



Oxford to Cambridge Arc flood risk investment study

Modelling and hydrology technical report

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Environment Agency



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Project Manager: Daniel Boyd
Author: Susannah Hardwick
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Jacobs

The West Wing
1 Glass Wharf
Bristol, BS2 0EL
United Kingdom
T +44 (0)117 910 2580
F +44 (0)117 910 2581
www.jacobs.com

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1. Introduction

This report is one of four documents that together make up the reporting for the OxCam economic evidence study for investment in flood resilience and adaptation – a summary report and three technical reports. This report describes the modelling and hydrology which was undertaken to support the study.

The OxCam economic evidence study provides the evidence to answer the question: what is the optimum level and timing of investment from an economic perspective? This study has generated a large quantity of useful data that explores the costs and benefits (including consideration of wider impacts such as unlocking development through flood resilience investment) under a range of future scenarios, and enables us to answer a number of important questions about flood risk management investment across the OxCam Arc. The study has built an evidence base to support the Environment Agency in engaging with and influencing national and local stakeholders, in particular HM Treasury, the Ministry of Housing, Communities and Local Government and local authorities across the Arc, to ensure that the value of flood resilience investment can be maximised to support the OxCam Arc in its rapid economic growth. Further detail on the geographical context, background to and purpose of the study can be found in the technical summary report.

The study has considered flooding from rivers and surface water. This includes the tidally-influenced reaches of rivers but excludes direct coastal risk (i.e. major events affecting The Wash). We have not explicitly modelled the impact of surface water flood risk, instead analysing existing datasets, as described in Section 4.

We have selected an approach to modelling (for rivers) that provides an appropriate balance between provision of sufficiently local detail and the complexity and effort required in production at a regional scale. Modelling approaches can be considered across a spectrum from the use of existing broad scale national data to new detailed local modelling, as illustrated in Figure 1-1. The selected approach lies towards the middle of this spectrum. We have combined existing in-channel water level data with representative hydrograph profiles in a full hydrodynamic floodplain model with a resolution able to pick up floodplain features and flow routes. The method ensures that water levels on the floodplain are always lower than in the river, better reflecting the reality than fully decoupled in-channel and floodplain models (such as the modelling used by NaFRA). The approach has avoided the need for extensive, complex and time consuming 1D modelling by using existing national in-channel water level data and making use of a simplified approach to estimate the impact of interventions (e.g. Flood Storage and NFM) on in-channel water levels.

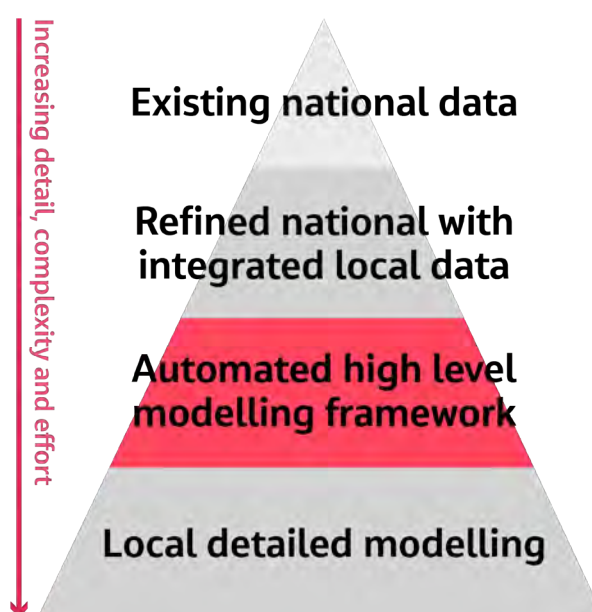


Figure 1-1. High level modelling framework.

The overarching framework for fluvial flooding is illustrated in Figure 1-2. In summary, we have used river level data to drive a high-level 2D model to create depth grids. We have represented the effects of climate change, flood storage and natural flood management (NFM) as changes to river levels. We have explicitly modelled the impact of changes to linear defences within the 2D domain. The treatment of each is described in Section 3.

We have considered the following scenarios, through a combination of explicit modelling and simulation look-ups:

- Seven annual exceedance probabilities (AEP%).
- Present-day and three climate change epochs (Section 3.4.1).
- Three climate change scenarios (Section 3.4.1).
- Three storage options (Section 3.5).
- Five fixed assets (linear defence) options (Section 3.7).
- Two natural flood management (NFM) options – with and without NFM (Section 3.6)
- Surface water flood risk management (sustainable drainage / SuDS) options (Section 4).
- Two property flood resilience options – with and without (described in the economics technical report).

This creates the need for approximately 2,100 river flooding scenarios, which would have translated to in excess of 21,000 model runs if each were modelled explicitly. However, the purpose of the modelling and hydrology within OxCam was to inform economic analysis and adaptive planning, and it was not intended for use in flood mapping. This allowed us to adopt a more efficient approach to analysis, avoiding the need to explicitly model each combination of scenarios. The modelling framework therefore maximised the opportunities for interpolation and 'simulation library' look-up of outputs. This is described in Section 5.

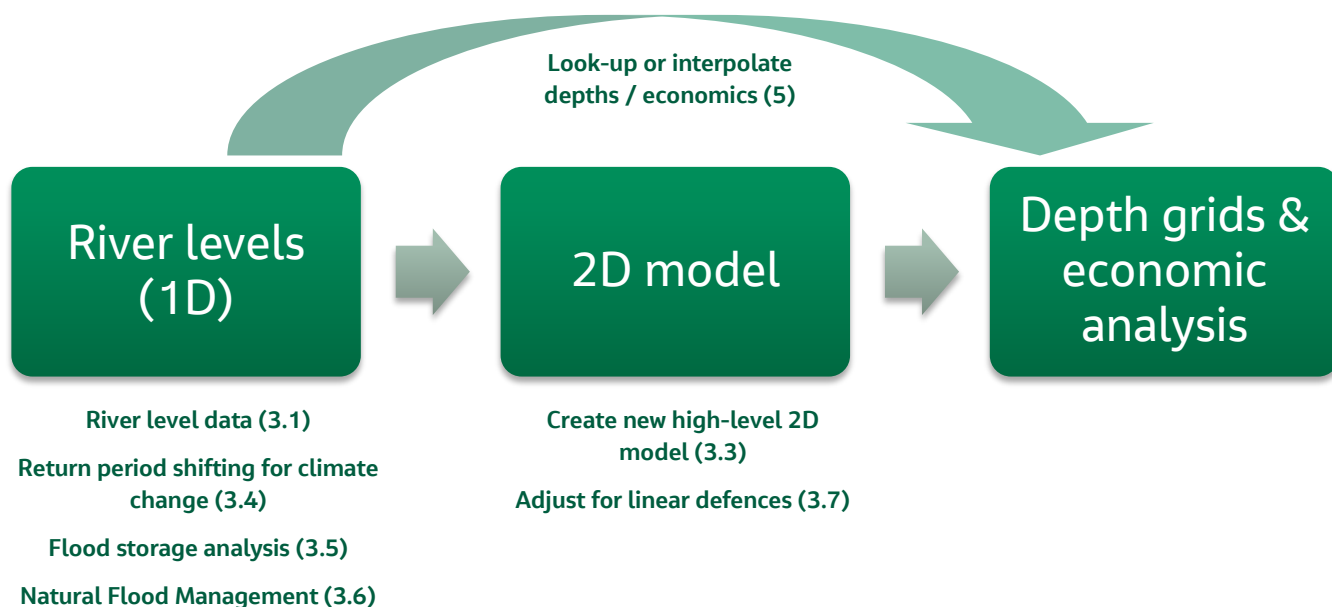


Figure 1-2. Modelling framework.

2. Data sources

Table 2-1 identifies the data sets and information used for our analysis.

Table 2-1. Modelling and hydrology data sources.

Dataset	Source	Purpose
State of the Nation (SoN) Model Databases	Environment Agency	<p>The SoN dataset shows the chance of flooding in any given year from rivers and sea, taking into account defences. While we have not used SoN outputs, we have used the inputs dataset for the SoN model as the primary input for High Level 2D modelling:</p> <ul style="list-style-type: none"> ▪ Flood Area: used for model domain/schematisation. ▪ Defence line (processed from AIMS and Continuous Defence Line CDL): used to model existing fixed defences. ▪ Peak water levels for each defence: The water levels are imported from National Fluvial Levels Database (NFLD) which provides estimates of river level at 100m intervals along channels designated as Main River and Critical Ordinary Watercourse. It includes levels for 40 return periods / AEPs. This is used as baseline level data used to run the 2D models.
National Height Product – Integrated Height Model (IHM) 2019	Environment Agency	This is a Digital Terrain Model (DTM) made with composite LIDAR, which we have used as the ground model for 2D models.
MapEdit	Environment Agency	<p>This data repository stores local detailed flood modelling outputs, i.e. modelled in-channel peak water levels and flood extents. We have used the following datasets for model verification:</p> <ul style="list-style-type: none"> ▪ Modelled Flood Groups (MFGs). ▪ Modelled Flood Outlines (MFOs). ▪ Modelled Flood Measurements (MMs). ▪ Modelled Information Locations (MILs).
AIMS asset geometries and crest levels	Environment Agency	<p>Linear and point spatial datasets containing flood risk asset information including crest level, standard of protection, asset condition.</p> <p>We have used this data to cross-reference the crest level information with the SoN defence layer.</p>

Dataset	Source	Purpose
Hydrograph profiles and Flood Frequency Curves	Environment Agency	<p>Hydrograph profiles and Flood Frequency Curves (FFCs) from existing studies at key locations throughout the catchment.</p> <p>We have used hydrograph profiles to estimate the impact of flood storage on levels (see Section 3.5 and Section 3.6).</p> <p>We have used Growth Curves to estimate the present day AEP of a flow with climate change uplift applied and therefore identify a suitable level for use in modelling (see Section 3.4).</p>
National Receptor Dataset (NRD) 2014	Environment Agency	<p>A static dataset of risk receptors including properties allowing us to compare impacts on a like for like basis. Includes additional information such as floor level, MCM code, building area and non-addressable properties to enable damage calculation.</p> <p>This was used as part of the model output verification process (see Chapter 6) and the modelling results in Chapter 7. NRD (and future development scenarios) were also part of the main economic analysis, described in the economics technical report.</p>
Property points for future development scenarios	Newcastle University and Jacobs	<p>Scenarios for future development in the OxCam area based around three combinations of annual residential property growth (23,000 30,000 and 43,000) and three combinations of location of growth (all development in new settlements, all development as expansion to existing settlements and a hybrid of new settlements and expansion of existing settlements).</p> <p>The outputs of Newcastle University's development models were housing density grids. We used these to produce property points that mirror the format of NRD. These were used to produce the modelling results in Chapter 7. NRD (and future development scenarios) were also part of the main economic analysis, described in the economics technical report.</p>
Flow data	Environment Agency	<p>Where hydrograph profiles are not available from existing studies we have created these using 15 minute flow data.</p> <p>We have used hydrograph profiles to estimate the impact of flood storage and NFM on levels (see Section 3.5 and Section 3.6).</p>
Local models	Environment Agency	The local flood models provide useful information for hydrograph generation.

Dataset	Source	Purpose
Climate change guidelines	Environment Agency	Guidance provided on the changes to fluvial flows, rainfall and sea levels due to climate change. We have used this guidance to inform our approach to climate change scenarios (see Section 3.4)

3. River flooding

3.1 Fluvial catchments

The OxCam area is into 3 main fluvial catchments; the Nene, the Great Ouse and the Thames. As illustrated in Figure 3-1 the OxCam area does not completely align to catchment boundaries. This is particularly the case for the Thames catchment in which only the parts of the catchment in Oxfordshire and Buckinghamshire (and therefore largely to the north of the River Thames) are included within the study. This has implications for comparing outputs of this study with others such as Thames Valley Flood Storage, as discussed in section 3.5.1.

For the purposes of this study we have subdivided the Great Ouse into two; the Bedford Ouse and the Ely Ouse (also referred to within this report as the Cam). The Bedford Ouse is the main channel, shown flowing through Bedford in Figure 3-1, Ely Ouse (not shown) flows to the south. They join just downstream of the OxCam study area. This approach was required to allow for the differing tidal limits of the two channels (see section 3.5).

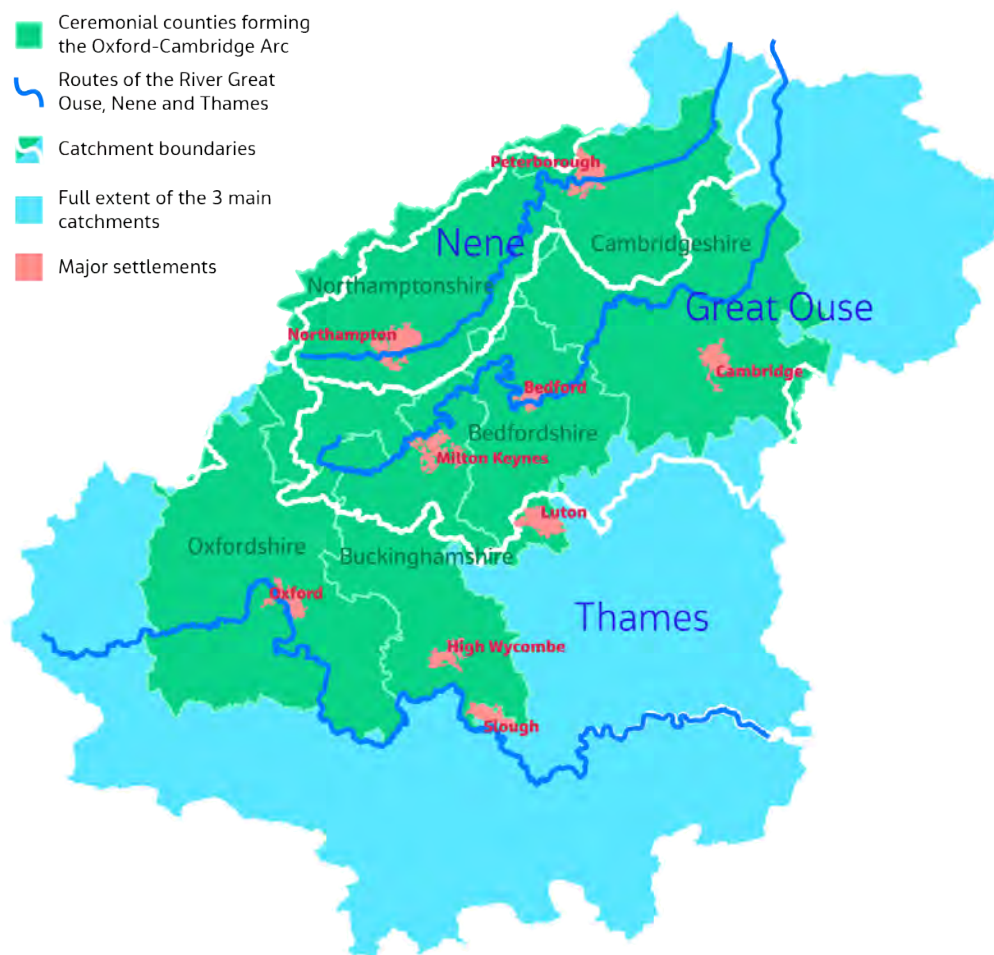


Figure 3-1. OxCam Arc. Ceremonial county boundaries (green), catchments (blue/white) and major settlements (pink)

3.2 Approach to deriving river levels and hydrograph profiles

We used 1D peak water levels from the State of the Nation database (SoN, 2018) as our base water levels for the modelling. This database contains modelled river levels throughout the study area from models prior to 2015/16, with levels for 40 AEP events. However, it does not contain water levels for climate change scenarios. We estimated these based on the method described in Section 3.4.

The Thames Valley Flood Scheme (TVFS) reviewed the viability of using flood storage to reduce flood risk across the Thames and as part of this collated water levels from recent modelled studies for parts of catchment. We considered and decided against the use of these levels because they are only available for a small part of the catchment (the Thames and a short length of the Windrush). Their use would have, therefore, lead to an inconsistent approach across the Thames catchment and study area and would not have provided value above use of the SoN data.

The advantages of the SoN data set are that it provides a consistent set of levels throughout the study area and can be applied rapidly. More recent study results are available within MapEdit but use of these data requires additional processing. Therefore, to meet project requirements on time and budget available, it was necessary to adopt use of SoN data. We have undertaken verification of baseline modelling and identified a number of inconsistencies within the SoN dataset (see Section 6.1), however given that it provides full coverage of the study area we consider it suitable for use. We have highlighted in our recommendations that future studies may wish to consider using level data from MapEdit.

Hydrograph profiles were required as part of the 2D modelling and flood spreading. Throughout much of the study area hydrograph profiles are available as part of local modelling. These reflect the differing catchment responses throughout the study area. Where hydrograph profiles are not available from local modelling we derived simple triangular hydrographs using the SoN hydrograph duration method.

3.3 Approach to 2D modelling and flood spreading

We have used SoN input data combined with hydrograph profiles from local models as the primary model inputs for our high-level 2D model, supplemented by Integrated Height Model. SoN input data provides consistent asset and water level data for the entire study area. It incorporates local modelling outputs (up to 2015/16) where possible, supplemented by national modelling data to provide full coverage.

We have used the industry standard 2D hydraulic solver TUFLOW HPC (GPU), to model floodplain spreading. The advantages of this modelling approach over the NaFRA and LTIS rapid flood spreading model are:

- A full hydrodynamic floodplain model developed in an industry-standard solver.
- Ability to obtain event flood extents and depth grids for flood impact calculations. NaFRA/LTIS produces Weighted Annual Average Damage (WAAD) which is calculated using flood probabilities instead of flood depth.
- Water level driven instead of inflow volume driven to better represent the flooding physics. The volume of water entering floodplain is calculated by the numerical engine considering both the water levels in the channel and on the floodplain for each timestep. This is significantly better than a simple weir equation as it accounts for the backwater effect from the floodplain. It also prevents the potential gross error of the inflow volume approach where water levels on the floodplain are higher than those in the channel for constrained floodplains.
- Finer grid resolutions (10-20 m) to pick up floodplain features and flow routes; NaFRA uses 50 m resolution.

The limitations of this high-level 2D modelling approach are:

- It is not as detailed as local modelling. For instance, it uses SoN crest levels (derived from AIMS) instead of surveyed crest levels and it cannot model in-channel structures and their complex hydraulics. If local modelling includes the in-channel hydraulic structures, our approach implicitly includes their influence, as they are already included in the input water levels that form part of the SoN water level dataset.
- Confidence in outputs may be affected by underlying issues in the input data – such as asset crest levels and in-channel water levels.
- It cannot explicitly model in-channel water level changes due to climate change and/or interventions. It relies on other (approximated) models and methods to estimate the climate and intervention impact on in-channel water levels.

- It does not simulate the cross-river impact on the water levels. For instance, increasing the height of a flood wall will increase in-channel water levels but reduce floodplain volume, which may have an adverse impact on other parts of the river.

We investigated the appropriate size for each 2D model domain. We developed models at the same scale as NaFRA flood areas but using a smaller grid size (NaFRA uses a 50 m grid). In most of the model we used a 10 m model. In the tidal areas of the Nene and Great Ouse we used a 20 m grid size. These flood areas also form the analysis units for the investment analysis.

Our original approach used 2D HT boundaries to link water level data to the 2D model domain. While running and reviewing the no defence model runs, we found that a 1D HT boundary model setup is more robust than a 2D HT boundary setup. 2D HT boundaries result in water level loading being duplicated (i.e. doubled) when two boundary lines fall onto the same grid cell, while 1D HT boundary handles this scenario more gracefully by taking the maximum of the two levels. We therefore adopted the 1D HT boundary setup universally for all models (and re-ran baseline models) to ensure a consistent approach across simulations.

3.4 Approach to representing climate change scenarios

3.4.1 Climate change projections

We considered scenarios for three climate change projections at three future epochs, as well as present day conditions (i.e. no increase in flow due to climate change).

The study area includes reaches of purely fluvial flows and reaches with a tidal influence. The climate change allowances used in this study are published by the Environment Agency (Flood risk assessments: climate change allowances, 2020) and are based around percentage increases to flows and an absolute increase to sea levels. As such the approach to climate change uplifts described below differ slightly for fluvial only and tidally influenced reaches.

Updated climate change allowances for peak river flows were released in July 2021 and therefore too late to be incorporated into this study. We therefore applied the peak river flow allowances available at the start of the study (Flood risk assessments: climate change allowances, 2020). These Environment Agency peak river flow allowances show the anticipated changes to peak flow by river basin district and are based on UKCP09 data. The study area falls into two of the river basin districts; Anglian and Thames. The published change factors used in this study are shown in Table 3-1.

The Environment Agency 2020 guidance on climate change allowance for flood and coastal risk projects states that in relation to river uplifts the central allowance should be used for design allowance, the upper end allowance to test sensitivity and the H++ to test options under more extreme climate change. The Environment Agency 2020 guidance on climate change for Flood Risk Assessments recommends allowances based on flood risk vulnerability of a development.

Table 3-1. Peak river flow allowances (based on 1961 to 1990 baseline and using UKCP09 data) (Environment Agency, 2020).

River basin district	Allowance category	Total potential change anticipated for the '2020s' (2015 to 2039)	Total potential change anticipated for the '2050s' (2040 to 2069)	Total potential change anticipated for the '2080s' (2070 to 2115)
Anglian	H++	25%	40%	80%
	Upper end	25%	35%	65%
	Higher central	15%	20%	35%
	Central	10%	15%	25%
Thames	H++	25%	40%	80%
	Upper end	25%	35%	70%
	Higher central	15%	25%	35%
	Central	10%	15%	25%

The newly released (2021) guidance provides climate change projections based on the UKCP18 data and provides projections at a more granular, Management Catchment Boundary Scale. It recommends that the central allowance should be used for the design allowance, the higher central allowance to test impacts of higher scenarios of climate change and the upper end¹ allowance to test options under more extreme climate change. A H++ projection is no longer provided.

The OxCam Arc lies across 5 Management Catchment boundaries in the Anglian river basin, and 5 in the Thames river basin. Table 3-2 compares the allowances used within this study (the 2020 guidance) with the range of climate change uplifts (the minimum and maximum from the management catchments) that would apply to the OxCam study area if the July 2021 values were applied. It is important to note that the two sets of uplifts are not directly comparable because they are based on different baseline line years; the 2021 uplifts are relative to a 1981-2000 baseline, whereas the previous were relative to a 1961-90 baseline. Within the Thames river basin the projections we have used for OxCam are all within the range of values provided for the various management catchments within the latest guidance (with the exception of the central and higher central estimates for the 2050s). These two estimates are however within 3% of the upper range of the latest estimates. Within the Anglian region the projections differ more and those used for 2050s and 2080s epoch are all higher than the latest estimates, albeit within a few percent. Despite these differences we consider that the OxCam results will adequately represent the range of climate change projections.

Given the modelling approach (and use of a 'simulation library' of outputs), it may be possible to update results based on changed uplift factors at a later date if required.

¹ The guidance states the "extreme allowance" should be used to test option under more extreme climate change however an "extreme allowance" is not provided and we have therefore interpreted this to mean the Upper End allowance.

Table 3-2. Range of climate change projections for management catchments within the OxCam Arc

River basin district	Allowance category	Total potential change anticipated for the '2020s' (2015 to 2039)		Total potential change anticipated for the '2050s' (2040 to 2069)		Total potential change anticipated for the '2080s' (2070 to 2125)	
		2021 guidance	2020 guidance	2021 guidance	2020 guidance	2021 guidance	2020 guidance
Anglian	Upper end	18% to 30%	25%	17% to 34%	35%	36% to 58%	65%
	Higher central	4% to 18%	15%	0% to 18%	20%	13% to 33%	35%
	Central	-2% to 13%	10%	-7% to 11%	15%	4% to 23%	25%
Thames	Upper end	24% to 33%	25%	27% to 43%	35%	49% to 84%	70%
	Higher central	11% to 17%	15%	10% to 22%	25%	25% to 43%	35%
	Central	6% to 12%	10%	4% to 14%	15%	15% to 31%	25%

Sea level allowances are based on UKCP18 projections of relative mean sea level rise around the UK coast. In addition, as these are based on UKCP18 data, projections to 2300 are available (river flow projections only extend to 2125). The guidance on climate change allowance for flood and coastal risk projects states that the higher central and upper end allowances based on the RCP8.5 scenario should be used. The H++ scenario for sea level rise is based on UKCP09 and is only projected to 2100. The guidance recommends that the higher central sea level rise should be used as a design estimate, the upper end to test sensitivity and the H++ to test options under more extreme climate change. Guidance recommends use of locally specific uplifts, however the flood risk assessment guidance provides uplifts based on region. We consider the latter is adequate for the strategic level of the OxCam study.

The Great Ouse and Nene catchments lie within the Anglian river basin district. The sea level rises for this region, as reported in the Flood Risk Assessment guidance (Environment Agency, 2020) are shown in Table 3-3. The H++ allowance is reported as a total sea level rise to 2100 of 1.9 m.

Table 3-3. Sea level allowances for the Anglian river basin district for each epoch (based on a 1981 to 2000 baseline), in mm per year (with the total sea level rise in brackets).

Allowance category	2000 to 2035 (mm)	2036 to 2065 (mm)	2066 to 2095 (mm)	2096 to 2125 (mm)
Upper end	7 (245)	11.3 (339)	15.8 (474)	18.1 (543)
Higher central	5.8 (203)	8.7 (261)	11.6 (348)	13 (390)

The climate change projections shown in Table 3-1 to Table 3-3 are for epochs (i.e. a time period) defined in the Environment Agency guidance rather than specific dates. Application of these uplifts for epochs would result in stepped changes of impacts and therefore have a significant effect on optimisation (see Climate Change Appendix A). Following discussion with the Environment Agency we have applied the climate uplifts using linear interpolation to create a smooth line. In doing this it was necessary to select a year within each epoch to which the uplift can be applied. The impact of selecting varying dates (start, middle or end) of the epoch is explored in Appendix A. Following discussion with the Environment Agency project team we agreed to apply linear interpolation between the mid-point of each epoch, but this has been implemented in a way that enables flexibility in this decision, for example, to support sensitivity analysis.

The study scope outlines the need to assess adaptive planning approaches up to 2150. The climate change guidance only provides peak flow allowances to 2115 for rivers and 2125 for sea level rise (although locally

specific uplifts can be identified to 2300 directly from UKCP18 data), in addition the H++ scenario for sea level rise only extends to 2100. We have therefore had to project climate change uplifts beyond the current guidance.

To allow the optimisation approach we created a linear interpolation and extrapolation of the H++ scenario, assuming a 1.9 m sea level rise in 2100 with a baseline year of 2010 (which ensures the H++ scenario is always larger than the Upper End). We have extended the H++ scenario for fluvial uplifts and for other tidal and fluvial uplifts using a linear extrapolation (using the same relationship established to interpolate between epochs). The issue is discussed further in Appendix A.

The reconsideration of the climate change approach, especially in relation to the extension of climate change projections beyond the period included in current guidance and the introduction of new guidance has been included within recommendations for periodic monitoring or update of the project. This will fit well with the adaptive management approach being followed by OxCam.

3.4.2 Application of climate change uplifts to fluvial only reaches

An overview of our approach to applying climate change uplifts in the fluvial only reaches is illustrated in Figure 3-2. As climate change allowances published by the Environment Agency (2020) for rivers are based around percentage increases to flows the most transparent approach to applying the change factors would be to directly adjust river flows for future epochs. This would, however, involve extensive modelling to develop flows throughout the study area and is not feasible for this study.

We have therefore used representative growth curves to relate climate change uplifts to the river levels used to drive the analysis. We have selected representative growth curves² and applied the climate change uplift to identify which present day AEP the climate change scenario equates. The level for this probability can then be selected or interpolated as the climate change scenario level. Where this results in a climate change uplift greater than the present day growth curve then we have extrapolated the growth curve and level relationship based on the last two points (lowest AEPs). This "AEP shifting" approach has been applied on other studies including Thames Valley Flood Storage (TVFS) and the Long Term Investment Scenarios (LTIS).

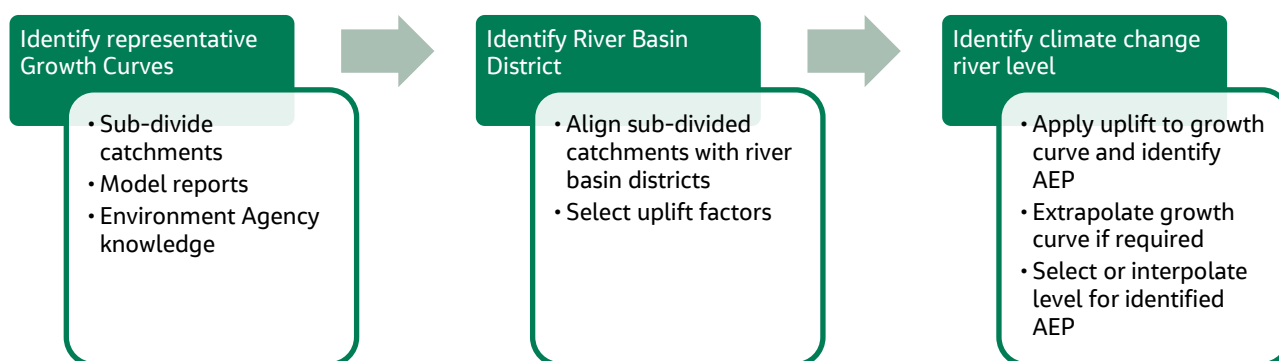


Figure 3-2. Summary of climate change approach.

One approach to selecting representative growth curves would have been to follow that used within LTIS and to apply the regional growth curves from the Flood Studies Report (FSR) (Natural Environment Research Council, 1975), as up-dated in the Flood Studies Supplementary Report No.14 (Natural Environment Research Council, 1983). The Flood Estimation Handbook (CEH, 1999), which superseded the FSR and its supplementary reports, does not have an equivalent of the FSR regional growth curves, meaning that it would not have been possible to incorporate the updated FEH data into this analysis.

² A growth curve is a flood frequency curve (which relates peak flow to Annual Exceedance Probability) scaled to have a value of 1 at the median annual maximum flood (QMED)

Using regional growth curves would have been quick to apply and is suitable for a national approach. However, their use would not have reflected variation in catchment responses throughout the region. We have therefore reviewed existing modelling studies to identify representative growth curves for sub-catchments within the study area.

We undertook an initial review of National River Flow Archive data to identify a long list of flow gauges that provide a good coverage of variation within the study area but without creating prohibitive granularity. We determined that the locations with available flood frequency curves at flow gauges did not provide sufficient coverage to identify variability across the catchment. We therefore identified locations for which we had local model results that we could use to identify a modelled flood frequency curve. These locations were determined based on review of model extents to ensure it recorded the full flow at that location (for example that model results accounted for floodplain flow). Table 3-4 identifies the flood frequency curves used in the analysis, which can be found in Appendix B.

Table 3-4. Locations selected as representative growth curves.

Station name and number / ID	Grid reference	Catchment	Source	Commentary on quality / limitation / assumptions
32002 - Willow Brook at Fotheringhay	506700, 293300	Nene	Report: Halcrow, September 2013, Willow Brook Model Report, version 3	
32003 - Harpers Brook at Old Mill Bridge	498400, 279800	Nene	Report: Halcrow, August 2013, Harper's Brook Model report, version 3	
32004 - Ise Brook at Harrowden	489900, 271300	Nene	Report: Halcrow, August 2013, River Ise Model Report version 4.0	
32007 - Nene/Brampton at St Andrews Total	474900, 261400	Nene	Report: CH2M, October 2016, Upper Nene Model Report. Version 4.1	
32008 - Nene/Kislingbury at Dodford	462800, 260700	Nene	Report: CH2M, October 2016, Upper Nene Model Report. Version 4.1	
32010 - Nene at Wansford	508100, 299600	Nene	Report: Halcrow, September 2013, Middle Nene Model Report, Version 3.0	
32020 - Wittering Brook at Wansford	508900, 299500	Nene	Model: Lower_Nene_2013, node z0619a	
32031 - Wootton Brook at Wootton Park	472600, 257700	Nene	Report: CH2M, October 2016, Upper Nene Model Report. Version 4.1	
33003 - Cam at Bottisham	550700, 265600	Ely Ouse	Report: Halcrow, February 2012, River Cam Flood Mapping Report.	QMED results not available so extrapolated linearly
33005 - Bedford Ouse at Thornborough Mill	473500, 235300	Bedford Ouse	Model: UpperOuse_Upper_2011, node OUS_155600	QMED results not available so extrapolated linearly
33012 - Kym at Meagre Farm	515600, 263100	Bedford Ouse	Model: LowerOuse_Kym_2015, node ky_0580	
33016 - Cam at Jesus Lock	545000, 259300	Ely Ouse	Report: Halcrow, February 2012, River Cam Flood Mapping Report.	
33017 - Bedford Ouse at St Ives	531400, 270600	Bedford Ouse	Model: LowerOuse_Downstream_2015, node GtO11600	

Station name and number / ID	Grid reference	Catchment	Source	Commentary on quality / limitation / assumptions
33018 - Tove at Cappenham Bridge	471100, 248700	Bedford Ouse	Report: Capita Symonds, 2011, Upper River Great Ouse: Brackley to Newport Pagnell	
33020 - Alconbury Brook at Brampton	520800, 271800	Bedford Ouse	Report: Mott MacDonald, December 2015, Lower Great Ouse Flood Risk Mapping	
33022 - Ivel at Blunham	515300, 250900	Bedford Ouse	Report: Jacobs, 2018, Ivel Model Project	
33024 - Cam at Dernford	546700, 250650	Ely Ouse	Report: Halcrow, February 2012, River Cam Flood Mapping Report.	
33027 - Rhee at Wimpole	533300, 248500	Ely Ouse	Report: JBA Consulting, 2014, River Cam & Tributaries Mapping Study	
33034 - Little Ouse at Abbey Heath	585100, 284400	Ely Ouse	Report: JBA Consulting, 2015, Easter Rivers Modelling Report: Lower Rivers	
33035 - Ely Ouse at Denver Complex	558700, 301000	Ely Ouse	Model: Fenland_2016, node Hund2_0	QMED results not available so extrapolated linearly
33037 - Bedford Ouse at Newport Pagnell Total	487700, 244200	Bedford Ouse	Report: Capita Symonds, 2011, Upper River Great Ouse: Brackley to Newport Pagnell	
33039 - Bedford Ouse at Roxton	516000, 253500	Bedford Ouse	Report: Halcrow, 2011, Middle Great Ouse Flood Mapping	
33053 - Granta at Stapleford	547000, 251400	Ely Ouse	Report: Halcrow, February 2012, River Cam Flood Mapping Report.	
39001 - Thames at Kingston	517800, 169900	Thames	Report: JBA consulting, 2017, Lower River Thames Flood Modelling Study	
39002 - Thames at Days Weir	456900, 193600	Thames	Report: CH2M, June 2017, Abingdon Flood Schemes – Hydrology Report	
39008 - Thames at Eynsham	444500, 208700	Thames	Report: Halcrow, August 2010, Thames: St Johns to Evenload Confluence Flood Risk Mapping Study	
39010 - Colne at Denham	505200, 186400	Thames	Report: JBA, 2014, Lower River Thames Flood Modelling Study - River Thames Hydrology Report, Flood Estimation Calculation Record Appendix	
39021 - Cherwell at Enslow Mill	448200, 218300	Thames	Report: CH2M, December 2015, Oxford Flood Alleviation Scheme – Hydrology Report	
39023 - Wye at Hedsor	489600, 186700	Thames	Report: JBA consulting, June 2020, Lower Thames, Jubilee River and River Ash Modelling study	
39034 - Evenlode at Cassington Mill	444800, 209900	Thames	Report: Halcrow Group Ltd:2010, Thames: St Johns to Evenlode Confluence Flood Risk Mapping Study	

Station name and number / ID	Grid reference	Catchment	Source	Commentary on quality / limitation / assumptions
39072 - Thames at Royal Windsor Park	498000, 177200	Thames	Report: JBA consulting, June 2020, Lower Thames, Jubilee River and River Ash Modelling study	
39081 - Ock at Abingdon	448100, 196700	Thames	Report: Report: CH2M, June 2017, Abingdon Flood Schemes – Hydrology Report	
39111 -Thames at Staines	503500, 171300	Thames	Report: JBA consulting, June 2020, Lower Thames, Jubilee River and River Ash Modelling study	
39121 - Thames at Walton	509900, 167100	Thames	Report: JBA consulting, June 2020, Lower Thames, Jubilee River and River Ash Modelling study	
39130 - Thames at Reading	471800, 174100	Thames	Report: JBA consulting, June 2020, Lower Thames, Jubilee River and River Ash Modelling study	
39140 - Ray at Islip	452300, 213700	Thames	Report: CH2M, December 2015, Oxford Flood Alleviation Scheme – Hydrology Report	
ID_17	492018, 267181	Nene	Model from: Halcrow, September 2013, Middle Nene, Nene Flood Map Improvements Project, node a5420 / Spill:WellingLB15U / Spill: WellingRB14U	
ID_36	519457, 298110	Nene	Model from: Halcrow, September 2013, Lower Nene, Nene Flood Map Improvements Project, node z0472a	
ID_38	520019, 297167	Nene	Model from: Halcrow, September 2013, Lower Nene, Nene Flood Map Improvements Project, node ST708d	A very shallow growth curve.
ID_39	541512, 305029	Nene	Model from: Halcrow, September 2013, Lower Nene, Nene Flood Map Improvements Project, node s23-6	Very shallow growth curve
ID_42	529221, 299931	Nene	Model from: Halcrow, September 2013, Lower Nene, Nene Flood Map Improvements Project, node s37-2 / Spill: s37-2sru	Very shallow growth curve
ID_43	529578, 299025	Nene	Model from: Halcrow, September 2013, Lower Nene, Nene Flood Map Improvements Project, node mo811000 / Spill: mo811000slu	
ID_45	510997, 213378	Thames	Model from: JBA consulting, January 2019, River Ver Modelling study, node VER_10752	
ID_46	542209, 279380	Bedford Ouse	Model: LowerOuse_Downstream_2015, node Hund2_2000	Very shallow growth curve
ID_49	485331, 246584	Bedford Ouse	Report: Halcrow, December 2011, Middle Great Ouse Flood Mapping Study, node GO119600U	QMED results not available so

Station name and number / ID	Grid reference	Catchment	Source	Commentary on quality / limitation / assumptions
				extrapolated linearly
ID_50	494394, 255613	Bedford Ouse	Report: Halcrow, December 2011, Middle Great Ouse Flood Mapping Study, node G092990	QMED results not available so extrapolated linearly
39138 - Loddon at Twyford	477800, 176800	Thames	Report: JBA, January 2008, River Loddon Flood Hydrology	
39105 - Thame at Wheatley	461200, 205000	Thames	Report: CH2M, August 2017, Thames Catchment Storage, Appendix - Hydrological Assessment of Thames Catchment Storage	
39142 - Windrush at Bourton on the Water	440200, 201900	Thames	Report: Halcrow, December 2013, Modelling Report - Thames Main River Limit to St John's Modelling and Mapping SFRM2	

3.4.3 Tidally influenced reaches

The study area includes tidally influenced river reaches within the River Nene and the Great Ouse catchments. Water levels within these reaches are therefore influenced by both river flows and sea levels, and climate change factors differ for these two sources. River flow increases are shown in section 3.4.1. Sea level allowances are provided by the Met Office UK Climate Projections website (Met Office, 2020) and vary depending on location.

The most transparent approach to determining the impact of the Environment Agency guidance climate change factors on levels in these areas would have been to directly adjust river flows and sea levels within a hydrodynamic model. This would have involved extensive modelling to develop flows throughout the study area and was not feasible for this study.

Our approach to adjusting water levels in tidal areas for the impact of climate change avoids direct modelling but allows for the differing climate change projections for sea level rise and river flow and the interaction of the two.

The approach is illustrated in Figure 3-3. As shown, at the point where the water level is entirely fluvially dominated then we have applied the climate change uplift based on river flows and at the point where water level is entirely sea level dominated we have applied the sea level uplift. Between these two points a combination of the two influences apply at each node, with fluvial influence increasing and sea level influence decreasing in relation to the distance from the coast. We have then combined the two influences with the present day water level at each node to create the water level for a given climate change scenario.

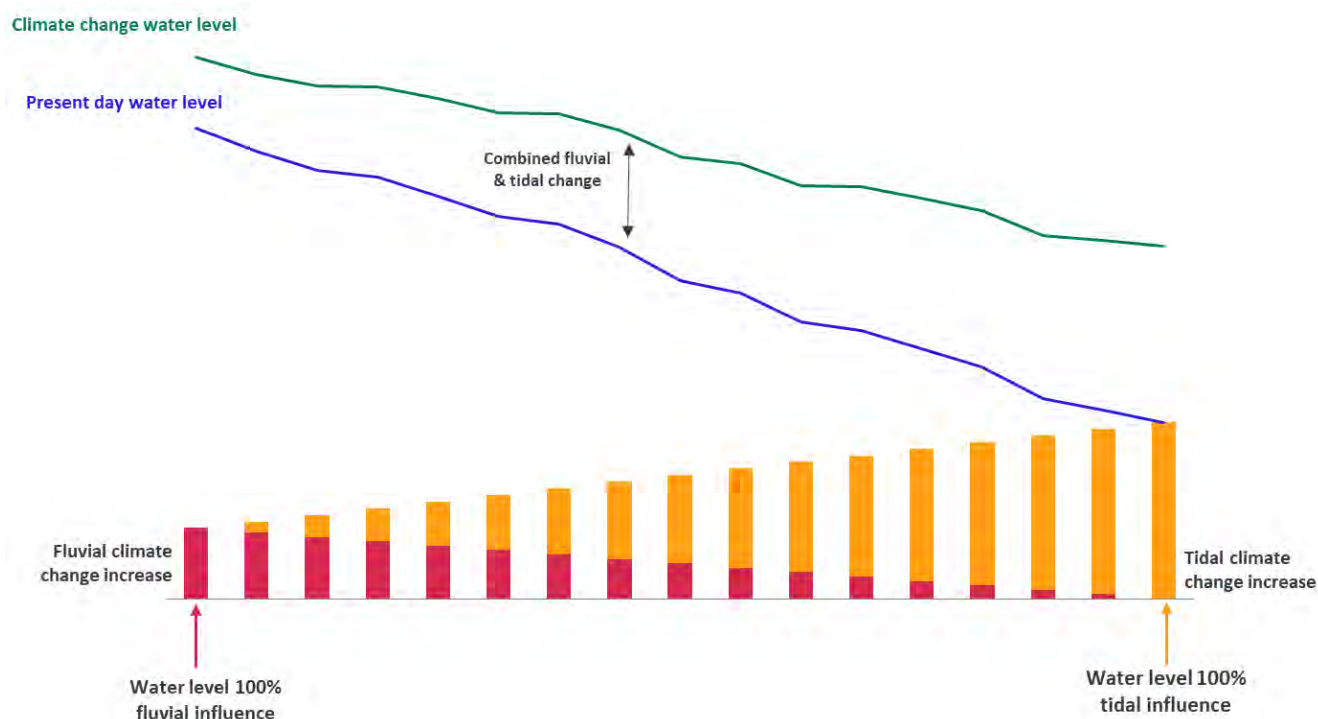


Figure 3-3. Application of climate change uplifts in tidally influenced reaches.

The method assumes that the tidal limit (i.e. point at which the river is no longer influenced by sea level) is fixed. This is a reasonable assumption given that the tidal limits on the Great Ouse and the Nene are defined by structures, if we assume that the structure will not be drowned by sea level rise. The approach does not reflect situations in which the tidal limit could change because of failure of those structures under the influence of sea level rise.

As highlighted, in-depth modelling would be required to develop an understanding of changes in tidal limit and to fully understand the interaction of fluvial and tidal systems and climate change impacts. Such modelling was not feasible as part of this study. Rather the outputs have been reviewed to identify and address anomalies in the results.

Whilst the method considers the influence of sea level rise on water levels within channels and consequently on the floodplain, it does not consider flooding as a result of overtopping or failure of coastal defences.

Figure 3-4 highlights the tidal reaches of the study area. The locations of tidal limits have been provided by the Environment Agency as:

- Tidal lock and sluice at The Dog in a Doublet on the River Nene (TL 27198 99283).
- Brownhill Stauch, tidal limit on the Bedford Ouse (TL 36947 72703).
- Denver Sluice, tidal limit on the Ely Ouse (TF 58787 00992).



Figure 3-4. Tidal reaches as agreed with the Environment Agency team.

3.5 Approach to representing flood storage

3.5.1 Our approach

The impact of flood storage cannot be directly related to water levels, rather storage can be considered to restrict or reduce flow from part of a catchment which will then result in a change in levels downstream. In a similar way to our approach to climate change we used the relationship between changes to flow and growth factors to identify an appropriate water level that would likely result from the use of storage.

Our analysis does not consider the location of possible storage, rather we examined the volume of water which requires storing to change from a given AEP to another AEP at the downstream reach of each of the three catchments (Thames, Nene and Great Ouse). We have then related this AEP to a flow, using the relationship with the growth curve as described in Section 3.4. We have assumed that a portfolio of storage interventions would be implemented to produce an equivalent change in AEP throughout the catchment. Using representative hydrograph profiles and Flood Frequency Curves we have then calculated the volume of storage required to prevent flow greater than the required value. We iterated these values where we found the required storage volumes were too extreme to be realistic, before selecting the 3 storage scenarios listed in Table 3-5. In tidally influenced reaches we have applied the method described in Section 3.4.3 to ensure that the impact of flood storage only affects the fluvially dominated water level and does not reduce water levels that are a result of sea level.

The Great Ouse has two tidal limits – one for the Bedford Ouse and one for the Ely Ouse. For the purpose of storage assessment we have assigned a flow gauge to each, resulting in the calculation of storage at four

locations. We have identified four gauged locations representing the downstream extent of each catchment at which we have undertaken the analysis:

- 33039 – Bedford Ouse at Roxton.
- 33003 – Cam at Bottisham.
- 32010 – Nene Wansford.
- 39111 – Thames at Staines.

We have assigned flood frequency curves for storage to geographical areas as shown in Figure 3-5. **Error! Reference source not found.** Flood Frequency Curves have been taken from local model reports. Where flow data was available we have used gauged data to develop non-dimensional hydrographs. Data was not available for the Cam at Bottisham so the hydrograph has been taken from local modelling. Further information about development of the non-dimensional hydrographs and source of the flood frequency curves is supplied in Appendix C.

We have investigated the impact of three storage options across each main catchment; small, medium and large. The approach of investigating small, medium and large storage options has successfully been used on the Thames Valley Flood Scheme to explore variations in economic benefits and numbers of properties at risk. We have not specifically used information from TVFS in the OxCam investigation, as the needs and limitations of the projects differ. The TVFS study was much more targeted at reducing risk to specific settlements, whereas in our approach we provide a 'blanket' risk reduction across the catchment. TVFS explicitly explored viable storage locations and sizes for individual interventions. In this project, we have made the conscious decision to avoid defining specific storage locations, and therefore have not investigated location feasibility or considered the maximum storage size of an individual intervention – instead we consider each 'size' of storage to be a portfolio of individual storage interventions that together provide a catchment-wide benefit. The effect of this is that under the OxCam study, higher storage volumes are needed to provide the same level of protection to 'key' settlements than in TVFS, but OxCam provides broader protection. Another key difference is the area included within each study. The OxCam study area excludes much of the Thames catchment area that TVFS aims to protect and conversely TVFS does not consider protection for the Great Ouse and Nene catchments. Results can not, therefore, be directly compared.

The advantage of our method for this high-level study is that it avoids the need for extensive modelling. It also avoids the need to identify specific areas for flood storage but rather assumes the storage is upstream of the gauge, which is consistent with the wider approach for this study. It does not however explicitly consider whether the identified volume of storage is feasible within the upstream catchment (i.e. due to land availability) – although we did adjust storage volumes based on a subjective assessment of viability.

3.5.2 Implementing the approach

We have developed a spreadsheet tool to identify the volume of storage required for the small, medium and large scenarios. This spreadsheet uses the non-dimensional hydrographs and flood frequency curves at each of the 4 gauges to identify this volume. A very similar spreadsheet method (based on recorded flows and without the relationship to levels) has been used by the Environment Agency Thames team to develop an understanding of the volume of storage required along the Thames to achieve certain standards of protection.

Our small, medium and large storage volumes have been selected to provide a broad range of scenarios. The volumes used approximately equate to that required to reduce flow at each of the 4 downstream gauges from one AEP to either the 10% AEP or 5% AEP in the present day (baseline) scenario. Note however that this is not a standard of protection but a means of defining a volume, for example whilst the large storage volume is calculate as reducing flow to 5%AEP (a lesser event than that listed for the Medium and Small storage) it still provides a larger storage volume and therefore greater flood protection. The Table 3-5 details the volumes used in each option.

Table 3-5. Storage volumes used for small, medium and large options in m³.

Storage option	Flow reduced from AEP	Flow reduced to AEP	39111 -Thames at Staines	32010 – Nene at Wansford	33039 – Bedford Ouse at Roxton	33003- Cam at Bottisham
Small	Baseline 2% AEP	Baseline 10% AEP	86,343,188	7,753,290	5,016,139	1,181,646
Medium	2050s Central climate change 1% AEP	Baseline 10% AEP	265,174,084	23,985,897	17,000,693	4,452,827
Large	2080s H++ climate change, 1% AEP	Baseline 5% AEP	1,034,101,877	78,163,589	64,151,779	13,463,214

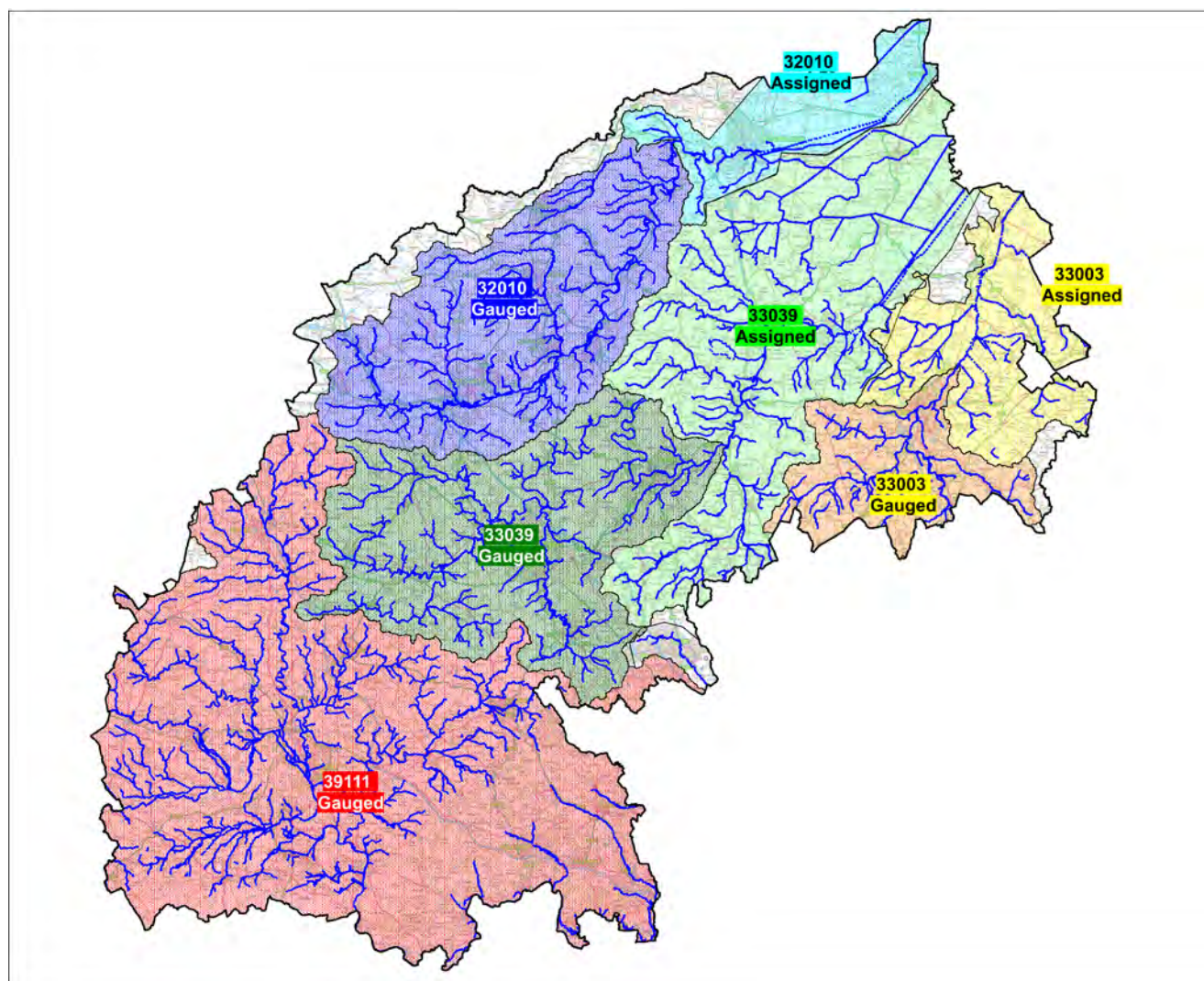


Figure 3-5. Geographical Assignment of Flood Frequency Curves for storage, showing both the catchments upstream of the gauge (Gauged) and the catchments downstream of the gauge but which use the gauged hydrograph profile (Assigned).

The volumes identified from this spreadsheet were then incorporated into the model automation process such that, for a given asset node and storage scenario (none, small, medium or large), the process was to:

- 1) Identify which main catchment the node lies in (Thames, Nene, Bedford Ouse or Cam) based on its XY coordinates (see Figure 3-5 **Error! Reference source not found.**).
- 2) For each return period an adjusted (reduced) return period is calculated based on the storage scenario:
 - a) If the storage scenario is 'none' then no adjustment is made to the return period.
 - b) The peak flow for the main catchment is taken from the FFC and is used to scale the pre-defined hydrograph profiles.
 - c) The total storage volume and threshold return period are looked-up for the given catchment and scenario (threshold return period defining the return period at which the storage begins to be used).
 - d) If the given return period is below the threshold return period, then no adjustment is made
 - e) The amount of storage used is then cumulatively calculated along the hydrograph above the threshold return period until all the storage is full, leading to three possible outcomes (illustrated in Figure 3-6):
 - i. Total storage is used on the rising limb before the peak flow, therefore no adjustment is made to the return period (and thus level).
 - ii. Total storage is used up on the falling limb but above the threshold return period, therefore the corresponding flow at this time is taken as the peak flow, and then converted to a new return period through linear interpolation of the flood frequency curve.
 - iii. Total storage is not used up before the falling limb drops below the threshold return period, therefore the adjusted return period is equal to the threshold return period.

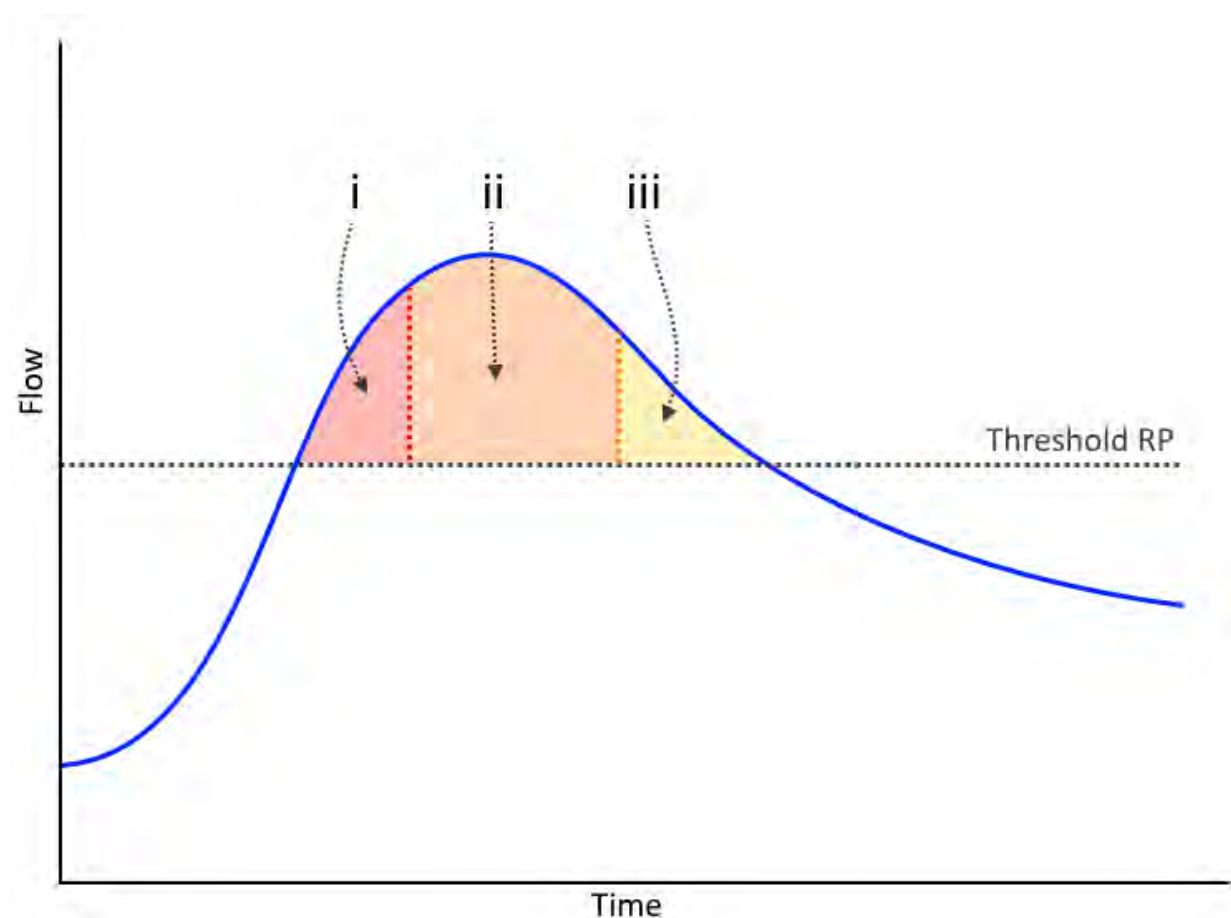


Figure 3-6. Calculation of the impact of storage.

3.6 Approach to natural flood management

3.6.1 Our approach

LTIS 2019 used the *working with natural processes opportunity mapping* as an indicator of the land available in a catchment, in order to estimate a realistic peak flow reduction that could be achieved in each catchment through NFM. Instead, following discussion with Environment Agency subject matter experts, we have represented the influence of NFM as an equivalent storage volume. We have followed a similar approach to that outlined for engineered storage (section 3.5). This has been applied at a tributary level with **no impact** shown on the main channel (to reflect the lack of evidence that supports the effectiveness of NFM on larger catchments). We have also used data associated with additional flow gauges to better represent variation of the characteristics of the more upstream catchments.

The benefit of this approach – within the constraints of this project – is that it ‘decouples’ the approach between a) the representation of the water level changes (and therefore risk reduction benefits) of a given ‘equivalent storage volume’ of NFM from b) the calculation of costs to deliver a given ‘equivalent storage volume’.

We have:

- 1) Developed a function of NFM investment vs. equivalent storage volume. This has been based on a series of indicative portfolios of NFM which would be expected to generate different equivalent storage volumes, from which we can derive costs associated with that portfolio. This is described in the economics report.
- 2) Used the *working with natural processes evidence directory* to identify a typical ‘standard of protection’ considered viable for NFM investment in each sub-catchment. As with other parts of the approach, this ‘standard of protection’ is not an SoP in the traditional sense, as NFM is just one of a portfolio of interventions that could be applied, but the SoP is used to derive meaningful and realistic intervention options.
- 3) Identified the equivalent storage volume required to achieve the desired standard of protection in each sub-catchment, through the storage spreadsheet tool and automation process referred to in section 3.5. This volume can then be used to attribute a cost to each NFM scenario for a given sub-catchment.
- 4) Assume that the volume required to achieve the standard of protection can be stored within a fully rural catchment. Adjust the identified equivalent storage volume based on rural area such that:

$$\text{Adjusted equivalent storage volume} = \text{Equivalent storage volume} \times \frac{\text{Rural land area}}{\text{Catchment area}}$$

- 5) Adopted the same approach as applied for engineered storage to translate a storage volume to shifted AEPs and therefore water levels for a given AEP, to enable modelled results to be extracted for the NFM scenarios in each sub-catchment.

In reviewing possible approaches to assessing NFM we considered an alternative method in which we used data from the *working with natural processes evidence directory* to identify the potential percentage peak flow reduction that could be achieved at different return periods through NFM. We decided against using this method because:

- It resulted in different peak flow reductions for different AEPs, making it difficult to derive the equivalent costs for a given intervention.
- We consider that drawing a varying relationship between AEPs and peak flow reductions suggests a level of precision and knowledge of NFM that is not yet available from the evidence base.
- Applying a percentage peak flow reduction to represent NFM does not provide the level of spatial variability in the effect of a given level of investment in NFM on the flow of water in the catchment.
- The relationship suggested by the *evidence directory* included a peak flow reduction even at higher return periods, which would likely result in a dramatic over-estimation of the risk reduction benefits of NFM. In hydrological terms, the peak flow reduction method effectively removes volume from the peak of the

hydrograph rather than the start, therefore assuming that there is always a reduction in flooding due to NFM, where in reality in large events the impact of NFM may not be evident.

By contrast our selected approach provides a means of estimating the cost of NFM, allows us to represent the understanding that NFM is effective at lower order events and is likely less effective at more extreme events (Dadson, et al., 2017) and makes use of available evidence whilst clearly acknowledging the uncertainty through the simplicity of the approach.

It is important to acknowledge that there is limited information available on the impact and costs of NFM at any scale and consequent uncertainty in the estimates. The proposed approach is intended to make best use of the available data and to provide consistency with the approaches being adopted by other aspects of the project.

3.6.2 Selection of flood frequency curves and hydrograph profiles

As volume has been used as a proxy for costing NFM and estimating the reduction in water levels due to NFM, the application of the approach is very similar to that for engineered storage (Section 3.5) and representative hydrographs and flood frequency curves are required. Figure 3-7 **Error! Reference source not found.** illustrates the gauges from which hydrograph profiles and FFCs have been used and the reaches in which data from each are applied. At each gauge the equivalent storage volume provided by NFM has been calculated and then adjusted by area for application to the sub-catchments.

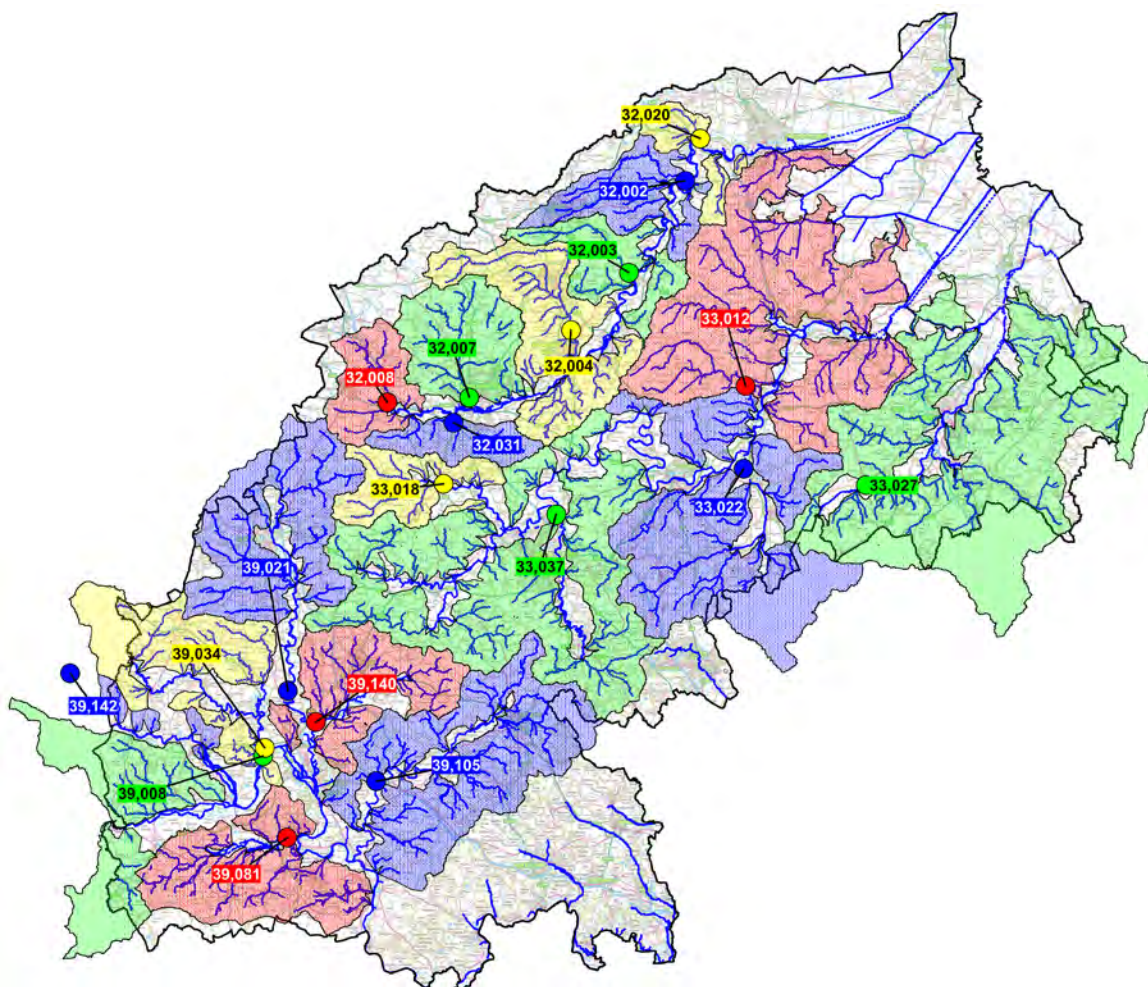


Figure 3-7: Catchment delineation for NFM analysis.

3.6.3 NFM standard of protection

The *working with natural processes evidence directory* provides studies across a range of catchments which present evidence of the impact of NFM. The directory largely includes outputs from modelled studies although there is some empirical evidence available.

We have assumed that NFM can provide a level of protection (for the purposes of OxCam, in the form of storage) that reduces the present day 5% AEP water level to the present day 50% AEP water level. This provides a level of storage less than that given by the “small” engineered storage options, which seems a sensible assumption. The exact level of protection offered by NFM is – much like the range of selected defence-raising options – arbitrary by design – the requirement is that they are broadly representative of a realistic possible NFM intervention in a catchment. The cost and benefit analysis around it will translate that level of protection to a meaningful level of investment needed to deliver the stated benefit. The resulting volumes of storage at each gauge are listed in Table 3-6.

We do not have model outputs for water levels below the 50% AEP event. This means that the benefits of NFM for the 50% AEP event cannot be modelled using this approach, however flood impacts at this level are likely to be small.

Table 3-6. NFM storage volume for gauged catchments.

Catchment ID	NFM Storage Volume (m3)
33018	1,382,289
32002	1,651,480
32003	1,063,653
32004	2,009,921
32008	1,563,317
32007	752,254
33012	514,186
33022	2,574,092
33027	265,796
33024	791,246
33037	14,839,418
33053	977,449
39008	28,961,911
39034	1,089,467
39081	3,152,343
39140	5,278,997
39142	2,358,765
39021	13,001,965
39105	6,760,919

3.7 Approach to linear defences/interventions

3.7.1 Introduction

We have included linear defences in the 2D model via an automated process that builds the models using a series of geodatabases. The linear defences are represented as line features, with different attributes, in the GIS database. These attributes are the existing defence level, the ground level (without defences) and the increased defence level.

We have considered 5 linear defence scenarios :

- Undefended. This is to represent scenarios where defences are not replaced at their end-of-life, and so are effectively removed. We have applied ground levels based on the SoN asset data to the model.
- Present day defence crest levels, using the existing defence levels from the SoN asset data.
- 3 increases in defences, based on providing the equivalent of a 'standard of protection' at 3 different levels. Present day defence crest levels are maintained at their current level or raised (never lowered).

3.7.2 Defence raising options

In this study, the concept of a 'standard of protection' is not highly relevant, because each intervention is just one of a portfolio of interventions that could be applied to reduce risk at a given location. However, the 'standard of protection' is still a useful mechanism for determining realistic defence-raising scenarios based on water levels for a given scenario – which are more locally meaningful than simply selecting homogenous defence raising levels across the study area. We reviewed the existing defence levels as part of the baseline model verification process (section 6.1), and explored possible defence raising scenarios. We adopted 3 defence raising scenarios, based on the defence crest level required to provide protection under 3 flood scenarios:

- 1) 2% AEP present day.
- 2) 1% AEP 2050s (central climate change).
- 3) 0.5% AEP 2080s (H++ climate change).

These scenarios were selected because they provide a useful spread of levels of protection at each location under different future scenarios. We assessed the scenarios by exploring the defence raising at sample points in all 745 flood areas, and produced summary statistics (Table 3-7) to check them.

Table 3-7. Current defence heights and increase in defence heights for different defence raising options.

	Current defences	Small	Medium	Large
Mean	2.2m	+ 0.2m	+ 0.4m	+ 0.6m
Median	2.0m	+ 0.2m	+ 0.3m	+ 0.4m
75%ile	3.5m	+ 0.2m	+ 0.5m	+ 0.7m
95%ile	4.3m	+ 0.6m	+ 1.1m	+ 1.6m
Maximum	5.0m	+ 1.7m	+ 3.8m	+ 5.2m

In general, we found the level of variation in water levels to be small, meaning that the distinction between the 3 defence levels is minimal in many locations. Note, however, that the statistics in the 'current defences' column in the table is based on just the 15 flood areas where the reference point included raised defences – a very small subset of the 745 flood areas, so conclusions should not be drawn about the difference in levels between that column and the adopted defence raising scenarios.

The levels were then applied to every entry in the continuous defence line (i.e. the SoN input data) based on the catalogue of water levels generated for the present day and climate change scenarios. These form the asset geodatabases used to generate the linear defence raising model runs.

3.7.3 Edge cases

In flood areas where **some** of the flood area has raised defences, but there are 'undefended' segments, we make an assumption that *in a scenario where there are raised defences, currently defended areas are assumed to be protected to **at least** the same crest level height*. This means that:

- Undefended (i.e. not replacing defences at their end of life) remains an option.
- Maintaining present defences retains the currently undefended 'gaps'.
- Raising defences to a set 'standard of protection' retains the maximum crest level of either the existing defences **or** the raised defence level for each asset – i.e. existing defences are not lowered.

3.8 Approach to property flood resilience

Property flood resilience is represented by modifying depth-damage curves as part of the damage calculation process, rather than as part of the core modelling process described in this report. This approach is described in more detail in the economics technical report.

4. Surface water flooding

4.1 Introduction and present day risk

The initial agreed study scope included new high-level modelling of surface water flooding. We reviewed available methods and determined that the improvements to outputs achievable within the constraints of this study would not warrant the additional cost of (and risk to the programme of) undertaking the modelling. It is, however, necessary to acknowledge the importance of surface water flooding to the overall risk in the OxCam area.

Rather than producing new modelling, we have made use of the existing 'detailed' Risk of Flooding from Surface Water dataset (RoFSW). We used depth information for the three available present day AEPs (3.3%, 1% and 0.1%). Each of these datasets was divided into the same Flood Risk Management Systems used for the fluvial investment analysis. We selected this scale over the NaFRA flood areas used for the fluvial modelling itself because the NaFRA flood areas are restricted to the fluvial/tidal floodplain, which would exclude areas at risk of surface water flooding outside the floodplain.

This surface water data was fed through the same impact analysis as the fluvial data – this is described in full in the *economics technical report*, and uses property point sampling of depth grids to obtain a flood depth to feed into property impact calculations. However, the RoFSW dataset does not accurately reflect the depth of flooding within property boundaries (as building outlines are raised in the terrain data used to feed into the modelling). We therefore followed a standard approach to estimate the depth of flooding for each property:

- Identifying the MasterMap building outputs that correspond to National Receptor Dataset property points.
- Buffering the building outlines and removing parts of the building outline which overlap with other buildings (e.g. for terraced properties) to identify the detached building perimeter.
- Identifying the average flood depth around the wetted perimeter.

Due to limitations in the existing tools used for the impact analysis, these calculated depths could not be directly attributed to property points. We therefore instead stamped these depths into a new derived depth grid, which formed part of the automated impact analysis alongside the fluvial model output data.

4.2 Representing future changes

We have represented both climate change and surface water interventions by considering the **volume of water** in the Risk of Flooding from Surface Water output data in each FRMS – calculated by analysing the available depth data. We assume that (as indicated by Figure 4-1) the total volume of water in the floodplain is equal to the cumulative volume of water which has collected on the surface in addition to the drainage network capacity, over the duration of the flood event.

Our approach is therefore based on the assumption that for the flood events represented by the 3 AEPs described in section 4.1:

- The drainage network is operating at/above capacity.
- The drainage network capacity is minimal compared to the total volume of water.

While we acknowledge these assumptions are not perfect – for example, for smaller (i.e. 3.33% AEP) events, the drainage network is likely to form an increasingly large proportion of the total volume of water – they are necessary simplifications to apply methods at this regional scale.

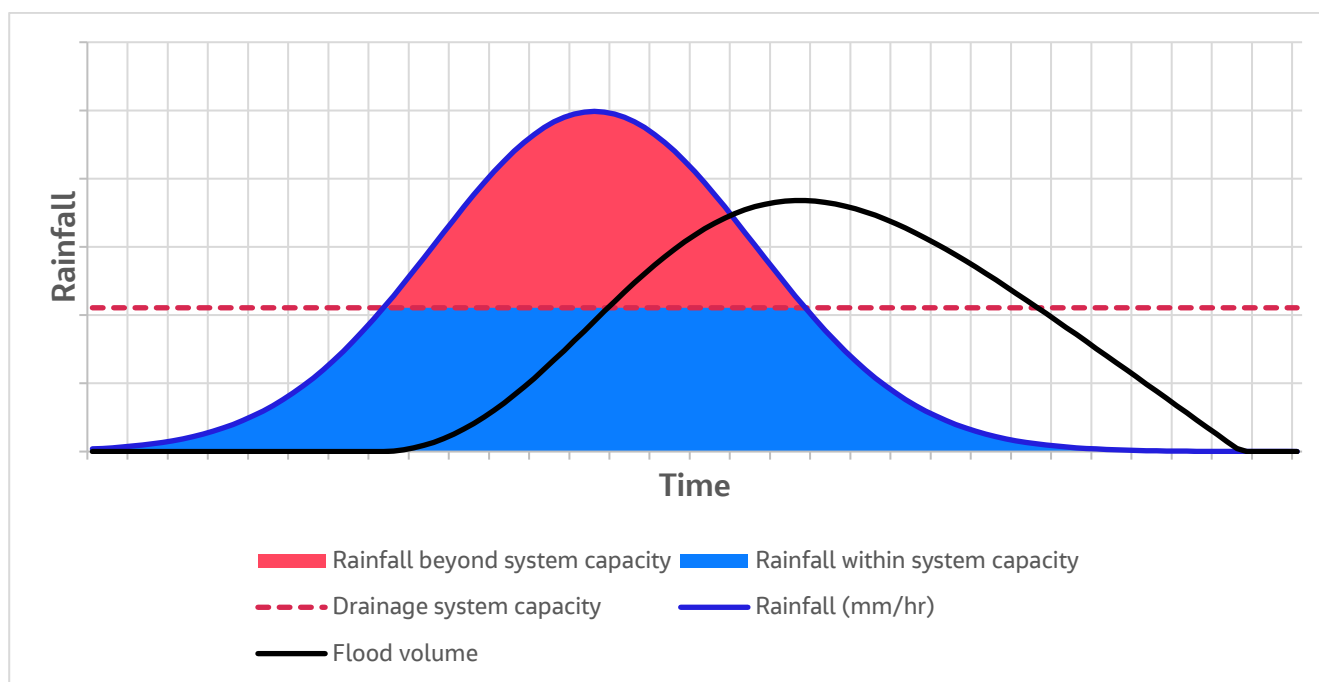


Figure 4-1. Assumptions underpinning our surface water analysis.

Building on these assumptions, we were able to modify the volume of water in the floodplain to represent a) climate change and b) surface water interventions, described in more detail below. Strictly speaking, rather than modifying the volume of water in the floodplain, we have used the modified relationship between volume and AEP to shift the AEP of each surface water scenario in each FRMS.

4.2.1 Climate change scenarios

We have represented the effect of climate change by shifting the AEP of the present day (without climate change) surface water events in each FRMS based on a percentage increase in surface water volume under each climate change scenario.

We have used the peak rainfall intensity allowances from the Environment Agency climate change allowances for flood risk assessments³ (Environment Agency, 2020), reproduced in Table 4-1, and have assumed that a predicted percentage increase in peak rainfall will equate to an equal percentage increase in the volume of water which pools on the surface during a surface water flood event.

Table 4-1. Peak rainfall intensity increases due to climate change.

Applies across all of England	Total potential change anticipated for the '2020s' (2015 to 2039)	Total potential change anticipated for the '2050s' (2040 to 2069)	Total potential change anticipated for the '2080s' (2070 to 2115)
Upper end	10%	20%	40%
Central	5%	10%	20%

This assumption is most appropriate if:

- We assume that climate change affects peak rainfall but not storm duration, so – in simple mathematical terms – the area under the rainfall graph in Figure 4-1 is increased proportionally to the height of the graph.

³ Note rainfall intensity estimates were not changed as part of the 2021 update.

- b) The drainage system capacity is negligible compared to the total storm volume, and therefore the volume of water on the floodplain. On Figure 4-1, this would mean that the height of the 'blue' section is small compared to the height of the 'pink' section. This is because we are effectively representing a percentage increase in the total height of the graph as a percentage increase in just the 'pink' section of the graph.

4.2.2 Future development

A by-product of relying on existing modelling for surface water is that we cannot directly represent changes in surface water risk due to future urbanisation. We therefore have to assume that there is no increase in risk due to new development, assuming that any increase in risk due to e.g. reduced permeability is mitigated directly by developers as part of meeting current planning policy. It is also worth noting that this is also the case for fluvial risk, as the simulation library approach developed for fluvial risk only applies development scenarios as changes in receptors (and therefore impacts), and not changes in hazard.

4.2.3 Representing interventions

Similar to the proposed approach for representing climate change, we have represented interventions based on an equivalent volume of water that an intervention would be capable of storing (in other words 'removing' from the volume of water on the surface) – and used that modified volume to adjust the relationship between AEPs and the available flood outputs.

This in turn shifts the onset of flooding for the location to be any flood event more severe (less likely) than that AEP. One approach to represent this would be to shift the onset of flooding in the annualisation process (i.e. set the damage at 3.3% AEP to 0), however this would mean that we would not represent the shifts in the more extreme (1% and 0.1% AEP) events because of the interventions. We have therefore shifted the AEP of each event to reflect the increased severity of event that would be required to lead to the same volume of surface water flooding with the proposed interventions in place (shown in the example in Figure 4-2), using linear interpolation/extrapolation between the three known AEPs and their corresponding volumes, and the reduction in volume assumed for a surface water intervention.

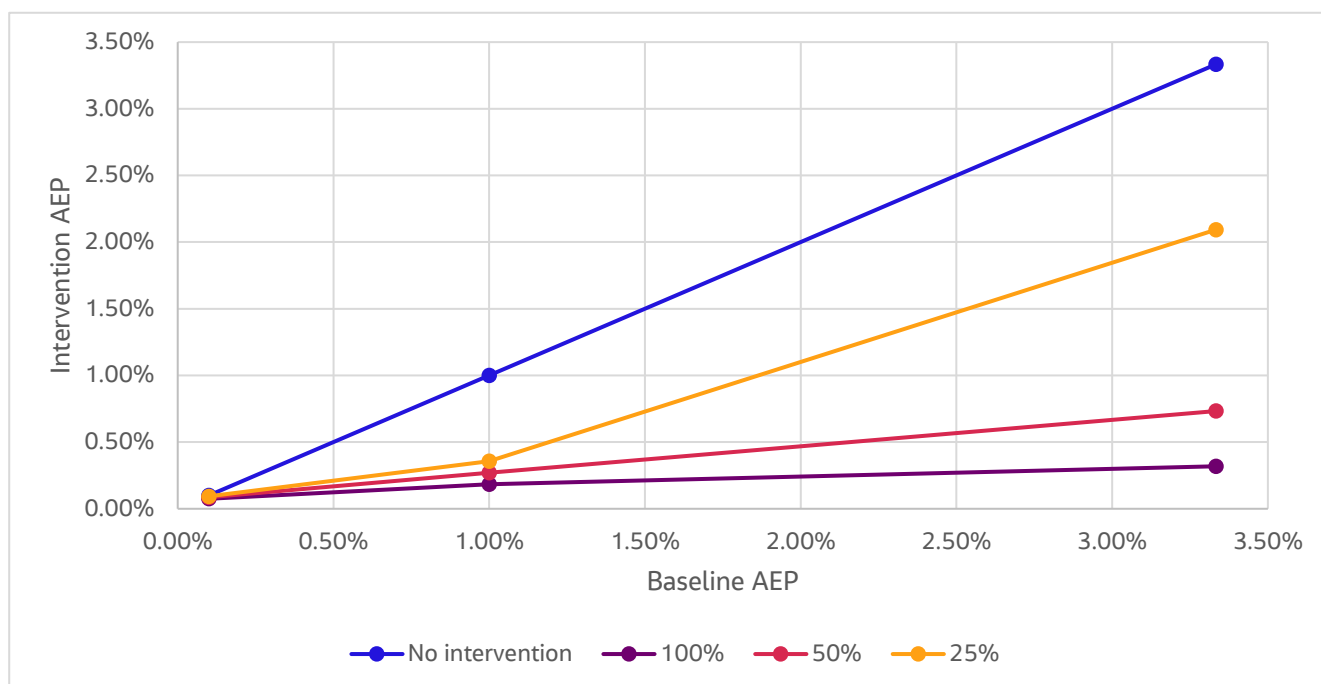


Figure 4-2. Example of modified AEPs under different levels of surface water intervention (removing all, half or a quarter of the 3.3% AEP flood volume).

This set of assumptions forms the basis of our method for representing surface water interventions for a given area. For the purpose of this analysis, we assume that interventions are applied across an FRMS and that interventions are effective up to a 3.3% AEP event, so base the volume analysis on that AEP. We have also considered – for a given area – what the potential for surface water risk management is likely to be. We separately identify the scale and therefore cost of surface water interventions required to reduce the surface water volume by this level.

This approach shares a number of features with the high-level approach adopted to represent NFM in the fluvial risk analysis, so provides a degree of consistency across approaches.

5. Automation & look ups

5.1 Automation and the simulation library approach to modelling

Given the number of 2D models likely required for 2,100 scenarios and the purpose of this strategic level study, we have combined explicit modelling of a representative range of scenarios with lookups and interpolation to provide efficient and appropriate flood impact results to inform economic analysis and adaptive planning.

Automation and efficient data management are the foundation of this study and required to handle the large quantity of data needed and link various analyses together. We used Flood Platform, Jacobs' in-house modelling platform, to automate:

- 1) 2D model-building for the TUFLOW GPU solver.
- 2) Distribution of the model runs through our high-performance computing cluster.
- 3) Post-processing of simulation results, including running Damage Calculator to generate property impact data for each simulation.

The platform was previously been successfully used in multiple regional and national high-level modelling projects, e.g. Scotland National Fluvial Mapping, Thames Breaching and the Somerset Climate Change Pilot study. We adapted Flood Platform to align with the wider data management needs of this project.

We have explicitly modelled all fixed asset (linear defence) options with a range of water levels at intervals between the highest and lowest required water levels. The baseline models have been run using the same AEP% events for each domain. The 'simulation library' look-up approach that we have adopted means that we did not need to run every climate change scenario explicitly, but it was important that the results provided coverage across the full range of scenarios. To ensure that there is sufficient coverage / spread of water levels as well as representing the greatest possible water level for any given node, we selected 4 additional climate change scenarios which we explicitly modelled (using a 0.1% AEP event for each):

- 'Upper end' allowance for the 2050s epoch.
- 'Upper end' allowance for the 2080s epoch.
- 'H++' allowance for the 2080s epoch.
- 'H++' allowance for the 2110s epoch.

We have represented all other climate change scenarios, along with storage and NFM scenarios, using the 'simulation library' of explicitly modelled simulations catalogued by water levels, and interpolating results (i.e. calculated impacts) between the available simulations. For example, a 10 mAOD water level at one location could represent:

- Present day 2% AEP scenario.
- 2050 H++ 3.3% AEP scenario.
- Present day 1.5% AEP with medium flood storage scenario.

As water levels are the only varying inputs in these circumstances, we can use one modelling result to represent all three scenarios. If the scenario we were exploring involved new property data and/or property level protection measures, flood impact analysis had to be re-run with the new property data using the same flood depth grids, but new hydraulic modelling was not needed. The spatial resolution of the lookup is at the NaFRA flood area level, i.e. hydraulic modelling units.

Although not explicitly modelled, we have pre-calculated the water levels for every combination of flood event, climate change allowance (including the different epochs) and intervention (i.e. storage and NFM), and stored these in the results database. These water levels – combined with the simulations catalogued by water level – make it possible to extract an appropriate result for any future scenario, even though they have not all been

explicitly modelled. Where necessary, this extraction process uses interpolation between a) stored water levels and b) between available results for a defined water level to produce the desired output.

5.2 Simulation library cataloguing approach

Since each model domain comprises many individual nodes, we originally planned to select a single 'reference' node for each domain, and to base the water level comparison and interpolation on that single node for each model. This would have been a suitable method if the change in water level followed the same relationship for all events, as the single reference water level would still have provided a proxy for the whole model domain.

However, we found that many of the model domains do not follow a simple relationship in water level across all scenarios due to several factors:

- Water level nodes within a single model domain can fall into multiple different 'assigned FFC' areas. The different FFCs mean that any future scenario or intervention which relies on adjusting flows and return period shift (for example, climate change uplifts or NFM) will affect water levels differently within the same model domain.
- In cases where model domains are tidally influenced, the water levels are adjusted using a hybrid fluvial/tidal method based on their distance along the tidal reach, therefore a single node may not adequately represent the entire domain.
- NFM has been represented as only having an impact on water levels in the upper catchments, therefore model domains which lie across these boundaries will have a different water level profile for scenarios where NFM is included.

To alleviate these we have used more than one reference node per model domain. Using every single node to lookup and interpolate impacts, although technically possible, would be prohibitively memory and CPU intensive and not appropriate for the scale and scope of the project. We therefore adopted an approach using 3 reference nodes ('A', 'B' and 'C') across the model domain to provide a more accurate representation of the water level profile, while still being reasonable to implement in the database and optimisation.

In order to assign 3 reference nodes for each model domain, we developed a series of rules to ensure that a good selection was made. For example, it would not be sensible for 3 reference nodes for a large model domain to all be in one location. These rules are summarised below.

For model domains with a single FFC:

- Reference node A is selected from the most upstream point.
- Reference node B is selected from the mid point along the flood area (based on median level).
- Reference node C is selected from the most downstream point.

For model domains with multiple FFCs:

- Each reference node is selected from a different FFC.
- If there are two FFCs, two reference nodes are selected from the FFC with the most nodes in, and one from the other.
- If there are more than three FFCs, nodes are simply selected from the first three FFCs encountered.

When reference nodes are selected, an additional check is made on the node to ensure that the water levels are suitable. This consists of checking that water levels increase with each successive return period, and that the total range in water level (between 50% AEP and 0.1% AEP events) is greater than a given threshold. If a node fails this check, the next node along will be tested until a suitable node is found.

Initially the level threshold is set to 300mm, however if a reference node is still not found, the program recursively lowers this threshold in steps and checks all nodes again until all reference nodes have been identified.

5.3 Extracting data from the simulation library

All possible combinations of water levels for each reference node are stored in the database. For any given scenario, these water levels can be directly looked up. These water levels are then compared to all the combinations of water levels which have been explicitly modelled in order to find the closest match. The closest match is always returned as an upper and lower set of levels (i.e. the closest above and below) along with a weighting that defines where those levels lie in relation to the upper and lower levels. This weighting is then used to interpolate the impacts between the upper and lower impacts.

Identifying an upper and lower set of water levels is not as straightforward as it would be with a single water level, as there are 3 levels which can sometimes move independently of each other. In order to select these, the following process is applied:

- For each reference node, the offset from the target level to the simulated levels is calculated.
- These three offsets are then summed to produce a 'total offset' for each simulated event.
- The total offset for each event is then used to determine the upper and lower set of levels. The upper set is the smallest offset greater than zero, and the lower set is the smallest offset less than zero.
- A 'performance score' is calculated for the upper and lower set which is the sum of the absolute offsets divided by 3. This essentially represents the average offset between the target levels and the simulated levels.
- The performance score is then used to calculate the weighting used to interpolate the impacts between the upper and lower impacts.

This allows for impacts to be calculated "on the fly" for any combination of interventions and future scenarios.

6. Verification and sensitivity analysis

We have verified the baseline and no defence flood extents with local data where it is readily available. The verification has allowed us to assess confidence in results and consider the most appropriate course of action, e.g. accepting the discrepancy or improving the modelling by checking and incorporating more local data.

6.1 Baseline model verification

We undertook initial verification of baseline model outputs by comparing results with flood extents from MapEdit, which provides a useful collated dataset of available local model data. All the baseline modelling outputs have been reviewed and compared with the MapEdit flood outlines for the 20%, 2% and 1% AEP events (1 in 5 year, 50 year and 100 year return period). We selected these events because they offer the greatest coverage across local model data from MapEdit.

In addition to the comparison of flood outlines, we categorised each model domain based on the difference between the number of properties identified at risk using the MapEdit flood outlines and the OxCam derived outlines.

We categorised models on a scale of 1 to 5, where 1 indicates very little difference between the property counts and 5 indicates high difference between the property counts and that the model requires 'more detailed' investigation. This score is based on two criteria:

- The absolute difference in property numbers.
- The percentage difference in property numbers.

The lower of the two values was selected as the final category for the model, to prevent the validation being biased for models with particularly small or large numbers of properties. The categories are shown in Table 6-1. Where there is no local MapEdit flood outline with which to compare the baseline model the comparison category is set to N/A.

Table 6-1. Property comparison categorisation, where 1 indicates very little difference between the property counts and 5 indicates high difference between the property counts

Criteria for absolute difference	Category		Criteria for percentage difference	Category
<10 difference	1		<10% difference	1
>10 but <20 difference	2		>10% but <20% difference	2
>20 but <30 difference	3		>20% but <30% difference	3
>30 but <40 difference	4		>30% but <40% difference	4
>40 difference	5		>40% difference	5
MapEdit flood outline not available or incomplete	N/A		MapEdit flood outline not available incomplete	N/A

For any model domain with a property category of 4 or 5, we carried out a more detailed review and update to correct any model build deficiencies that caused instability and poor fit to local property counts. This process reduced the number of models in categories 4 and 5 by about 10% and made improvements to approximately 50 unstable models. However, during this process, we identified a number of issues related to the data used. These models were re-categorised from category 4 or 5 to 'Data Issue'. The issues encountered are detailed in Appendix D. Fixing these data issues is beyond the scope of this project, and we have instead sought to understand the influence they could have on the final economic results through sensitivity analysis.

Table 6-2 shows the number of models by property comparison category before and after verification.

Table 6-2. Number of model domains by property comparison category before and after verification (baseline).

Category	20% AEP (5 year)		2% AEP (50 year)		1% AEP (100 year)	
	Before verification	After verification	Before verification	After verification	Before verification	After verification
1	187	186	125	120	142	139
2	11	14	14	13	25	14
3	8	11	19	14	18	19
4	3	-	6	-	7	-
5	64	-	89	-	86	-
Data issue	-	7	-	49	-	55
N/A	468	512	488	534	463	503

Table 6-3 shows the total number of properties within the flood extents of the models in each category after verification. For example, for the 1 in 5 year event, there are 186 models within Category 1 (see Table 6-2), within these model domains, there are 275 properties in the local MapEdit flood extents and 10 in the OxCam model flood extents. The table shows that the property counts produced by the OxCam model differ to those in the local MapEdit models. This is most noticeable for the Category 4 and 5 models. These differences are primarily due to differences in the data used between the two methods.

Overall, while the differences in property numbers are quite high, they are dominated by a relatively small number of model domains. This means that their influence on the overall economic analysis is likely to be limited. It also means that future data improvements could be targeted towards this small number of models.

For example, the 1% AEP figures show that in total there are around 4,000 additional properties within the flood extents of the OxCam modelling than the corresponding local models. However, similar number of properties are contributed by 5 models with particularly significant differences.

Table 6-3. Summary of number of properties by property comparison category following verification (baseline).

Category	20% AEP (5 year)		2% AEP (50 year)		1% AEP (100 year)	
	Local	OxCam	Local	OxCam	Local	OxCam
1	275	10	341	526	832	978
2	283	86	460	634	747	818
3	272	3	1,390	1,595	1,940	1,807
4 (due to data issue)	103	1	361	468	948	863
5 (due to data issue)	496	0	760	6,377	7,111	11,075
Total (1-5)	1,429	100	3,312	9,600	11,578	15,541
N/A	N/A	1,886	N/A	48,706	N/A	60,731

Table 6-4. Summary of number of properties by property comparison category following verification (no defence).

Category	1% AEP (100 year)		0.1% AEP (1000 year)	
	Local	OxCam	Local	OxCam
1	40,571	42,646	125,908	127,195
2	37,403	40,869	11,630	9,684
3	13,468	11,056	32,423	25,265
4 (due to data issue)	15,568	17,032	6,688	5,298
5 (due to data issue)	15,387	29,977	15,980	19,643
Total (1-5)	122,397	141,580	192,629	187,085
N/A	N/A	10,394	N/A	19,124

Model results were verified by inspection of outputs, ensuring that increases in return period always corresponded with increased water level.

7. Results

Whilst model results (such as mapped flood extents or counts of properties at risk) are not key outputs of the study, they provide a useful check and visualisation of one of the stages of the analysis required to achieve the outcomes of the project. The results presented below provide an example of the outputs of the modelling stage. It is important to note that the results presented here have not been optimised, i.e. if a Large Storage option is selected it is applied across the full study area. The main results from the study are presented in the economics and adaptation report that the main results will be in the economics and adaptation reports..

7.1 Example flood extents

Figure 7-1 to Figure 7-4 provide examples of the flood extents produced from the OxCam modelling. The Winslow flood area is used as the example to illustrate the difference in flood extent that result from the various modelling scenarios. Flood outlines have not been produced for each combination of scenario and intervention, rather a look up approach has been applied.

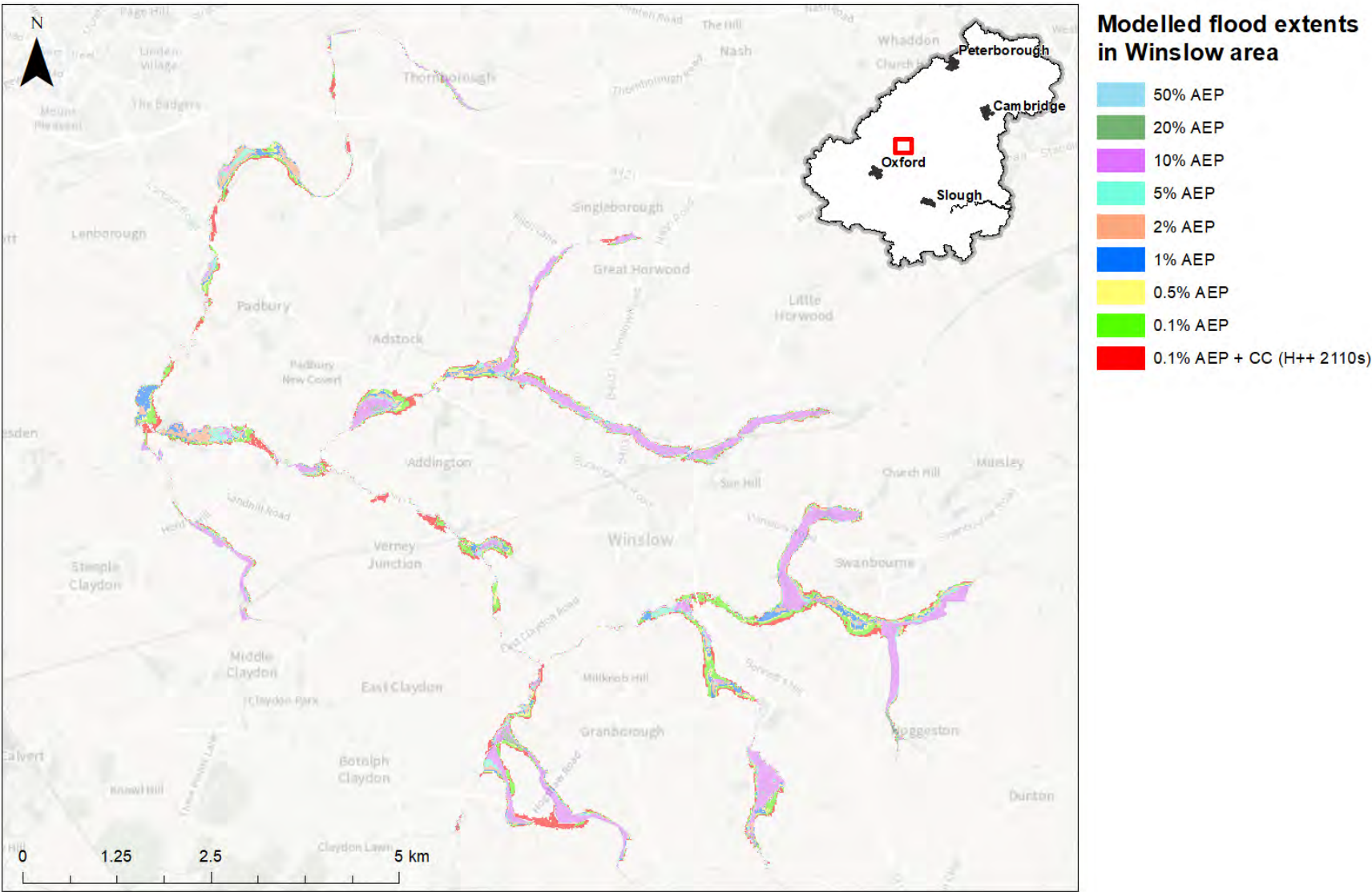


Figure 7-1. Baseline Modelled flood extents, Winslow.

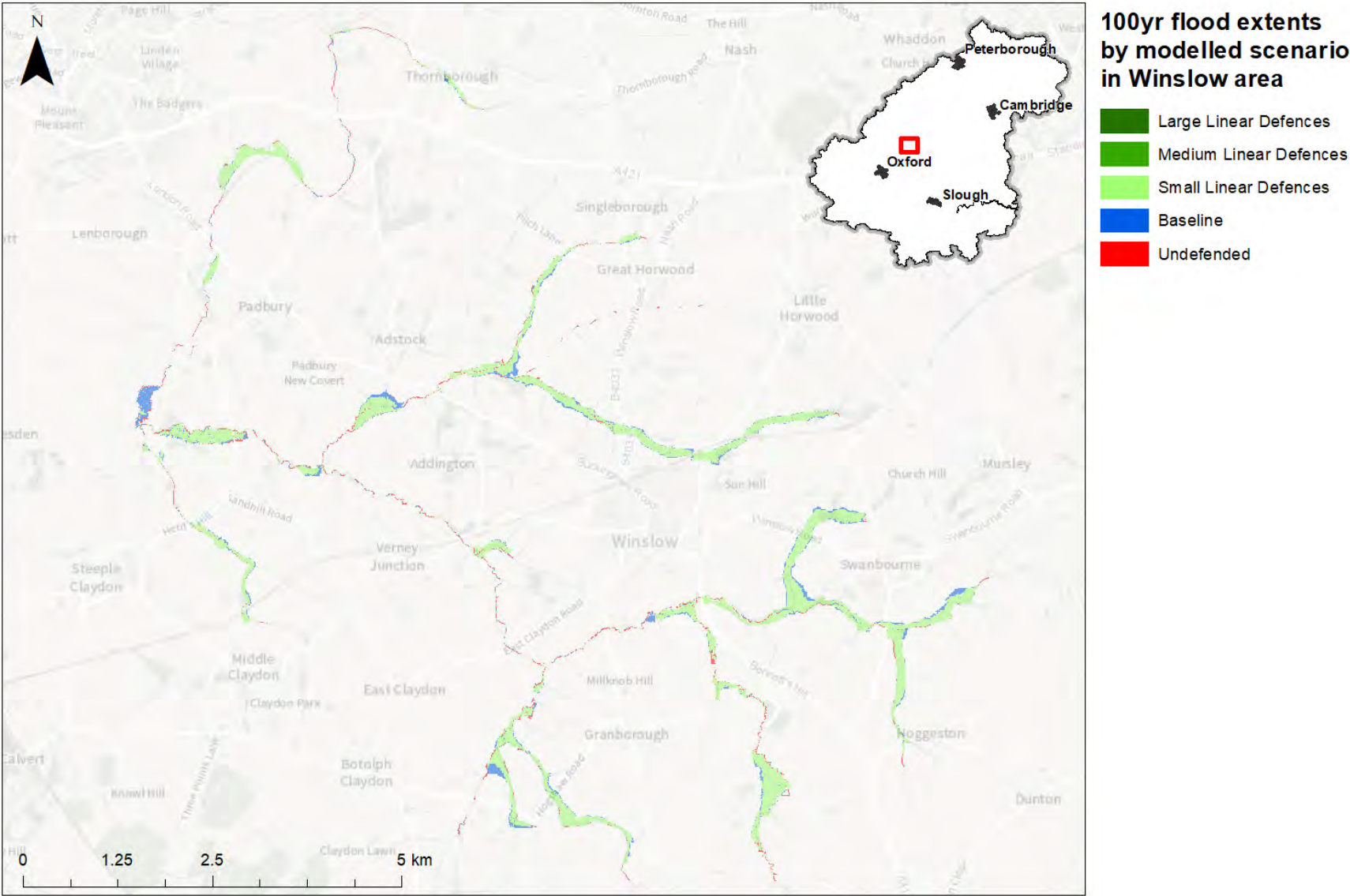


Figure 7-2. Winslow, 1% AEP flood extent, Winslow.

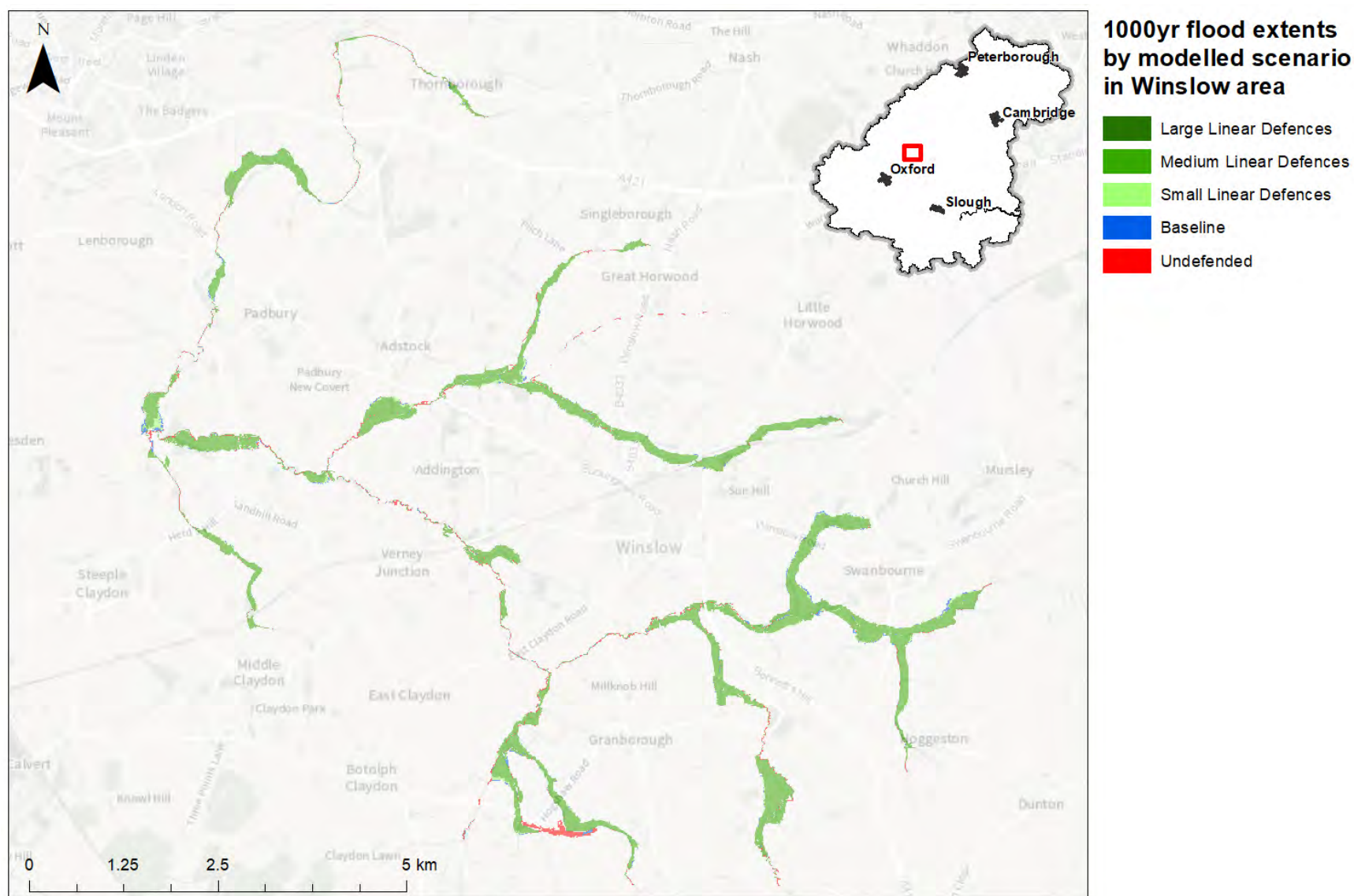


Figure 7-3. Winslow, 0.1% AEP flood extent.

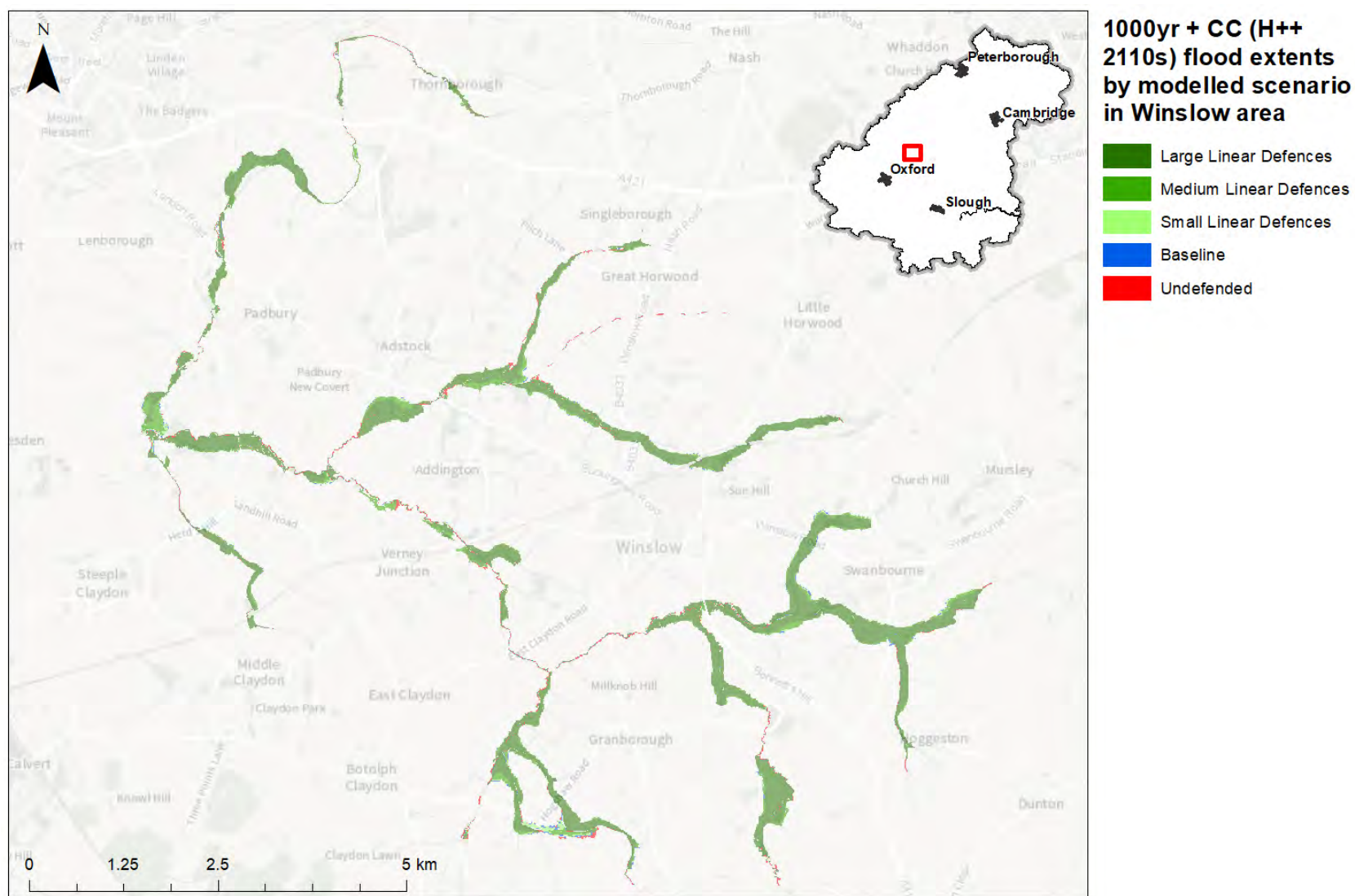


Figure 7-4. Winslow, 0.1% AEP with H++ in 2110s.

7.2 Impact of climate change and development

The impact of the climate change scenario and development scenario on the numbers of properties flooded in each catchment is visualised in Figure 7-5. This shows the total number of properties flooded by catchment (each pie), by climate change scenario (each nested pie) and by development scenario⁴ (the 3x3 grid). It is based on a 1% AEP event in the mid-point of the 2050s epoch. The pies are all scaled from the centre of each plot by their relative increase in number of flooded properties compared to baseline present day. This information is presented in tabular format in Table 7-1 to

Table 7-8.

The plots indicate that as expected, the numbers of properties at risk from flooding increase with both the number of new properties and in relation to the climate change scenario. The change in properties at risk is much greater due to climate change than due to development. The impact of climate change appears greater in the Cam/Ely Ouse and Great Ouse than in the Thames and Nene catchments. The impact of the development scenarios also, varies slightly across catchments.

The plots show that there are relatively few additional properties at risk under the H++ scenario than the Upper scenario (in the 2050s). This is primarily because the H++ climate change uplift in the 2050s is not much larger than those for the Upper Scenario (Central scenario 15% increase, Upper scenario 35% increase and H++ scenario 40% increase). Other factors may also have a lesser influence, for example whether a larger flood extent causes property flooding is dependent on the location of properties.

The impact of climate change and the development scenarios for each catchment are also shown geographically for each catchment in Figure 7-6 to Figure 7-21. These figures show the relative increase (i.e. the multiplication factor) in the number of properties flooding in a 1% AEP event, compared to the baseline, under the various climate change and development scenarios (for the mid-point of the 2050s epoch). They do not indicate the absolute number of properties at risk. For example if the properties at risk in a flood area increase from 200 to 400 the number of properties at risk is increased by a factor of 2, equally if the number of properties at risk in a flood area increases from 2 to 4 the properties at risk also increase by a factor of 2.

The baseline plots for each catchment indicate impact of development scenarios only as they compare the baseline scenario with the various development scenarios but without climate change. These plots therefore illustrate the variable distribution of development and resulting flood risk to this new development under the 9 development scenarios.

The location of development under the varying development scenarios is less clearly visible in the other figures because of the additional impact of climate change. Many locations which do not show an increase in flood risk due to development alone do show an increase in in flood risk due to climate change. As expected, the risk increases with the severity of the climate change assumption.

The figures illustrating changes in flood risk due to climate change and development scenario are as would be expected and therefore provide confidence that the modelling approach is performing appropriately.

⁴ Development scenarios are a combination of the annual increase in the number of properties (23,000, 30,000 or 43,000) and the location of that development, either as new settlements, expansion to existing settlements or a combination (hybrid) of both.

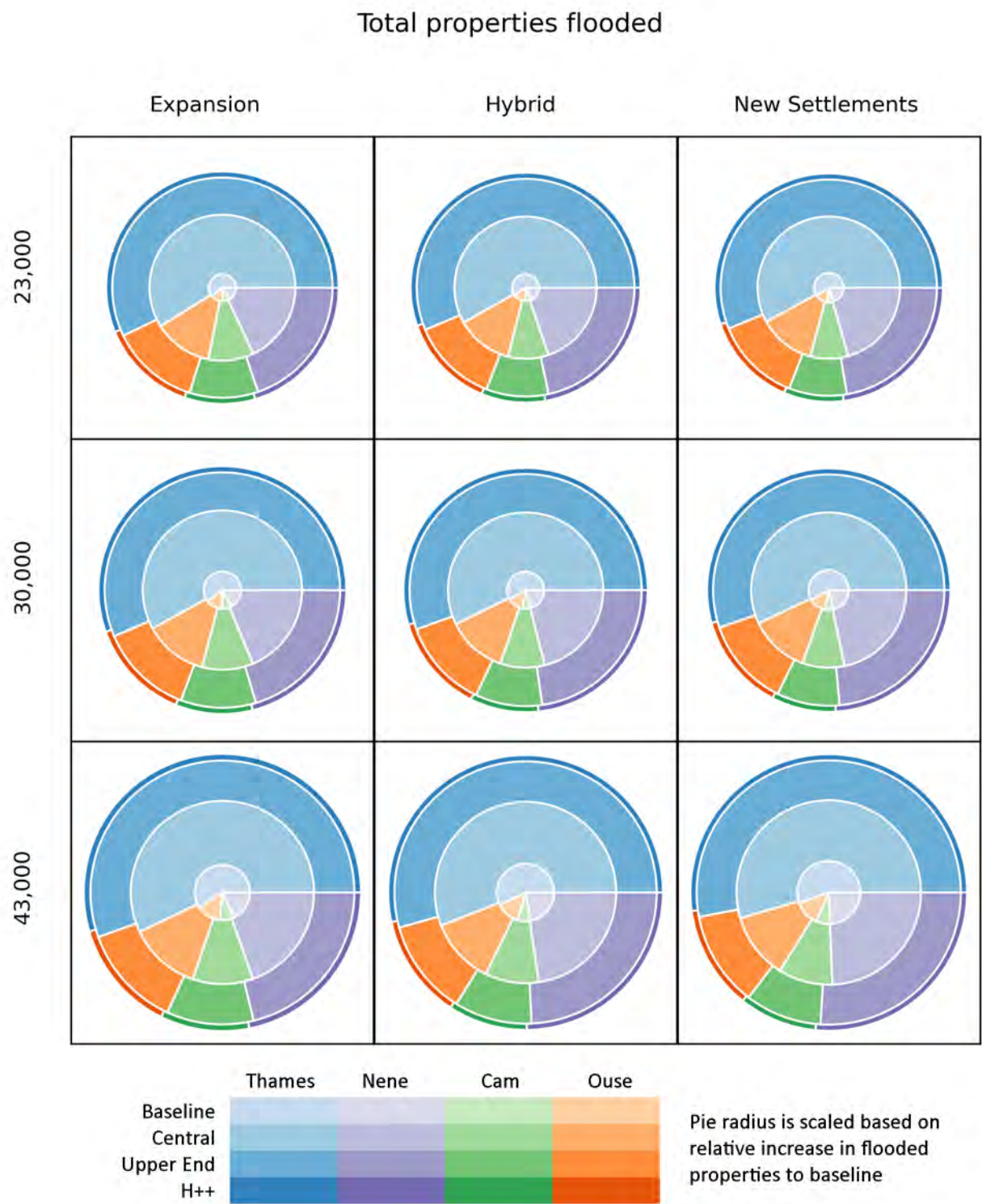


Figure 7-5. Total properties flooded for 1% AEP event at the mid point of the 2050s epoch, for each rate and shape of development.

Table 7-1. Number of properties flooded in the Thames catchment, by climate change and development scenario, based on a 1% AEP event in the mid-point of the 2050s epoch.

Climate change	Development scenario									
	None	23000			30000			43000		
		Expansion	Hybrid	New Settlement	Expansion	Hybrid	New Settlement	Expansion	Hybrid	New Settlement
Baseline	53,317	56,566	55,215	55,315	57,678	56,107	56,428	60,400	58,777	57,987
Central	73,448	78,047	76,372	76,118	79,534	77,653	77,413	82,843	80,867	79,358
Upper End	84,638	90,184	88,335	87,823	91,855	89,757	89,201	95,693	93,381	91,403
H++	85,438	91,003	89,143	88,623	92,696	90,563	90,001	96,567	94,191	92,203

Table 7-2. Relative increase (factor), from present day baseline, in properties flooded in the Thames catchment, by climate change and development scenario, based on a 1% AEP event in the mid-point of the 2050s epoch.⁵

Climate change	Development scenario									
	None	23000			30000			43000		
		Expansion	Hybrid	New Settlement	Expansion	Hybrid	New Settlement	Expansion	Hybrid	New Settlement
Baseline	1.00	1.06	1.04	1.04	1.08	1.05	1.06	1.13	1.10	1.09
Central	1.38	1.46	1.43	1.43	1.49	1.46	1.45	1.55	1.52	1.49
Upper End	1.59	1.59	1.60	1.59	1.59	1.60	1.58	1.58	1.59	1.58
H++	1.60	1.61	1.61	1.60	1.61	1.61	1.59	1.60	1.60	1.59

⁵ In these table "relative increase" is based on number of properties flooded divided by number of properties flooded in the baseline scenario (no climate change and no development). It is not an absolute increase. A flood area with an increase in flooded properties from 200 to 400 properties and a flood area within an increase in flooded properties from 20 to 40 would both have a relative increase of 2

Table 7-3. Number of properties flooded in the Great Ouse catchment, by climate change and development scenario, based on a 1% AEP event in the mid-point of the 2050s epoch.

Climate change	Development scenario									
	None	23000			30000			43000		
		Expansion	Hybrid	New Settlement	Expansion	Hybrid	New Settlement	Expansion	Hybrid	New Settlement
Baseline	10,725	14,949	17,224	18,288	16,362	19,320	20,288	18,380	22,656	25,082
Central	18,196	23,871	25,978	27,006	25,687	28,487	29,480	28,403	32,737	35,481
Upper End	24,257	31,105	33,850	34,836	33,194	36,678	37,906	36,523	41,733	44,864
H++	26,106	33,067	35,803	36,786	35,193	38,654	39,867	38,734	43,778	46,891

Table 7-4. Relative increase (factor), from present day baseline, in properties flooded in the Great Ouse catchment, by climate change and development scenario, based on a 1% AEP event in the mid-point of the 2050s epoch.

Climate change	Development scenario									
	None	23000			30000			43000		
		Expansion	Hybrid	New Settlement	Expansion	Hybrid	New Settlement	Expansion	Hybrid	New Settlement
Baseline	1.00	1.39	1.61	1.71	1.53	1.80	1.89	1.71	2.11	2.34
Central	1.70	2.23	2.42	2.52	2.40	2.66	2.75	2.65	3.05	3.31
Upper End	2.26	2.08	1.97	1.90	2.03	1.90	1.87	1.99	1.84	1.79
H++	2.43	2.21	2.08	2.01	2.15	2.00	1.97	2.11	1.93	1.87

Table 7-5. Number of properties flooded in the Nene catchment, by climate change and development scenario, based on a 1% AEP event in the mid-point of the 2050s epoch.

Climate change	Development scenario									
	None	230000			30000			43000		
		Expansion	Hybrid	New Settlement	Expansion	Hybrid	New Settlement	Expansion	Hybrid	New Settlement
Baseline	13,445	13,729	13,454	13,445	14,060	13,504	13,445	14,702	13,596	13,445
Central	16,882	17,233	16,891	16,882	17,639	16,949	16,882	18,417	17,090	16,882
Upper End	20,112	20,498	20,121	20,112	20,935	20,183	20,112	21,836	20,353	20,112
H++	21,522	21,913	21,536	21,522	22,354	21,601	21,522	23,350	21,769	21,522

Table 7-6. Relative increase (factor), from present day baseline, in properties flooded in the Nene catchment, by climate change and development scenario, based on a 1% AEP event in the mid-point of the 2050s epoch

Climate change	Development scenario									
	None	23000			30000			43000		
		Expansion	Hybrid	New Settlement	Expansion	Hybrid	New Settlement	Expansion	Hybrid	New Settlement
Baseline	1.00	1.02	1.00	1.00	1.05	1.00	1.00	1.09	1.01	1.00
Central	1.26	1.28	1.26	1.26	1.31	1.26	1.26	1.37	1.27	1.26
Upper End	1.50	1.49	1.50	1.50	1.49	1.49	1.50	1.49	1.50	1.50
H++	1.60	1.60	1.60	1.60	1.59	1.60	1.60	1.59	1.60	1.60

Table 7-7. Number of properties flooded in the Cam catchment, by climate change and development scenario, based on a 1% AEP event in the mid-point of the 2050s epoch.

Climate change	Development scenario									
	None	23000			30000			43000		
		Expansion	Hybrid	New Settlement	Expansion	Hybrid	New Settlement	Expansion	Hybrid	New Settlement
Baseline	5,681	7,053	6,350	6,064	7,646	6,711	6,553	8,368	7,551	7,956
Central	10,817	13,348	12,050	11,313	14,206	12,603	11,910	15,495	13,840	13,847
Upper End	13,002	15,883	14,506	13,565	16,819	15,065	14,190	18,374	16,442	16,184
H++	13,002	15,883	14,506	13,565	16,820	15,065	14,190	18,374	16,442	16,184

Table 7-8. Relative increase (factor), from present day baseline, in properties flooded in the Cam catchment, by climate change and development scenario, based on a 1% AEP event in the mid-point of the 2050s epoch

Climate change	Development scenario									
	None	23000			30000			43000		
		Expansion	Hybrid	New Settlement	Expansion	Hybrid	New Settlement	Expansion	Hybrid	New Settlement
Baseline	1.00	1.24	1.12	1.07	1.35	1.18	1.15	1.47	1.33	1.40
Central	1.90	2.35	2.12	1.99	2.50	2.22	2.10	2.73	2.44	2.44
Upper End	2.29	2.25	2.28	2.24	2.20	2.24	2.17	2.20	2.18	2.03
H++	2.29	2.25	2.28	2.24	2.20	2.24	2.17	2.20	2.18	2.03

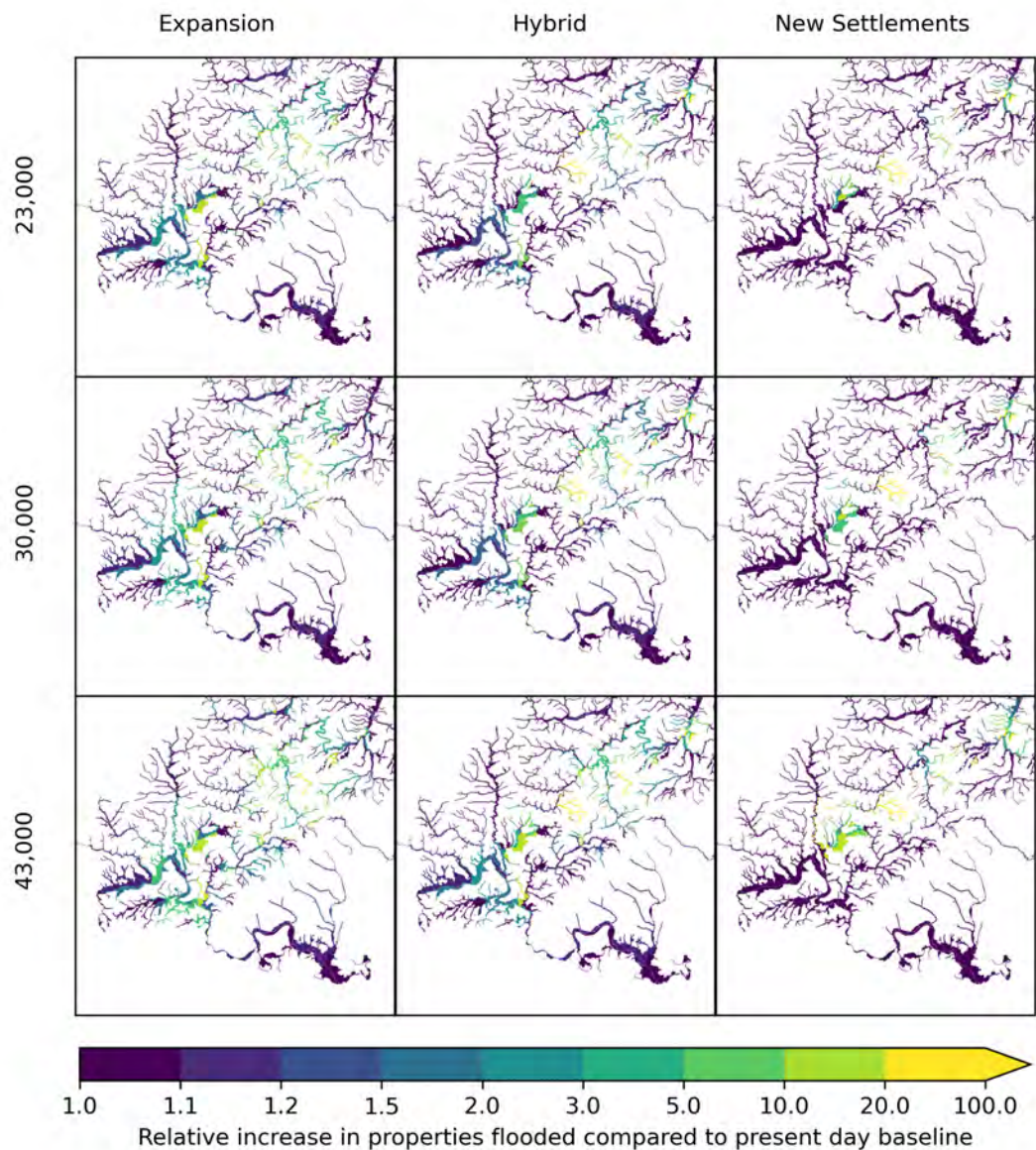


Figure 7-6. Thames Catchment, without climate change.⁶

⁶ In these figures "relative increase" is based on number of properties flooded divided by number of properties flooded in the baseline scenario (no climate change and no development). It is not an absolute increase. A flood area with an increase in flooded properties from 200 to 400 properties and a flood area within an increase in flooded properties from 20 to 40 would both have a relative increase of 2

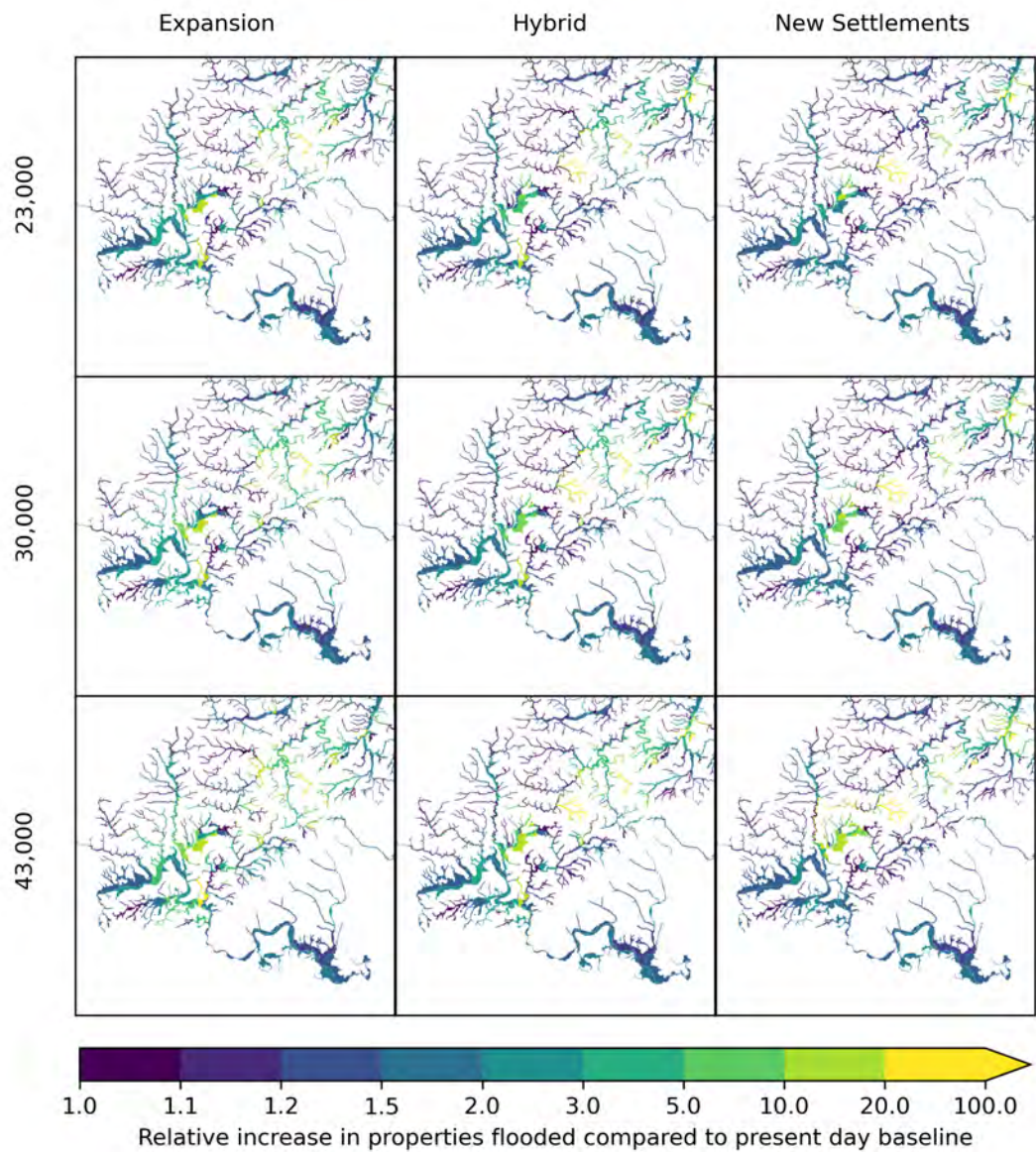


Figure 7-7. Thames catchment, central climate change allowance.

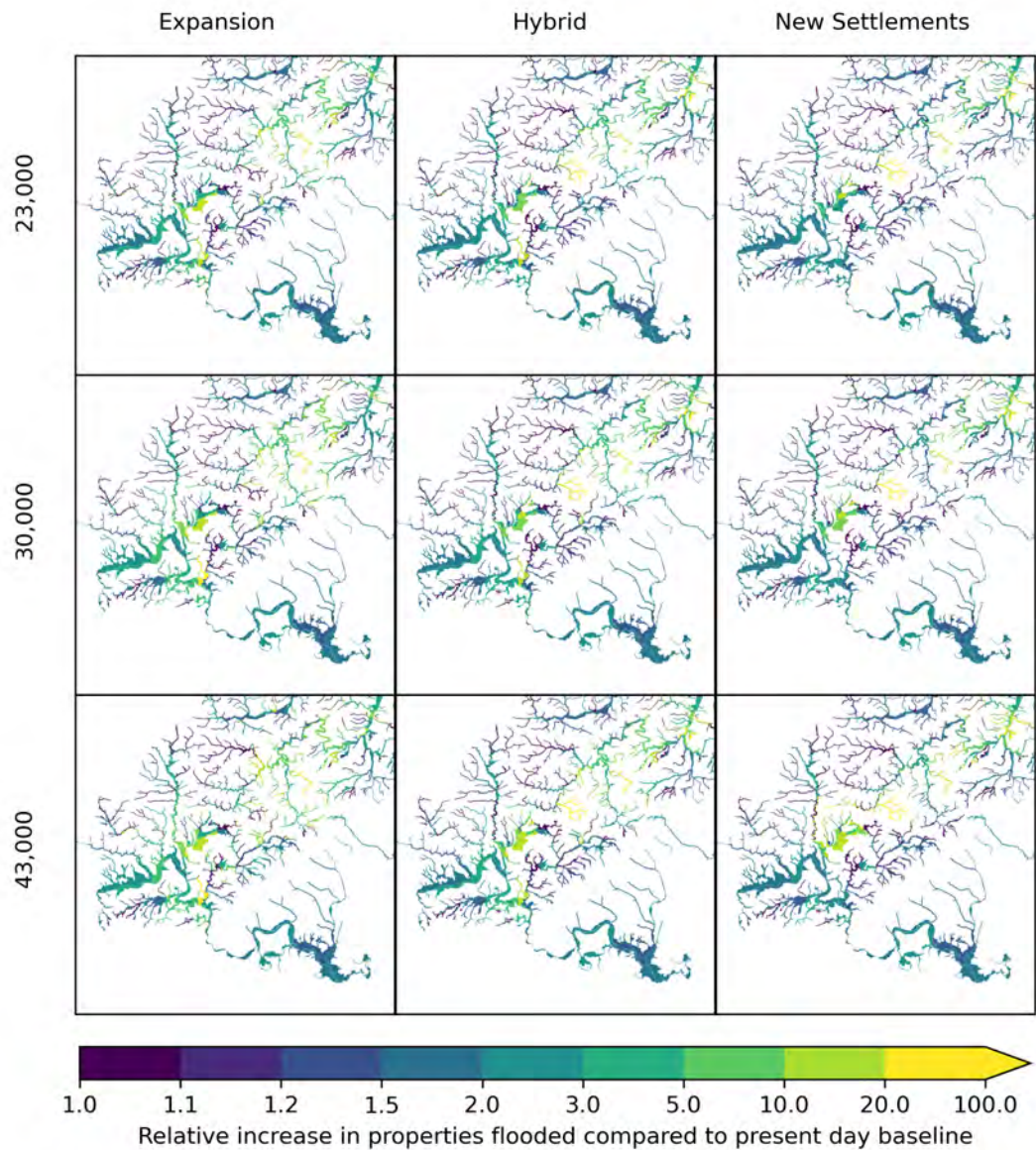


Figure 7-8. Thames catchment, upper climate change allowance.

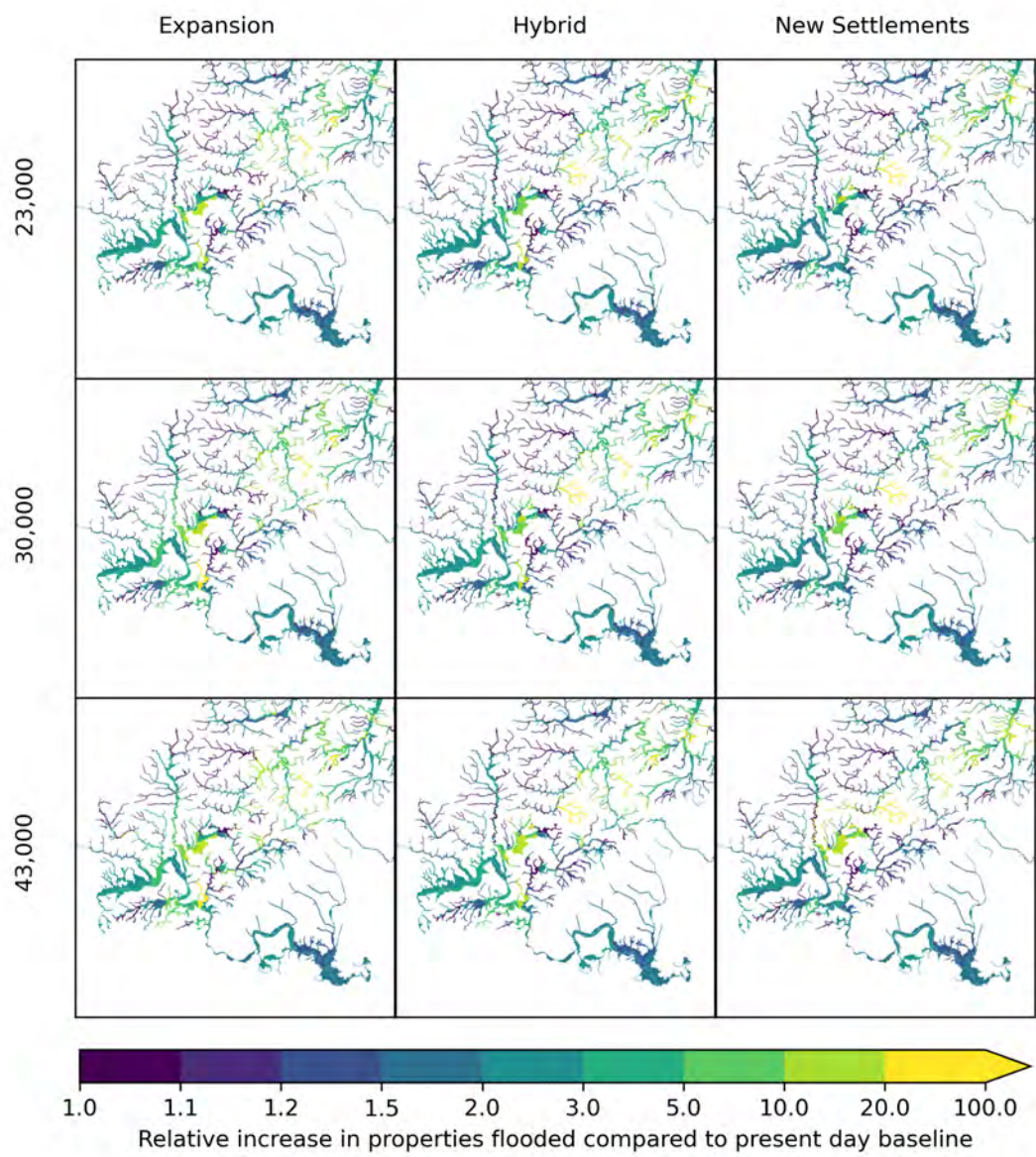


Figure 7-9. Thames catchment, H++ climate change allowances.

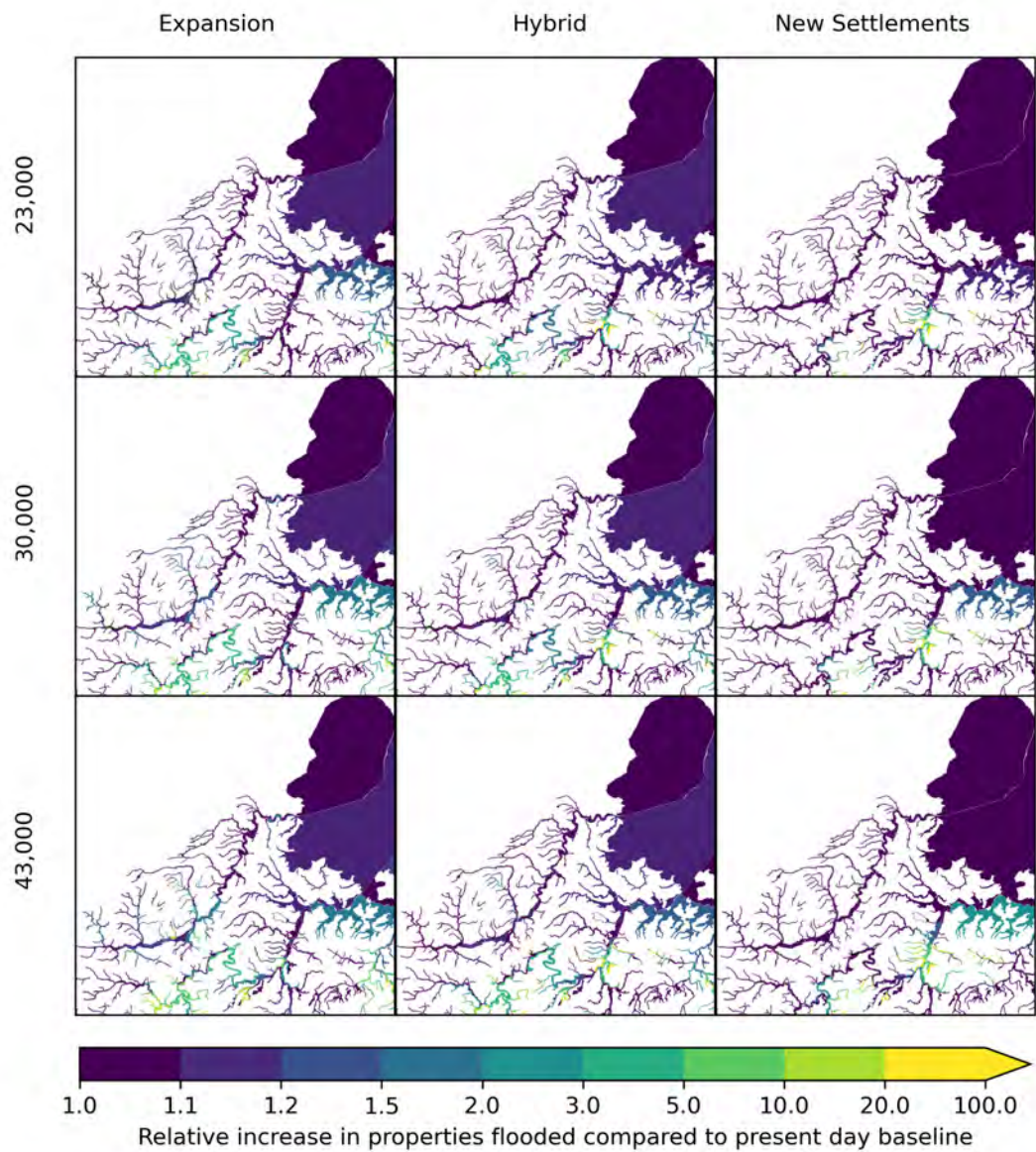


Figure 7-10. Nene catchment, without climate change.

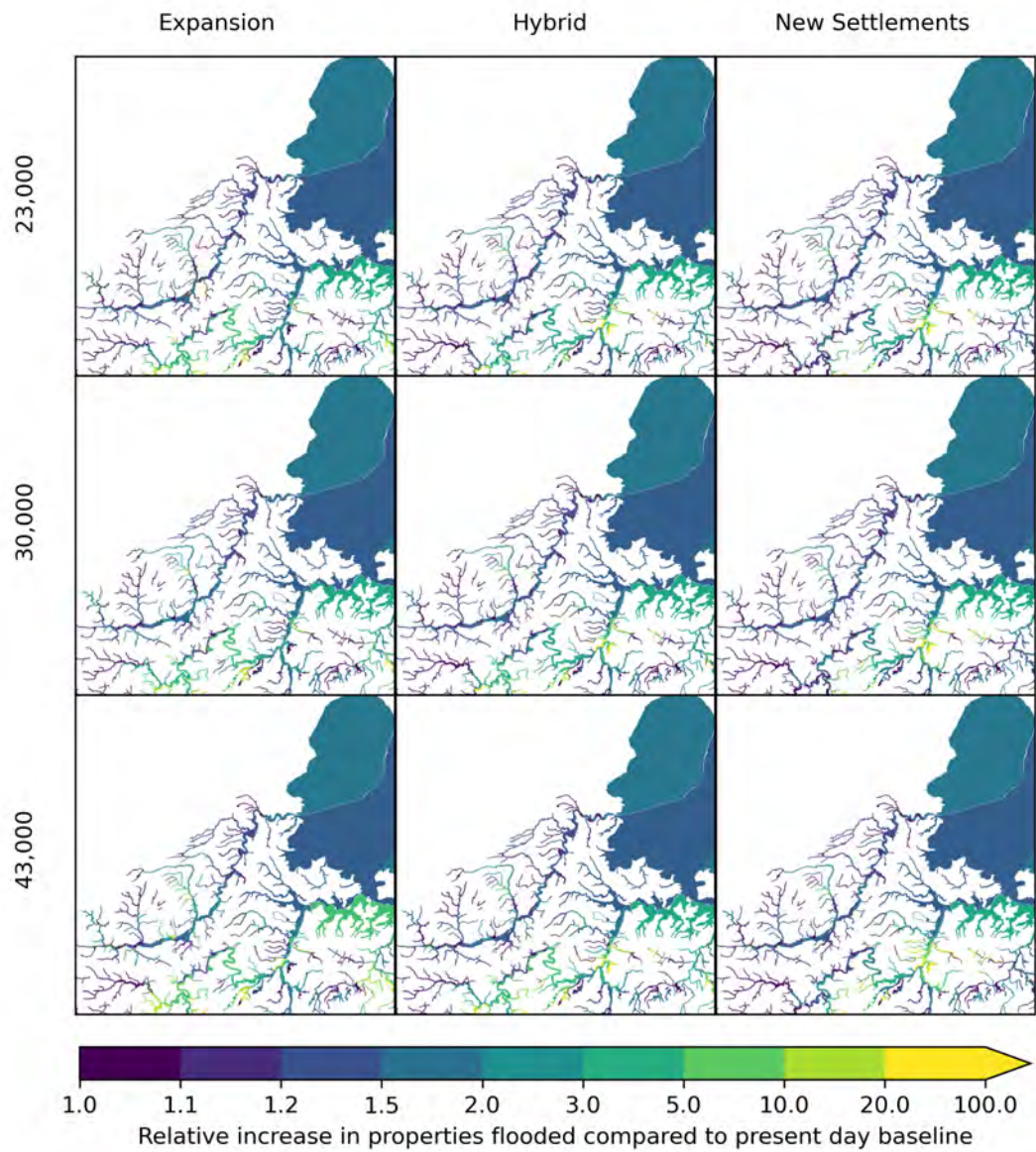


Figure 7-11. Nene catchment, central climate change allowance

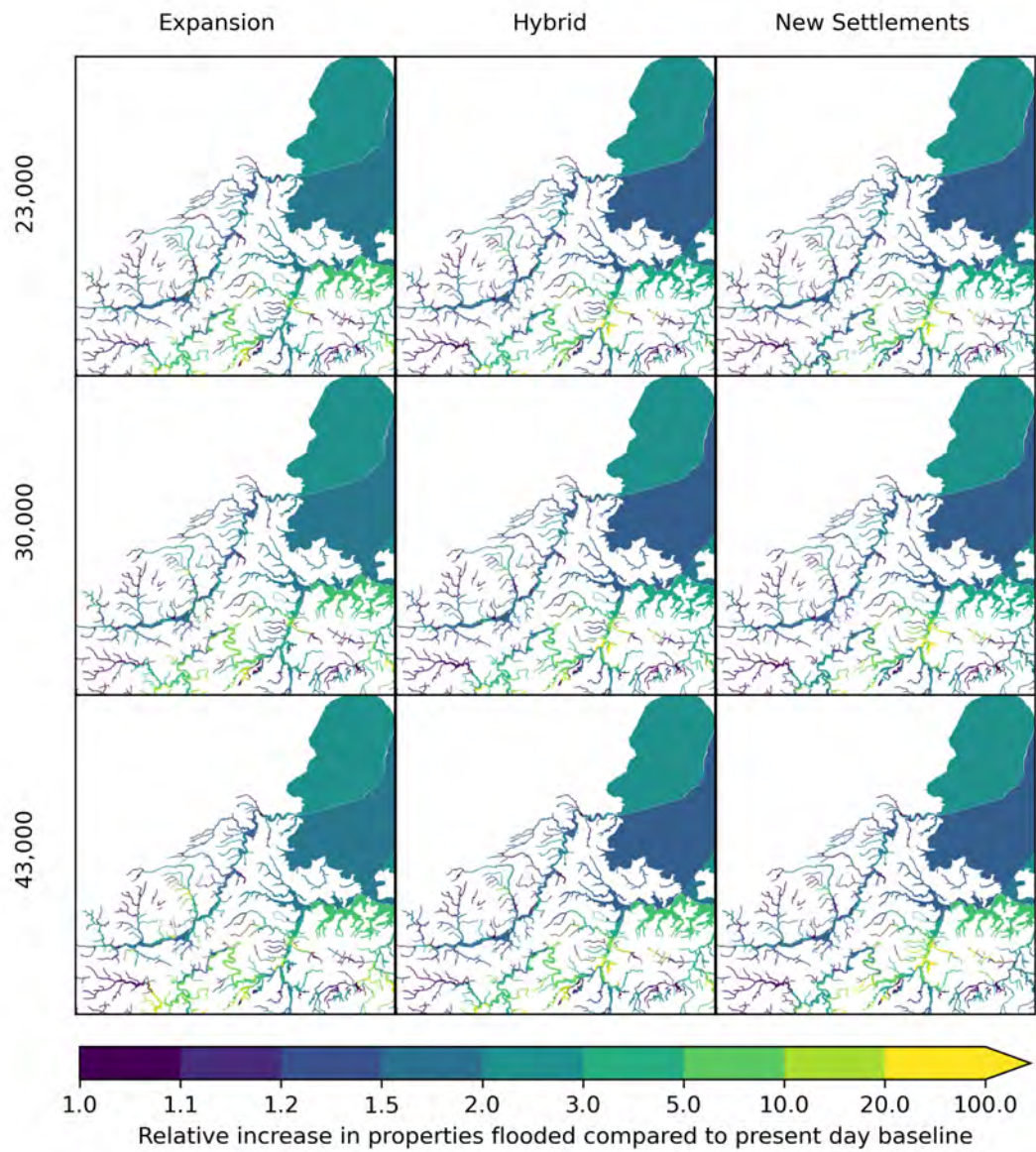


Figure 7-12. Nene catchment, upper climate change allowance

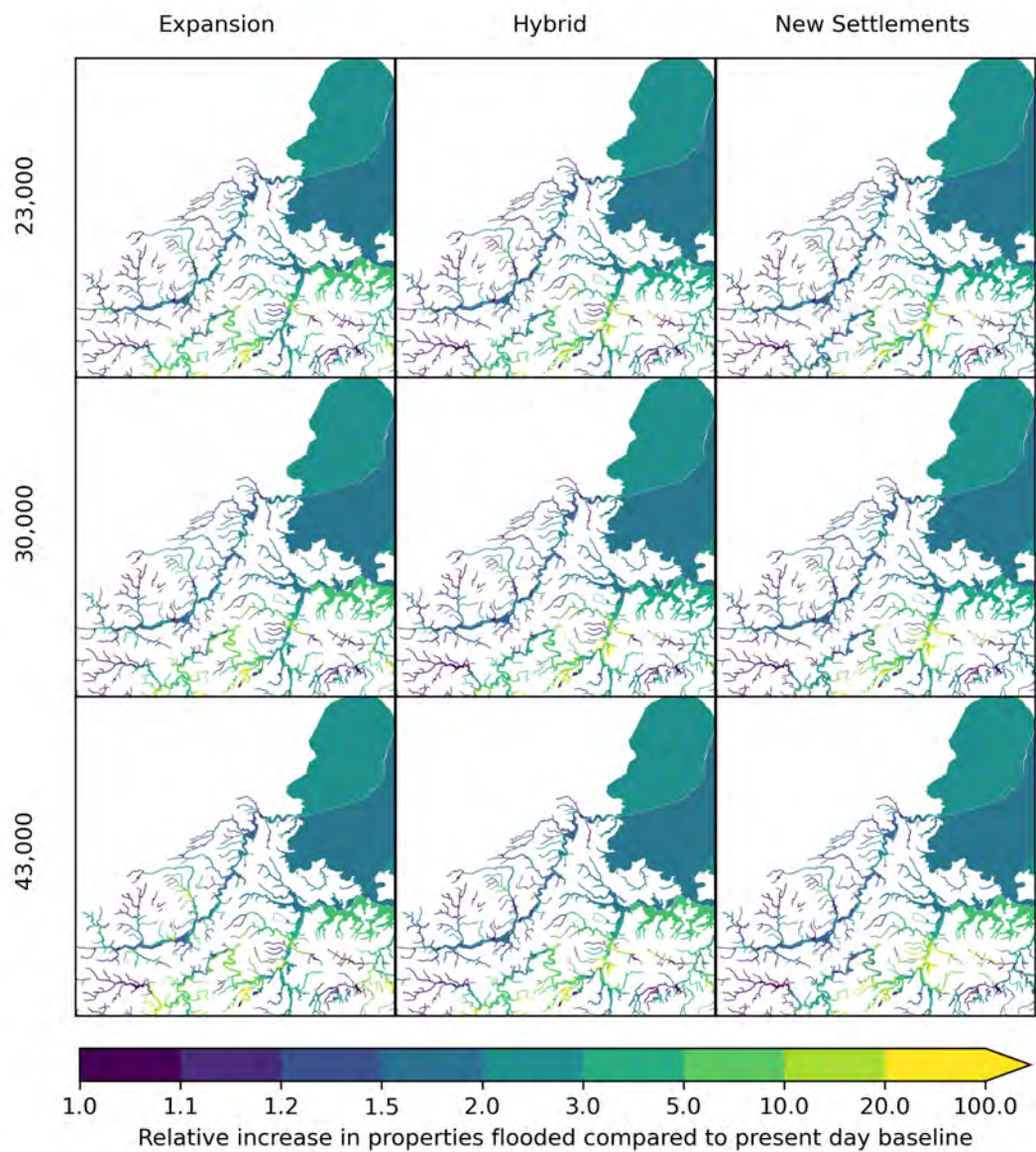


Figure 7-13. Nene catchment, H++ climate change allowance

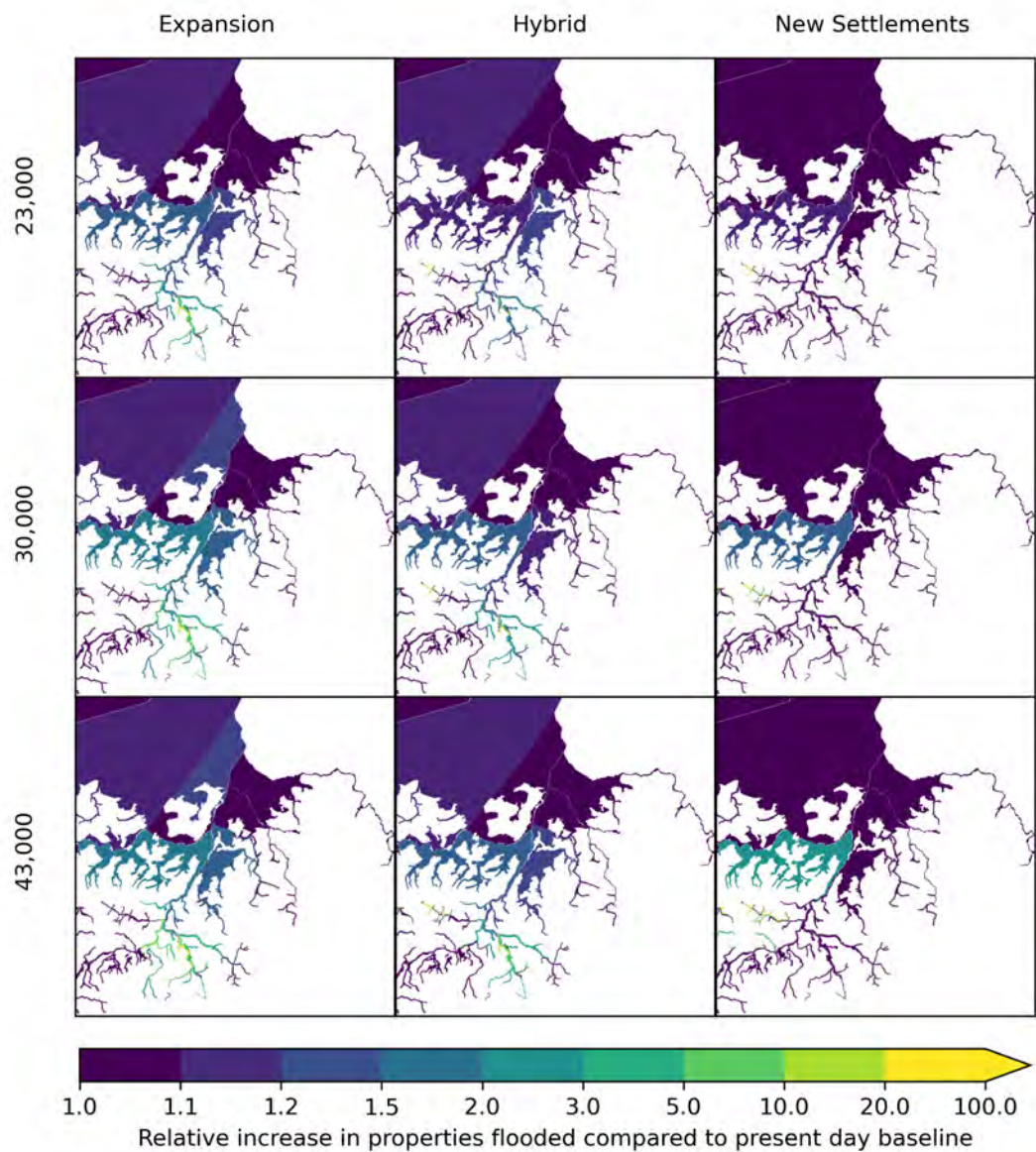


Figure 7-14. Cam catchment, without climate change

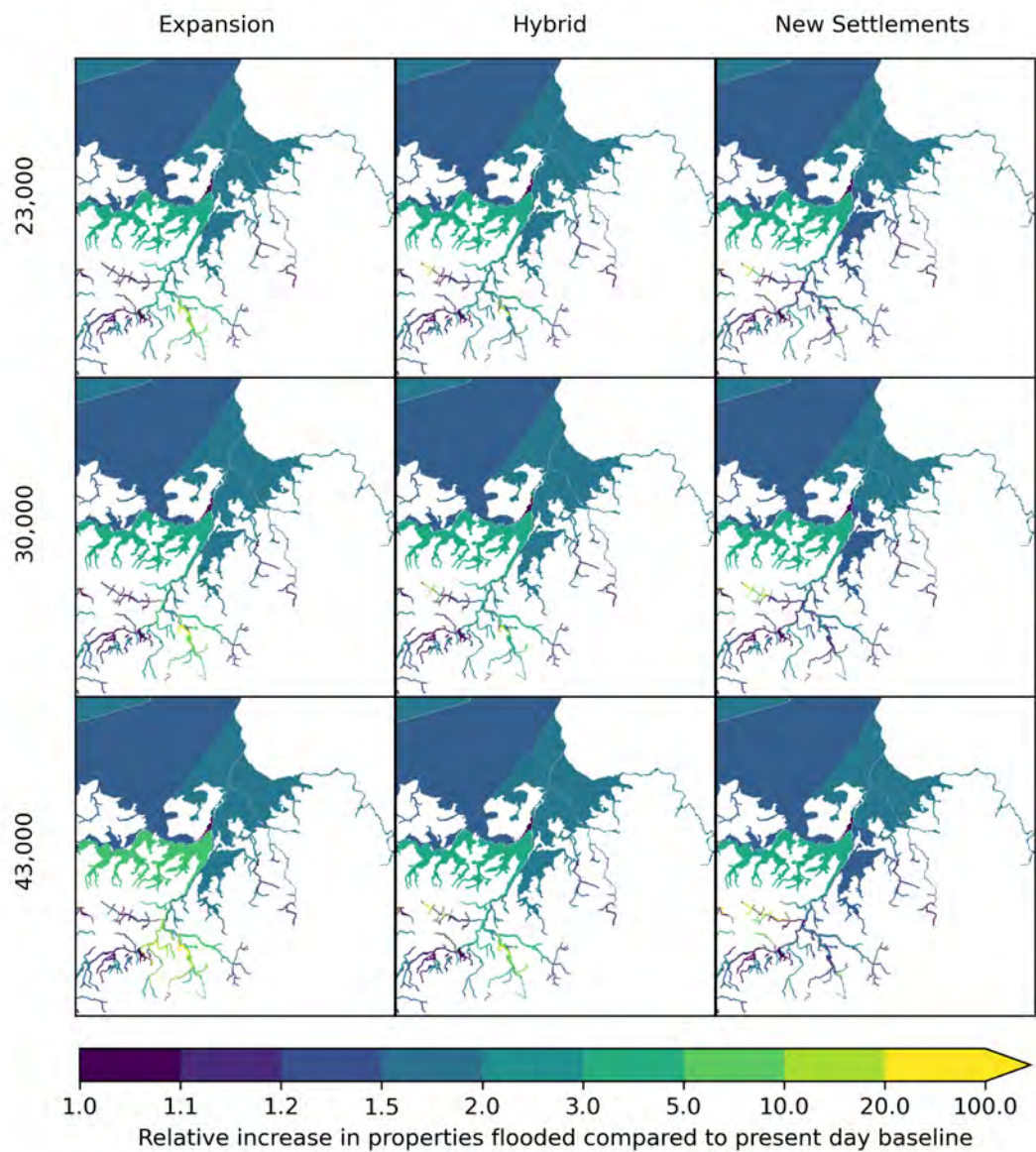


Figure 7-15. Cam catchment, central climate change allowance

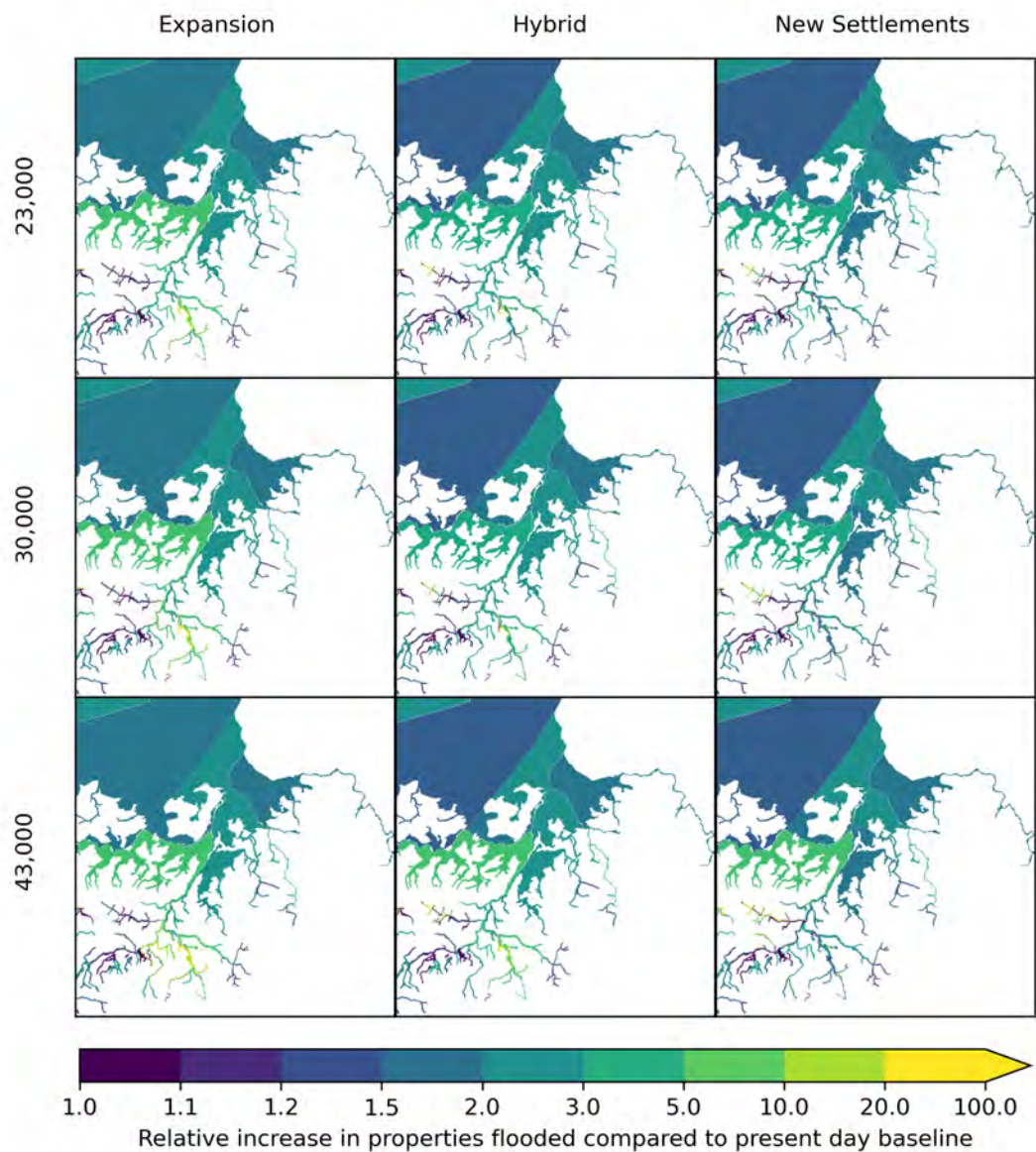


Figure 7-16. Cam catchment, upper climate change allowance

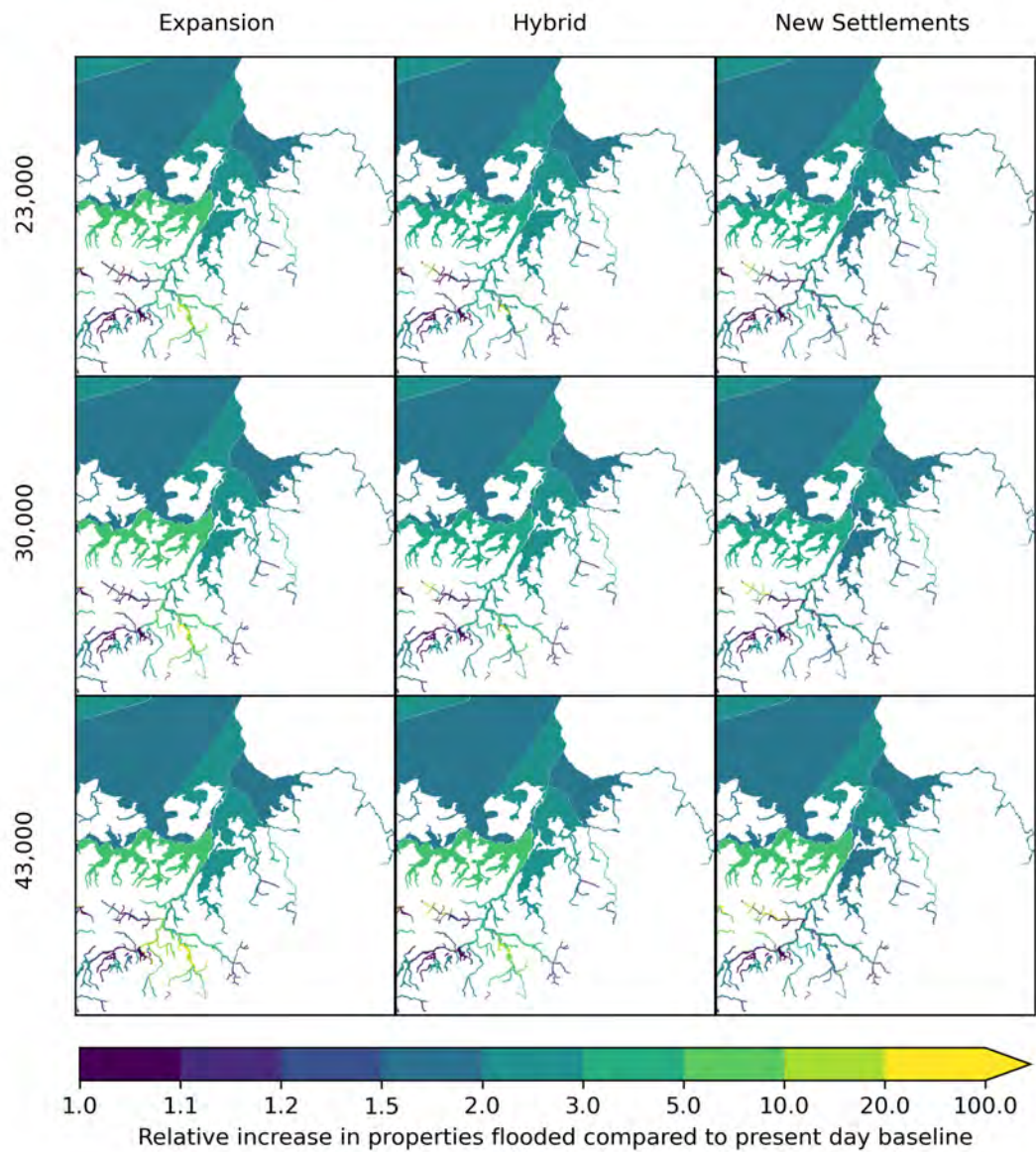


Figure 7-17. Cam catchment, H++ allowance

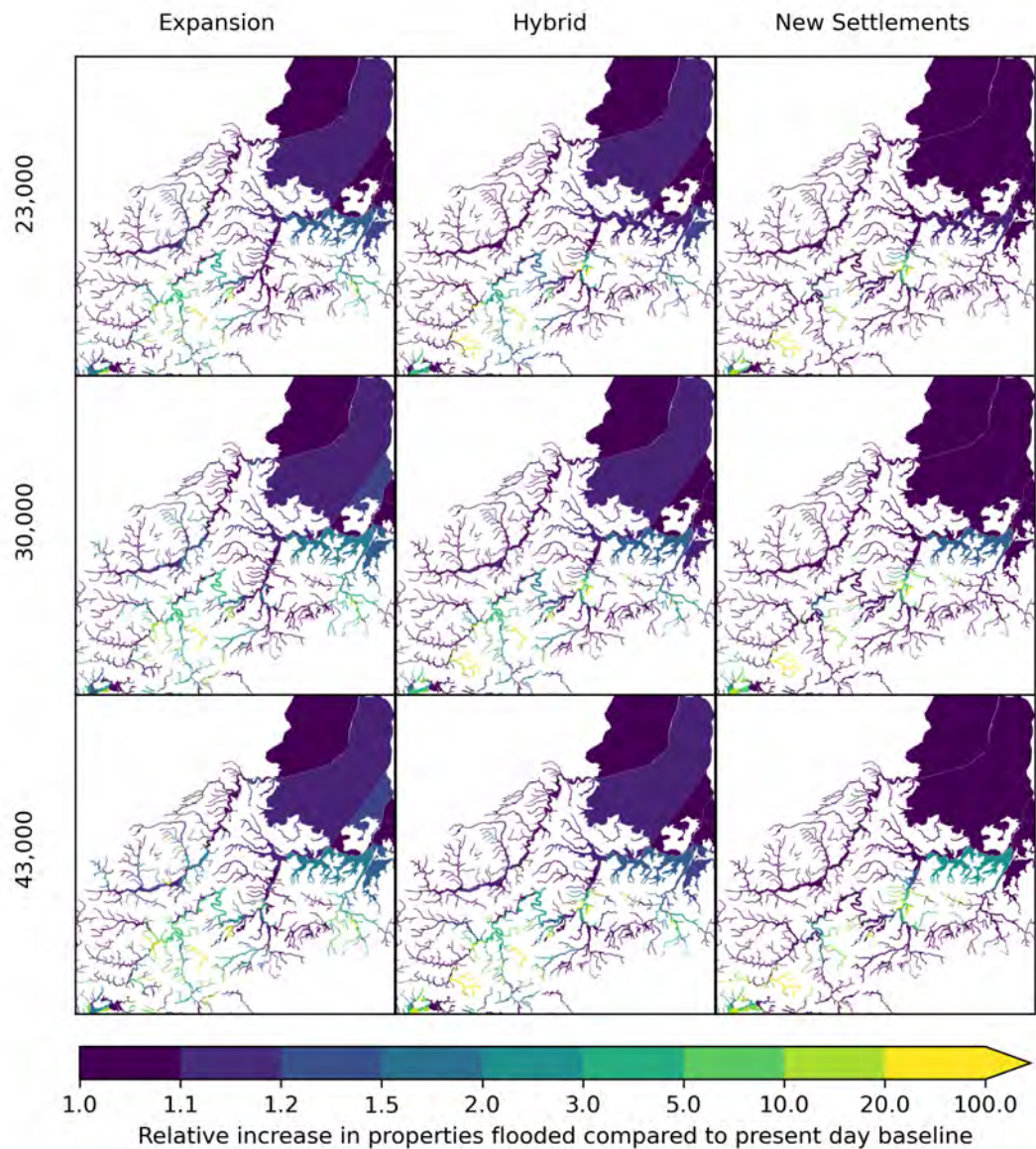


Figure 7-18. Ouse catchment, without climate change

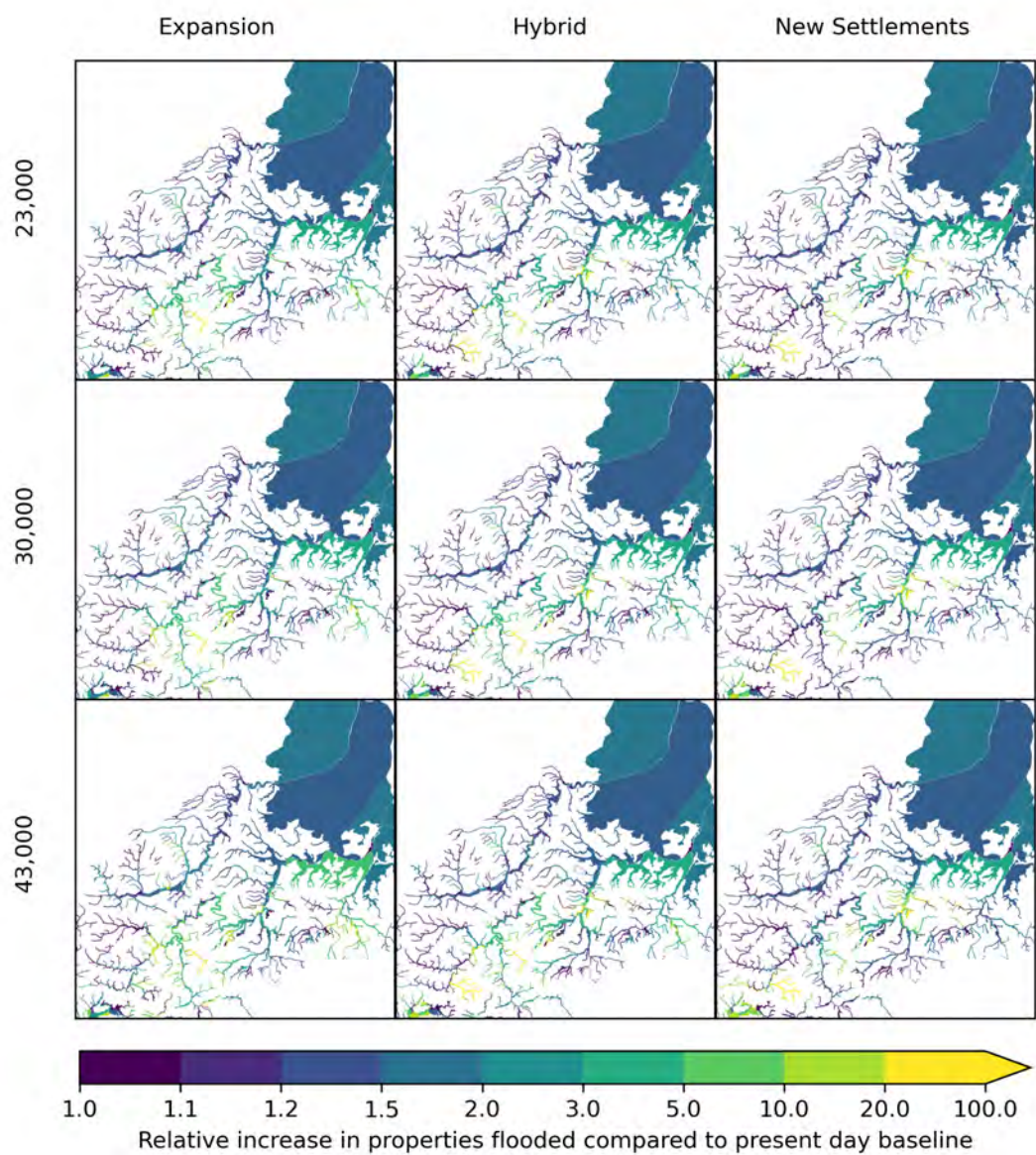


Figure 7-19. Ouse catchment, central climate change allowance.

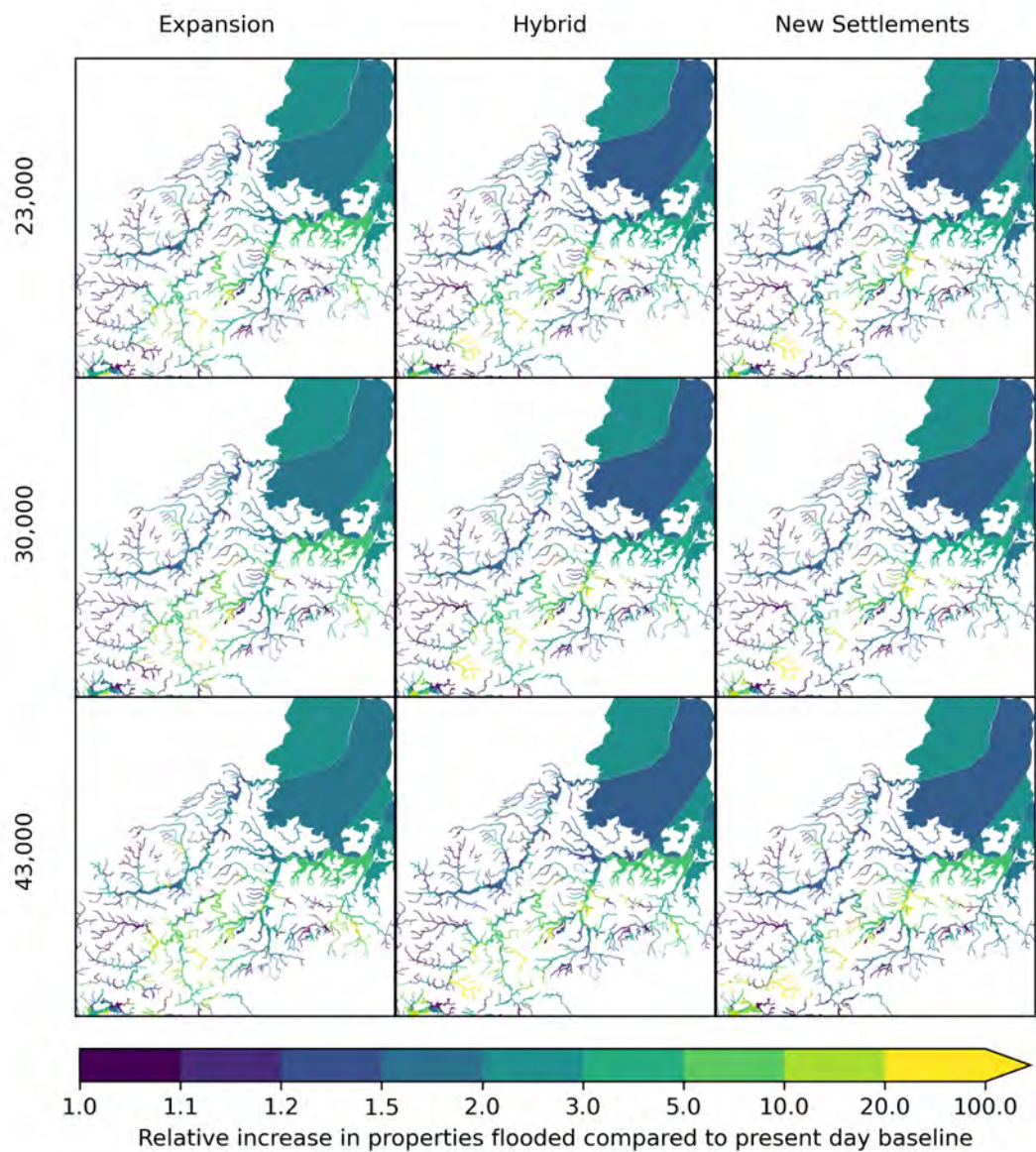


Figure 7-20. Ouse catchment, upper climate change allowance.

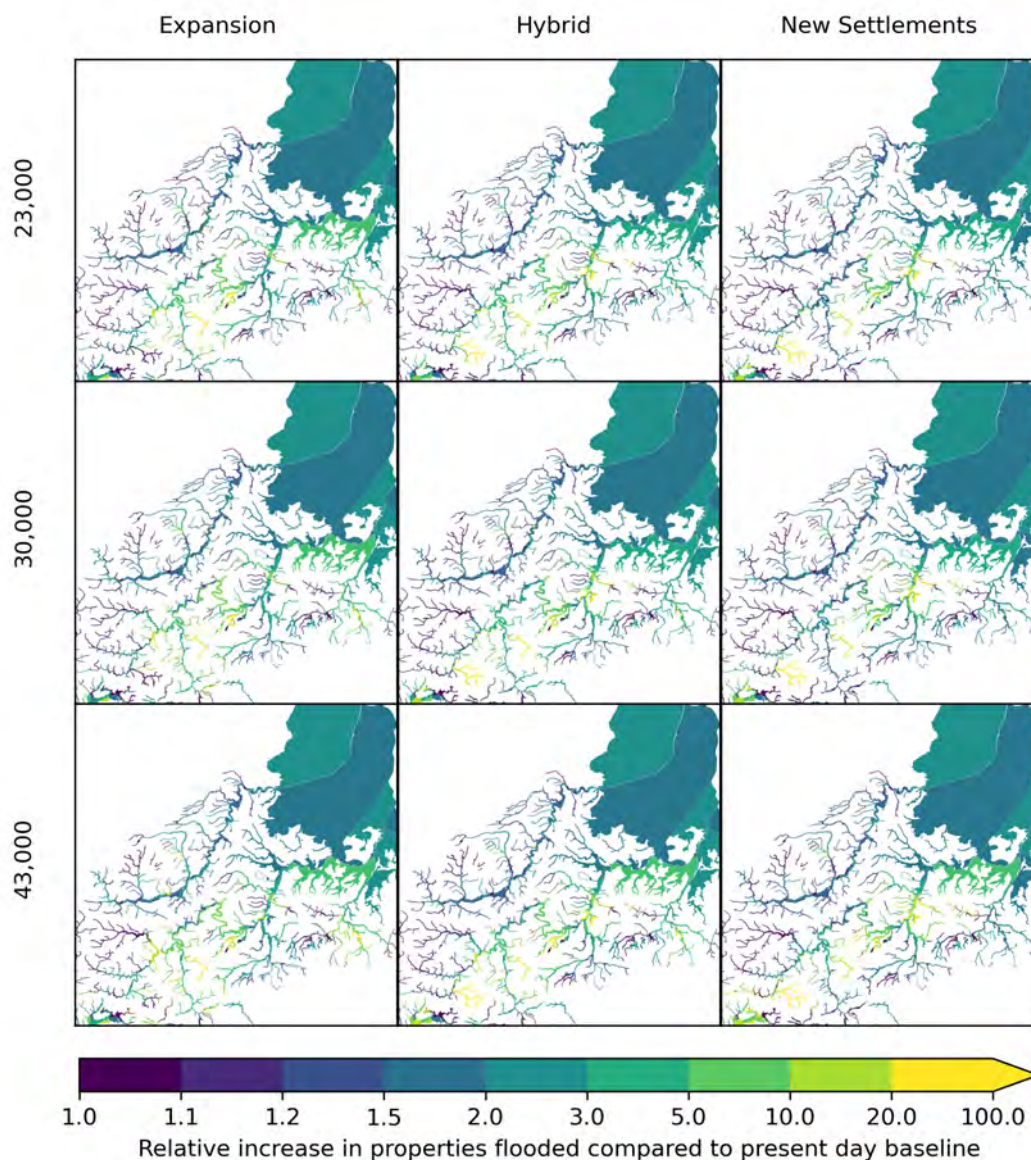


Figure 7-21. Ouse catchment, H++ climate change allowance.

7.3 Impact of interventions

Given the extensive number of combinations of development scenarios, climate change scenarios and epochs and flood risk management options it is impractical to present the full set of property count results here. Rather the tables below present a small selection of the outputs from modelling the impacts of the various interventions. For simplicity we have presented the interventions singularly, rather than as combinations of multiple interventions.

Property floor resilience (PFR) interventions are not shown below because they do not result in a reduction in the number of properties within a flooded area and therefore the property counts undertaken within the modelling stage of the property to not accurately reflect the impact of PFR.

Table 7-9 and Figure 7-22 demonstrate the number of properties at risk across the OxCAM study area following various interventions at a 1% AEP event in the 2050s epoch under various climate change scenarios assuming a Hybrid 30,000 properties per year development scenario. In this scenario NFM provides little or no reduction to

the number of flooded properties, whilst medium and large storage and linear defence options provide substantial reductions.

Table 7-9. Properties affected at a 1% AEP event under the Hybrid 30,000 properties per year development scenario under various climate change scenarios in the 2050s epoch.

Intervention	No climate change	Central	Upper End	H++
No New Interventions	88,537	123,427	147,026	149,824
Small Storage	87,284	115,753	145,105	147,285
Medium Storage	2,105	12,707	98,235	109,988
Large Storage	2,105	2,105	8,379	9,333
NFM	88,537	123,423	147,026	149,592
Small Linear	62,396	108,528	136,645	139,630
Medium Linear	1,705	68,988	117,757	122,412
Large Linear	1,640	1,634	14,790	14,906
Undefended	165,998	201,132	224,984	228,252

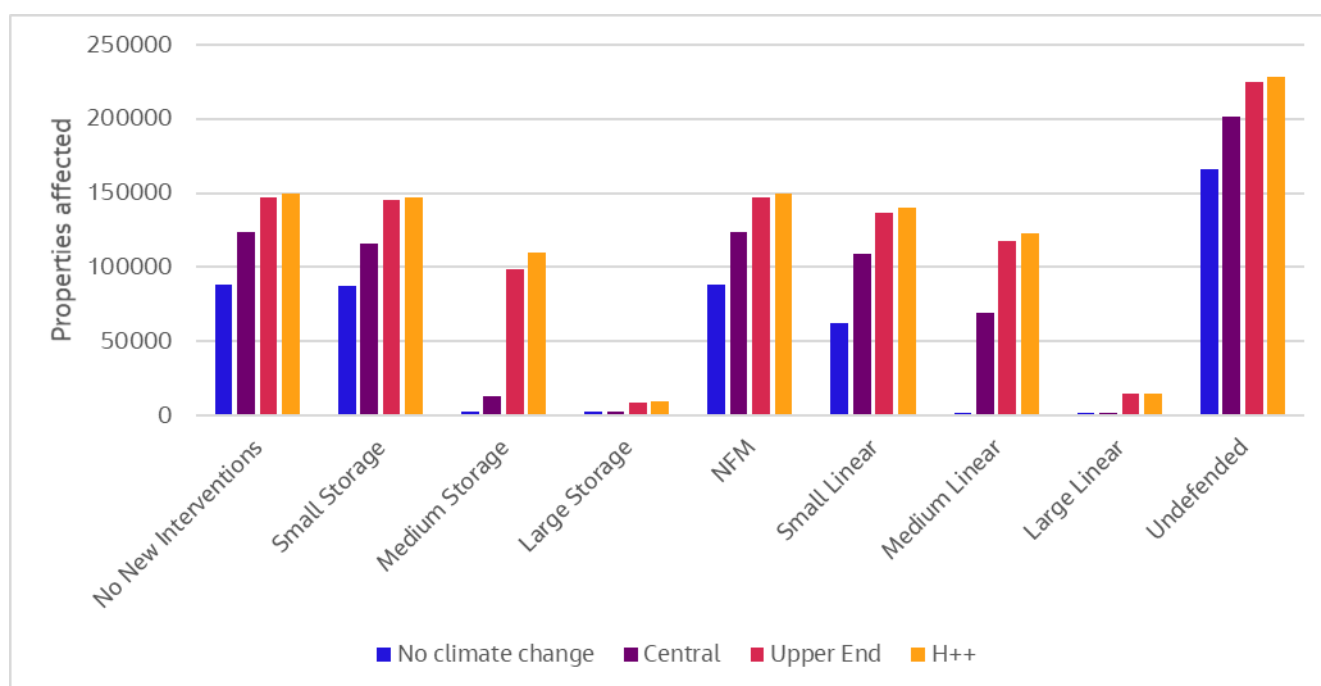


Figure 7-22. Properties affected at a 1% AEP event under the Hybrid 30,000 properties per year development scenario under various climate change scenarios in the 2050s epoch.

Table 7-10 lists the number of properties at risk under the three development scenarios, assuming 30,000 properties per year, in a 1% AEP event in the 2050s under the Central climate change scenario. Under this scenario, if current interventions are maintained, more than 15,500 additional properties would be affected by flooding under all scenarios. The New Settlements scenario would result in the greatest increase in properties at risk and the Hybrid scenario the fewest. Application of both the Large Linear and Large Storage scenarios result in an equal reduction in properties at risk across all three development scenarios and the baseline case. With the exception of the application of the Small Storage intervention, the New Settlements development scenario results in the greatest number of properties at risk under each intervention scenario. The Hybrid development scenario results in the fewest properties at risk under all interventions except for the small and medium storage scenario.

Whilst development itself has an impact on the number of properties at risk, the development scenario has a limited impact on the number of properties at risk. Much greater variation is shown between the intervention scenarios under any development scenario.

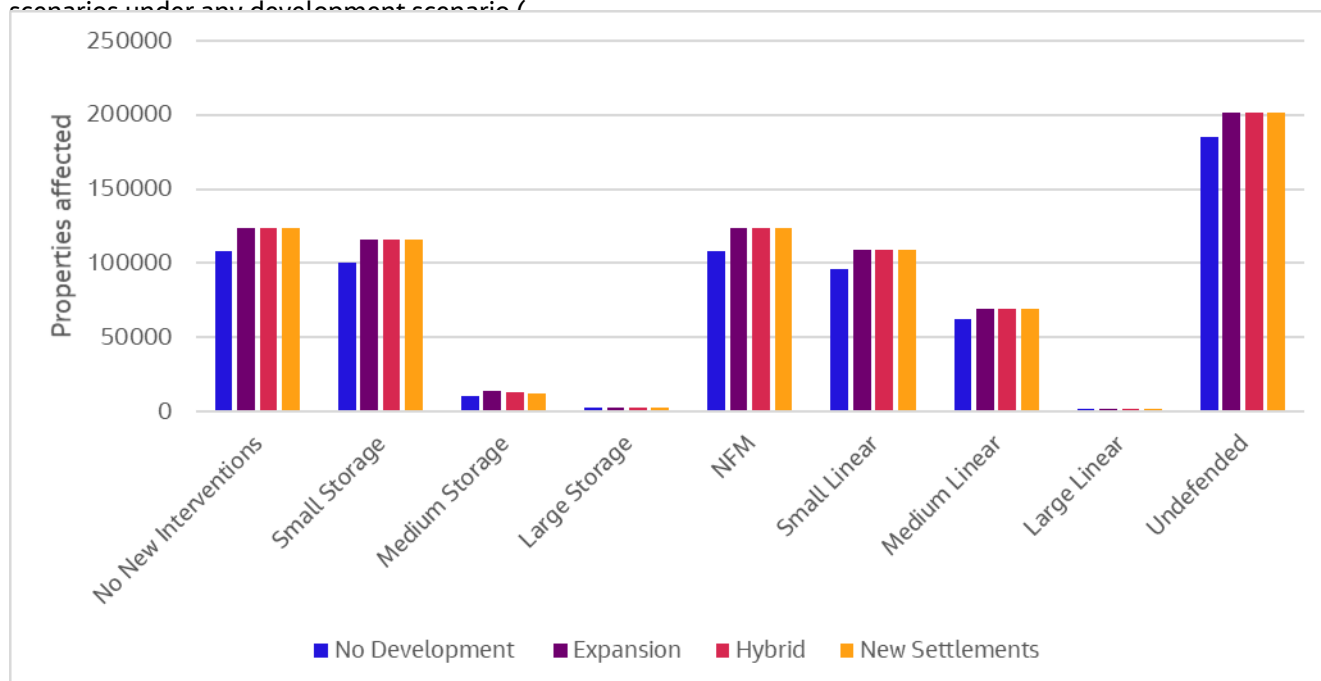


Figure 7-23).

Table 7-10. Properties affected at a 1% AEP event under the Central climate change scenario in the 2050s epoch, assuming 30,000 properties per year.

Intervention	No Development	Expansion	Hybrid	New Settlements
No new interventions	107,866	123,544	123,427	123,651
Small Storage	100,282	115,696	115,753	116,067
Medium Storage	10,717	14,172	12,707	12,298
Large Storage	2,105	2,105	2,105	2,105
NFM	107,862	123,540	123,423	123,647
Small Linear	95,701	108,634	108,528	108,963
Medium Linear	62,092	69,192	68,988	69,379
Large Linear	1,634	1,634	1,634	1,634
Undefended ⁷	184,665	201,364	201,132	201,668

⁷ The undefended scenario is included for context. It was not used within the economic analysis.

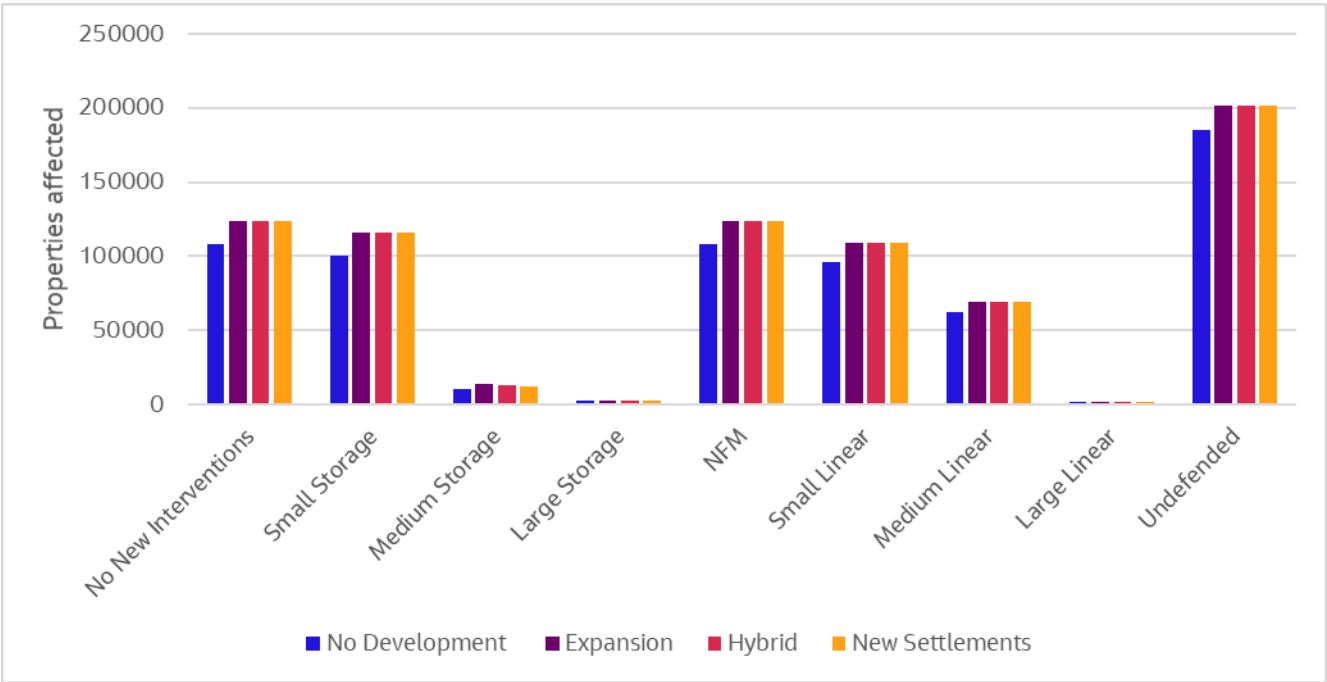


Figure 7-23. Properties affected at a 1% AEP event under the Central climate change scenario in the 2050s epoch, assuming 30,000 properties per year.

8. Limitations, assumptions and lessons learned

A large scale study of this nature inevitably involves numerous assumptions and resulting uncertainty and limitations. The focus of this project is on the economic analysis rather than the direct results of the modelling. Therefore, where possible, we have selected methods which limit the impact on the outputs of the study or allow us to understand the extent of the impact. This section describes these assumptions and limitations.

As a pilot study much of the approach has been experimental and innovative and lessons have been learned in the development of the approach. These lessons are noted below to aid future work.

8.1 Limitations and Assumptions

8.1.1 Storage

The impact of storage is assessed at a single location (a suitable downstream node) as a reduction in flow from one AEP to another. This same change is then assumed to occur throughout the catchment. The method does not consider the location of storage or varying hydrological responses throughout the catchment. In reality the location of storage would have an impact on the areas benefiting from its implementation. For example, at the simplest level areas upstream of a flood storage area would not benefit from that storage or a storage area on a tributary would be likely to have a larger relative impact on that tributary than on the river downstream that would also receive flow from other parts of the catchment.

As the method does not consider the location of storage, or whether this is applied in a single location or as multiple storage locations, it does not account for changing of the timings of flood peaks (lag effects). In reality storage would require careful consideration of design and location to ensure that the timing of flood peaks were not aligned causing an increased flood risk.

Our method assumes that storage starts operating as soon as water levels are above a set impoundment threshold (for this study this is set at a 10% AEP event). At this point the storage begins to fill, storing a 100% of the flow above this threshold until the storage is fully used. In addition, it assumes that the storage is empty at the onset of flooding. The method therefore assumes 'perfect' storage performance. In reality storage will not operate as effectively as this and the method may overestimate the impact of storage on water levels.

If the storage is fully used before the peak flow the method assumes that there is no impact on water levels. In such circumstances the benefits of storage may be underestimated as the volume stored is only accounted for implicitly within calculation of the new water level, and not explicitly as the volume of any flooding.

8.1.2 Climate change

The study area includes both reaches of purely fluvial flows and reaches with a tidal influence. The climate change allowances published by the Environment Agency (Flood risk assessments: climate change allowances, 2020) are based around percentage increases to flows and an absolute increase to sea levels.

The 2020 Environment Agency peak river flow allowances show the anticipated changes to peak flow by river basin district and are based on UKCP09 data. Updated climate change allowances for peak river flows were released on July 2021 and therefore too late to be incorporated into this study. These climate change projections within the 2021 guidance are based on the UKCP18 data and are provided at a more granular, Management Catchment Boundary Scale.

Within the Thames river basin the projections we have used for OxCam are all within the range of values provided for the various management catchments within the latest guidance (with the exception of the central and higher central estimates for the 2050s). These two estimates are however within 3% of the upper range of the latest estimates. Within the Anglian region the projections differ more and those used for 2050s and 2080s epoch are all higher than the latest estimates, albeit within a few percent. Application of the updated climate change projections should be considered within any periodic monitoring or update of the OxCam evidence base.

In tidally influenced areas we have applied a method which weights fluvial and tidal climate change allowance in an effort to replicate the interaction of the two sources without the need to undertake hydrodynamic modelling. We have assumed that the amount of tidal climate change influence on water levels is based on distance along the tidal reach. This is a novel approach and as far as we are aware has not been used in other studies and its effectiveness is therefore uncertain.

The simplified approach does not account for the possible changing location of the tidal limit. Within the OxCam area the tidal limits of the main rivers are defined by sluices, so the method implicitly assumes that they are maintained in order to prevent tidal ingress. The method does not consider the possible overtopping or failure of these sluices.

Fluvial climate change projections are provided for epochs (i.e. a time period) rather than specific dates. Application of these uplifts for epochs would result in stepped changes of impacts and therefore have a significant effect on optimisation. We have applied the climate uplifts using linear interpolation to create a smooth line. In doing this it has been necessary to select a year within each epoch to which the uplift can be applied. The impact of selecting varying dates (start, middle or end) of the epoch is explored in Appendix A. Following discussion with the Environment Agency project team we have agreed to apply linear interpolation between the mid-point of each epoch, but this has been implemented in a way that enables flexibility in this decision, for example, to support sensitivity analysis.

Whilst applying a linear interpolation/extrapolation for the 'return period shift' of flow for climate change, we have assumed a log-linear interpolation/extrapolation to adjust water levels against return period.

This study needs to assess adaptive planning approaches up to 2150, beyond the published fluvial uplifts. It has therefore been necessary to extrapolate these uplifts. We have done this assuming a linear extrapolation using the 2050s and 2080s uplift factors. The values used are therefore beyond those within published research and are consequently less certain than the published values.

The tidal uplift H++ climate change allowance provides a single value at 2100. To incorporate this scenario within the analysis we have therefore had to interpolate and extrapolate the scenario, assuming a 1.9m sea level rise in 2100 with a baseline year of 2010. This assumption ensures that the H++ scenario is always larger than the Upper end scenario.

8.1.3 Modelling

The modelling undertaken for this study is not as detailed as local hydrodynamic modelling. For instance, it uses SoN crest levels (derived from AIMS) instead of surveyed crest levels and it cannot model in-channel structures and their complex hydraulics. If local modelling includes the in-channel hydraulic structures, our approach implicitly includes their influence, as they are already included in the input water levels that form part of the SoN water level dataset.

The model does not explicitly model flow changes and therefore in-channel water level changes due to climate change and/or interventions. Rather it relies on an assumed relationship between a flood frequency level (return period or AEP and flow) and the levels associated with given AEPs. As such, the model is not able to simulate some effects for instance, the impact of increasing the height of a flood wall will increase in channel water levels but reduce floodplain volume. The model will represent the reduction in flood plain water levels but will not show the increase in in-channel water levels, which could have an adverse impact on other parts of the river.

The model explicitly incorporates linear defences along HT boundaries (i.e. those defences adjacent to the channel). These are the defences which are raised as part of the defence raising scenarios. The model does not explicitly incorporate secondary defences set back across the flood plain (with the exception of 9 models containing secondary defences which, during validation, were identified as significant and were thus incorporated). In all cases the model does not incorporate defence raising of these secondary defences in the defence raising scenarios.

SoN data has been used to drive the modelling as it provides full coverage for the study area, there are however some issues with the that cause uncertainty in the outputs:

- Discrepancies between SoN derived water levels and MapEdit water levels which incorporate local studies.
- Differences between SoN peak water levels on opposite banks of the same river reach
- Differences between bank crest levels recorded in SoN and AIMs.

As such, future studies may wish to consider using level data from MapEdit.

In some locations we have identified unexpectedly large elevation differences within the Digital Terrain Model (DTM) used for 2D modelling. Models with data related issues have been flagged as "Data Issue" as part of the verification process.

8.1.4 NFM

The assumptions and limitations of our method for assessing the impact of NFM relate to both the nature of NFM and the assumptions we have had to make as part of this study.

NFM can include a wide variety of measures the selection of which depend on the nature of the catchment and the context in which NFM is undertaken. Alongside the environmental benefits delivered by NFM such measures can also reduce flood risk by both reducing the runoff from a catchment (for example by improving infiltration) and slowing the flow, thereby reducing peak flows. The evidence base for these impacts is still being developed and therefore quantification of flood risk benefits due to NFM is not a simple processes. Our method has applied current understanding of NFM in assuming that:

- NFM has a larger impact on smaller catchments.
- NFM has an impact a lower order events and does not influence extreme events.

In order to apply the method we have had to select a means to quantify the benefit of NFM. We have used an "equivalent volume" in order to do this. With limited evidence on which to base this assumption it is a key uncertainty in the NFM process.

Other limitations of our method are that:

- We are not able to represent the location specific variability in both the type of NFM appropriate and the performance of NFM measures.
- As the study does not include full hydrodynamic modelling we can not represent the impact of slowing the flow from a catchment and therefore, like the storage method, can not consider downstream impacts that may occur due to changes in relative timings of peak flows.
- We do not have model outputs for water levels below the 50% AEP event. This means that the benefits of NFM for the 50% AEP event can not be modelled.

8.1.5 Automation

Although not explicitly modelled, the water levels for every combination of flood event, climate change allowance and intervention have been pre-calculated, and can be compared to those which have been simulated explicitly to determine how to interpolate the results and impacts. Each model domain comprises many individual nodes. Using every single node to lookup and interpolate impacts, although technically possible, would be prohibitively memory and CPU intensive and not appropriate for the scale and scope of the project. We therefore originally planned to use a single 'reference' node for each domain for comparison and interpolation. As detailed in section 5 this would be a suitable method if the change in water level followed the same relationship for any event, as the single reference water level would still provide a proxy for the whole model domain. Instead, it can be observed that many of the model domains do not follow a simple relationship in water level across all scenarios. To alleviate this we used 3 reference nodes within each model domain to provide a

more accurate representation of the water level profile, while still being reasonable to implement in the database and optimisation. Whilst a pragmatic solution for the scale of the study this still results in more uncertainty in outputs than if every individual node were used.

8.2 Lessons learned

8.2.1 Simulation library approach

To manage the volume of flood modelling required to represent the full breadth of millions of scenarios, in particular to enable us to represent climate change, storage and natural flood management without explicitly modelling each scenario, we adopted a 'simulation library' approach, with each simulation result indexed by water levels in an analysis unit – in this case we flood areas. In general, we have found this approach to be highly effective for regional-scale modelling (and, indeed, links closely to the *simulation library* approach that will be at the heart of the NaFRA2 national-scale flood risk analysis system), with the limitations described elsewhere in this report (in particular that using a single set of water levels does not enable a bidirectional relationship between linear defences and water levels).

We have also learnt a great deal from the challenges of adopting this approach:

- 1) The approach is highly dependent on data quality. In particular, the quality of water level and asset crest level data. Ongoing data improvements across the Environment Agency should improve the state of these datasets, but future studies could also focus more on data improvements at an early stage.
- 2) Representing climate change uplifts to water levels using the flow-probability relationships from flood frequency curves was successful. See 8.2.1.1 below for more information.
- 3) Representing storage and natural flood management, while suitable for a study of this scale, could be refined. For example, using existing 1D flood models to predict water level shifts, or by simpler means of representing the variable level of protection offered across a catchment by real-world interventions – as seen in TVFS. See 8.2.1.1 below for more information.
- 4) Existing national datasets representing hydraulic units / analysis units – flood areas and flood risk management systems – are inconsistent in size, making them challenging to use as the basis of model domains and investment decision making. Future studies should seek to adopt alternative spatial units.
- 5) A single model node is not sufficient for indexing water levels. This is linked to the point above, as it is exacerbated by large analysis units, but in general the challenge is that the water level gradient is not consistent between different scenarios. This is especially true at confluences and in tidally-influenced river reaches. See 8.2.1.2 below for more information.

8.2.1.1 Water level indexing

A significant part of this study was the need to be able to use the explicitly modelled outputs to represent a large number of potential scenarios indirectly, and this required being able to define new scenarios purely by calculating what their water levels should be at each reference node. Overall this approach worked very well as it allowed for millions of potential scenarios to be defined purely by adjusting the water levels and querying and interpolating existing results. Based on our experience throughout the project it was clear that certain types of scenarios or interventions were able to be represented using water levels with greater confidence than others. For example, uplifting the water levels based on climate change scenarios was a relatively straightforward task as we were able to use the existing flow probability relationships from the various FFCs to apply the Environment Agency's climate change guidance and get a water level. The biggest assumption for this method was how the nodes were assigned to a gauge, but based on the review of the uplifted water levels the method worked well. Other scenarios however, required more assumptions and were more difficult to accurately validate. One example is the representation of NFM in the upper catchments as we needed to make numerous assumptions on the amount of suitable storage potential in the catchments as well as how NFM interventions would impact the shape of hydrographs at each location.

8.2.1.2 Indexing nodes

As discussed previously, the intention to use a single model node to index model outputs was dropped in favour of a three-point indexing method. This methodology worked well and allowed better representation for scenarios where the water level profile did not have a simple linear relationship. This is especially important for flood areas such as those with multiple different FFCs associated, or which are partially influenced by tidal flooding. A big limitation of this method was that it required significant effort to select the reference nodes for each flood area. Originally, we intended to simply select a reference node from the upper, middle and lower section of each flood area. However, after further analysis and trialling of this method, we found that we needed to apply many more rules to select appropriate reference nodes. Some of these rules were required to capture the potential variation in the water level profile, for example selecting nodes assigned to different FFCs, different sources of flooding and ensuring adequate spatial coverage, however, many rules were also required due to the poor quality of the water level data in certain locations. These rules aimed to omit any nodes where water levels were missing, dropped in level at any successive AEP or had a flat water level profile. Application of these rules meant that some flood areas were without any points which satisfied the requirements. In these cases we needed to relax the rules and manually select the best available points.

8.2.2 Hydraulic Modelling

Overall, despite the high level of automation employed to build, run and post-process models, a higher than expected proportion of the project duration was spent with hydraulic modelling. A large part of this was dealing with data issues – linked to point 1) above:

- 1) **Water level data.** Our review of model outputs identified erroneous source water level data in many more locations than expected. As the modelling relies on an assumed relationship between a flood frequency level (return period or AEP and flow) and the levels associated with given AEPs these erroneous data impacted results, resulting in additional computational and review time. A more streamlined data review process (e.g. review of pre-calculated water head) undertaken before water levels were applied to the model would have been a more efficient approach.
- 2) **Secondary defences.** Our review also identified that we had underestimated the influence of secondary defences at the outset of the modelling work. Identification of key secondary defences using AIMS and the inclusion of those key secondary defences within the first iteration of modelling could expediate the programme of similar work.
- 3) **HT boundaries.** While running and reviewing the no defence model runs, we found that a 1D HT boundary model setup is more robust than a 2D HT boundary setup. 2D HT boundaries result in water level loading being added when two boundary lines fall onto the same grid cell, while 1D HT boundary handles this scenario more gracefully by taking the maximum of the two levels. Therefore, 1D HT boundary setup has been adopted universally for all models, and baseline models was rerun to ensure consistency.

8.2.3 Data and code management

A key positive lesson learned was the importance of good quality end-to-end data management. Due to the nature of the project, a very large amount of data required storing, processing and analysing. Overall, our management and storage of this data was very well handled, and we were able to work with many thousands of model simulations and millions of potential scenarios in an accurate and efficient manner. Our solution incorporated both a well-structured file system for modelling outputs and a relational database for handling the various scenarios, water levels and pre-calculated impacts for each flood area. Spending time developing this database structure early in the project based on the proposed end-to-end approach was an important step in the overall project process.

The initial tight programme of the project and phased structure of the project scope led us to develop and implement a number of methods in relative isolation and in parallel. While this was broadly successful because we had a) first outlined an overarching approach into which each method needed to fit, and b) worked hard to ensure a common understanding of the approach across the team, it still led to challenges – in particular, because each step of the process required a level of maturity in data outputs from previous steps to enable the

detailed method to be developed. A lesson for future studies is to a) maintain the high-level end-to-end method development, but b) adopt a more iterative approach to implementing methods, to ensure they are efficiently developed in tandem. For example, implementing the end-to-end process in full in pilot areas, to ensure each part of the method reaches maturity together.

Closely related to this, the importance of software development and data analysis to the project meant that we would have benefitted from adopting more formal software development practices from the start, including:

- 1) Comprehensive use of source code repositories.
- 2) Agile sprint cycles to support the proposed iterative development.
- 3) Continuous integration and continuous deployment to support automated testing of iterative builds.

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Appendix A. Climate Change

A.1 Summary

As discussed in section 3.4, climate change impacts on river levels were applied through the use representative growth curves to relate climate change uplifts (Environment Agency, 2020) to the river levels used to drive the analysis. A representative growth curve was selected and used to identify the present day AEP to which the climate change scenario equates. The level for this present day event was then be selected or interpolated as the climate change scenario level. Where the uplift was greater than that in the the present day growth curve then the growth curve and level relationship were extrapolated based on the last two points (lowest AEPs).

The peak river flow allowances / climate change uplifts available at the start of the study were used (Flood risk assessments: climate change allowances, 2020) and are shown in Table 3-1 These provide percentage uplifts to flows for three epochs; the 2020s, 2050s and 2080s. These staged uplifts are represented by the solid yellow line in the plots below.

There were a number of uncertainties around the application of climate change guidance to the OxCam study:

- 1) The present day scenario is based on level data used in State of the Nation (SoN), which was last updated in 2018. The levels therefore include estimates made up to 2018, but many will be based on much earlier studies. Present day for the purpose of the OxCam study is 2020. The first epoch for climate change is the 2020s which encompasses 2015 to 2039. This raised the question: Should a climate change uplift be applied to the SoN levels to create present day estimates?
- 2) The river flow climate change projections extend only to 2115, the end of the 2080s epoch and the sea level high ++ projection to 2100. The OxCam study considers impacts up to 2150. This raised the question: How should climate change uplifts be extrapolated beyond 2115?
- 3) The intention of the project was to view outputs from the study at 10 year intervals. The river flow climate change projections are provided for an epoch, not a specific date. This raised the question: Should these be interpolated to show a gradual increase in flows resulting in climate change and if so to which year should the reported climate change uplifts be applied?
- 4) The recommended climate change scenarios differ for river flows and sea level rise. This raised the question: Which three scenarios should be applied?

The plots below (Figure A.1 to A.4) illustrate the various possible river flow uplifts (based on the above considerations) for the Central, Upper and H++ scenarios. Note that the Anglian and Thames basin uplifts vary slightly for the Upper scenario but not for the Central and H++. Each plot shows the same information, with the same legend for the different climate change projections.

The first two vertical black lines mark 2018, the latest possible year on which SoN level data is based and 2020, the present day. The third vertical line marks 2115, the point at which any climate change projection is extrapolated beyond values presented in current guidance.

The solid yellow line marks the stepped climate change projections, with a single uplift for each epoch. The orange, green and blue lines represent interpolated values for climate change uplifts depending on whether the reported uplift is assumed to occur at the start, middle or end of each epoch.

The dashed lines represent a linear extrapolation based on the last two climate change uplift factors for each solid curve. The dotted lines represent a polynomial extrapolation based on all three climate change uplift factors for each solid curve.

The plots illustrate that the assumptions made around climate change have a large influence on flows and thus the levels used to drive the study and, it would therefore be expected, on the outcomes and decisions resulting from the study.

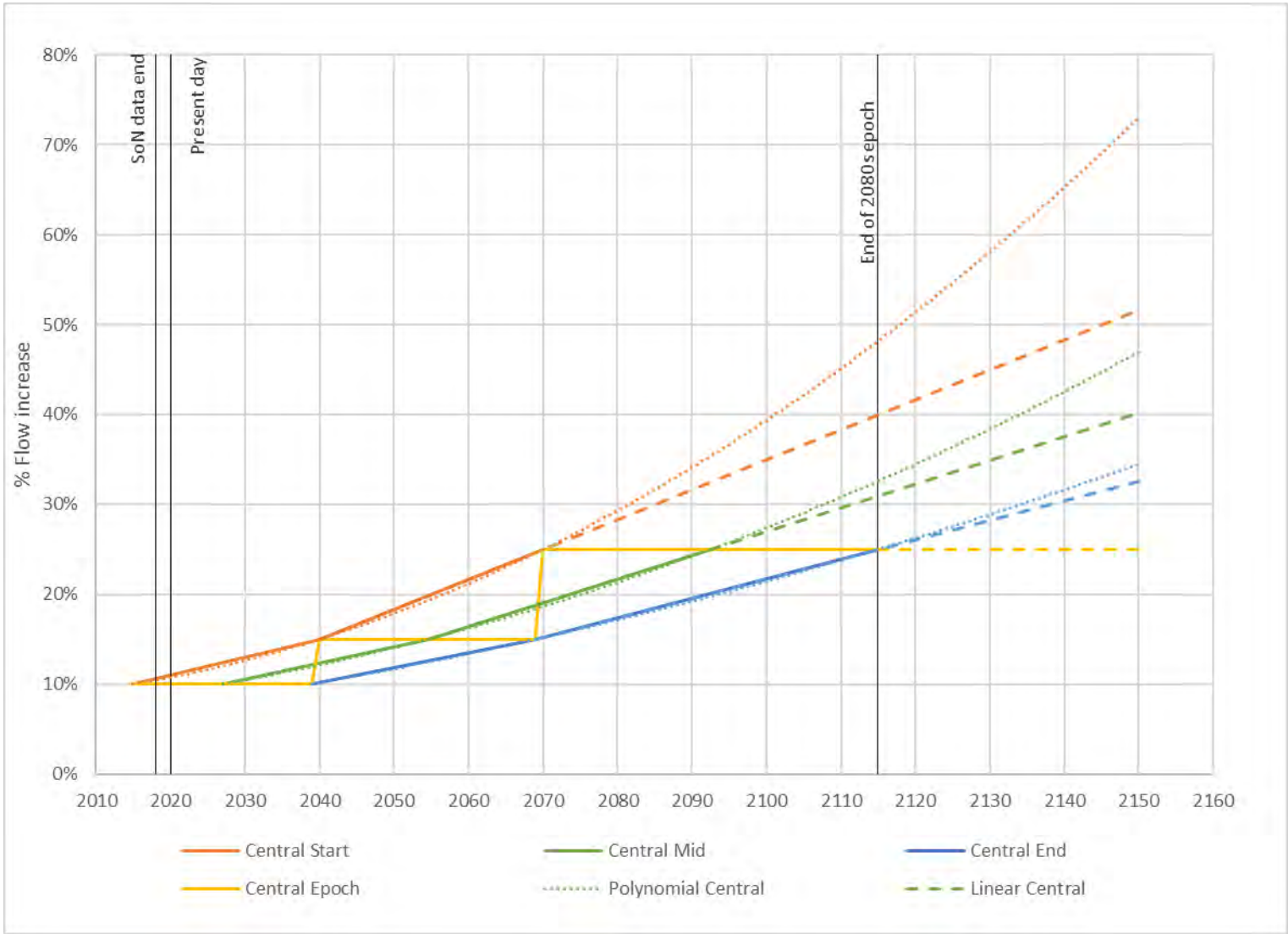


Figure A.1. Possible approaches to climate change projections – Central estimate.

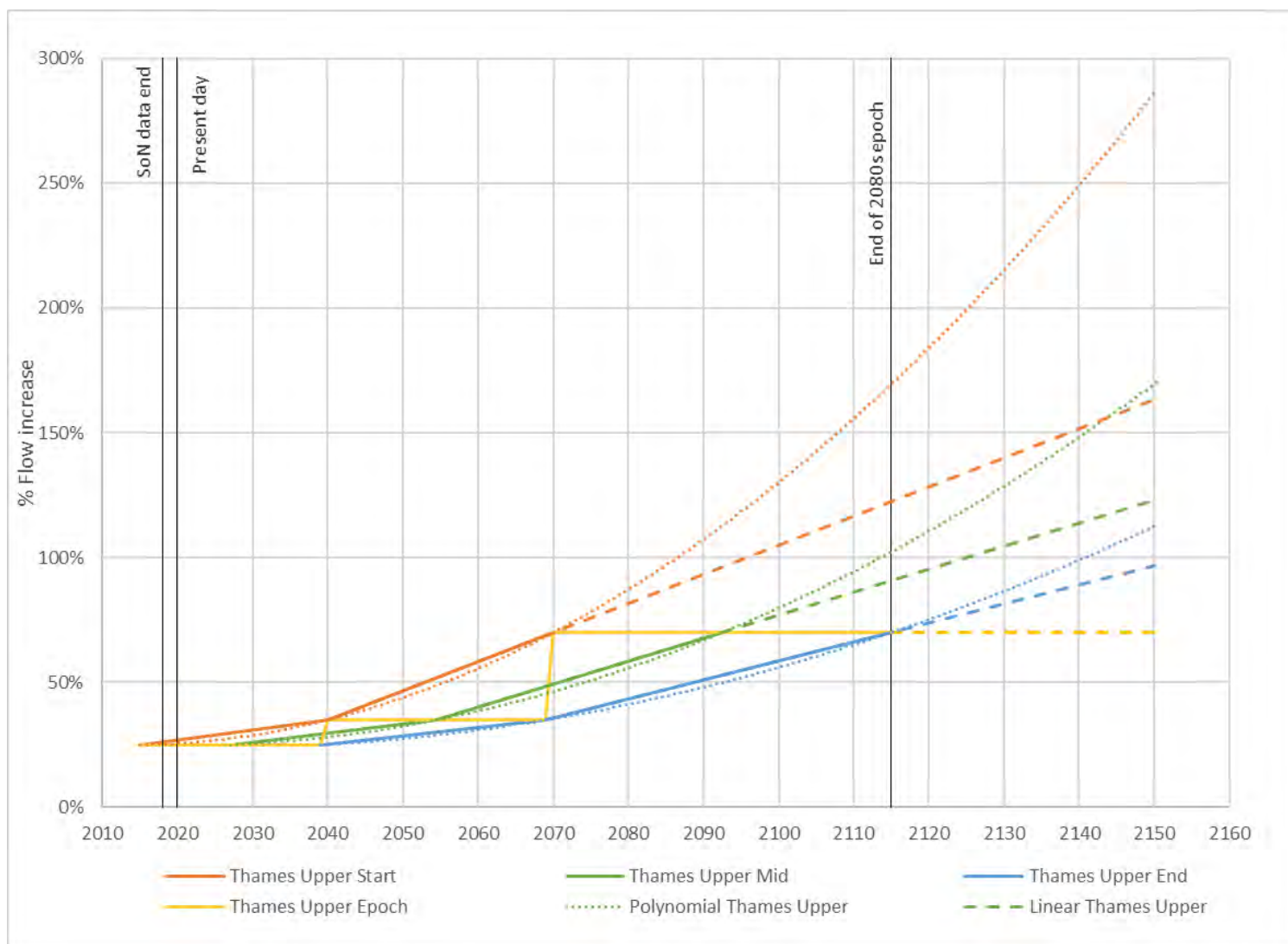


Figure A.2. Possible approaches to climate change projections – Upper estimate for Thames River Basin.

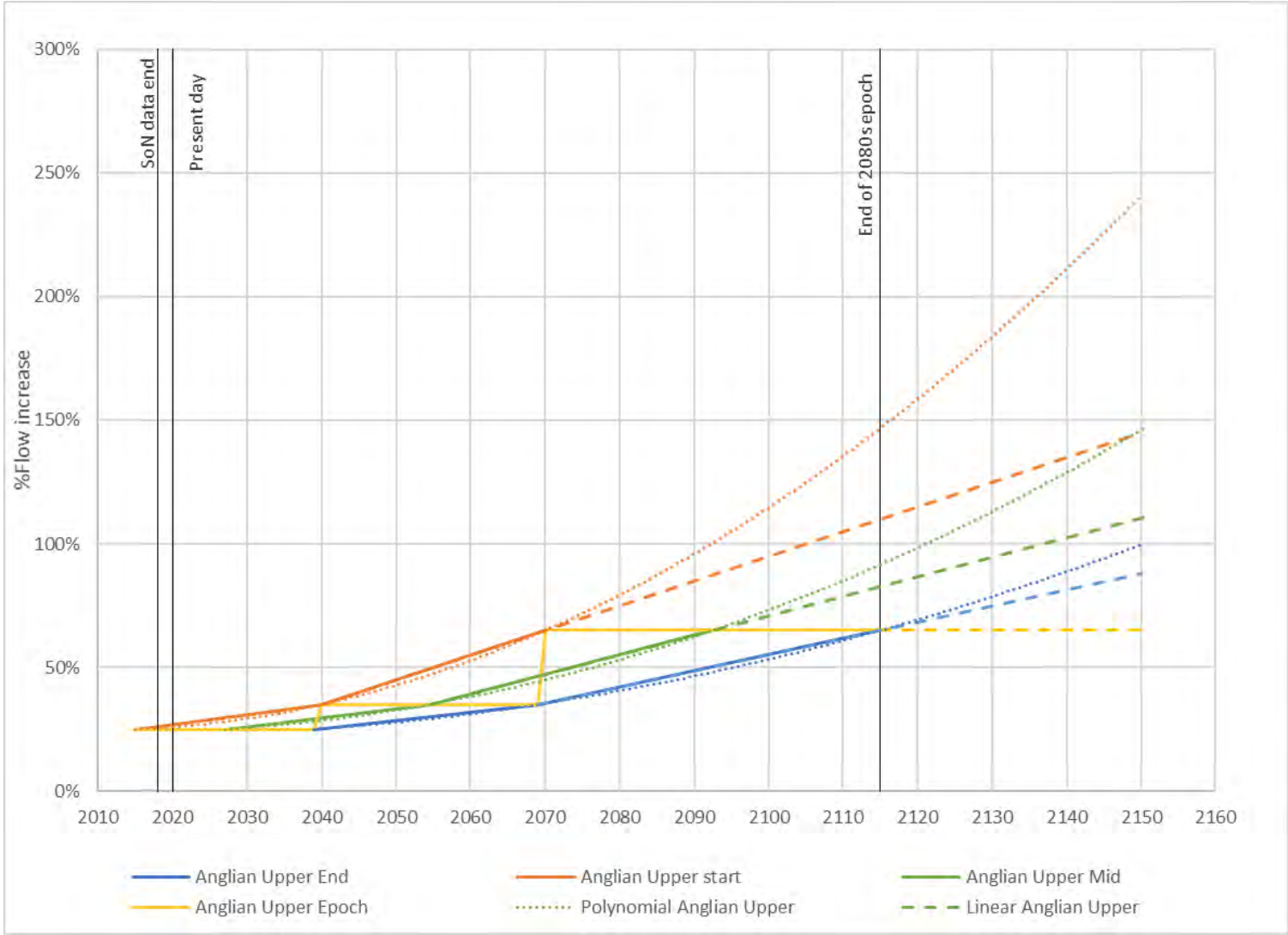


Figure A.3. Possible approaches to climate change projections – Upper estimate for Anglian River Basin.

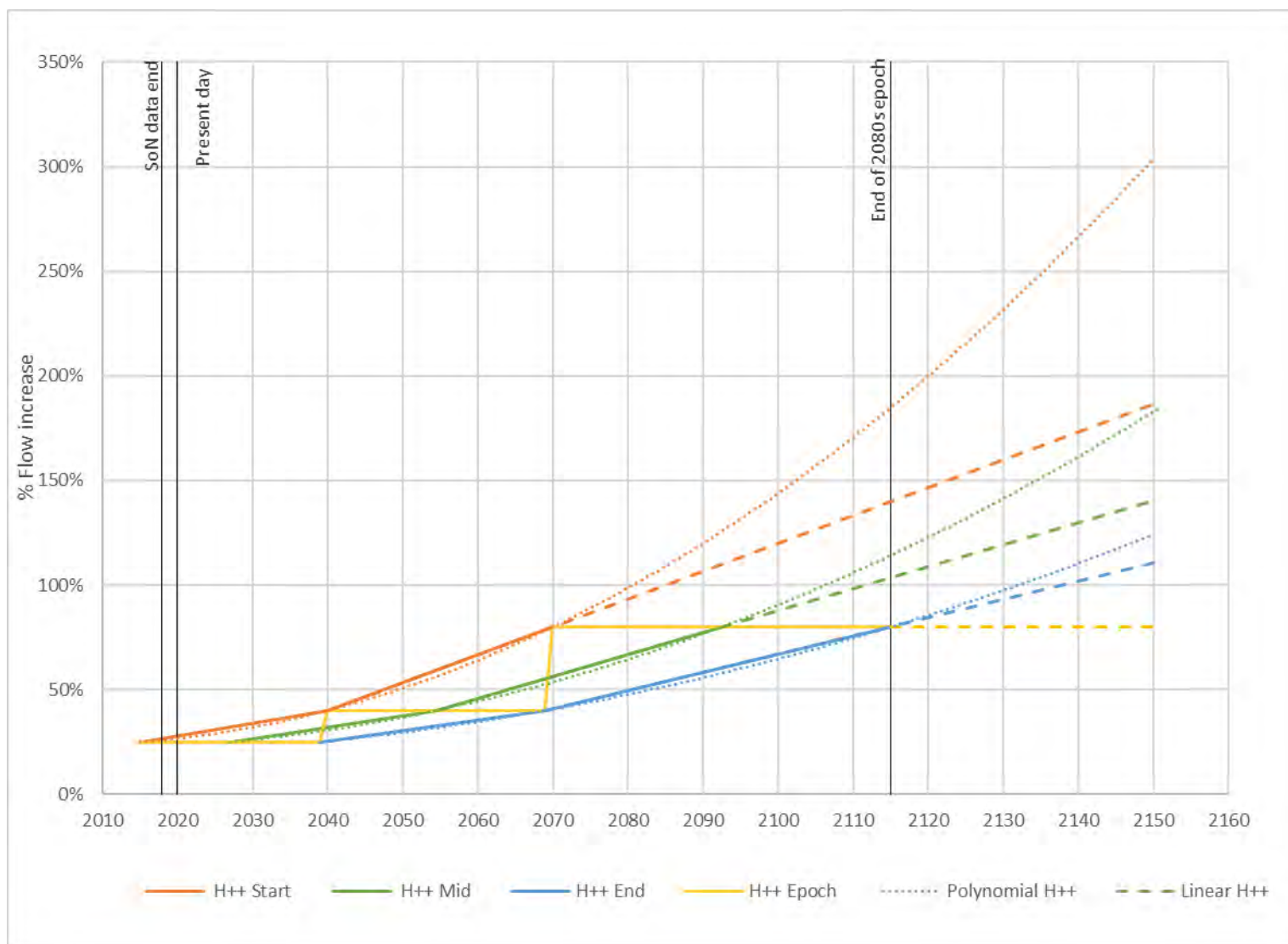


Figure A.4. Possible approaches to climate change projections – H++ estimate.

A.2 Application of uplift to present day

The SoN water levels used to drive the modelling and selection of outputs (where not being directly modelled) are based on a variety of sources varying from locally modelled outputs produced in the period up to 2018, older modelled outputs and national scale modelling. The results are therefore 'present day' for the period at which they were produced and may not represent the influence of climate change on water levels.

The first climate change epoch provided in the guidance for river flows is the 2020s (2015 to 2039). It is not clear from the guidance whether these uplifts should be applied to present day estimates.

We considered two options; either to assume that the levels in SoN represent current (2020) present day or to assume that they require update to reflect the impacts of climate change since the production of the levels. The implications of these assumptions are shown in Table A.1.

It is important to note that whilst difference in present day water levels would affect the relative difference between benefits, without testing within the study, it is not clear whether they would reflect the overall outcome of the study, i.e. the ability to use the study to adaptively plan.

Another consideration around this decision was whether it is nationally consistent with strategic studies being undertaken elsewhere. We understand, for example, that a climate change uplift to present day estimates has been applied as part of the Humber Extreme Water Level studies.

Following discussion with the Environment Agency, we assumed that the SoN levels represent present day.

Table A.1. Implication of assumptions about application of climate change uplifts to water levels.

Assumption	Advantages	Disadvantages
SoN levels are present day	Simple to apply. Provides a single estimate of present day estimates	May overestimate the return period (underestimate the AEP) of a level, suggesting it is less likely to occur than it is. By increasing the annual average damages, we would expect that it would have a knock-on effect on the net present value (most likely increasing it, as benefits of interventions would likely be greater).
SoN levels require climate change uplift in order to represent present day	May result in a dataset more representative of present day conditions	May underestimate the return period (overestimate the AEP) of a level, suggesting it is more likely to occur than it is. Would result in multiple "Present Day" estimates due to the climate change scenarios being applied (Central, Upper H++)

A.3 Extrapolation to 2150

The climate change guidance includes uplifts to 2115 (the 2080s epoch). The OxCam study provides estimates to 2150, well beyond the current climate change guidance. The plots (Figure A.1. to Figure A.4.) illustrate the variation in uplifts that could be applied depending on the assumption selected.

Assuming that a consistent uplift is applied across each epoch (the solid yellow line) the climate change estimate beyond 2115 could be maintained (dashed yellow line). This would result in the lowest climate change uplift in all possible scenarios shown in the plots.

Possible means of extrapolating climate change uplifts, assuming climate change uplifts are interpolated throughout each epoch (see Section A.4), are shown in the plots as either a polynomial relationship based on all three uplift points or a linear extrapolation based on the last two points. The polynomial extrapolations result in higher estimates than the linear extrapolation.

These plots help to illustrate the uncertainty related to climate change extrapolation. It is important to note that the plots are based purely on extrapolation and not evidence from climate science about changes after 2115. Following discussion with the Environment Agency team, we applied linear extrapolation to climate change uplifts after the 2080s epoch.

A.4 Interpolation

The climate change guidance for river flows specifies a single uplift for each epoch and climate change scenario. This is illustrated by the solid yellow line in the plots. The study intend reviewed adaptive strategies at 10 year intervals..

To allow this, climate change uplifts were interpolated between epochs. As such it was necessary to select a representative date at which to apply the climate change projection. The plots above show the difference in uplifts that would result from applying the climate change uplift at the start (orange), middle year (green) and end (blue) of each epoch. They show that for a given year the resulting uplift varies greatly depending on the date at which the climate change uplift applied, with each presenting different risks (Table A.2).

The advantage of interpolating between the climate change uplifts is that it provides differentiation between decades (the period at which study outputs will be reported). In addition, it was the intention of this study to interpolate overall results (i.e. not just water levels) rather than running potentially thousands of models (see Section 5). This would result in an automatically assumed interpolation of the impact of climate change (alongside the other influences on study outputs) and it was therefore important to consider the point at which each climate change uplift allowance should be applied.

Interpolating climate change uplifts is not a standard approach and was therefore discussed with the Environment Agency. As a result, the mid date of each epoch was selected as the representative date upon which to base climate change uplifts. This represents a balance between potential under or overestimation of influence at a given date.

Table A.2. Issues associated with timing of climate change application.

Start of epoch	<ul style="list-style-type: none"> ▪ Potential overestimate of climate change throughout each epoch. ▪ Would be extrapolating climate change impacts after 2070.
Mid epoch	<ul style="list-style-type: none"> ▪ Potential under or overestimate of climate change within each epoch. ▪ Would not demonstrate climate change impacts until 2027. ▪ Would extrapolate climate change impacts after 2092.
End of epoch	<ul style="list-style-type: none"> ▪ Potential underestimate of climate change throughout each epoch. ▪ Would not demonstrate climate change impacts until 2040.

Appendix B. Flood Frequency Curves

Table B-1. Flood Frequency Curves proposed for climate change uplifts.

Station name and number/ID	50%	20%	10%	5%	4%	2%	1.33%	1%	0.5%	0.1%
	2	5	10	20	25	50	75	100	200	1000
32002 - Willow Brook at Fotheringhay	18.60	28.50	33.80	0.00	44.70	53.00	-	61.00	71.90	107.00
32003 - Harpers Brook at Old Mill Bridge	11.80	20.50	27.30	37.90	41.10	47.50	-	59.00	72.80	116.80
32004 - Ise Brook at Harrowden	11.90	17.10	20.60	0.00	25.50	29.60	-	34.00	38.90	52.30
32007 - Nene/Brampton at St Andrews Total	15.40	22.00	26.50	29.00	32.50	37.40	-	42.70	48.40	63.80
32008 - Nene/Kislingbury at Dodford	18.60	28.90	36.50	41.40	47.30	56.70	-	67.30	79.40	114.70
32010 - Nene at Wansford	62.70	85.70	101.90	119.10	124.90	144.30	156.70	166.00	190.30	259.40
32020 - Wittering Brook at Wansford	60.18	88.21	100.33	120.49	124.18	150.86	155.85	163.17	188.02	258.80
32031 - Wootton Brook at Wootton Park	10.30	14.80	17.80	21.00	21.60	24.60	-	27.70	31.10	39.60
33005 - Bedford Ouse at Thornborough Mill	-	19.68	28.53	37.88	41.22	50.93	57.29	61.90	72.94	100.83
33012 - Kym at Meagre Farm	15.26	19.44	22.37	24.55	25.63	28.18	29.86	30.69	36.86	55.97
33016 - Cam at Jesus Lock	32.10	41.10	48.30	55.20	0.00	66.30	-	76.80	89.80	133.80
33017 - Bedford Ouse at St Ives	150.60	192.67	219.32	244.19	252.43	291.30	305.83	318.89	359.50	450.06
33018 - Tove at Cappenhams Bridge	17.30	25.80	34.10	45.10	49.40	65.90	78.30	88.70	120.10	247.90
33020 - Alconbury Brook at Brampton	16.40	27.80	35.80	44.50	47.50	57.60	64.10	68.90	83.40	135.90
33022 - Ivel at Blunham	23.05	31.00	36.71	42.81	44.91	51.90	56.40	59.79	70.50	107.59
33027 - Rhee at Wimpole	4.70	6.20	7.10	-	8.10	8.90	9.30	9.60	10.40	12.10
33034 - Little Ouse at Abbey Heath	17.00	22.90	26.70	30.40	31.60	35.40	37.70	39.40	-	-
33035 - Ely Ouse at Denver Complex	-	140.35	154.89	168.44	173.45	194.75	210.62	225.28	270.13	-
33037 - Bedford Ouse at Newport Pagnell Total	68.40	110.90	142.60	177.50	189.70	231.10	258.20	278.90	334.50	502.00
33039 - Bedford Ouse at Roxton	82.40	110.50	129.60	149.10	-	176.80	190.00	199.80	224.90	292.80
39001 - Thames at Kingston	317.00	417.00	491.00	569.00	596.00	685.00	742.00	786.00	899.00	1160.00
39002 - Thames at Days Weir	149.60	188.30	214.50	241.30	-	279.30	297.40	310.80	345.20	438.30
39008 - Thames at Eynsham	72.00	94.40	107.40	118.70	-	131.60	-	140.30	148.10	163.60
39010 - Colne at Denham	10.48	13.87	16.23	18.69	-	22.27	24.01	25.30	28.67	45.33
39021 - Cherwell at Enslow Mill	34.65	47.41	56.12	65.07	-	77.86	83.99	88.53	100.21	132.05
39023 - Wye at Hedsor	2.77	3.52	4.05	4.59	4.93	5.39	5.77	6.06	6.81	14.31
39072 - Thames at Royal Windsor Park	229.00	302.00	355.00	412.00	431.00	497.00	538.00	570.00	650.00	838.00
39081 - Ock at Abingdon	10.70	15.30	19.50	24.50	26.40	33.50	38.70	42.80	54.40	79.40

Station name and number/ID	50%	20%	10%	5%	4%	2%	1.33%	1%	0.5%	0.1%
	2	5	10	20	25	50	75	100	200	1000
39105 - Thame at Wheatley	42.70	57.69	67.89	78.40	0.00	93.43	100.60	105.90	119.60	156.88
39111 - Thames at Staines	236.00	310.45	365.54	423.61	443.71	509.97	552.40	585.16	669.29	863.60
39121 - Thames at Walton	266.00	349.91	412.01	477.46	500.11	574.79	622.62	659.55	754.37	973.38
39130 - Thames at Reading	174.00	228.89	269.51	312.32	327.14	375.99	407.28	431.43	493.46	636.72
39138 - Loddon at Twyford	41.30	53.94	61.12	-	70.21	81.31	-	90.19	-	-
39140 - Ray at Islip	14.94	20.10	23.46	26.81	0.00	31.41	33.56	35.12	39.06	49.28
39142 - Windrush at Bourton on the Water	1.60	2.40	-	3.80	-	-	5.70	6.20	-	12.00
ID_17	44.91	73.24	84.31	105.84	107.65	132.40	138.44	145.77	169.72	230.43
ID_36	62.56	89.39	100.34	119.78	123.63	149.75	154.34	161.18	186.05	255.46
ID_38	4.90	6.54	7.02	8.00	8.26	9.09	9.16	9.14	9.84	11.11
ID_39	97.06	109.67	112.77	115.45	115.85	117.89	118.25	118.66	125.24	170.29
ID_42	60.23	71.54	75.38	80.34	80.81	82.43	83.04	83.62	83.78	87.91
ID_43	5.85	8.87	10.34	11.39	12.93	14.29	14.79	14.94	19.61	31.92
ID_45	1.71	2.36	2.62	3.01	3.24	3.82	4.20	4.43	5.04	7.66
ID_46	111.91	135.54	149.57	162.05	166.51	182.34	187.49	189.36	194.07	210.30
ID_49	-	93.27	108.62	135.17	143.72	171.55	187.88	198.67	227.23	300.30
ID_50	-	94.15	112.39	139.68	147.57	166.89	185.55	197.61	227.42	307.11

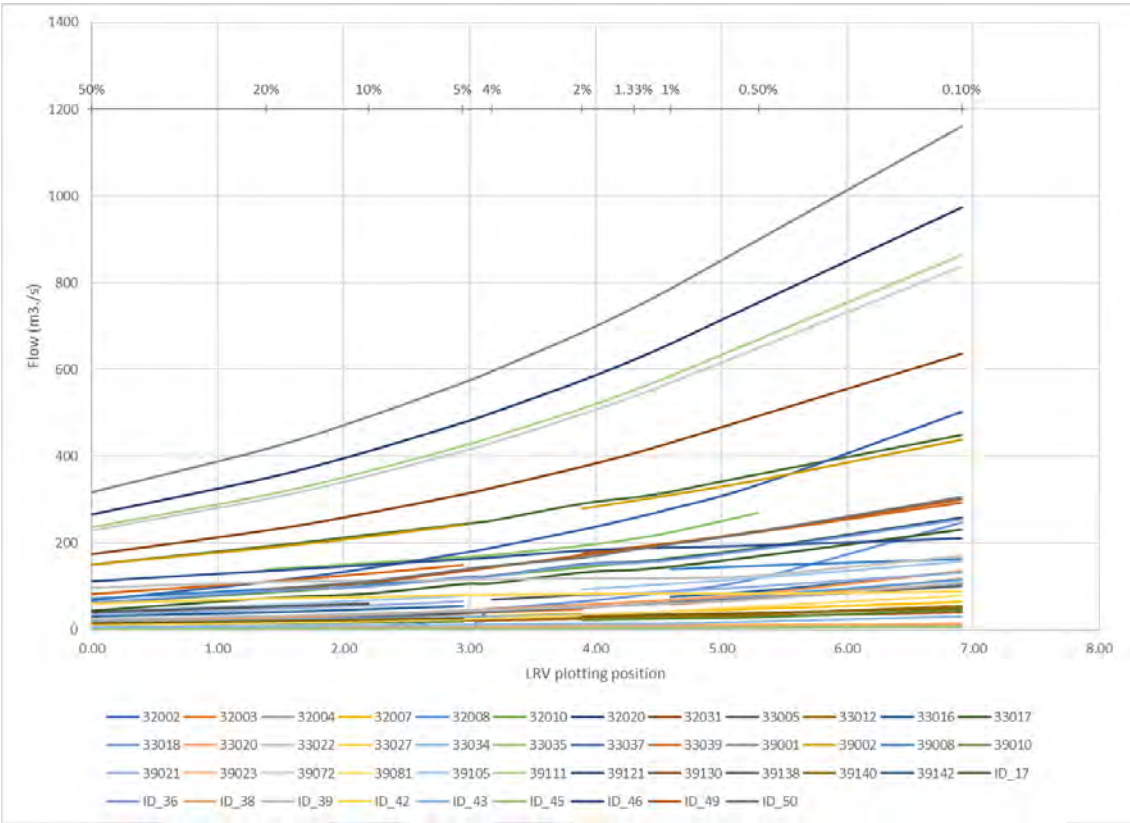


Figure B-1. Flood Frequency Curves selected for climate change uplifts.

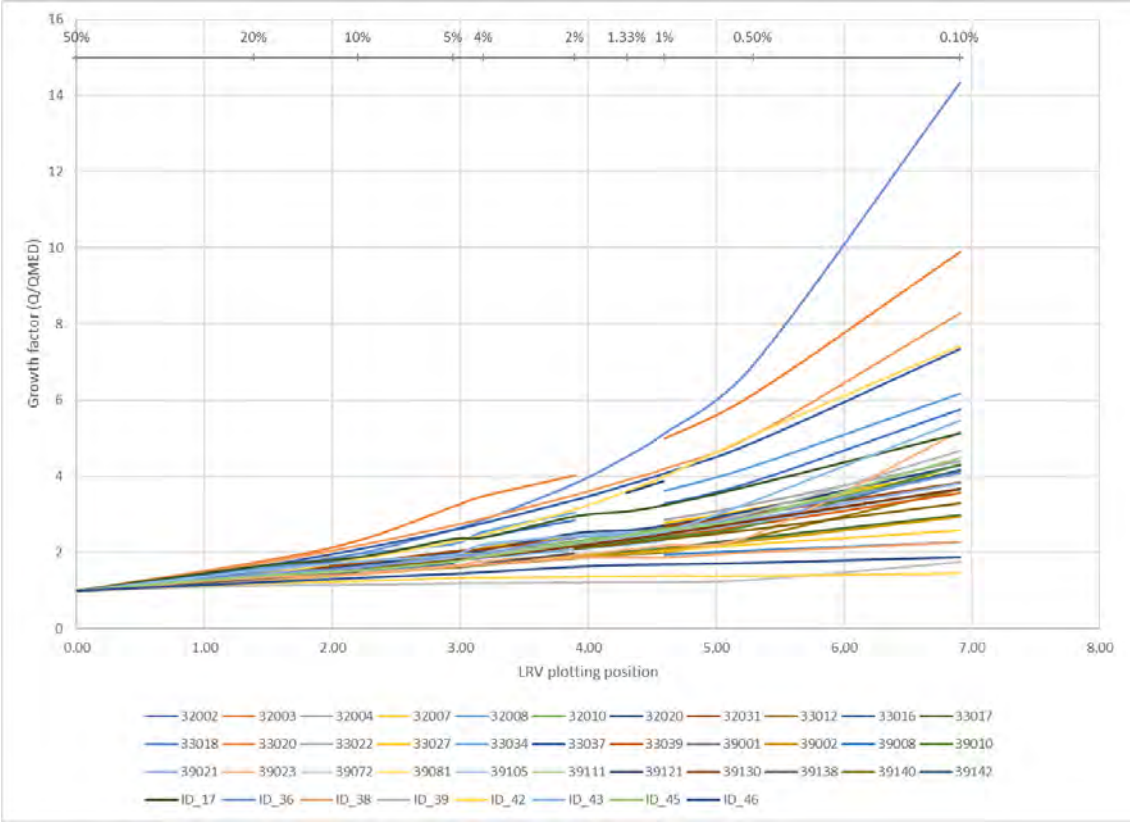


Figure B-2. Growth curves selected for climate change uplifts.

Appendix C. Non-dimensional hydrograph

C.1 33039 Bedford Ouse at Roxton

The non-dimensional hydrograph for the Bedford Ouse at Roxton was created using the seven annual maximum flow hydrographs from the available record (from 1979) listed in Figure C-1. All seven profiles showed independent peaks (i.e. did not contain multiple peaks that could be a result of multiple storm events) and had flow greater than QMED. The resulting non dimensional hydrograph is shown as the black line in Figure C-1.

The flood frequency curve used in the analysis was from Middle Great Ouse Flood Mapping study (Halcrow 2011) and is shown in Table C-1.

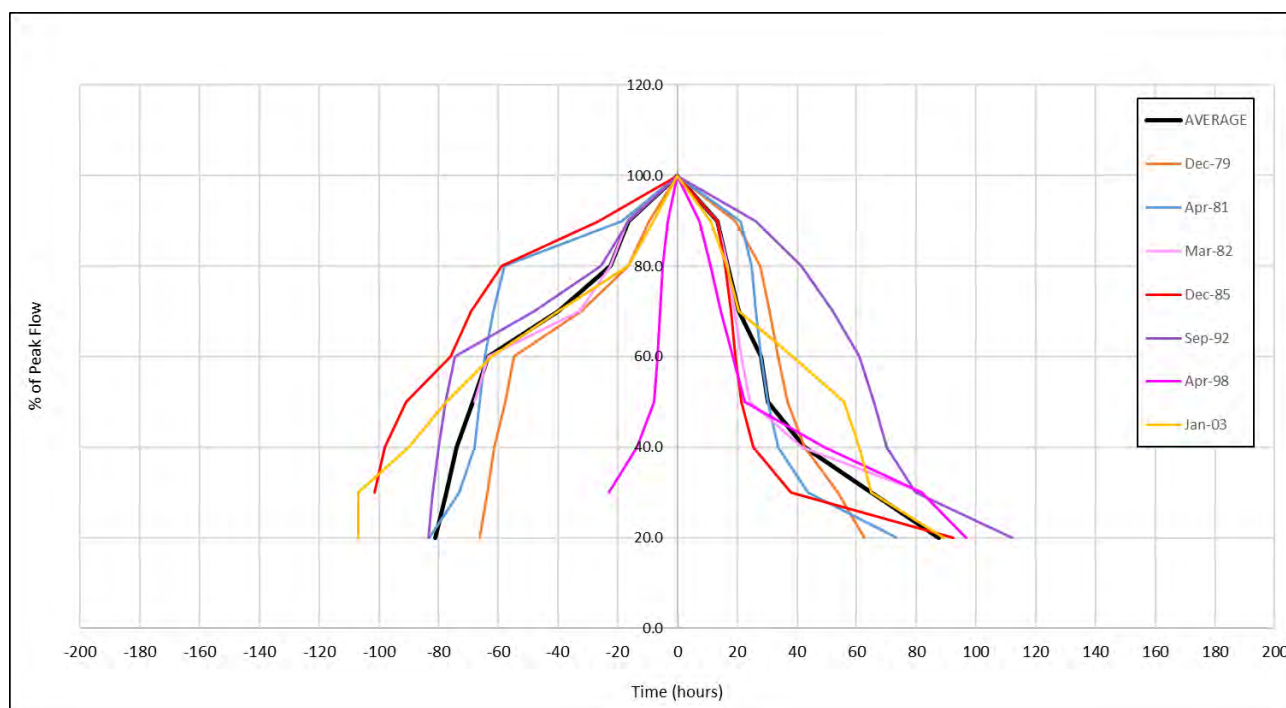


Figure C-1. Non-dimensional hydrograph profile for the Bedford Ouse at Roxton.

Table C-1. Flood Frequency Curve for the Bedford Ouse at Roxton.

Return period	2	5	10	20	25	50	75	100	200	1000
AEP%	50	20	10	5	4	2	1.33	1	0.5	0.1
Flow (m ³ /s)	82.4	110.5	129.6	149.1	N/A	176.8	190	199.8	224.9	292.8

C.2 33003 Cam at Bottisham

The non-dimensional hydrograph for the Cam at Bottisham was created based on the 1% AEP (1 in 100 year) modelled outputs from the River Cam Flood Mapping Improvements Phase 2 model (Halcrow 2012) as suitable flow data was not available to create a hydrograph directly. The resulting non dimensional hydrograph profile is shown as the black line in Figure C-2.

The flood frequency curve used in the analysis was from the Halcrow 2012 model and is shown in Table C-2.

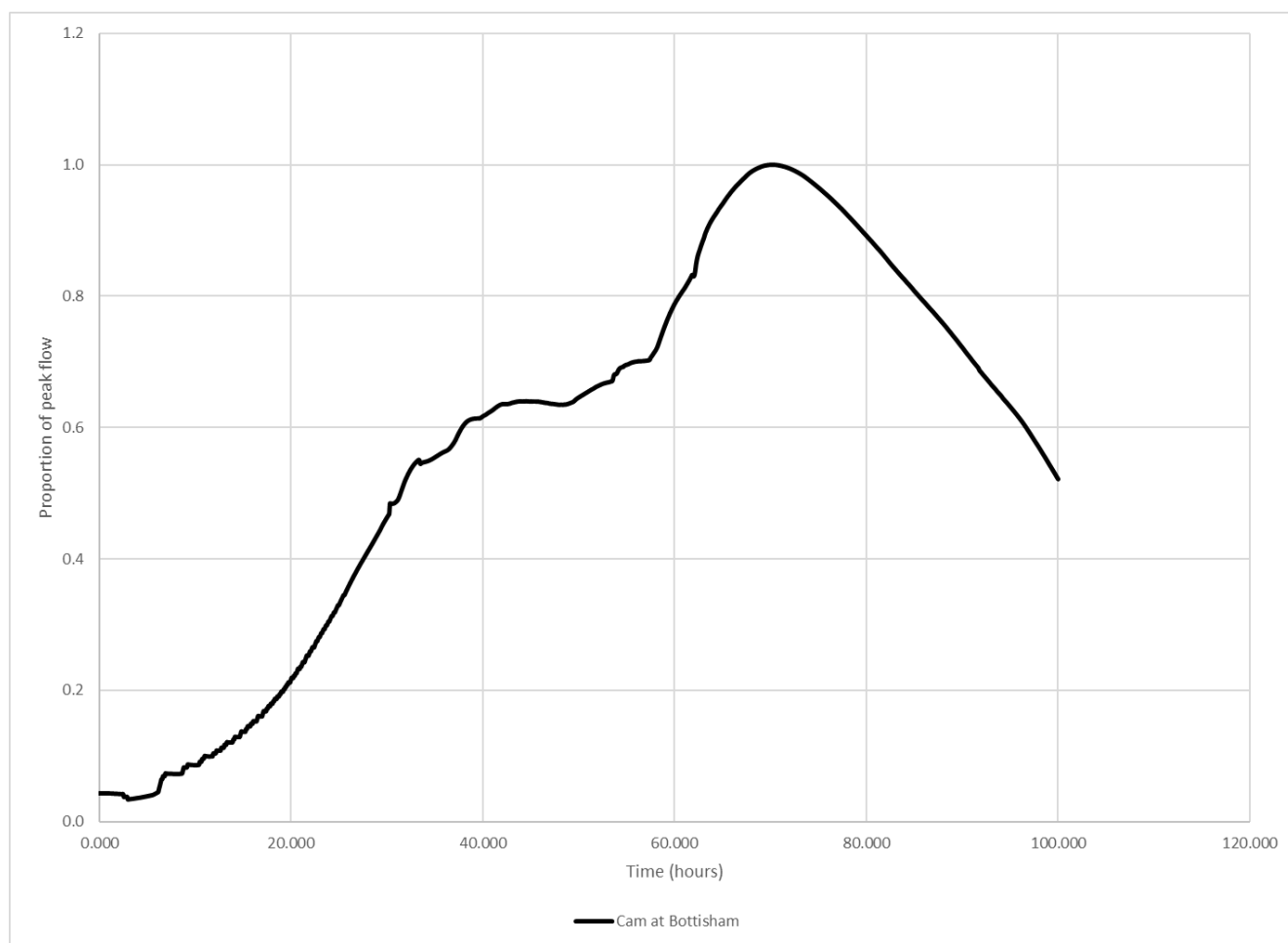


Figure C-2. Non-dimensional hydrograph profile for the Cam at Bottisham.

Table C-2. Flood Frequency Curve for the Cam at Bottisham.

Return period	2	5	10	20	25	50	75	100	200	1000
AEP%	50	20	10	5	4	2	1.33	1	0.5	0.1
Flow (m ³ /s)	N/A	34.24	37.74	41.08	42.36	54.05	60.85	64.79	72.74	84.55

C.3 32010 Nene Wansford

The non-dimensional hydrograph for the Nene at Wansford was created using the eight annual maximum flow hydrographs from the available record (from 1997) listed in Figure C-3. All eight profiles showed independent peaks (i.e. did not contain multiple peaks that could be a result of multiple storm events) and had flow greater than QMED. The resulting non dimensional hydrograph is shown as the black line in Figure C-3.

The flood frequency curve used in the analysis was from Middle Nene Model Report (September 2013) and is shown in Table C-3.

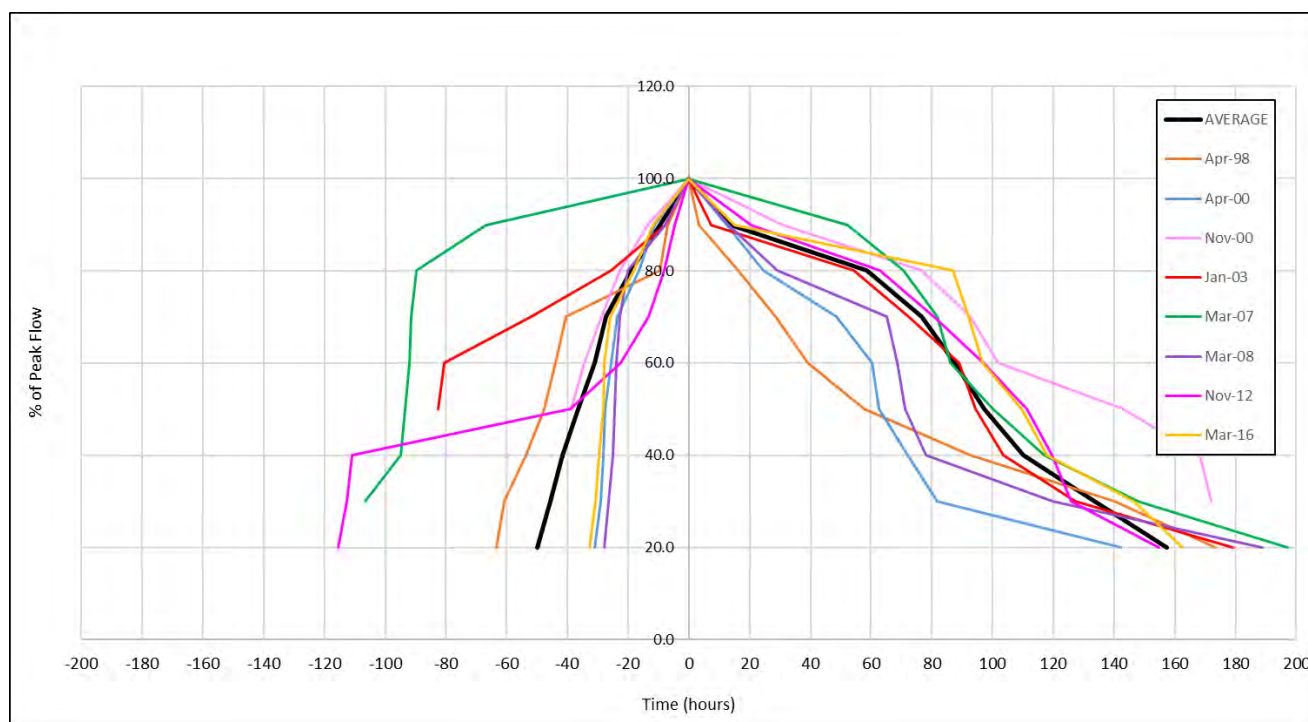


Figure C-3. Non-dimensional hydrograph profile for the Nene at Wansford.

Table C-3. Flood Frequency Curve for the Nene at Wansford.

Return period	2	5	10	20	25	50	75	100	200	1000
AEP%	50	20	10	5	4	2	1.33	1	0.5	0.1
Flow (m ³ /s)	62.7	85.7	101.9	119.1	124.9	144.3	156.7	166	190.3	259.4

C.4 39111 Thames at Staines

The non-dimensional hydrograph for the Thames at Staines was created using the ten highest annual maximum flow hydrographs in the available record (from 1990) listed in Figure C-4. The resulting non dimensional hydrograph is shown as the black line in Figure C-4.

The flood frequency curve used in the analysis was from the Thames (Hurley to Teddington) 2019 model and is shown in Table C-4.

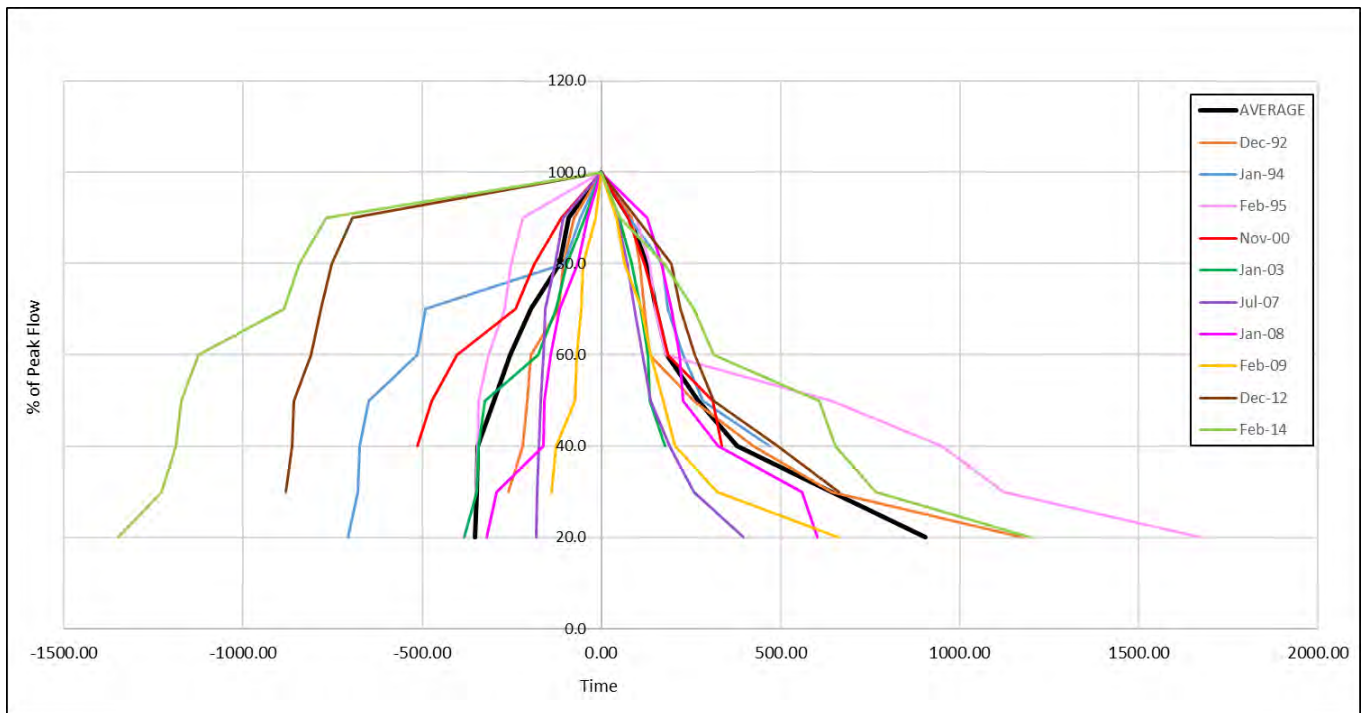


Figure C-4. Non-dimensional hydrograph for the Thames at Staines.

Table C-4. Flood Frequency Curve for the Thames at Staines.

Return period	2	5	10	20	25	50	75	100	200	1000
AEP%	50	20	10	5	4	2	1.33	1	0.5	0.1
Flow (m ³ /s)	236	310.45	365.54	423.61	443.71	509.97	552.4	585.16	669.29	863.6

Appendix D. Examples of model limitations

Verification of the baseline model identified a number of limitations or uncertainties caused by data incorporated into the modelling. The following sections describe some examples of these issues.

D.1 Water level differences between SoN and MapEdit

In the OxCam modelling, the State of the Nation (SoN) dataset has been used to derive the peak water level (PWL) values that are used as boundary conditions to the 2D models. This dataset contains PWL values for every return period in a series of locations at both banks (left and right) along the river reaches. In addition to the SoN dataset, in certain areas of the OxCam study domain the MapEdit dataset (which is used as the validation flood outlines) also contains PWLs along the river reaches.

The SoN data set should incorporate the MapEdit information (minus the most recent local model updates). The peak water levels at any given reach should therefore be comparable. However, in many poorly performing models (i.e. those with a property comparison category 4 or 5) where there is a larger difference between the OxCam and MapEdit derived flood extents, there has also been a discrepancy in the SoN and MapEdit PWLs values.

An example of a peak water level value discrepancy is illustrated in Figure D-1 and Figure D-2, which show domain 30200293. These figures show the OxCam and MapEdit flood outlines for the 1 in 100 year return period (1% AEP). The OxCam model results in flooding of an urban area (identified by the red box in Figure D-1 which does not flood using the MapEdit model.

Figure D-2 shows water levels and defence levels within the reach in question. The 1 in 100 year SoN peak water level on the left bank (52.7 mAOD, shown in light blue) is used as the Head-Time boundary in the OxCam modelling. The 1 in 100 year peak water level from MapEdit (shown in black) is lower at 49.11 mAOD). The AIMS Defence Crest Level of the left bank is 49.5 mAOD (shown in red). This is applied as a Z-line topographic modification in the OxCam modelling. In this example the 1 in 100 year peak water level applied within the OxCam model is higher than the AIMS Defence Crest Level, resulting in overtopping of the defence, however the MapEdit level does not result in defence overtopping. The PWL discrepancy therefore results in different flood outlines and in this example impacts the number of properties at risk of flooding.

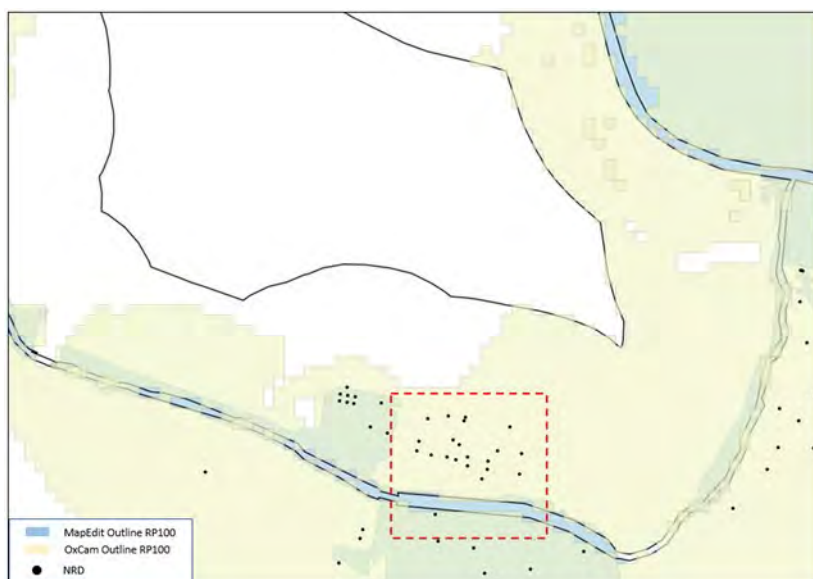


Figure D-1. Domain 330200293 1% AEP (1 in 100 year).

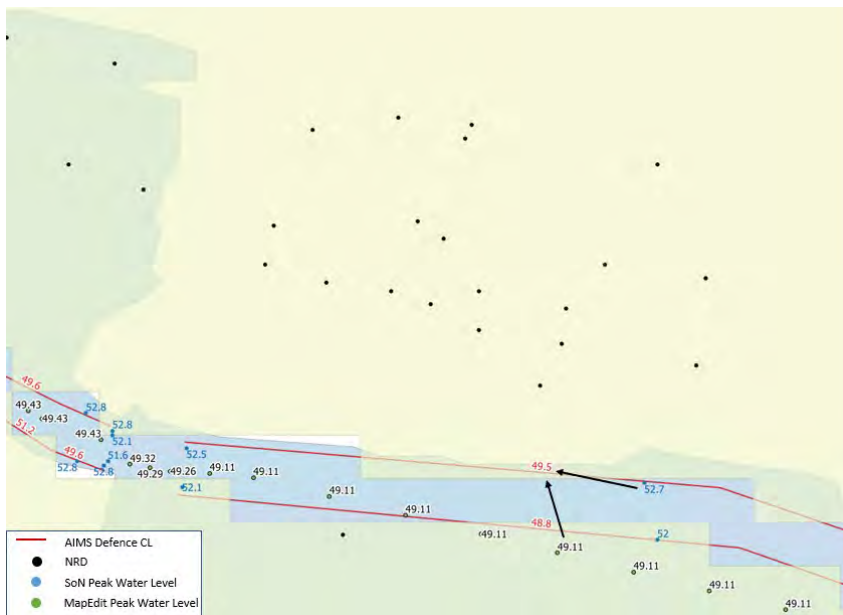


Figure D-2. Domain 330200293 1% AEP (1 in 100 year), zoomed in.

D.2 Differing water levels between banks

Another water level related data issue identified during the validation process was the occurrence of significant differences in SoN peak water level values at opposite banks. Domain 330200002 provides an example of this. Figure D-3 and Figure D-4 illustrate that at a certain reach within this model domain the SoN peak water levels indicate a difference of approximately 3 m on opposite banks. This raises questions about the accuracy of the SoN values in this location. The MapEdit dataset does not provide peak water level coverage at this location so it is not possible to compare the two.

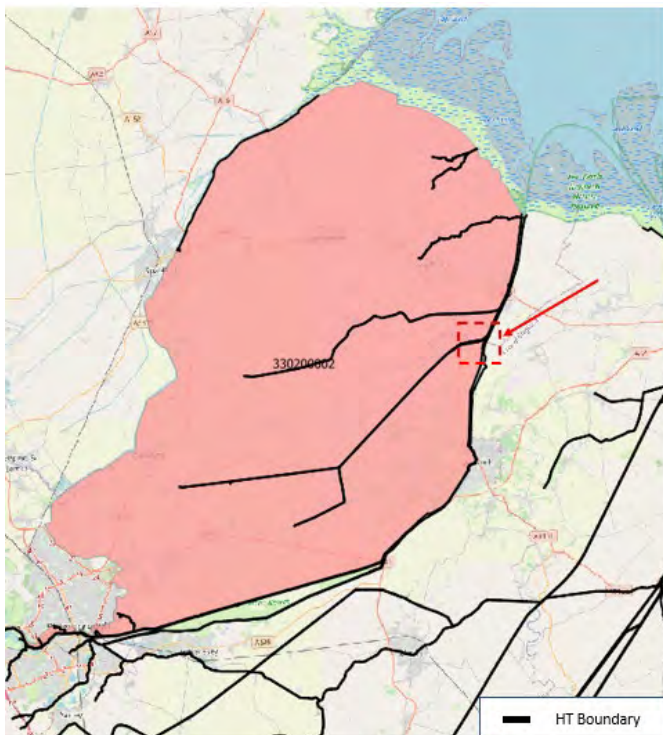


Figure D-3. Domain 330200002

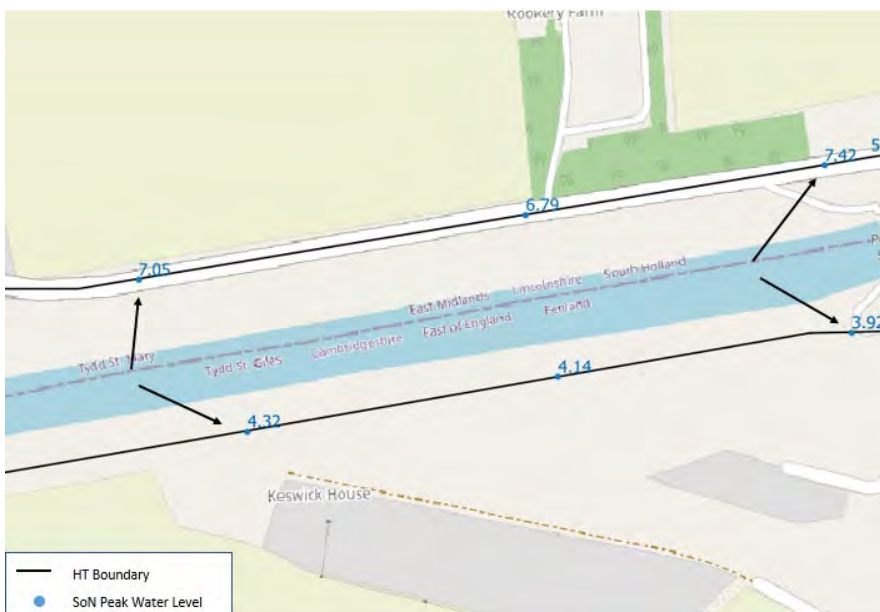


Figure D-4. Water levels for the 1% AEP (1 in 100 year) event in domain 330200002.

D.3 Embankment crest level

The embankment crest levels adopted as the OxCam Z-line embankment crest levels were extracted from the SoN model input dataset (which in turn is generated from AIMS and LiDAR). For some models with a category of 4 or 5, we found differences between these crest levels and those recorded in AIMS.

Another embankment crest level data issue found during the validation process was that in some areas the adopted Z-line embankment crest level was below the DTM elevation values.

D.4 Digital Terrain Model

In some model domains it has been found that instabilities were caused by big elevation differences within the Digital Terrain Model (DTM) which resulted in unexpectedly large flood extents and hence affected the property comparison category. Figure D-5 illustrates the issue using domain 3901000001.



Figure D-5. Domain 3901000001- DTM issue.

D.5 Location of defences

The validation process identified that some differences in flood outlines and the resulting property count categories occurred as a result of the differences between the strategic scale modelling approach applied within OxCam and the approach likely applied in local modelling studies incorporated into MapEdit. The OxCam embankment and defence lines are applied solely across the reaches where HT Boundaries are applied. Secondary defences across the floodplain are omitted and not modelled within OxCam unless they are included in the terrain data, however they may be included within the MapEdit model. An example of this is described below for domain 330200007. Figure D-6 shows the 1 in 100 year (1% AEP) flood outlines for the OxCam and MapEdit models. The OxCam model shows extensive flooding within the urban area (highlighted in yellow), whereas MapEdit appears to be restricted by the secondary AIMS Defence line (in red).

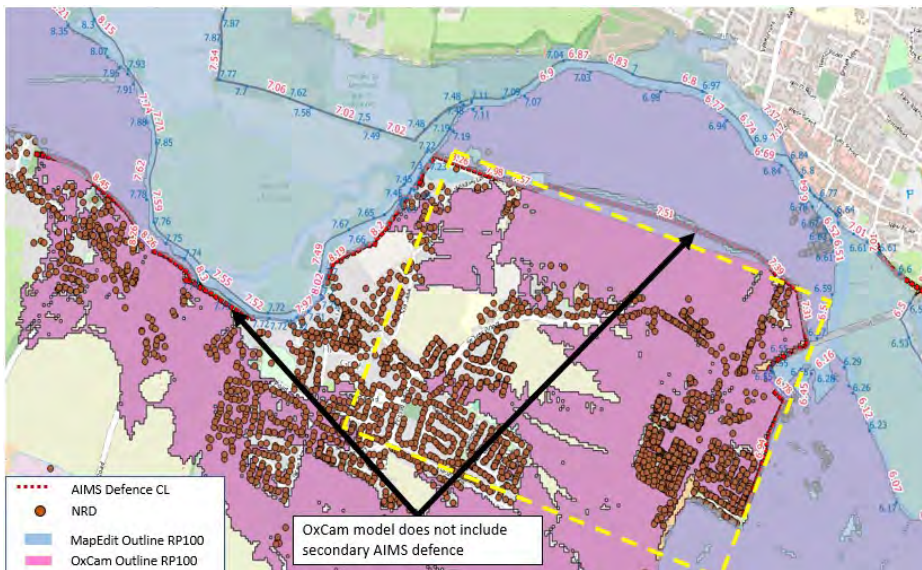


Figure D-6. Domain 330200007 flood extent differences due to treatment of set back defences.