been re-run to ensure the analysis results are reproducible. This has been tested and is the case for those tested.

C.3.3 Does the batch server call the correct files and upload the correct files back to the server?

The batch service enables model runs to be queued and run overnight. This has been a useful addition and the process of drawing from the queue and re posting to the results has been tested to ensure file sets remains intact.

C.4 Independent review of the input costs

The base costs and approaches to costing have been reviewed with sector specialists where possible – for example with Barry Hankin (JBA) on the NFM levers, with Peter May (JBA) and Robbie Craig (Defra) on RLR costs and with the Environment Agency (Mike Steel and Rob Yarnall) on existing costs.

C.5 Validity of cost estimates generated by the tool

The QA process does not explicit refer to the accuracy of the risks. The accuracy of NaFRA has been actively debated for over 15 years and is difficult to determine. Projections of costs given climate and population are even more problematic. See Section 6.18.

C.6 Team review of overall tool functionality

Full day meeting in Wallingford in April 2018 introducing a new member to the JBA team (Peter Robinson) that had not been involved previously to undertake user testing.

C.7 Client scrutiny

We have held regular meetings to test and review progress and results. The client has also emailed interim results, as they emerged, to a wide group of experts for comments and review. Where possible these have been responded to.

C.8 Validation of the FFE

A detailed process of validation of the FFE was completed from the CCRA (https://www.theccc.org.uk/wp-content/uploads/2015/10/Appendix-G-Validity-of-present-day-and-future-risks-Final-06Oct2015.pdf)

It has not been possible to repeat this with the inclusion of the SoN - but basic tests have been undertaken to confirm existed present day risks are similar to those expected from the SoN. No change in the structure of the FFE has been made.

D Exploratory results

A wide range of model runs have been completed that explore the relationships between climate change, population growth and adaptation (Table D-1). Illustrative example results from these runs are given below with a brief narrative. Note, these results are included here for the illustration of the model outputs and are not a formal reporting of the results.

Table D-1: Basic summary of runs undertaken

Run name	Label	Epoch	Climate scenario	Population scenarios
Present_day	Present Day	PD	na	na
2050s_CLA_2c_PopB	2c LowP CLA	2050s	2c	B
2050s_CLA_4c_PopC	4c HighP CLA	2050s	4c	C
2050s_CLA_2c_PopB_Defences160	2c LowP CLA + 1.0% min (everywhere)	2050s	2c	B
2050s_CLA_4c_PopC_Defences350	4c HighP CLA + 1.0% min (everywhere)	2050s	4c	C
2050s_CLA_2c_PopB_Defences180	2c LowP CLA + 0.5% min (everywhere)	2050s	2c	B
2050s_CLA_4c_PopC_Defences270	4c HighP CLA + 0.5% min (everywhere)	2050s	4c	C
2050s_CLA_2c_PopB_Defences190	2c LowP CLA + 0.1% min (Urban conurbations)	2050s	2c	B
2050s_CLA_4c_PopC_Defences280	4c HighP CLA + 0.1% min (Urban conurbations)	2050s	4c	C
2050s_CLA_2c_PopB_Defences300	2c LowP CLA + 0.1% min (everywhere)	2050s	2c	B
2050s_CLA_4c_PopC_Defences310	4c HighP CLA + 0.1% min (everywhere)	2050s	4c	C
2050s_CLA_2c_PopB_Defences330	2c LowP CLA + 0.1% min (conurbations), 0.5% elsewhere (all)	2050s	2c	B
2050s_CLA_4c_PopC_Defences340	4c HighP CLA + 0.1% min (conurbations), 0.5% elsewhere (all)	2050s	4c	C
2050s_CLA_2c_PopB_Defences360	2c LowP CLA + 0.1% min (conurbations), 1% min (urban towns)	2050s	2c	B
2050s_CLA_4c_PopC_Defences370	4c HighP CLA + 0.1% min (conurbations), 1% min (urban towns)	2050s	4c	C
2050s_CLA_2c_PopB_Defences420	2c LowP CLA + 0.1% min (conurbations), 1% all other PD defended areas	2050s	2c	B
2050s_CLA_4c_PopC_Defences430	4c HighP CLA + 0.1% min (conurbations), 1% all other PD defended areas	2050s	4c	C
2050s_CLA_2c_PopB_Defences440	2c LowP CLA + 1.0% all PD defended areas	2050s	2c	B
2050s_CLA_4c_PopC_Defences450	4c HighP CLA + 1.0% all PD defended areas	2050s	4c	C
2050s_CLA_2c_PopB_Defences460	2c LowP CLA + 0.1% min (conurbations), 0.1% all other PD defended areas	2050s	2c	B
2050s_CLA_4c_PopC_Defences470	4c HighP CLA + 0.1% min (conurbations), 0.1% all other PD defended areas	2050s	4c	C
2050s_CLA_2c_PopB_Defences480	2c LowP CLA + 0.1% min (conurbations), 0.5% all other PD defended areas	2050s	2c	B
2050s_CLA_4c_PopC_Defences490	4c HighP CLA + 0.1% min (conurbations), 0.5% all other PD defended areas	2050s	4c	C
2050s_CLA_2c_PopB_Defences600	2c LowP CLA + 0.5% min (minor conurbations) and Urban cities and towns	2050s	2c	B
2050s_CLA_4c_PopC_Defences610	4c HighP CLA + 0.5% min (minor conurbations) and Urban cities and towns	2050s	4c	C
2050s_CLA_2c_PopB_Defences620	2C LowP CLA + 0.5% all PD defended areas	2050s	2c	B
2050s_CLA_4c_PopC_Defences630	4C HighP CLA + 0.5% all PD defended areas	2050s	4c	C
2050s_CLA_2c_PopB_Defences640	2C LowP CLA + 0.1% all PD defended areas	2050s	2c	B
2050s_CLA_4c_PopC_Defences650	4C HighP CLA + 0.1% all PD defended areas	2050s	4c	C
2050s_CLA_2c_PopB_Defences660	2C LowP CLA + 1.3% all PD defended areas	2050s	2c	B
2050s_CLA_4c_PopB_Defences670	4C HighP CLA + 1.3% all PD defended areas	2050s	4c	C
2050s_CLA_2c_PopB_Defences680	2C LowP CLA + 0.1% (urban) and 1% elsewhere PD defended areas	2050s	2c	B
2050s_CLA_4c_PopC_Defences685	4C HighP CLA + 0.1% (urban) and 1% elsewhere PD defended areas	2050s	4c	C
2050s_CLA_2c_PopB_Defences690	2C LowP CLA + 0.1 - Urban defended	2050s	2c	B
2050s_CLA_4c_PopC_Defences700	4C HighP CLA + 0.1 - Urban defended	2050s	4c	C
2050s_CLA_2c_PopB_Defences710	2C LowP CLA + 0.1 - Urban + 0.5% defended elsewhere	2050s	2c	B
2050s_CLA_4c_PopC_Defences720	4C HighP CLA + 0.1 - Urban +0.5% defended elsewhere	2050s	4c	C
2050s_CLA_2c_PopB_Defences730	2C LowP CLA + 0.1 - Urban + 1% defended elsewhere	2050s	2c	B
2050s_CLA_4c_PopC_Defences740	4C HighP CLA + 0.1 - Urban + 1% defended elsewhere	2050s	4c	C
2050s_CLA_2c_PopB_Urban05	2c LowP Cla + Improved urban man	2050s	2c	B
2050s_CLA_2c_PopB_Urban10	2c LowP Cla + Improved urban man	2050s	2c	B
2050s_CLA_2c_PopB_Urban20	2c LowP Cla + Improved urban man+	2050s	2c	B
2050s_CLA_2c_PopB_Urban30	2c LowP CLA + Improved urban man++	2050s	2c	B
2050s_CLA_4c_PopC_Urban30	4c High CLA + Improved urban man++	2050s	4c	C
2050s_EWS_2c_PopB	2c LowP EWS	2050s	2c	B
2050s_EWS_4c_PopC	4c HighP EWS	2050s	4c	C
2050s_EWS_2c_PopB_Defences05	2c LowP EWS+1% in selected urban towns	2050s	2c	B
2050s_EWS_4c_PopC_Defences05	4c HighP EWS+1% in selected urban towns	2050s	4c	C
2050s_EWS_2c_PopB_Defences10	2c LowP EWS + 0.5% (min in urban towns) and selected 1%/0.5% elsewhere	2050s	2c	B
2050s_EWS_4c_PopC_Defences10	4c HighP EWS + 0.5% (min in urban towns) and selected 1%/0.5% elsewhere	2050s	4c	C
Tests				
2050s_CLA_2c_PopB_Defences195	2c LowP CLA + 0.1% min (Major urban conurbations only)	2050s	2c	B

The following figures are structure to provide insight into the range of outputs from the analysis. They are non-exhaustive, with many other variable (cost and risk) readily extracted.

D.1 Cost estimates

These are presented in Figure D1 to D2 (including expenditure profiles, annual average spends and Present Value) and show the significant increase in costs associated with continuing to provide present day standards of protection in a 4ºC future, and the significant costs associated with attempting to provide a common standard of protection to all areas (a finding that reflects previous studies)

D.2 Future risks

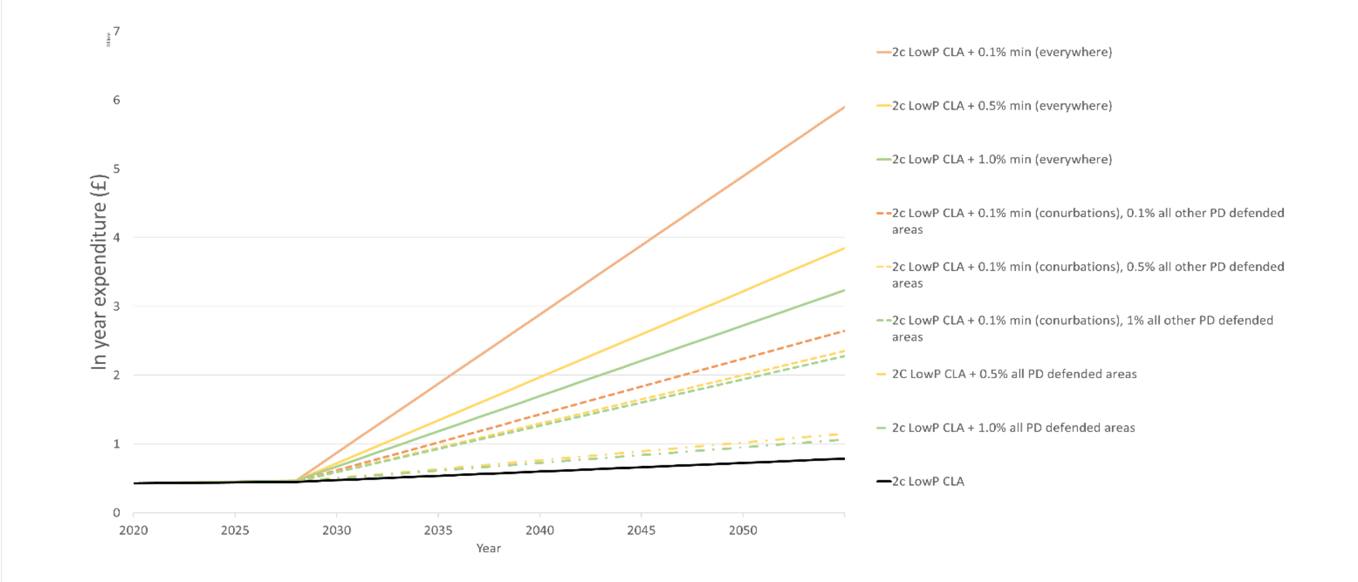
Figures D1 to D2 present series of figures representing the change in:

- Expected Annual Damages (EAD)
- Expected Annual (all) Properties flooded (EAP, as defined by Sayers et al, 2017),
- Distribution of properties at risk across multiple bands.

The results are shown for selected adaptation futures and highlight that a continuation of current levels of adaptation will not be sufficient to manage future risks under a 4ºC future. Significant defence improvements or a more broadly-based adaption approach (based on an enhanced Whole Systems adaptation paradigm, Sayers et al, 2015) will be needed.

Note: the results here are presented in the context of settlement type. The underlying analysis takes place at a much smaller spatial scale.

Public capital expenditure estimates of flood resilience - 2C, low population future



Public capital expenditure estimates of flood resilience - 4C, high population future

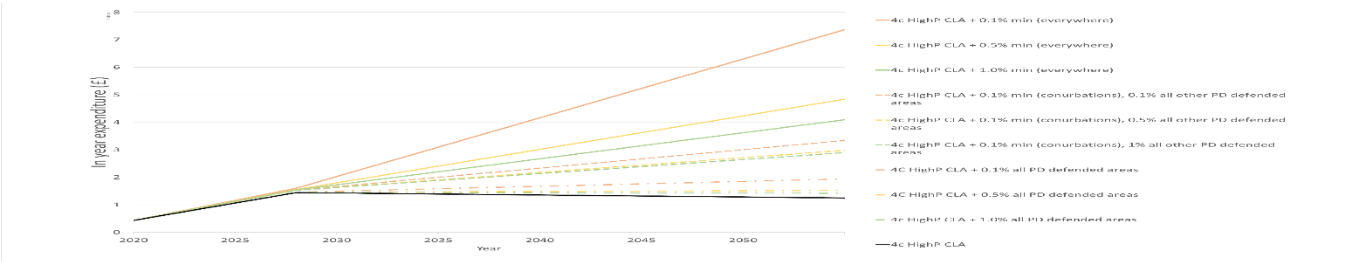
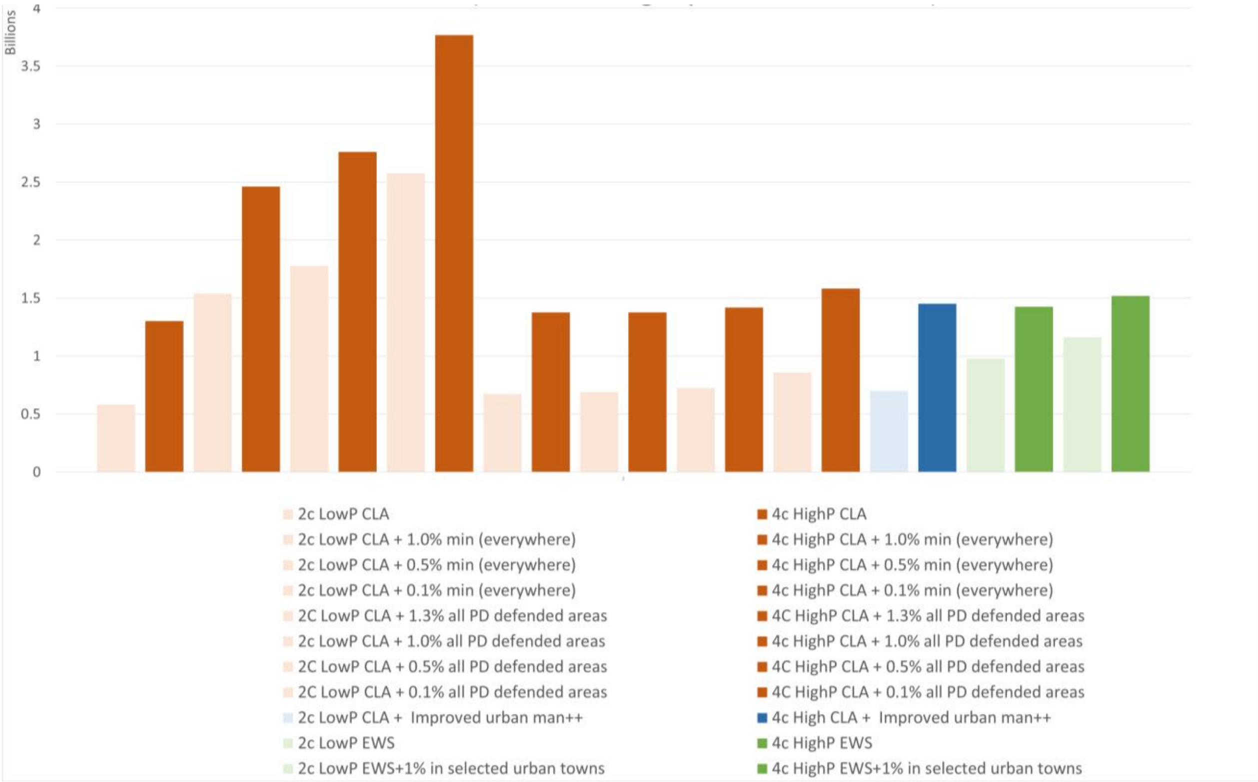


Figure D-1: Public capital estimates

Public capital spend (annual average spend - 2020s-2050s)



Public capital spend (annual average spend - 2020s-2050s)

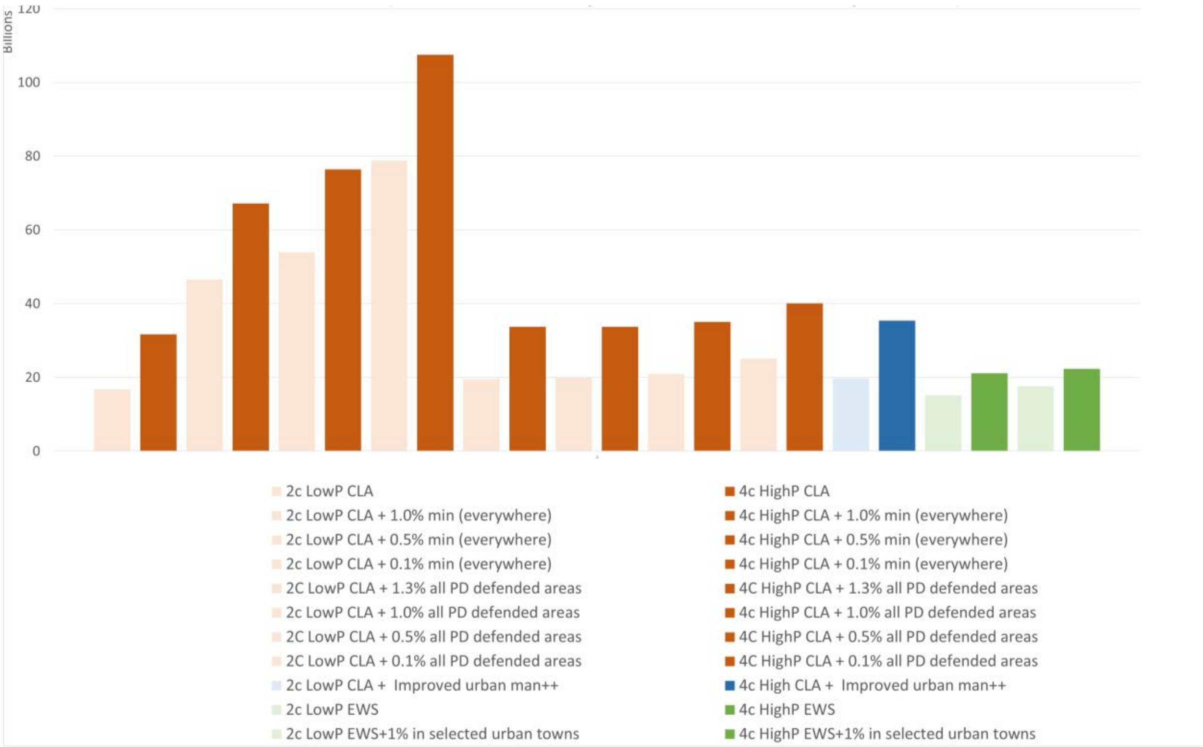
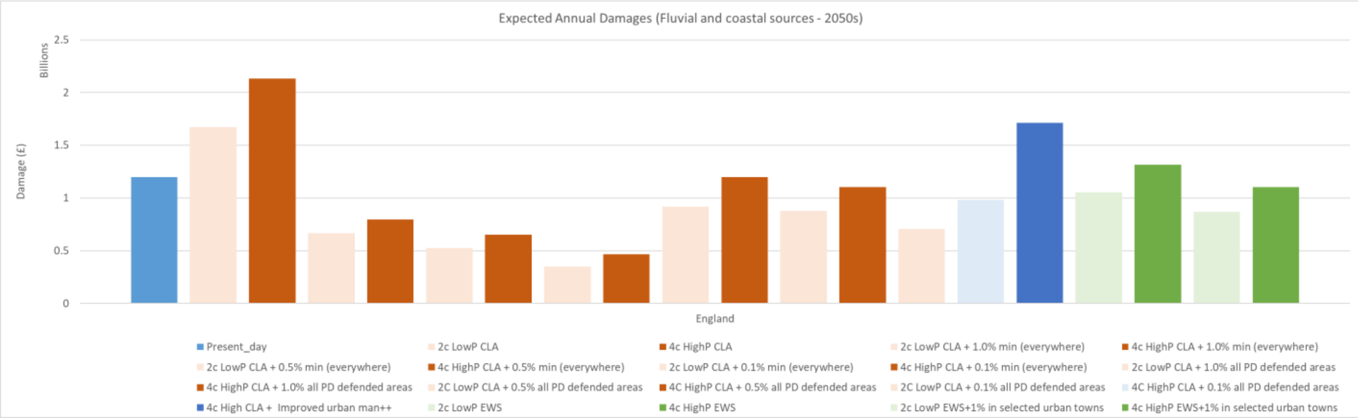
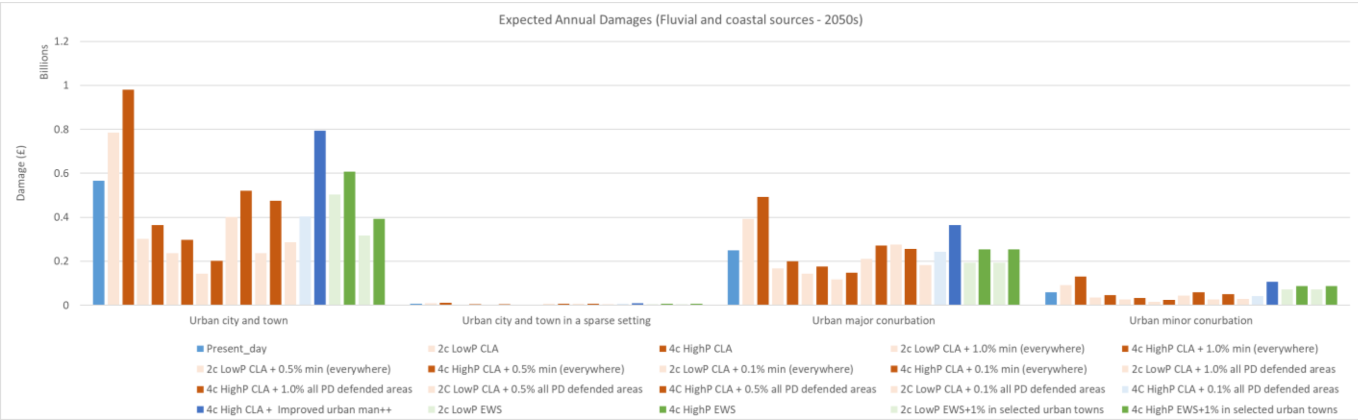


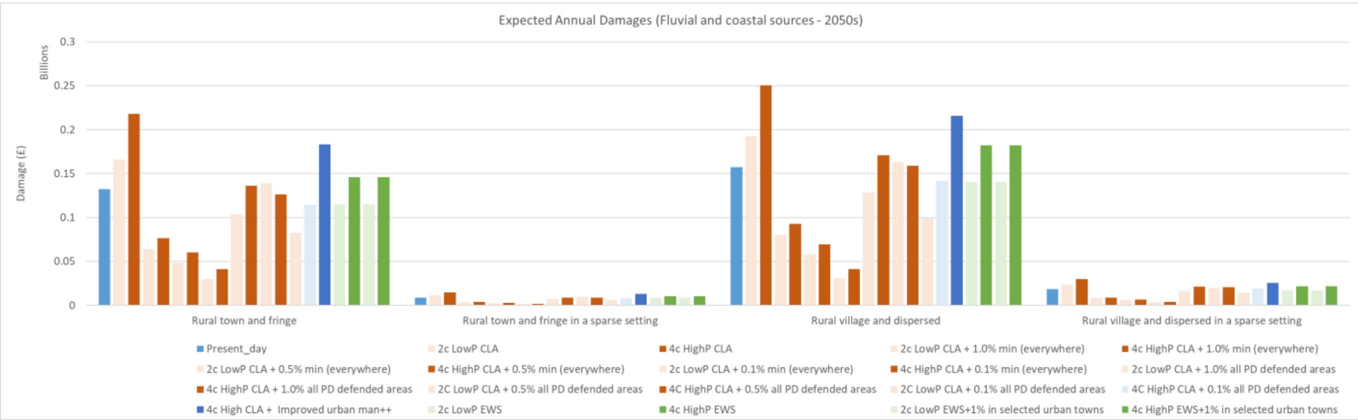
Figure D2: Public capital expenditure: Present value and annual average expenditure



England

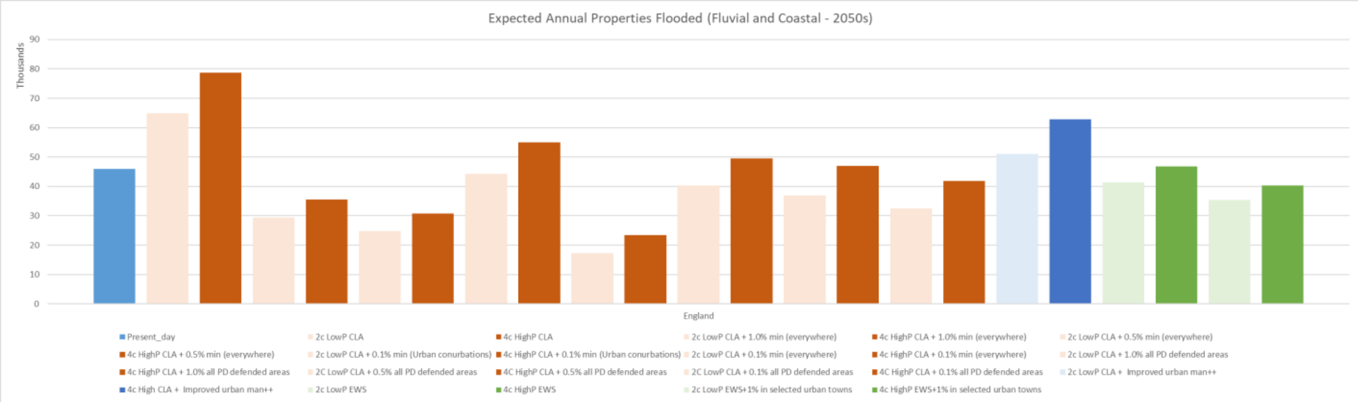


Urban settlements

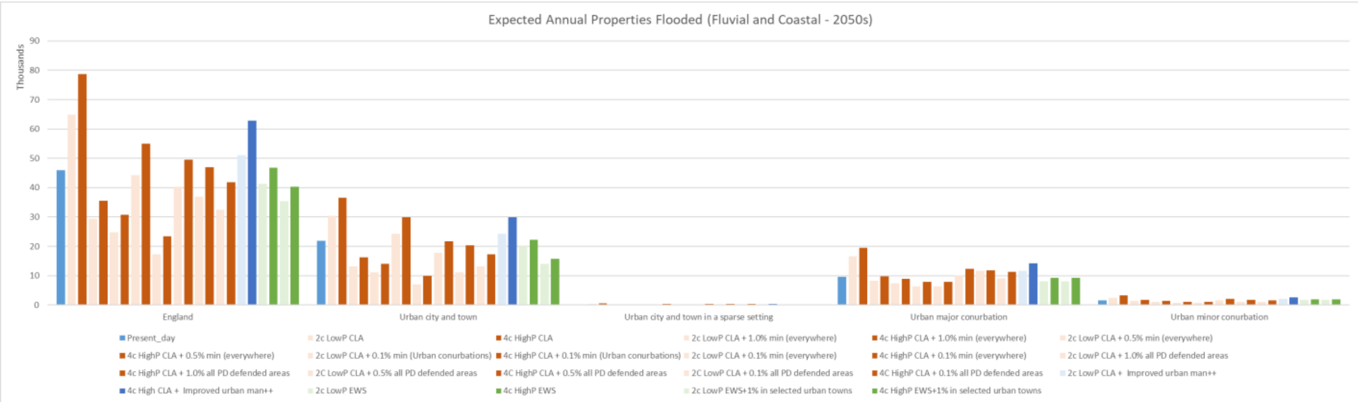


Rural settlements

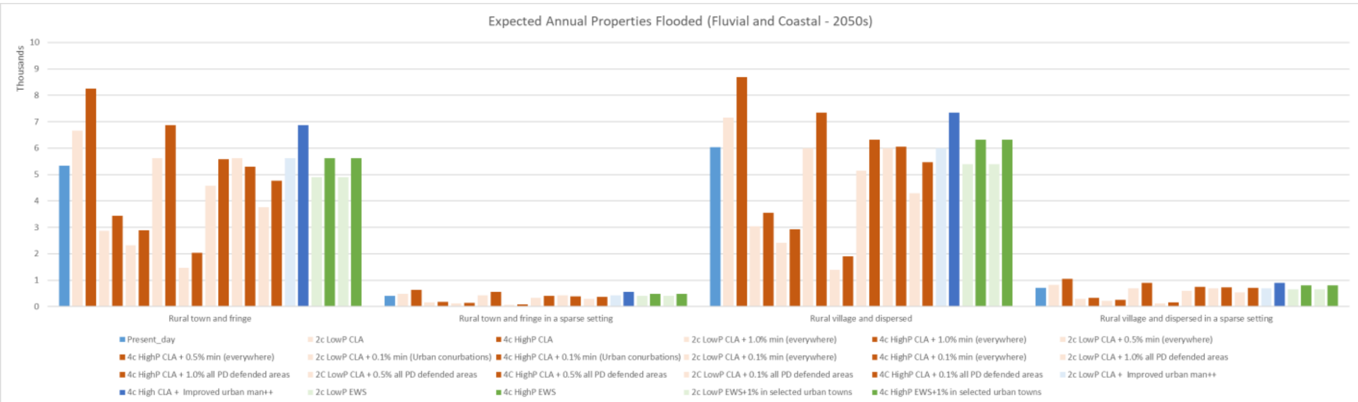
Figure D3: Fluvial and coastal EAD by England, Urban and Rural settlements



England

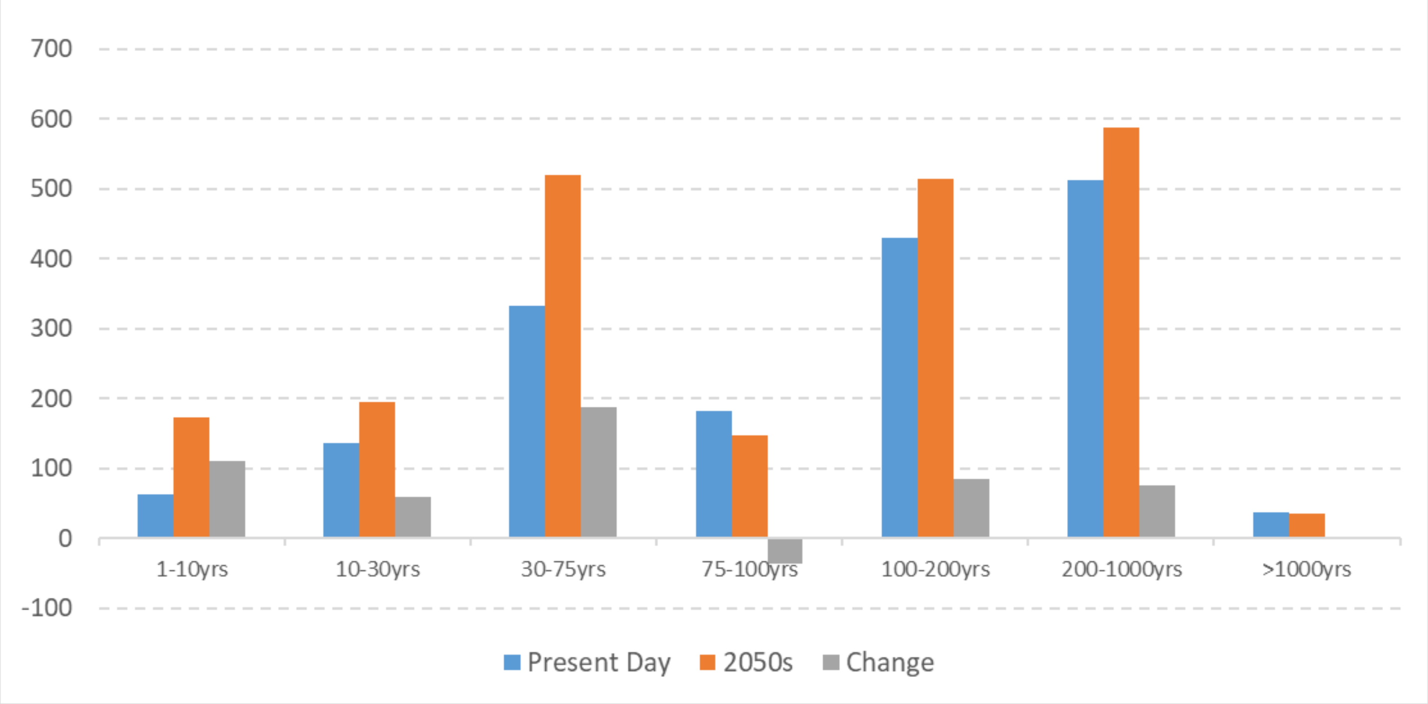


Urban settlements

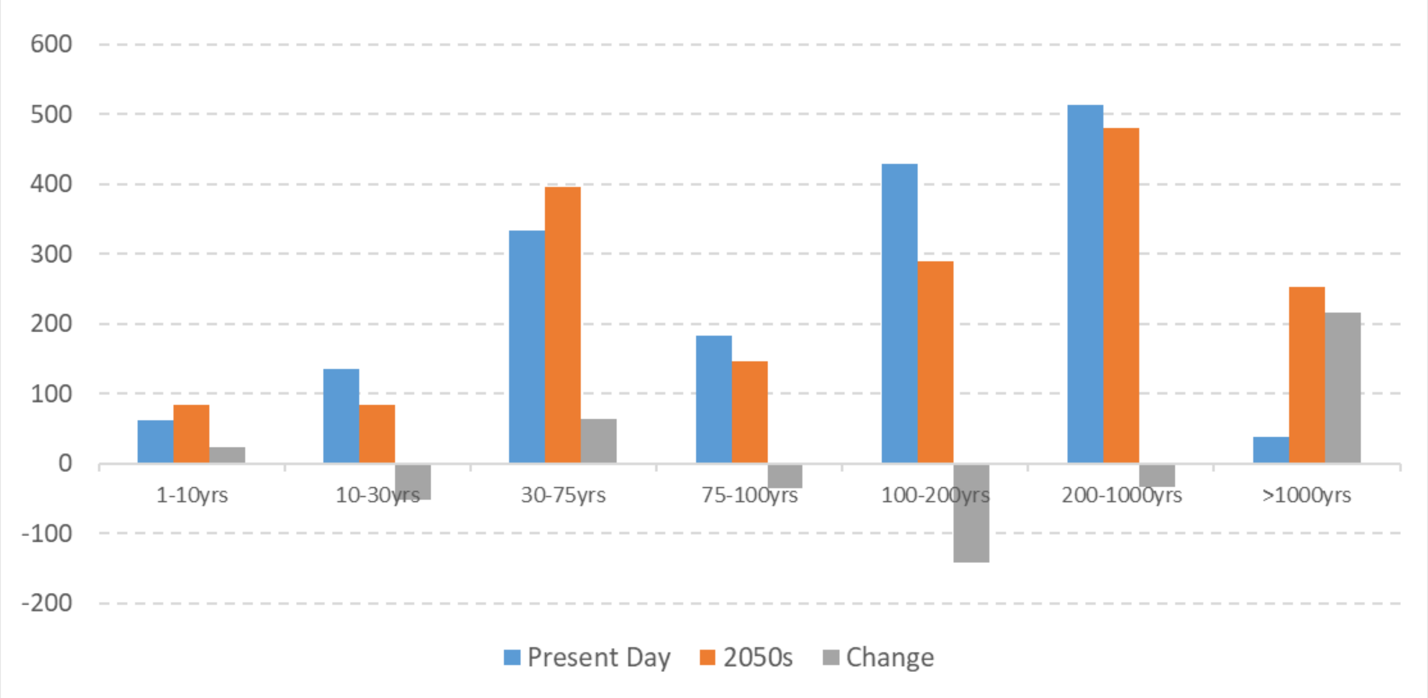


Rural settlements

Figure D4 - Fluvial and coastal EAD by England, Urban and Rural settlements

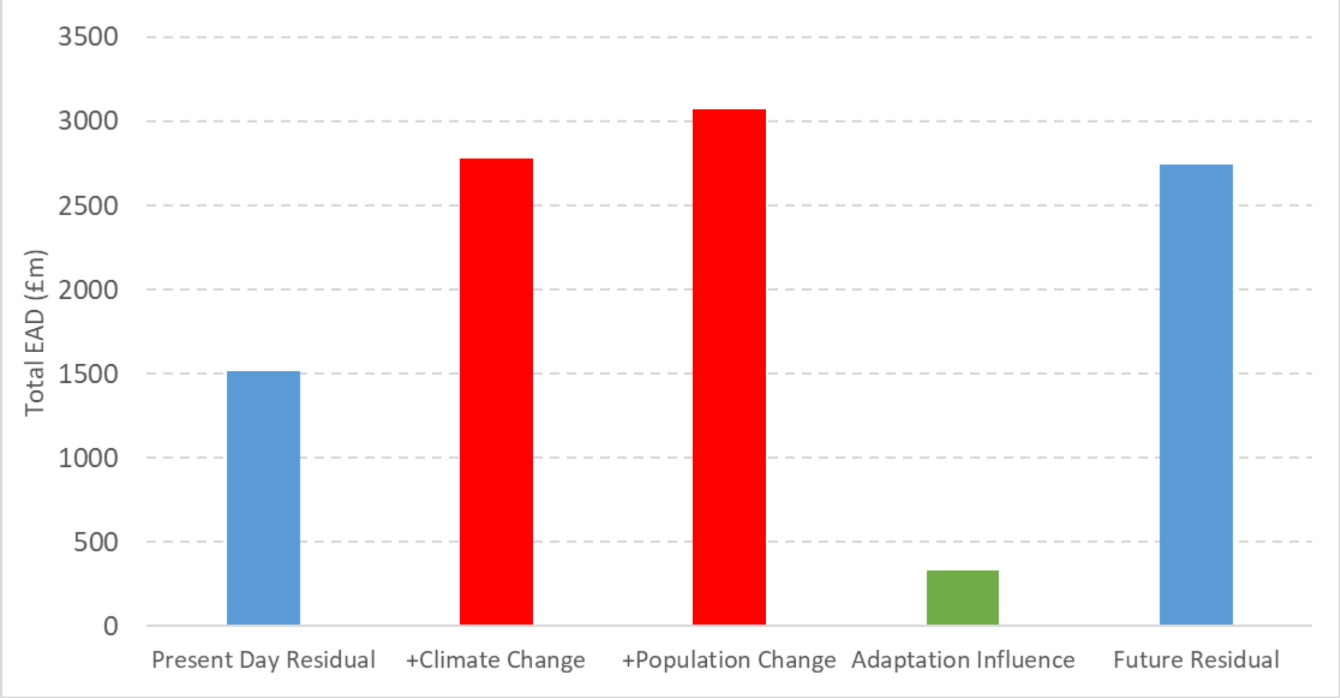


Fluvial and coastal - Given a 4ºC future and high population growth, assuming a continuation of current levels of adaptation (England)

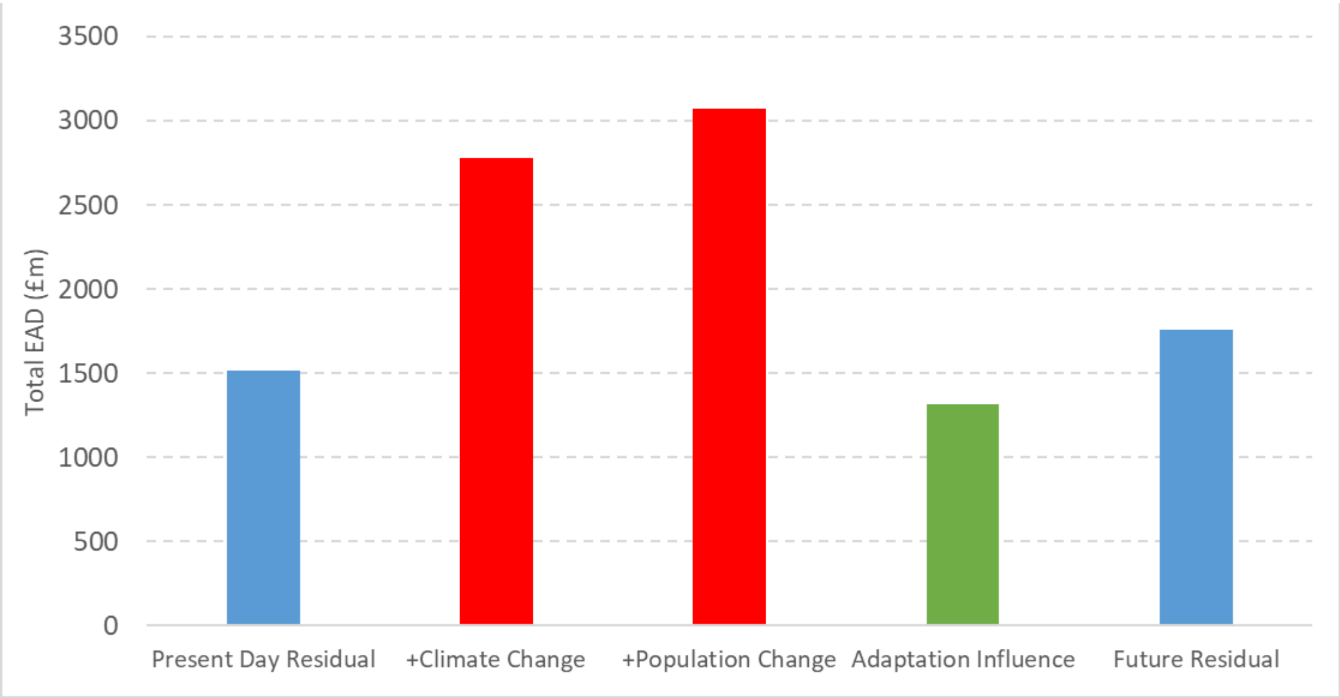


Fluvial and coastal - Given a 4ºC future and high population growth, assuming an enhanced whole system adaptation (England)

Figure D5 - Distribution of properties in 000s by probability of flooding

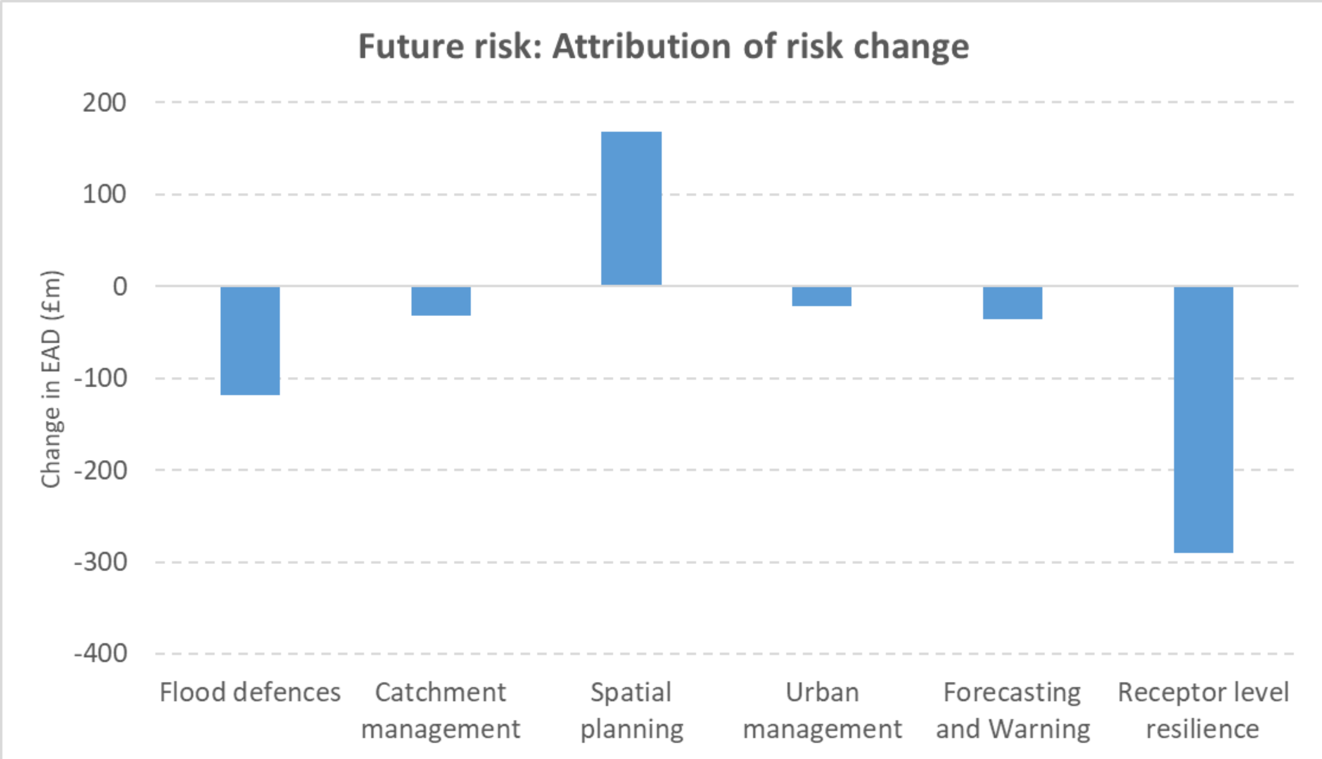


All sources - Given a 4ºC future and high population growth, assuming a continuation of current levels of adaptation (England)

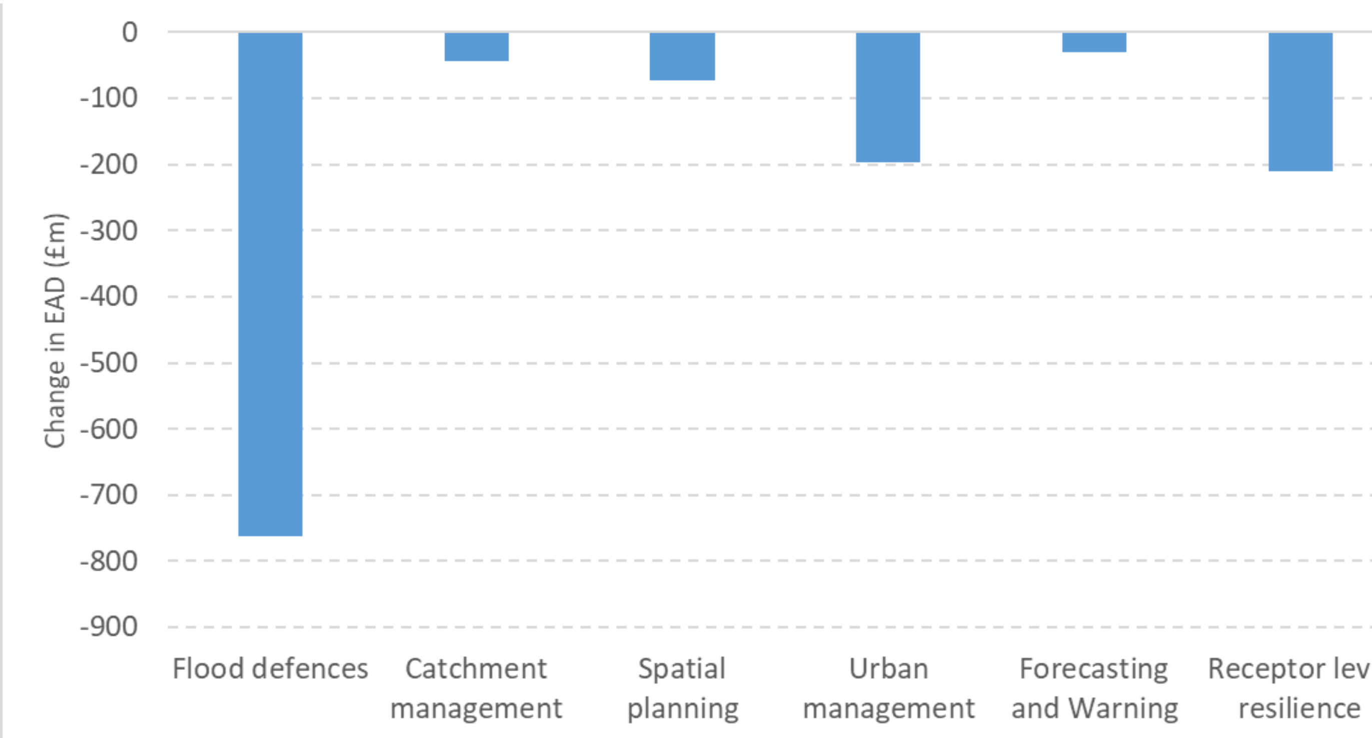


Fluvial and coastal - Given a 4ºC future and high population growth, assuming an enhanced whole system adaptation (England)

Figure D-6: Example output from the Future Flood Explorer risk analysis

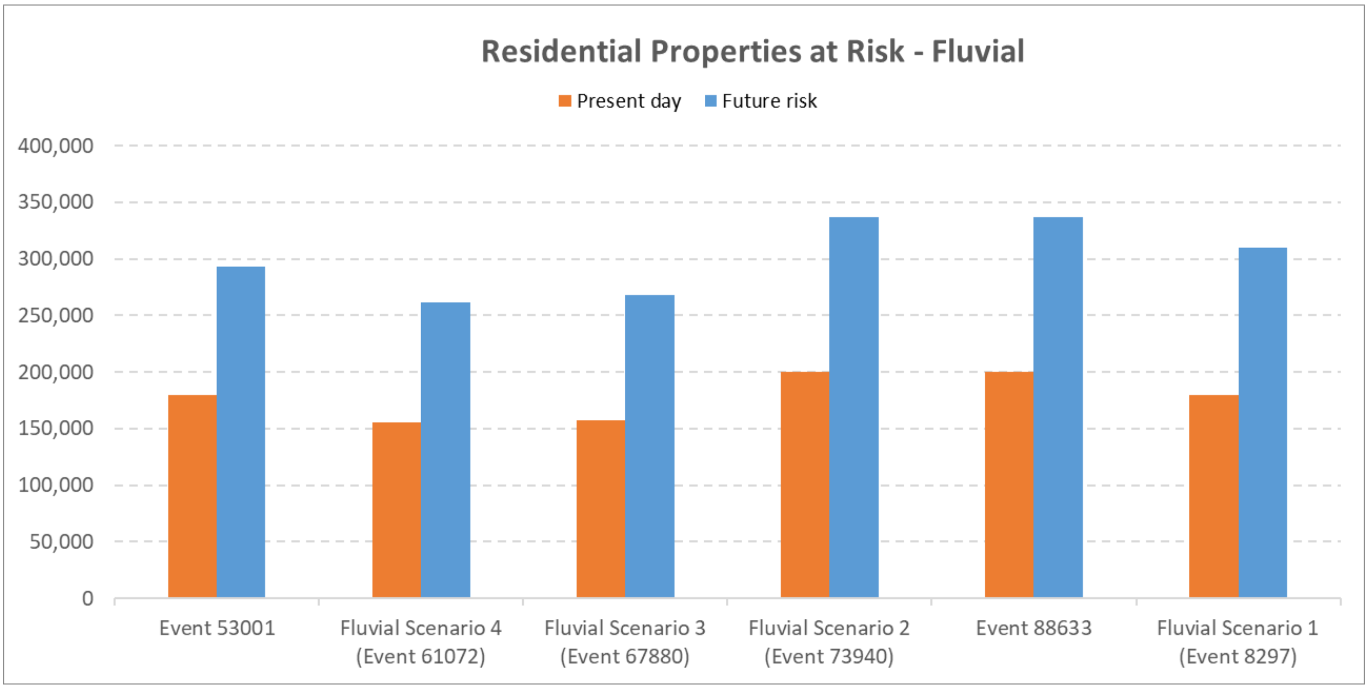


All sources - Given a 4ºC future and high population growth, assuming a continuation of current levels of adaptation (England)

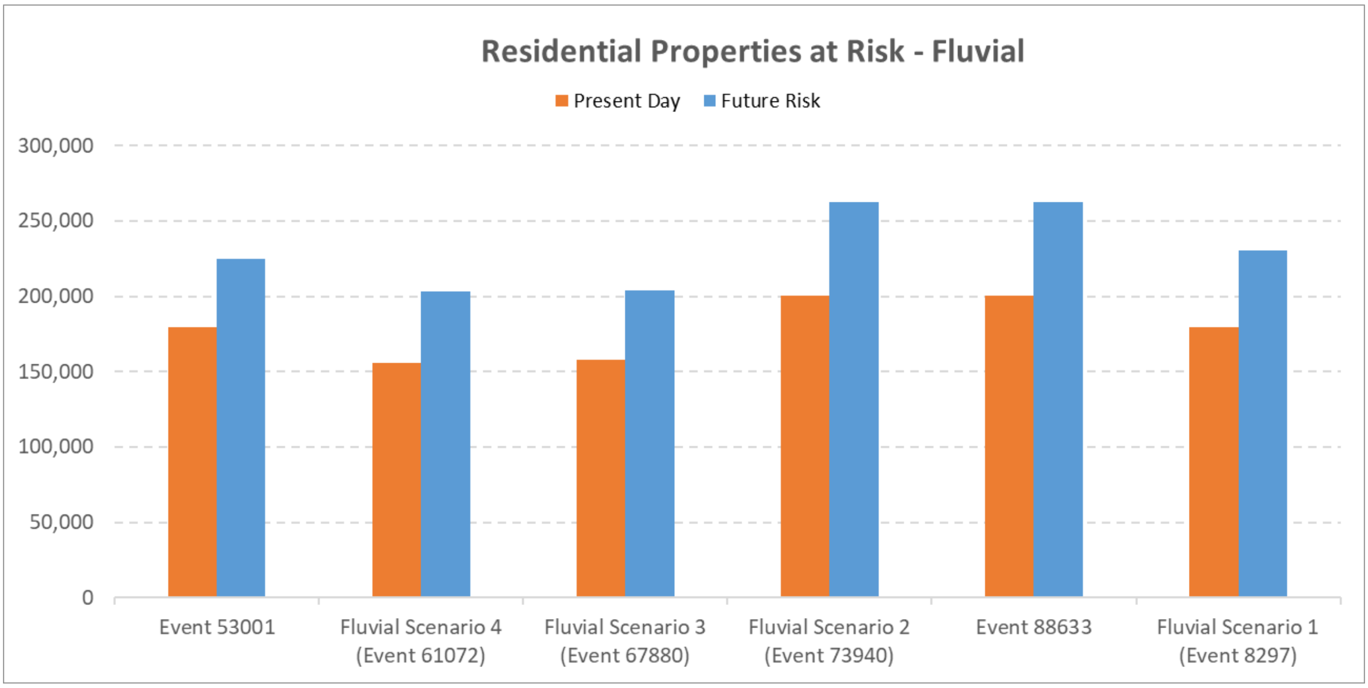


All sources - Given a 4ºC future and high population growth, assuming an Enhanced Whole System adaptation (England)

Figure D7: Future risk: Attribution of adaptation contribution to risk management

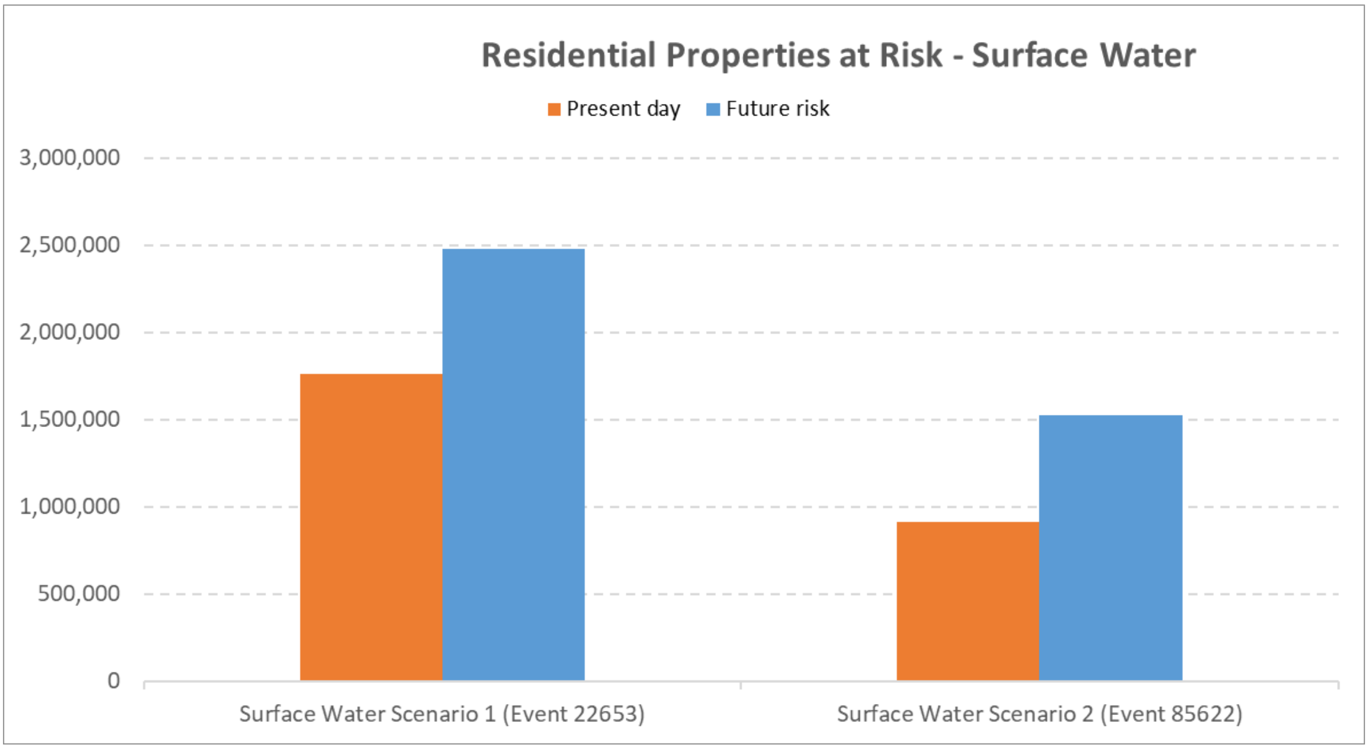


Continuation of current level of adaptation

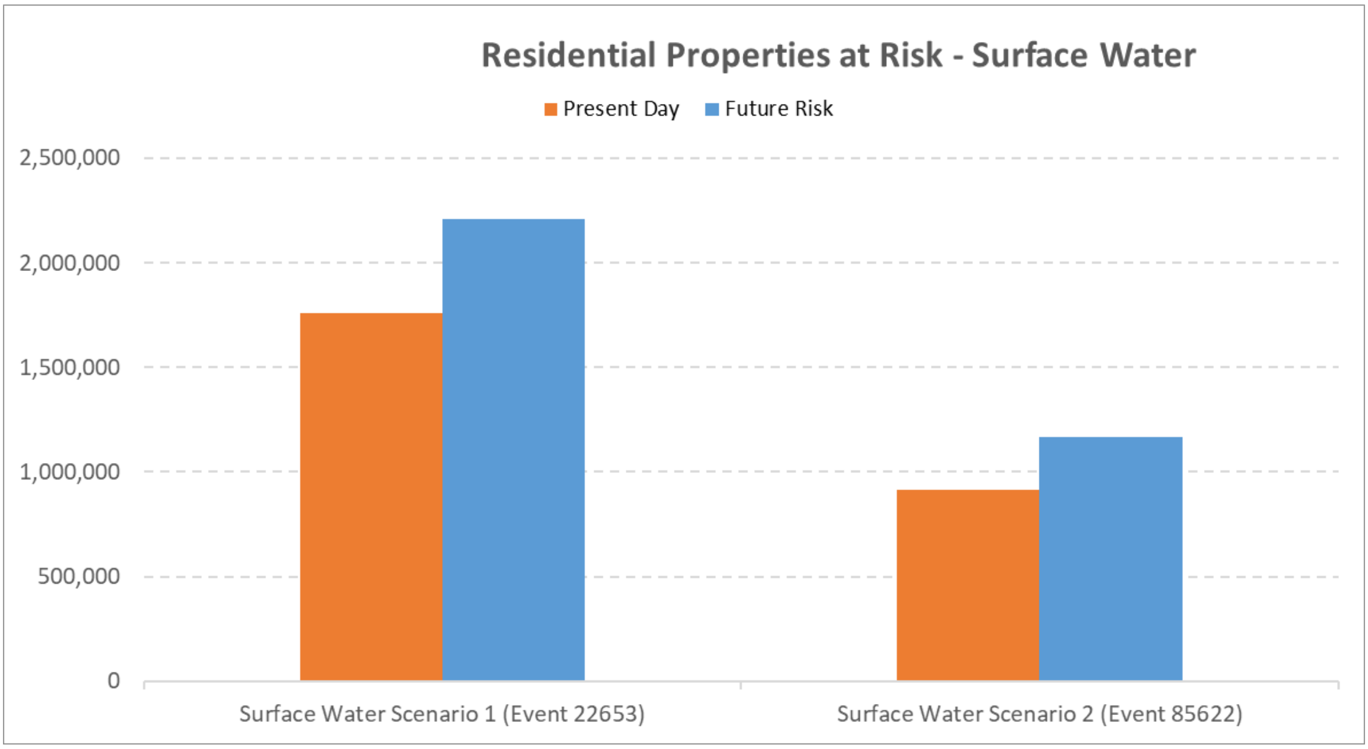


Enhanced Whole System adaptation

Figure D-8: - Changing impact of (credible) extreme fluvial widespread events under a 4ºC, high population future



Continuation of current level of adaptation



Enhanced Whole System adaptation

Figure D-9: Changing impact of (credible) extreme surface water widespread events under a 4ºC, high population future

Figure D-10: Comparing the future changes in risk and role of adaptation

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