

## Oxford to Cambridge Arc flood risk investment study - summary report

Revision no: 3

Environment Agency

Oxford to Cambridge Arc flood risk investment study  
26 April 2022

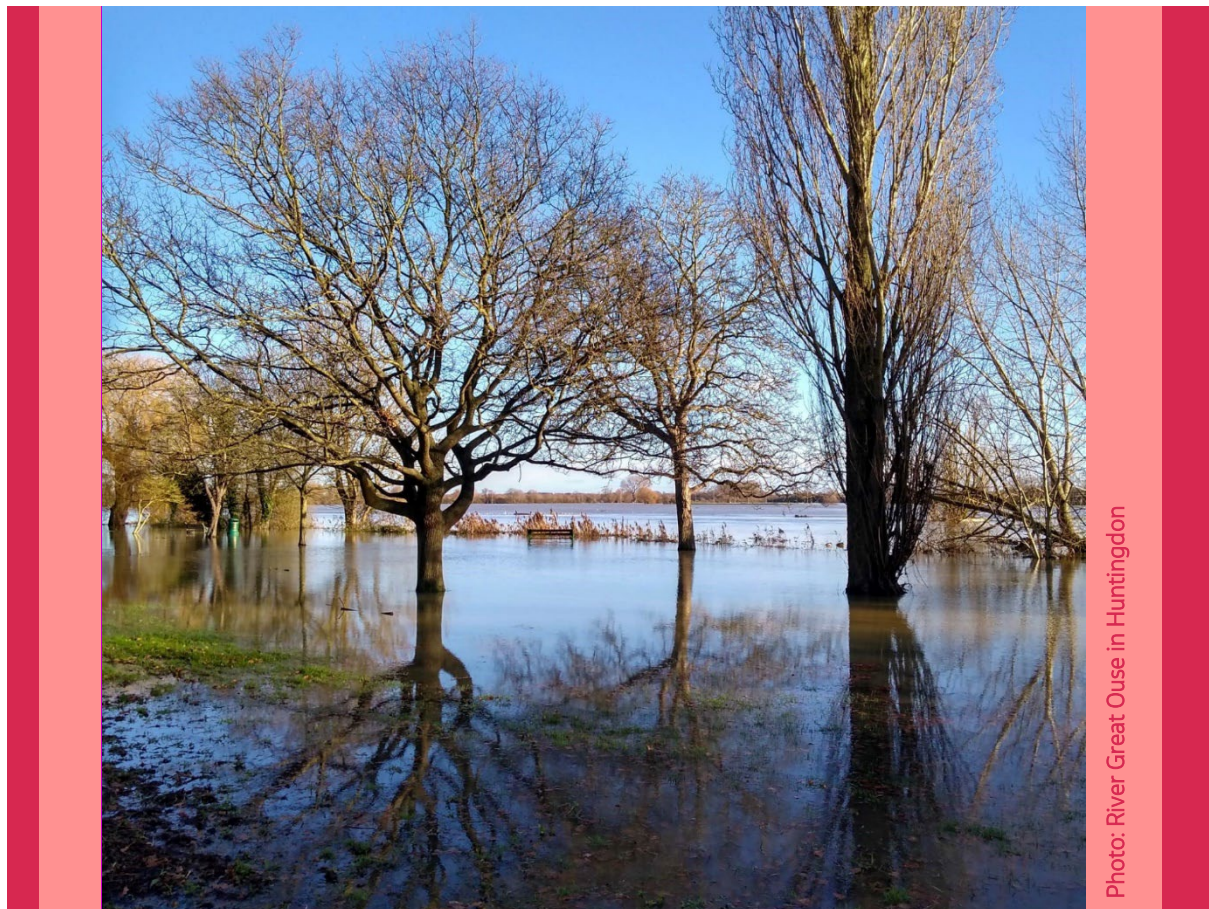


Photo: River Great Ouse in Huntingdon

## Oxford to Cambridge Arc flood risk investment study - summary report

**Client name:** Environment Agency

**Project name:** Oxford to Cambridge Arc flood risk investment study

**Revision no:** 3

**Project manager:** Daniel Boyd

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**Prepared by:** Joe Clarke

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## Executive summary

The Oxford-Cambridge Arc (OxCam) is home to nearly 4 million people and supports 2 million jobs, and it is estimated that 1 million new homes would be needed over just 30 years to help the region meet its economic potential. The region also spans significant parts of three major river catchments – the Thames, Nene and Great Ouse.

This project is a pilot study to develop the evidence to answer one key question (from a primarily economic perspective), in a way which reflects the uncertainty in how climate change and development will affect risk over time and which enables adaptive future decision-making:

**What is the optimum level and timing of investment in flood risk management?**

We represented flood risk for present day and a range of future scenarios (with 18 core climate change and development scenarios), quantified economic impacts under each future for a range of impact types, and represented the costs (including carbon) and risk reduction benefits of a portfolio of interventions. This data fed into a real options analysis optimisation to find the optimal level and timing of investment that is robust under the 18 possible futures. Our overall approach to delivering the study comprised six key stages:

1.  
Representing  
flood risk

2.  
Representing  
future  
scenarios

3.  
Representing  
flood  
interventions

4.  
Quantifying  
flood impacts  
and benefits

5.  
Quantifying  
costs and  
carbon

6.  
Optimising  
the level and  
timing of  
investment

### Properties at risk

**83,000**

present day

**130,000 – 183,000**

2050, without new investment

We found that there are currently 83,000 properties currently at risk from a 1% annual exceedance probability (AEP) event, which could increase to between 130,000 and 183,000 by 2050.

### Annual average damage

**£1.94 billion**

present day

**£2.73 – £3.91 billion**

2050, without new investment

We estimate that present day annual average damage from rivers and surface water (across the range of impact categories included in the analysis) is £1.94 billion, which could increase to between £2.73 and £3.91 billion by 2050 if there were no new investment.

### Optimum investment

**£5.63 billion**

100 year present value investment

**£1.21 billion**

capital investment which is cost beneficial independent of future changes in risk

We estimate that the optimum present value level of investment (over 100 years) in flood risk management for the OxCam Arc is £5.63 billion, but this could be between £4.63 and £6.20 billion depending on future risk. This equates to an average of £177 million annual investment (between £140 and £206 million depending on future risk) – but a significant proportion of this investment (£1.21 billion capital investment, £2.11 billion including carbon and maintenance costs) is cost beneficial now, i.e. is not dependent on future increases in risk.

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## 1. Introduction

### 1.1 The Oxford to Cambridge Arc

The Oxford-Cambridge Arc (also referred to as the OxCam Arc, OxCam or simply 'the Arc') is a 'strategic belt' spanning the ceremonial county areas of Oxfordshire, Buckinghamshire, Northamptonshire, Bedfordshire and Cambridgeshire (Ministry of Housing, Communities and Local Government, 2019), shown in Figure 1.1.



Figure 1.1. Location of the OxCam Arc in the UK.

OxCam is home to nearly 4 million people and supports 2 million jobs, and it is estimated that 1 million new homes would be needed over just 30 years to help the region meet its economic potential. Alongside that growth comes significant investment in infrastructure.

The region also spans significant parts of three major river catchments – the Thames, Nene and Great Ouse. Figure 1.2 shows how the OxCam Arc (green) overlaps with the catchments (blue with white borders) – and the areas of the catchments which extend beyond the reach of the Arc itself.



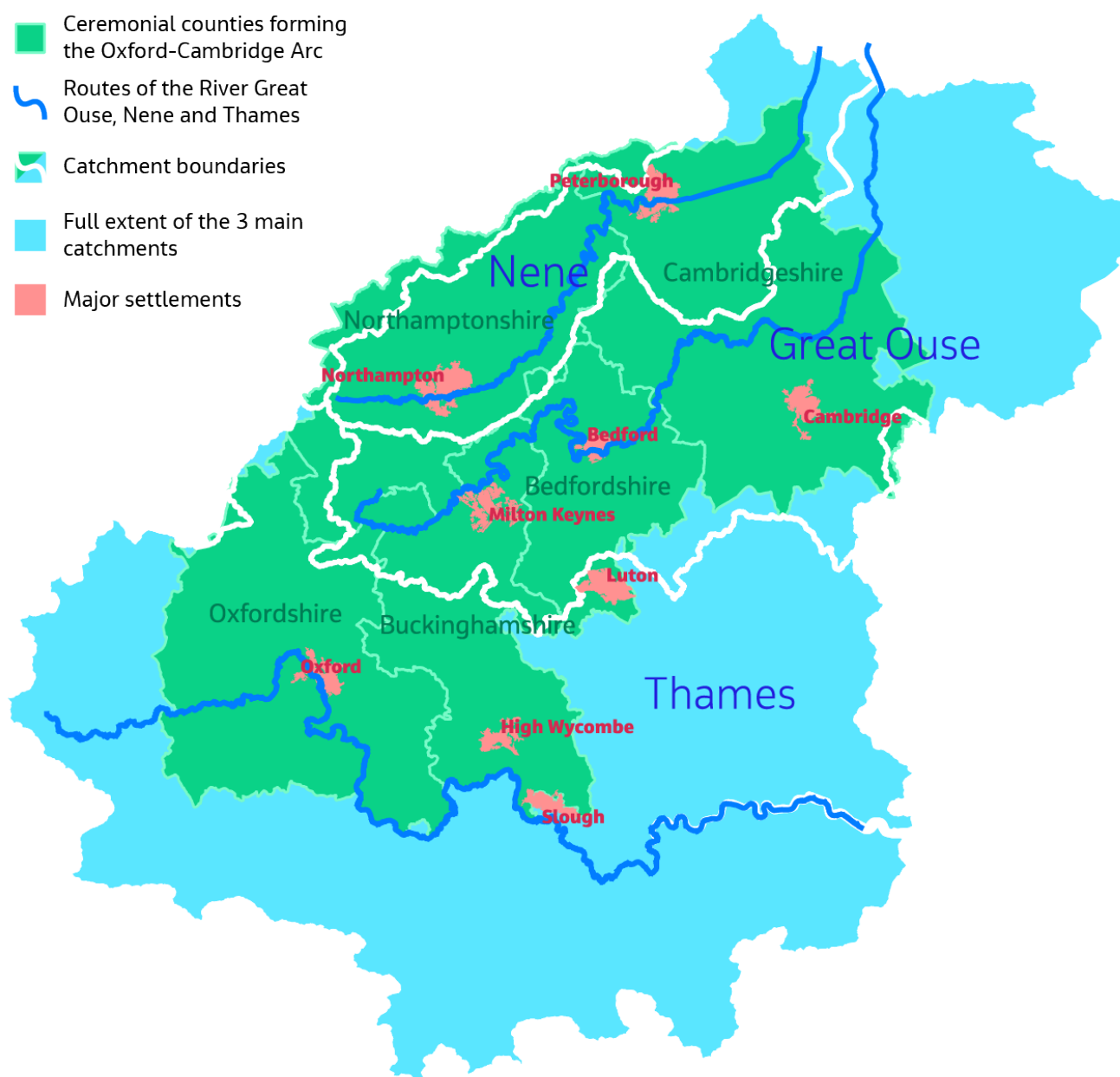


Figure 1.2. OxCam Arc: ceremonial county boundaries (green), catchments (blue/white) and major settlements (pink).

## 1.2 Purpose of the study

This project is a **pilot study** to develop the evidence to answer one key question (from a primarily economic perspective):

**What is the optimum level and timing of investment in flood risk management?**

In the OxCam Arc, there is significant uncertainty in how flood risk could change over time – as a result of both climate change and of the substantial levels of development that could take place. Within the context of this study as an economic evidence study, we have therefore considered how to marry **economic optimisation** and **adaptation**. To do this, we have developed a modelling evidence base to enable economic analysis to support an **adaptive optimisation**, that considers a portfolio of interventions at different points in time.

The purpose of this study is to build an evidence base to support the Environment Agency in engaging with and influencing national and local stakeholders, and to ensure that the value of flood resilience investment

can be maximised to support the OxCam Arc in its rapid economic growth. Key stakeholders include HM Treasury, the Ministry of Housing, Communities and Local Government, Local Authorities across the Arc, Homes England and the Infrastructure Projects Authority.

There are a number of core threads running through this project (Figure 1.3):

Representing future risk	Portfolio of interventions	Adaptive optimisation
Understanding and quantifying future changes in risk, as a result of both climate change and possible future development, through flood and development scenario modelling.	Exploring the costs and benefits of a portfolio of responses to take a catchment-scale approach to managing flood risk.	Optimising investment to ensure that it is robust across the range of possible futures and that adaptive decisions can be made as future risk unfolds.

Figure 1.3. Core threads of the project.

This study has generated a large quantity of useful data that through rich analysis explores the costs and benefits, including consideration of wider impacts such as unlocking land for future development through investments in flood resilience. The analysis has been carried out under a range of future scenarios, which provides evidence to answer a number of important questions about flood resilience investment across the OxCam Arc. In particular, it helps us to understand how optimal investment may change (in time, space and absolute terms) under different future scenarios, and what that can tell us about the robustness and flexibility of investment decisions made over the next 30 years.

It is important to note that the Thames, Nene and Great Ouse all have active catchment-scale projects exploring in more detail the management of flood risk in each catchment. This study is intended to complement those more detailed studies by providing a higher-level view across the whole OxCam Arc and a wider portfolio of interventions, but steering clear of making recommendations of the precise location and nature of those interventions.

## 1.3 Reports

This **summary report** provides an overview of the full study, the approaches taken and the findings. It is accompanied by a series of technical reports, which provide technical detail about specific aspects of the approach:

1. **Modelling and hydrology technical report:** Describing the approach to modelling, including representation of flood storage, natural flood management, linear defences and surface water flood risk management.
2. **Economic analysis technical report:** Describing the economic analysis, including our approach to quantifying costs, impacts and carbon. This report also describes the representation of property flood resilience interventions.
3. **Adaptive approaches and optimisation technical report:** Describing the decision-tree analysis which underpins our optimisation and adaptive analysis.

## 2. Approach

### 2.1 Overall approach

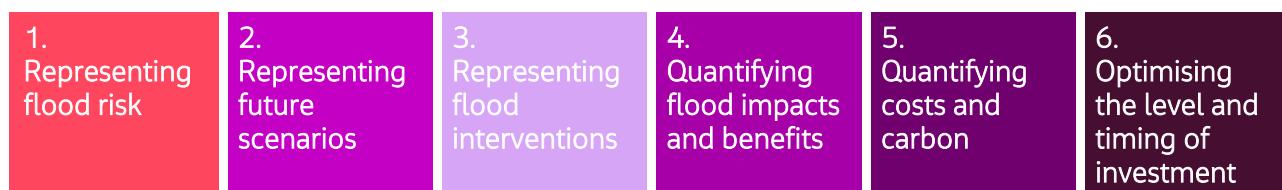


Figure 2.1. Steps in our approach.

Our overall approach (Figure 2.1) has been to represent flood hazard for present day and future climate change scenarios using a library of flood simulations and existing flood hazard data. This is linked to a library of water level information and representing the benefits of flood interventions with a range of methods appropriate to the type of intervention (and the costs using unit cost models). We have quantified economic flood impacts for a range of impact types for each of those simulations, and to represent the benefits of flood interventions. These feed into an optimisation approach which reflects the need for adaptation in response to future changes in risk, to derive an optimal level and timing of investment that is robust to future changes in risk.

<b>1. Representing flood risk</b> Creating a simulation library of flood scenarios, with 2D flood modelling to represent the risk of flooding from rivers. Representing surface water flood risk using existing national surface water flood maps.	<b>2. Representing future scenarios</b> Representing future changes in risk through 3 climate change scenarios over the next 100 years, plus 3 different shapes and 3 rates of future development over the next 30 years, forming 27 possible futures.	<b>3. Representing flood interventions</b> Representing a portfolio of interventions to manage flood risk from rivers and surface water: <ul style="list-style-type: none"> <li>▪ Catchment storage.</li> <li>▪ Natural flood management.</li> <li>▪ Linear flood defences.</li> <li>▪ Sustainable urban drainage.</li> <li>▪ Property flood resilience.</li> </ul>
<b>4. Quantifying flood impacts and benefits</b> Representing the economic impacts of flooding through a wide range of categories: <ul style="list-style-type: none"> <li>▪ Residential and non-residential properties.</li> <li>▪ Evacuation.</li> <li>▪ Mental health.</li> <li>▪ Business continuity.</li> <li>▪ Traffic delays.</li> <li>▪ Agriculture.</li> <li>▪ Habitat.</li> <li>▪ Gross value added.</li> <li>▪ Carbon cost of flood recovery.</li> </ul>	<b>5. Quantifying costs and carbon</b> Generating unit cost models for the portfolio of interventions to enable capital, maintenance and carbon costs to be calculated for interventions of different scales, based on relevant metrics (such as the volume of storage or the height, length and type of linear defences).	<b>6. Optimising the level and timing of investment</b> Exploring the decision tree of possible intervention options and the timing of those intervention options across each catchment. Using a real options analysis to represent the robustness of investment and different investment choices that might be made under the range of futures, to find an optimum level and timing of investment that takes into account how future investment will be adaptive to future risk.

Figure 2.2. Summary of the overall approach.



## 2.2 Representing flood risk

### 2.2.1 River flooding

We used a series of existing national-scale datasets collated for the most recent (2018) National Flood Risk Assessment (NaFRA) 'State of the Nation' (SoN) to define the set of flood models (Figure 2.3):

Flood areas	Continuous defence line	Peak water levels
Breaking the study area down into the 730 hydraulic units which form our model domains. They provide full coverage of areas at risk of river flooding. Flood areas also formed the spatial units for the optimisation – so flood risk management intervention options are considered at a flood area scale.	Defining the location and crest level of existing flood defence assets. It combines linear asset data from the Environment Agency Asset Information Management System (AIMS) with terrain data describing high ground.	Providing a consistent set of river levels across the study area for a wide range of annual exceedance probabilities, generated from local model information where available. These were combined with representative hydrograph profiles to provide the boundary conditions for each simulation.

Figure 2.3. Datasets from the NaFRA State of the Nation.

SoN has been a valuable source of nationally and consistently collated data suitable for a regional analysis. However, there are some issues with the data (such as crest level data, the infilling of 'holes' in defences to form the continuous defence line, and the exclusion of the most recent local model water levels), which were highlighted through verification checks between OxCam and local model outputs.

While the models were built using national data, unlike SoN the models themselves use industry standard modelling software for local detailed modelling, the TUFLOW Heavily Parallelised Compute (HPC) solver. This provides high quality flood spreading information, including flood depths which feed into the impact calculations. Use of a full 2D solver was enabled by using **Jacobs Flood Platform**, a high throughput cluster computing system for automating the process of building, running and post-processing flood simulations. We used Flood Platform to manage model input and output data, build the 730 models, run 45,000 simulations and run damage calculations.

### 2.2.2 Surface water flooding

We explored the possibility of developing surface water models to mirror the production of the river models. We ultimately rejected this approach because without modelling local drainage networks, it was felt that we could not substantially improve on national surface water mapping i.e. the Risk of Flooding from Surface Water. We therefore developed an approach around using this available data, acknowledging the limitations of using this dataset, namely that it is limited to three present day likelihoods (3.3%, 1% and 0.1% annual exceedance probability), and that we could not explicitly represent interventions.

We used **flood risk management systems** (FRMS) as the spatial units for analysing surface water risk, climate change, the effect of interventions and flood risk management intervention options. FRMS provide full coverage and have been used by the long-term investment scenarios projects as the standard spatial unit of investment

## 2.3 Representing future scenarios

We explored future risk under 27 future scenarios (Figure 2.4) representing combinations of **climate change**, **development shape** and **development rate**. The core ‘real options analysis’ (see Section 2.7) considered 18 of these futures, as the highest development rate (43,000 homes per year) was considered too extreme.

Climate change	Development shape	Development rate
<b>3</b> scenarios <ul style="list-style-type: none"> <li>Central</li> <li>Upper end</li> <li>H++</li> </ul>	<b>3</b> patterns <ul style="list-style-type: none"> <li>Expansion of existing settlements</li> <li>Creation of new settlements</li> <li>Hybrid of the two patterns</li> </ul>	<b>3</b> rates <ul style="list-style-type: none"> <li>23,000 homes per year</li> <li>30,000 homes per year</li> <li>43,000 homes per year (excluded from the <b>real options analysis</b>)</li> </ul>

Figure 2.4. Future scenarios.

### 2.3.1 Climate change

We considered three climate change scenarios at three points (epochs) in the future (Figure 2.5), and assumed that risk linearly increases between these set points in time:

Central	Upper end	High++	2020s	2050s	2080s
			2015-2039	2040-2069	2070-2115

Figure 2.5. Climate change scenarios and epochs.

For each scenario, we represented climate change using changes in peak flow, sea level rise and increases in rainfall (Figure 2.6).

River flooding Peak flow increases	Tidal river flooding Sea level rise	Surface water flooding Peak rainfall intensity
<p>Predicted changes in peak flow for each epoch, defined by Environment Agency guidance on climate change allowances (Environment Agency, 2020), for each river basin district (in our case Thames and Anglian) based on UKCP09 climate change projections.</p> <p>We linked changes in peak flow to changes in water level using modelled flood frequency curves at 36 locations, which enabled us to generate predicted water levels for the full range of climate change scenarios, which could be used to ‘look up’ results in the simulation library.</p>	<p>Sea level allowances from the Met Office UK Climate Projections (Met Office, 2020), based on UKCP18 projections of mean sea level rise per year for different periods of time in the future.</p> <p>We identified the tidal limit for each river and represented the relative contribution to future water level changes based on a linear distance along the watercourse between the tidal limit (100% fluvial, 0% tidal) and the river mouth (100% tidal, 0% fluvial). This enabled us to generate predicted water levels – as for river flooding.</p>	<p>Predicted changes in peak rainfall from Environment Agency guidance on climate change allowances (Environment Agency, 2020). We have assumed that a predicted percentage peak rainfall increase will translate to an equal percentage increase in the volume of water during a flood event. For each <i>flood risk management system</i>, we estimated the increase in volume we would expect for each Annual Exceedance Probability (AEP) event, and used ‘AEP shifting’ to estimate the future AEP for the three available sets of outputs.</p>

Figure 2.6. Representation of climate change.

### 2.3.2 Future development

We worked with members of the Infrastructure Transition Research Consortium (ITRC) at Newcastle University to develop a broadly representative range of future development scenarios, which are based on a defined **rate** of housing growth (i.e. number of new houses per year) and a defined **shape** of housing growth (defined by a series of constraints and attractors). These are fed into a model that predicts the spatial pattern of housing development, called the Urban Development Model (UDM). We considered three **rates** of housing growth (Figure 2.7) of 23,000, 30,000 and 43,000 homes per year (and ultimately excluded the most extreme from the core analysis), and three **shapes** of housing growth (Figure 2.8): expansion of existing settlements, creation of new settlements, and a hybrid of the two.

23,000 homes per year	30,000 homes per year	43,000 homes per year
Estimated growth required to meet local housing demand (National Infrastructure Commission, 2017)	Estimated growth required to meet local housing demand plus the need from other connected economies, such as London (National Infrastructure Commission, 2017)	An extreme scenario – not representative of expected growth in the OxCam Arc. This was excluded from the core 'multiple futures' optimisation.

Figure 2.7. Rates of development.

Expansion of existing settlements	Creation of new settlements	Hybrid of expansion and new settlements
Adopting a series of attractors and constraints in the development model that encourage development around existing settlements, such as current development proximity, road and rail proximity and employment access.	Seeding the model with five settlement locations around which growth is focussed to the extent where they become new towns or cities.	A hybrid of the settlement expansion and new settlement scenarios.

Figure 2.8. Shapes of development.

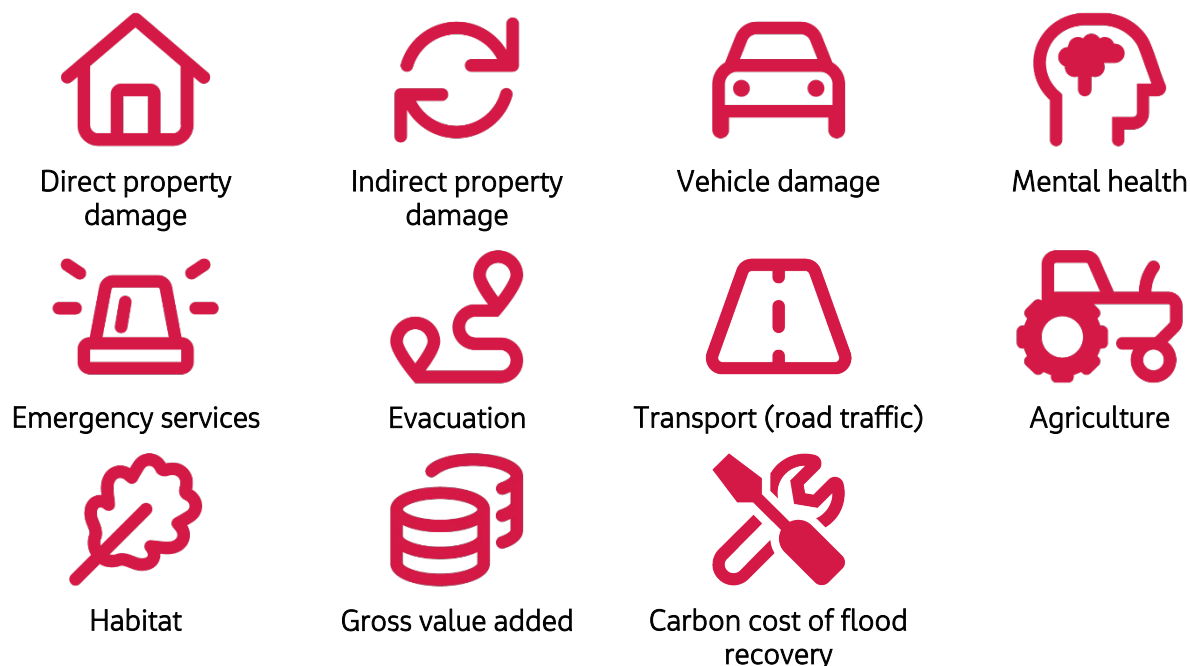
## 2.4 Representing flood interventions

We considered a portfolio of flood risk management interventions (Figure 2.9):

Catchment flood storage	We divided the study area into four catchment storage areas, and developed three levels of storage in each, based on the storage volume required to reduce flows from one AEP to a target AEP. Using representative hydrograph profiles and flood frequency curves, we calculated the storage volume required to achieve the desired flow reduction. We then estimated the effect that the identified volume reduction would have on floods of different severities – and translated that to modified water levels by assuming it would have a uniform effect across the catchment. We did not consider specific storage locations – instead assuming that a portfolio of individual storage interventions, amounting to the total storage volume required, would combine to produce the overall catchment-wide effect on reducing risk.	Small	Reducing 2% AEP to 10% AEP
		Medium	Reducing 2050s central climate change 1% AEP to baseline 10% AEP
		Large	Reducing 2080s H++ climate change 1% AEP to baseline 5% AEP
Natural flood management	We represented natural flood management as an equivalent volume of storage, and applied the same method as for catchment flood storage – but applying it to smaller sub-catchment areas, and acknowledging that NFM is typically more effective for smaller events.	NFM	Reducing 5% AEP to 50% AEP
Linear flood defences	We considered investment in linear defences at the same scale as the flood model domains (flood areas). We defined three levels of raised defence, based on the defence height required to contain water levels associated with an AEP (using the peak water level data described in Section 2.2.1). We represented proposed raised defences as new crest levels along the Continuous Defence Line (also described in Section 2.2.1) – including both locations with and without existing defences, and ran new simulations for each crest level to explicitly represent the change in flood risk. It is assumed that existing defences would never be lowered, so defence heights are retained at or above their current level.	Baseline	Existing crest levels
		Small	Crest level set to 2% AEP present day water level
		Medium	Crest level set to 1% AEP 2050s central climate change water level
		Large	Crest level set to 0.5% AEP 2080s H++ climate change water level
Sustainable urban drainage	We defined surface water flood risk management interventions as the volume of storage required to avoid flooding from a specified AEP in a flood risk management system. This was represented by assuming that the volume of surface water flooding is equal to the volume of rainfall that exceeds current drainage system capacity – and that providing SuDS with that volume will remove the equivalent volume from the flood map. From this assumption, we used the relationship between AEP and volume of water on the floodplain to shift the AEP for each available surface water output to represent the presence of SuDS.	SuDS	Storing rainfall for a 3.3% AEP event
Property flood resilience	We represented PFR using representative depth-damage curves developed to represent a typical package of property measures (such as flood guards, airbrick covers and non-return valves) that would be expected to reduce damages up to depths of 0.6m, and incorporated these depth damage curves into explicit depth-damage calculations at each property.	PFR	Reduced damages up to 0.6m flooding

Figure 2.9. Representation of a portfolio of flood risk management interventions.

## 2.5 Quantifying flood impacts and benefits




**Figure 2.10. Flood impact categories.**

We represented a broad range of impacts (and therefore benefits), as shown in Figure 2.10. These include direct property damages and wider impacts commonly included in economic appraisals. We have also included gross value added and the carbon cost of flood recovery, which are not included as economic benefits under current guidance for FCERM appraisals (Environment Agency, 2022).

The development of new 2D flood models which produce depth grid outputs enabled us to apply industry standard impact analysis calculations from the Multi Coloured Handbook (MCH) (Penning-Rowse, et al., Flood and Coastal Erosion Risk Management: Handbook for Economic Appraisal, 2020), Multi Coloured Manual (MCM) (Penning-Rowse, et al., Flood and Coastal Erosion Risk Management: A Manual for Economic Appraisal, 2013) and other industry standard guidance.

Figure 2.11 describes the approaches we took to calculating impacts.

 <p><b>Property-related impacts</b></p> <p>We used MCH depth-damage curves with National Receptor Dataset property points and depth grids from model outputs, and applied capping and write-off for residential and non-residential properties. We also applied MCH standard calculations for impacts linked to properties: indirect business impacts, vehicle damages, emergency services and evacuation, and the 'Advice for Flood and Coastal Erosion Risk Management Authorities – Mental Health Costs of Flooding and Erosion' guidance to calculate mental health impacts (Priest &amp; Viavattene, 2020).</p>	 <p><b>Transport (road traffic)</b></p> <p>We used Ordnance Survey road information with Annual Average Daily Flow data (Department for Transport, 2020) to apply the MCH delayed hour approach to quantifying road traffic disruption impacts.</p>	 <p><b>Agriculture</b></p> <p>We applied the Defra standard approach for quantifying agricultural losses (as published in MCH), representing permanent loss of agricultural land, one-off damages from infrequent flooding and permanent changes in agricultural land productivity. We used Agricultural Land Classification data from Natural England, Savills Farmland Values Survey data and figures from MCH.</p>
 <p><b>Habitat</b></p> <p>We applied habitat values from Outcome Measure OM4A and river habitat values from OM4B in the partnership funding calculation, combined with data from the Priority Habitat Inventory and flood extents, to estimate the gains/losses from permanent changes in condition (assuming a shift from moderate to poor) as a result of flooding.</p>	 <p><b>Gross value added</b></p> <p>We developed an approach aligned with guidance from FD2662 'Flood and coastal erosion risk management and the local economy' (Frontier Economics, 2014) to value the loss of economic productivity due to flooding – valuing both temporary disruption and the permanent loss of jobs.</p>	 <p><b>Carbon cost of flood recovery</b></p> <p>We applied the Environment Agency Carbonomics approach to value the carbon cost of property flood recovery based on a depth-damage approach (aligned with the property impact analysis), and followed guidance on monetisation of carbon from the Department for Business, Energy and Industrial Strategy (BEIS) to translate tCO<sub>2</sub>e to economic impacts.</p>

**Figure 2.11. Impact analysis approaches.**



## 2.6 Quantifying costs and carbon

We applied cost data from the **long term costing tool for flood and coastal risk management** (JBA Consulting, 2015), updated for inflation, combined with data on the cost of large-scale flood storage from Thames Valley Flood Scheme. Costs and carbon are defined as a function (some are power functions, some linear, depending on the data available for the intervention) based on a specified way of defining the scale of intervention (Figure 2.12), which aligns with the representation of benefits.

Intervention	Definition	Cost model	
Catchment flood storage	Volume to provide target AEP reduction per catchment	Capital	Unit cost per volume (m <sup>3</sup> ) of storage
		Maintenance	Annual, as a percentage of capital costs
		Carbon	Tonnes of CO <sub>2</sub> e per volume of storage
Natural flood management	Volume to provide target AEP reduction per sub-catchment	Capital	Unit cost per equivalent volume (m <sup>3</sup> ) of storage
		Maintenance	Annual unit cost per equivalent volume (m <sup>3</sup> ) of storage
		Carbon	Tonnes of CO <sub>2</sub> e per equivalent volume of storage
Linear flood defences	Height (crest level – ground level) length of each asset (by type) required to provide defences at target water levels per flood area	Capital	Unit cost per m length and m height (for different types of linear defence)
		Maintenance	Annual unit cost per m length
		Carbon	Tonnes of CO <sub>2</sub> e per metre of height x (for different types of linear defence)
Sustainable urban drainage	Volume to provide protect from target AEP event in flood risk management system	Capital	Unit cost per equivalent volume (m <sup>3</sup> ) of storage
		Maintenance	Unit cost per equivalent volume (m <sup>3</sup> ) of storage
		Carbon	Tonnes of CO <sub>2</sub> e per equivalent volume of storage
Property flood resilience	Number of properties in flood area / flood risk management system	Capital	Unit cost per residential property protected
		Maintenance	Assumed to be 0
		Carbon	Tonnes of CO <sub>2</sub> e per property

Figure 2.12. Summary of cost models.

## 2.7 Optimisation

Real options analysis	Portfolio of interventions	Net present value
<p>Enabling the direct comparison between different approaches to investment by:</p> <ul style="list-style-type: none"> <li>Evaluating the costs and benefits of options under multiple possible futures.</li> <li>Demonstrating the value of adaptive investment by allowing different future decisions to be made under those different futures.</li> </ul>	<p>Optimising investment across a whole catchment, enabling the analysis to trade off between e.g. catchment-scale storage and more localised investment.</p>	<p>The optimisation seeks to find the maximum net present value, which is the whole life benefit minus the whole life cost, with 'discounting' of future costs and benefits to their 'present value'.</p> <p>This takes into account the full breadth of whole life costs and the full breadth of whole life benefits over the 100 year appraisal period.</p>

Figure 2.13. Requirements of the optimisation.

To meet the needs of the study, the optimisation needed to meet certain requirements (Figure 2.13). These attributes have a dramatic effect on the optimisation approach. For example, the real options analysis means having to optimise under multiple futures at the same time. The portfolio of interventions means we need to optimise at a catchment scale, which in turn means there are exponentially more combinations and permutations of investment. We explored a range of approaches to optimisation to meet these needs, but ultimately developed a bespoke iterative process. We first found an upper bound of investment (based on the optimum level and timing of investment in each intervention in turn), then iteratively explored three sets of variables (Figure 2.14):

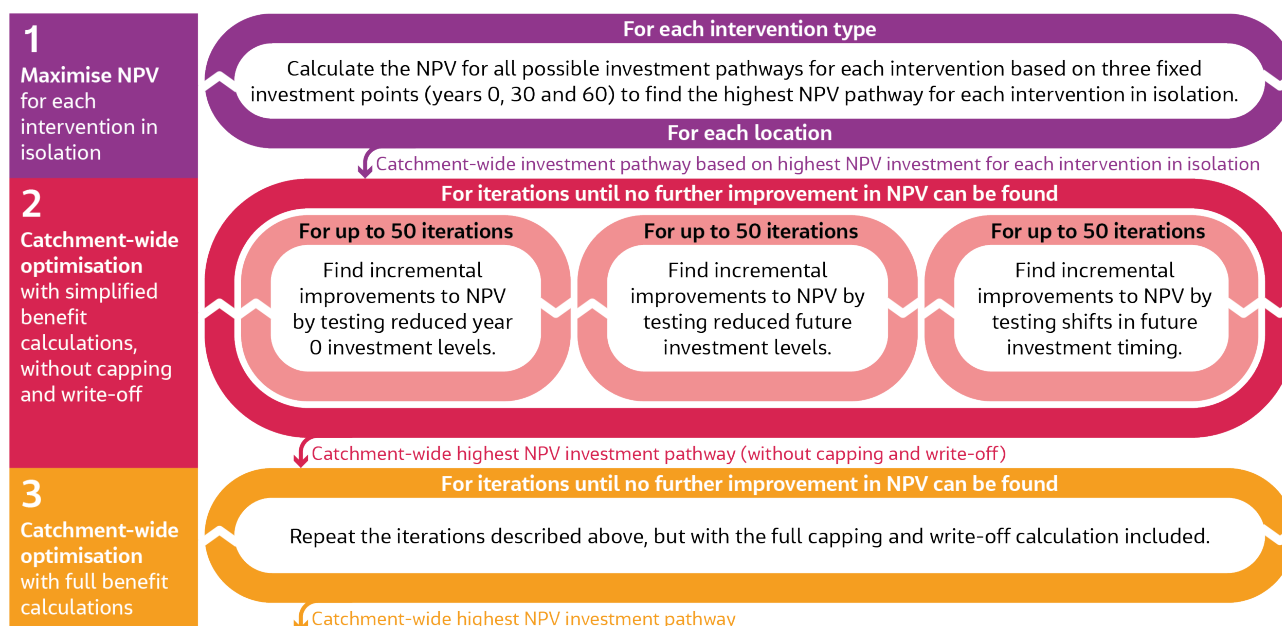


Figure 2.14. Summary of the iterative optimisation approach.

Future investment levels and timings were based on the principle of **decision points** at 10 year intervals (and the predefined set of possible intervention levels). The optimisation would, for example, test the change in net present value from bringing investment in a particular intervention forward by 10 years. Future investment decisions can be made independently under each future, but take into account previous investment. Investment in year 0 forms the start of investment pathways under all futures, and investment under each future influences further investment in that future.

## 2.8 Key assumptions and limitations

Each stage of the process introduced a range of assumptions and limitations. Each technical report explores these in more detail, but Figure 2.15 highlights some of the key assumptions and limitations.

Representation of interventions	Representation of surface water	Representation of future development
<p>For a regional-scale study, there would inevitably have to be simplifications in the representation of interventions.</p> <p>Most notably, the impact of storage (on flow) is assessed at a single location, with an AEP reduction applied as a blanket benefit across the catchment. The 'simulation library' approach was designed in a way that would enable future studies to model the effect of storage on water levels more explicitly.</p>	<p>We took a simplified approach to representing surface water, using existing national surface water mapping. The main limitation of this approach is that it only provides three AEPs. It also constrains the approaches that can be taken to represent interventions and climate change.</p>	<p>The approach to representing future development through spatial distribution of housing density has enabled us to incorporate spatially-defined development in the analysis. But there are some limitations:</p> <ul style="list-style-type: none"> <li>▪ The results shown in Section 4.6 and 4.7 show that results are more sensitive to climate change than on development, but it is likely that this is in part a by-product of the definition of the development scenarios, which were defined in such a way that development on the present day floodplain would not occur.</li> <li>▪ The development modelling predicted where future housing would be developed, which meant we had to estimate where future non-residential development would take place.</li> </ul>
Flood modelling dependencies on underlying datasets	Representation of benefits	
<p>The flood modelling used available asset (specifically crest level) and water level datasets, but we found issues with the quality and consistency of these datasets that would have a direct knock-on effect to the accuracy of the modelling results.</p>	<p>At a regional scale, simplifications were needed in how we represent certain benefits. While we were able to calculate full depth-related impacts (including capping and write-off), we applied simplified approaches to represent e.g. transport and habitat impacts, and were unable to represent utilities infrastructure due to a lack of data.</p>	

Figure 2.15. Key assumptions and limitations.

### 3. Findings: Flood risk in OxCam

#### 3.1 What is the current level of flood risk across the OxCam Arc, and how could it change in the future?

The current and future risk across the OxCam Arc is based on the flood defence assets which are currently in place, assuming they continue to be maintained for the duration of the study period. As described in Section 0, we have explored a core range of 18 futures made up of three climate change scenarios, three shapes of the development and two rates of development.

We estimate that the present day annual average damage in the OxCam Arc is £1.94 billion.	Over the next 100 years, annual average damage could increase to between 2 and 5 times its current value if there is no new investment in flood risk management.	Surface water contributes 58% towards whole life present value damages, and river flooding contributes 42%.
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##### 3.1.1 Properties at risk

Present day 1% AEP 2020	2050 1% AEP with no new investment, across 18 likely futures
83,000	130,000 – 183,000
	157% – 220%

Figure 3.1. Present day and 2050 properties at risk in a 1% AEP event.

We estimate that there are currently 83,000 properties at risk in the OxCam Arc, and that this could increase to 157% to 220% of that value by 2050 with no new investment (Figure 3.1). 64% of these properties are in the Thames catchment, with 16% in the Nene and 20% in the Ouse (Figure 3.2).

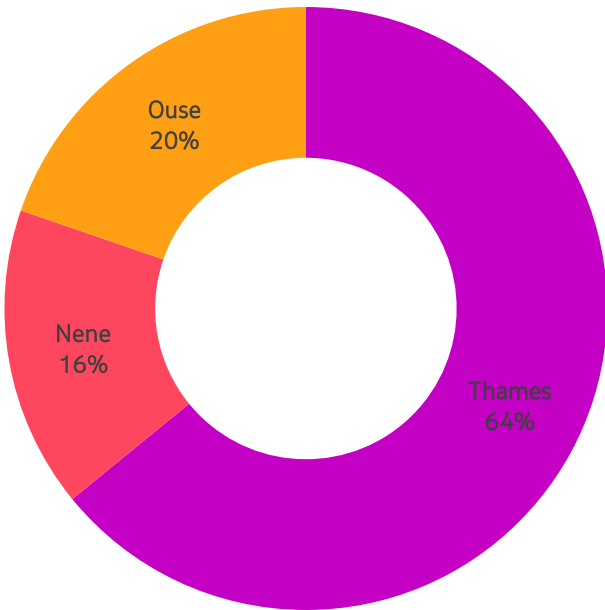


Figure 3.2. Distribution of present day properties at risk in a 1% AEP event.

### 3.1.2 Annual average damage

Our modelling indicates that the present day annual average damage for the OxCam Arc is **£1.94 billion** (Figure 3.3). This value includes both river and surface water flooding, and includes a range of economic impacts beyond property damages.

Present day 2020	2050 with no new investment, across 18 likely futures	2120 with no new investment, across 18 likely futures
<b>£1.94</b> billion	<b>£2.73 - £3.91</b> billion 140% - 201% × present day	<b>£3.92 - £10.18</b> billion 202% - 524% × present day

Figure 3.3. Annual average damage in the OxCam Arc.

With no new investment, in 2050, when our development scenario modelling assumes the planned development in the OxCam Arc will be complete, the analysis suggests that economic impacts could increase to 140% to 201% of its present day value. By the end of the study period in 2120, the increase could be 202% to 524% of its present day value.

### 3.1.3 Whole life (present value) impacts

Over a 100 year study period, this annual average damage translates to whole life present value impacts of £63.5 billion (Figure 3.4). Under the 18 futures included in the core analysis, there is also a clear range in the present value damage impacts of around +/- 10% from the mean. However, the dramatic differences shown in the annual average damage are dampened by the effect of discounting, as economic impacts further into the future make less of a contribution to present value impacts.

Mean across 18 likely futures	Range across 18 likely futures	Maximum under extreme development
<b>£63.5</b> billion	<b>£56.0 - £68.7</b> billion	<b>£71.7</b> billion

Figure 3.4. Present value impacts in the OxCam Arc

### 3.1.4 Contribution from difference sources

We separately represented risk from surface water and rivers, with risk from rivers including some tidally-influenced stretches of river.

Surface water contributes 70% of present day risk, with rivers contributing 30%. The effect of climate change reverses that, so that by 2120, surface water only contributes 29%, with rivers contributing 71%. Figure 3.5 shows how the contribution from the two sources shifts throughout the study period.

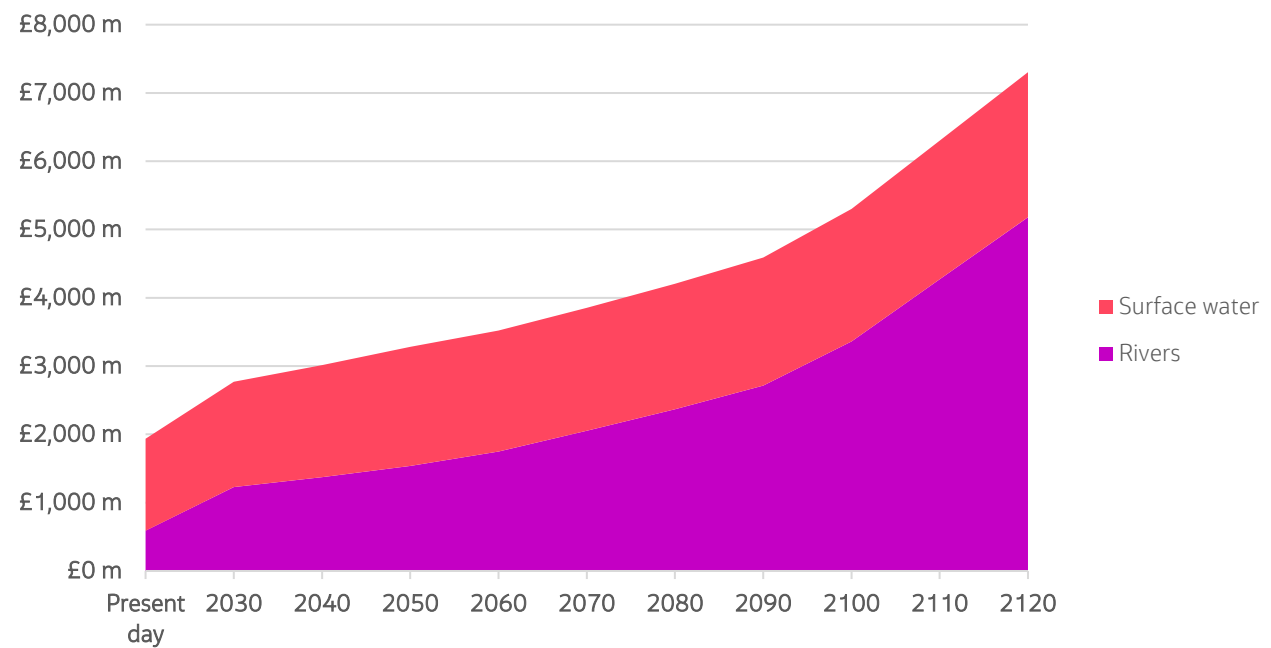


Figure 3.5. Annual average damage by source, through time.

Over the whole life of the study with no new investment, surface water would contribute over half of the baseline present value damages (Figure 3.6).

Surface water	Rivers
58%	42%
£36.7 billion	£26.8 billion

Figure 3.6. Present value impact by source.



### 3.2 How is risk distributed across the OxCam Arc?

The study area includes the upstream River Thames, the Nene and the Ouse. The Thames contributes over half (54%) of the overall risk (Figure 3.7), based on the whole life risk over the study period.

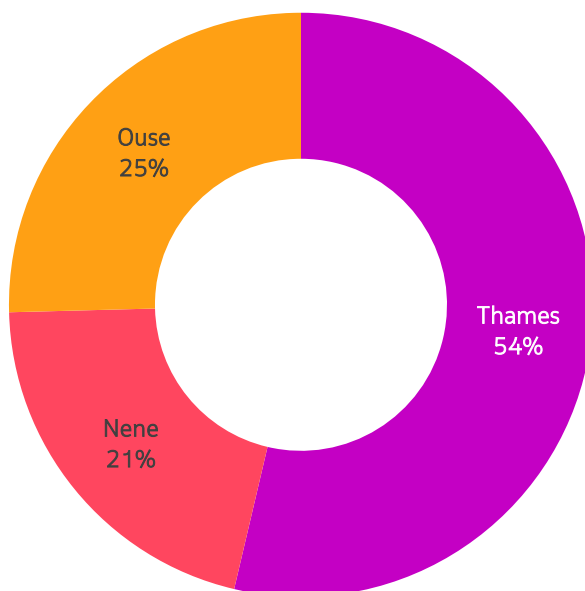


Figure 3.7. Distribution of risk between catchments in the OxCam Arc.

### 3.3 What types of impact contribute most to overall risk?

As described in Section 2.5, we explored a wide range of impacts. This included a broad selection of standard economic appraisal impacts, alongside the carbon cost of flood recovery and the **gross value added** (GVA) measure of economic productivity.

Property damages are the largest single contributor to risk (38%). Wider and indirect impacts contribute a further 32%. Together, these make up the types of impacts commonly included in economic appraisals, and collectively they make up 70% of the total OxCam impacts (Figure 3.8).

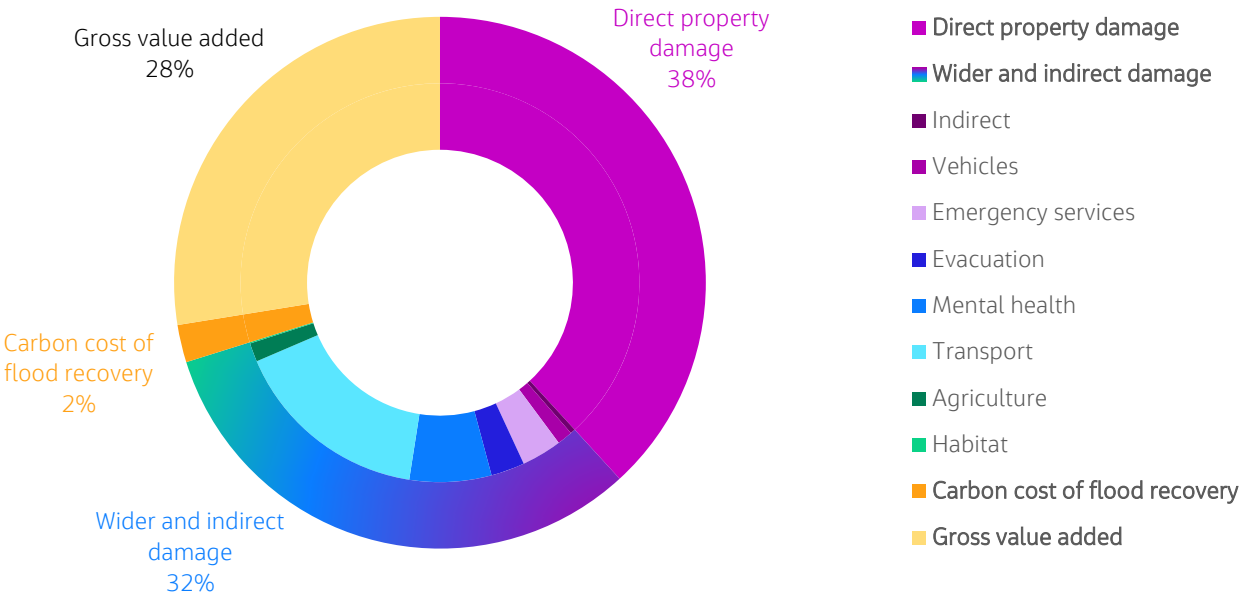


Figure 3.8. Contribution to risk from different types of impact.

## 4. Findings: Flood risk management investment

### 4.1 What is the optimum level of investment in flood risk management in the OxCam Arc?

We have optimised investment under 18 possible futures, and found the optimum present value level of investment to be **£5.63 billion** over the 100 year study period (Figure 4.1). Depending on how climate change and development affect risk in future, the optimal present value investment could be between £4.63 and £6.20 billion.

Mean	Range
across 18 likely futures	across 18 likely futures
<b>£5.63</b>	<b>£4.63 – £6.20</b>
billion	billion

Figure 4.1. Optimum present value investment in the OxCam Arc.

Present value investment includes the whole life costs of interventions including capital, maintenance **and carbon** costs. These are discounted, following HM Treasury Green Book guidance, so that investment in future years contributes less to the total present values. While the results of the analysis include peaks and troughs of spending (explored in Section 4.2), the whole life investment translates to an annual average investment (Figure 4.2) of £177 million per year.

Mean	Range
across 18 likely futures	across 18 likely futures
<b>£177</b>	<b>£140 – £206</b>
million	million

Figure 4.2. Optimum annual average investment in the OxCam Arc.

Over the whole life of the study, maintenance costs are the biggest contributor to overall present value investment (Figure 4.3). This makes up 51% of the total (plus an additional 6% for the carbon costs associated with maintenance), compared with 37% for capital investment (and 6% for the carbon costs associated with that capital investment).

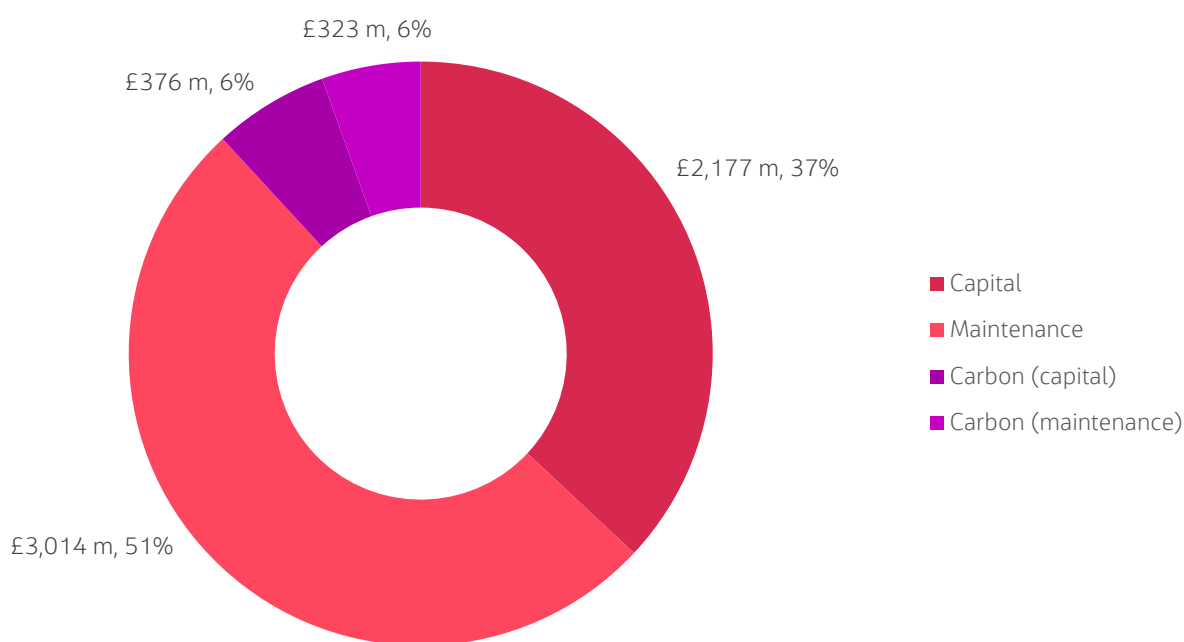


Figure 4.3. Breakdown of investment.

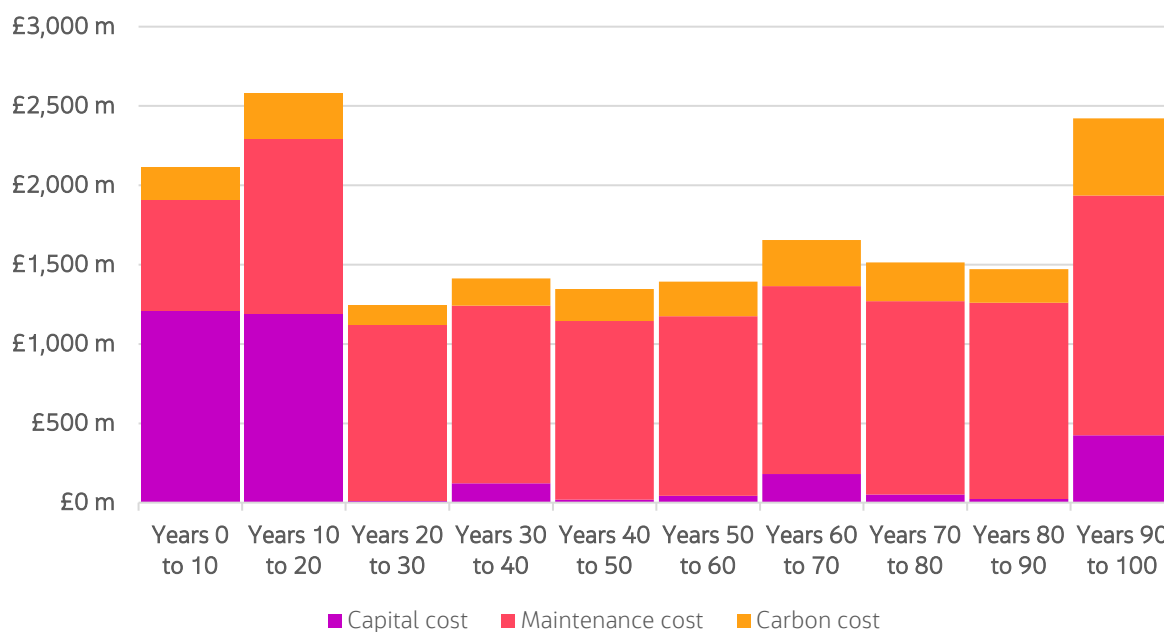
## 4.2 What is the optimum timing of investment?

The previous question explored whole life investment, and how that could be averaged across the study period. But the results of the analysis indicate that there is a significant amount of investment (£2.11 billion) which is likely to be cost beneficial under the full range of futures (Figure 4.4). Because these interventions are cost beneficial under all futures, the value that can be derived from that investment (measured as net present value) is maximised when the investment happens in the first decade. This is because benefits accrued early in the appraisal period are subject to less discounting in the present value calculation. This means that to maximise this benefit, a significant proportion of the capital investment would be required at the start of the study period.

2020 - 2030	2030 - 2040	2040 - 2050
Total optimum investment	Total optimum investment	Total optimum investment
<b>£2.11</b> billion	<b>£1.59 - £3.07</b> billion	<b>£1.05 - £1.41</b> billion
Capital investment	Capital investment	Capital investment
<b>£1.21</b> billion	<b>£0.51 - £1.53</b> billion	<b>£0 - £0.04</b> billion

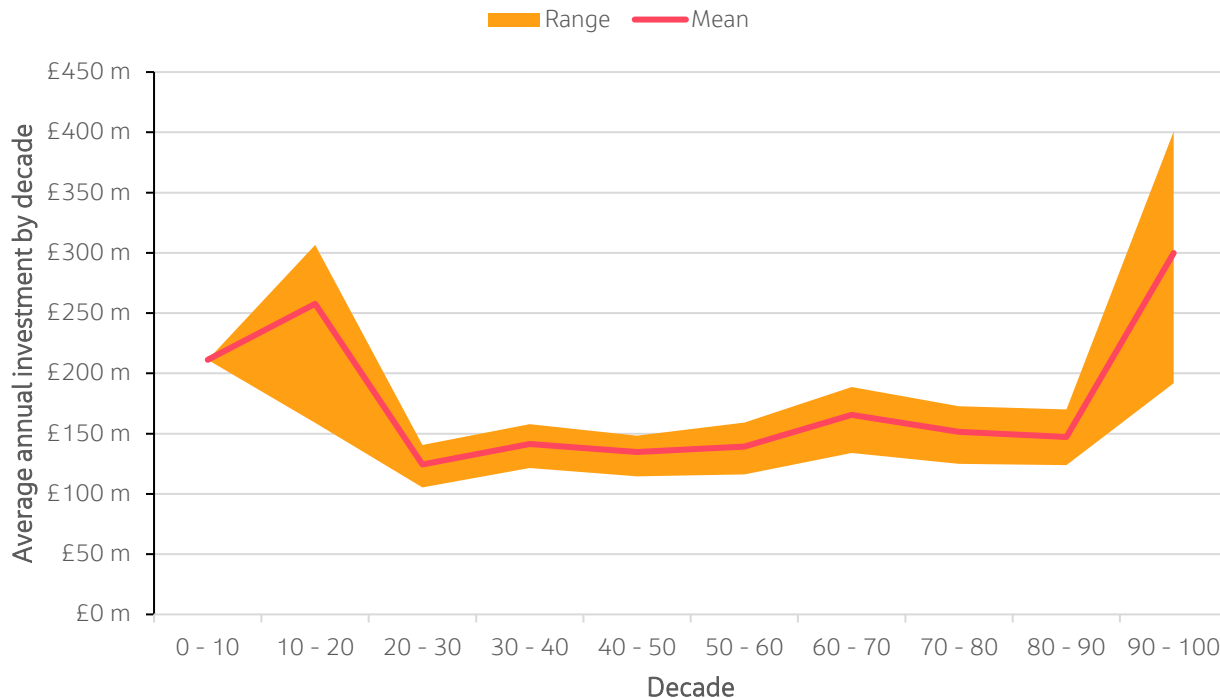
Figure 4.4. Optimum investment over the first three decades of the study (in cash costs, not discounted).

Investment that is found not to be cost beneficial in all futures will be deferred to a future year, and only selected in futures where it is cost beneficial. Figure 4.4 shows between £0.5 and £1.5 billion of investment in the second decade, all of which we would expect to be investment which is future-dependent, from a climate, development rate, and development type perspective.



**Figure 4.5. Cost breakdown, through time.**

Over the course of the study period, there are peaks in troughs in capital investment (Figure 4.5), but as Figure 4.6 shows, after the first 20 years of intensive investment, it is broadly level for the next 70 years - indicative of the fact that (as shown in Figure 4.5), much of the ongoing investment is maintenance of the earlier capital schemes.



**Figure 4.6. Possible range of average annual investment, by decade.**

### 4.3 How robust is the optimum investment under different futures?

We have adopted a **real options analysis** approach, which evaluates the investment decisions we can make now – and the future investment decisions they unlock – and seeks to find the highest net present value under the range of possible future outcomes. At the heart of the approach is the idea that **different decisions** may be made in the future depending on how future conditions change. We therefore make the investment now that leaves the best options open in the future. “Decisions should be taken with the best available information, recognising that this may change in future” (HM Treasury, 2020).

The outcome of the real options analysis is the optimum investment, based on the investment that we can make now which leads to the highest overall net present value when factoring in the balance of future changes in risk and the future decisions we may make as that risk changes.

We can therefore say that an initial investment of £2.11 billion in the first decade (shown in Figure 4.4 in the previous section) would form part of a whole life (present value) investment of between £4.63 and £6.20 billion, depending on future changes in risk. The initial investment tells us that a significant amount of investment is independent of future changes in risk. The variation in future investment shows that as the future risk picture emerges, different levels of investment may be needed – but the modest level of variation should provide confidence in the likely total present value investment.

When describing robustness, we also need to consider the return on investment. The expected present value benefit is £28.2 billion, with a range of £22.2 to £32.0 billion depending on future changes in risk. This equates to a net present value of £22.6 billion, but with a range of £17.6 to £25.9 billion. These figures indicate that the absolute return on investment is more sensitive to different futures than the optimum investment, but the benefit-cost ratio of the optimum investment remains relatively stable, between 4.7 and 5.2.

Total present value investment	Expected present value benefit	Expected net present value
<b>£5.63</b> billion	<b>£28.2</b> billion	<b>£22.6</b> billion
Full range, depending on the future:	Full range, depending on the future:	Full range, depending on the future:
<b>£4.63 – £6.20</b> billion	<b>£22.2 – £32.0</b> billion	<b>£17.6 – £25.9</b> billion

Figure 4.7. Range of present value investment and expected net present value.



## 4.4 What can we say about the OxCam adaptation pathway?

This section draws on the outputs described in the sections above and adds additional analysis to explore what we can say about the OxCam adaptation pathway.

### 4.4.1 Precautionary and adaptive investment

As described in Section 4.2, the analysis recommends early capital investment of £1.21 billion over the first decade. This indicates that a significant amount of capital investment is cost beneficial irrespective of future changes in risk, either as a result of different climate change outcomes, or different development scenarios. It may therefore be considered to be a **precautionary** investment, although in some cases it forms the first step towards future adaptive investment, depending on the location. However, this precautionary investment is coupled with between £1.01 and £2.70 billion of future **adaptive** investment (in cash costs), which is dependent on future risk (Figure 4.8).

Initial capital investment	Mean future capital investment	Future capital cost range
<b>£1.21</b> billion Cash cost over first decade	<b>£2.06</b> billion Cash cost in future decades	<b>£1.01 - £2.70</b> billion Cash cost in future decades

Figure 4.8. Initial and future capital investment.

#### 4.4.2 Decision tree



**Figure 4.9. OxCam decision tree.**

Adaptive pathways are commonly visualised as timelines of future changes in flood risk management approaches that may be required in response to trigger points. For example, the Thames Estuary 2100 Plan plots the need for action based on future tidal water level rise that affects the whole interconnected flood risk management system. However, OxCam is at risk from multiple sources of flooding including three distinct river catchments, tidally-influenced river reaches and surface water, with significant variation in levels of current and future risk, such as between urban and rural areas across the region. There is therefore significant variation in the type and level of investment across the Arc. There is also not just one driver for changes in future risk, with both climate change and development giving different futures, so there is no single linear scale that could be used to define 'trigger points'.

This complexity in the system means that distilling all the individual investment decisions and how they could change under different physical drivers is unlikely to be meaningful, or possible. However, we can explore the range of future decisions at a high level across the portfolio of interventions as a high-level decision tree (Figure 4.9). The graphic shows (from left to right):

<b>Intervention</b>	The overall distribution of investment between interventions.
<b>Any Investment?</b>	The proportion of areas (defined appropriately for each intervention) where the analysis finds that investment is beneficial at some point in time.
<b>Year 0 Investment</b>	The proportion of these areas with investment in year 0, vs. those in which investment is deferred.
<b>Investment up to Year 30</b>	The proportion of these areas with investment (after year 0) in the first 30 years – and whether that investment occurs in some futures (less than half), most futures (more than half) or all futures – vs. those in which investment is deferred again.
<b>Investment beyond Year 30</b>	The proportion of these areas with investment beyond the first 30 years – again showing some, most and all futures.

Each individual intervention could also have different trigger points (such as a particular level of development, level of climate change or combination of the two), and different combinations of interventions that influence risk at any given location, so drawing conclusions at a regional scale would not be possible. However, we can consider what the different timings of investment mean, drawing the following key points about the timing of investment:

- Investment in year 0 means we know enough now to be confident that investment would be cost beneficial, irrespective of the course future risk takes.
- Investment after year 0 in the first 30 years is driven by a combination of development and climate change. Where this investment only happens in some futures, investment is dependent on knowing more about the rate of climate change.
- Investment after year 30 is driven by climate change.

### 4.4.3 The cost of robust investment

In the core real options analysis described in the sections above, we optimised investment to be robust under all futures. This section compares those results with investment optimised under the same 18 futures, but without consideration of robustness under different futures, optimising investment for each single future. We found that the cost of investment which is robust under multiple futures is only slightly higher than the cost optimised under a single future – around 1% higher. This also means that the reduction in net present value is very small (0.2%). This is partly driven by the amount of investment which is identified for year 0, and the contribution it makes to the present value investment.

Increase in present value investment Average additional cost of robust investment		Reduction in net present value Average change in value for robust investment	
£49 million	0.9%	£34 million	0.2%
Largest increase:		Largest reduction:	
£78 million	1.3%	£55 million	0.2%

Figure 4.10. Increase in investment (and reduction in net present value) to achieve robust investment.

## 4.5 Can flood risk investment mitigate future increases in risk due to climate change and development?

Present day 2020, with the optimum investment	2050 with the optimum investment, across 18 likely futures	2120 with the optimum investment, across 18 likely futures
£1.35 billion 30% damages avoided Compared with £1.94 billion without any new investment	£1.58 – £1.72 billion 42% damages avoided 117% – 127% × present day	£1.79 – £2.57 billion 54% damages avoided 132% – 190% × present day

Figure 4.11. Residual annual average damage with the optimum level of investment.

Under the optimum level of investment, there is still a noticeable increase in residual risk over time – from £1.35 billion annual average damage up to between £1.79 and £2.57 billion (Figure 4.11), depending on the climate change development scenario. This means that within the range of interventions included and the limitations of the study, there is not a cost beneficial way to fully mitigate future increases in risk at a regional scale.

However, the increase in residual risk (1.3-1.9× the present day annual average damage) is small compared with the estimated increase in baseline risk over the study period (2.0-5.2× the present day annual average damage by the end of the study period, as described in Section 3.1.1). This is illustrated by Figure 4.12, which shows the future risk profile with and without interventions, and how much it could vary under different futures. This demonstrates that while it does not fully mitigate future increases in risk, the optimum level of investment is still effective at managing risk into the future.

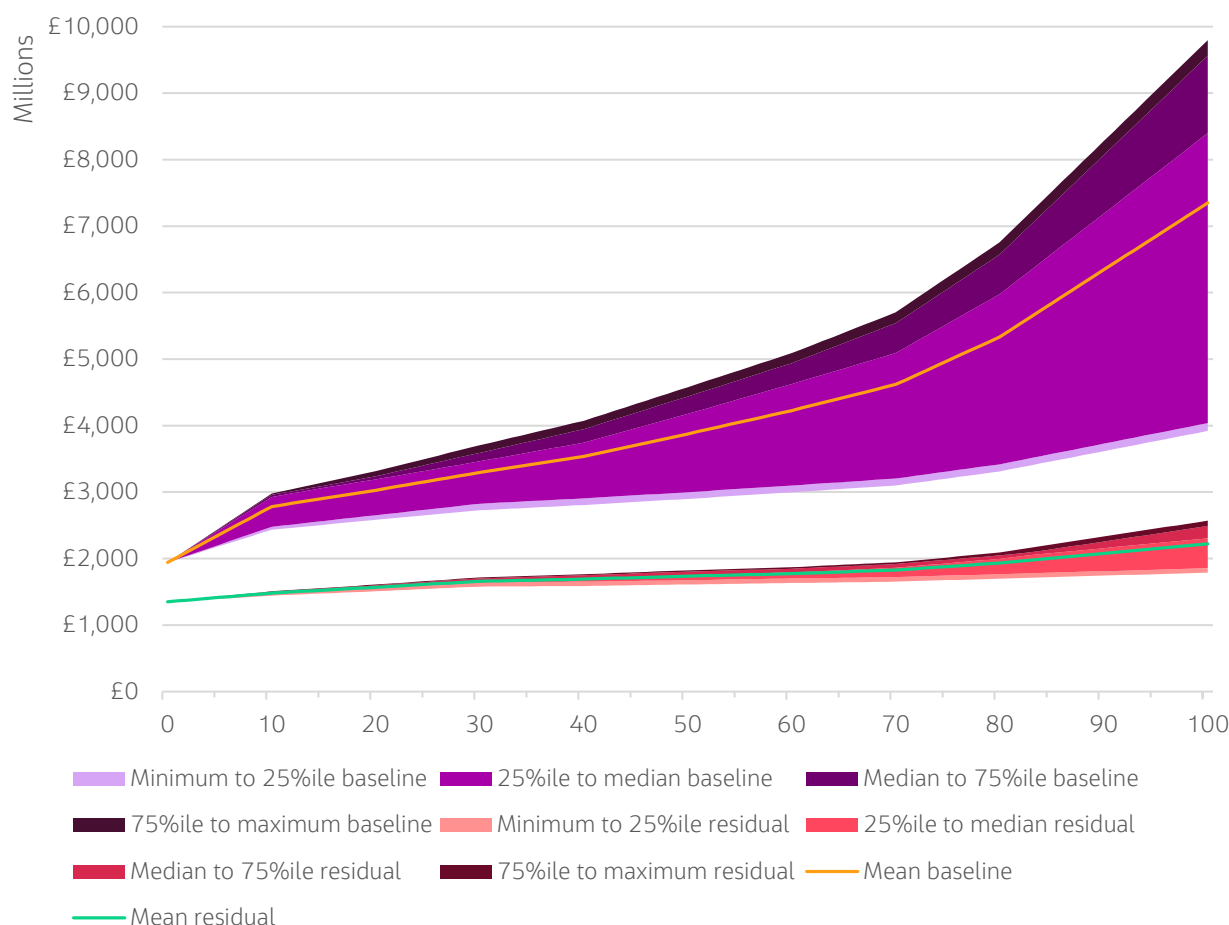


Figure 4.12. Profile of residual risk under the optimum investment.

## 4.6 How could different levels of climate change affect risk and the optimum investment?

Central Baseline risk, across 6 development scenarios	Upper end Baseline risk, across 6 development scenarios	H++ Baseline risk, across 6 development scenarios
<b>£58.1</b> billion	<b>£67.0</b> billion	<b>£68.9</b> billion
<b>£56.0 - £61.0</b> billion	<b>£60.9 - £70.6</b> billion	<b>£66.4 - £72.1</b> billion

Figure 4.13. Variation in baseline present value risk under different climate change futures

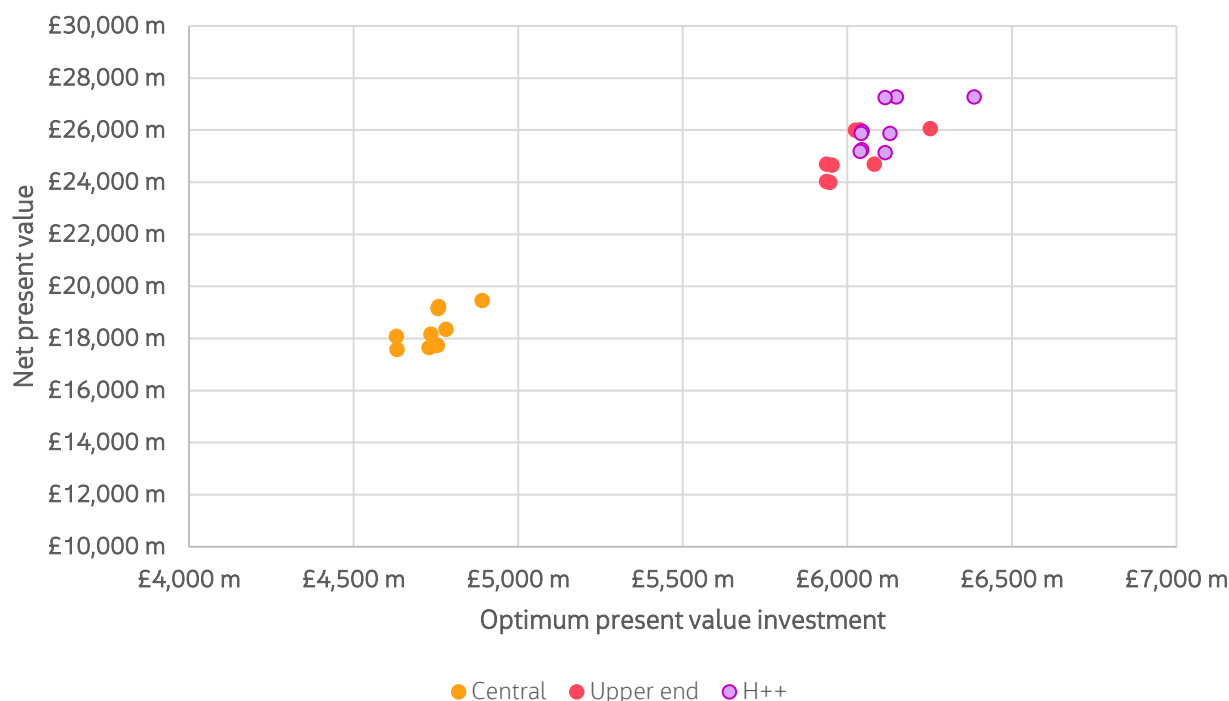
There is a significant level of variation in the baseline risk under different climate futures (Figure 4.13), in particular the jump from **central** to **upper end** climate change scenarios. As would be expected, risk increases with more extreme climate change. This translates to a significant level of variation in the optimum level of investment under different climate change futures (Figure 4.14). The optimum level of investment increases with more extreme climate change, from an expected £4.74 billion in Central climate change up to £6.12 billion in H++, with clear clusters of results shown in Figure 4.15.

Comparing the results with those in Section 4.7, it shows that both baseline risk and the optimum level of investment are more sensitive to the climate change scenarios than to the development scenarios.

Central Optimum investment, across 6 development scenarios	Upper end Optimum investment, across 6 development scenarios	H++ Optimum investment, across 6 development scenarios
<b>£4.74</b> billion	<b>£6.02</b> billion	<b>£6.12</b> billion
<b>£4.63 - £4.89</b> billion	<b>£5.94 - £6.25</b> billion	<b>£6.04 - £6.38</b> billion

**Figure 4.14. Variation in optimum present value investment under different climate change futures.**

For reference, these results are taken from optimising investment in each future in turn, rather than the real options analysis that optimises investment across 18 likely futures, but the results are very similar. Under the real options analysis, the optimum investment is £4.71 billion for central, £6.06 billion for upper end and £6.13 for H++ climate change scenarios.



**Figure 4.15. Variation of optimum present value investment and net present value under different climate change futures, optimised individually.**

## 4.7 How could different rates and shapes of development affect the optimum investment?

The different rates and shapes of development we explored do not have a significant impact on baseline risk or the optimum level of investment, as shown by the similarity in the mean baseline risk and investment figures between the scenarios in Figure 4.16, Figure 4.17, Figure 4.19 and Figure 4.20.

### 4.7.1 Rate of development

23,000 homes per year Baseline risk, across 3 climate change scenarios and 3 shapes of development	30,000 homes per year Baseline risk, across 3 climate change scenarios and 3 shapes of development	43,000 homes per year Baseline risk, across 3 climate change scenarios and 3 shapes of development
<b>£62.3</b> billion (mean)	<b>£64.3</b> billion (mean)	<b>£67.4</b> billion (mean)
<b>£56.0 – £67.0</b> billion (range)	<b>£57.5 – £68.7</b> billion (range)	<b>£60.1 – £72.1</b> billion (range)

Figure 4.16. Variation in baseline present value risk under different rates of development.

The mean baseline risk (Figure 4.16) and investment (Figure 4.17) increase with the rate of development, but to a much lesser degree than in response to climate change – the values are similar across the three scenarios.

23,000 homes per year Optimum investment, across 3 climate change scenarios and 3 shapes of development	30,000 homes per year Optimum investment, across 3 climate change scenarios and 3 shapes of development	43,000 homes per year Optimum investment, across 3 climate change scenarios and 3 shapes of development
<b>£5.58</b> billion (mean)	<b>£5.59</b> billion (mean)	<b>£5.71</b> billion (mean)
<b>£4.63 – £6.11</b> billion (range)	<b>£4.63 – £6.13</b> billion (range)	<b>£4.76 – £6.38</b> billion (range)

Figure 4.17. Variation in optimum present value investment under different rates of development.

As with the climate change exploration above, these results are taken from the optimisation of individual futures. We also explored a **no development** scenario, and found that baseline risk was noticeably lower – which extends the pattern described above where increased development leads to increased risk. However, while there is a corresponding reduction in the optimum investment, it is not significant (£5.56 billion, compared with £5.58 billion for the 23,000 homes per year scenario), as shown in Figure 4.18.

No new development Baseline risk:	23,000 homes per year Baseline risk:
<b>£57.4</b> billion (£51.2 – £61.2 billion range)	<b>£62.3</b> billion (£56.0 – £67.0 billion range)
Optimum investment:	Optimum investment:
<b>£5.56</b> billion (£4.62 – £6.09 billion range)	<b>£5.58</b> billion (£4.63 – £6.11 billion range)

Figure 4.18. Comparison between no development and 23,000 homes per year scenarios.

## 4.7.2 Shape of development

Creation of new settlements	Expansion of existing settlements	Hybrid of expansion and new settlements
Baseline risk, across 3 climate change scenarios and 3 rates of development	Baseline risk, across 3 climate change scenarios and 3 rates of development	Baseline risk, across 3 climate change scenarios and 3 rates of development
<b>£65.1</b> billion (mean)	<b>£64.0</b> billion (mean)	<b>£64.8</b> billion (mean)
<b>£56.3 – £72.1</b> billion (range)	<b>£56.0 – £71.1</b> billion (range)	<b>£56.2 – £71.7</b> billion (range)

**Figure 4.19. Variation in baseline present value risk under different shapes of development.**

The shape of development has a similar level of impact on baseline risk as the rate of development, which is to say, much less significant than the impact of climate change. Unlike climate change and rate of development, the different shapes of development are not on a clear linear scale – so the relationship between shape of development, risk and investment is less clear.

We can still draw out two patterns from the individual results, demonstrated by the values in Figure 4.19:

- The *creation of new settlements* scenarios consistently exhibit the highest baseline risk, compared with the same climate change and rate of development for other shapes of development.
- The *expansion of existing settlements* scenarios consistently exhibit the lowest baseline risk.

This pattern of baseline risk does not translate to the optimum level of investment. In fact, the *expansion of existing settlements* scenarios consistently exhibit the highest optimum investment level, as shown in Figure 4.20. However, the variation between scenarios is so small that it is difficult to draw meaningful conclusions about how different shapes of development are likely to influence risk.

Creation of new settlements	Expansion of existing settlements	Hybrid of expansion and new settlements
Optimum investment, across 3 climate change scenarios and 3 rates of development	Optimum investment, across 3 climate change scenarios and 3 rates of development	Optimum investment, across 3 climate change scenarios and 3 rates of development
<b>£5.57</b> billion (mean)	<b>£5.71</b> billion (mean)	<b>£5.59</b> billion (mean)
<b>£4.63 – £6.15</b> billion (range)	<b>£4.75 – £6.38</b> billion (range)	<b>£4.73 – £6.11</b> billion (range)

**Figure 4.20. Variation in optimum present value investment under different shapes of development.**

## 4.7.3 Influence of the development scenarios

It is important to note that for this part of the analysis in particular, the results are likely to be influenced strongly by the way in which the driving scenarios are defined. The underlying development scenario modelling, which predicts where future housing development will take place, uses flood risk (based on present day flood zone mapping) as a constraint – this means that by definition, there will be limited development in the areas with the highest risk, with the exposure of future development driven largely by the extent to which future risk differs from the present day risk which is driving the flood zone mapping used to constrain the development model.

This means that while the results above indicate patterns in the results, they need to be considered carefully alongside the origins of the development scenarios themselves. For example, we may not be able to say with



confidence that future risk is more dependent on climate change than it is on development, because those differences could be a result of the development scenario definition.

## 4.8 What can we say about the balance of investment across a portfolio of interventions?

The main purpose of this study is to consider the overall level and timing of investment, and not to make recommendations for the specific levels of investment in different interventions – this requires more local exploration of location-specific factors which cannot be explored at this regional scale. More specifically, the key limitations of the approach are:

- Storage is represented as offering a 'blanket' level of protection across a whole catchment. This means that higher storage volumes are likely to be needed compared with more 'targeted' protection of key locations.
- The study focusses on the flood risk benefits of investment. While this includes quantification of habitat and agricultural benefits, the analysis is likely to undervalue the holistic contribution that natural flood management could provide to a catchment, such as water quality and wider ecosystem services.
- The representation of surface water did not involve new modelling – rather, we used existing national surface water flood maps – which limits the extent to which we could represent surface water flood risk management interventions.
- At this scale of analysis, simplifications and generalisations are necessary for all interventions.

However, we can still draw useful meaning at a high level from the outputs of the analysis:

A portfolio of flood risk management interventions is important to robustly managing flood risk in the OxCam Arc.

A catchment approach which considers a system of interventions at different scales is likely to deliver the best value flood risk management approach for the OxCam Arc.

With these limitations in mind, Figure 4.21 shows the distribution of present value investment between the types of interventions included in the analysis.

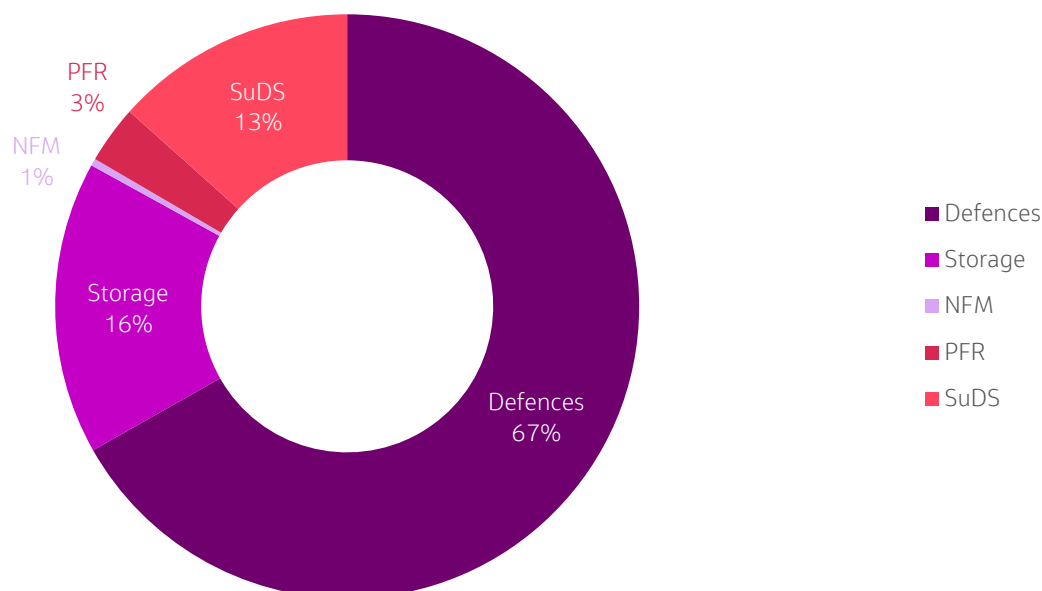


Figure 4.21. Distribution of investment between different types of intervention.

## 4.9 How is the investment need distributed across the OxCam Arc?

Figure 3.7 explored how baseline risk is distributed across the OxCam Arc, with 54% of risk in the Thames catchment, 25% in the Ouse and 21% in the Nene. Figure 4.22 shows how that baseline risk translates to the distribution of investment across the region.

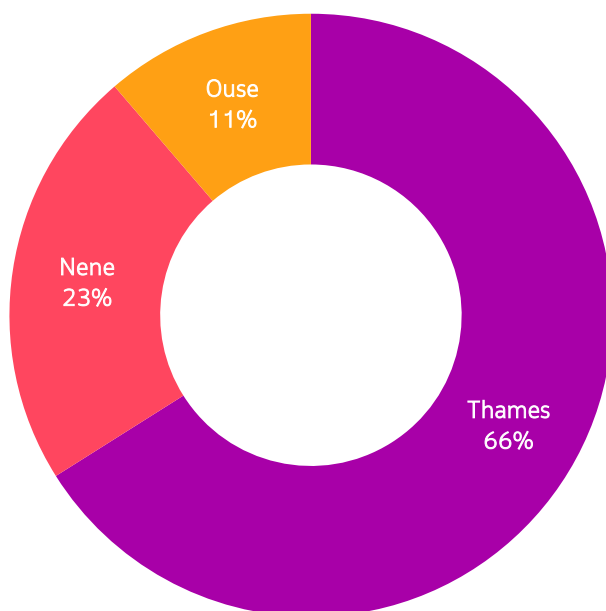


Figure 4.22. Distribution of investment across the OxCam Arc.

## 5. Lessons learnt

Each technical report explores more detailed lessons learnt. This section explores two key questions:

1. What have we learnt about economic optimisation in the context of adaptation?
2. What have we learnt about regional-scale flood resilience investment analysis?

### 5.1 What have we learnt about economic optimisation in the context of adaptation?

#### 5.1.1 Real options analysis

Real options analysis can provide a bridge between optimisation and adaptation.

We developed our economic optimisation around the concept of the **real options analysis**, which is part of HM Treasury Green Book guidance. In the guidance, it is demonstrated with 2 decision points and 2 possible future climate change scenarios, used to compare 2 intervention options – precautionary vs adaptive. In this most basic form real options analysis is proven to show the possible advantage of deferring investment when future benefits are uncertain – and to compare adaptive investment directly with precautionary (upfront) investment. The approach:

- Allows adaptive investment pathways to make different future investment choices under different futures, and weighting the present value cost by the likelihood that each future will occur.
- Evaluates, and seeks to maximise, the net present value based on how an option performs under different futures, and weighting it by the likelihood that each future will occur.

For the OxCam economic evidence study, we have applied a much more complex version of the analysis – with 10 decision points, 18 possible futures and thousands of future options – but the principles remain the same. The computational complexity (described below) because of the number of possible pathways means that we could not adopt an approach which explicitly calculated the costs and benefits of every possible pathway. However, the aim of our optimisation process (to maximise the net present value across all futures) is exactly the same as the aim of a real options analysis.

#### 5.1.2 Computational complexity

Catchment-scale optimisation introduces huge computational complexity.

We optimised investment at a catchment scale. This enabled us to explore the trade-offs between investment in catchment interventions, such as storage, and more localised interventions such as linear defences.

If we were considering the combinations of possible **river** flood risk management interventions and levels of investment in each in a single location, with the interventions defined in this analysis we would have (Figure 5.1):

Catchment storage		Natural flood management		Linear defences		Property flood resilience
×4 None, small, medium, large	×	×2 None, some	×	×4 Baseline, small, medium, large	×	×2 None, some

Figure 5.1. Combinations of interventions.

This equates to 64 possible intervention options for this location. However, at a **catchment** scale, we need to consider every possible combination of interventions. Our largest catchment included one of the four storage areas, 243 of the 740 flood areas (for linear defences and property flood resilience) and 109 of the 285 subcatchments (for natural flood management) – which equals 520 million possible combinations across the catchment.

But we then introduce the added dimension of **timing** of investment, and the optimisation across multiple futures. This means that the number of possible permutations is an absolutely vast  $5.15 \times 10^{99}$ . This imposes substantial computational complexity, and led us to have to change the approach to optimisation, recognising there would not be a feasible way to explore every branch of that decision tree.

The underlying data to support this optimisation is also complex. With 740 flood models and 45,000 simulations, the optimisation would not be possible without a high throughput computing cluster to process and run those models in a reasonable timeframe.

For future projects, the following options could be considered:

1. Implementing the analysis in the way we have, and identifying ways to improve computational performance (such as more scalable computing resources).
2. Defining 'policies' for each intervention (such as 'keep pace with climate change' for linear defences), and optimising based on these pre-defined policies. This would simplify the analysis in each future by 'baking in' the timing of investment as part of defining the policy. However, it would be difficult to apply a real options analysis.
3. Optimising each intervention in turn – e.g. optimising investment in storage first, then using the outputs of that to optimise investment in natural flood management, then linear defences, etc. Intermediate results from our optimisation process (after step 1 described in Figure 2.14) indicated that optimising investment in each intervention in isolation would lead to dramatically different results compared with optimising across all intervention. We would therefore need to 'carry forward' sub-optimal options at each stage – or carry forward all options but with optimised timing.

This range of approaches is relevant to any future regional studies, but also to the upcoming **long term investment scenarios (LTIS) 2025** project, which will be exploring and optimising investment in a portfolio of interventions at different scales and for different futures.

### 5.1.3 Adaptive capacity

Economic optimisation – in the form we have applied it – is not directly comparable to adaptive capacity metrics

The Environment Agency Adaptive Capacity Guidance (Environment Agency, 2018) introduced metrics to measure the adaptive capacity of branches along the pathways in a decision tree:

- **Flexibility:** how many interventions remain open following an investment choice.
- **Robustness:** proportion of possible futures with this intervention as highest performer.
- **Opportunity lost:** difference between chosen intervention and best performing intervention.
- **Expected performance:** an average of the economic performance over all defined futures.

We have found that the OxCam analysis does not translate directly to these metrics at a regional scale, but that they are implicitly part of the analysis:

**Flexibility:** the analysis considers the overall optimum pathways across futures. It would therefore reject pathways which do not provide the flexibility to enable the best value future decisions under multiple futures. However, the analysis would not consider 'flexibility' on its own to be a consideration – as it would allow for poorly performing future interventions to be 'closed off'.

**Robustness:** we do not value interventions by their individual performance, or by their 'best case' performance (i.e. the number of futures where they perform best). Instead, we measure the robustness of the portfolio of interventions across the whole region in pure economic terms – taking into account their performance under all futures – so robustness is at the heart of the analysis, but is measured in a way which is closer to the definition of expected performance below.

**Opportunity lost:** we do not measure opportunity lost – because of the complexity of different investment pathways, we have not been able to pull out results for suboptimal interventions.

**Expected performance:** the core output of the analysis is the average economic performance of the portfolio of interventions over all defined futures. However, through the real options analysis as applied to OxCam, we

do not consider the expected performance of individual interventions, and we measure expected performance that includes the potential value delivered by the different interventions that might take place in later years under different futures.

## 5.2 What have we learnt about regional-scale flood resilience investment analysis?

### 5.2.1 Portfolio of interventions

In the section above, we described the computational complexity of optimising investment for a portfolio of interventions at a catchment scale, but it is also worth reflecting on the range of interventions we have been able to include. The national flood and coastal erosion risk management (FCERM) strategy for England (Environment Agency, 2020) describes different components of resilience (Figure 5.2):

Improve place making	Better protect	Recover quickly	Ready to respond
Making the best land use and development choices to manage flooding and coastal change	Building and maintaining defences and managing the flow of water	Getting back to normal and building back better	Preparing for and responding effectively to incidents

Figure 5.2. Components of resilience.

The strategy outlines examples of resilience actions falling under each of these components. The interventions in this study are focussed on **better protecting**, in our case through investing in linear defences and managing the flow of water through the environment through upstream storage and natural flood management. However, there is also a strong element of **improving place making**, in terms of including property flood resilience measures and retrofitted sustainable urban drainage systems, and by considering how future development will link to changes in future risk.

There are other types of intervention in those categories which could be included in future studies, but there are clear gaps in **recovering quickly** and being **ready to respond**. Further work is needed to understand how to value the full breadth of resilience actions in economic terms and specifically flood risk reduction terms, and consider how they contribute, directly and indirectly, to the flood resilience management system. For example, the Environment Agency research project SC090039 (Clarke, McConkey, Samuel, & Wicks, 2015) developed a systems model based on previous work by Flood Hazard Research Centre (Parker, Priest, Schildt, & Handmer, 2008) to help connect resilience actions through sequences of actions. For example, linking improvements to the flood warning service to more time to take action to avoid damages, or linking community engagement with preparedness and therefore the effectiveness of actions to avoid damages.

### 5.2.2 Decoupled approach

We adopted an approach to the modelling in which we ‘decoupled’ physical boundary conditions (i.e. water levels) associated with a given model output from the scenario which leads in those physical boundary conditions to build up a ‘simulation library’ of outputs. While high levels of automation were still required to run the 45,000 simulations for 740 models, this is significantly less than would be required to explicitly generate outputs for every scenario combination (i.e. every climate change epoch combined with every intervention). This was therefore fundamental to the approach to representing both climate change and the range of interventions we included.

There is also a link to the ongoing development of the next generation **national flood risk assessment** for England (NaFRA2), which is adopting a similar approach, to enable the Environment Agency to maximise the use of modelling data using a **simulation library**. This approach is not unique to OxCam, but we learnt important lessons through its application, such as the importance of considering the changes in water level gradient across an area under different future scenarios, in particular where there is both sea level rise and changes in river flow. It is also particularly relevant for the LTIS 2025 project, which will draw data from NaFRA2, but like OxCam, will need to represent a portfolio of interventions. Hence the use of a decoupled simulation library approach to represent interventions is an important lesson from this project.

### 5.2.3 Representation of interventions

The introduction of 2D modelling to this project enabled us to carry out a much more detailed impact analysis using receptor-level depth information. We can therefore be relatively confident, data issues aside, in the floodplain inundation that would be experienced for a given water level. However, the representation of catchment interventions is linked to how well we can represent the change in water levels that each intervention could deliver.

While appropriate for the scale of study, we found that the representation of catchment storage is the area which would benefit most from the incorporation of more locally-specific information. We found that the catchment-wide approach (i.e. providing a consistent reduction in AEP across the catchment) was significantly different to the way real schemes consider catchments, such as the Thames Valley Flood Scheme, which provides much more targeted storage to reduce risk in high risk built-up areas.

Future approaches could include:

- Explicitly modelling the effect of introducing storage, such as through the use of 1D modelling. Water levels from this modelling could be incorporated into the 'simulation library' to make use of the 2D floodplain spreading developed by the OxCam project. This could involve a significant amount of work, but would enable representation of more 'targeted' storage options in places that will deliver the greatest benefit to downstream communities, in a more realistic manner.
- Adopting a subcatchment approach, similar to our representation of natural flood management. The main challenge with this approach, without explicit modelling, would be how the interactions between different tributaries and main rivers could be represented.

Similarly, the representation of surface water and surface water interventions was limited.

### 5.2.4 Carbon

We found that by adopting a unit cost model approach to the cost of interventions, we were able to include the carbon costs of interventions alongside the capital and maintenance costs. While there are limitations in the available cost data, this was an important inclusion for this study. The main limitation from a carbon perspective was that while we were able to incorporate carbon into the whole life cost-benefit analysis of interventions, the Environment Agency's target of reaching net zero carbon by 2030 may need to act as a stronger constraint on investment options. This would need to be coupled with a wider range of low-carbon intervention options, such as linear defences with low-carbon concrete or with embankments where space would allow, and/or costing which includes carbon offsetting costs.

## 5.3 Sensitivity

We explored the sensitivity of results to a number of variables. The key messages we can draw from the sensitivity analysis are shown in Figure 5.3:

Understanding sensitivity through the core results	The core results tell us a lot about sensitivity to future risk, described in Section 4.6 and 4.7.	Investment is more sensitive to climate change than development – although we can only say with confidence that this is the case within the constraints of our project, as it is possible that this is a by-product of the scenario definitions.
Sensitivity to impacts	We explored sensitivity to impacts by re-running the optimisation with a range of impact multipliers from x0.5 to x2, and by removing specific impact categories.	The optimum level of investment does not appear to be sensitive to the impacts. This is likely to be because the benefit-cost ratio is high enough (5:1 for the overall OxCam analysis) that even a halving of benefits does not dramatically shift which interventions are cost-beneficial.
		Including or excluding gross value added or the carbon costs of flood recovery has no discernible effect on the optimum level of investment, but does affect the return on investment.
Sensitivity to costs	We explored sensitivity to costs by re-running the optimisation with a range of cost multipliers from x0.5 to x2.	Similarly, the intervention options adopted in the analysis are not sensitive to the costs. This is likely to be for the same reason as for insensitivity to changes in impacts. However, the overall level of investment required to implement those interventions is directly linked to costs – so the optimum investment level is highly sensitive to the cost data (i.e. if costs were doubled, the optimum investment would be doubled). Given that the level of investment is the core output of this project, this sensitivity is key. We would recommend that further work is needed to improve the cost models available for studies like OxCam (and, for example, the long-term investment scenarios project).
Sensitivity to different weightings of future scenarios	We explored sensitivity to different weightings of future scenarios by re-running the optimisation with two alternative scenarios of future weightings.	The core analysis applied equal probabilities to future scenarios. We found that the results do not change significantly when adopting different weightings (+/-0.3% of the optimum investment). However, if investment were optimised for a <b>single</b> future, the optimum investment could be much higher (e.g. a worst case of 31% higher under extreme climate change and extreme development) – this indicates that if we knew with absolute confidence that climate change and development would be extreme, we should invest more earlier to mitigate the changing risk, but that given the uncertainty, the present value investment is lower because we <b>defer</b> investment until we know more. This does not mean that the overall cash costs would be much different, but the effect of deferring investment is to reduce present value investment because of discounting.
Sensitivity to the level and timing of investment	We explored sensitivity to the level and timing of investment by calculating the change in NPV if investment were shifted up or down, forwards or backwards.	The results of this sensitivity analysis were as expected. Shifting investment forwards or backwards leads to a reduction in net present value, which should offer confidence that the optimisation process has found an optimum timing of investment.

Figure 5.3. Sensitivity analysis findings.

## 6. Conclusions

The main goal of this study was to find the optimum level and timing of investment for flood risk management in the Oxford to Cambridge Arc. **The findings in Section 4 show that the optimum whole life (present value) investment for the OxCam Arc is £5.6 billion over the 100 year study period.** Following the real options analysis approach, this single figure is a weighted average of the level of investment under different futures. **The optimum investment could be between £4.6 and £6.2 billion, depending on how future risk unfolds.**

The analysis enables different levels and timings of investment to be made under each future, but the findings show that **a significant amount of investment is likely to be cost beneficial irrespective of how future risk unfolds.** To maximise the return on investment, **the optimisation places over £2 billion of investment in the first decade.** Because the analysis optimises levels and timings of investment for every intervention (and under each future), the resulting investment profile is highly complex and does not follow a meaningful regional or catchment-scale pattern. There are no decisive catchment-wide trigger points – the variation in present day and future risk across the region means that the level and timing of investment is intervention-specific.

To find the optimum level and timing of investment, the project also posed a number of unique challenges which we addressed:

1. **How to ensure that adaptive planning forms part of a regional-scale analysis.** We found that the real options analysis enabled us to consider the relative merit of precautionary and adaptive investment and the likelihood that there will be a return on investment given uncertainty in the future.
2. **How to represent present day and future flood risk at a regional scale.** We used existing water levels, which were uplifted to represent climate change, to form the input to 730 models. Confidence in these models is closely linked to the quality and consistency of national asset and water level data, which presents challenges in a regional scale analysis. But using the same modelling software as local detailed modelling enabled us to generate meaningful floodplain depth information that could form the basis of an economic analysis.
3. **How to represent the benefits of flood risk interventions at a regional scale.** We developed approaches to representing interventions that were appropriate to the scale of the analysis – with necessary simplifications.
4. **How to optimise investment, given the complexity of a multi-catchment scale analysis with interventions at every scale from catchment down to property level.** The permutations of different interventions meant that calculating the results for every possible branch of the decision tree was not possible. We therefore had to adopt a more iterative approach to finding the optimum investment.



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