

Third UK Climate Change Risk Assessment (CCRA3) Future flood risk Main Report

Final Report prepared for the Committee on Climate Change, UK

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In association with



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SUMMARY

Background

Under the Climate Change Act 2008 the UK Government is required to publish a Climate Change Risk Assessment (CCRA) every five years. Following publication of the first two assessments (2012, 2017) the third is due in 2022 and will feed into the development of the next National Adaptation Programme (NAP) for England due in 2023, as well as the National Adaptation Programmes of Scotland, Wales and Northern Ireland. Each of these previous assessments include supporting research into future flood risks. This report builds upon those previous assessments to provide an updated (highly spatially resolved and disaggregated) assessment of current and future flood risks.

Approach

The Future Flood Explorer (FFE) is used to provide an estimate of future flood risk across the UK using the latest UKCP18 climate projections. The updated analysis (an evolution of the model used in CCRA2, Sayers *et al.*, 2015) provides a credible emulation of the UK flood risk system and its response to future change (climate change, population growth and adaptation) within a highly efficient computational framework. This enables multiple future scenarios to be explored. Here this includes two future epochs (2050s and 2080s); two climate futures (a 2°C and 4°C rise in Global Mean Surface Temperature (GMST) by 2100 relative to pre-industrial times); and two population projections (low and high). These are combined with three alternative adaptation portfolios representing: (i) a continuation of Current Levels of Adaptation (CLA), assuming current policies continue to be implemented; (ii) an Enhanced Whole System (EWS) adaptation approach, assuming more ambition adaptation is implemented, and (iii) a Reduced Whole System (RWS) approach, assuming a less ambition adaptation.

Key messages

How might flood risk change in the future if we continue to manage flood risk as at present?

Assuming a continuation of Current Levels of Adaptation, Expected Annual Damages (EAD, including direct economic damage to residential and non-residential properties and associated indirect damages) are set to increase from present-day levels. Under a 2°C future EAD rises from £2bn today to between £2.7-3.0bn in the 2080s (depending upon associated population growth). Under a 4°C future risks rise to between £3.5-3.9bn.

What is the relative importance of different flood hazards on future flood risk?

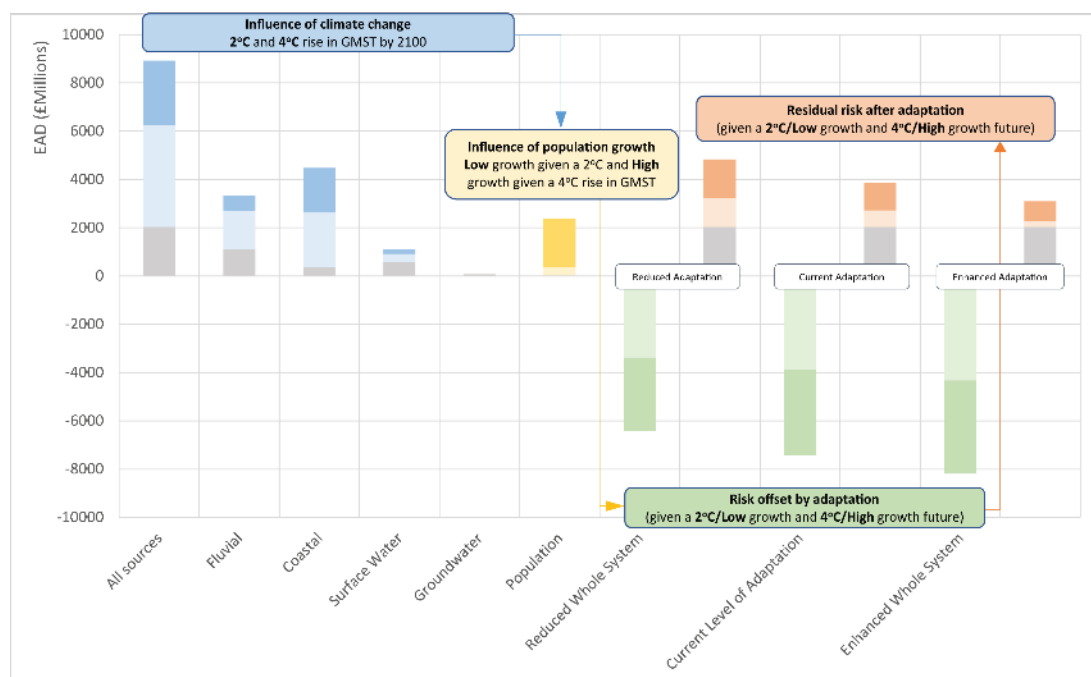
Fluvial flood risk is dominant today when looking at the UK as a whole, and remains so in the future; rising from an EAD of ~£1.1bn today to between ~£1.2bn (2°C low population growth) and ~£1.6bn (4°C high population growth) by the 2080s assuming a continuation of Current Levels of Adaptation. The increase in fluvial flood risk is, however, proportionally less than for either coastal or surface water flooding. Surface water and coastal risks more than double under a 4°C high population growth future (surface water risks rising from ~£0.6bn to ~£1.2bn by the 2080s and coastal risks increasing from ~£0.4bn to ~£1.0bn). Groundwater flooding remains a small proportion of the UK risk (rising from £54m to £95m).

What is the relative influence of climate change, population, and adaptation on future flood risk?

Climate change is the dominant influence in driving up future risk (increasing Expected Annual Damages EAD - direct and indirect – by £4.2bn under a 2°C future and £6.9bn under a 4°C future in the absence of any adaptation). The influence of climate change is greatest at the coast; especially when the rise in GMST exceeds 2°C, with EAD rising by a further 70% under a 4°C rise in GMST compared to 2°C. For comparison, the risks associated with all other flood sources increase by ~20% between a 2 and 4°C future. The influence of population varies with the projection of growth.

Assuming a low population growth the additional impact on risk is limited (although not insignificant, adding £364m to EAD), whereas a high population growth future has a much greater influence (adding ~£2.4bn to the EAD assuming a 4°C rise in GMST). By the 2080s the combination of a 4°C climate change and high population growth future drives an increase of ~£9.2bn EAD in the absence of adaptation. The future is therefore bleak in the absence of adaptation and mitigation.

All three adaptation portfolios limit this increase. A continuation of Current Levels of Adaptation offsets ~£7.4bn of Expected Annual Damages in the 2080s (under a 4°C high population growth future) resulting in a net increase in risk of ~£1.8bn. An Enhanced Whole System (EWS) approach to adaptation offsets ~£8.2bn of EAD (total) in the same scenario; limiting the net increase in risk to ~£1.1bn. A Reduced Whole System (RWS) approach offsets much less (~£6.4bn); consequently, the net increase in risk much greater (~£2.8bn). The Figure below illustrates these disaggregated risks.

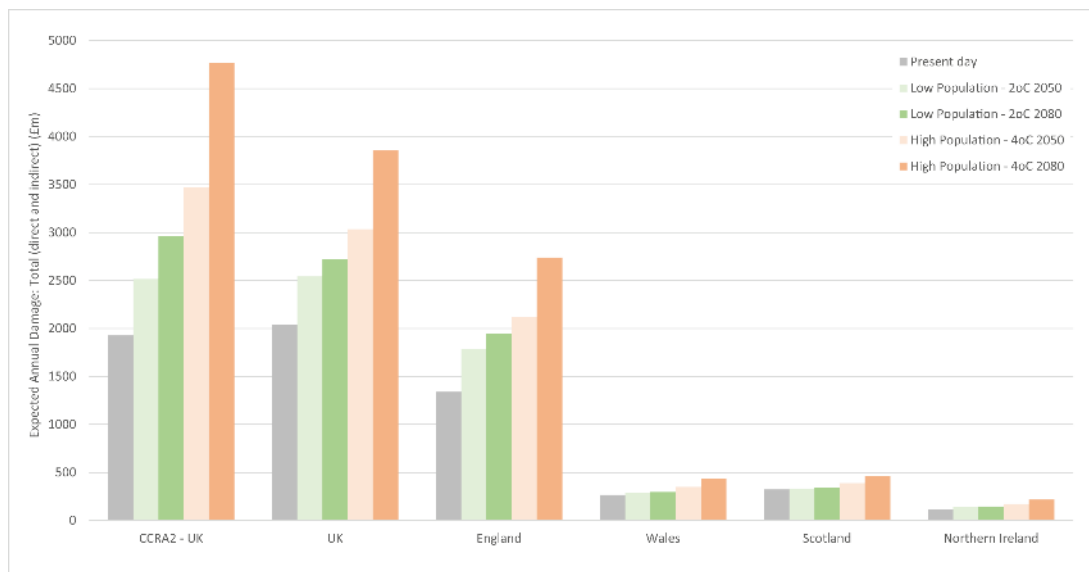


Drivers of changes in risk by 2080s – Expected Annual Damage (total)

Positive bars show present-day and increases in present-day risks as a result of climate change or population growth by the 2080s. Negative bars show how the EAD for a 4°C, high population, scenario can be offset by applying the three adaptation portfolios. Grey shading: Present-Day risk. Lighter non-grey shading: Additional risk in the 2080s compared to present-day under a 2°C future; Darker non-grey shading: Additional risk under a 4°C future compared to a 2°C future.

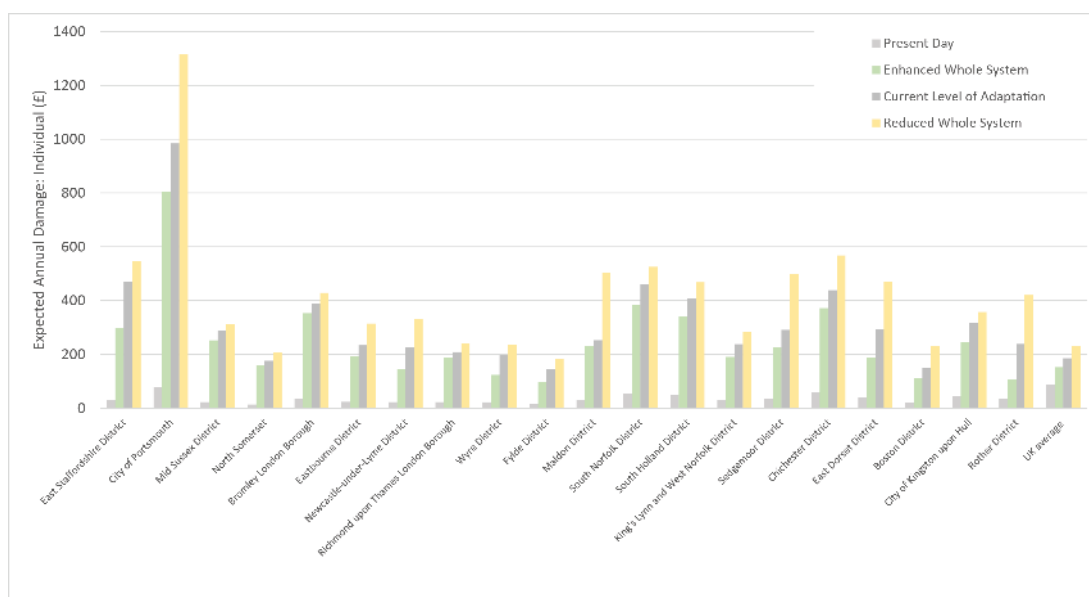
How might the spatial pattern of flood risk change?

Flood risk varies across the UK today and this variation persists into the future. Most of the present-day and future flood risk is in England. Under a 4°C (high population) future the rapid rise in risk from today to the 2050s continues through to the 2080s. This is particularly the case in England where, for example, under a 4°C (High population) EAD (total) increases from £1.3bn today to £2.2bn by the 2050s and reaches £3.0bn by 2080s. When risks are normalized by the flood exposed population (i.e. the average Expected Annual Damage per individual, EADi) a different picture of the distribution of risk emerges. Those living in the flood prone areas in Northern Ireland, Scotland and Wales, on average, are exposed to a higher Expected Annual Damage than those living in England (Northern Ireland £506, Scotland £450, Wales £316 and England £109 EAD per person by the 2080s under a 4°C high population growth future).



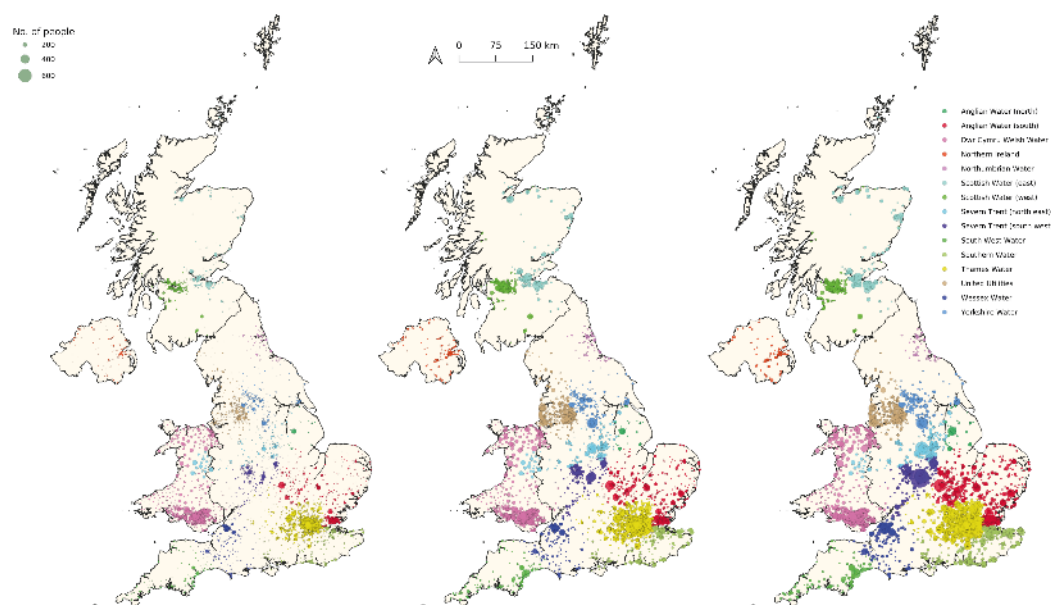
CLA - Expected Annual Damages (Total) – By Country

Many of the Local Authorities with the largest future risk are in coastal areas, including the top three of Hull, the City of Portsmouth, and Sedgemoor District Council (see below). In some locations the influence of climate change on flood risk is much less; including fluvial authorities experiencing decreased peak flows.



Local Authorities with the largest proportional increase in flood risk by the 2080s (4°C excluding population growth)

The influence of climate change on exposure to surface water flooding also varies across the UK. This changing pattern of surface water flooding, assuming a continuation of Current Levels of Adaptation, is illustrated below.



Left: Present-day. Middle: 4°C High Population Growth 2050s; Right: 4°C High Population Growth 2080s. 20% of neighbourhoods with the highest exposure

Number of people exposed to surface water flooding more frequently than 1 in 30 years (on average)

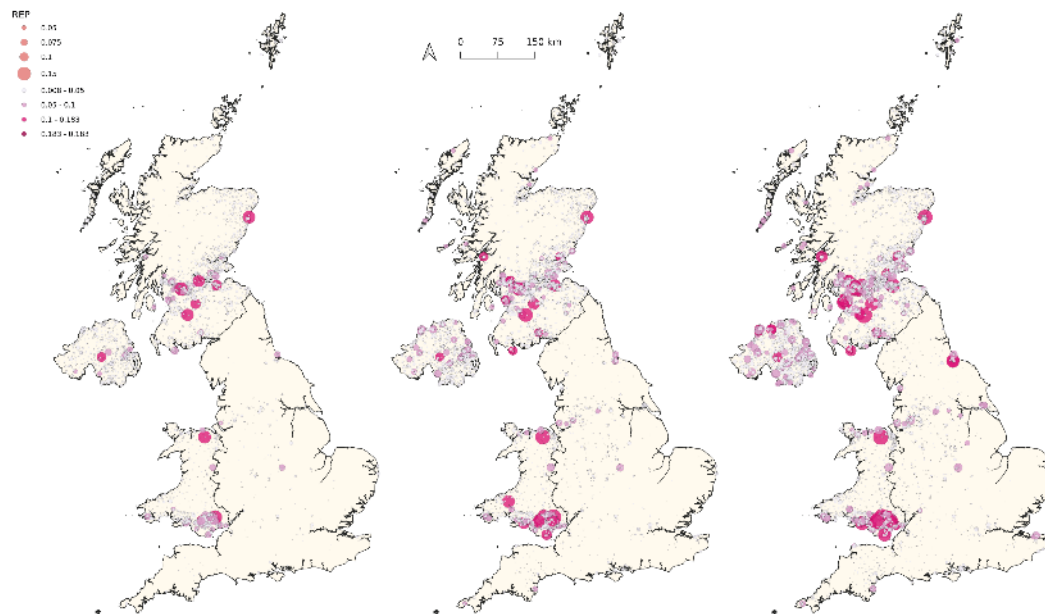
How might the socio-economic distributional pattern of flood risk change?

In many rural towns and villages and smaller urban cities and towns the most socially vulnerable¹ are, on average, exposed to greater flood risk. For example, in *rural towns and fringes in sparse setting* the present-day Expected Annual Damage is ~£150 per person (for those living in a flood prone areas) but almost double this (~£280 per person) in the most socially vulnerable neighbourhoods (on average). In the future the most socially vulnerable, particularly in *urban cities and towns* experience disproportional increases in risk with the EAD per person increasing by a factor of 2.5 on average but by 2.8 in the most socially vulnerable neighbourhoods.

When considered at an aggregated national scale, the most socially vulnerable experience flood disadvantage in Northern Ireland, Wales, and Scotland; this is the case today and in the future.

When considered through the lens of Relative Economic Pain (*i.e.* the ratio of uninsured loss to income) the differential between the risk faced by the more and less socially vulnerable is significant. This reflects in part lower income, but also levels of insurance take-up; an issue that will need to be addressed in the transition planning as Flood Re comes to an end in 2039.

¹ As defined by the 20% most socially vulnerable neighbourhoods according to the Neighbourhood Flood Vulnerability Index, NFVI.

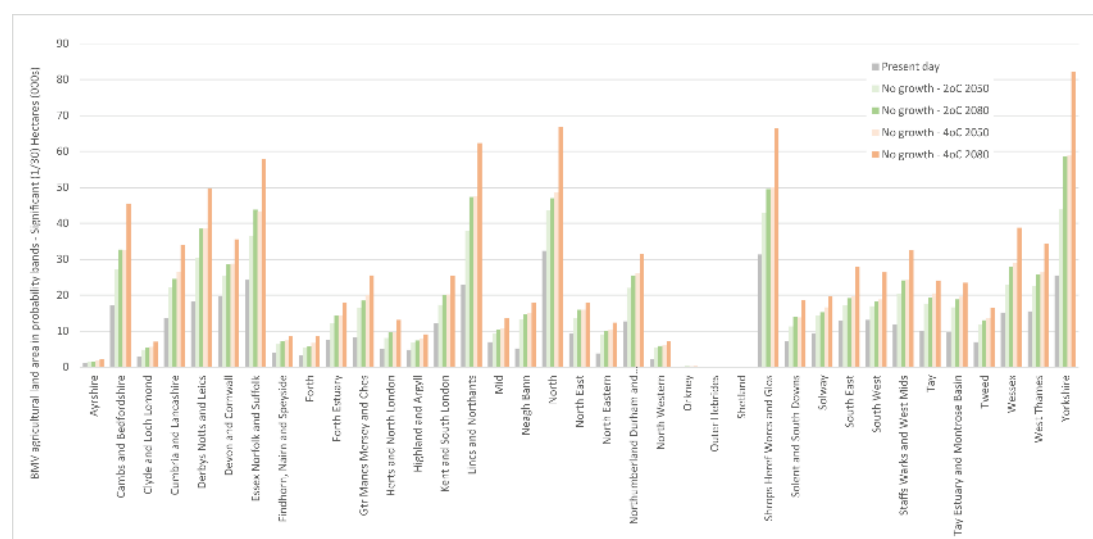


Left: Present-day. Middle: 4°C High Population Growth 2050s; Right: 4°C High Population Growth 2080s. REP is the ratio of uninsured loss to income

Relative Economic Pain (REP) assuming a continuation of Current Levels Adaptation: All sources of flooding

How might climate change influence the frequency of flooding to agriculture and habitats?

The changing nature of habitats and the impact of climate change on agricultural damage responds to multiple variables not explicitly considered here (changes in the seasonality, salinity, chosen crops, local land management practice etc.). There is however an increase in exposure of agricultural land (Best and Most Versatile land) to frequent flooding (1in30 years return period or more frequent). The largest increases are projected in the agricultural heartlands of Lancashire and Northamptonshire as well as Bedfordshire, Cambridgeshire and Yorkshire. Flooding may also impact agriculture in more marginal locations that have little (or no) Best and Most Versatile land. The impact on these more marginal lands (and associated activities and communities) is not considered here.



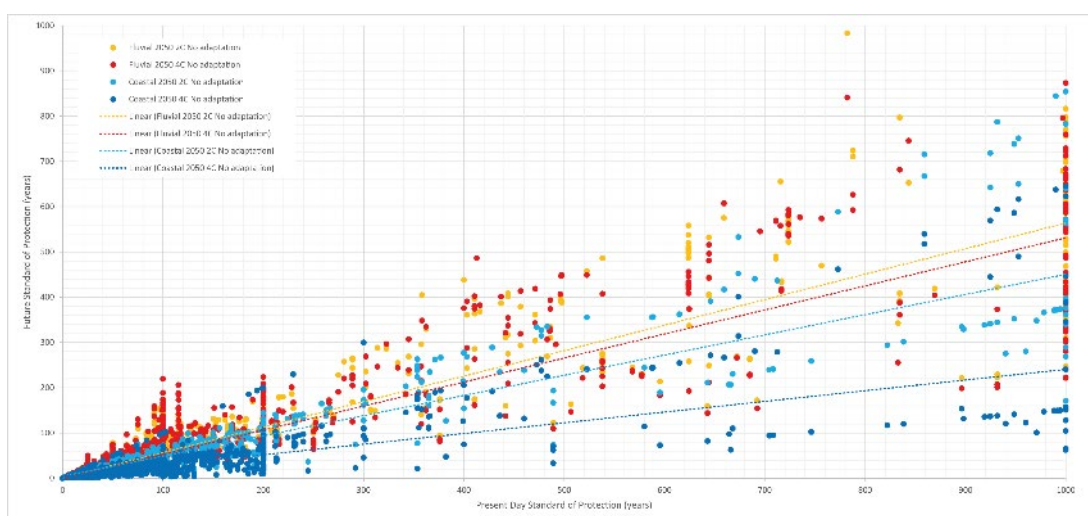
By CCRA Region (short names used on chart for reasons of space)

Changing exposure of Best and Most Versatile Land to frequent flooding (1in30 or more frequent): Assuming a continuation of Current Level of Adaptation

How might climate change impact infrastructure?

A significant increase in exposure of both Category A (including water treatment, energy and communication infrastructure sites) and Category B (including railway stations, landfill sites, hospitals and blue light service stations, care homes, GP surgeries, and schools) is projected across the UK. The results highlight concentration of infrastructure risks in many metropolitan regions (such as Greater Manchester) and significant number of smaller (Category A) infrastructure sites exposed to frequent flooding. These results are likely to be an underestimate (as no effort is made to include the growth in infrastructure provision that is likely to accompany population growth or explicit consideration of the impact of critical infrastructure network failures).

Climate change also impacts the standard of protection afforded by flood defences. In the absence of any further adaptation the reduction in the standard of protection provided is significant. This reduction is most marked at the coast (see below). The impact of climate change on fluvial defences is more mixed with some areas experiencing an effective increase the standard of protection as peak flood flows reduce (reflecting the complex spatial pattern of future changes in peaks flows).



x-axis represents the present-day representative standard of protection (for each fluvial and coastal neighbourhood). y-axis presents the future standard by the 2050s under a 2 and 4°C climate future.

Impact of climate change on defence standards: 2050s assuming no adaptation

What types of risks appear to be the hardest to manage?

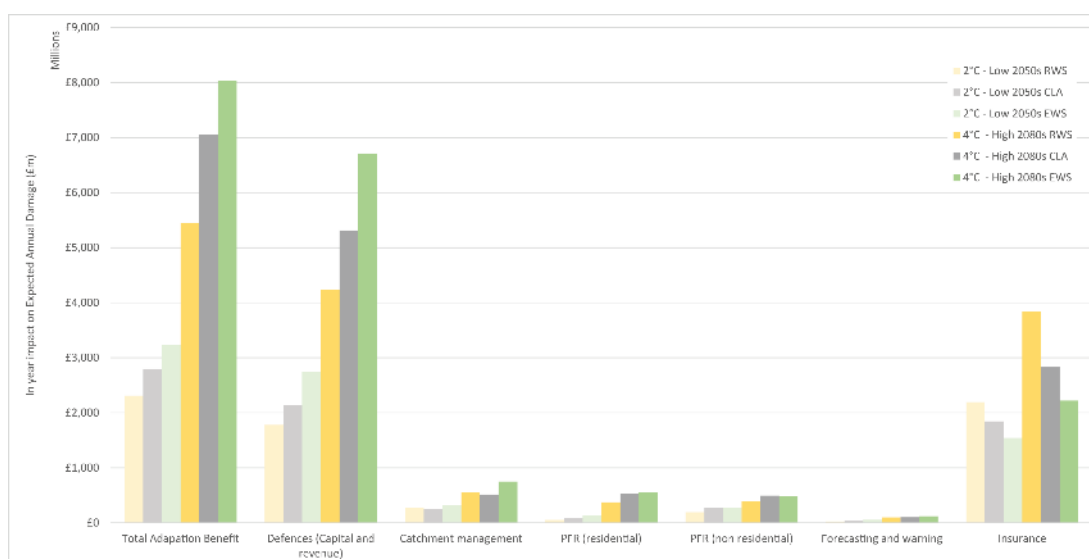
Flood risk responds to climate change and population growth but also adaptation. But there are more subtle aspects to the changes. In some Local Authorities the increase in risk is more sensitive to the adaptation choice than in others, with opportunities for adaptation in many smaller Local Authorities and islands more limited (e.g. due to the lack of available land outside of the floodplain for new development). Elsewhere, some Local Authorities have little choice but to develop on the floodplain (for example many estuary and coastal towns and cities such as Hull).

Under a 4°C high population growth future coastal flood risks increase under all three adaptation approaches considered here, including the Enhanced Whole System approach (that continues to see coastal flood risks increase from an EAD of £361m today to £793m by the 2080s). This is a particularly important finding given the greater risk to life and livelihoods often associated with coastal than for other sources of flooding. This also reinforces the difficulty of managing coastal risks as sea levels rise through flood risk management measures alone. Long term integrated development planning will be needed to support communities if coastal risks are to be managed in the context of 4°C future.

Surface water flood risks also increase rapidly (rising from £587m² today to £1.1m by the 2080s under 4°C high population growth future associated an Enhanced whole System approach to adaptation). Increasing the capacity of conventional drainage infrastructure and retrofitting Sustainable Urban Drainage Systems (SUDS) in existing neighbourhoods can be costly and presents multiple challenges. Addressing these challenges will require integrated management actions across multiple organisations.

What action is needed?

Under all adaptation futures considered here, risks rise (see earlier). The increase in risk is least under an Enhanced Whole System to adaptation. Across all alternative portfolios conventional flood defences (both capital and revenue investment) remain the most important management measure. Catchment management (natural flood management), property flood resilience (both residential and non-residential take up) are also significant in reducing EAD (reflecting their ability to contribute to the management of more frequently occurring events). Flood forecasting and warning provide an underpinning response across all portfolios (but the full benefits associated with saving lives and minimizing wider disruption are not included here). Effective spatial planning however remains the only measures of avoiding increases in flood exposure due to development; where possible making greater space for water provides a central response. Developing our understanding of the performance of more innovative approaches (such as catchment management) will be important in realizing their potential in practice. The residual risk covered by insurance reduces (despite wider take-up) with more ambitious adaptation portfolios, reflecting the reduction in risk due to other measures.



Impact of adaptation expressed through a reduction in Expected Annual Damages compared to no adaptation.

Adaptation benefit: Disaggregated contributions

The most socially vulnerable experience disproportionate flood risks today and in some settings their disadvantage increases in the future. Addressing this issue presents significant adaptation challenge but will be central to 'leveling up' flood risks across the UK. Preferential weighing within investment approaches to flood risk management will continue be necessary (such as within the Partnership

² The assessment of present-day surface water flood risks is less maturity that either coastal or fluvial flooding and hence less certain.

Funding rules used by Defra), but may not be sufficient. To be successful, joined up investment in economic development and flood risk management will be required.

The increase in risk is greatest under a 4°C future with the estimates of risk diverging significantly from a 2°C future from the 2050s (for example raising from ~£2bn today to ~£2.7bn under a 2°C rise by the 2050s and reaching ~£3.9bn under a 4°C rise by the 2080s assuming high population growth and a continuation of Current Level of Adaptation). This highlights the importance of a ‘*twin-track*’ approach focused on both adaptation and mitigation (to reduce Greenhouse Gas emissions) if flood risk is to be managed. Given a 4°C climate future transformational adaptation objectives may be required in some aspects of spatial and development planning, particularly at the coast (including relocation or much greater levels of investment not considered here), if present-day risk levels are to be maintained or reduced.

Keywords: flood, risk, climate change, risk assessment, adaptation

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LIST OF ABBREVIATIONS

AM	Adaptation Measure
AIMS	Asset Information Management System (used by the Environment Agency)
AP	Adaptation Portfolio
CCRA	Climate Change Risk Assessment
CG (rCg)	(Representative) Condition Grade of a flood defence asset. <i>Within this report Cg 3 is used to imply the asset is in 'fair' condition; 1 implies in as built condition and 5 implies poor condition.</i>
CLA	Current Level of Adaptation
CCC	Committee on Climate Change
CWF	Clear Water Flooding (i.e. groundwater flooding from chalk and limestone aquifers)
DA	Devolved Administration (Wales, Scotland, and Northern Ireland)
Defra	Department for Environment, Food and Rural Affairs
DfINI	Department for Infrastructure, Northern Ireland
EA	Environment Agency
EAD	Expected Annual Damages
EWS	Enhanced Whole System adaptation
FCERM	Flood and Coastal Erosion Risk Management
FFE	Future Flood Explorer (the analysis model used here)
FRAW	Flood Risk Assessment Wales
FRM	Flood Risk Management
GCM	General Circulation Model
GMST	Global Mean Surface Temperature
ICT	Information and Communications Technology
IPCC	Intergovernmental Panel on Climate Change
LTIS	Long Term Investment Scenarios (as undertaken by the Environment Agency)
LUA	Local Unitary Authority
NAP	National Adaptation Programme
NaFRA	National Flood Risk Assessment (undertaken by the Environment Agency)
NIFRA	Northern Ireland Flood Risk Assessment
NFM	Natural Flood Management
NFVI	Neighbourhood Flood Vulnerability Index
NFRA	National Flood Risk Assessment (undertaken by SEPA)
NRD	National Receptor Database (England and Wales only)
NRW	Natural Resources Wales
MSfW	Making Space for Water
PSD	Permeable Superficial Deposits
PFR	Property Flood Resilience
RASP	Risk Assessment for Strategic Planning (method of risk analysis underpinning NaFRA and LTIS)
RBD	River Basin District
RCP	Representative Concentration Pathway - a greenhouse gas concentration trajectory (not an emissions scenarios).
ReFH	Revitalised Flood Hydrology
RWS	Reduced Whole System adaptation
rSLR	Relative Sea Level Rise
SEPA	Scottish Environment Protection Agency
SOP (rSOP)	(Representative) Standard of Protection provided by a flood defence asset. Used here to express the frequency – expressed as a return period in years – that a given defence is likely would be overwhelmed by a storm event; this includes significant wave overtopping, river overflow or surcharging.
uFMfSW	Updated Flood Map for Surface Water
WAAD	Weighted Annual Average Damage

GLOSSARY OF TERMS

Adaptation	The adjustment of behaviour of individuals, communities, organisations, investors, and the performance of natural and built infrastructure to moderate harm, or exploit beneficial opportunities, arising from future change.
Adaptation Measure	An individual adaptation action taken to manage risk or enable projected future risks to be better managed.
Adaptation Scenario	The implementation of a combination of Adaptation Measures. Three alternative adaptation strategies are considered: (i) a continuation of the Current Level of Adaptation (CLA – equivalent to ‘ <i>current objectives</i> ’ used elsewhere in the CCRA3); (ii) reduced whole system (RWS) adaptation (equivalent to the ‘ <i>no additional action</i> ’) and (iii) enhanced whole system (EWS) adaptation (equivalent to ‘ <i>current objectives+</i> ’).
Annual Exceedance Probability	The probability of a flood hazard occurring, or being exceeded, in any year.
Climate Projection	A plausible climate future. Two primary climate change projections are reported here, namely a 2°C and 4°C rise in GMST by 2100 (from a pre-industrial baseline).
Coastal flooding	Flooding from the sea when tidal surge, wave action or a combination of tidal surge and waves overtop or overflow the shoreline boundary.
Endogenous change	Changes to the flooding system that are either directly controlled or strongly influenced by flood risk management policy.
Exogenous change	Changes to the flooding system that are outside of the control of flood risk management policy and associated activities.
Emulation (of future risk)	A credible interpolation and extrapolation of existing knowledge (formal and informal) to estimate future risks.
Flood risk system	The combination of sources, pathways and receptors that influence flood risk.
Fluvial flooding	Flooding from a watercourse when water from an established river or drainage channel spills onto the floodplain (also called river flooding).
Future	A combination of climate change, population growth and adaptation.
Groundwater flooding	Flooding from the ground caused by high groundwater levels in aquifers.
Mitigation (climate)	Actions taken to reduce the causes of anthropogenic climate change (e.g. through the reduction of greenhouse gas emissions)
Relative Sea Level Rise	The increase in mean sea level relative to the land – in doing so rSLR accounts for both absolute (eustatic) and land movement (e.g. isostatic rebound that is driving the southeast of England to sink and Scotland to rise).
Representative concentration Pathways (RCP)	A Description of different levels of greenhouse gases and other radiative forcing that might occur in the future. IPCC developed four pathways, defined by a broad range of forcing by 2100 (2.6, 4.5, 6.0, and 8.5 watts per metre squared, Moss et.al.2010). RCP2.6 is also occasionally referred to as RCP3-PD (Peak Decline).
Resilient society	In the context of this report, a society that exhibits an acceptable loss of social well-being, economic prosperity or ecosystem health in the short to longer term in response to an unusual event (or combination of events) or trend.
Return period	The expected (mean) time (expressed here in years) between the exceedance of a threshold (e.g. peak flow, overtopping, inundation etc.). See Sayers, 2015.
Surface water flooding	Flooding arising from the run-off generated by a rainfall event prior to reaching an established river or drainage channel (also referred to as pluvial flooding).

1.0 INTRODUCTION

1.1 Background

The UK Government is required under the Climate Change Act 2008 to publish a Climate Change Risk Assessment (CCRA) every five years. Following publication of the first two assessments (2012 and 2017) the third is due in 2022. To meet this deadline the Department for Environment, Food and Rural Affairs (Defra) has on behalf of the Government asked the Adaptation Committee of the Committee of Climate Change (CCC) to prepare an Evidence Report by July 2021. The Government will then lay before Parliament its summary of the CCRA by January 2022. Both the CCC and Government reports will feed into the development of the next National Adaptation Programme due in 2023 (covering mainly England), as well as the National Adaptation Programmes in Wales, Scotland and Northern Ireland. These reports do not cover the Crown Dependencies or Overseas Territories. Future flood risk has been a central consideration in these previous assessments (Ramsbottom *et al.*, 2012, Sayers *et al.*, 2015) and is the focus of this report. In doing so, advantage is taken of significant advances in climate change data (from UKCP18), national data on present-day flood risks as well as changes in flood risk management policies (and evidence on their effectiveness).

1.2 Aims and objectives

The aim of this study is to assess the impact of climate change and population growth on future flood risk (up to 2100) and the opportunity to manage these risks through adaptation. In doing so, the objectives of the supporting analysis are to:

- Be credible at the chosen scales of aggregation (UK wide, national, and regional, and local authority for some results).
- Use data that are recognised by the lead authorities in England, Wales, Scotland, and Northern Ireland as appropriate (given the context of the study).
- Use a consistent analysis structure to assess future risks across the whole of the UK.
- Assess four sources of flood risk (fluvial, coastal, surface water and groundwater).
- Develop, in collaboration with relevant policy colleagues, a range of future adaptation scenarios and assess their ability to manage future flood risk.
- Consider combined scenarios of climate change, population growth and adaptation to enable a meaningful comparison between risks now and in the future.

Note:

Adaptation costs are out of scope. No attempt is made to identify those adaptations that present the best value for money or offer the most efficient course of action. The analysis presented here considers the benefits of adaptation in terms of risk reduction and a high-level assessment of potential costs.

Coastal and river erosion risks are out of scope. No attempt is made to assess losses due to erosion. For further information on coastal erosion the reader is referred to CCC, 2018 and Sayers, 2018. The influence of river flows on scour and bank erosion (and the associated impacts on bridge collapse or bank failure) are also not considered here.

1.3 Target audience

This report is primarily for those involved in the long-term management of flood risks and the impact of climate change on those risks. This includes the lead authors of the CCRA3 Evidence Report due to be published in July 2021. Given the expertise of this audience a reasonably high level of prior knowledge regarding the assessment of flood risk and the associated policy options is assumed.

Effort is made throughout the report to highlight the assumptions made as well as the confidence in the underlying data used and the results presented.

1.4 Report structure

Following this introductory chapter, the report is structured as follows:

- **Chapter 2: Context of the assessment:** Sets out the time and spatial scales of the analysis together with the sources of flooding, the drivers of future change and risk metrics considered.
- **Chapter 3: Analysis framework: The Future Flood Explorer (FFE):** Summarises the analysis method, the data used as well as the limitations, assumptions, and associated uncertainties.
- **Chapter 4: Metrics of flood resilience:** Sets out and describes the rationale for the chosen metrics of exposure, vulnerability, and risk.
- **Chapter 5: Climate and population projections:** Sets out the population and climate change projections used.
- **Chapter 6: Adaptation Measures and Scenarios:** Sets out the individual Adaptation Measures (influencing flood probability, exposure, and vulnerability) together with how individual Adaptation Measures have been brought together into Adaptation Scenarios.
- **Chapter 7: Future flood risk: Analysis and discussion of results:** Provides an overview of the analysis results (the headline results in table, map, and chart form) and an associated discussion.
- **Chapter 8: Conclusions and Recommendations:** Provides a short conclusion and a summary of recommendations for areas that could be developed to improve future risk assessments.
- **Chapter 9: References**

More detail on specific aspects is provided through a series of Appendices:

- Appendix A: Supporting datasets
- Appendix B: Resilience metrics
- Appendix C: Climate change projections
- Appendix D: Adaptation measures: Supporting evidence
- Appendix E: Comparing the Future Flood Explorer to present-day estimates
- Appendix F: Supporting results

Note:

Shaded 'Notes' are used through the Main Report and Appendices to highlight assumptions made and known limitations within the data and analysis.

2.0 CONTEXT OF THE ASSESSMENT

2.1 Flood hazards

Four sources of flooding are considered (Figure 2-1):

- **River:** Flooding from a watercourse when water from an established river or drainage channel spills onto the floodplain (also called **fluvial** flooding).
- **Coastal:** Flooding from the sea when tidal surge, wave action or a combination of tidal surge and waves overtop or overflow the shoreline boundary.
- **Surface water:** Flooding directly from a rainfall event prior to the generated run-off reaching an established river or drainage channel (also called **pluvial** flooding).
- **Groundwater:** Flooding from the ground caused by high groundwater levels in aquifers.

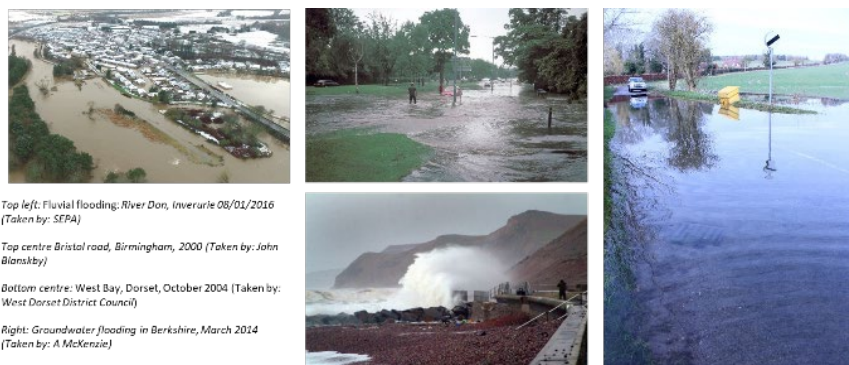


Figure 2-1 Flood sources: Fluvial, coastal, surface water and groundwater

Note:

Credibility of the underlying data provided: The data used are assumed to be representative of the present-day (2018) system and reliable. Different sources of data were collected at different moments in time, and no data is free of some uncertainty, but they are the best available sources recognised by the national policy leads.

Changes in the probability of coastal or fluvial flooding are assumed to respond to either coast or inland climate changes but not both: As in CCRA2, floodplains are defined as either exclusively subject to coastal (including tidal) flooding related climate change (e.g. sea level rise) or changes in inland flows, but not to both. Previous work has considered how likely it is to get multi-source flooding; a recent assessment suggest coastal and fluvial flooding are more likely to occur together at the same time on the west coast of the UK than the East (Hendry *et al.*, 2019).

Surface water flooding is assumed to be uncorrelated to coastal or fluvial flooding: As in CCRA2, it is assumed that damages from surface water flooding occur separately to fluvial or coastal flooding (and hence are in addition to fluvial or coastal flood damages). This is recognised as bias towards over estimating surface water risks (as it represents an upper bound assumption). The impact of this assumption is however likely to be limited in fluvial floodplains given the way the national surface water hazard modelling is undertaken. The impact may be more important in coastal areas.

Groundwater flooding: The underlying analysis supporting groundwater flooding remains primarily based on the analysis undertaken as part of CCRA2 (Sayers *et al.*, 2015). However, changes in groundwater flooding from permeable surface deposits (PSD) respond to changes in fluvial flooding and therefore PSD groundwater risks respond to the new analysis of fluvial risks presented here. Coastal flooding is assumed not to be a significant driver of PSD groundwater flooding. The change in, and extent of, Clear Water flooding remains as in CCRA2. The associated risks will still change however in response to the changes in population used here.

Dam failure, canal breach and tsunamis: These flooding sources are excluded here. The risks from all will be impacted by future change and should be considered in future assessment (in some form). Some literature-based evidence on dam failure risk was included in the technical chapters for CCRA2 and will also be covered in the infrastructure technical chapter for CCRA3.

2.2 Future changes in drivers of risk

Exogenous change: Population and climate change projections

Exogenous change refers to those changes outside of the influence of flood risk management policy. Two drivers of exogenous change are considered:

- **Population growth:** A lower growth and a higher growth projection (based on Cambridge Econometrics, 2019).
- **Climate change:** A 2°C and 4°C rise in Global Mean Surface Temperature (GMST) by 2100 (from the pre-industrial period).

Further detail on both the climate change and population growth projections is provided later in Chapter 5.

Note:

Future demographic change is excluded: Changes in income, age profile, social networks etc. are excluded in this analysis. These considerations are included in the assessment of the effect of social vulnerability on risk – see later – but are assumed unchanged into the future.

Endogenous change: Purposeful adaptations

Endogenous change refers to changes to the flooding system that are either directly controlled or strongly influenced through policies and actions that modify flood risk. In this context a broad range of individual Adaptations Measures (AMs) are considered including those that:

- **Manage the probability of flooding:** By improving conventional flood defences, managing catchment flows (such as rural and urban storage and run-off management) or realigning the coast to improve the Standard of Protection (SoP) afforded by a defence.
- **Manage exposure to flooding:** By limiting new development on the floodplain.
- **Manage the vulnerability of those exposed to flooding:** By encouraging individuals and organisations to improve the flood resilience of their properties/assets or improving forecasting and warning (for example through awareness raising, coverage etc.) to enable more effective action to be taken.

Further detail on the Adaptation Measures (and how multiple measures are combined to form alternative Adaptation Strategies) is presented in Chapter 6.

Note:

Responsibility for adapting to future flood risks: Society has a role in adapting to climate change and managing flood risk. This includes individual households, landowners, communities, organisations, and governments. It is unlikely that adaptation will be successful without these collective actions. The adaptations explored within this report embed a consideration of actions by these stakeholders. No attempt is made to attribute specific roles or responsibilities.

2.3 Temporal and spatial reporting scales

Base date and reporting epochs

Two future time horizons are used: 2050s and 2080s with a base date for the analysis of October 2018.

Two primary assumptions are made in reconciling the various aspects of the analysis to this base date:

- **All data provided on present-day risks are representative of the flood risk system as of October 2018:** All of the datasets provided for use in the analysis are considered to represent the state of the flood risk system as of October 2018 (despite the individual data within these datasets being derived at various times).

- **Climate change is assumed to influence flood risk from October 2018 onwards:** The climate change analysis is based on UKCP18. The analysis of these data uses several baselines: (i) for GMST, pre-industrial times are used; (ii) for changes to fluvial flows, 1960-1990; (iii) for coastal issues, 1981-2000; and (iv) for surface water and groundwater flooding the baseline is less defined and assumed to be 2018. Any change in these variables (e.g. fluvial flow) between the given baseline and 2018 (the baseline of this report) is assumed to be within the observational record and included within the data provided on the present-day flood risk system.

Note:

Data provided by national leads, for example of defence standards, are assumed to represent 2018. In making this assumption it is recognised that although such events are within the observational record, industry standard statistical models applied to estimate extreme variables (such as flood flows and wave conditions) do not routinely account for non-stationarity within that record (Sayers *et al.*, 2014, Faulkner *et al.*, 2020). On balance, this is likely to translate to an understatement of change in risk with climate change (as recent changes may not be captured in the 2018 dataset and there is emerging evidence that historical Green House Gas emissions have already increased the probability with which recent flood events should be expected, compared with a pre-industrial climate, Kay *et al.*, 2018) – this is however difficult to quantify. Sea level data is typically detrended prior to analysis of extremes. As industry standard methods improve to incorporate non-stationarity this assumption will not be needed.

Reporting geographies

The analysis covers the UK with primary outputs reported using a mix of geographies covering one or more of the following lenses:

- **Administrative region:** Five administrative scales are used: (i) UK; (ii) National; (iii) Regional (River Basin Districts) - Figure 2-2 **Error! Reference source not found.**; (iv) Local authorities; and (v) Water company (based on sewerage undertaker company boundaries).
- **Flood source:** Each source of flooding is used: (i) Coastal (including tidal); (ii) Fluvial; (iii) Surface water; and (iv) Groundwater.

Settlement type: Eight categories of urban and rural settlements are as used (Sayers *et al.*, 2017a,b). These are based on the settlement types used in England and Wales and those used in Scotland and Northern Ireland have been mapped to these (Table 2-1 and Figure 2-2 **Error! Reference source not found.**).

- **Social setting:** The most socially vulnerable Neighbourhoods (as defined by the highest 20 percentile of the Neighbourhood Flood Vulnerability Index (NFVI), see Box 1 and Figure 2-2).

Note:

Coastal and tidal flood areas: Tidal and coastal flooding are treated in the same way, and therefore coastal risk includes some areas that are a long way inland: the tidal Thames and Trent, for example.

Not all metrics by all geographies will be calculated or reported: We have explored the results and chosen those to be presented in the report. It would be impractical to calculate and report all combinations. A separate spreadsheet of results at a Local Authority scale is available on request.

Table 2-1 Settlement types used in the UK

	England and Wales (ONS, 2011)	Scotland (Scottish Government, 2016)	Northern Ireland (NISRA, 2015)
Urban	Major Conurbation	Large Urban Areas	Urban
	Minor Conurbation	None	
	City and Town	Other Urban Areas	
	City and Town in a Sparse Setting	None	
Rural	Town and Fringe	Accessible Small Towns	Mixed urban/rural
	Town and Fringe in a Sparse Setting	Remote Small Towns and Very Remote Small Towns	
	Village and Dispersed	Accessible Rural Areas	Rural
	Village and Dispersed in a Sparse Setting	Remote Rural Areas and Very Remote Rural Areas	

Reporting (flood hazard) bands

The lead authorities in England, Wales, Scotland, and Northern Ireland all assess flood hazards using different bands of probability and vary according to the source of flooding. For this report, the results are presented using a common set of Annual Exceedance Probabilities (AEP) as follows:

Significant chance of flooding

- More likely than 1/30 AEP (an average return period of less than 30 years)
- Between 1/30 and 1/75 AEP (an average return period of between 30 to 75 years)

Moderate chance of flooding

- Between 1/75 and 1/200 AEP (an average return period of between 75 to 200 years)

Low chance of flooding

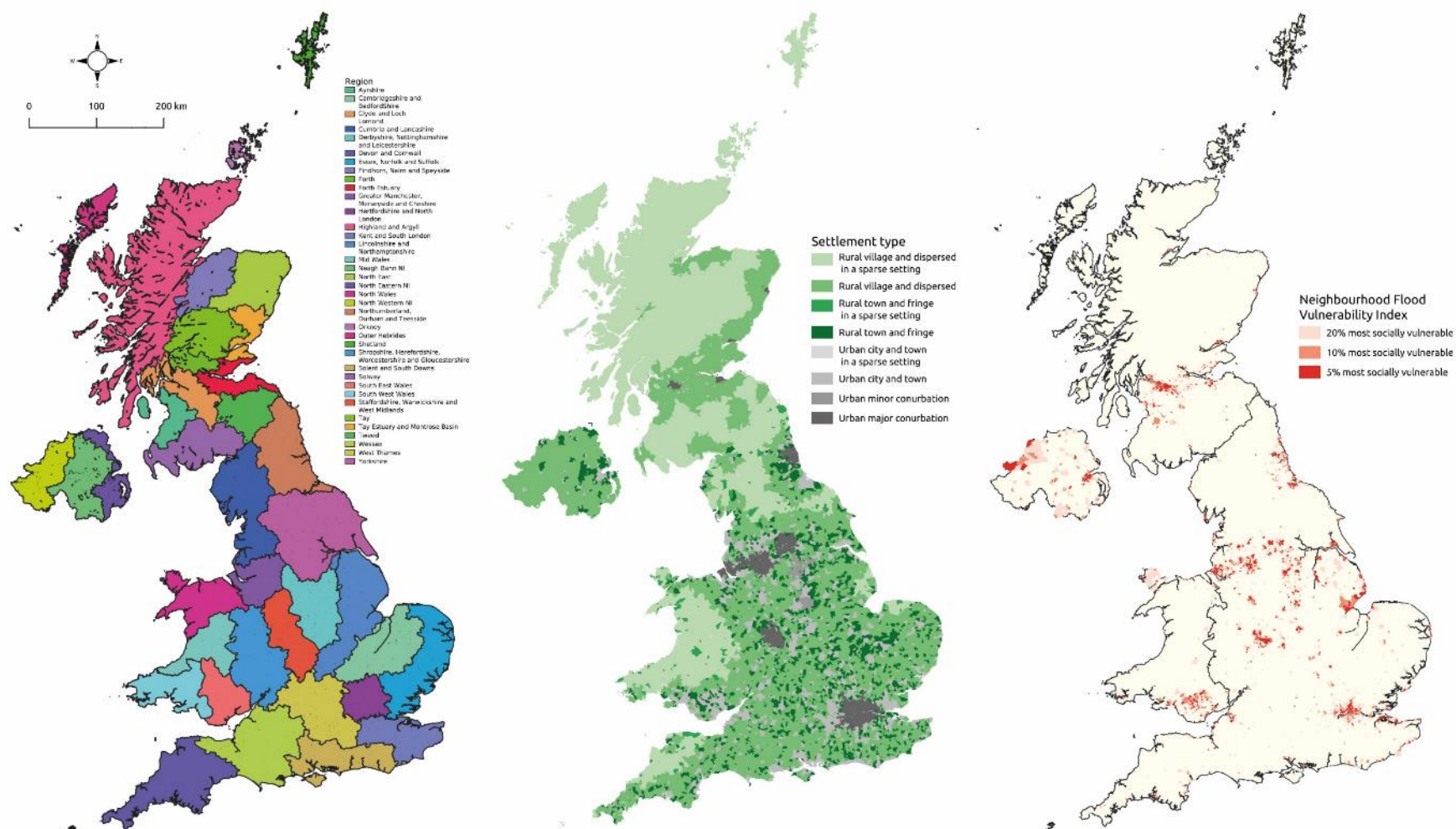
- Between 1/200 and 1/1000 AEP (an average return period of between 200 to 1000 years)
- Less likely than 1/1000 AEP (an average return period more than 1000 years)

Note:

Other bands are possible: The Future Flood Explorer can provide results for any probability band or exceedance. The simplified set used here all have significance in terms of planning or practical guidance and provide ease of reporting.

Understanding the terms of probability and return period: These terms are often mis-used (Sayers, 2015). Here we adopt an Annual Exceedance Probability to define the bands but for ease of communication we adopt simplified terminology of 'return period' where return period is approximated as 1 / AEP (recognising that this is only a reasonable approximation for AEPs less likely than around 1/5).

The extent of the flood prone area does not change in response to climate change: The coastal and fluvial floodplain is defined here by the largest (undefended) modelled extent. For surface and ground water flood prone areas these are the most extreme events considered by the national policy leads. In Wales, Scotland and Northern Ireland this results in the flood prone area being defined by the present-day 1in1000 year event with an allowance for climate change applied (although for different return periods and different allowances – See Appendix A). In England, the extent of the undefended floodplain under climate change is not available.



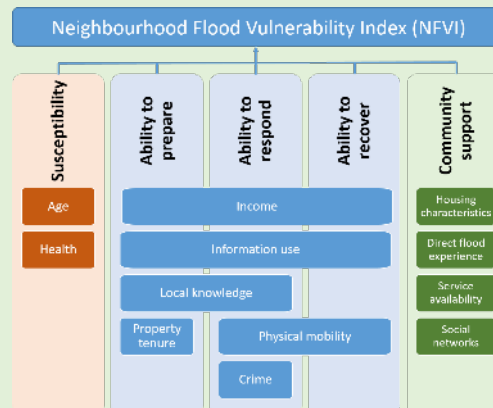
Left: Regions; Middle: Settlements; Right: Neighbourhoods

Figure 2-2 Example aggregation areas

Box 1 Neighbourhood Flood Vulnerability Index (NFVI) – Sayers et al., 2017a,b

The Neighbourhood Flood Vulnerability Index (NFVI) is used here to differentiate the likely impacts of flooding between neighbourhoods (where ‘neighbourhoods’ are defined by census geographies). The NFVI integrates the domains and indicators of vulnerability (see opposite) into a single measure based upon multiple locally quantified variables (see table below). The supporting evidence for the selection of each vulnerability indicator is discussed at length in Sayers et al., 2017b.

Right: NFVI: Influential domains and associated indicators



Below: NFVI: Indicators and associated variables

Indicator	Supporting variables	
Age	a1	Young children (% people under 5 years)
	a2	Older people (% people over 75 years)
Health	h1	Disability / people in ill-health (% people whose day- to-day activities are limited)
	h2	Households with at least one person with long-term limiting illness (%)
Income	i1	Unemployed (% unemployed)
	i2	Long-term unemployed (% who are long-term unemployed or who have never worked)
	i3	Low income occupations (% in routine or semi-routine occupations)
	i4	Households with dependent children and no adults in employment (%)
	i5	People income deprived (%)
Information use	f1	Recent arrivals to UK (% people with <1-year residency coming from outside UK)
	f2	Level of proficiency in English (threshold)
Local knowledge	k1	New migrants from outside the local area (%)
Tenure	t1	Private renters (% Households)
	t2	Social renters (% households renting from social landlords)
Physical mobility	m1	High levels of disability (% disabled)
	m2	People living in medical and care establishments (%)
	m3	Lack of private transport (% households with no car or van)
Crime	c1	High levels of crime (relative)
Housing characteristics	hc1	Caravan or other mobile or temporary structures in all households (%)
Direct flood experience	e1	No. of properties exposed to significant flood risk (%)
Service availability	s1	Emergency services exposed to flooding (%)
	s2	Care homes exposed to flooding (%)
	s3	GP surgeries exposed to flooding (%)
	s4	Schools exposed to flooding (%)
Social networks (non-flood)	n1	Single-pensioner households (%)
	n2	Lone-parent households with dependent children (%)
	n3	Children of primary school age (4-11) in the population (%)

3.0 ANALYSIS FRAMEWORK: THE FUTURE FLOOD EXPLORER

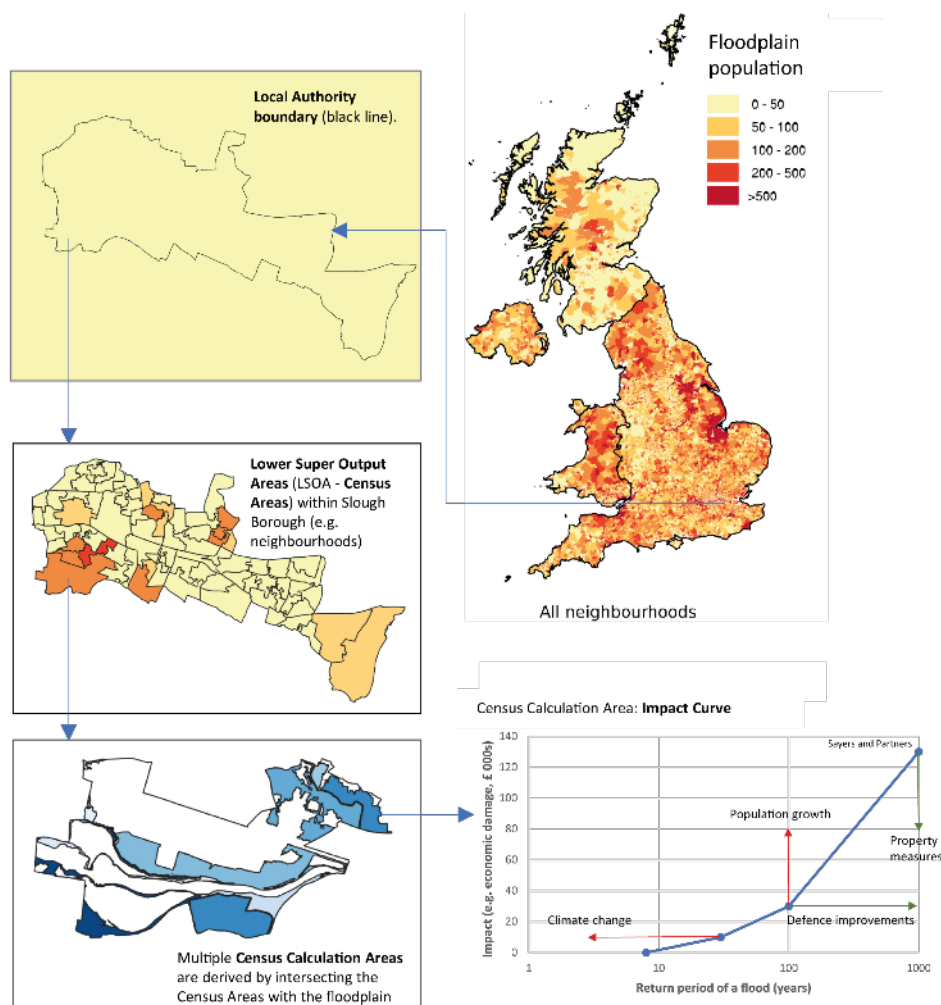
3.1 Overview

The Future Flood Explorer (FFE) is used here to provide an estimate of future flood risk across the UK based on an assessment of the flood hazard, exposure and vulnerability that takes account of flood defences (their standard and condition) where they exist and future climate change, population growth and a portfolio of adaptation measures. The FFE uses nationally recognized source, pathway and receptor data and meta modelling approaches to develop a credible emulation of the UK flood risk system that can represent future change (*e.g.* Sayers *et al.*, 2016 – see section 3.2 for more detail). The high computational efficiency of the FFE allows a consistent assessment of flood risk across England, Wales, Scotland and Northern Ireland under multiple future scenarios (*e.g.* for this study that includes two climate change scenarios, 2°C and 4°C rise in Global Mean Surface Temperature (GMST) by 2100, low and high population projections and taking account of future adaptation).

The FFE uses present-day exposure (for example, from the National Receptor Dataset in England) and the concept of a 'Neighbourhood' to aggregate socio-economic factors (such as demographics, income *etc.*). The FFE defines a Neighbourhood by census geographies (*i.e.* Lower Super Output Areas (LSOAs) in England and Wales, Data Zones (DZs) in Scotland and Super Output Areas (SOAs) in Northern Ireland). The average population in each Neighbourhood varies by country: 1600 people in England, 760 in Scotland, 1600 in Wales and 2000 in Northern Ireland.

The FFE also uses hazard mapping produced by national lead authorities (for each flood source and including climate change where available – see Appendix A). This hazard data is (to different degrees) scrutinized and validated by local teams and produced for a range of return periods (from frequently occurring to very rare). The underlying spatial resolution of the available flood hazard data reflects this underlying flood data and hence varies across the UK and ranges from 2m-50m (depending upon flood source and location). These data are combined with defence datasets (both standard, condition and type) to enable the potential for breach (and how this may change with time) to be included.

The FFE assesses risk at the scale of 'Census Calculation Areas' (CCAs). The CCAs are generated within the FFE by sub-dividing each Neighbourhood using the flood hazard data into variable size polygons. This is done for all flood sources. Impact Curves for each CCA are then calculated (relating the return period of a flood event, experienced locally within the CCA, to the magnitude of the impact within the same CCA) - Figure 3-1.



Top left to bottom left: Each Local Authority contains multiple Census Areas (CA) that are in turn subdivided into Census Calculation Areas (CCAs) by flood hazards. Source: Adapted from Sayers *et al.*, 2015, 2016

Figure 3-1 Impact curve for a Census Calculation Area used to relate return period to impact

Each CCA represents an area which is broadly consistent in both its response to flooding and socioeconomic characteristics. There are 842,864 CCAs in the UK, covering fluvial, coastal, surface water and groundwater flooding. Each CCA is also associated with a representative Standard of Protection (SOP) and Condition Grade (CG) based upon the standards and conditions of the individual defences that relate to it (Sayers *et al.*, 2015). The FFE manipulates the Impact Curves to quantify the influence of climate and population change as well as adaptations on flood risk (shown conceptually in Figure 3-1 and more fully in Figure 3-2).

Table 3-1 Comparison of Census areas used to describe ‘Neighbourhoods’

Area (ha)	10%ile	50%ile	90%ile	Average
England and Wales – LSOA	18	47	1,000	430
Scotland – DZ	9.7	23	1,900	1,200
Northern Ireland - SOA	32	150	5,700	1,600
Population	10%ile	50%ile	90%ile	Average
England and Wales – LSOA	1,300	1,600	2,000	1,600
Scotland – DZ	540	750	980	760
Northern Ireland - SOA	1,400	1,925	2,770	2,000

The FFE manipulates the Impact Curves to quantify the influence of climate and population change as well as adaptations on flood risk (shown conceptually in Figure 3-1 and more fully in Figure 3-2).

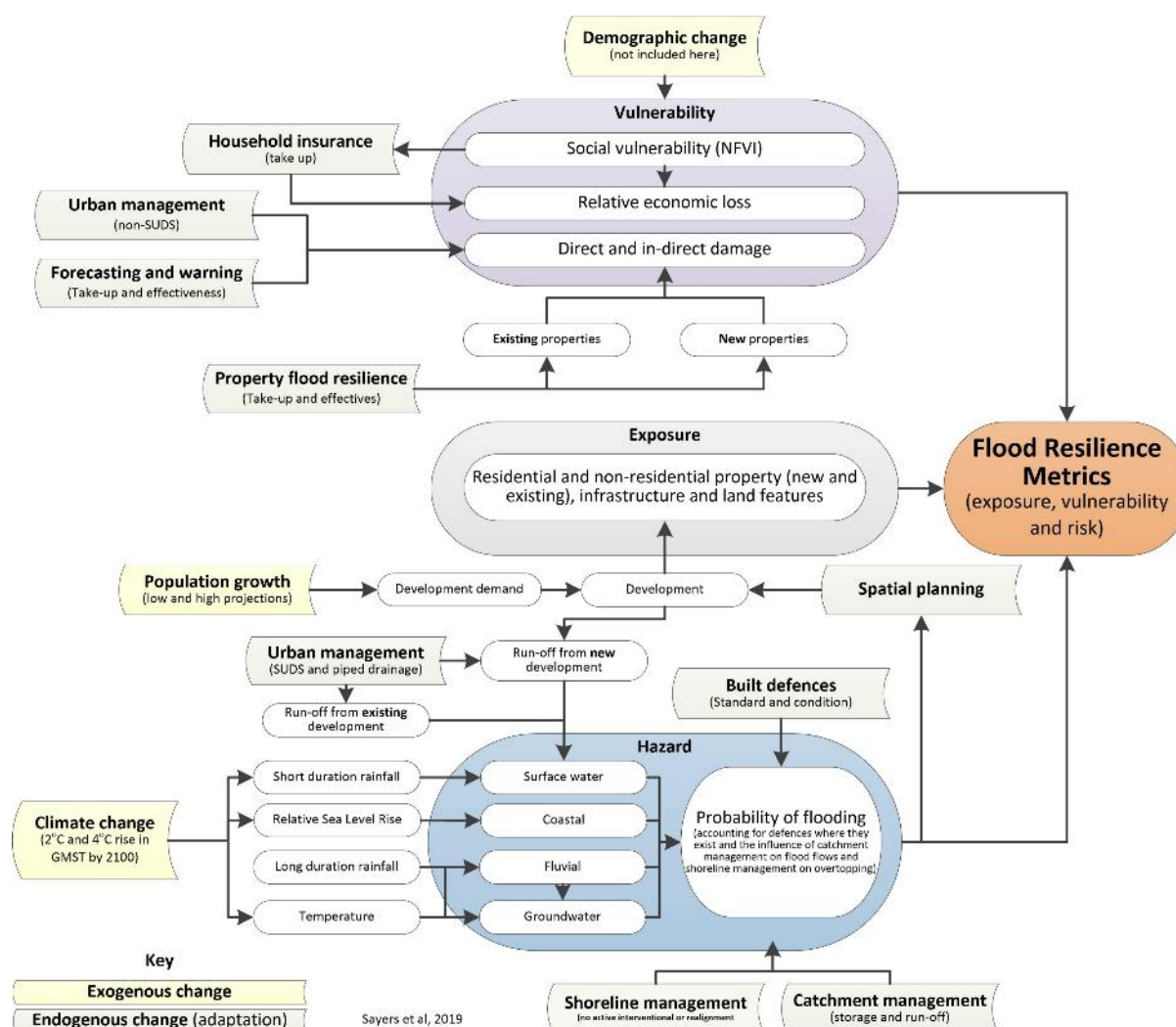


Figure 3-2 Framework of the Future Flood Explorer as applied to CCRA3

Note:

Updates to the FFE since CCRA2: Since its application in support of the CCRA2 (Sayers *et al.*, 2016) the FFE has continued to develop including a wider range of risk metrics (Sayers *et al.*, 2017a) and a refined defence adaptation representation (Sayers *et al.*, 2018). The underlying hazard, exposure, vulnerability, climate change, socio-economic projections and adaptations have also all been updated. A forensic comparison to understand how individual changes and updates within this multitude of changes between CCRA2 and CCRA3 is not feasible (in context of this study) given the interactions between these factors. Instead the focus is on producing an updated assessment of future risks; although it is recognised that the comparison would be both interesting and potentially instructive from a research perspective.

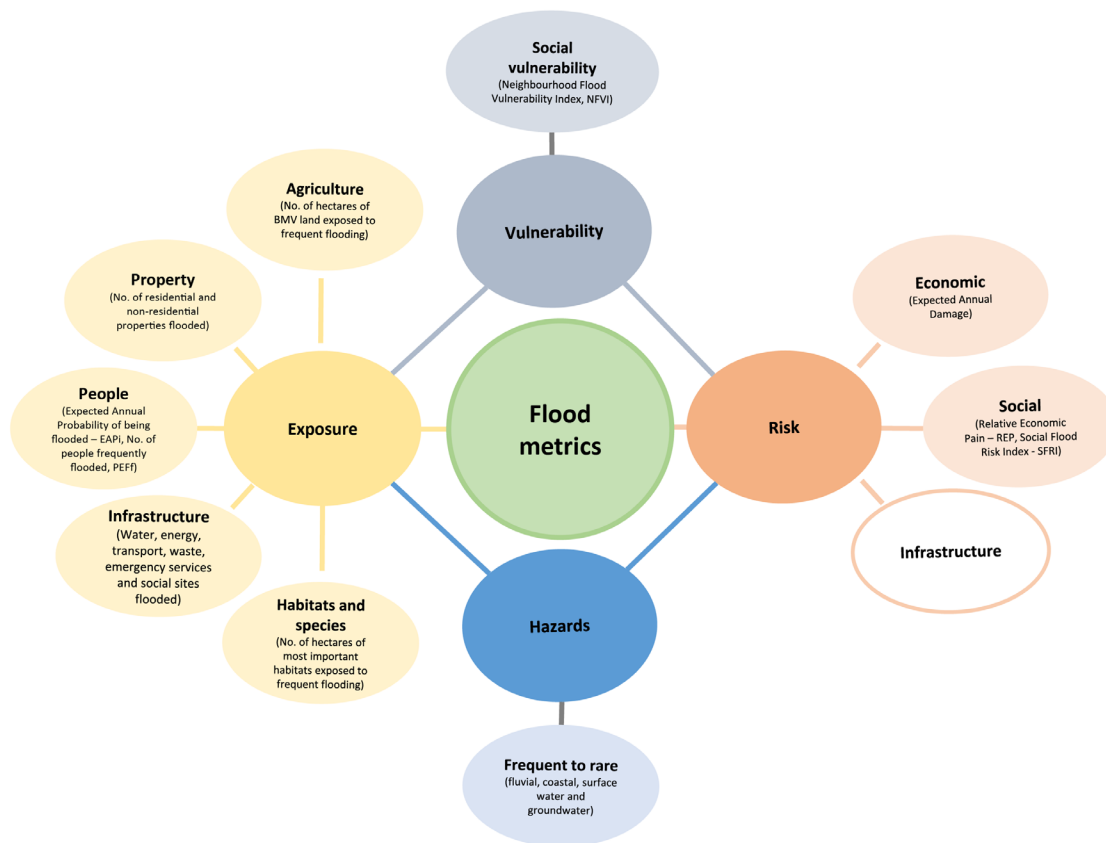
3.2 Confidence and validity of the analysis

The validation of future flood risk is difficult (and philosophically impossible, as neither the present or future or risk can be directly observed, Sayers *et al.*, 2016). Confidence that the analysis is valid in the context of the objectives of the analysis can only be achieved indirectly; by setting out the assumptions and limitations (as highlighted throughout the report and the papers cited therein), and exposing these assumptions to expert challenge. To help determine the degree to which the assumptions are 'reasonable', three aspects are discussed below:

- **Input data:** The input data provided by the national leads and used by the FFE (including, but not limited to, flood hazard, defence standards and conditions, property data) is assumed fit for purpose. This is a reasonable assumption given all the datasets are routinely used by various national and local organisations. This includes in support of national flood risk assessments (in England, by the Environment Agency National Flood Risk Assessment (NaFRA, 2018), in Scotland by SEPA for the National Flood Risk Assessment, in Wales by NRW for the Flood Risk Assessment Wales and by the DfI (NI) in Northern Ireland). These studies all have extensive validation processes, which in some cases have included detailed checks carried out locally by the relevant agencies to identify any significant errors or inconsistencies, and to rectify these – an approach to validation that involves detailed local scrutiny (*e.g.* Blair *et al.*, 2019). For example, in the development of flood hazard maps for surface water, which are part of the underlying input data, checks have been carried out by the model developers and Local Authorities including (Environment Agency, 2019, SEPA, 2020): (i) using local recorded flood data and local knowledge to identify areas that are known to flood, and to highlight unexpected patterns of flooding; (ii) comparing locally produced information with the nationally produced mapping to determine which mapping is more representative for each area; (iii) automated analysis to ensure that the data are logically consistent (*e.g.* modelled flood depths and extents increase with increasing rarity of flooding); and (iv) comparisons with reviews of areas known to have flooded historically. The UKCP18 climate data and the socio-economic projections are also assumed to be appropriate without further specific validation here.
- **Processing of climate analysis:** The UKCP18 data is used here as input to hydrological response analysis within the Grid-2-Grid model and a multi-variate approach to changes in coastal overtopping (both described in detail later in Chapter 5). Both approaches are well validated.
- **Future Flood Explorer:** The FFE was extensively validated as part of CCRA2 (Sayers *et al.*, 2015) and compared to results from the State of the Nation flood risk analysis National Flood Risk Assessment, England as part of the National Infrastructure Assessment (Sayers *et al.*, 2018). Further comparison has been made here, including comparison with the latest selected outputs Flood Risk Assessment Wales (using data exacted from the datasets provided by NRW). These studies show that FFE provides a faithful reproduction of the underlying data through comparison to standalone estimates of present-day risks and responses to defined changes in a credible way.
- **Results:** Engagement with the project stakeholder group throughout has provided useful challenges and gives confidence that the results reflect collective experience. This process has been supplied with internal checks on the response of the FFE enabling sense checking inputs and results (that provide confidence that the FFE response is explicable).

4.0 METRICS OF FLOOD RESILIENCE: EXPOSURE, VULNERABILITY AND RISK

The notion of ‘*flood resilience*’ has emerged in recent years as a concept in support of Sustainable Development and increasing flood risk management (and is now a fundamental concept within the National Flood and Coastal Erosion Strategy for England and similarly in Wales). Although no formally agreed practical definition of resilience exists, here ‘resilience’ is understood as an emergent property of the system of interest and, as such, cannot be measured directly. Rather resilience is assessed here through proxy metrics; the most important being risk. More specifically a resilient society is defined here as one that exhibits an acceptable loss (including no loss) of social well-being, economic prosperity, or ecosystem health over the short or longer term in response to an unusual event (or combination of events) or trend. This definition extends beyond the loss during the event and explicitly considers the post event processes of recovery. Given this definition, several headline metrics are used to provide insights into the multiple, and sometimes subtle, dimensions of flood resilience. The metrics used include a combination of conventional metrics (as introduced in CCRA2, Sayers *et al.*, 2015) and socially focused metrics introduced by Sayers *et al.*, (2017a) that provide some insight into the capacity of difference groups and communities to recovery (for example the Relative Economic Pain metric). These metrics are summarized in Figure 4-1 and introduced below. More detail on the definition and rationale for each metric is provided in Appendix B.



Source: After Sayers *et al.*, 2016.

Note: Disruption of infrastructure services and resulting cascading risks are excluded.

Figure 4-1 The framework of flood resilience metrics

4.1 Metrics of flood risk

The flood risk metrics used here combine hazard, exposure, and vulnerability in an ‘*annual expectation*’ (i.e. average) calculation based on an integration of *annual exceedance probability v consequence* curve. The selected risk metrics are summarized in Table 4-1.

Table 4-1 Flood risk metrics

Metric	Basic description
Economic	
Expected Annual Damage (direct damages - £): Residential and non-residential properties (separately)	The annual ‘average’ direct property damages in economic terms. Determined using an integration of the probability of flooding (taking account of defences and other management measures) and the associated damages.
Expected Annual Damage (total damages - £)	Direct damages plus additional indirect damages (with indirect damages assumed to be 70% of the direct (residential and non-residential) damages plus intangibles assumed to be an additional 20% of the direct (residential) damages)
Expected Annual Damage: Individual (EADi) - £	The annual ‘average’ total - direct and indirect - economic loss faced by an individual living within a flood prone area. Although not representative of the risk faced by any specific individual this provides a means of comparing risks between communities.
Infrastructure	
Expected annual disruption	Excluded here.
Social	
Relative Economic Pain (REP) (dimensionless)	The ‘relative pain’ of the economic risks faced by those exposed to flooding (expressed as the ratio between uninsured economic damages and household income).
Social Flood Risk Index (SFRI) (z-score)	The level of social flood risk (a combination of exposure, vulnerability, and probability of flooding), at a neighbourhood scale (SFRI) and as an individual ‘average’ (iSFRI) – as developed in Sayers <i>et al.</i> , 2016.

4.2 Metrics of exposure

Exposure is considered here as a binary term; a person, property or other receptor is either exposed to a given flood hazard or not. In assessing ‘exposure’ no consideration is given to the nature of hazard (*e.g.* shallower or deeper flooding, only the chance of the flood). Neither is consideration given to the severity of the harm that may be caused to the receptor (*e.g.* reflecting the vulnerability of a given receptor). Therefore, exposure provides a simple metric that presents risk in native parameters (*e.g.* number of people exposed to flooding *etc.*). The selected exposure metrics are summarized in Table 4-2.

Table 4-2 Flood exposure metrics

Metric	Basic description
People (for all Neighbourhoods and the 20% most socially vulnerable Neighbourhoods as defined by NFVI)	
Exposed Population (EP)	No. of people living in flood prone areas defined by 1in1000 year event in the absence of flood defences.
No. of People Exposed to Frequent Flooding (PEFF)	No. of people exposed to flooding more frequently than 1/75 years, on average (accounting for defences and other measures that influence the chance of flooding).
Expected annual probability of flooding: Individual (EAPi)	An individual's annual 'average' exposure to flooding taking account of defences and other management measures.
Property (for residential and non-residential - taking account of defences where they exist)	
Expected Annual number of residential properties flooded	The annual average number of residential properties flooded.
No. of Residential Properties exposed to flooding (by probability band)	No. of properties exposed to different flood frequencies (taking account of defences where they exist).
Number of non-residential Properties exposed to flooding (by probability band)	As above
Habitats and species (taking account of defences where they exist)	
No. of hectares most important habitats exposed to frequent flooding	No. of hectares of the most important habitats (defined as SPA, SAC & Ramsar sites) flooded more frequently than 1/30 years, on average.
Agriculture (taking account of defences where they exist)	
No. of hectares BMV land exposed to frequent flooding	No. of hectares of the Best and Most Versatile (BMV) land flooded more frequently than 1/30 years, on average.
Infrastructure (taking account of defences where they exist)	
Category A infrastructure (exposed by flood probability band)	
Water: No. of water distribution and wastewater treatment sites	Accounts for protection provided by flood defences where they exist.
Energy: No. of power stations (generation) and sub-stations (transmission / distribution)	Accounts for protection provided by flood defences where they exist
Category B infrastructure (exposed by flood probability band)	
Transport: No. of railway stations and length (km) of major roads and railway track	Accounts for protection provided by flood defences where they exist
Waste: No. of operational (licenced) landfill sites	Accounts for protection provided by flood defences where they exist
Emergency Services: No. of Hospitals and blue light service stations (police, ambulance, fire stations)	Accounts for protection provided by flood defences where they exist
Social support networks: No. of care homes, GP surgeries, and schools	Accounts for protection provided by flood defences where they exist

5.0 CLIMATE AND POPULATION PROJECTIONS

5.1 Population growth associated increases in residential property

Analysis by Cambridge Econometrics (2019) is used here to provide two projections of population growth:

- **High growth:** Based on the ONS 'young age structure' variant of its principal population projection, the high growth projection assumes fertility rates and net migration are higher than in the central case while life expectancy is lower. The UK population grows to ~88 million in 2100, an increase of almost 27 million from 2016. The population has a younger age structure than in the central projection, with 59% of the population of working age (4% more than the central projection). The proportion of dependents aged between 0-15 is also slightly higher in the high scenario, reflecting higher birth rates.
- **Low growth:** Based on the ONS 'old age structure' variant of its principal population projection, the low growth projection assumes fertility rates and net migration are lower than in the central case while life expectancy is higher. The UK population reaches to ~68 million in 2100, an increase of just 1 million from 2016 and leads to an older age structure (with over 65s accounting for 36% of the population, compared to 29% in the central scenario).

The demand for new residential properties reflects a combination of population growth and the average household occupancy. The central projections of household occupancy at a local authority scale are taken from Cambridge Econometrics (2019) and show the average UK household size decreasing from 2.35 persons per household in 2016 to 1.96 in 2100. This change factor is applied to present-day local occupancy rates (at a Neighbourhood level) to establish a local development demand in both the high growth and low growth scenarios.

These changes are summarised in Table 5-1 and illustrated in Figure 5-1 by Local Authority.

Note:

Non-residential properties or infrastructure: Important growth or changes (e.g. in the context of transitioning to a net zero economy) in non-residential properties or infrastructure could not be represented in this study due to a lack of reliable scenario data but should be considered in future analyses.

Wealth or demography profile: Although these demographics are captured within the NFVI and SFRI metrics, including changes in these aspects is out of the scope for this study but should be considered in future analyses.

Change in the value of damage: No consideration is given to inflation or a shift in household and business inventories that may be flooded. This implicitly assumes income patterns remain as today. This could be considered for future inclusion if there is a spatial or demographic dimension to these changes. Given the CCRA is not an investment appraisal, discounting future damages and costs is not necessary or included here.

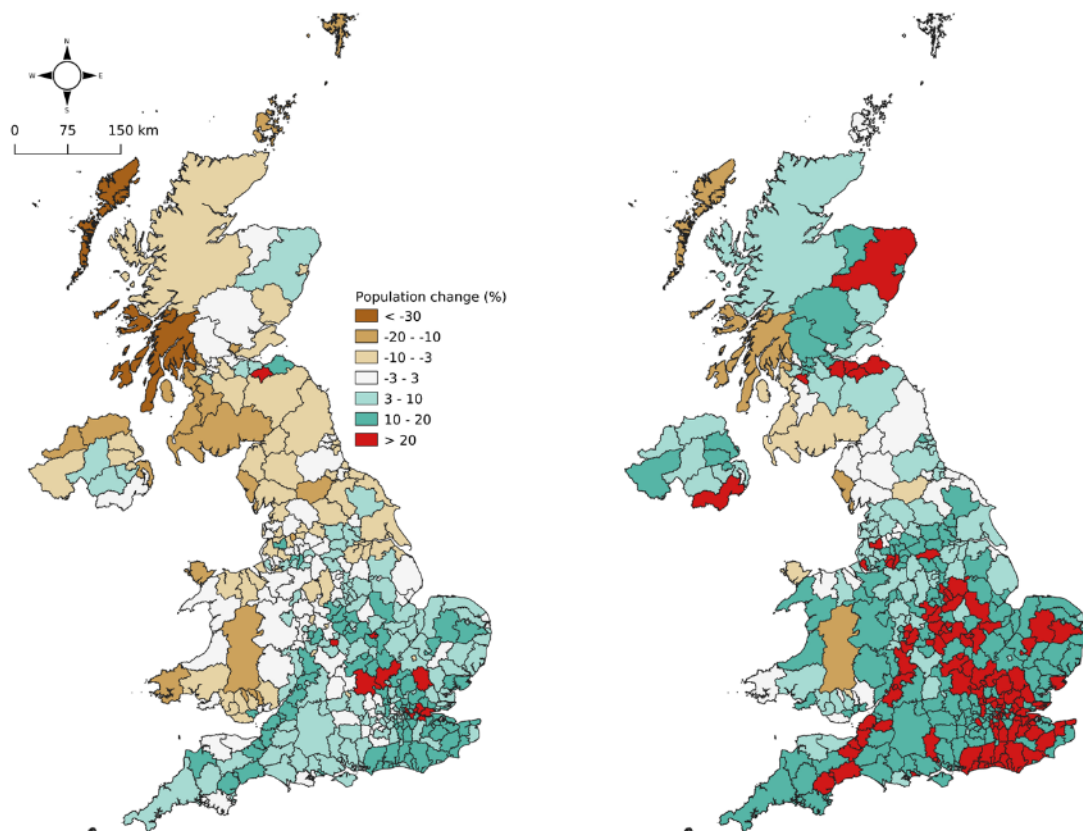
Reductions in population: Given the difficulty in determining how a reduced population in each Authority may impact floodplain occupancy, it is excluded here and it is assumed that the floodplain property portfolio remains unchanged in the case of a reducing population.

Comparison with CCRA2: CCRA3 relies on a set of population projections based upon historical data to 2016, with local authority area projections provided to 2041 and national projections to 2100. In contrast, CCRA2 made use of the 2012-based projections providing local authority area projections to 2037 and national projections to 2100. In addition, different variants are used to represent the Low and high population scenarios. CCRA2 relied upon the ONS High and Low Fertility variants whereas CCRA3 uses more recent Young Age and Old Age Structure scenarios to represent High and Low projections. The impact of this difference on the results has not been explored here as it is simply taken as the most up to date scenarios.

Table 5-1 Population growth projections

Region	Current population	Future population							
	As at 2018 (millions)	Percentage change in population (from present-day)				Average household occupancy			
		Absolute values in millions of people							
		% change from 2018							
		Low		High					
		2050s	2080s	2050s	2080s	2050s	2080s		
UK	66.47	69.51 5%	67.65 2%	79.56 20%	87.79 32%	2.14	2.00		
England	56.00	59.68 7%	59.01 5%	67.67 21%	75.09 34%	2.16	2.01		
Wales	3.14	2.96 -6%	2.66 -15%	3.47 10%	3.67 17%	2.11	2.00		
Scotland	5.45	5.13 -6%	4.53 -17%	6.17 13%	6.59 21%	1.96	1.81		
Northern Ireland	1.88	1.74 -7%	1.45 -23%	2.25 20%	2.45 30%	2.35	2.19		

Source: Based on data provided in Cambridge Econometrics, 2019



Left: low population growth. Right: high population growth. Data source: Cambridge Econometrics, 2019

Figure 5-1 Population projection by UK Local Authority – 2080s

5.2 Climate change

Two climate scenarios are defined by the increase in Global-Mean-Surface-Temperature (GMST) reaching 2°C and 4°C in 2100 (from pre-industrial times). The way the associated changes in climate drivers are assessed under each scenario necessarily varies to reflect the available underlying data from UKCP18 and the priority given to analysis of those data within the constraints of this project as follows:

- **Rate of rise in GMST to 2100:** based on the UKCP18 Probabilistic Projections rebased to pre-industrial times.
- **Changes in peak fluvial flows:** based on the UKCP18 Probabilistic Projections and national-scale 1km flood response surfaces produced using the Grid-to-Grid hydrological model (running at a 15min time step, Bell *et al.*, 2009). The UKCP18 Probabilistic Projections (as monthly delta changes with a fitted harmonic function) are then overlaid on the flood response surfaces, to derive the change in flood flows (using the approach set out in Kay *et al.*, 2020).
- **Changes in short duration rainfall intensity (< 6hours):** based on a combination of Dale *et al.*, 2017 (that uses pilot analysis from a 1.5km grid climate model, a pre-cursor to the 2.2km UKCP18 short duration rainfall projections, Kendon *et al.*, 2014) and data used in CCRA2 (Sayers *et al.*, 2015).
- **Changes in sea levels at the coast and in estuaries:** based on the relative Sea Level Rise (rSLR) data within the UKCP18 Marine Report (Palmer *et al.*, 2018) changes in wave overtopping are assessed. This process accounts for the offshore to nearshore wave propagation and defence overtopping response (using the approach set out in Gouldby *et al.*, 2017).
- **Changes in groundwater flooding:** As in CCRA2 (not updated here) based on BGS Groundwater Susceptibility Mapping undertaken as part of the Future Flows project (Jackson *et al.*, 2011) as used within CCRA2 (Sayers *et al.*, 2015).

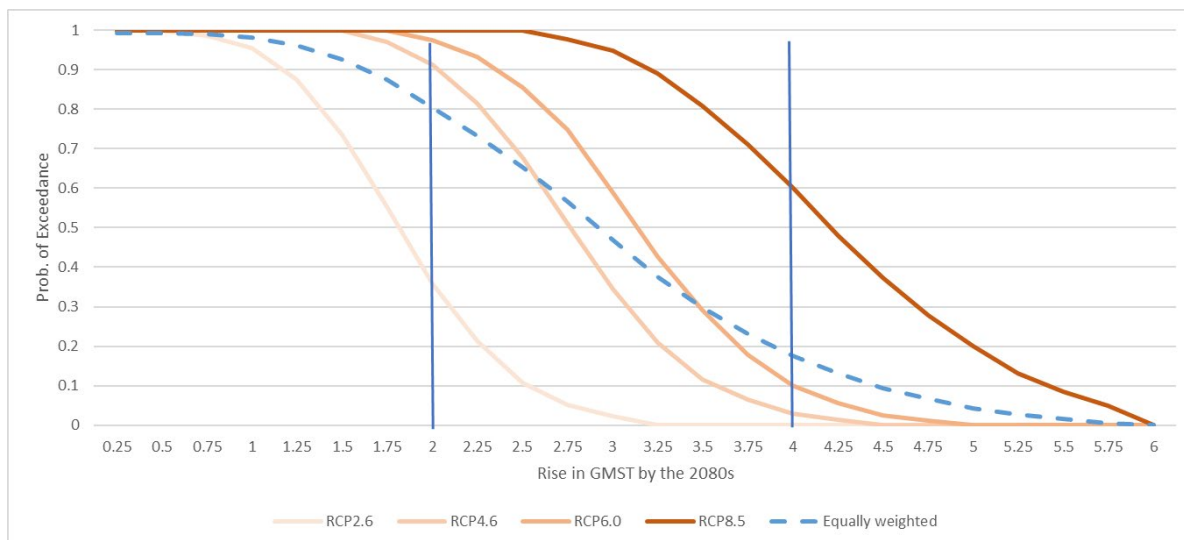
The data and analysis under each heading are set out below with more detailed discussion provided in Appendix C.

Note:

At the time of writing, extreme value analyses of the UKCP18 2.2km grid outputs are not available and hence could not be used here. Equally, for groundwater the Future Flows 2 project will update the results here but are not currently available (due end of Summer 2020).

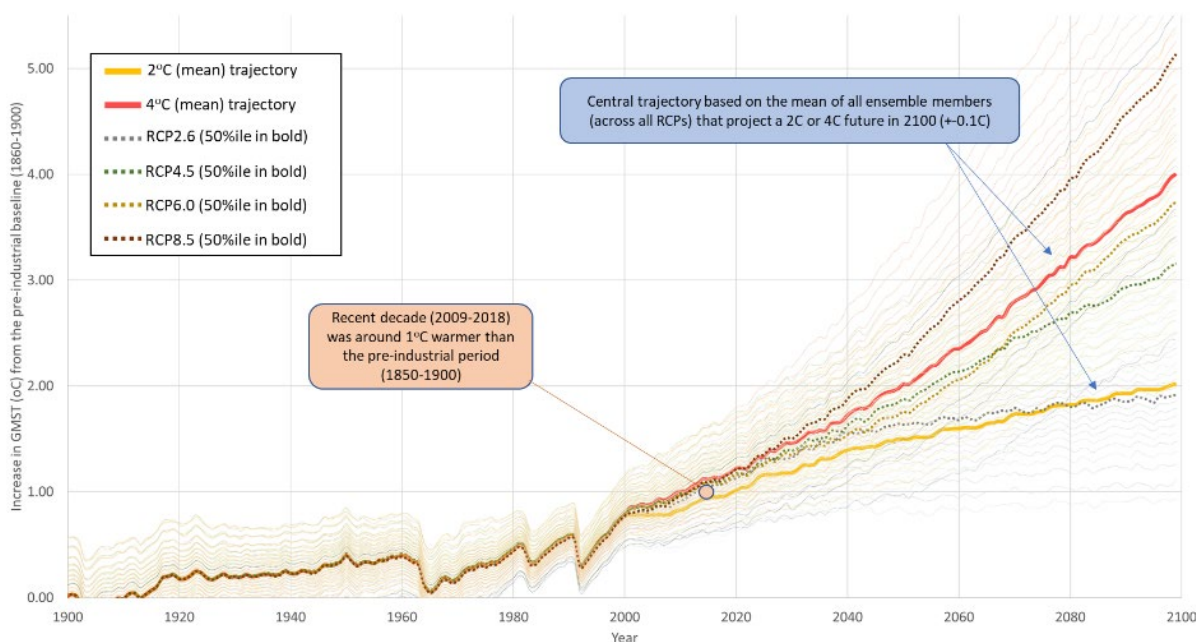
Rate of rise in GMST

Across the Representative Concentration Pathways (RCPs – see note) many of the ensemble members from UKCP18 Probabilistic Projections show an increase in GMST of 2° or 4°C by 2100 (Figure 5-2). A mean of those members that project a rise of 2°C and 4°C (within a tolerance of +/- 0.1 between 2090-2100 from a pre-industrial baseline) are used to construct a profile in the rise in GMST with time (Figure 5-3). The central (mean) estimate is used to determine this profile. The GMST in any year that is consistent with a 2 or 4°C rise by 2100 is then determined from this profile. This value is then used to determine the related changes in fluvial flows, sea levels *etc.* in the 2050s and 2080s (as described in the following sections).



Source: Met Office 2019 - a pre-release GMST anomaly dataset made available prior to upload to CEDA Data Archive

Figure 5-2 Rise in GMST under each RCP



Note: Central trajectory based on a mean of all ensemble members (across all RCPs) that project a 2°C or 4°C future. After 2000 the 2 and 4°C trajectories diverge, which reflects the variation in the UKCP18 projections.

Figure 5-3 Rise in GMST to 2100 (from UKCP18 probabilistic projections)

Note

A basic introduction to each RCP (based on van Vuuren *et al.*, 2011): RCP 8.5 - representative of increasing greenhouse gas emissions over time and high greenhouse gas concentration levels; RCP 6.0 - represents a scenario that stabilizes shortly after 2100. UKCP18 sea level anomalies have not been estimated for this RCP and therefore is not used here at the coast; RCP 4.5 represents a second scenario that stabilizes shortly after 2100; RCP 2.6 represents a “peak-and-decline” scenario that leads to low greenhouse gas concentration levels by 2100.

Coastal flooding

Climate change variable of interest: Relative sea level rise

Wave conditions around much of the UK coast are depth limited. Relative Sea Level Rise (rSLR) therefore has a dominant influence on coastal flooding (increasing both wave-driven overtopping, the chance of a breach and tidal overflow). As there is a lack of evidence of climate driven changes in other aspects of coastal storms, rSLR is considered here as the single driver of climate related change at the coast (an assumption also made in CCRA2, Sayers *et al.*, 2015).

Sea level projections for the UK used here are based on the UKCP18 Marine Report (Palmer *et al.*, 2018). The UKCP18 sea level projections are based on the climate model simulations of the Coupled Model Inter-comparison Project Phase 5 (CMIP5, Taylor *et al.*, 2012). These models formed the basis of the climate projections presented in the IPCC Fifth Assessment Report of Working Group I (IPCC, 2013) and provide improvements over their predecessor models that formed the basis of UKCP09 (Meehl *et al.*, 2007). The most significant methodological difference is the inclusion of ice dynamics in UKCP18 projections of future sea level rise, resulting in systematically larger values than were presented in the UK Climate Projections 2009 (UKCP09) (Lowe *et al.*, 2009). For full technical details of the modelling carried out in UKCP18 see Palmer *et al.*, (2018). UKCP18 sea level projections also include the spatial patterns of sea level change due to oceanographic processes as well as gravitational and other adjustments due to ice melt and changes to terrestrial water storage. The projections include the elastic response of the land to the last de-glaciation to provide relative sea level rise estimates (a main reason for spatial variations in projected mean sea level change around the UK).

The UKCP18 Marine Report (Palmer *et al.*, 2018) provides percentile values of sea level rise for three RCPs (2.6, 4.5 and 8.5). The rise in GMST and SLR estimates associated with these values are used to interpolate an assessment of rSLR given a 2 and 4°C rise in GMST in 2100 (re-based to give the rSLR relative to a 2018 baseline – see Appendix C). A detailed processing chain is used to assess the change in the Standard of Protection (SoP) afforded by a given coastal defence in response to changes in rSLR that includes issues of depth-limitation, refraction, and nearshore beach levels and defence geometry (as set out in Gouldby *et al.*, 2017 Figure 5-4). The central estimates from this analysis are illustrated in Figure 5-5 with the change in rSoP at a regional scale for illustration in Table 5-2.

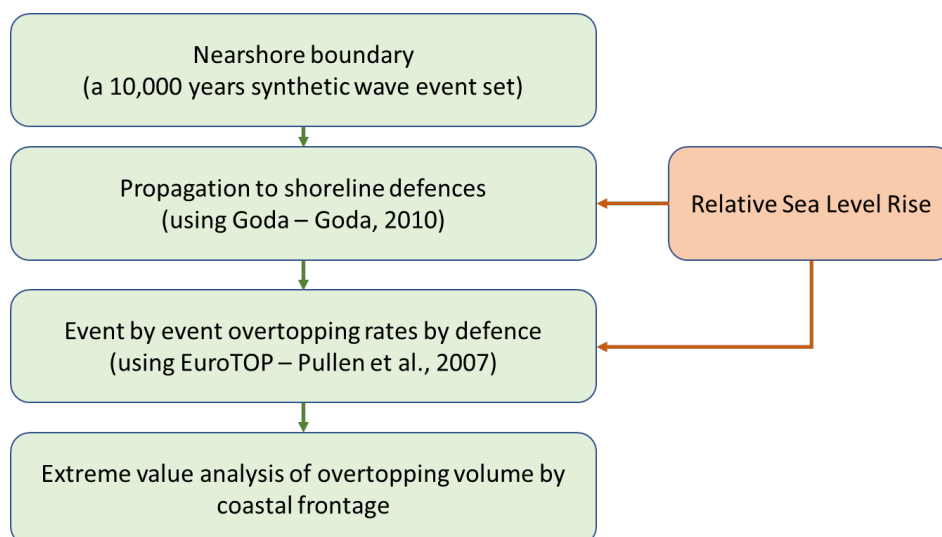
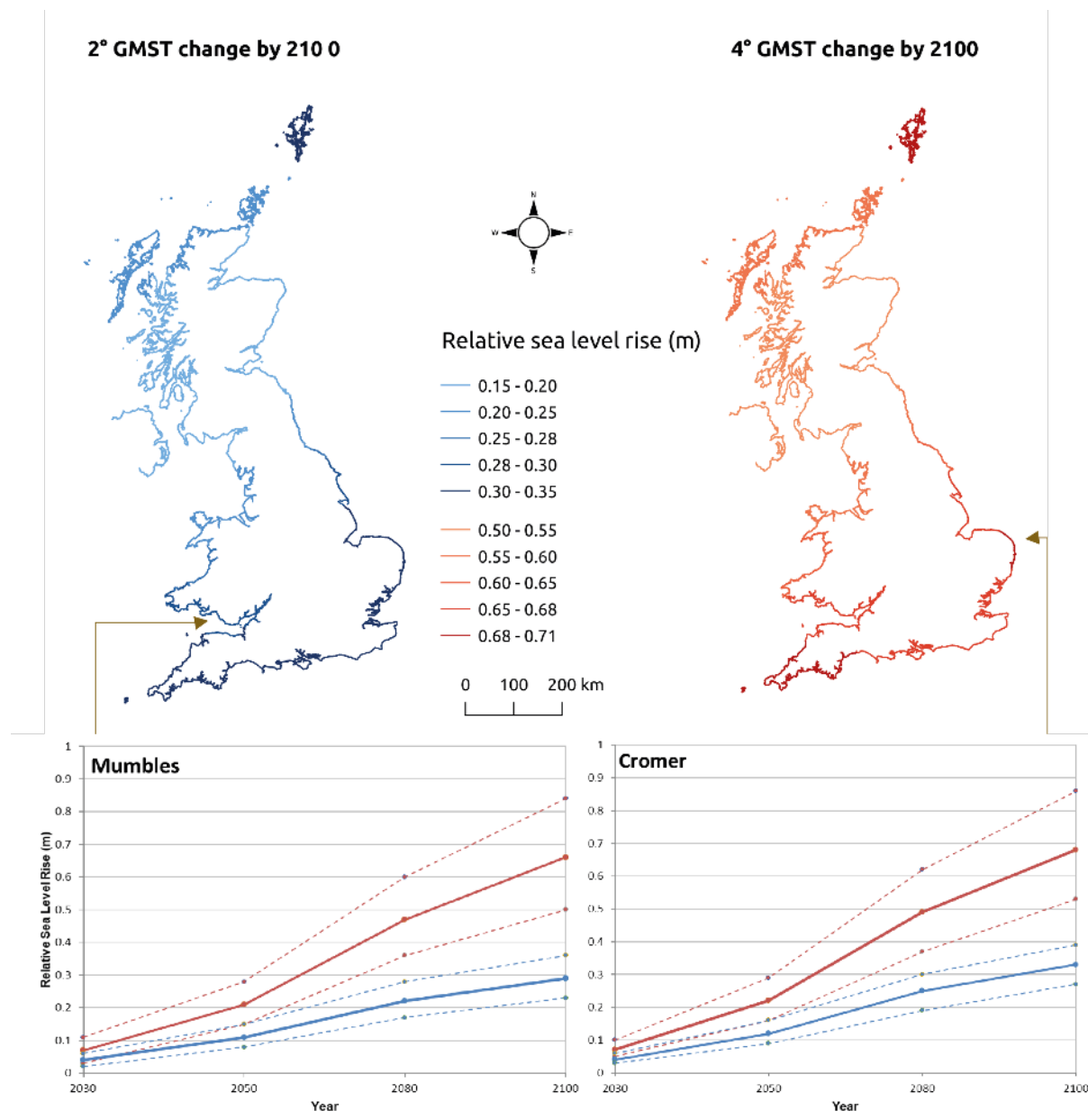


Figure 5-4 Assessing the impact of rSLR on coastal defence standards



Blue: 2° future. Red: 4° future. Solid lines central estimate, dashed lines present the envelope of change from the available data in Palmer et al – 5th and 95th percentiles.

Figure 5-5 Relative sea level rise (2018 to 2100)

Table 5-2 Relative Sea Level Rise and impact on defence standards

	Typical values of rSLR (m)													
	50th percentile (10th - 90th percentiles)													
	2°		4°		Impact on Present Day Standard of Protection (Return Period - Years) of a 0.35m rSLR									
	2050	2100	2050	2100	2	5	10	20	50	100	200	500	1000	
England														
01 - Scottish Border to River Tyne	0.09 (0.05-0.14)	0.27 (0.16-0.39)	0.20 (0.13-0.27)	0.65 (0.47-0.85)	0	1	3	5	12	23	44	107	202	
02 - The Tyne to Flamborough Head	0.12 (0.07-0.17)	0.32 (0.22-0.44)	0.22 (0.15-0.29)	0.71 (0.53-0.9)	1	3	5	10	24	47	91	256	567	
03 - Flamborough Head to Gibraltar Point	0.13 (0.09-0.18)	0.37 (0.27-0.49)	0.24 (0.17-0.31)	0.75 (0.58-0.94)	1	2	3	7	17	35	70	198	370	
04 - Gibraltar Point to Hunstanton	0.13 (0.09-0.18)	0.38 (0.28-0.49)	0.24 (0.17-0.31)	0.76 (0.58-0.95)	1	3	5	8	18	32	60	145	288	
05 - Hunstanton to Kelling Hard	0.14 (0.1-0.19)	0.39 (0.29-0.5)	0.25 (0.18-0.32)	0.77 (0.6-0.96)	0	2	3	7	15	28	53	128	243	
06 - Kelling Hard to Lowestoft	0.14 (0.1-0.19)	0.40 (0.3-0.51)	0.25 (0.18-0.32)	0.78 (0.61-0.96)	1	2	4	9	23	42	84	232	420	
07 - Lowestoft to Felixstowe	0.14 (0.1-0.19)	0.39 (0.29-0.5)	0.25 (0.18-0.32)	0.77 (0.6-0.96)	0	2	3	6	18	38	78	231	449	
08 - Essex and South Suffolk	0.14 (0.09-0.2)	0.38 (0.29-0.49)	0.25 (0.17-0.32)	0.77 (0.6-0.95)	0	1	3	5	14	30	64	186	435	
09 - River Medway and Swale Estuary	0.14 (0.09-0.19)	0.38 (0.28-0.49)	0.24 (0.18-0.31)	0.76 (0.59-0.95)	0	2	4	7	18	37	73	229	622	
10 - Isle of Grain to South Foreland	0.14 (0.09-0.19)	0.38 (0.28-0.49)	0.24 (0.17-0.32)	0.77 (0.6-0.95)	0	1	3	6	15	31	63	162	360	
11 - South Foreland to Beachy Head	0.13 (0.09-0.18)	0.38 (0.28-0.49)	0.24 (0.17-0.31)	0.76 (0.59-0.95)	1	3	5	8	17	33	64	145	288	
12 - Beachy Head to Selsey Bill	0.14 (0.09-0.19)	0.38 (0.28-0.49)	0.25 (0.18-0.32)	0.76 (0.59-0.95)	1	1	2	4	11	21	40	105	215	
13 - Selsey Bill to Hurst Spit	0.14 (0.09-0.19)	0.38 (0.28-0.49)	0.25 (0.18-0.32)	0.77 (0.59-0.95)	0	0	1	3	7	13	25	62	119	
14 - Isle of White	0.14 (0.09-0.19)	0.38 (0.28-0.49)	0.25 (0.17-0.32)	0.77 (0.6-0.96)	0	1	2	5	10	20	40	95	185	
15 - Hurst Spit to Durlston Head	0.14 (0.09-0.2)	0.38 (0.28-0.5)	0.25 (0.18-0.33)	0.77 (0.6-0.96)	1	2	3	7	18	36	70	171	331	
16 - Durlston Head to Rame Head	0.14 (0.1-0.19)	0.39 (0.29-0.51)	0.25 (0.18-0.32)	0.78 (0.61-0.97)	1	2	5	9	22	41	79	197	379	
17 - Rame Head to Hartland Point	0.14 (0.1-0.19)	0.40 (0.29-0.52)	0.25 (0.18-0.33)	0.79 (0.61-0.99)	1	2	4	8	19	37	72	176	351	
18 - Hartland Point to Anchor Head	0.13 (0.09-0.18)	0.37 (0.27-0.49)	0.24 (0.17-0.31)	0.76 (0.58-0.96)	1	2	3	6	14	26	50	123	265	
19 - Anchor Head to Lavernock Point	0.13 (0.09-0.18)	0.37 (0.27-0.48)	0.24 (0.17-0.31)	0.76 (0.58-0.95)	0	2	4	7	17	33	70	190	369	
22 - Great Ormes Head to Scotland	0.1 (0.06-0.15)	0.28 (0.18-0.4)	0.21 (0.14-0.28)	0.67 (0.49-0.86)	0	1	3	6	15	30	55	135	249	
Wales														
19 - Anchor Head to Lavernock Point	0.13 (0.09-0.18)	0.37 (0.27-0.48)	0.24 (0.17-0.31)	0.76 (0.58-0.95)	0	1	3	5	12	23	47	129	278	
20 - Lavernock Point to St Ann's Head	0.13 (0.08-0.18)	0.36 (0.26-0.48)	0.24 (0.17-0.31)	0.75 (0.57-0.95)	0	1	2	4	9	18	35	86	175	
21 - St Ann's Head to Gread Ormes Head	0.11 (0.07-0.16)	0.32 (0.21-0.44)	0.22 (0.15-0.29)	0.7 (0.52-0.9)	0	1	2	5	13	24	46	111	212	
22 - Great Ormes Head to Scotland	0.1 (0.06-0.15)	0.28 (0.18-0.4)	0.21 (0.14-0.28)	0.67 (0.49-0.86)	0	1	3	5	14	28	51	126	225	
Scotland														
East	0.08 (0.04-0.13)	0.23 (0.12-0.36)	0.19 (0.12-0.26)	0.62 (0.43-0.82)	0	1	1	3	8	16	32	79	158	
North	0.11 (0.07-0.16)	0.29 (0.17-0.42)	0.22 (0.15-0.29)	0.67 (0.48-0.88)	1	1	2	5	12	23	44	105	207	
North-West	0.11 (0.07-0.16)	0.29 (0.17-0.42)	0.22 (0.15-0.29)	0.67 (0.48-0.88)										
West	0.08 (0.04-0.13)	0.23 (0.12-0.35)	0.19 (0.12-0.26)	0.61 (0.42-0.81)	0	1	3	5	14	27	51	126	225	
Northern Ireland														
Northern Ireland	0.08 (0.04-0.13)	0.24 (0.13-0.36)	0.19 (0.12-0.26)	0.62 (0.43-0.82)	0	1	3	5	14	28	51	126	225	

Note: The 50th percentile values shown as used in the analysis of risk presented later in the report.

Example: For a defence in SMP 22 (Wales) with a current SoP of 1:50, the standard would reduce to 1:14 years. The boundaries of the shoreline region are shown in Figure 6-3.

Note:

Exclusion of other influences of climate change on coastal extremes: UKCP18 finds no evidence for significant changes in future storm surges or offshore wave conditions (Palmer *et al.*, 2018). There is some indication that the relative contribution of swell waves (i.e. longer period waves) may be increasing. There is little confidence in this indicator, and as such it has not been included in this study. UKCP18 also suggests that offshore wave heights are changing (moderately) but makes no suggestion of a change in direction. Given the process of refraction and depth-limitation the influence of such changes in the offshore conditions are likely to be limited at the coast. Changes to storm sequence, surge, wave direction, wetting and drying of embankments and other changes in climate that may be important to the performance of coastal defences (Sayers *et al.*, 2015) are out of scope. Palmer *et al.*, 2018 also suggests there may be changes in low and high tide in response to mean sea level change (and this may influence flooding, Haigh *et al.*, 2020); these are excluded here. These exclusions are considered reasonable given the accepted dominance of sea level rise.

High scenarios of sea level rise: Both the IPCC Special Report on the Ocean and Cryosphere and UKCP18 marine report highlight the uncertainty associated with the influences of ice sheet loss and other processes not fully captured in UKCP18. It is possible that the sea level rise may be considerably greater than those set out here.

Temperature independent uncertainty: Some drivers of SLR, such as the contribution of ice melt, are not necessarily strongly coupled to surface temperature and others are independent of temperature (such as isostatic rebound). This adds uncertainty to the suitability of the GMST as a means of describing a future state. A future CCRA should consider the importance of this and consider an approach that enables GMST independent and GMST dependent changes to be sampled whilst maintaining a simplified frame of reference (as provided by the GMST based futures here).

Extrapolation to Wales, Scotland and Northern Ireland using analogues from England: In the absence of the underlying coastal dynamic models to estimate the impact of rSLR on coastal overtopping in Wales, Scotland and Northern Ireland it has been necessary to use more aggregated frontage lengths that reflect areas exposed to similar wave climates and rSLR projections. Although necessary given the lack of quantified analysis data, this assumption is recognized as a weakness.

Comparison to CCRA2: This approach is a significant improvement on CCRA2. CCRA3 includes a much greater spatial resolution of the change in sea levels (covering 2450 frontages around the UK coast compared to the small number of regional estimates used in CCRA2).

Fluvial flooding: Changes in peak flood flows and changes in standard of protection

Climate change influences fluvial flood risk through changes in flood flows that in turn change in-river levels (and hence standard of protection). These two steps are introduced below with more detail provided in Appendix C.

Assessing changes in peak fluvial flows

The UKCP18 Probabilistic Projections that reach a 2 or 4°C rise in GMST **in or before** 2100 (from a pre-industrial baseline) are used in assessing the change in fluvial flows. This ‘time-sampling’ approach (James *et al.*, 2017) maximizes the number of ensemble members that are used to assess the change for a given rise in GMST. The selected combinations of ensemble members and time-slices are used to derive changes in peak flows on a 1km grid using the flood response surface approach, set out in Kay *et al.*, (2020) – an approach that uses a national-scale grid-based hydrological model, Grid-to-Grid (see Box 3). This process leads to percentile changes in return period peak flood flows on a 1km grid that correspond to each required GMST change (Figure 5-6Figure).

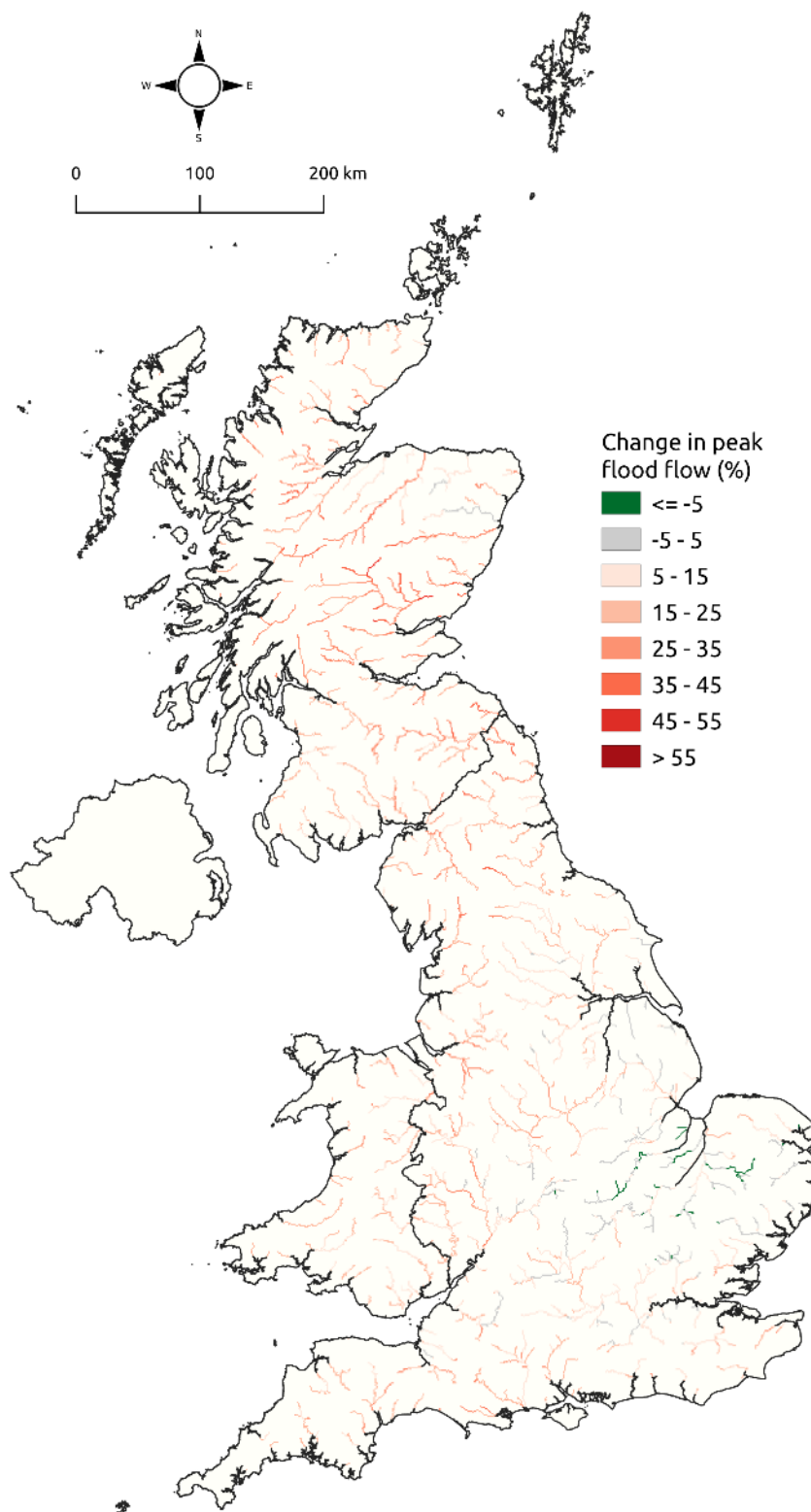
Box 3 Grid-to-Grid – Evidence of validation

Grid-to-Grid (G2G) is a national-scale hydrological model for Great Britain (GB) that runs on a 1km x 1km grid (aligned with the GB national grid), at a 15-minute time-step, and is parameterised using digital datasets (*e.g.* soil types, land-cover) (Bell *et al.*, 2009). The effect of urban and suburban land-cover on runoff and downstream flows is accounted for in the model. G2G has been shown to perform well for a wide range of catchments across Britain (Bell *et al.*, 2009, 2016; Rudd *et al.*, 2017; Formetta *et al.*, 2018) particularly those with more natural flow regimes as it currently does not include the effect of artificial influences such as abstractions and discharges on river flows. G2G is routinely used for high flow applications, for example operational fluvial flood forecasting (Cole and Moore, 2009), pluvial flood forecasting (Speight *et al.*, 2016) and assessments of the effect of projected climate change on peak river flows (*e.g.* Bell *et al.*, 2009, 2016). The G2G generally uses spatial datasets in preference to parameter identification via calibration, and where model parameters are required (such as the kinematic wave speeds used in lateral routing) nationally applicable values are used. Thus, calibration has not been used to identify separate model parameters for individual catchments.

Note:

Flood peak changes for Northern Ireland: The national-scale sensitivity framework modelling described here does not provide any information for Northern Ireland (NI), and to our knowledge there is no equivalent work that does, so for NI a simpler approach was taken, but one still based on the sensitivity framework. For each of the three river-basin regions covering NI the precipitation changes derived from the UKCP18 probabilistic projections were overlaid on the representative flood response surface for the ‘Neutral’ response type. The Neutral response type is the one most prevalent in the north/west of GB (Kay *et al.*, 2014), so represents the best guess of the response type for catchments in Northern Ireland.

Small catchments: The G2G flow projections cover catchments > 100km²; for smaller catchments it is assumed the climate response (*i.e.* percentage changes in flow) is the same as the nearest available grid point. There is currently no data available to test the validity of this assumption.



4°C rise in GMST by 2100 based on RCP8.5 and 50th percentile estimate of changes in flow. This is applied across all return periods. Note: NI is not covered in the same detail within the Grid-2-Grid UKCP18 analysis as elsewhere but is based on change factors in the four river basins (discussed further in Appendix C).

Figure 5-6 Gridded changes in peak fluvial flows

Assessing the impact on extreme river levels

Changes in peak fluvial flow are translated to a change in water levels (the effective storm loading on a defence where it exists) through application of the Flood Estimation Handbook (FEH) statistical method (Kjeldsen *et al.*, 2008) to each 1km grid (based on catchment descriptors from the most appropriate 50m FEH pixel). The FEH flood frequency curve for each grid point is used to estimate the change in the return period of the current T-year flood corresponding to a set of percentage changes in flow, as illustrated in Table 5-3. This processing chain (climate change, hydrological response and extreme value response) enables the local context of the response to climate change to be captured and leads to highly spatially differentiated (credible) changes. For example, two tributaries immediately upstream of a confluence can be quite different in their physical geography. These differences mean that two nearby locations can have different responses to a change in rainfall and the flood flows. Figure 5-7 illustrates this by plotting the flood frequency curves for two points upstream and one point downstream of a confluence of the rivers Teme and Corve near Ludlow, Shropshire. This figure shows how the change in return period in response to climate change – at one location the 1000-year flood reduces to 341-year flood flow whilst at another, close by point, to the 533-year flood flow. How this change manifests in terms of a flood hazard will reflect the local defences (if present) and their standards and conditions (a consideration that adds further spatial differentiation).

Notes:

Other changes driven by climate change: More subtle influences of climate change, as such the sequencing and clustering of wet and dry or hot and cold periods (e.g. Sayers *et al.*, 2015), are not included here.

Not all ensemble members for a given RCP reach the required GMST changes: RCP8.5 provides the largest number of ensemble members that at some point reach the required rise in GMST and has been used to drive the fluvial flow analysis. The uncertainty arising from the sole use of RCP8.5 has been assessed to be relatively low (by comparing across RCPs ensemble members yielding the same rise in GMST). Note: The results have been corrected for the bias arising from incomplete ensemble membership under a 4°C rise (as set out in Appendix C).

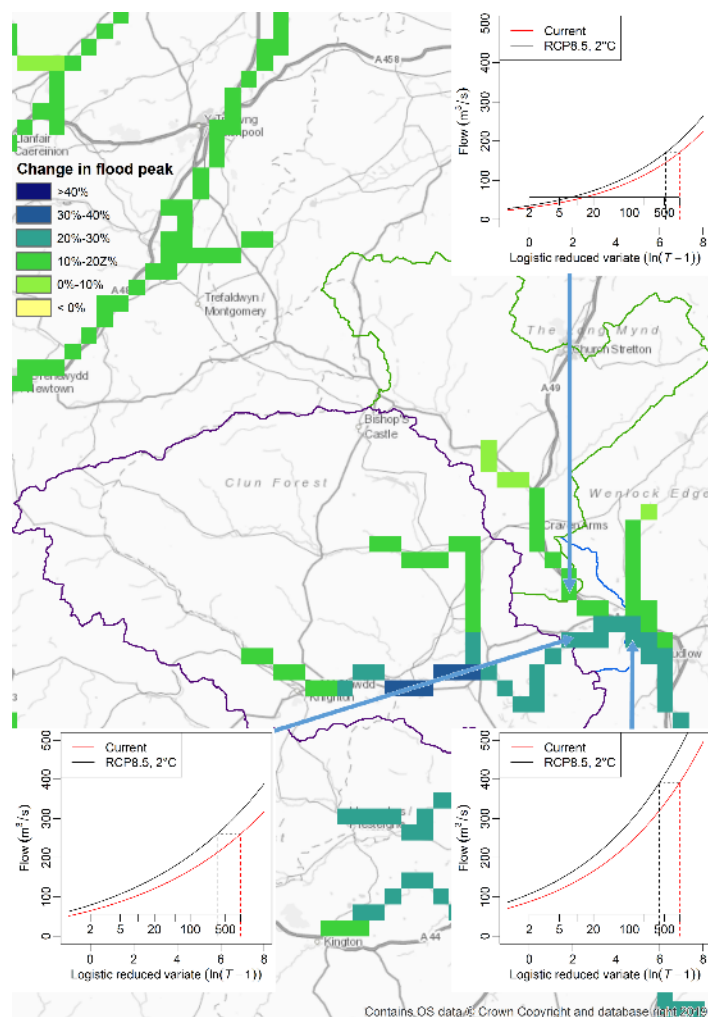
Extrapolation to extreme storms: It should be recognized however that FEH Vol.1 (Reed 1999) states that the statistical method is intended principally for use for return periods between 2 and 200 years, and thus the higher return period estimates should be used with caution, especially as the average length of record of the NRFA Peak Flow data is only 42 years. However, the FEH statistical method has previously been used for return periods of up to 1000 years in flood mapping studies (EA 2015) and the use of a single estimation procedure across the full range of frequencies was considered to provide consistency.

Increased spatial resolution in comparison to CCRA2: In the CCRA2 regional growth curves were taken from the Flood Studies Report (NERC, 1975). CCRA3 significantly improves upon this by using the latest analytical methods set out in the FEH and applied at each 1km grid point in Great Britain where percentage changes in peak flows are estimated. This enables a change in return period of the water level to be associated with a range of percentage changes in peak flows at a very high spatial resolution (capturing local response features simply missed in CCRA2).

Table 5-3 Fluvial flooding: Relating percentage changes in peak flow to changes in return period

ID: 30243	Current Return Period (years)					
	2	10	50	100	200	1000
	Revised return period (years) given a change in peak flow					
-20%	4.8	33	173	346	690	3419
-10%	2.9	18	90	180	359	1788
-5%	2.4	13	67	133	266	1327
0%	2	10	50	100	200	1000
5%	1.7	7.8	38	76	152	764
10%	1.6	6.2	30	59	118	590
20%	1.3	4.1	18	36	72	364
30%	1.2	2.9	12	23	46	233
40%	1.1	2.2	8.1	16	31	154
50%	1.1	1.8	5.8	11	21	105

In this example a 10% increase in peak flow (+10%) would reduce the return period of a present-day 1:100-year flow to 1:59 years.



Example flood frequency plots for three nearby locations with differently shaped baseline curves, showing how different changes in return period can result from different changes in flow peak, especially for the baseline 1000-year return period flood.

Figure 5-7 Local physical geographies have a significant influence on changes in flood flows under climate change

Surface water flooding: Changes in short duration rainfall

Assessing changes in intense rainfall (<6 hours duration)

Surface water flooding primarily responds to intense short duration rainfall (defined here as sub-daily rainfall of less than 6 hours duration). It has long been known that climate models are relatively poor at simulating short duration precipitation extremes (Flato *et al.*, 2013, Chan *et al.*, 2014a; Fowler and Ekström, 2009, Kendon *et al.*, 2014). This is primarily due to the relatively coarse resolution of climate models to date and their inability to capture important processes, such as convection. Recent developments in kilometre-scale climate modelling is however, for the first-time, promising credible projections of changes in sub-daily rainfall (Kendon *et al.* 2014, Kendon *et al.* 2019). The reliability of such estimates is yet to be fully explored but they generally support the underlying principle of the Clausius–Clapeyron relationship (that predicts an increase in the water holding capacity of air of approximately 7% per degree Celsius rise in temperature) and associated empirical evidence that demonstrates temperature change is a significant driver of changes in rainfall intensity (Dale *et al.*, 2015).

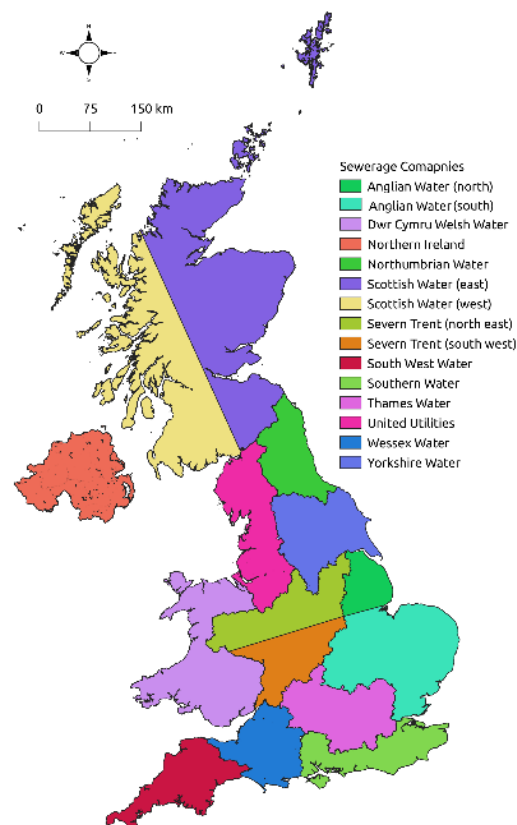
These finer-grid models remain in their infancy and data from the Met Office UKCP 2.2km climate model (Kendon *et al.*, 2019) is yet to be fully mined (although studies are progressing – see note below). It is therefore necessary to use non-UKCP18 based estimates of change here, including the Environment Agency guidance on climate allowances (Environment Agency, 2016 based on UKCP09 and its well-known inability to represent convective storms that drive intense rainfall) and the more recent estimates within Dale *et al.*, 2017 (based on 1.5km a pre-cursor to the 2.2km UKCP18 short duration rainfall projections, Kendon *et al.*, 2014). In bringing together these two sources of evidence, the generally lower estimates within the Environment Agency guidance have been used to moderate the generally higher projections of change in Dale *et al.*, 2017 have been applied to the Sewerage Undertaker boundaries (Table 5-4).

Note:

Uplifts in intense rainfall are assumed constant across return periods: In the absence of additional information it is assumed credible to use a single uplift value across all return periods of intense rainfall at a given location. This assumption should be revised as new analysis of the 2.2km results emerges.

Table 5-4 Surface water flooding: Percentage changes in intense rainfall of < 6 hours duration)

Duration < 6 hours	2050s		2080s	
GMST by 2100:	2	4	2	4
Water company				
North west				
Scottish Water (west)	30	40	40	60
United Utilities	30	40	40	60
Northern Ireland	30	40	40	60
North east				
Northumbrian Water	20	30	35	53
Anglian Water (north)	20	30	35	53
Severn Trent (north east)	20	30	35	53
Scottish Water (east)	20	30	35	53
Yorkshire Water	20	30	35	53
South west				
Dwr Cymru Welsh Water	15	23	25	43
South West Water	15	23	25	43
Wessex Water	15	23	25	43
Severn Trent (south west)	15	23	25	43
South east				
Thames Water	15	23	25	43
Southern Water	15	23	25	43
Anglian Water (south)	15	23	25	43



Note: Changes are relative to present-day although an absolute baseline amount cannot be given

Source: Table - Sayers - developed based on discussions with Dale, Fowler and Kendon. Map: Sewerage Undertaker boundaries (subdivided here by rainfall region) after Dale *et al.*, 2017:

Assessing the impact on surface water run-off

Surface water flooding is not only affected by changes in rainfall but is also influenced by drainage. The climate change influence on short-duration rainfall is therefore processed through a simplified rainfall-runoff relationship (Sayers *et al.*, 2015) to produce a change in the runoff-frequency curve (in rural and urban settings). In doing so, this process takes account of the assumed capacity of the conventional piped drainage network (assumed to be 12mm/hr today and future variations in development and adaptation) to yield the effective influence of climate change on surface water run-off.

Note:

Further analysis: The Met Office / NERC have recently supported an extremes analysis of the UKCP18 2.2km outputs (Future Drainage studies, a consortium led by Newcastle University). The outputs from this analysis should improve the estimates of changes in intense rainfall used here and should be readily updated in the FFE. Once the updated rainfall data is published it would be straightforward to assess the impact on risk.

Level of confidence: Uncertainty in intense rainfall estimates is considered significantly higher than uncertainty in either peak fluvial flows or sea level rise.

Comparison with CCRA2: CCRA3 uses an update to the same analysis used in CCRA2 based on additional detail from the Met Office 1.5km (UKCP18 pilot) model as published in Dale *et al.*, 2017. The uplift factors used here are in general higher than those used in the CCRA2 under a 2°C future and similar under a 4°C future; with the CCRA2 using single values across the UK of +20% and +50% under a 2°C and 4°C future in the 2080s – see Sayers *et al.*, 2015 – Appendix C Table C3-1.

Groundwater flooding

Groundwater levels are governed by the amount and timing of groundwater discharge, use and recharge. Assuming no change in use (outside the focus of this study), groundwater levels are considered to respond to changes in recharge which is in turn a function of rainfall and evapotranspiration. The relationship between rainfall and groundwater recharge is non-linear because soil moisture deficits need to be satisfied before recharge can take place, and the properties of soil and rock constrain the volume of water that can recharge in each period. These relationships drive a seasonal groundwater response, with recharge typically greatest in the winter months when evapotranspiration is low.

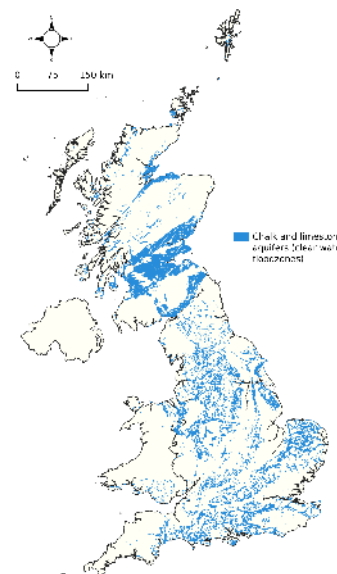
The projections of groundwater levels used here are based on the Futureflows projects (Jackson *et al.*, 2011) and are the same as used in CCRA2 (Sayers *et al.*, 2015). The likelihood of extreme groundwater events is a complex function of climate change, reflecting not only changes in annual rainfall and evapotranspiration, but the seasonality of rainfall, rainfall intensity and temperature, as well as aquifer characteristics and land cover. The analysis undertaken by BGS as part of CCRA2 enables the impacts of climate change on three forms of groundwater flooding to be considered, including: (i) *Clearwater flooding* (from Chalk or Limestone aquifers); (ii) *Clearwater flooding* (from other aquifers); and (iii) flooding from *Permeable Superficial Deposits (PSD)* (where groundwater and fluvial systems are well linked). The areas susceptible to these different types of groundwater flooding are presented in Sayers *et al.*, 2015. In areas subject to clearwater flooding the influence of climate change on susceptibility to groundwater flooding is taken from the Futureflows (Jackson *et al.*, 2011) as reported in CCRA2 (Table 5-5).

Table 5-5 Groundwater: Influence of climate change on the frequency of clearwater flooding

			Change factors					
			2020		2050		2080	
			2°C	4°C	2°C	4°C	2°C	4°C
Region	Baseline recurrence (years)							
Chalk North Downs + Kent	30		1	1	1.2	0.3	1.3	0.5
Chalk South Downs	20		0.8	1.1	1.8	1	2	1.9
Chalk Wessex	15		1	1	1.5	0.9	1.6	1.5
Chalk Berks/Bucks	25		0.9	0.8	1.2	0.6	1.2	0.7
Chalk East Anglia	50		0.5	0.6	0.6	0.2	1.3	0.3
Jurassic Yorkshire	25		0.7	1	0.8	0.8	1	0.4
Jurassic South	25		0.7	0.7	1.2	1	1.5	1.1
Chalk Yorkshire	30		0.6	0.9	0.7	0.5	1	0.5
Chalk Lincolnshire	40		0.6	0.9	0.7	0.6	1.2	0.5
Chalk Hampshire	20		0.8	0.7	1.2	0.7	1.5	1.2
Non Chalk/Lst CWF	50		1.2	0.8	1.2	1	1.5	0.9

Source: CCRA2 Sayers *et al.*, 2015 Appendix D, Table D3

Left: Map of Clearwater groundwater flood zones (BGS in CCRA2, Sayers *et al.*, 2015)



Note:

Comparison with CCRA2: No change has been made to the underlying groundwater analysis between CCRA2 and CCRA3.

6.0 ADAPTATION MEASURES AND ALTERNATIVE ADAPTATION PORTFOLIOS

6.1 Overview

It is widely recognised that flood risk is best managed through a portfolio of measures implemented through a continuous process of adjustment (e.g. Evans et al 2004a&b, Sayers *et al.*, 2014). The need for a ‘portfolio of responses’ is reflected in much of the UK flood risk management and the policies that influence its delivery (e.g. Delivering Sustainable Flood Risk Management (Scottish Government, 2019); Well-being of Future Generations (Wales) Act 2015, the 25 Year Environment Plan (HM Government, 2018)). Defra’s second National Adaptation Programme 2018-2023 (Defra, 2018)) and similar national adaptation plans in each Devolved Administration also reflect a focus on ‘portfolios’. CCRA2 reinforced this concept and promoted the need for an ‘enhanced whole system’ approach to adaptation (Sayers *et al.*, 2015); a finding echoed in the Environment Agency’s Long-Term Investment Scenarios (LTIS, Environment Agency, 2019) and a direction of travel likely to be reinforced in the Environment Agency’s new Flood and Coastal Erosion Risk Management Strategy (not published at the time of writing) and in the Welsh Government’s National FCERM Strategy for Wales.

The portfolio approach is also reflected here. Nine individual Adaptation Measures (AMs) are considered that relate to the management of sources and pathways of flooding (hazard), and the exposure and vulnerability of a range of different receptors. The AMs are combined into three alternative Adaptation Portfolios (AP) that represent different levels of ambition. The APs, and AMs they are assumed to contain, are elaborated below.

6.2 Alternative adaptation portfolios

Three alternative Adaptation Portfolios (AP) are considered (Figure 6-1). Each represents a whole system approach that builds upon the CCRA2 (Sayers *et al.*, 2015). The guiding philosophy behind each AP reflects the CCRA3 Method and is discussed below.

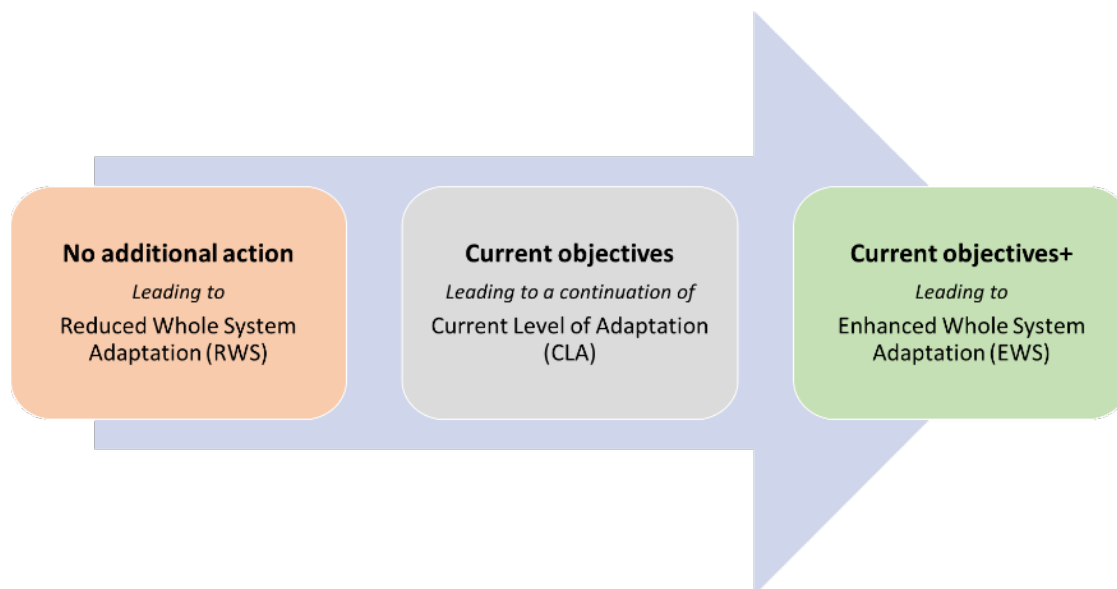


Figure 6-1 Three alternative Adaptation Portfolio scenarios

Note:

Adaptation to flooding crucially depends upon the degree to which policies are implemented: This implies that, rather than the policy objectives simply being adopted, the degree to which such policies promote long term resilience reflects the process of implementation. For example, across the UK, policies exist to limit floodplain development, but the policies recognise broader local issues that may mean further development is, on balance, appropriate

No additional action: Leading to Reduced Whole System (RWS) Adaptation

The baseline policy is one of ‘*no additional action*’. In the context of flooding, this does not mean taking no further action to maintain or improve flood defences for example or to assume that existing defence standards are maintained at present-day levels in all locations in all climate futures. Instead the ‘no additional action’ baseline assumes adaptation to flood risk continues but implementation is in-line with a **lower level of ambition** (as described for each AM in the following section). For example: investment in conventional defences fails to keep pace with climate change; there is limited take up of innovative catchment-based or urban run-off measures; pressure for development and economic growth lead to continued new development on the floodplain; receptor (property) level flood resilience (PFR) continues to experience limited take-up amongst existing properties. Flood forecasting and warning systems continue to be as effective in reducing risk as today. There are several plausible reasons that may lead to such a situation. Other threats may become increasingly dominant in public funded priorities (translating to a reduction in the willingness to pay for flood risk management) or our collective capacity to promote and deliver flood risk management may wane as political and social capital is directed towards other priority issues. We provide this scenario to provide a baseline counterfactual for future risk against which we measure the effects of additional adaptation.

Current objectives: Leading to a continuation of Current Levels of Adaptation (CLA)

The ‘*current objectives*’ policy response used here assumes flood risk management policies continue to be implemented as in the recent past whilst taking on board anticipated changes that are likely to result from recent changes in policy. For example, the influence of new and emerging policy frameworks such as the 25 Year Environment Plan and the National Planning Policy Framework (in England), the most recent consultation draft of the revised TAN15³ guidance in Wales and similar documents in Scotland, National Planning Framework No. 4⁴. All of these and similar plans, guidance and strategies are likely to encourage a longer-term perspective. They are also likely to encourage greater uptake of Natural Flood Management (NFM) and property flood resilience (PFR) measures than achieved in recent years. The influence of assessments such as the Long-Term Investment Scenarios (LTIS - Environment Agency, 2019) also encourage greater investment in FRM (and in the short term are consistent with the announcement in the 2020 Budget for additional funding for flood risk management in response to the widespread flooding in Winter 2019/20). The precise value of overall investment is difficult to determine, but Defra expect it to be at least £1 billion per year for England (as recommended from LTIS).

Current Objectives+: Leading to an Enhanced Whole System adaptation (EWS)

The ‘*current objectives+*’ scenario goes beyond the current implementation of policy (and recently introduced policy) to represent an ‘Enhanced Whole System’ (EWS) approach to adaptation (i.e. implementation is in-line with the **higher level of ambition** described for each AM below). For example, investment in flood defence increases (including in more socially disadvantaged neighbourhoods) and land use planning policy is more successful in restricting development in the floodplain than currently achieved or anticipated. Awareness raising and a strengthening of building regulations and planning controls encourage greater receptor level resilience. Forecasting and warning systems develop with increased levels of sophistication, targeting those at risk more accurately than has been possible to date. Opportunities for more integrated planning and implementation are sought (e.g. as presented for England in the 25 Year Environment Plan and the National Planning Policy Framework, MHCLG, 2019), Planning Policy Wales (WG, 2018) and, together

³ <https://gov.wales/technical-advice-note-15-development-flooding-and-coastal-erosion>

⁴ <https://www.transformingplanning.scot/national-planning-framework/>

with increasing momentum towards a ‘net zero’ emissions future, nature-based solutions are increasingly promoted and greater resilience delivered (e.g. as promoted within the National Infrastructure Assessment, 2018).

6.3 Individual Adaptation Measures

Nine individual Adaptation Measures (AMs) that address the three components of risk (set out earlier in Chapter 4) are considered. Three levels of implementation are considered for each:

- **Lower level ambition:** assuming the measure is implemented **less** effectively than in the recent past (used to create the Reduced Whole System (RWS) adaptation future).
- **Current level of ambition:** assuming the measure **continues** to be implemented as effectively as experienced in the recent past (used to create the Current Level of Adaptation (CLA) future).
- **Higher level of ambition:** assuming the measure is implemented **more** effectively than in the recent past (used to create the ‘Enhanced Whole System (EWS) adaptation future).

The FFE enables the implementation and effectiveness of each AM to be differentiated by its context. For example, both existing and new flood defences standards vary by the type of settlement they protect; the effectiveness of natural flood management reflects the scale of the opportunity to implement such measures within the catchment; urban drainage capacity can be varied by wastewater company; spatial planning by local authority; and the uptake of property level resilience measures, the ability to respond to flood warning and access to affordable insurance at Census Calculation Area scale.

The settings used for each AM under each level of ambition are summarized in Table 6-1 and discussed below (with further detail provided in Appendix D). The notes below give some important context to the table for those unable to read the additional detail.

Note:

Representation of adaptation across the UK: A consistent representation of each measure is used throughout the UK unless there is compelling evidence to do otherwise (e.g., in recent years the take-up of flood warning services has been more widespread in England than in Scotland and in Scotland proportionally fewer properties are built on the floodplain).

The importance of governance: Governance is considered as an enabling environment, with good governance a prerequisite for successfully achieving the higher levels of adaptation set out here. Governance itself is not considered to impact risk directly but through the AMs and therefore is not included in Table 6-1.

Shoreline management: Shoreline management is considered only from the perspective of limiting the impact of SLR on the standard of protection afforded by the coastal defences. No consideration is given here to issues associated with the relocation of communities or the benefits managed realignment affords to nature.

Urban management: Estimates of SUDS take up represent implementation and are therefore lower than the % of planning conditions that require SUDS. This reflects the lack of implementation in some cases and the influence of various developments that are typically outside of planning conditions (e.g. small single dwelling, extensions etc.).

Spatial planning: The values shown here are national averages; where data exist, information on recent development at a local authority scale are used (see more detailed discussion later in this chapter)

Insurance: This lever is applied to residential properties only and impacts the value of Relative Economic Pain (REP).

Table 6-1 Summary of individual adaptation measures

	Defences	Shoreline management	Catchment management	Urban management	Spatial planning	Property flood resilience (PFR)	Forecasting and warning	Insurance
Reduced Whole System	Protection standards fail to keep pace with climate change and reduce from present-day to 75% of their existing standards. Where present-day standards are very low (<1in25years) they reduce further. Where present-day standards are very high (>1in500 years) these are maintained.	Shoreline management policies remain largely unchanged from today with little active realignment of the coast.	NFM plays a more limited role than it does today as other land use priorities take precedence (such as pressures on food security). NFM potential is assumed to be constrained, with only 10% BMV Class 2 and 15% of BMV Class 3 contributing to NFM (where potential exists) by the 2080s.	Retrofitting of SUDS in existing urban areas stops and implementation in new development drops to ~30% (around half the rate of take up today). Conventional drainage capacities also reduce (to 10mm/hr).	The proportion of new development built in the fluvial and coastal floodplains increases (to an average of 9% in Scotland and 15% elsewhere). Development in the most socially vulnerable neighbourhoods remains 1.5 percentage points higher than elsewhere.	<i>Existing households:</i> Take-up is limited (reaching only 5% by 2080s). <i>New development:</i> Planning regulations are less effective, and only 50% are flood resilient. Limited take-up by non-residential properties and infrastructure providers outside of fluvial and coastal floodplains exposed to frequent flooding continues. Take-up in significant risk areas and amongst Cat A providers continues to grow but slowly – reaching ~30% by 2080s.	Differences are relatively narrow (compared to other measures) across the adaptation portfolios. This reflects the significant advances over the past 50 years and the more evolutionary advances expected in the future (reflects behavioural constraints as well as technologies ones). By the 2080s between 77-87% of properties in coastal areas successfully receiving and acting upon a warning compared to 53-60% in fluvial areas and 13-15% in surface water flood prone areas by 2080s under the three portfolios.	After Flood Re ends in 2039 insurance penetration reduces significantly from the today – dropping from around 75% today to 53% from the 2050s. In the most socially vulnerable neighbourhoods the reduction is from ~40% today to ~30% from the 2050s.
Current Level of Adaptation	Protection standards continue to be maintained where the present-day standards are high (typically more than 1in75 years). Elsewhere standards fall with climate change to 75% of their present-day value before action is taken. Where present-day standards are >1in100 years these are maintained.	Some realignment takes place through the implementation of 'no active intervention' and 'realignment' policies. This helps limit the impact of sea level rise on coastal overtopping (although the impact on defence standards is small).	In the short term NFM implementation remains limited to pilot locations and a small number of frontrunner locations. These provide evidence for further projects, but implementation for the full potential of NFM remains limited (with 20% BMV 2 and 30% BMV 3 contributing by the 2080s)	Retrofitting of SUDS continues in a limited way (~5% by area). The incorporation of SUDS in new developments remains high in Wales and Scotland (~70%) with less take-up in England and Northern Ireland (~50%). Conventional drainage capacities are maintained (at 12mm/hr).	The proportion of new development built in the fluvial and coastal floodplains continues as today (i.e. an average of 6% in Scotland and 12% elsewhere and slightly higher in the most socially vulnerable neighbourhoods).	<i>Existing households:</i> Take-up continues to grow slowly reaching 20% by 2080s). <i>New development:</i> Planning regulations are effective in ensuring 80% are flood resilient. Take-up by non-residential properties and infrastructure providers continues to grow reaching 50% by 2080s in fluvial and coastal floodplains exposed to frequent flooding. Take-up amongst Cat A providers continues to grow, to around 50% by 2080s.	In the most socially vulnerable neighbourhoods, the effectiveness of warning is much less – around half as effective in coastal and surface water areas. The differential is more marked in fluvial areas, around a fifth as effective.	Transitional arrangements are assumed to enable present-day penetration to continue in both adaptation portfolios. (~76% of properties exposed to flooding more frequently than 1in75 years assumed to have insurance). In the socially vulnerable locations penetration is assumed to remain around 40%.
Enhanced Whole system	In addition to the actions taken above, protection standards are raised to a minimum of 1in100 years in urban conurbations (major and minor). This includes building defences in currently undefended areas. A 1in75 year standard is maintained in urban and rural towns with highest standards of protection today.	Polices are largely implemented as set out within SMPs – including transitions to no active intervention and managed realignment; although the impact on standards remains limited.	The success of the pilot studies, a stronger evidence base, changes in land stewardship payment schemes and demand for NFM co-benefits (including in support of diversity and 'net zero' targets) drive an increase in the uptake of NFM potential (with 30% BMV 2 and 50% BMV 3 contributing by the 2080s).	The use of SUDS in both new and existing developments increases (to around 80% and 30% respectively by the 2080s – slightly more in Scotland and Wales). Conventional drainage capacities also increase in major urban areas (to 15mm/hr).	The proportion of new development built in the fluvial and coastal floodplains decreases (to an average of 3% in Scotland and 9% elsewhere by the 2050s). Differential development rates in socially vulnerable neighbourhoods also comes to end.	Compared to CLA, there is an increase in take-up amongst existing residential properties resulting in 95% of all new developments including flood resilient measures. Take-up in by non-residential properties and Cat A providers in areas at significant risk continues to grow but slowly – reaching ~60% by 2080s. In surface water flood prone areas take up by Cat A providers increases to ~40%.	The reduction in damage given action is assumed to be 14% in all cases. Although regional differences exist, common values are applied across the UK. For example, in Scotland take up is less than in England. This may be because in Scotland the process is based on 'opting in' and in England is based on 'opting out'.	

Coastal and river flood defence and control infrastructure

Overview of evidence

Protecting areas from river and coastal flooding by investing in flood defence infrastructure will continue to be an important response to flooding across the UK (Figure 6-2). In England, for example, ~70% of annual expenditure on flood risk management is associated with investing in new or managing existing flood defences (Sayers *et al.*, 2018). Various studies confirm that physical flood protection infrastructure (including flood walls, sea defences and embankments, demountable defences, or large scale storage, barriers as well as innovative approaches that may emerge) are likely to continue to play a significant (but not sufficient in order to keep risk constant) role in the future (*e.g.* Evans *et al.*, 2004a, b; Sayers *et al.*, 2015a, NIC, 2018 and Environment Agency, 2019).

It is assumed here that present-day protection standards indicate the strength of the case for investment. This implies that where higher standards exist, the standard is maintained into the future. In urban areas this assumption is reasonable as the increase in the benefits accrued by protection is likely to keep pace with the additional costs of raising and maintaining larger defences (an assumption broadly supported by the findings of LTIS, Environment Agency, 2019 and NIC studies, Sayers *et al.*, 2018). Where low standards exist today the opposite is assumed, as the standard economic case for increased investment in flood defence infrastructure is weakest; as a result, present-day standards are generally assumed to fall. Although Scotland, Wales and Northern Ireland do not yet have published equivalents of the most recent version of LTIS, the inferences from the LTIS are assumed to apply across the UK.

Representation

Under a **current level of ambition**, it is assumed that protection standards and condition grades continue to be maintained where the present-day standards are high (typically more than 1in75 years). Elsewhere standards fall. A **higher level of ambition** sees defence standards maintained to a minimum of 1in100 years in urban conurbations (major and minor); including areas that are currently undefended. A **lower level of ambition** sees investment failing to keep pace with climate change and asset condition and standards of protection are assumed to reduce from present-day in all settings, excluding urban conurbations (major and minor).

Note:

The FFE has been significantly improved for CCRA3 compared to CCRA2. Primarily this includes significantly improved defence datasets in England and Wales (although gaps remain particularly in Scotland) and an improved ability to represent flood defences adaptation. CCRA3 however continues to adopt a scenario approach rather than a benefit cost assumption to investment in defences.

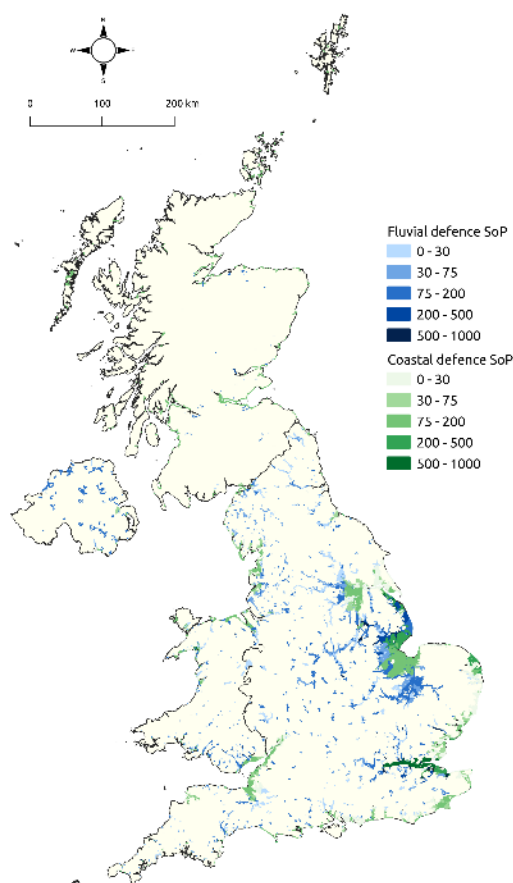


Figure 6-2 Present-day representative defence standards of protection (rSOP, years)

Shoreline management

Overview of evidence

Around half of all sea defences in England are protected against the full forces of waves and storm surges by coastal habitats (CCC, 2013); a finding that is assumed to be reflected across the UK. As sea levels rise, in some places beaches and coastal habitats will reduce in width as they are squeezed between fixed backshore structures and the high-water mark (so-called ‘coastal squeeze’). Shoreline Management Plans (SMPs) across England and Wales (Figure 6-3) provide some recognition of this and promote a ‘Managed Realignment’ policy for around 9 percent of the coastline by 2030, rising to 14 percent by 2060 (CCC, 2013) – although the local drivers for, and definition of, MR can vary (as elaborated in the note below). The current rate of managed realignment since 2000 (in England with only 2% by length implemented to date) would need to increase five-fold (to around 30km a year) for this to be achieved. In England, the Environment Agency are working with Local Authorities to refresh Shoreline Management Plans; this may lead to revised policies and may accelerate this process. Analysis by Sayers, 2018 for the CCC suggest that for some locations where ‘hold the line’ is the current policy, the economic case for longer term protection is low (of those that anticipate major investment in shoreline management - greater than £25m Present Value - between 130-150km may not be cost effective to implement, achieving a BCR less than 1). Although it is recognized that national cost effectiveness is not necessarily the overriding criteria, or national funding the only source of support, the inference from this is that significant areas currently operating under a ‘Hold the Line’ policy may need to be realigned (see note below). Little is planned in Northern Ireland or Scotland where few SMPs exist.

This highlights that transitioning from maintaining the present-day shoreline (so called ‘hold-the-line’ in the SMPs) to a realigned coast presents significant social justice issues; a challenge exemplified through the ongoing discussions regarding the future of Fairbourne, Wales.

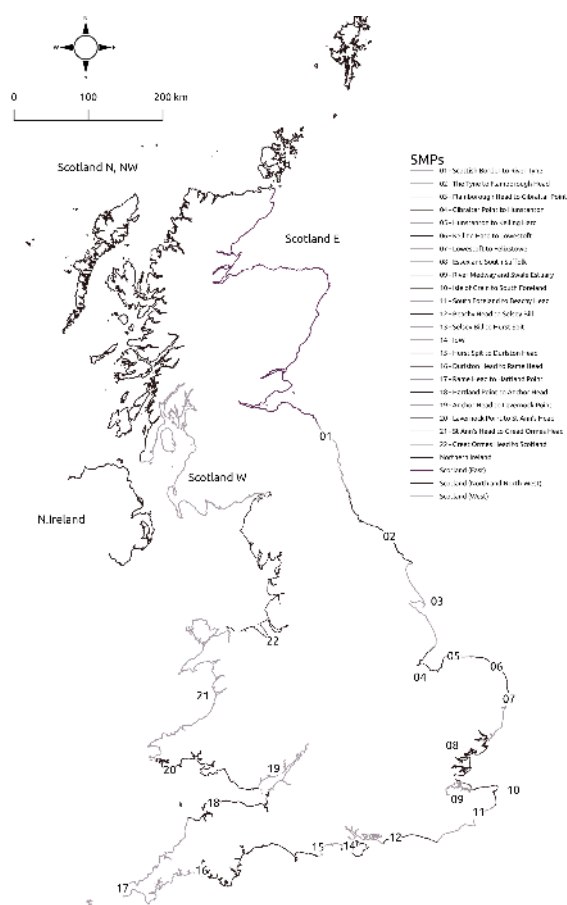
Representation

Under the **current level of ambition** realignment continues to be limited, with only 5% of frontages designed as MR within SMPs implemented by the 2020s rising to 40% by 2080s. This is based on an analysis of SMP policies in England (CCC, 2018, Sayers, 2018) and by inference elsewhere. A **higher level of ambition** sees these issues resolved and policies largely implemented as set out within shoreline plans (facilitated, for example, by changes to compensation rules, or through other means). A **lower level of ambition** sees MR become more difficult and little realignment is achieved (as in the recent past).

More detail on the representation of this measure within the FFE is given in Appendix D.

Note:

Shoreline management policies in England and Wales: What is meant by the policies of ‘Managed Realignment, MR’, ‘Hold the Line, HtL’, ‘No active intervention, NAI’ and ‘Advance the line, AtL’ will always be context specific and locally interpreted. In some locations, for example, MR may be motivated by habitat creation and in others by cost considerations that involve a significant movement in shoreline position, in other areas MR may be policy but reflect relatively minor modification to the shoreline. Here, the policy of MR is used as proxy for a significant change in the shoreline geomorphological processes that implies additional adaptation.



Source: Aggregations of England and Wales, Shoreline Management Plans, Scotland, Dynamic Coast

Figure 6-3 Shoreline regional definitions

Catchment management

Overview of evidence

Catchment management is used to refer to the measures to slow the flood flows through the catchment. Often referred to as Natural Flood Management (NFM) or Working with Natural Processes (WwNP), such approaches are increasingly recognised as a legitimate supporting measure in FRM (capable of delivering multiple outcomes). Indeed, NFM practices (including upland storage, the management of run-off from agriculture, floodplain/river restoration, and tree planting) are now widely promoted in guidance (e.g. Environment Agency, 2010; 2014, Sayers *et al.*, 2014, Rivers Agency, 2008; Forbes *et al.*, 2015) and policy initiatives (e.g. EU Floods Directive 2007, Scotland's Flood Risk Management Act 2009, Welsh Government's Natural Resources policy call for greater use of nature-based solutions, and England's 25 Year Environment Plan, Defra, 2018). All recognize the important role NFM will play in delivering FRM as well as biodiversity net gain. Internationally the role of natural infrastructure as a legitimate component of FRM is also increasingly promoted (e.g. Sayers and Smith, 2018; Bridges *et al.*, 2018; Sayers *et al.*, in press).

The desire to promote NFM (and the multiple benefits it provides beyond managing flood flows) has not yet been matched by implementation. In part, this is due to the lack of scientific evidence regarding the performance of NFM measures, particularly during more extreme flood events and at larger scales, in addition to a lack of understanding of how their performance may change over time (e.g. Sayers *et al.*, 2014; Dadson *et al.*, 2017; Kay *et al.*, 2019). Further evidence and experience is however being gathered. For example, the Environment Agency commissioned a Literature Review and Evidence Directory and systematic reviews of performance are emerging (for example, on the effect of trees on floods, Stratford *et al.*, 2017). Significant research is currently underway to improve this evidence base funded by NERC (e.g. LANDWISE, Q-NFM and PROTECT-NFM). Experience is also being gained through practical actions studies (e.g. Dadson *et al.*, 2017, Black *et al.*, 2018) and in Scotland the Scottish NFM network has been established to share knowledge and best practice. Defra have provided support funding for further NFM pilots to encourage take-up and similarly Welsh Government (WG) have announced funding to deliver NFM and catchment management schemes in Wales. NFM opportunity maps continue to mature (e.g. NFM opportunity maps in Scotland were first produced in 2013 followed by the Environment Agency NFM strategic maps in 2016 – covering England and Wales - with similar mapping studies more recently in Northern Ireland). These advances will continue to help make the case for NFM.

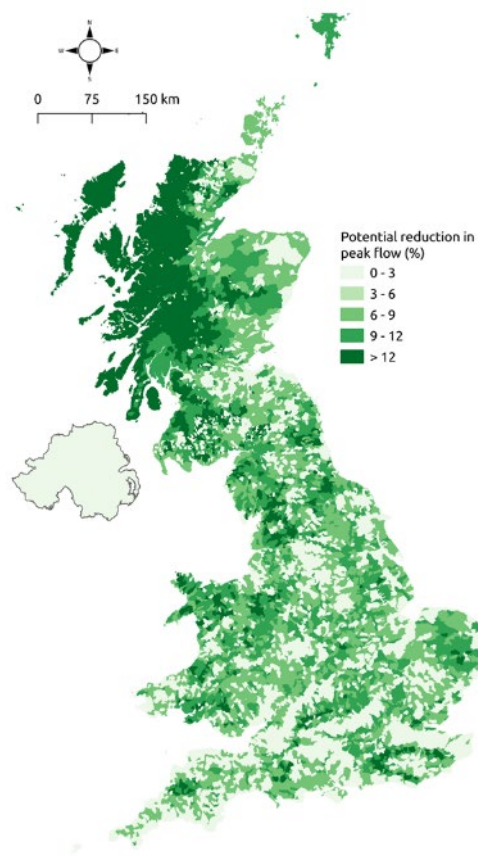
Representation

The **current level of ambition** sees NFM implementation remain limited. The emerging Environmental Land Management (ELM) incentives in England and similar schemes elsewhere, may make it easier to pay land managers for environmental outcomes. These developments are assumed in this report to promote the implementation of NFM beyond flood management and lead to greater take up under a **higher level of ambition** (delivering multiple biodiversity and well-being benefits alongside flow management). The impact of this higher level of ambition is illustrated in Figure 6-4. Conversely, a **lower level of ambition** may see NFM play a more limited role than it does today (reflecting for example, other priorities such as pressures on food security).

More detail on the representation of this measure within the FFE is given in Appendix D.

Note:

CCRA3 significantly improves the representation of catchment management compared to CCRA2. The approach extends the method recently developed for National Infrastructure Assessment (Sayers *et al.*, 2018). The confidence in the performance of NFM measures to reduce downstream flood flows remains however an area of active research. An improved understanding is expected in coming years as three on-going NERC programmes develop new evidence. This does not imply a lack of confidence in catchment measures – they are accepted as beneficial – but it remains difficult to determine by how much.



Source: Sayers and Partners (based on various sources of opportunity including analysis by JBA Trust for England and Wales). The combined impact of woodland and surface storage features on flood flows assuming a higher level of adaptation. It has not been possible to include the available data for Northern Ireland as part of this project and values in NI are assumed to be an average of the GB values.

Figure 6-4 Natural flood management – Percentage reduction in peak flow (1in10 year return period)

Urban management

Overview of evidence

Widespread flooding across England in 2007 damaged 55,000 properties, with significant damage resulting from drains and sewers being overwhelmed by heavy rain (Environment Agency, 2007). This event, and many surface water flood events since, highlight that lack of capacity within conventional piped sewer systems, particularly those in dense urban areas. This observation is supported by an RSPB, 2014 study that concluded half of the national sewer network in England is at capacity (RSPB, 2014); a finding echoed in UKWIR, 2018 (Understanding drainage capacity for the 21st Century, UKWIR 2018). UKWIR have also suggested that investment in the maintenance of sewerage assets in England and Wales is currently only one sixth of the required level to keep the assets functioning (UKWIR, 2017). Through projects such as the Thames Tideway⁵, significant investments are being made. Increasingly however a range of responses are used to complement conventional piped networks. In recent years this has focused on slowing down and storing flood water in urban areas through the promotion of Sustainable Urban Drainage Systems (SUDS).

⁵ <https://www.tideway.london>

For new development, Schedule 3 of the Flood and Water Management Act 2010 in Wales requires local authorities to either adopt a SUDS scheme or agree a long-term maintenance strategy via a management company. This enables developers to incorporate SUDS without necessarily taking on the long-term maintenance commitment – a significant barrier previously. In Scotland, preference is also given to the use of SUDS in new development over conventional piped infrastructure^{6,7}. In both cases emphasis is given to multiple functional SUDS schemes (i.e. approaches that deliver biodiversity, health, and other benefits alongside flood benefits). Authorities in England and Northern Ireland agree implementation of SUDS locally; a process that often defaults to agreeing readily delivered mono-functional run-off and storage flood benefits rather than multi-functional SUDS that are central to the broader concepts of SUDS. The National (England) Planning Policy Framework (NPPF, Ministry of Housing, Communities and Local Government, 2019) was significantly strengthened in July 2018 however to improve the focus on the multifunctional benefits of SUDS as part of any development. Coupled with publication of the 25-Year Environment Plan and the stated aim of net biodiversity gain, Local Authorities will increasingly be required to prioritize multi-functional SUDS where possible (given space, geological constraints) and discourage adopting mono-functional approaches that have limited environment benefits (such as geo-cellular storage or urban tanks, Melville-Shreeve *et al.*, 2018).

Retrofitting SUDS into existing development also remains limited across the UK but examples are emerging and programmes are being promoted (such as the RainScape initiatives in Wales⁸). In part this is because of perceived costs but also the lack of priority given to mainstreaming the opportunity for multiple benefits that well-considered retrofitted SUDS schemes deliver. It may also be because water companies have little incentive to seek multi-benefits embedded with their business models (that are typically driven by conventional asset inventories, Ashley *et al.*, *in press*). It is argued that this lack of incentive means it remains difficult to achieve cost-shared multiple benefit outcomes.

Surface water management in urban areas also has macro-planning dimensions. Building on the contemporary Garden City approaches promoted in the 1960s and before, some examples of integrated planning are returning today; for example the development of preferential flood routes through the urban landscape and the creation of ephemeral urban storage areas, for example as London's River Quaggy to the City of Dordrecht, Gersonius *et al.*, 2016.

Representation

The **current level of ambition** sees conventional drainage capacities unchanged (assumed to be 12mm/hr⁹) and the take-up of SUDS within new development continuing at around 50% (England), higher in Scotland and Wales less in Northern Ireland. Retrofit is less, at around 5% (by area)¹⁰.

Higher level of ambition increases the take-up of SUDS in response to greater integration of planning and investment resources and the incentive for delivering net biodiversity gain. Conventional drainage capacity is also improved in major urban settlements, increasing to 15mm/hr by the 2080s. With a **lower level of ambition** take-up of SUDS reduces (due to less controlled

⁶ https://www.climatexchange.org.uk/media/3239/sustainable_urban_drainage_systems_in_scotland.pdf

⁷ <https://www.susdrain.org/delivering-suds/using-suds/adoption-and-maintenance-of-suds/adoption/SuDS-adoption-in-Scotland.html>

⁸ <https://www.dwrcymru.com/en/My-Wastewater/RainScape.aspx>

⁹ As assumed within the Environment Agency surface water hazard mapping.

¹⁰ A review of the application and effectiveness of planning policy for SuDS in England since 2014 (Ministry of Housing, Communities and Local Government, 2018) found that almost 90% of sampled approved planning applications explicitly stated that 'SuDS would feature in the proposed development'. It is not known if these conditions were implemented or those implemented will be maintained over the coming century. It is also recognised that permitted developments (patios, driveways, extensions) are excluded from this process and unlikely to incorporate SUDS.

development) and the capacity of conventional drainage reduces (to 10mm/hr). Across all portfolios, other surface water management actions are assumed to reduce economic damages by around 5% in all but the most socially vulnerable neighbourhoods.

More detail on the representation of this measure within the FFE is given in Appendix D.

Note:

CCRA3 significantly improves the representation of urban flood management compared to CCRA2. The approach now includes the ability to vary conventional drainage capacity (for each wastewater company boundary) as well as continuing to reflect the impact of SUDS on run-off generation (in new and existing developments) and the potential to reduce damages through other urban management measures.

Spatial planning (development control)

Overview of evidence

Across the UK, planning authorities seek to avoid development in flood prone areas (England: National Planning Policy Framework (NPPF), Wales: TAN 15, Scotland: Online Planning Advice¹¹, Northern Ireland: SPPS 2015 and PPS15). For example, in England the Government's policy on planning and flood risk states that: *'inappropriate development in areas at risk of flooding should be avoided by directing development away from areas at highest risk (whether existing or future). Where development is necessary in such areas, the development should be made safe for its lifetime without increasing flood risk elsewhere.'* In Wales, revised planning policy is seeking more stringent measures and will advise that there should be no highly vulnerable development permitted in undefended flood zone 3 (1:100) plus climate change. In Scotland, the planning system is also undergoing a substantial review that may further strengthen these requirements¹². None of these policies avoid all development on the floodplain (an impractical and perhaps undesirable goal).

Around 21,000 homes were built in the floodplain (defined as Flood Zones 2 or 3) every year (on average) between 2001 and 2014 in England (CCC, 2015); with around 27 per cent of the development in the coastal and fluvial floodplains (68,000 new homes between 2001 and 2014) taking place in areas subject to flooding more frequently than 1-in-100-years (on average, assuming an absence of defences) and around 9 per cent (23,000) in areas subject to flooding more frequently than 1-in-30-years (on average, assuming an absence of defences). Reanalysis of this research (Environment Agency, 2019) provides insight into the spatial variation in these national figures. The results highlight a complex picture, with the proportion of new developments on the floodplain varying significantly across local authority areas. In Hull, for example, there is little opportunity to avoid development on the floodplain (with 95% of existing property lying on the floodplain and hence new development is inevitably built on the floodplain). There is no equivalent data in Scotland, but it is perceived to be similar across Local Authorities (with approximately 6% of new development build on the floodplain). Further analysis of these datasets for JRF (Sayers *et al.*, 2017) found a greater proportion of new development on the floodplain takes place in the most socially vulnerable communities (~1.5% greater) and determined how new developments have been distributed within flood risk probability bands (highlighting the majority is within the low probability areas). In Wales the Sustainable Development Indicators report the number of planning permissions for development in the floodplain granted and refused, but do not provide insight into the

¹¹ <http://www.gov.scot/Topics/Built-Environment/planning/Policy/Subject-Policies/natural-resilient-place/Flood-Drainage/Floodrisk-advice>

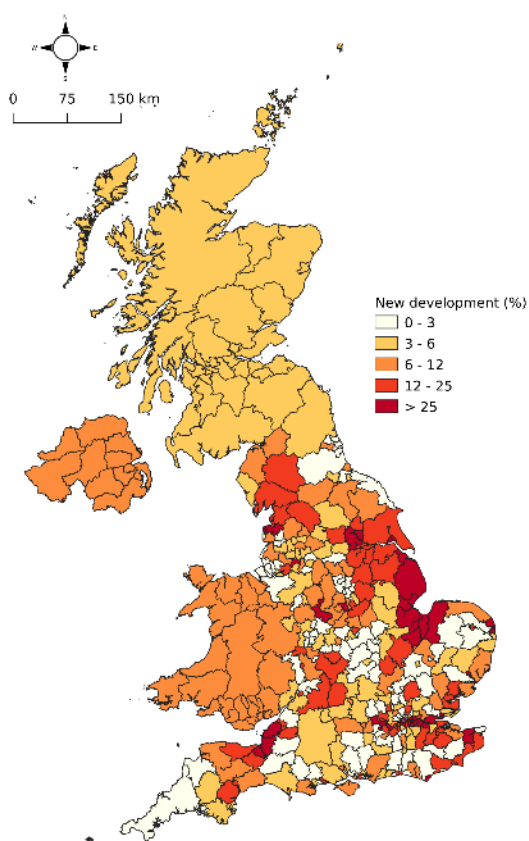
¹² <https://www.transformingplanning.scot/>

percentage of all development being built on the floodplain (see for example SD4 of the 'All Wales Planning Annual Performance Report 2017-18').

Representation

Under the **current level of ambition**, the percentage of new development built on the floodplain continues as in the recent past and varies across the UK as illustrated in **Error! Reference source not found..** Under the **lower level of ambition**, a greater proportion of the new development is built on the floodplain (assumed here to be 3 percentage points more than the current proportion of development). A **higher level of ambition** sees less development on the floodplain (3 percentage points less). This small differentiation reflects the long-lived nature of the existing planning rules that seek to limit floodplain development and hence significant variation from current level is unlikely. Where new development does take place on the floodplain it is assumed that building regulations and planning conditions (such as appropriately designed raised floor levels that continue to provide accessibility and safe egress) ensure flood damage to and from any new development is minimized. This aspect is covered under the receptor (property) level measures discussed later.

More detail on the representation of this measure within the FFE is given in Appendix D.



Source: Multiple - ASC, 2018; Environment Agency, 2019 and discussion with Scottish Government. In the absence of quantified data in Wales and Northern Ireland, the UK average has been assumed. It is however noted that lead authorities in both Wales and NI expect the number to be lower than the UK average.

Figure 6-5 Proportion of new development built on the floodplain in the recent past

Property flood resilience measures

Residential properties

Overview of evidence: Several policies encourage individual property owners to protect themselves and their property from flooding. The Environment Agency's Flood & Coastal Erosion Risk Management Strategy (Environment Agency, 2011) and Defra's partnership funding (Defra, 2011) policies, for example, encourage local communities to contribute towards their risk reduction, not least by implementing property flood resilience (PFR) measures. This is a theme that is expected to be reinforced with the Environment Agency updated FCERM Strategy. Equally, Welsh Government's (WG) National FCERM Strategy promotes property level resilience and similar efforts to promote PFR exist in Scotland (e.g. Living with Flooding Action Plan, Scottish Government 2019) and to a lesser extent Northern Ireland. Building Regulations have also been under review in recent years but the call for more significant changes in Building Regulations set out in the Pitt Review are yet to be fully responded to. Guidance to promote take-up is however maturing (and subsidies and grants are often made available for those in flood affected areas to be '*built back better*' (Lamond *et al.*, 2016, 2018a) and will be further encouraged in the coming years in response to the publication of the Industry Code of Practice (CIRIA, 2019) and the continued evolution of the British Standards (with the publication of BS 851188, 2019¹³) that updates the existing PAS 1188 for the testing of flood resistance products).

Property owners are often reluctant to implement risk-reducing measures (such as external flood gates, see Harries, 2008; 2012) and may be ill-equipped to ensure they are appropriately implemented. Because of this they are not effective in all cases so increasing implementation is not as straightforward as one might initially assume. Furthermore, some measures may only be cost-effective if the frequency of flood events is high (Defra, 2014a) and when the external flood depth is less than 600mm (Defra, 2007). Even given this limitation, effective floodwater exclusion can be hard to achieve unless there is attention to detail at the design and application stages. This may require ensuring neighbours act to prevent flood waters propagating through party walls and shared basement spaces. Estimating uptake and efficacy of such measures under the different future scenarios is therefore difficult (a difficulty exacerbated by the lack of national scale data). There is proxy data however, for example the Defra-funded assessment of the availability and affordability of insurance (Wiseman and Hughes, 2018) notes '*the proportions of households which have themselves installed the measures (as opposed to them being in place when they moved in to the property) have increased substantially since 2015 – for example, from 2% to 11% for wall sealing, from 1% to 9% for non-return valves*'. They also highlight the installation of resilience measures is much more frequent amongst households which have experienced flooding (ranging from 15% for flood doors to 21% for airbrick covers and flood gates and barriers). Equally the focus on 'flood recoverability' is growing – promoting the use of property elements that can be readily cleaned without lasting damage (even when depths exceed 600mm).

For new developments built on the coastal and fluvial floodplain it is highly likely that planning policy will require resilience measures to be included – to at least the 1in100 year event or in some locations higher (often achieved by raising property thresholds). For example, in Wales more stringent planning policies are used that include an allowance for climate change. In all cases however the decision to develop in flood prone areas is ultimately for the Local Planning Authority and associated building control. The presence of such planning requirements does not therefore mean they are implemented. A review by the CCC of a small sample of planning applications

¹³ <https://standardsdevelopment.bsigroup.com/projects/2018-00164#/section>

identified examples of non-compliance with such planning conditions. This suggests that actual take up is less than the near 100% of applications that receive such advice in England¹⁴ (for example). It is also the case that many properties that sit outside of the coast and fluvial floodplain would also benefit from measures however it is unlikely that planning authorities will impose such conditions.

Representation: Under the **current level of ambition** ~80% of new developments and ~5-10% of existing properties in high risk areas take up PFR measures. Under a **lower level of ambition** this reduces (by around half) and under a **higher level of ambition** take-up increases (by up to 15 percentage points to 95%).

Non-residential properties and infrastructure

Overview of evidence: The economy and society depend on a secure supply of services such as electricity, telecommunications, water, healthcare, and transport. Businesses rely on secure supply chains to continue to service their customers, and communities rely on businesses for local goods and services. Because of this interdependence, flooding that leads to infrastructure disruption not only impacts the business owners and the infrastructure providers, but also those that rely upon their services. Consequently, impacts can cascade and even escalate through supply chains and communities when water, wastewater, communications, transport, and power services are disrupted (as initially explored in LTIS, Environment Agency, 2019). Developing resilient infrastructure and businesses is widely recognised as the cornerstone of flood resilience (a conclusion reinforced by the National Resilience Review in the aftermath of the 2014/15 floods, HM Government, 2016). Businesses however remain responsible for their own flood resilience and there is emerging evidence that some are investing in resilience measures (where their flood risk is clear).

CCRA2 highlighted that Category A infrastructure providers (defined here as energy and water infrastructure) are increasingly recognising flooding as a business risk. CCRA2 also highlighted the importance of providing contingency plans and local protection to high risk sites. After widespread flooding in England in 2007, electricity transmission and distribution companies developed a sector-wide approach to investigating the vulnerability of their substations to river and coastal flood risk, from which a programme of site level protection measures was put in place with funding agreed by the regulator (Ofgem). As a result, there has been significant take-up of site protection measures that will continue during the current price control period (i.e. to 2023). Water providers have been less active in taking action to protect their assets than the electricity sector but are nonetheless assumed (for the purposes of this analysis) to have similar levels of property level measures. There is evidence to suggest some take-up of property level flood resilience measures by Category B infrastructure providers (defined here as emergency services, businesses, GP surgeries, roads, railways). For example, National Rail and NRW are starting to jointly identify opportunities for collaborative working in the future. It is however unlikely that more than a few percent of properties outside of areas exposed to a high probability of flooding will be protected. The evidence on the uptake of resilience measures by businesses is (very much more) limited.

Representation: Category A infrastructure (water and energy): Under the **current level of ambition** around 80% of infrastructure exposed to fluvial or coastal flooding will have implemented local measures by 2080s and 50% of those exposed to surface water only. Under a **lower level of ambition** this reduces (to 50% and 20% respectively). In a **higher level of ambition** future take-up increases (to 95% and 65%). **Category B infrastructure (all other):** Under each level of adaptation ambition, take-up by Cat B infrastructure providers is assumed to be half of that for residential properties (see previous section).

¹⁴<https://www.parliament.uk/business/publications/written-questions-answers-statements/written-question/Commons/2020-02-25/20551/>

Forecasting and warning

Overview of evidence

Providing actionable forecasts and warnings to communities is an essential component of flood risk management (e.g. Parker *et al.*, 2009; Parker *et al.*, 2011, Sayers *et al.*, 2014). Communities and individuals that are aware of risk and who receive trusted and meaningful flood warnings are better able to prepare for, and respond to, a flood (including taking damage-reducing actions and developing strategies to minimise the impact of the flood on their families and property). The ability to respond is therefore fundamentally affected by the timeliness of reliable warnings, the clarity of the message to act, and the ability of those involved to take action to help themselves or others.

Good forecasting and warning are necessary but not enough, and ultimately, it is the ability of people to respond to this information which makes the difference (Thrush *et al.*, 2005). Local authorities and agencies often have records of vulnerable people (such as older people with physical disabilities in receipt of care services) to help target assistance when a flood is imminent. Community networks (including informal and formal networks and “action groups”) also play a significant role in improving the response and recovery of the community (Walker *et al.*, 2010; Geaves and Penning-Rowsell, 2014). But the impact of such networks on individual’s experience of flooding is less clear, with Green (1995) finding that the extent and type of social support received by victims of flooding seemed to have no effect on the victims’ level of stress or amount of disruption from a flood event.

In England, the Environment Agency allocates spending on flood warning based on a Flood Warning Investment Strategy (Ball *et al.*, 2012). They conduct a ‘levels of service assessment’ to allocate funding priorities for flood warning according to location, thereby establishing target standards of quality for the service in each flood warning area. This assessment reflects the likelihood of flooding and impact, without any specific consideration being given to vulnerability (Andrzejewski *et al.*, 2005). In recent years there has been a significant expansion of flood warning systems that sends messages to the telephones of people in flood warning areas. SEPA provides a similar service in Scotland (although in Scotland current sign-up rates are significantly lower than those in England at around 16 per cent in coastal areas - although only provided in some areas - and 32 per cent in fluvial areas, as advised by SEPA). In Wales, Natural Resources Wales (NRW) have been responsible for flood warnings since April 2013 (Wales Audit Office, 2016). This is based on a managed service from the Environment Agency for access, maintenance, and improvements to the system. In Northern Ireland, the DfI(NI) have published maps of areas at high flood risk (Rivers Agency, undated) - as have other nations – but do not currently provided an automated warning service.

Representation

The effectiveness of forecasting and warning is applied consistently across the UK (despite known differences) and considers the reduction in damage reflecting multiple issues:

- **The take-up of warning services is greatest in coastal areas:** This reflects the heightened perception of risk (Parker, 1991; Parker *et al.*, 2007), the maturity of the flood warning system since it was implemented after the 1953 event and the forecasting challenge that may exist in rapid response catchments. Numerous events have been tracked since this time, and warnings to the communities affected have become better publicized and more targeted because of this experience.
- **Surface water flood forecasting:** Effective forecasting and warning of surface water flooding (capable of reducing direct damages) remains limited but efforts to improve this (by e.g. the Met Office, Environment Agency *etc.*) are under development.
- **The effectiveness, in terms of reduction in damage, increases with return period of the event:** It is assumed here that more extreme events are more foreseeable in terms of providing a longer lead time, and hence greater opportunity to act, that is typically associated with more

extreme events (Parker, 1991). It is a recognized simplification and may not be the case in rapid catchments. For example, the ability of warnings to reduce damage during flash flood events (e.g. in Boscastle in 2004) is typically very low despite the rarity of the event, but in the majority of fluvial and coastal storm events a higher return period (often associated with longer lead times) increases the opportunity for people to take risk reducing actions, such as in Tewkesbury in 2007. This is counterbalanced by the increased likelihood that those that have previously experienced flooding, or live in a high-risk area, are more likely to act on a warning (although the evidence for this is mixed).

- **The absence of community networks:** In the most vulnerable neighbourhoods (as defined by the NFVI – see earlier) informal community networks can be much reduced (RSPB, 2014, Sayers *et al.*, 2017).
- **Ability to respond:** Not everyone is able to respond as easily to warnings as others. For example, a limited physical mobility may impact an individual's ability to deploy flood protection measures at home, such as flood gates (Defra, 2014a).

All these aspects are represented in FFE and vary across the adaptation scenarios. Under the **current level of ambition**, it is assumed that by the 2050s, 53% of households in fluvial floodplains successfully receive and act upon a warning reducing their damage by ~12% in a large event. Those acting upon a warning reduces to 13% in surface water areas and rises to 77% in coastal areas¹⁵. In the most socially vulnerable neighbourhoods those acting upon a warning is assumed to be significantly less (14% in fluvial floodplains for example). Under a **higher level of ambition**, take-up increases in all areas (to around 87% in coastal areas for example) and is assumed to reduce under a **lower level of ambition** (to around 68% in coastal areas for example).

More detail on the representation of this measure within the FFE is given in Appendix D.

Note:

CCRA3 extends the representation used in the CCRA2 to include differentiation by social vulnerability and revisits the assumed effectiveness based on evidence presented in detail in Sayers *et al.*, 2016. Although it is recognised that flood forecasting and warning is primarily targeted towards saving lives, the impact on people (and the ability for people to successfully evacuate etc.) is not included here.

Insurance

Overview of evidence

Flood insurance is made available in the UK for domestic properties and businesses through private insurance companies and aims to compensate victims for the flood damage that they incur, therefore enhancing recovery after flood events (and reducing vulnerability of residents). This has been the situation since the 1960s (Penning-Rowsell *et al.*, 2014; Penning-Rowsell and Priest, 2015) and this insurance underpins all other FRM policies in the UK, relieving the government of the obligation to pay compensation for the damage caused by flooding.

Insurance take-up is uneven (Box 4). Based on the government's Household Expenditure Survey and evidence from its own members, the Association of British Insurers (ABI) estimate that the take-up of insurance in the UK is such that 93 per cent of all homeowners have buildings insurance that covers the structure of their home, but this falls to 85 per cent of the poorest 10 per cent of households purchasing their own property. Some 75 per cent of all households have home contents insurance, but half of the poorest 10 per cent of households do not have this protection. This

¹⁵ In Scotland only around 25% of those living in coastal and fluvial areas sign up to a warning and hence these values are likely to overstate the importance of forecasting and warning in Scotland. Personal communication with SEPA – Flood Warning Target Area data – dated 2018 October.

prompted Watkiss *et al.*, (2016) to note “while most owner occupiers have building insurance, there are much lower levels of contents insurance among tenants, with many in the lowest income decile having no insurance at all”. Although there are recognized challenges in understanding access to appropriate insurance, several aspects of concern are widely noted (see Sayers *et al.*, 2016):

- **Insurance take-up is driven by levels of income:** ONS, 2015 shows a marked difference in penetration levels with different levels of disposable income. The Pitt Review noted ‘*in some of the areas affected by the summer 2007 floods the figure is barely over a quarter, with vulnerable, low income households most likely to be uninsured*’. Within Flood Re (Box 5), premiums are linked to the Council Tax banding as a proxy for income thresholds; a link that is not without controversy.
- **There are lower levels of take up for households in rented accommodation:** ONS, 2015 shows that households in rented accommodation have a far greater chance of not being insured at all, although local authorities and housing associations would be responsible for the repair of the structure of the buildings they own if flooded, rather than the tenant, so the penetration figure here represents the penetration of contents insurance rather than full domestic property insurance. Nevertheless, the difference between owner occupiers and tenants is striking, and is compounded by the fact that the private rented accommodation sector in the UK is growing quite rapidly, whereas owner occupation is declining proportionately (ONS, 2016). For structural repairs following a flood the occupants of those houses are dependent upon the landlord to fund and make any repairs. Therefore, the insurance position of the landlord is what is critical here rather than that of the tenant, and many local authorities self-insure rather than insure through the market.
- **Under-insurance:** Sayers *et al.*, 2016 raises the question that this may vary with type of tenure and household income levels; however, at present, the available information here is sparse or virtually non-existent.

Representation

Variation under the **current** and **higher level of ambition** is relatively small (compared to other measures) with around 76% of properties exposed to flooding more frequently than 1 in 75 years assumed to have insurance. A much lower level of insurance is assumed in the socially vulnerable locations (20%). Under the **lower level of ambition** insurance penetration is assumed to reduce assuming the market fails to fully adjust to full actuarial pricing mechanisms in the absence of Flood Re (see Box 4) – with penetration falling by half against tenants in socially vulnerable neighbourhoods and significantly elsewhere.

More detail on the representation of this measure within the FFE is given in Appendix D.

Box 4 Insurance penetration levels used here are based on household expenditure survey.

The difficulties in assigning penetration levels arise from several sources, including (but not limited to):

Building cover: understanding coverage of ‘buildings cover’ can be misunderstood because the survey asks householders if they have purchased this cover. They may correctly answer ‘no’ because they either rent or are a leasehold property owner. If this is the case, it is actually incorrect to interpret that there is no cover for the property they are living in, rather what may be meant is that they are not responsible for purchasing it. This is because the renter will not be responsible for buildings insurance as this will fall to the landlord. Contents insurance however will be available for the renters and ceded to Flood Re if desired by the retail insurer. **Contents cover:** The level of penetration implied by the survey is probably reasonable (although without direct evidence this is difficult to determine). It is also the case that contents insurance is not tied to mortgages and Flood Re places no restriction on contents take-up (other than excluding properties built after 2008).

Box 5 Flood insurance in the UK

Since April 2016 an arrangement termed Flood Re has created a pool into which all insurers contribute to subsidise a sub-set of insurance premiums that individual insurers choose to pass on to Flood Re for a further fee to the insurer. Householders purchasing insurance that includes flood cover may not know whether they are in this sub-set or not, since they will deal with their conventional insurance company, but that company will cede the policy and the liability for flood related claims to the Flood Re pool if where they deem necessary and certain eligibility criteria are met (including being built before 1st January 2009¹⁶).



Flood Re is intended to make flood insurance affordable for those who otherwise would pay large premiums to be protected against current levels of flood risk, but the arrangement ends in 2039 after which the insurers and government have agreed that flood insurance becomes fully risk-reflective. The Flood Re Transition Plan discusses how the shift to affordable risk-reflective pricing will require more effective flood risk management, insurers’ support for homes to be more resilient to flooding, and better and cheaper reinstatement to reduce the costs when flooding happens. Householders too will need to act to make their homes and communities more resilient and so reduce the risk of flooding and the costs of repair. However, if risk is not reduced, the transition to market prices could further discourage many and especially the most socially vulnerable from accessing insurance.

Source: Flood Re website and Transition Plan, 2018

¹⁶ Flood Re criteria: [//www.floodre.co.uk/homeowner/eligibility/](http://www.floodre.co.uk/homeowner/eligibility/) Accessed May 2018

Governance and organisational arrangements

Overview of evidence

The Pitt Review (2008) led to significant changes being enacted via the Flood and Water Management Act (2010) (in England and Wales) and similar legislation in Scotland and Northern Ireland (as introduced earlier). Since the 2010 Act, significant improvements in the governance of fluvial and coastal flood risk have been recognized (Alexander *et al.*, 2016; Maiden *et al.*, 2015). The partnership working between Risk Management Authorities and others has continued to improve the coordination of the management of surface water floods (Maiden *et al.*, 2018). In Scotland, for example, the FRM Act emphasizes partnership working and co-operation to help reduce flood risk. However, the publication of a series of policy recommendations from an EU Interreg Programme (FAIR) highlights several barriers to further progress. These echo previous discussions on the importance of governance issues as barriers to achieving even greater resilience (Sayers *et al.*, 2017), including:

- **How to deliver appropriate policy integration.** Despite multiple initiatives to promote an integrated approach to FCERM, progress has been slow. In part, this is due to the absence of a unifying, but practical, strategic framing. This is easier said than done, and requires a ‘joining up’ of national, regional and local governance to ensure the multiple policies, regulations and programmes they promote are appropriately integrated (as discussed in CCC, 2019). Work done at one level of government, or in one sector, should support other levels of government and in other sectors (a challenge explicitly recognized in the apparent lack of linkage between economic regeneration with flood risk management, Sayers *et al.*, 2016).
- **How to deliver innovative, long-term, solutions.** To be successful a society must learn to manage risk and not simply seek to avoid it (Walport *et al.*, 2015); a philosophy that is equally applicable to flood risk management. Innovative solutions, and how to generate the political momentum to deliver them, remain central barriers to progress. For example, the policy in recent years within England and Wales has been guided by the principle of “Making Space for Water”, ‘Sustainable Flood Management’ in Scotland and Social Well-being in Wales. The sentiment of these policy goals is clear but often at odds with the local political and public response to a flood event (*e.g.* a desire for better protection from flooding), local economic development choices (*e.g.* continued development in the floodplain, for example) and insurance industry agreements that focus on reducing the chance of flooding. Increasingly there will be a need to confront more controversial issues including how to make appropriate provision for the relocation of communities (*e.g.* in extreme cases of coastal erosion on the East Coast or areas like Fairbourne, Wales). Such decisions raise philosophical issues of moral obligations (and questions of procedural justice as well as investment utility) and very tangible issues of neighbourhood blight.
- **How to secure whole-life ‘fair’ financing.** Many well-intentioned plans have failed due to the lack of clear roles and responsibilities (with associated budgetary security) that bridge the gap across policy, planning and implementation. In particular, the funding of infrastructure (defences, sewers *etc.*) maintenance has been an “Achilles’ heel” of a more strategic approach (Sayers *et al.*, 2015). Equally, current utilitarian approaches also arguably fail to assign enough weight to the full social, environmental and economic costs of failure to invest in effective FRM solutions (Knox and England, 2015). Whole-life costing is now widely promoted as an analysis tool, but typically not allied to long-term funding commitments. Equally, approaches to value adaptive capacity are available (Brisley *et al.*, 2015) but have not been taken up widely (outside of high profile programmes). Across the UK however all countries are seeking to mainstream an adaptive approach.
- **How to embed effective participation in decision making.** Public participation is now universally considered to be an essential element of FCERM and will play an increasing role. The

shape and success of the FCERM initiatives delivered will reflect how committed local and national stakeholders are to a common strategy and how willing they are to contribute monetary and non-monetary resources.

- ***How to reduce impacts whilst maximising opportunities to deliver co-benefits from the strategy.*** Managing rivers and coasts presents both opportunities and challenges for joint uses and multiple benefits. Blending natural and conventional built infrastructure (linking natural flood management and conventional defences for example) can be effective and efficient in managing flooding as well as delivering wider environmental, social and economic benefits. FCERM has an opportunity to support multiple levels of decisions making and contribute to other important policy agendas. For example, on inclusive growth and natural capital benefits alongside flood management, as well as climate change mitigation alongside adaptation.

Experience in flood risk reduction implementation reinforces our belief that flood risk management is a human endeavor that requires clear leadership and collaboration to be successful. The success of the whole system approach outlined here will be dependent upon the capacity of governance arrangements. Such arrangements are of course difficult to quantify but that does not mean they should be ignored.

Representation

No standalone representation of the influence of governance and organisational arrangement is included here. Governance capacity however does feature in the settings used for each other lever and in differentiating the values used in each Adaptation Portfolio. Further assessments should consider more subtle influences of governance.

7.0 FUTURE FLOOD RISK: ANALYSIS AND DISCUSSION OF RESULTS

The Future Flood Explorer (FFE) produces results for a wide range of flood risk metrics and spatial scales. These are calculated for combinations of the climate, population, and adaptation scenarios. This Chapter presents a small sample of those results to highlight important or interesting findings. Further results can be found in Appendix F.

7.1 Flood risk: UK and by country

A continuation of Current Levels of Adaptation (CLA) leads to a significant increase in Expected Annual Damages (EAD) by the 2080s (Figure 7-1). Under a 2°C (low population) future, the rate of increase slows after the 2050s. This reflects the slower rate of increase in GMST from the 2050s through to the 2080s under this future (Figure 5-2). Under a 4°C (high population) future the rapid rise in risk from today to the 2050s continues through to the 2080s. This is particularly the case in England where, for example, under a 4°C (High population) EAD (total) increases from £1.3bn today to ~£2.1bn by the 2050s and reaches £2.7bn by 2080s.

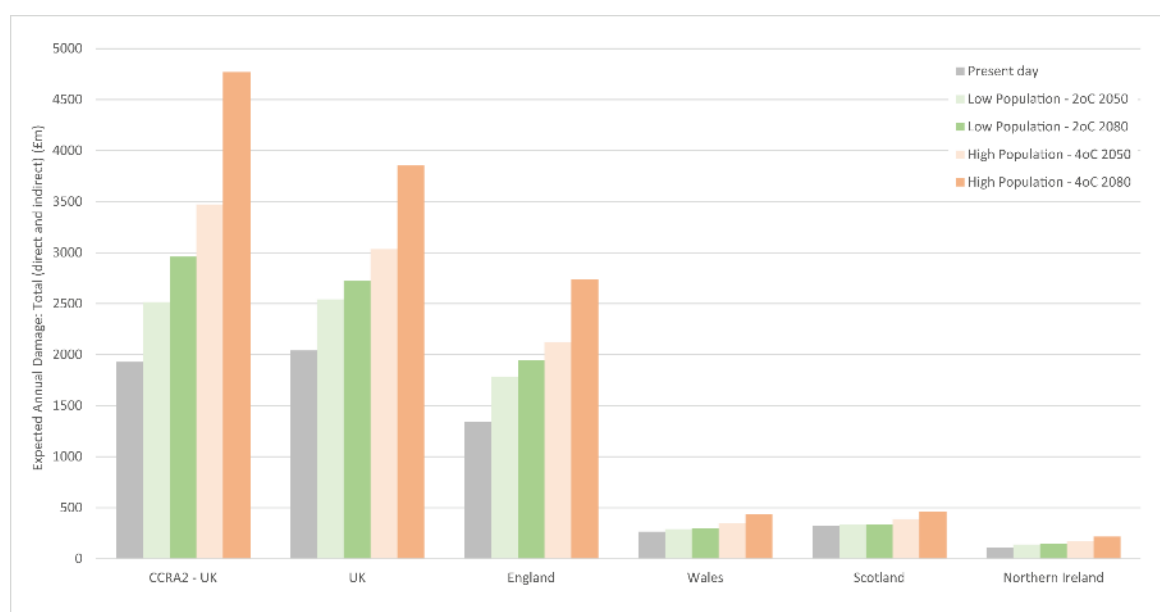


Figure 7-1 CLA - Expected Annual Damages (Total) – By Country

The change in Expected Annual Damage under the three alternative adaptation portfolios are compared in Table 7-1. Under all adaptation portfolios tested here risks increase. By the 2080s under a 4°C high population growth future EAD (total) is projected to rise 137% under a Reduced Whole System (RWS) approach to adaptation, 89% under CLA, and 52% under an Enhanced Whole System (EWS) approach to adaptation. In the absence of population growth and a 2°C rise in GMST, a continuation of Current Level of Adaptation sees risk rise by 26% above present-day levels; under EWS adaptation approach risk is maintained close to present-day levels (rising by 5%).

Table 7-1 Expected Annual Damages (Total) – Summary by Country and adaptation portfolio

Expected Annual Damage: Total (direct and indirect) - £m	Present-day	2050						2080					
		None		Low		High		None		Low		High	
		2	4	2	4	2	4	2	4	2	4	2	4
Population projection													
Climate future (rise in GMST by 2100)													
Current Level of Adaptation (CLA)													
UK	2,042	19%	35%	25%	42%	31%	49%	26%	60%	33%	69%	48%	89%
Country													
England	1,340	26%	44%	33%	52%	39%	59%	34%	72%	45%	87%	58%	105%
Wales	266	7%	19%	9%	20%	18%	31%	14%	38%	12%	36%	34%	64%
Scotland	324	-1%	11%	2%	14%	7%	20%	2%	24%	4%	27%	16%	42%
Northern Ireland	111	23%	41%	24%	42%	35%	55%	34%	66%	29%	59%	57%	95%
Enhanced Whole System													
UK	2,042	1%	14%	5%	19%	9%	24%	5%	32%	11%	40%	21%	52%
Country													
England	1,340	5%	19%	11%	25%	14%	29%	10%	39%	18%	50%	26%	60%
Wales	266	1%	12%	4%	15%	10%	22%	4%	26%	6%	29%	21%	48%
Scotland	324	-22%	-12%	-19%	-9%	-16%	-6%	-20%	-2%	-17%	1%	-10%	10%
Northern Ireland	111	18%	35%	20%	37%	28%	47%	26%	56%	23%	53%	45%	80%
Reduced Whole System													
UK	2,042	35%	56%	41%	63%	50%	74%	49%	95%	58%	106%	80%	137%
Country													
England	1,340	44%	68%	53%	78%	62%	88%	61%	114%	75%	133%	97%	163%
Wales	266	19%	34%	19%	35%	31%	49%	30%	62%	26%	57%	54%	95%
Scotland	324	11%	28%	14%	30%	21%	39%	19%	50%	20%	51%	38%	75%
Northern Ireland	111	28%	47%	28%	47%	41%	64%	40%	80%	33%	71%	66%	114%

Note: Percentage change shows the increase from present-day. For example, 50% indicates the risk has increased by 50%.

Most of the present-day and future flood risk is in England. This is to be expected given the significantly larger population in England than elsewhere. When risks are normalized by the flood exposed population (*i.e.* the average Expected Annual Damage per individual, EADi) a different picture of the distribution of risk emerges. Those living in the flood prone areas in Scotland, Northern Ireland and Wales, on average, are exposed to a higher Expected Annual Damage than those living in England (Figure 7-2). For example, today the EADi in Scotland is £241, rising to £450 by the 2080s (under a 4°C, high population growth, future). For those living in England the increase is proportionally less, increase from £49 to £109.

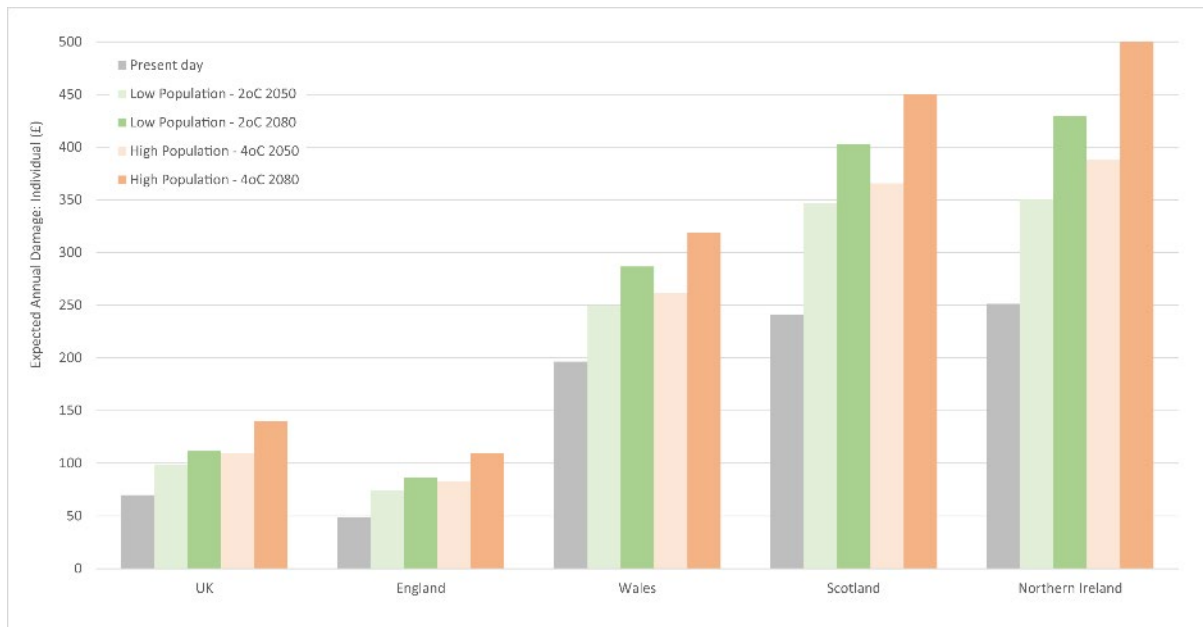


Figure 7-2 CLA - Expected Annual Damage: Individual (Residential) – By Country

These risks reflect the changing frequency of flooding, with those in Northern Ireland, Scotland and Wales experiencing, on average, more frequent flooding compare to people living in England (Table 7-2); although by the 2080s under a 2°C and 4°C high population growth future the number of people exposed to frequent flooding increases under all adaptation approaches. The country scale lens used here however masks significant spatial variation in the risks faced – for example by Local Authority and flood source a more nuanced picture emerges as discussed in later sections.

Table 7-2 People exposed to frequent flooding (1in75 years or more frequent) – Summary by Country

People counts in bands - Significant - (000)'s	Present-day	2050						2080					
		None		Low		High		None		Low		High	
		2	4	2	4	2	4	2	4	2	4	2	4
Current Level of Adaptation (CLA)													
UK	1,889	44%	68%	51%	77%	73%	102%	54%	88%	56%	91%	103%	149%
Country													
England	1,554	49%	77%	60%	89%	81%	114%	61%	98%	69%	108%	115%	166%
Wales	148	13%	23%	3%	13%	22%	35%	20%	48%	-4%	20%	36%	73%
Scotland	155	26%	33%	18%	25%	39%	46%	24%	32%	2%	8%	43%	52%
Northern Ireland	33	26%	40%	15%	28%	53%	70%	34%	63%	-2%	17%	77%	116%
Enhanced Whole System													
UK	1,889	23%	44%	28%	50%	45%	70%	31%	61%	31%	62%	67%	108%
Country													
England	1,554	25%	48%	33%	58%	49%	77%	33%	66%	39%	73%	74%	118%
Wales	148	15%	27%	4%	16%	23%	36%	22%	52%	-3%	23%	36%	73%
Scotland	155	14%	22%	6%	14%	23%	32%	10%	19%	-10%	-3%	23%	33%
Northern Ireland	33	26%	41%	14%	29%	50%	69%	34%	64%	-2%	19%	74%	112%
Reduced Whole System													
UK	1,889	52%	79%	61%	89%	86%	118%	73%	108%	78%	115%	135%	185%
Country													
England	1,554	59%	89%	71%	103%	97%	133%	83%	122%	94%	136%	153%	209%
Wales	148	14%	25%	4%	15%	24%	38%	22%	51%	-2%	23%	40%	80%
Scotland	155	26%	33%	18%	25%	41%	49%	26%	33%	3%	8%	49%	57%
Northern Ireland	33	26%	40%	15%	28%	55%	73%	34%	63%	-3%	17%	81%	121%

Note: Percentage change shows the increase from present-day. For example, 50% indicates the risk has increased by 50%.

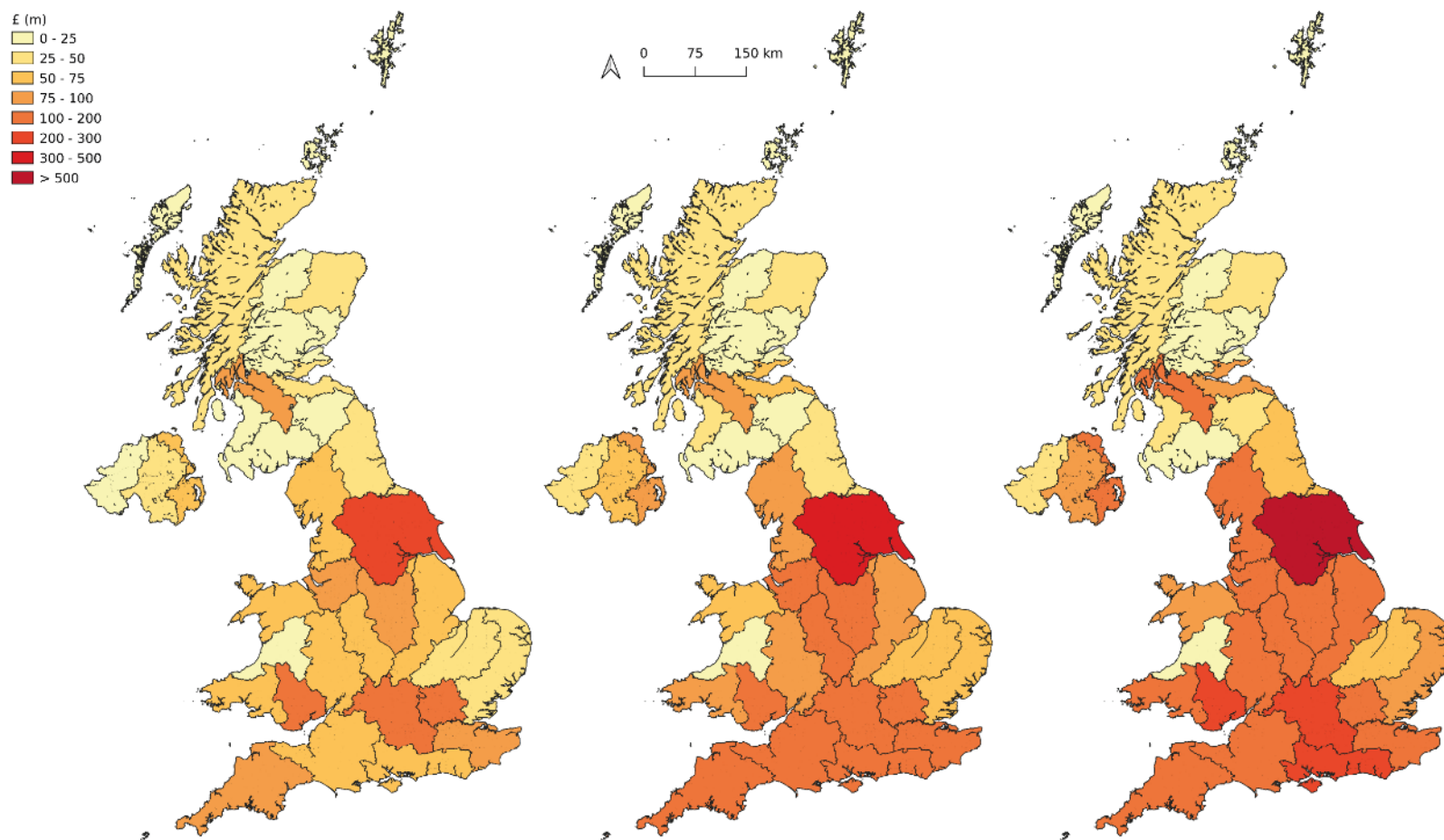
7.2 Flood risk: By Region and Local Authority

Today flood risk varies markedly across the UK and this variation persists into the future (Figure 7-3). At a Local Authority scale flood risk is influenced by climate change and population growth but also to adaptation. Figure 7-4 compares future risk under each adaptation portfolio for the twenty Local Authorities with the highest levels of risk in the 2080s (assuming a 4°C and no population growth in future and a continuation of Current Levels of Adaptation) and highlights the significant increase in risk in many coastal (and tidal) Authorities – such as Hull, Portsmouth, and Sedgemoor. The differences in future risk under each adaptation portfolio are significant (as to be expected).

There are, however, more subtle aspects to the changes. Figure 7-5 ranks the Local Authorities by the proportional increase in risk between the present-day and the 2080s. This highlights those Local Authorities that experience the greatest relative impact of climate change and again many coastal authorities feature. In some Local Authorities the increase in risk is more sensitive to the adaptation choice than in others (Figure 7-6). This highlights the limited opportunities for enhanced adaptation in many smaller Local Authorities and many coastal settings with limited available land outside of the floodplain for new development. Elsewhere the difference between the alternative adaptation portfolios is more marked – most profoundly in Runnymede and Wigan. This suggests in these areas future risks will respond well to an enhanced adaptation effort.

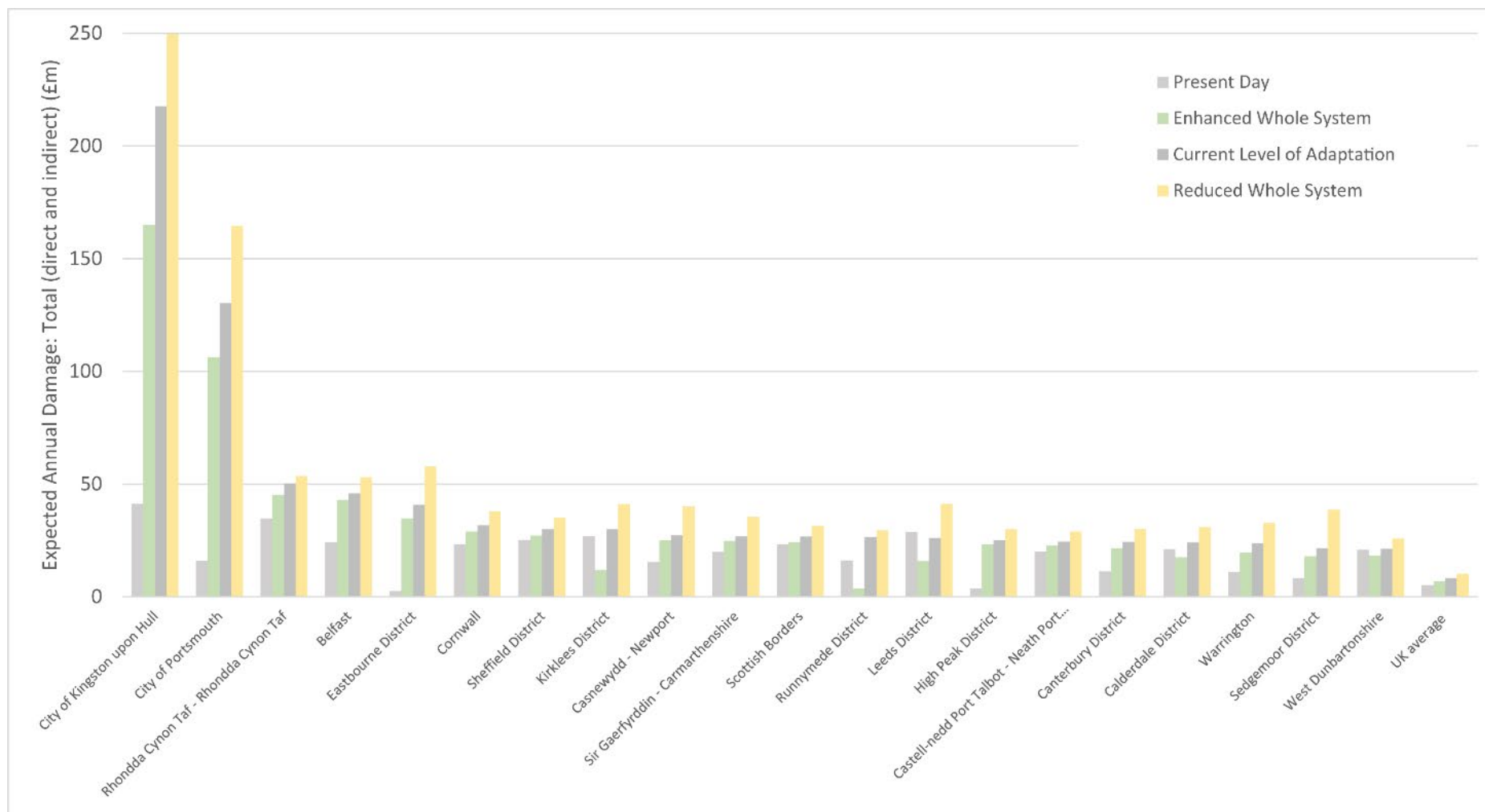
Note:

Ranking of risk by Local Authority: It is recognised that the confidence in the underlying flood hazard model varies between local authorities; reflecting underlying datasets and local validity of the assumptions made in those models around highly localised features (the performance of culverts, the assumed interaction between surface water and fluvial flows etc.). These differences may affect the relative ranking, however the broad ranking has higher confidence along with the changing risks within an authority.



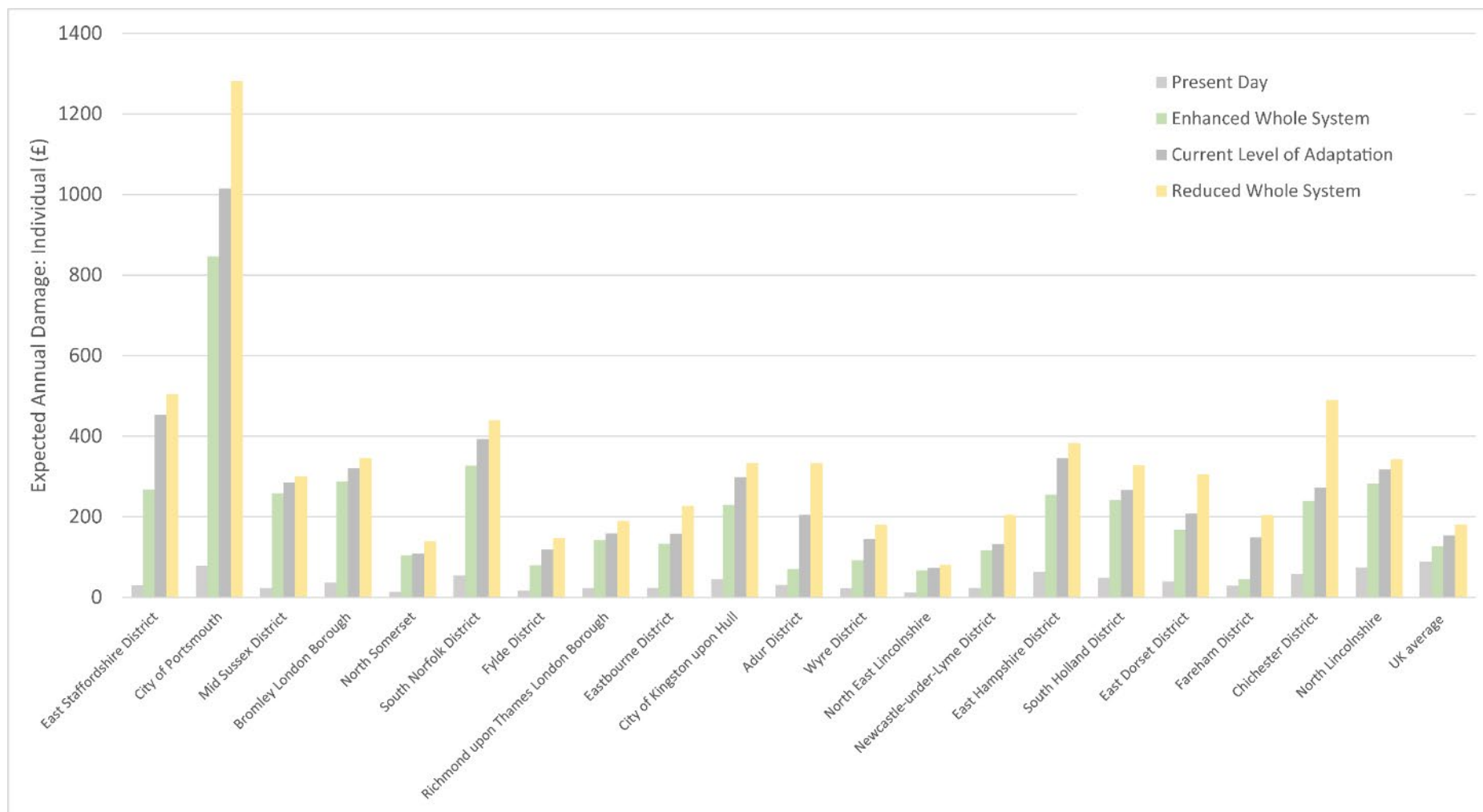
Left: Present-day; Middle: 4°C High Population Growth 2050s; Right: 4°C High Population Growth 2080s

Figure 7-3 CLA - Expected Annual Damages (Total): By Region



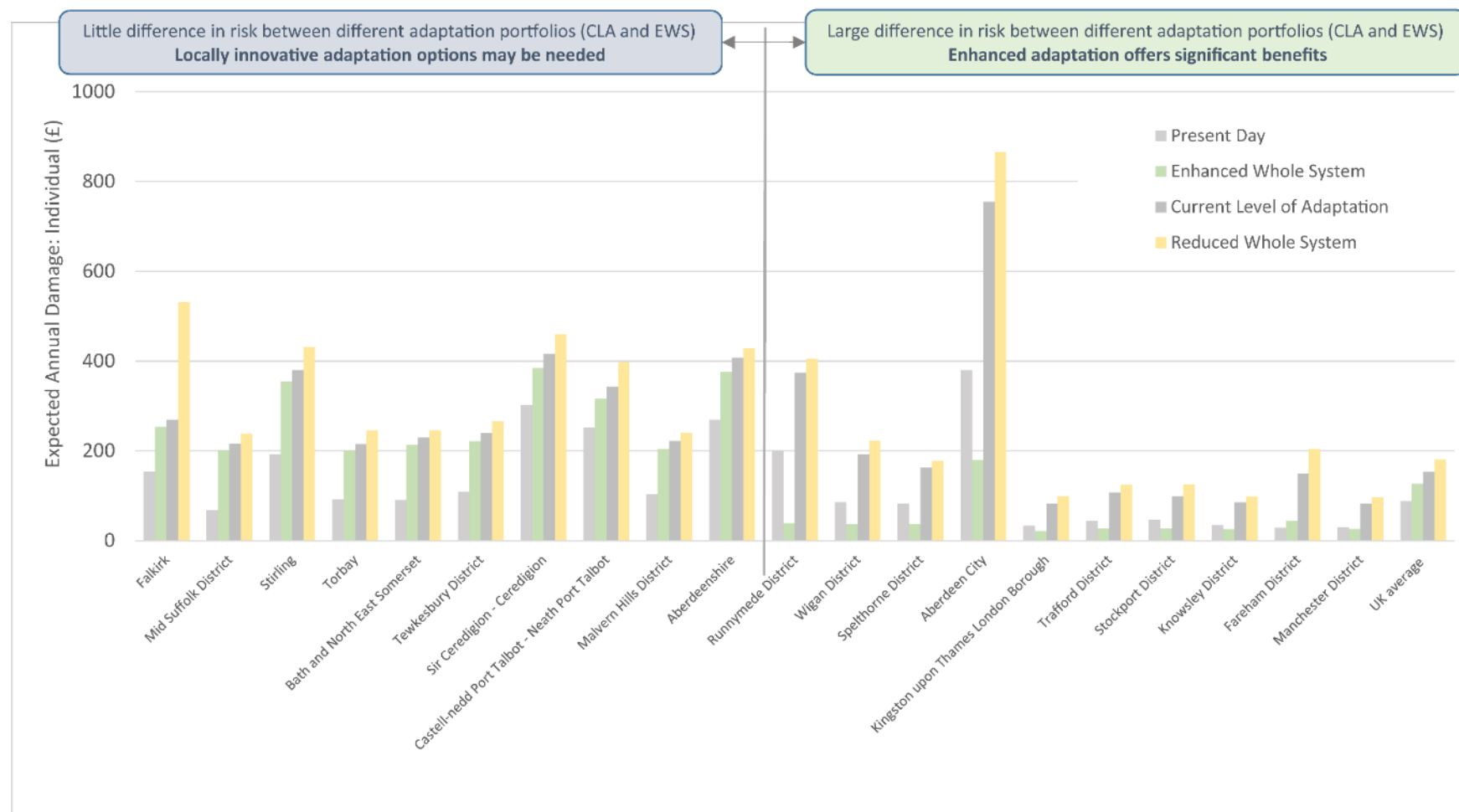
Ranked by Expected Annual Damages (total – i.e. direct and indirect) in the 2080s under a 4°C, no population growth and Current Level of Adaptation (CLA) future

Figure 7-4 Adaptation comparison – Expected Annual Damage (total) by Local Authority in 2080s (ranked)



Ranked by proportional increase in the Expected Annual Damages: Individual by the 2080s assuming a 4°C no population growth and Current Level of Adaptation (CLA) future compared to present-day

Figure 7-5 Adaptation comparison - Expected Annual Damage (Individual) by Local Authority in 2080s (ranked)



4°C 2080s No population growth: *Left hand side*: 10 local authorities with significant future risk (greater than £200 per person per year under a EWS future) but the least differential in risk between CLA and EWS portfolios. *Right hand side*: 10 with the greatest differential between the CLA and EWS portfolios (regardless of EADi).

Figure 7-6 Adaptation comparison - Local Authorities with the largest and smallest differential in risk by adaptation portfolio

7.3 Flood risk: By settlement type

Under a continuation of Current Levels of Adaptation (CLA) urban flood risk remains the dominant flood risk in the 2080s under both a 2°C and 4°C future (Figure 7-7). Urban towns (away from larger urban conurbations) contribute the most to these risks. This reflects: (i) the large number of people living in ‘urban cities and towns’ (~50% of all people living in flood prone areas, equal to ~3.3m people); and (ii) the slightly lower flood defence standards (on average) in these areas leading to a high proportion exposed to frequent flooding (Figure 7-8) when compared to other centres of populations captured as ‘major conurbations’ such as London.

When considered through the lens of the average Expected Annual Damage for an Individual (EADi) a different picture again emerges. Those living in flood prone rural areas are, on average, exposed to a much higher risk (e.g. present-day between £107-252 per person) compared to their urban counterparts (£44-87 per person) – see Figure 7-9. This difference exists today but is exacerbated in the future (most noticeably in a 4°C high population growth future).

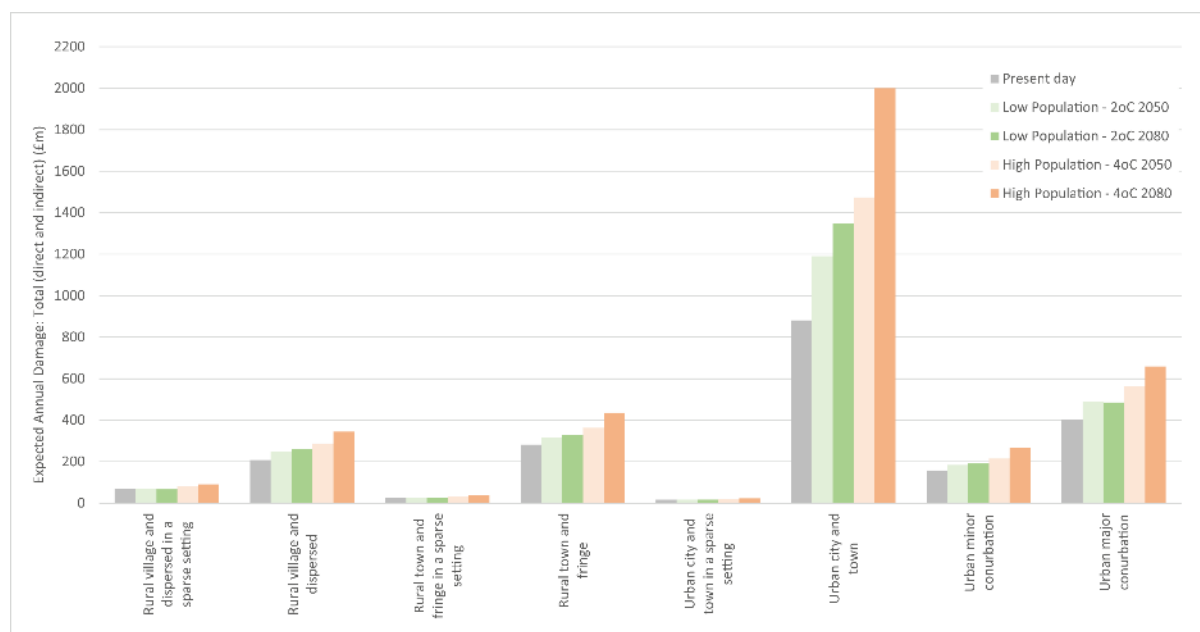


Figure 7-7 CLA - Expected Annual Damages (Total) – By Settlement Type

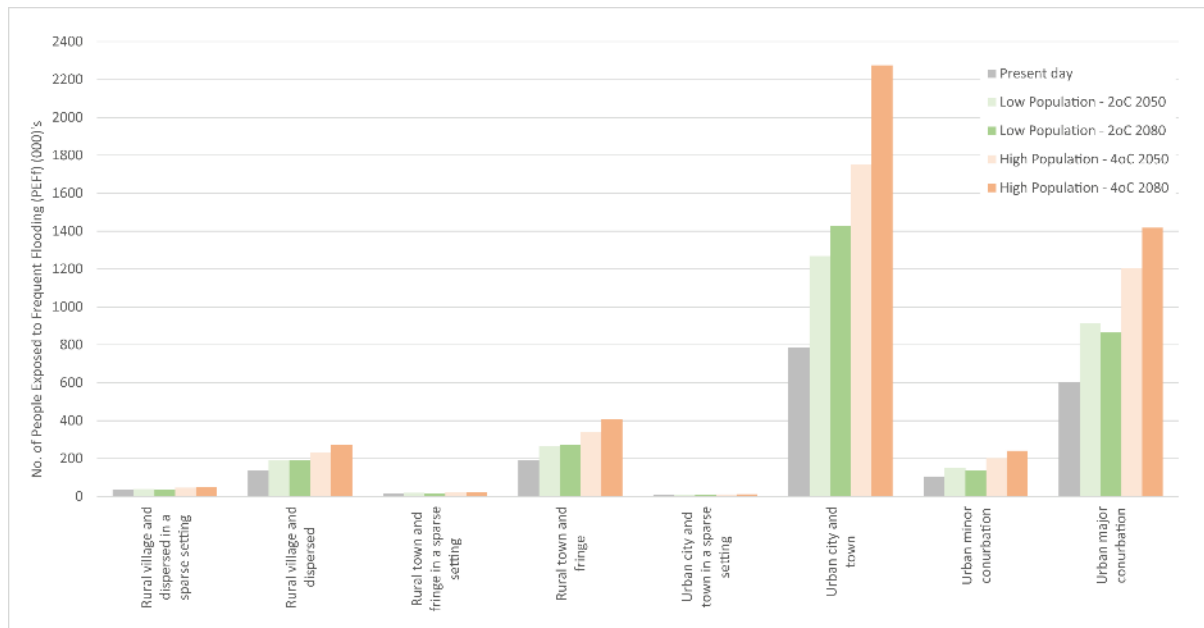


Figure 7-8 CLA – Population exposed to frequent flooding (1in75 years) (all sources) – By Settlement Type

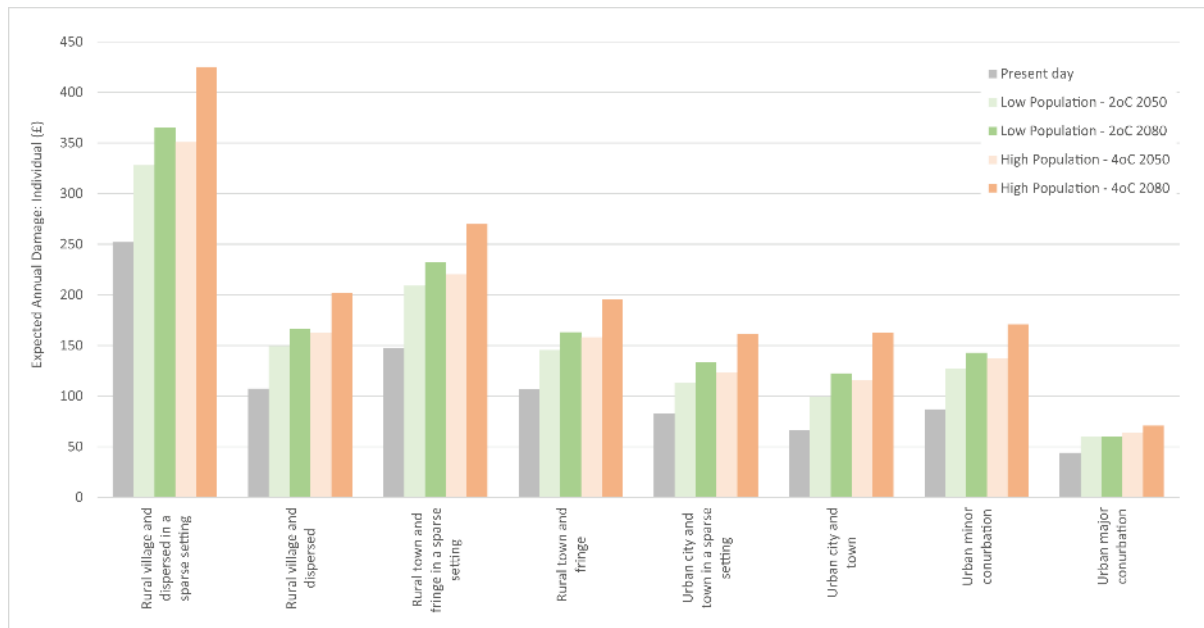


Figure 7-9 CLA - Expected Annual Damage: Individual – By Settlement Type

7.4 Flood risk: By flood source

Fluvial flooding is the dominant risk today. In the future, assuming Current Level of Adaptation (CLA) continues, surface water and coastal flood risks increase their relative contribution UK flood risk. Groundwater continues to have a limited contribution at national scale, although will be important locally.

The increasing significance of surface water and coastal flooding (in terms of Expected Annual Damage) is particularly pronounced under a 4°C high population growth future (Figure 7-10). By the 2080s surface water risks increase by a factor of two – from £587m today to £1.2bn. This significant increase reflects the anticipated increase in the intensity of short duration rainfall (Table 5-4) and the difficulty in adapting existing urban drainage networks (with only moderate enhancements to drainage capacity envisaged within the Current Levels of Adaptation portfolio). Those living in coastal areas see the greatest proportional increase in flood risk however, rising from £361m today to £1bn by the 2080s (given a 4°C high population growth future).

The inability of many coastal authorities to avoid floodplain development (Figure 6-5) and the significant impact sea level rise (rSLR) on coastal defence standards (leading to much lower standards even for modest increases in sea level rise) are important drivers in the escalation of risk in coastal areas (Figure 7-11). Similarly, development continues to take place in surface water flood prone areas driving a similar increase under the high population growth future.

Flood risk from each source is significantly influenced by the degree of adaptation effort (Figure 7-12). The opportunity to reduce risk through an Enhanced Whole System (EWS) approach is most noticeable for fluvial sources; enabling risk to be maintained at similar levels to today (raising from ~£1.1bn from ~£1.21bn under the 4°C High Population future). This is partly explained by spatial variation in changes in peak fluvial flows with some areas experiencing reduced extreme flows with climate change. For all other sources of flooding, risk increases significantly in all adaptation futures considered here (with coastal flood risk rising from £361m today to £793m, EAD-Total assuming an Enhanced Whole System approach). This is a particularly important finding given the greater risk to life and livelihoods often associated with coastal flooding when compared other sources.

The changing pattern in the annual average number of people flooded by fluvial and coastal flood sources are shown in Figure 7-15 to Figure 7-16. Surface water sources are discussed further in Section 7.6.

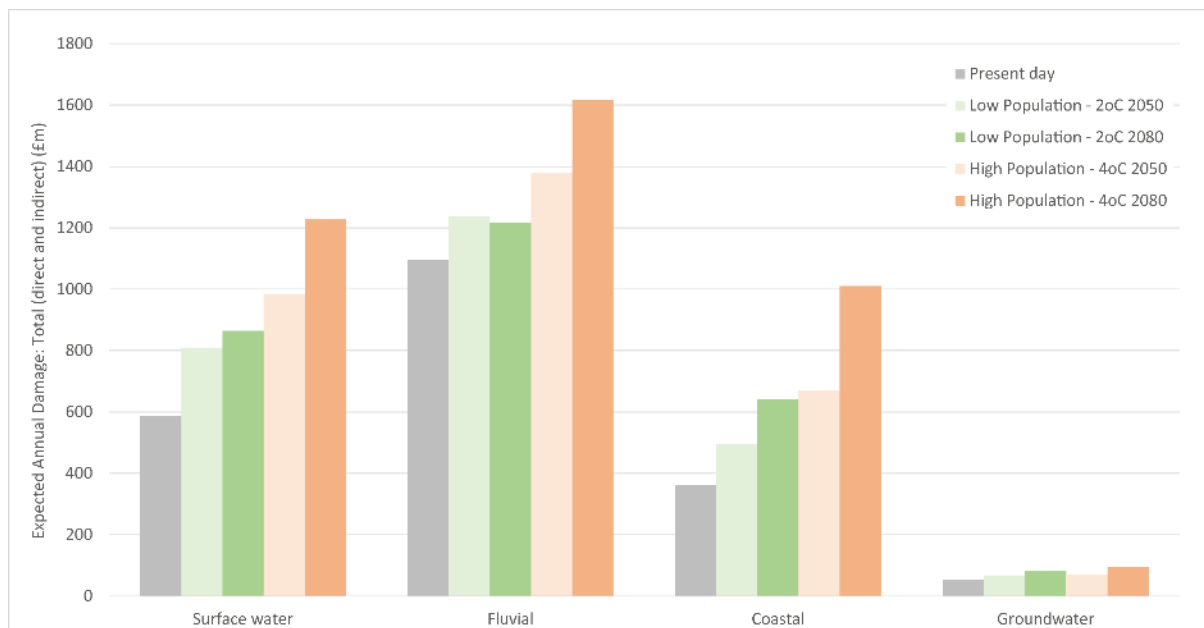
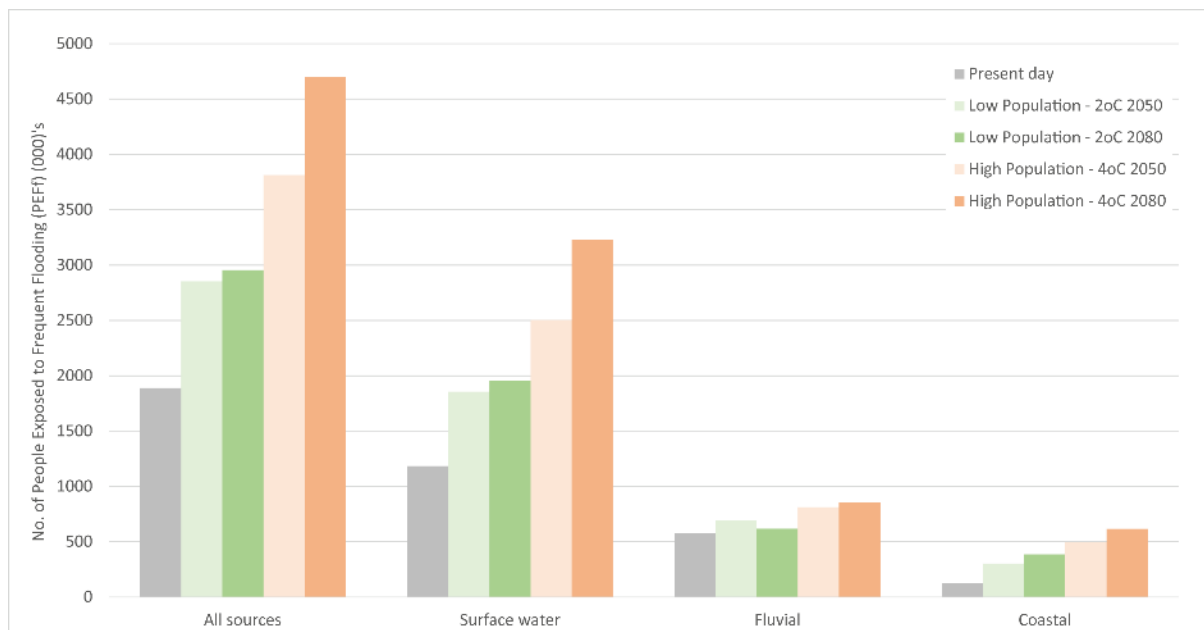
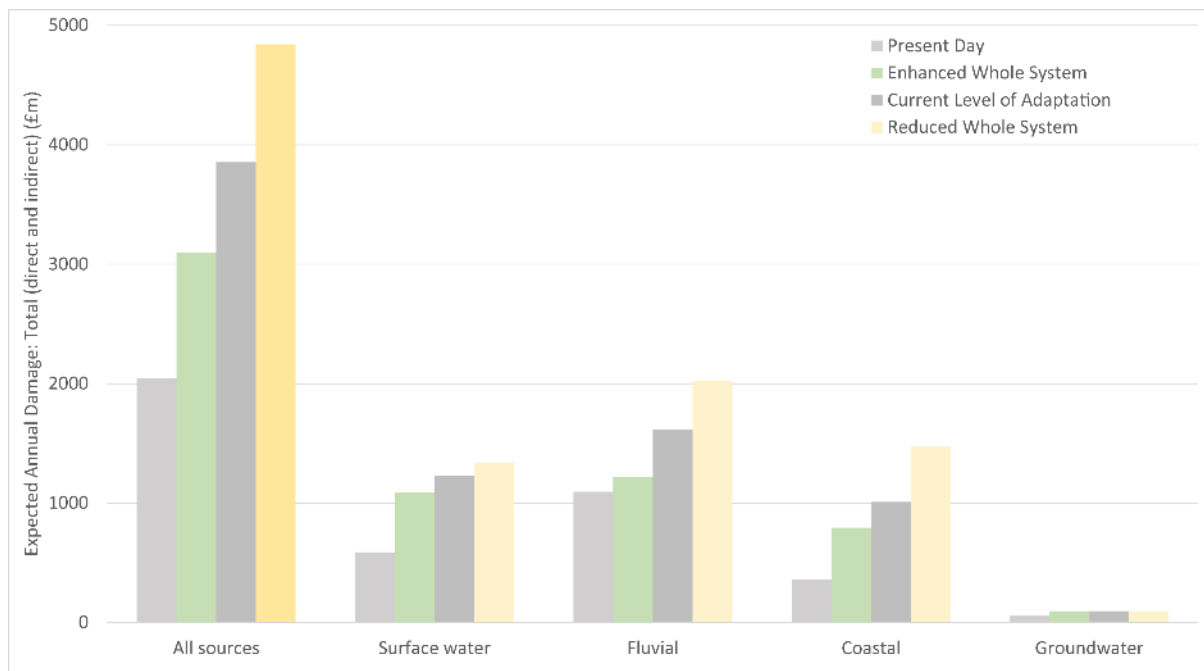


Figure 7-10 CLA - Expected Annual Damages (Total) – By Flood Source



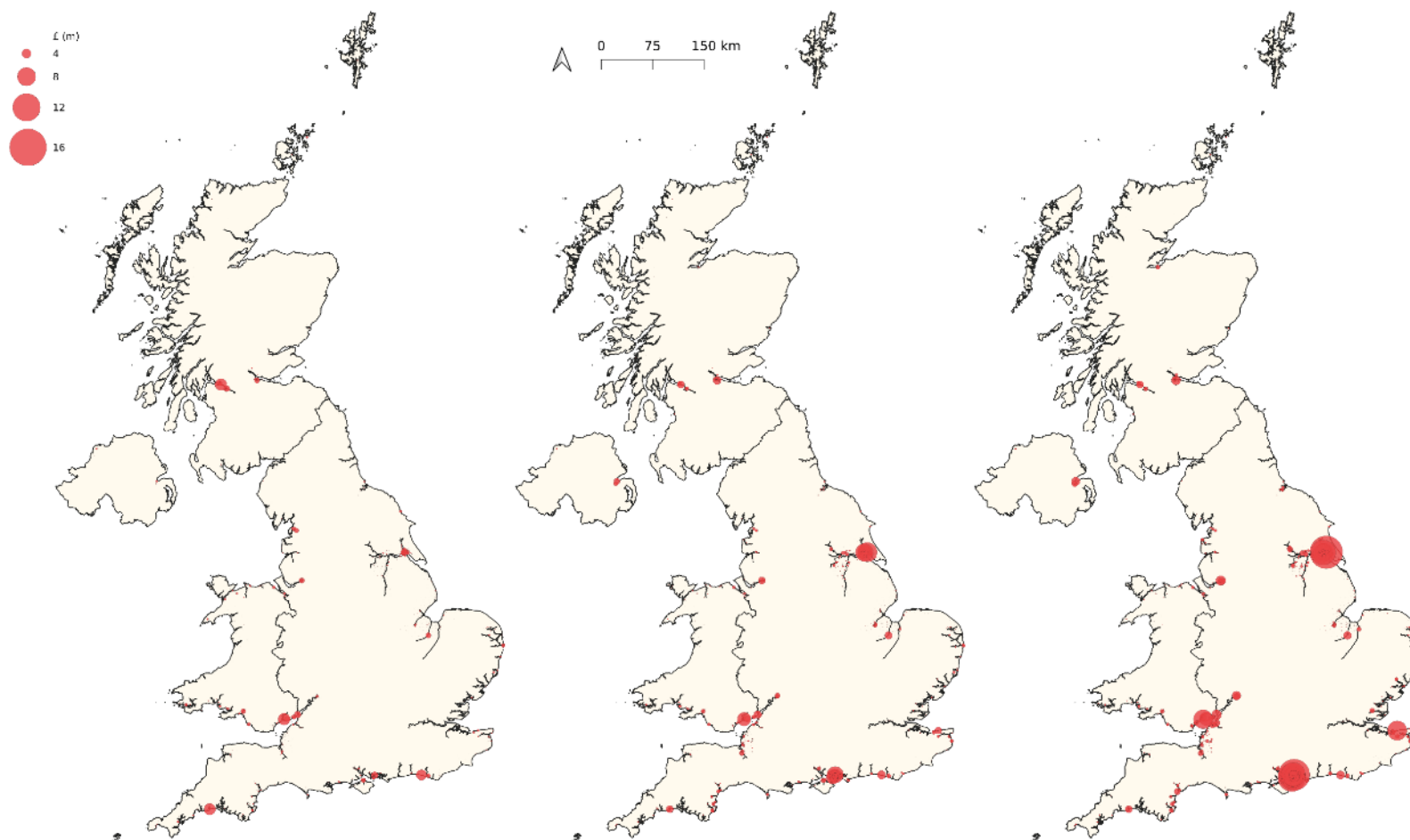
1in75 years or more frequent is used in this figure to define frequent flooding across all sources. Typically, 1in30 years to define frequent flooding for surface water, hence the dominance in this figure.

Figure 7-11 CLA – Number of people exposed to frequent flooding – By Flood Source



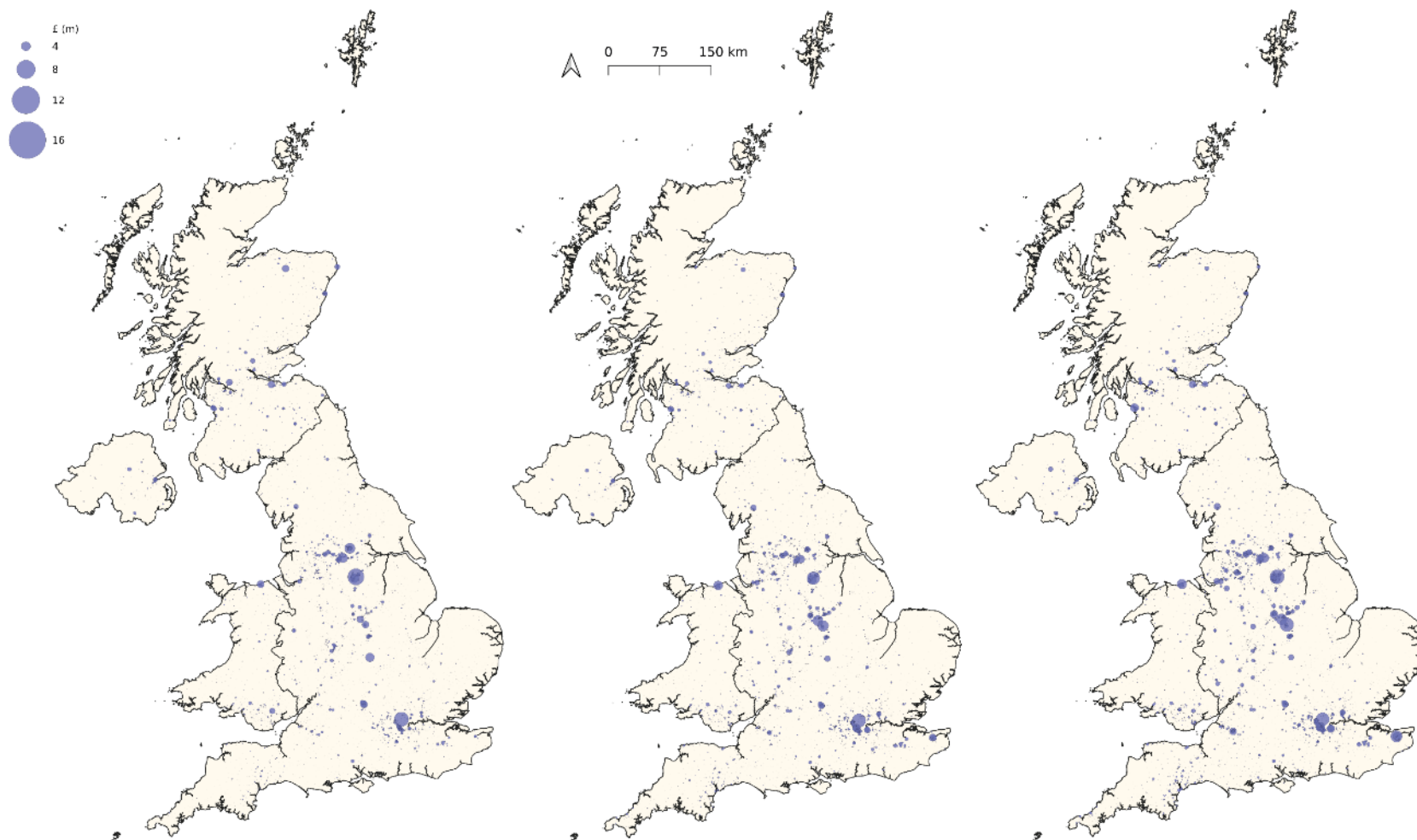
By the 2080s assuming a 4°C, no population growth future

Figure 7-12 Adaptation comparison - Expected Annual Damages (Total) – By Flood Source



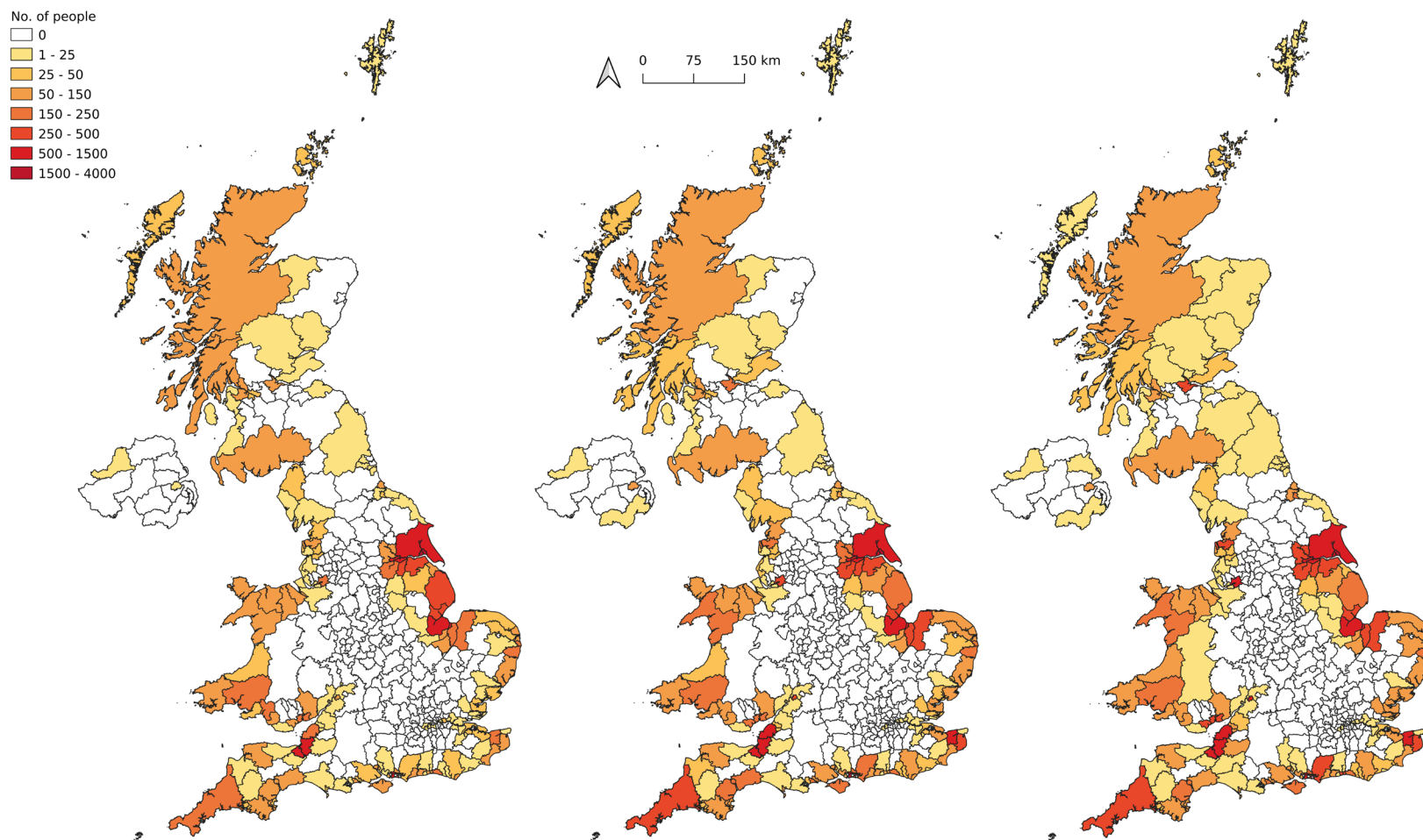
Left: Present-day; Middle: 4°C High Growth 2050s; Right: 4°C High Growth 2080s. Top 20% of neighbourhoods within Local Authorities with the greatest risk

Figure 7-13 CLA - Expected Annual Damages (Total): By flood source (coastal)



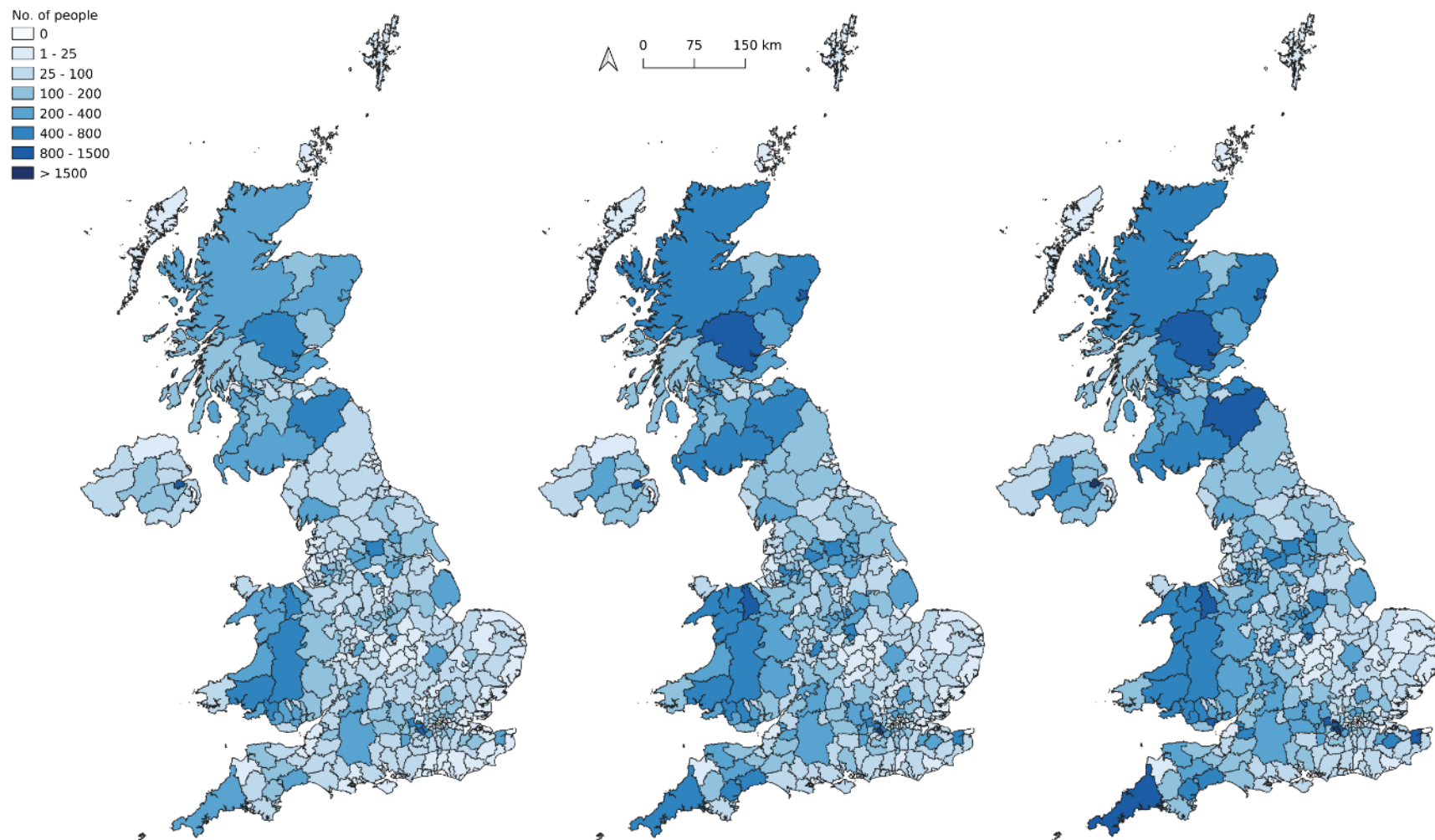
Left: Present-day; Middle: 4°C High Growth 2050s; Right: 4°C High Growth 2080s. Top 20% of neighbourhoods within Local Authorities with the greatest risk

Figure 7-14 CLA - Expected Annual Damages: By flood source (fluvial)



Left: Present-day; Middle: 4°C High Growth 2050s; Right: 4°C High Growth 2080s. Coastal areas including tidal reaches.

Figure 7-15 CLA – Expected annual number of people flooded: By Local Authority and flood source (Coastal)



Left: Present-day; Middle: 4°C High Growth 2050s; Right: 4°C High Growth 2080s

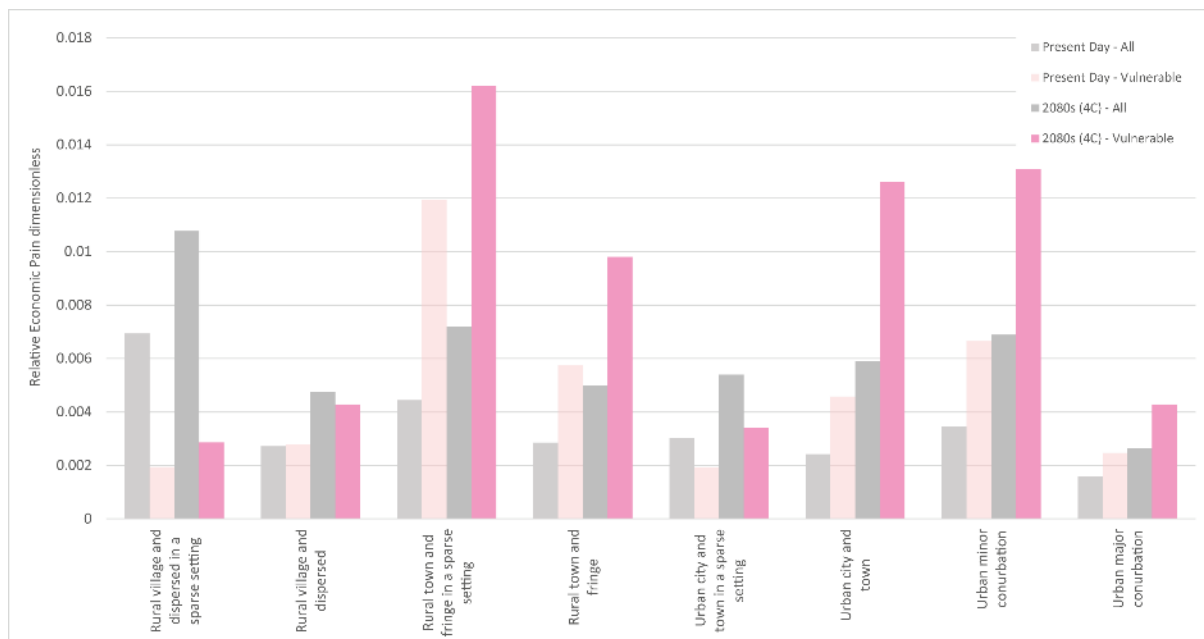
Figure 7-16 CLA – Expected Annual number of people flooded: By Local Authority and flood source (Fluvial)

7.5 Flood risk: By social vulnerability

The following figures compare flood risk between socially vulnerable neighbourhoods (as defined by the 20th percentile of the NFVI – as defined earlier in Section 2.3) and all neighborhoods. Assuming a continuation of Current Levels of Adaptation (CLA) the most socially vulnerable in rural settings (particularly rural towns) face higher risks when compared to others (Figure 7-17). This differential exists today and deepens through to the 2080s (most dramatically under the 4°C future); a finding that echoes the analysis of flood disadvantage by the Joseph Rowntree Foundation (Sayers *et al.*, 2017a).

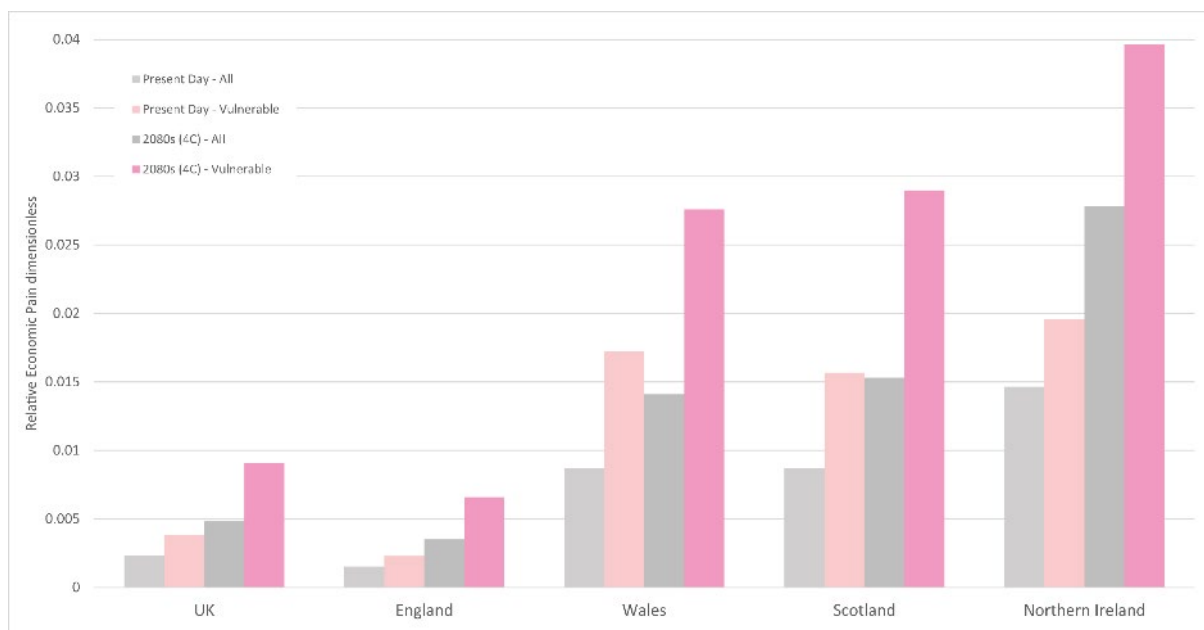
Social disadvantage as measured through the metric of Relative Economic Pain (REP) is greater, on average, in the Devolved Administrations than in England (Figure 7-18). Within each country however the spatial variation in disadvantage is significant (Figure 7-19). These variations reflect the differentially (lower) insurance penetration in the most socially vulnerable neighbourhoods compared to others that, when combined with lower household incomes and exposure to more frequent flooding (on average) leads to significant disadvantage. This REP is sensitive to access to insurance and the gap between the most socially vulnerable and others will widen further if Flood Re is not replaced (in some form) when it comes to an end in 2039 (as assumed in the Reduce Whole System adaptation).

The Local Authorities with the greatest social flood risk (as defined by the Social Flood Risk Index – SFRI – introduced in Section 4.1) include Local Authorities from across the UK (Figure 7-20). The Local Authorities experiencing the largest systemic disadvantage (i.e. the difference between the risk faced by the most socially vulnerable and all other neighbourhoods) highlights the significant disadvantage that exists in some areas (Figure 7-21a). Climate change exacerbates disadvantage in many Local Authorities (Figure 7-21b presents those Local Authorities experiencing the greatest differential increase in risk between the socially vulnerable and others). These two figures highlight the pervasive adaptation challenge to reduce flood disadvantage across the UK (and not only in those locations with high levels of social flood vulnerability today).



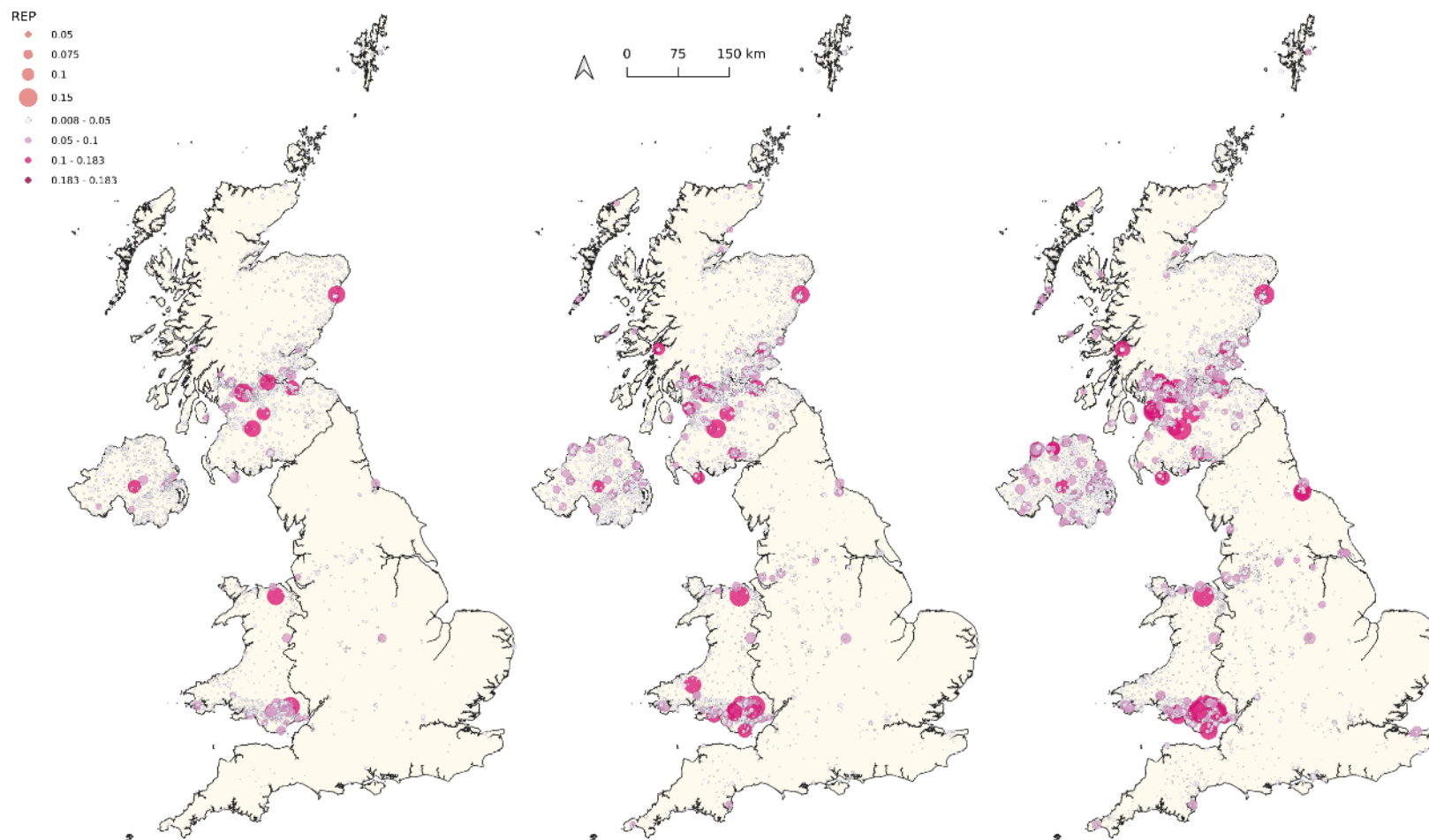
No population growth. 'Vulnerable' refers to the most socially vulnerable neighbourhoods as defined by the top 20 percentile of the Neighbourhood Flood vulnerability Index.

Figure 7-17 CLA – Expected Annual Damage: Individual – By Settlement type and Social Vulnerability



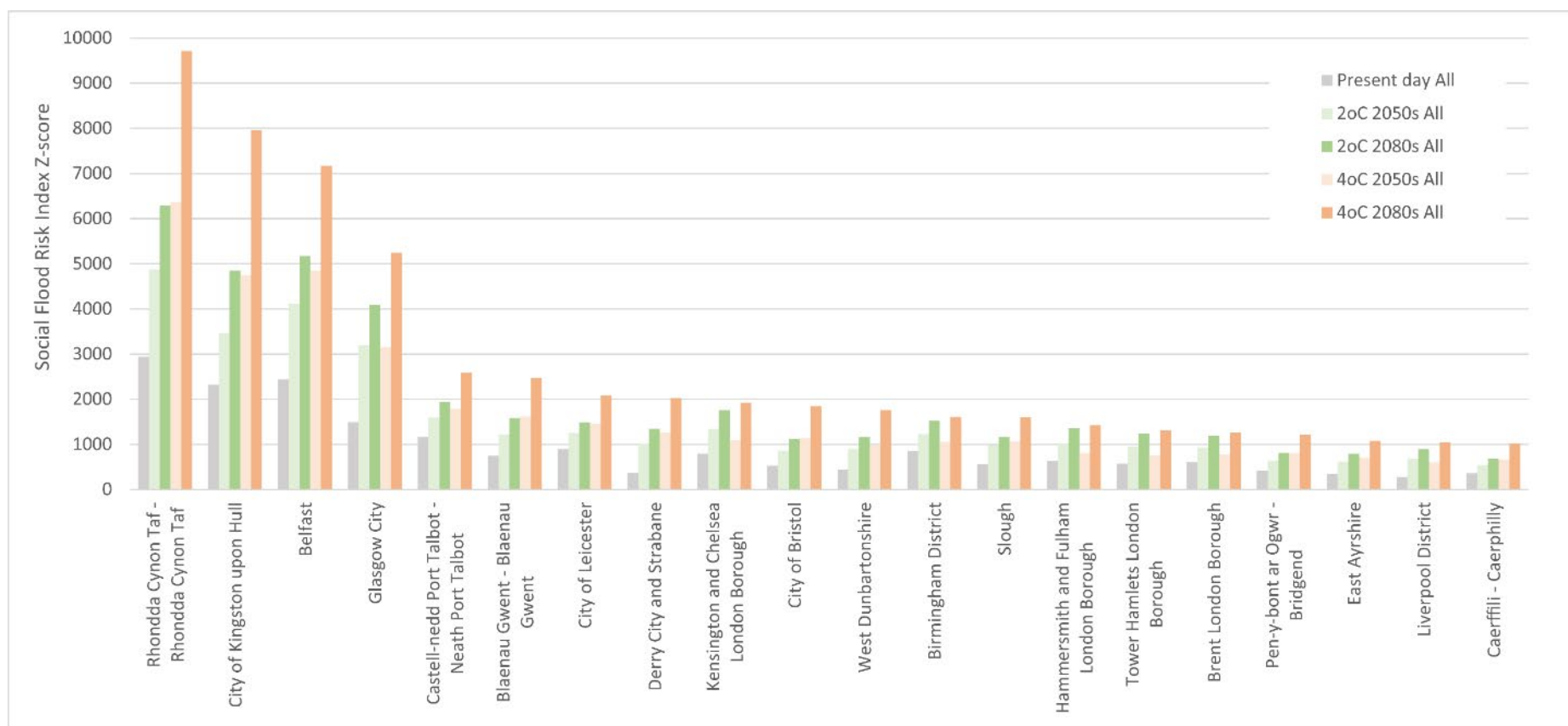
No population growth. 'Vulnerable' refers to the most socially vulnerable neighbourhoods as defined by the top 20 percentile of the Neighbourhood Flood vulnerability Index.

Figure 7-18 CLA – Relative Economic Pain – By Country and Social Vulnerability



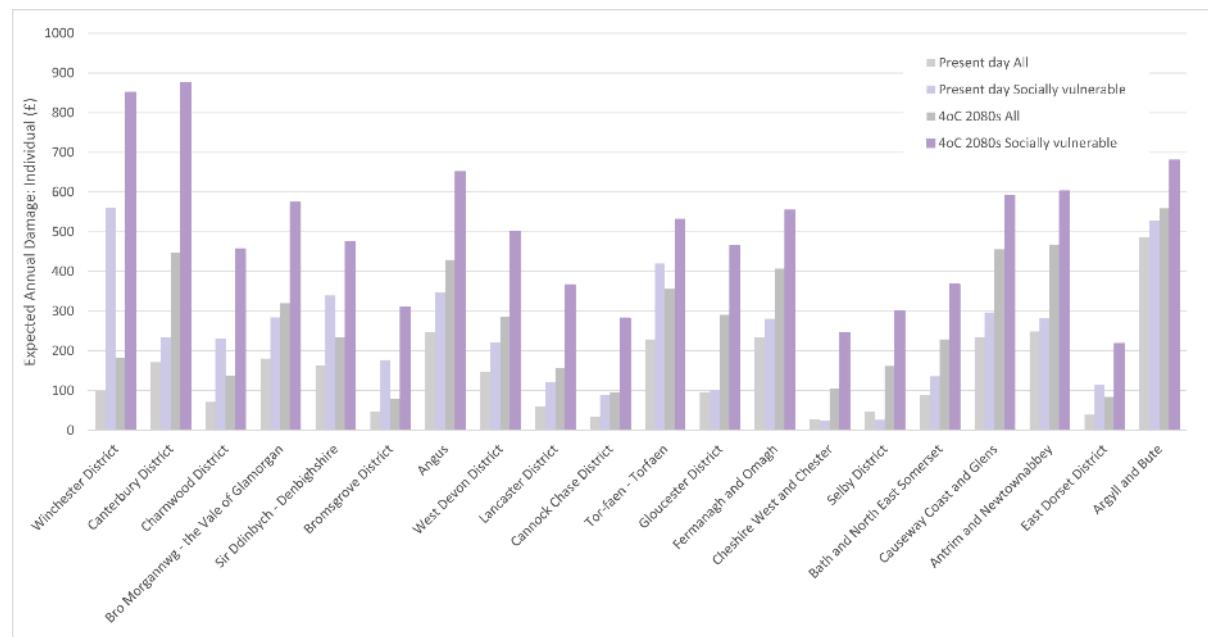
Left: Present-day. Middle: 4°C High Growth 2050s; Right: 4°C High Growth 2080s. REP is the ratio of uninsured loss to income. Top 20% of neighbourhoods within Local Authorities

Figure 7-19 CLA – Relative Economic Pain (REP): All sources of flooding

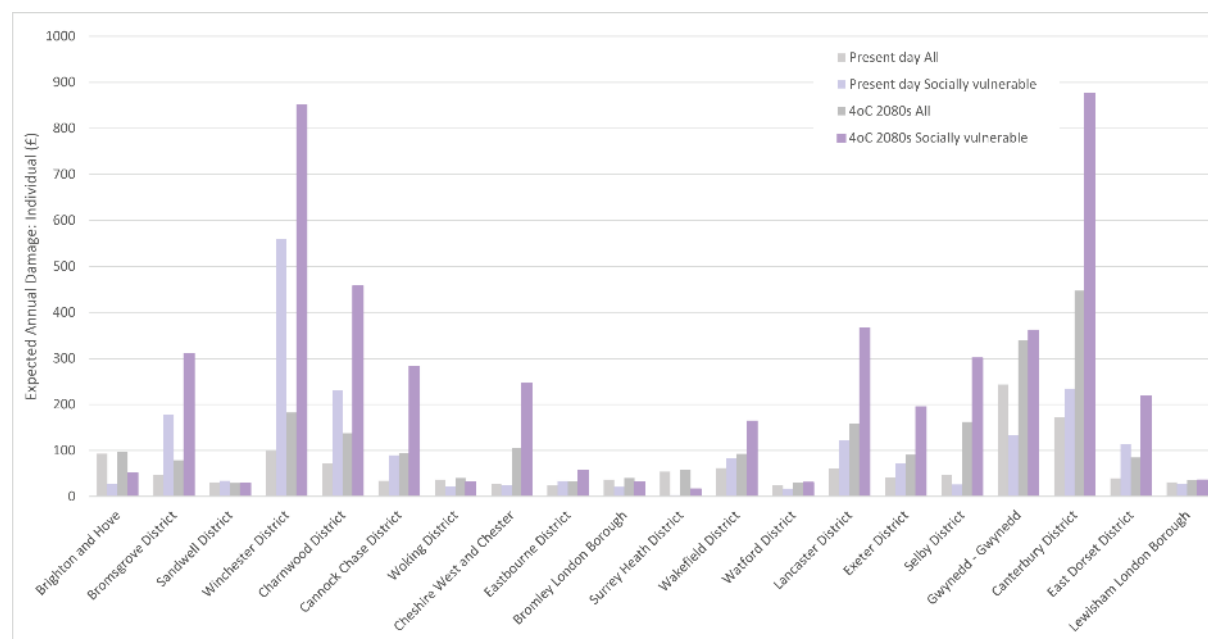


No population growth. The Social Flood Risk Index (SFRI) is defined earlier in Section 4.1. The non-monotonic behavior in risk in some locations this reflects the complex interplay between influences of adaptation (see Chapter 6) and the spatial variation in climate change (see Chapter 5).

Figure 7-20 CLA – Social Flood Risk Index: By Local Authority (20 highest)



a) Local Authorities with the largest **future flood systemic disadvantage** (difference between the risk faced by most socially vulnerable - defined by top 20% NFVI - and all other neighbourhoods). No population growth.



b) Local Authorities experiencing the **greatest differential increase in risk** between the most socially vulnerable (defined by top 20% by NFVI) and all other neighbourhoods. No population growth. Ordered by the ratio of differential increase.

Figure 7-21 CLA – Expected Annual Damage: Individual – All and socially vulnerable neighbourhoods

7.6 Flood risk: By water company

All water company regions experience an increasing risk by the 2080s (Figure 7-22). This highlights the significant increases from present-day across the regions, but also the importance of adopting an enhanced approach to adaptation (Figure 7-23). With a Reduced Whole System adaptation risks increase significantly across most regions.

These figures show the changing risk in response to **all sources** of flooding. This will be an increasingly important lens as integrated (collaborative) approaches to adaptation are sought. It is however recognized that the present-day focus for the majority of water companies is surface water flooding and both Sustainable Urban Drainage (SUDS) and upgrades to conventional drainage infrastructure capacity. In the future natural flood management and property level measures will all be important adaptation considerations.

The number of people exposed to frequent flooding is increases in all water company regions under all adaptation futures. Figure 7-24 **Error! Reference source not found.** shows the number of people exposed to frequent surface water flooding (1in30 years or more frequent) by water company area and how these numbers change through to the 2080s (assuming a continuation of Current Levels of Adaptation, a 4°C rise in GMST and high population growth). Figure 7-25 shows the number of people exposed to frequent fluvial and coastal flooding (1in75 years or more frequent).

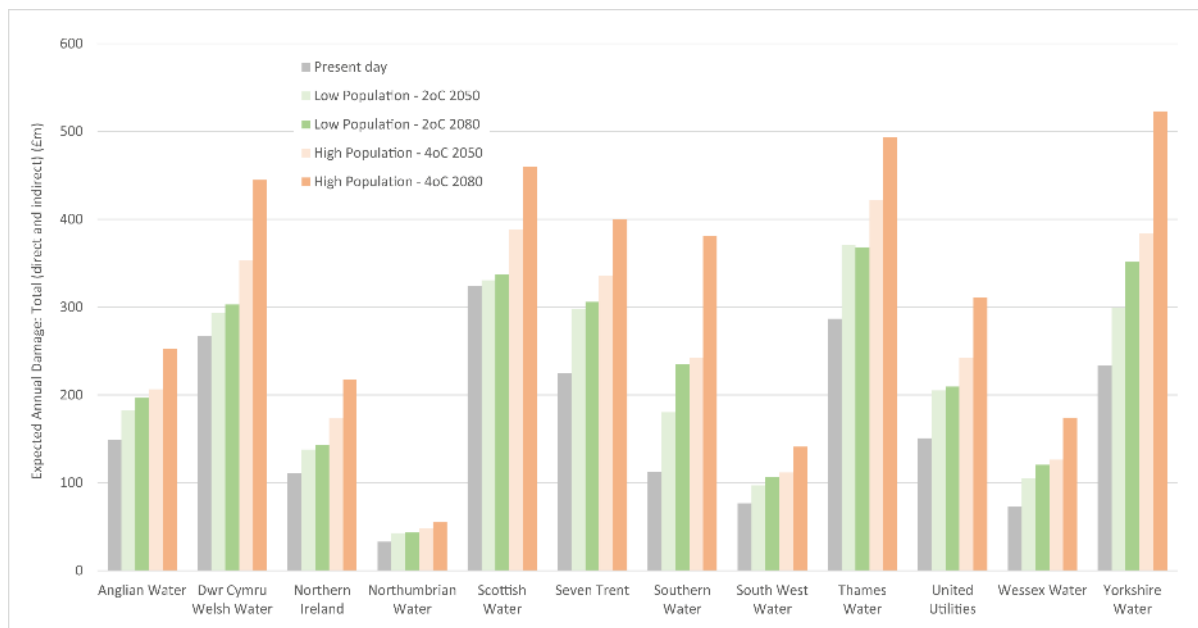
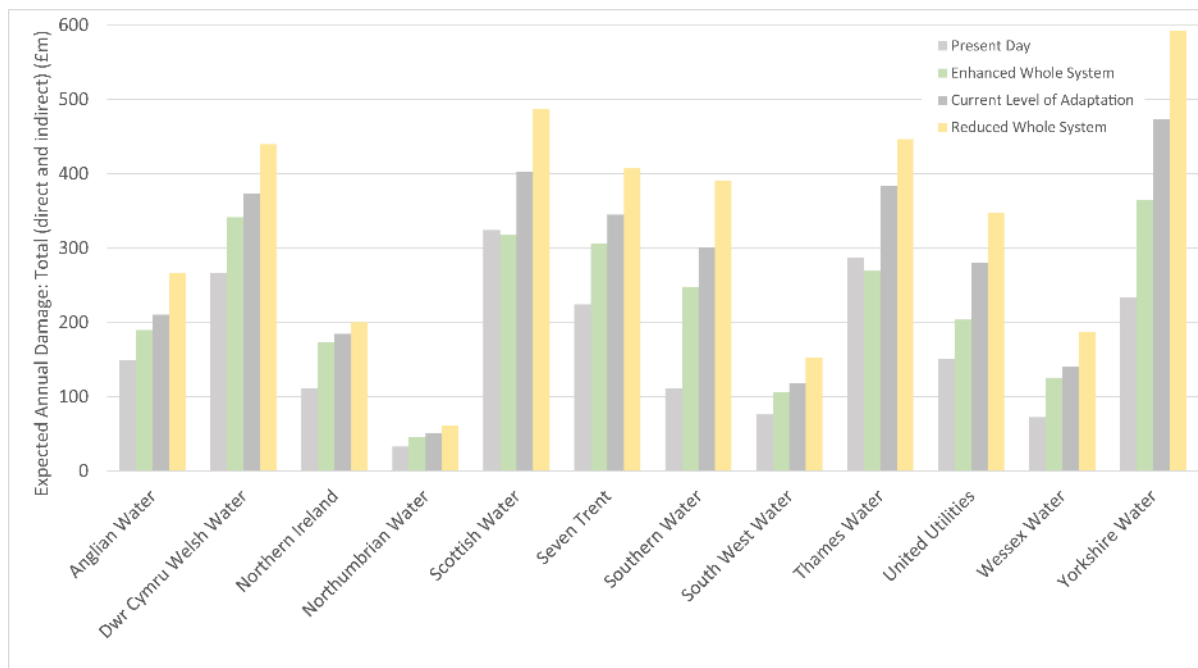
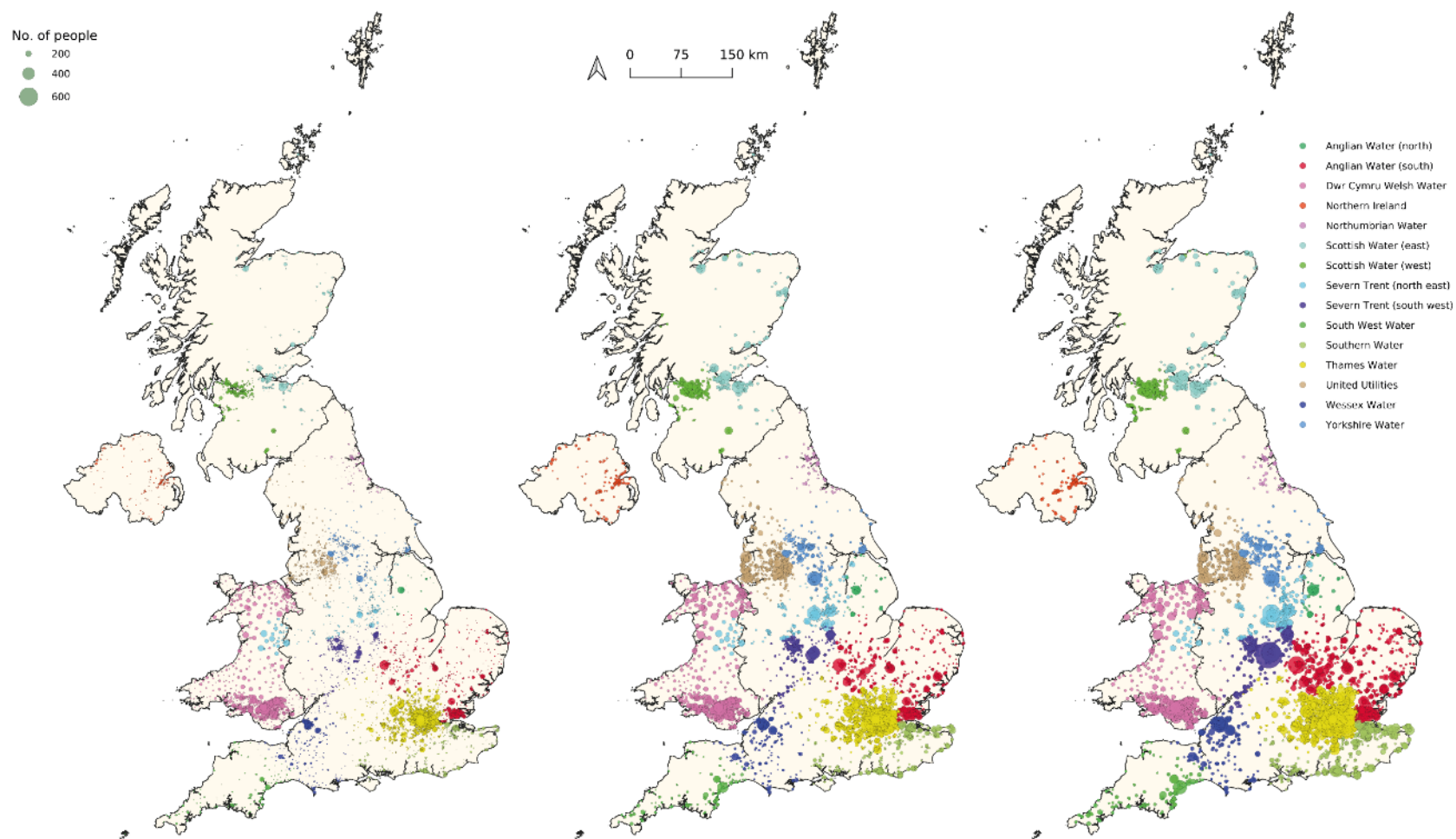


Figure 7-22 CLA – Expected Annual Damage: Total – By Water Company region



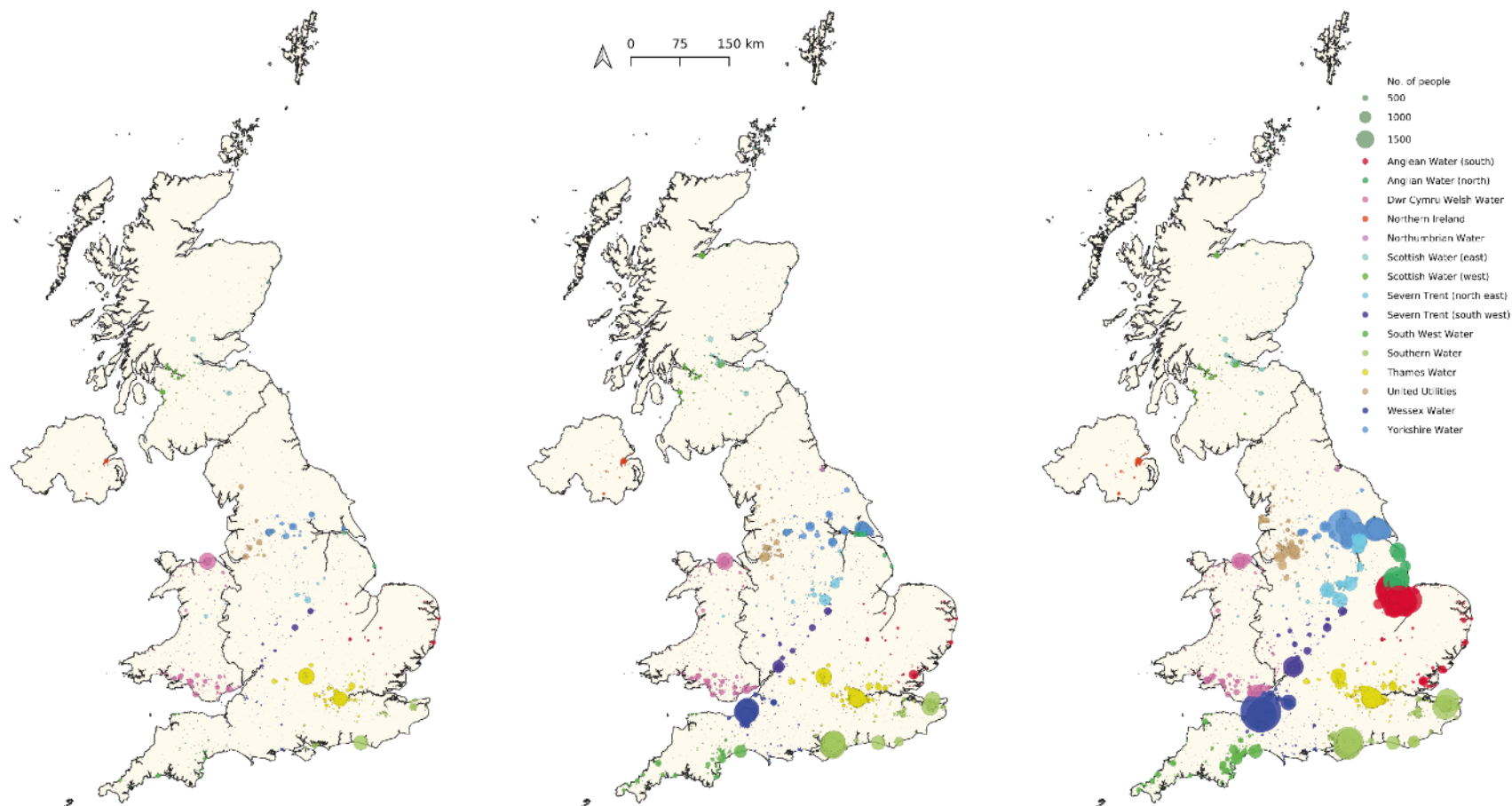
Future risks - 4°C 2080s No population growth

Figure 7-23 Adaptation comparison - Expected Annual Damages (Total): By Water Company region



Left: Present-day. Middle: 4°C High Growth 2050s; Right: 4°C High Growth 2080s. Frequent flooding refers to a return period of 1 in 30 year return period or more frequent.

Figure 7-24 CLA – Number of people exposed to frequent (1 in 30 year) surface water flooding – By Water Company region



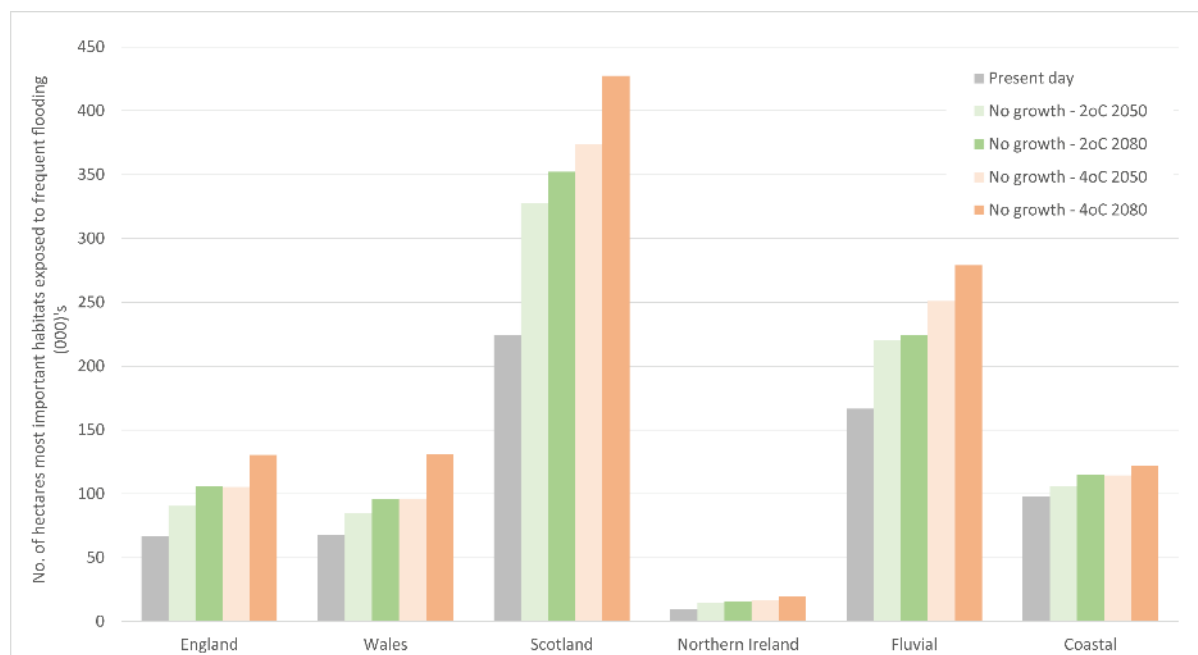
Left: Present-day. *Middle:* 4°C High Growth 2050s; *Right:* 4°C High Growth 2080s. Frequent flooding from fluvial and coastal sources refers to a return period of 1 in 75 year return period or more frequent.

Figure 7-25 CLA – Number of people exposed to frequent (1 in 75 year) fluvial and coastal flooding – By Water Company region

7.7 Flood risk: By agricultural and designated land area

Habitats

Nationally important habitats are represented here by Ramsar, SPA and SAC areas. Although it has not been possible to provide a detailed assessment of the impact of changing flood processes in these areas, a simple metric of the change in their exposure to frequent flooding (1in30 year return periods or more frequent) highlights the pressure many Designated Areas will be under from climate change (Figure 7-26). These changes are particularly acute under a 4°C climate future, and may be most significant in coastal areas, where more frequent exposure to saline flood waters may have significant impacts (although impacts will be highly localised and required site analysis that is beyond the scope of this report).

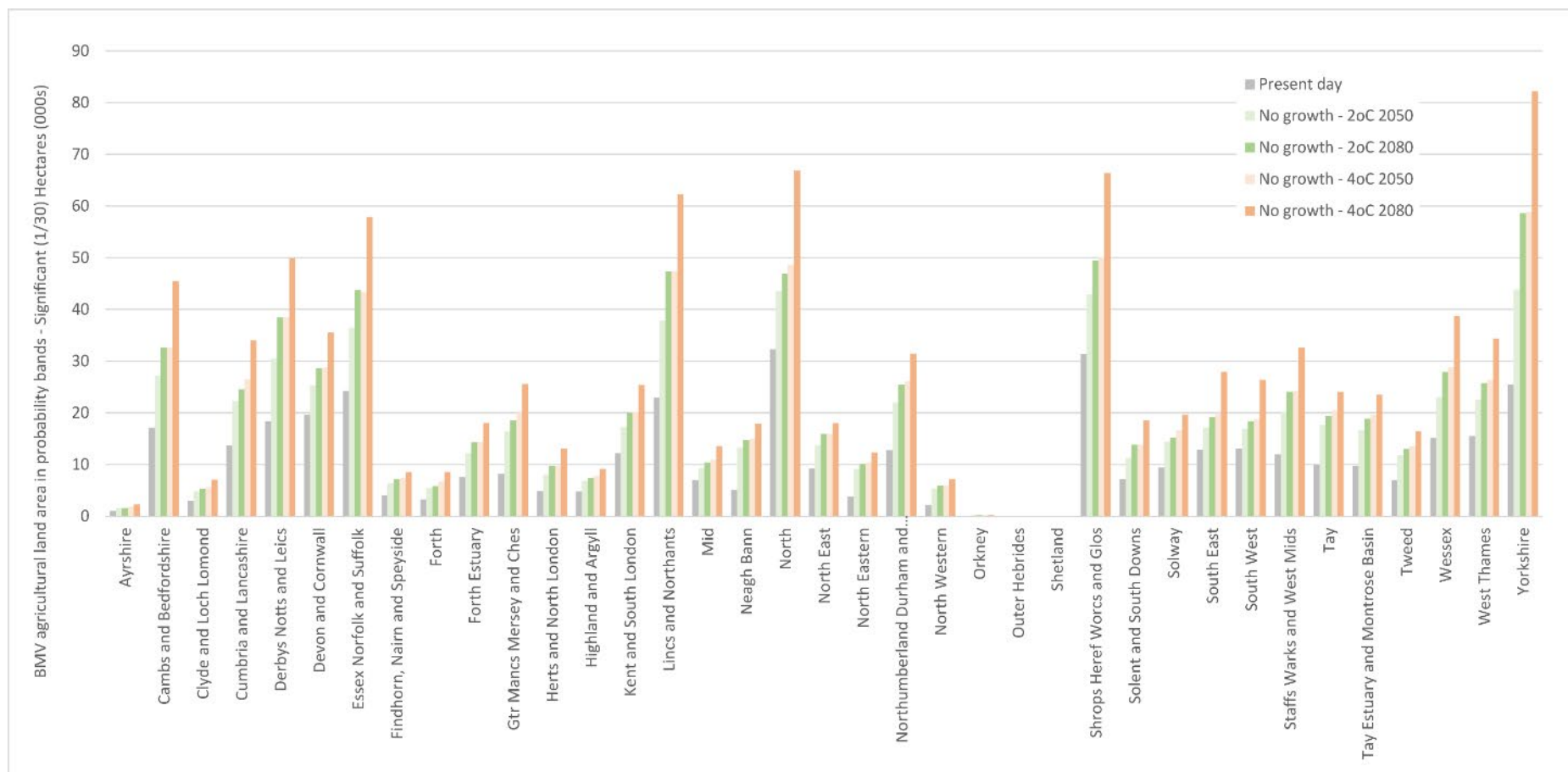


No population growth

Figure 7-26 CLA – Designated Habitats exposed to frequent flooding (1in30 or more frequent): By country

Agricultural land

Agriculture responds to climate change and flooding in multiple ways not explicitly considered here (changes in the seasonality, chosen crops, farm management practice etc.). It remains useful however to understand the changing exposure of agricultural land to frequent flooding (1in30 years return period or more frequent). The results show a significant increase in exposure to frequent flooding across the UK with the largest increases in the agricultural heartlands of Lancashire and Northamptonshire as well as Bedfordshire and Cambridgeshire and Yorkshire (Figure 7-27). Flooding may also impact agricultural in more marginal locations that have little (or no) Best and Most Versatile (BMV) land. The impact on these more marginal land (and associated activities and communities) is not considered here.



By CCRA Region (short names used on chart for reasons of space)

Figure 7-27 CLA – Best and Most Versatile Land exposed to frequent flooding (1in30 or more frequent): By Region and flood source

7.8 Flood risk: By infrastructure type

Category A

Category A infrastructure is defined here as assets linked to water (clean and wastewater treatment sites) and energy (generation, transmission, and distribution). The datasets to support this assessment are less well described than other property datasets (and so too is the relationship between flooding and economic damage or disruption, although this is improving). It remains useful however to explore the changing exposure of Category A infrastructure under climate change (noting future expansion of the infrastructure provision is not considered). Given infrastructure is owned and managed at multiple spatial scales, the changing exposure is reported by CCRA Region (Figure 7-28). The results highlight a significant increase in exposure across the UK. These risks are mapped for the present-day and the 2050s and 2080s under a 4°C future in Figure 7-29 (assuming a continuation of Current Levels Adaptation).

Note:

The datasets underlying the Category A infrastructure are less well established than other datasets used here. Equally the small number of sites in some areas means the aggregated results are less robust as they will be heavily influenced by local site conditions that may not be captured here.

Category B

Category B infrastructure assets are defined here as transport (railway stations), landfill sites, emergency services sites (hospitals and blue light service stations) as well as sites that provide social support services (care homes, GP surgeries, and schools). The changing exposure of these sites to frequent flooding is shown by CCRA Region in Figure 7-30. The results highlight a concentration of Category B infrastructure in metropolitan regions (such as Greater Manchester) and significant increases in exposure with climate change. These risks are mapped for the present-day and the 2050s and 2080s under a 4°C future in Figure 7-31 (assuming a continuation of Current Levels Adaptation).

Flood defence standards

Figure 7-23 shows the impact of climate change on flood defence standards of protection by the 2050s in the absence of further adaptation for both fluvial and coastal defences. The reductions are significant, this is most marked at the coast. In fluvial settings most defences experience a reduction in standard, but in some areas climate change acts to increase the effective standard provided. This reflects the complex spatial pattern of future changes in peaks flows, that in some case (particularly under the 4°C future) reduce.

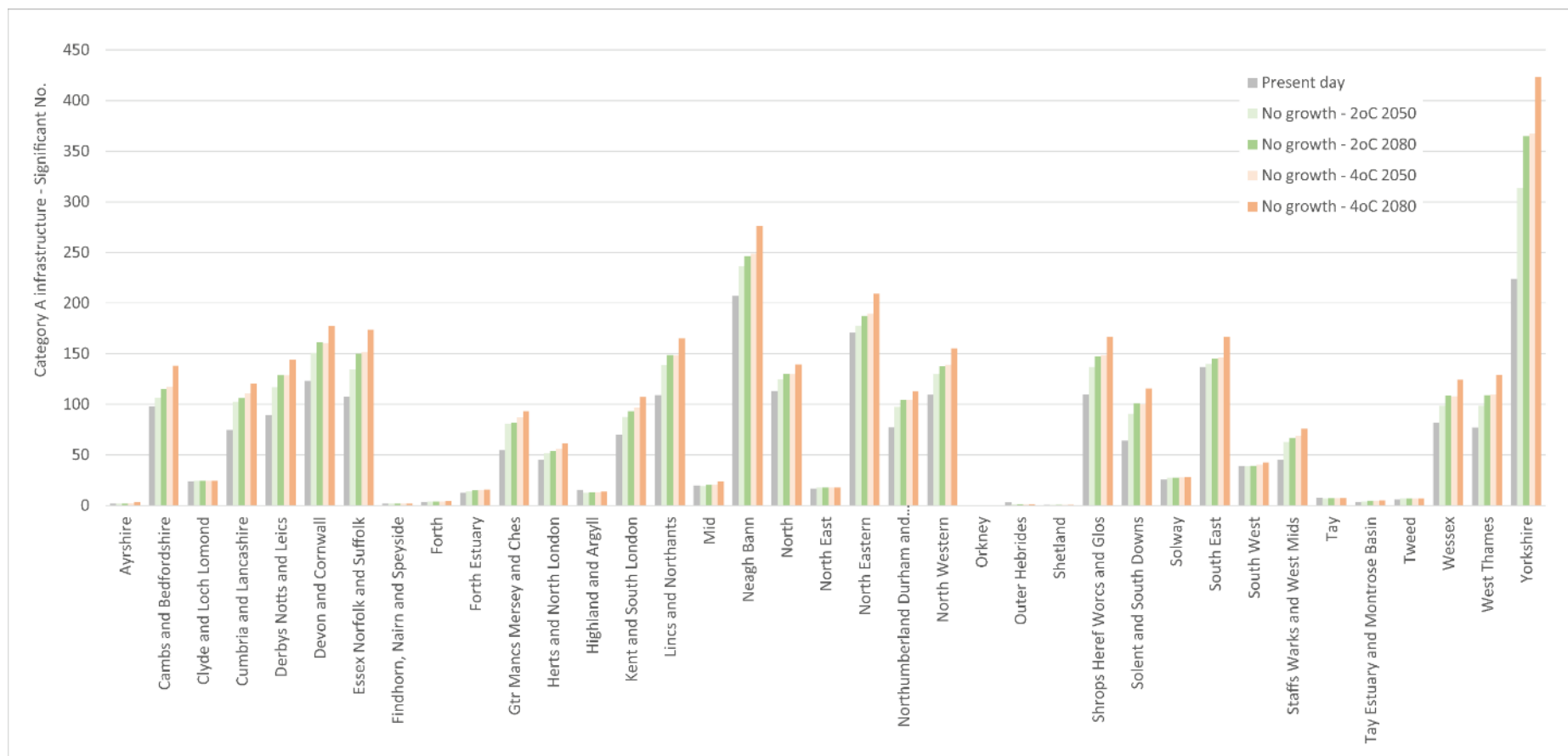
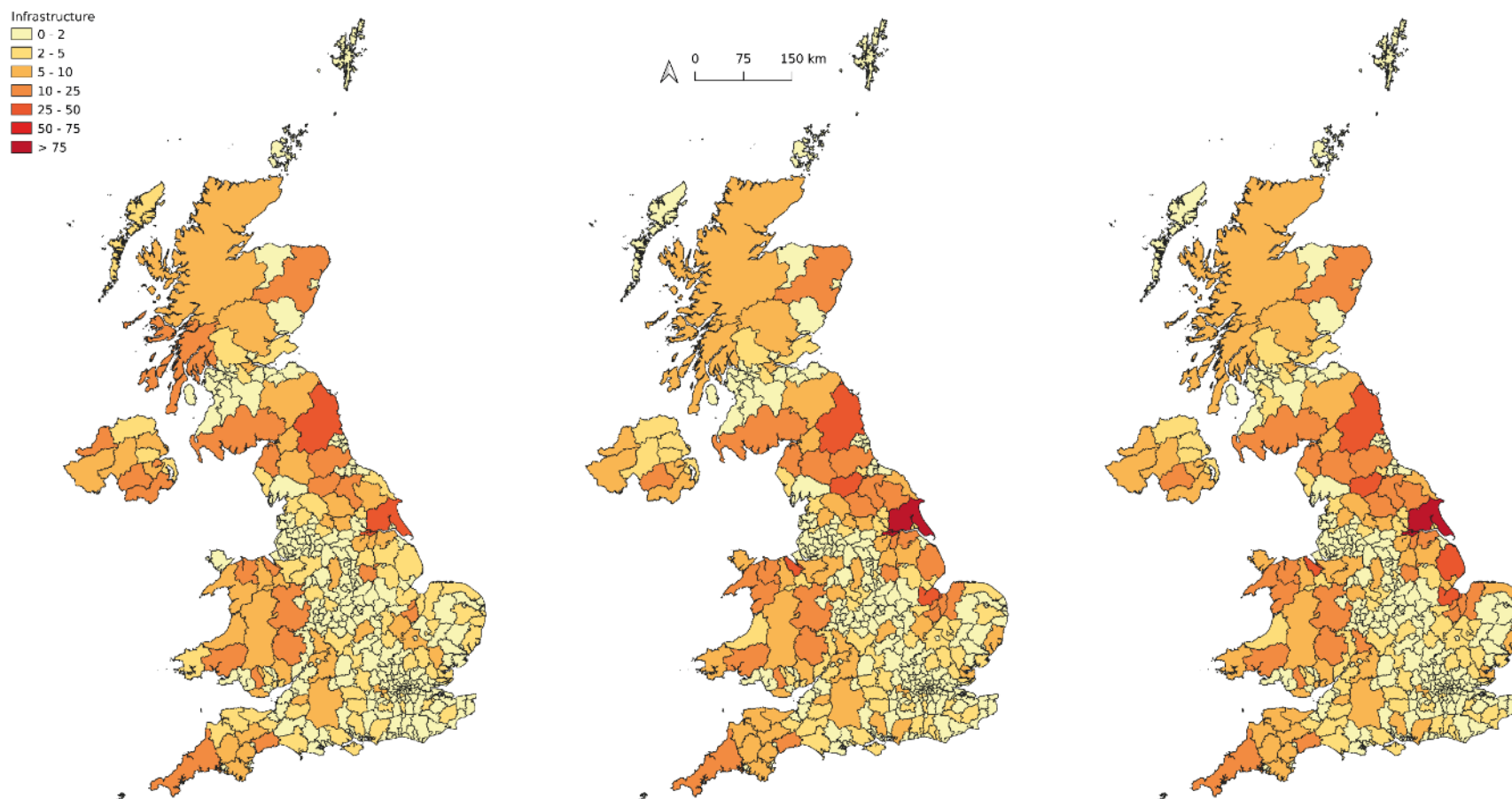


Figure 7-28 CLA – Category A infrastructure (no. of sites) exposed to frequent flooding (1in75 or more frequent): By CCRA Region



Left: Present-day. Middle: 4°C High Growth 2050s; Right: 4°C High Growth 2080s

Figure 7-29 CLA – Category **A** infrastructure (no. of sites) exposed to frequent fluvial or coastal flooding (1 in 75 or more frequent): **By Local Authority**

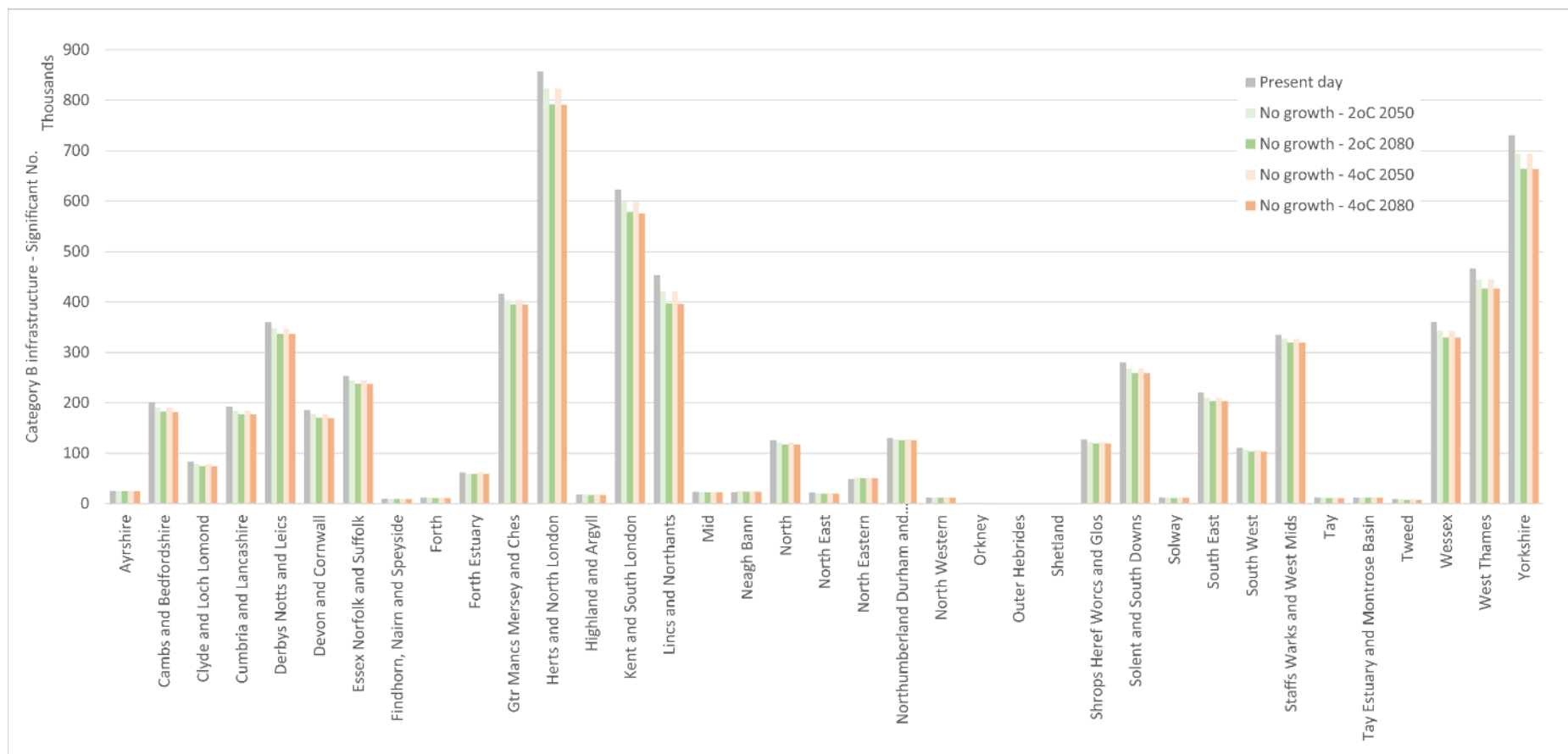
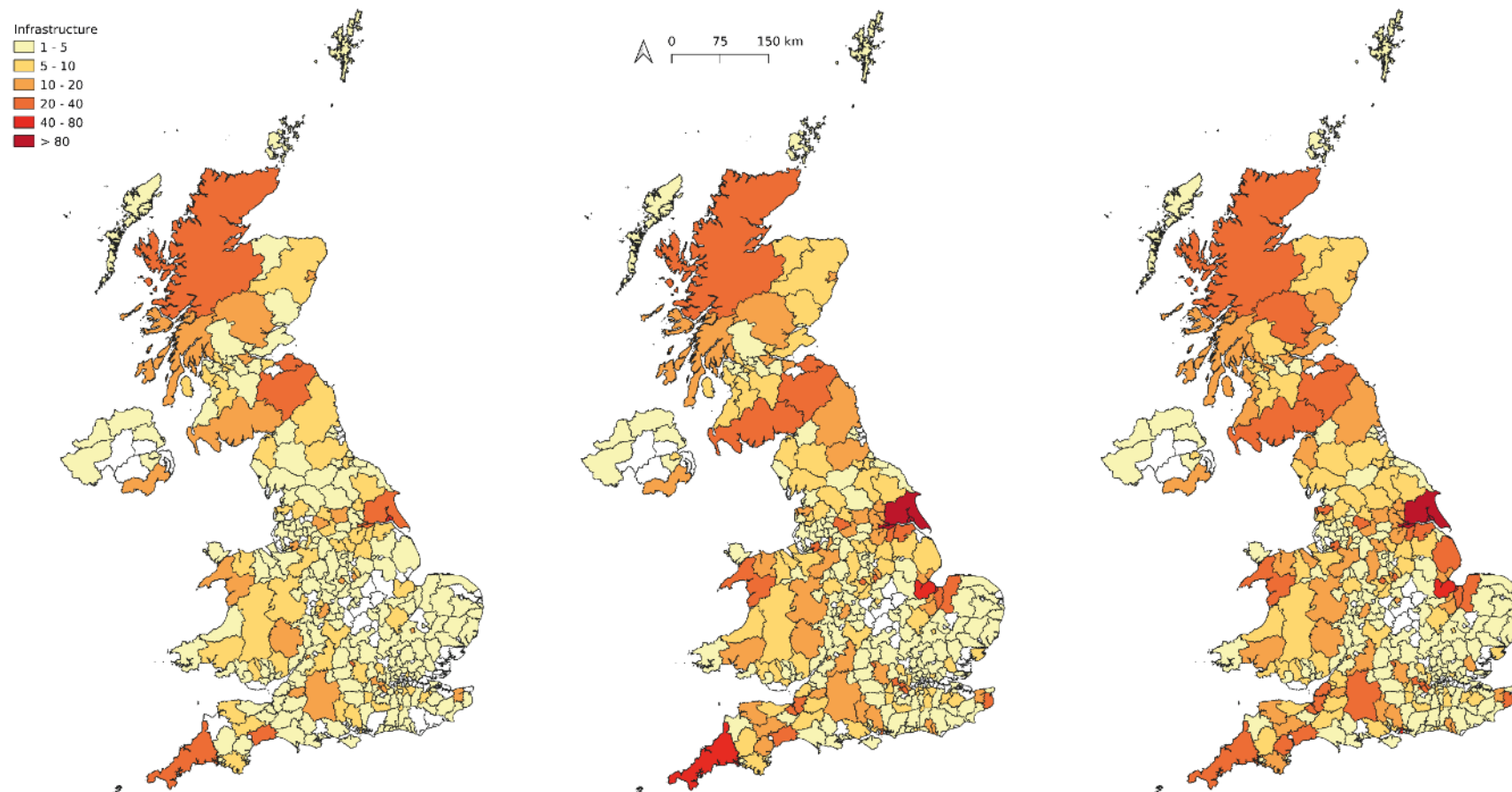
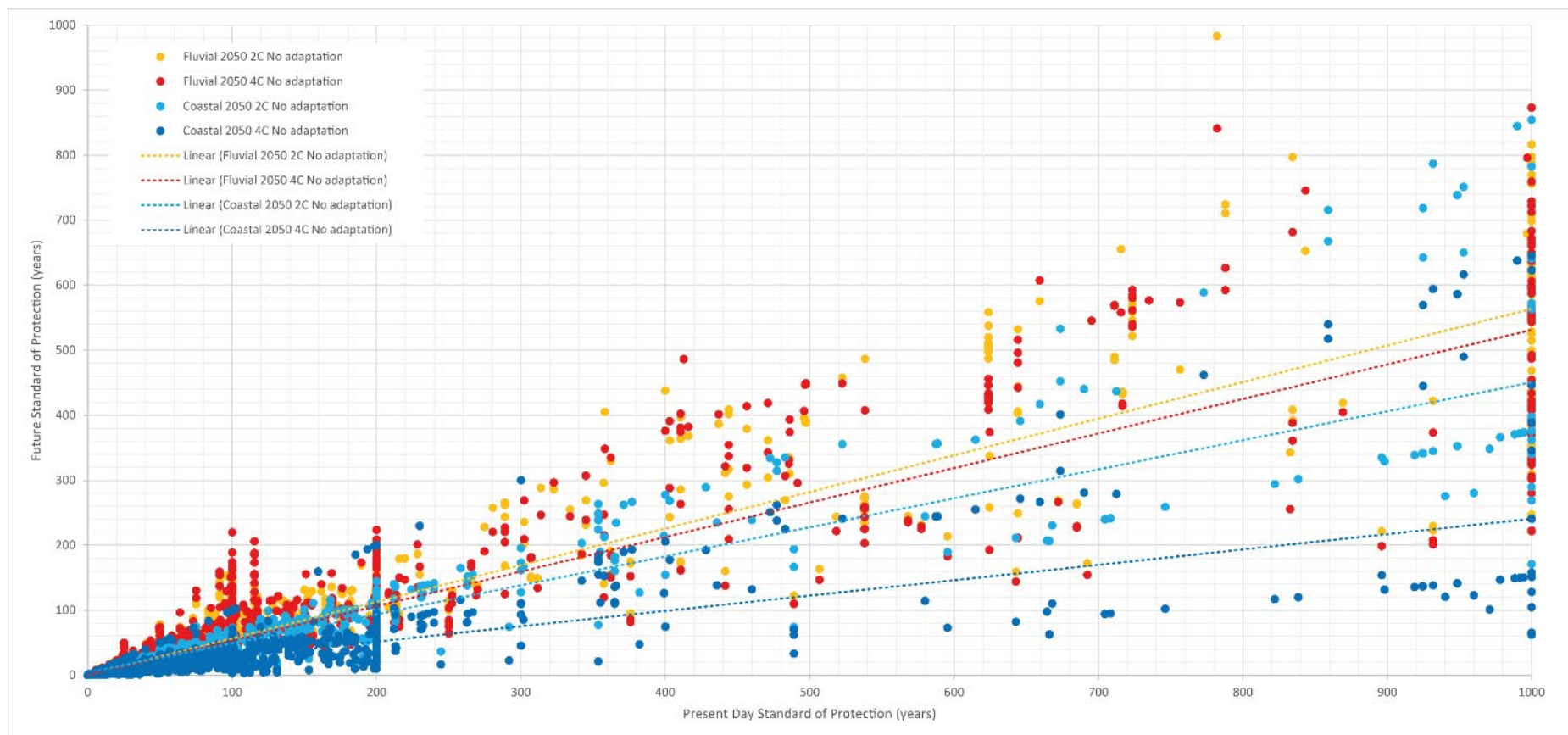


Figure 7-30 CLA – Category B infrastructure (no. of sites) exposed to frequent flooding (1in75 or more frequent): By CCRA Region



Left: Present-day. Middle: 4°C High Growth 2050s; Right: 4°C High Growth 2080s. Fluvial and coastal flooding only.

Figure 7-31 CLA – Category B infrastructure (no. of sites) exposed to frequent fluvial or coastal flooding (1 in 75 or more frequent): By Local Authority



x-axis represents the present-day representative standard of protection (for each fluvial and coastal neighbourhood). y-axis presents the future standard by the 2050s under a 2 and 4°C climate future.

Figure 7-32 Impact of climate change on defence standards: 2050s assuming no adaptation

7.9 Future flood risk: Important drivers

Drivers of the changes in risk

Figure 7-33 disaggregates the influence of climate change, population growth and adaptation on future flood risk (by the 2080s). The chart reinforces the dominant influence of climate change in driving future risk (increasing Expected Annual Damages (total) by £4.2bn under a 2°C future and £6.9bn under a 4°C future in the absence of adaptation). The difference between a 2°C and 4°C is greatest at the coast (with an additional ~£1.8bn of EAD incurred under a 4°C rise in GMST compared to 2°C). The additional influence of population growth also varies with the projection. Assuming low population growth the impact is limited (although not insignificant, adding £364m to EAD), whereas a high population growth future has a much greater influence (adding £2bn to the EAD). By the 2080s the combination of a 4°C climate change and high population growth future drives an increase of £9.2bn EAD in the absence of adaptation.

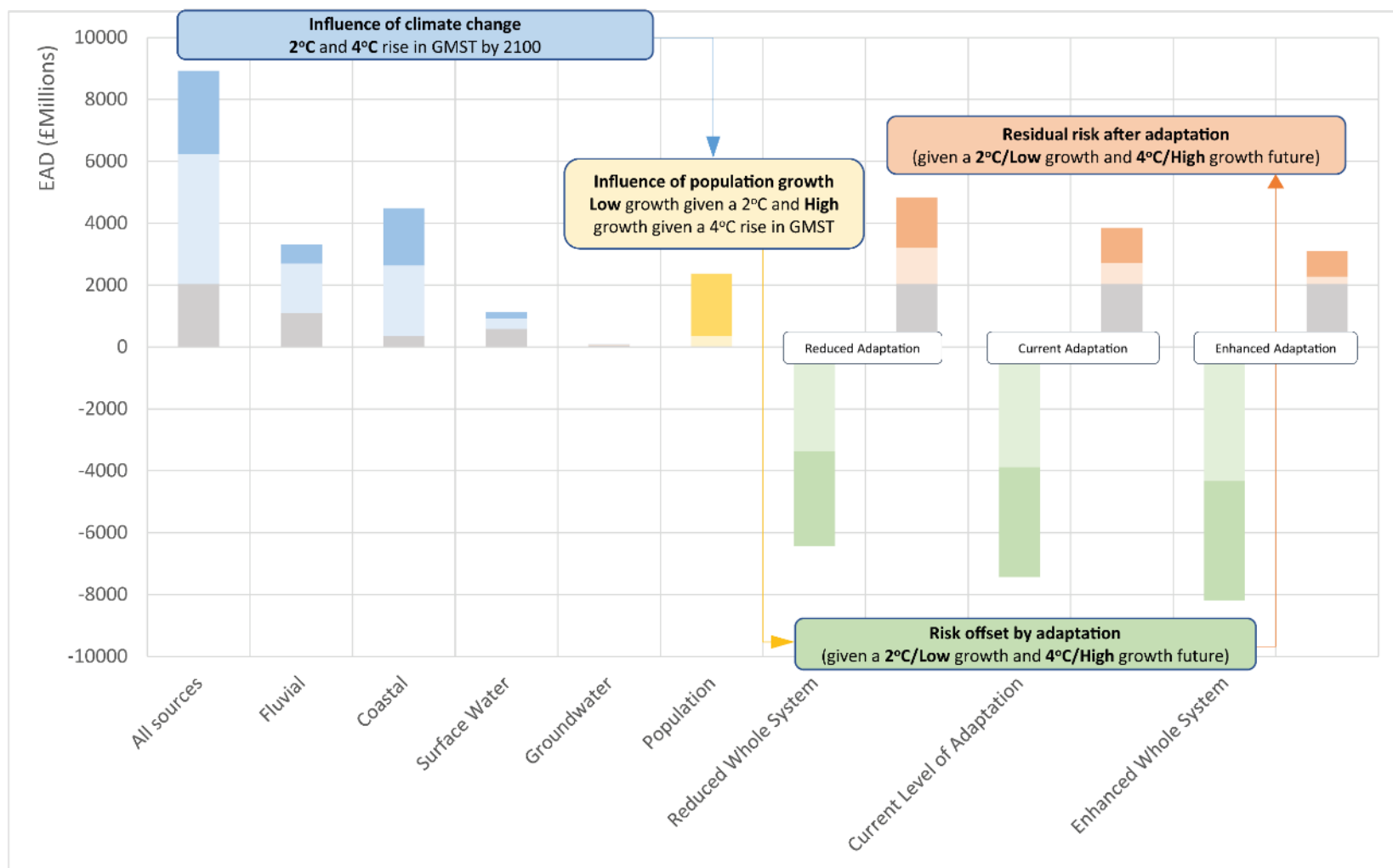
All three adaptation portfolios limit this increase. A continuation of Current Levels of Adaptation offsets ~£7.4bn of Expected Annual Damages in 2080s (under a 4°C high population growth future). This results in a net increase in risk and an approximate doubling of Present-Day risks. Under a 2°C low population growth future the net increase is much less (~£0.7bn). An Enhanced Whole System (EWS) approach to adaptation offsets ~£8.2bn of EAD (total). This limits the increase in risk from Present-day levels to £0.2bn in a 2°C low population growth future. Under a 4°C high population growth future the increase remains significant (rising by ~£1.1bn). The increase in risk offset by a Reduced Whole System (RWS) approach is much more limited (~£3.4bn in 2°C low population growth future) and results in risks increasing to £4.8bn by 2080s under a 4°C high population growth future.

Within the alternative portfolios conventional flood defences (both capital and revenue investment) remains the most important management measure. Catchment management, property flood resilience (both residential and on-residential take up) are also significant in reducing EAD (reflecting their ability to contribute to the management of more frequently occurring events). Flood forecasting and warning provide an underpinning response across all portfolios (but the full benefits associated with saving lives and minimizing wider disruption are not included here). The residual risk covered by insurance reduces (despite wider take-up) with more ambitious adaptation portfolios went compared to other adaptation approaches (reflecting greater reduction in risk due to other measures).

Adaptation costs

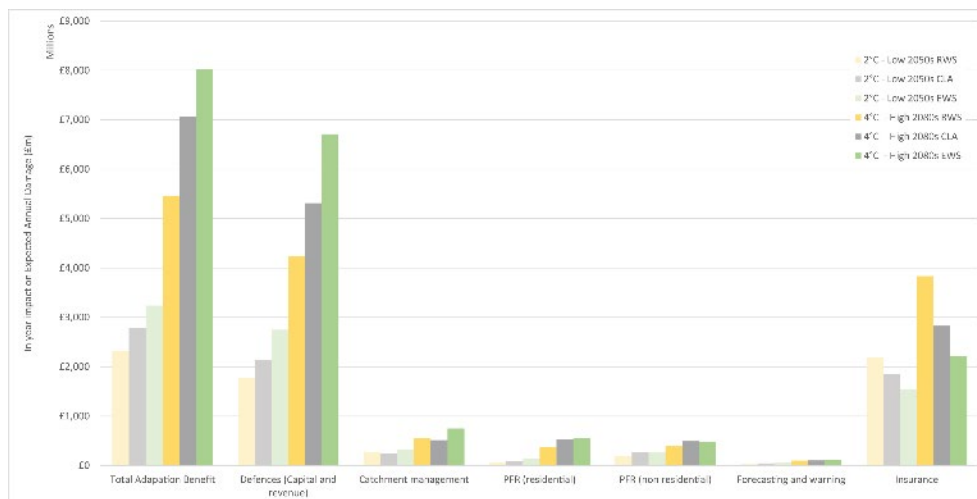
The costs associated with the alternative adaptation portfolio vary (Figure 7-35). The variation is most marked in scale of investment directed towards conventional defences, urban management and natural flood management. A comparison of the benefits and costs however shows the significant returns across all adaptation responses and the shifting balance of benefits and costs under each portfolio (Figure 7-36). Under a Reduced Whole System approach, for example, benefits are lower but so too are the costs, hence the Benefit-Cost Ratio is often higher than alternative portfolios. Within an Enhance Whole System approach the opposite is true. The balance between measures also varies within each portfolio. For example, in the Enhanced whole System approach, the contribution of PFR measures reduces as greater protection is provided by conventional and catchment-based responses. These findings support national scale analysis; such as the Environment Agency's Long-term Investment Scenarios (2019) that suggests a long-term annual average investment of over £1 billion in FCRM activities and the importance of adopting a portfolio response.

Note: The costs are indicative and based on a similar approach set out in Sayers *et al.*, 2018 (as used in the National Infrastructure Commission's assessment of flood investment needs for England).



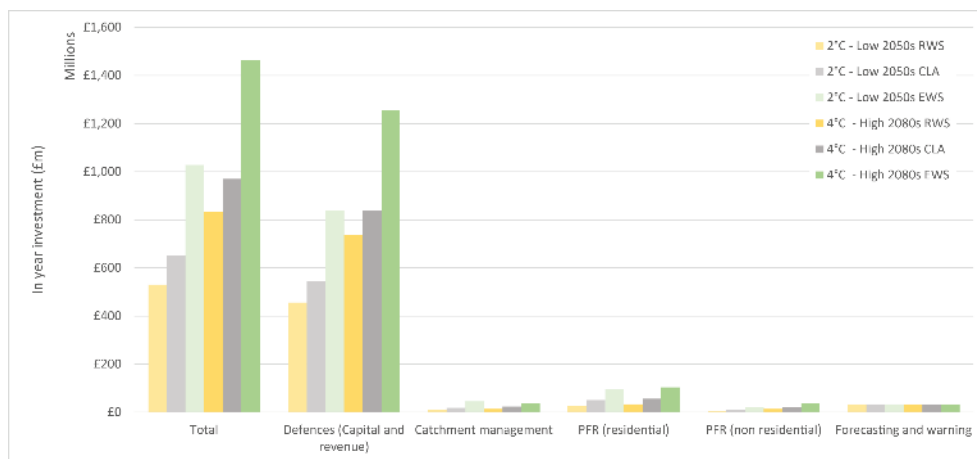
Grey: Present-Day risk. Lighter shading: Additional risk compared to present-day under a 2°C/Low growth future; Darker shading: Additional risk compared to a 2°C/low population growth future under a 4°C/high population growth future.

Figure 7-33 Drivers of changes in risk by 2080s – Expected Annual Damage (total)



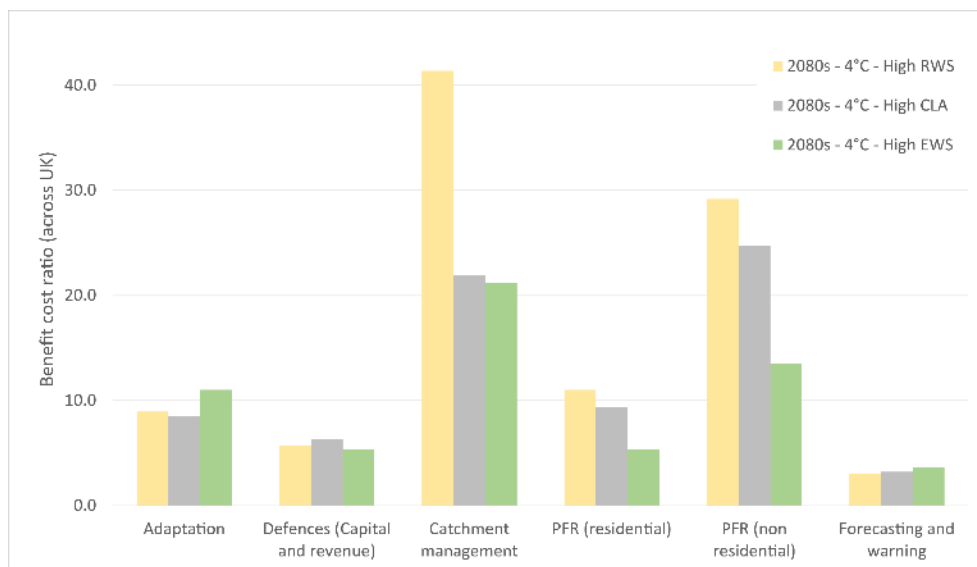
Note: Impact on Expected Annual Damages here (ii) Excluding spatial planning, shoreline management and urban management.

Figure 7-34 Adaptation benefit: Disaggregated contributions



Note: (i) Excluding inflation; (ii) Excluding backroom and central costs, spatial planning, shoreline management and insurance costs. Potential major infrastructure investment (for example a new Thames Barrier) are excluded.

Figure 7-35 Annual adaptation investment



Note: A high level assessment of the benefit to cost ratio aggregated across the UK

Figure 7-36 Benefit cost of adaptation measures within each portfolio

8.0 SUMMARY AND CONCLUSIONS

In the absence of any adaptation climate change is the dominant influence in driving future risk, increasing Expected Annual Damages (EAD, direct and indirect) by £4.2bn under a 2°C future, and £6.9bn under a 4°C, future by the 2080s. The influence of climate change is greatest at the coast, with EAD rising by a further 70% under a 4°C rise in GMST compared to 2°C. For comparison, the risks associated with all other flood sources increase by ~20% between a 2 and 4°C future.

The influence of change in population varies with the growth projection. Assuming a low population growth future the additional impact on risk is limited in a 2°C future (although not insignificant, adding £364m to EAD by the 2080s in the absence of adaptation). A high population growth future has a much greater influence (adding ~£2bn to the EAD in a 4°C future). By the 2080s, the combination of a 4°C climate change and high population growth future drives an increase of £9.2bn in EAD (direct and indirect) in the absence of adaptation.

All three adaptation portfolios limit the increase in risk, but in no scenario is risk lower in the future compared to today. A continuation of Current Levels of Adaptation (CLA) offsets ~£7.4bn of Expected Annual Damages in 2080s (under a 4°C high population growth future) resulting in a net increase in risk of ~£1.8bn above present-day (rising from ~£2bn today to ~£3.9bn in the 2080s). An Enhanced Whole System (EWS) approach to adaptation offsets ~£8.2bn of EAD (total) in the same scenario; limiting the net increase in risk to ~£1.1bn. A Reduced Whole System (RWS) approach offsets much less (~£6.4bn); consequently, the increase in risk from present-day is much greater (~£4.8bn).

Concluding comments under each adaptation portfolio are elaborated in turn below followed by review of the challenges and issues that appear across all portfolios.

8.1 Current Objectives: Current Level of Adaptation

A continuation of Current Levels of Adaptation will lead to an increase in risk – even assuming success in mitigating climate change and limiting the rise in GMST to 2°C by 2100.

The ‘current objectives’ policy response used assumes flood risk management policies continue to be implemented as in the recent past whilst taking on-board anticipated changes that may result from recent changes in policy. For example, the influence of new and emerging policy frameworks such as the 25 Year Environment Plan and the National Planning Policy Framework (in England), the most recent consultation draft of the revised TAN15¹⁷ guidance in Wales and similar documents in Scotland, National Planning Framework No. 4¹⁸. All of these and similar plans, guidance and strategies are likely to encourage a longer-term perspective. They are also likely to encourage greater uptake of Natural Flood Management (NFM) and property flood resilience (PFR) measures than achieved in recent years. The influence of assessments such as the Long-Term Investment Scenarios (Environment Agency, 2019) also encourage greater investment in FRM.

By continuing with the Current Level of Adaptation, flood risks are projected to change:

- **By the 2080s:** Expected Annual Damages (EAD, including direct and in-direct impacts) are set to increase from present-day levels. Under a 2°C future, EAD rises from £2bn to between £2.7-3.0bn depending upon the associated population growth. Under a 4°C future, EAD rises to

¹⁷ <https://gov.wales/technical-advice-note-15-development-flooding-and-coastal-erosion>

¹⁸ <https://www.transformingplanning.scot/national-planning-framework/>

between £3.5-3.9bn. Much greater adaptation action will be needed if risks are to be maintained at (or reduced from) present-day levels.

- **Risk by Country:** England contributes most to the UK flood risk today (~£1.3bn) and in the future (contributing around 70% of the economic risk and ~90% of the number of people living in flood prone areas by the 2080s). When normalised by the population exposed to flooding, individuals experience higher levels of Expected Annual Damage in Scotland, Northern Ireland, and Wales (rising from ~£200-250 today to ~£300-500 per person by 2080s under 4°C climate future across all sources of flooding). Equivalent present-day risks in England are much less, but also double by the 2080s under the same future (from £49 to £109).
- **Risk by settlement:** Urban flood risk is dominant today and in the future. Urban towns (away from larger urban conurbations) contribute the most to these risks (~50% of all people living in flood prone areas living here, equal to ~3.3m people). Those living in flood prone rural areas are, on average, exposed to a much higher risk (e.g. present-day between £107-252 per person) compared to their urban counterparts (£44-87 per person). This difference exists today but is exacerbated in the future (most noticeably in a 4°C high population growth future – rising to between £195-425 in rural areas and £71-162 in urban areas).
- **Risk by source:** Fluvial flood risk is dominant today and remains so in the future. The proportional increase in fluvial flood risk is however much less than either coastal or surface water sources (rising from an Expected Annual Damage (direct and indirect) of £1.1bn to £1.6bn under a high population 4°C future). Surface water risks more than double in same scenario (from ~£0.6bn to ~£1.2bn) and coastal areas experience a threefold increase in risk (from £0.4bn to £1bn). This increase is reflected in significant increase in the average EAD per person at the coast (raising from £60 to £210 per person). Coastal erosion (excluded here) may add further to these risks. Groundwater flooding remains a small proportion of the UK risk (rising from £54m to £95m).
- **Risk for the socially vulnerable:** In many rural towns and villages, and smaller urban cities and towns, the most socially vulnerable are exposed, on average, to greater levels of flood risk. Across the UK's *rural towns in spare setting* the Expected Annual Damage is ~£148 per person (living in a flood prone area) but £279 per person in the most socially vulnerable neighbourhoods. These differentials continue in the future and widen in some settings, particularly urban towns and cities away from the larger conurbations (where the average damage per person increases by a factor of 2.8 in the most socially vulnerable neighbourhoods compared to 2.5 elsewhere).
- **Links to mitigation:** The increase in risk is substantially greater under a 4°C future compared to a 2°C future; with the estimates of risk diverging significantly from the 2050s. This highlights the importance of a 'twin-track' approach focused on both adaptation to mitigation efforts if flood risk is to be managed.

8.2 No additional action: Reduced Whole System adaptation

A Reduced Whole System (RWS) approach to adaptation (no additional action) sees risk increase substantially by the 2080s

In the context of flooding, an assumed policy of 'no additional action' this does not mean taking no further action to maintain or improve flood defences or maintaining existing defence standards at present-day levels in all locations in all climate futures. Instead 'no additional action' assumes adaptation to flood risk continues but implementation with a lower level of ambition.

Consequently, investment in conventional defences fails to keep pace with climate change; there is limited take up of innovative catchment-based or urban run-off measures; pressure for

development and economic growth lead to continued new development on the floodplain; and property level flood resilience continues to experience limited take-up amongst existing properties. Flood forecasting and warning systems continue to be as effective in reducing risk as today. There are several plausible reasons that may drive such a change. Other threats may become increasingly dominant in public funded priorities (translating to a reduction in the willingness to pay for flood risk management) or our collective capacity to promote and deliver flood risk management may wane as political and social capital is directed towards other priority issues).

The Reduced Whole System (RWS) portfolio of adaptation measures reflects this policy context and leads to a substantially greater increase in risk than experienced assuming a continuation of Current Levels of Adaptation. Across the UK, Expected Annual Damages, for example, rise from ~£2bn today to £4.8bn by the 2080s (4°C and high growth) compared to £3.9bn under *Current Objectives*. This increase is driven by increases in risk across all sources and settlement types under a reduced approach to adaptation.

The reduced access to insurance (in the assumed absence of an effective replacement for Flood Re) sees take-up rates reduce and the Relative Economic Pain (ratio of uninsured loss to income) increase. This is greatest in most socially vulnerable neighbourhoods in coastal areas and urban towns and cities.

8.3 Current Objectives+: Enhanced Whole System adaptation

An Enhanced Whole System (EWS) approach to adaptation (Current Objectives+) limits the increase in risk.

The ‘current objectives+’ policy response goes beyond the current implementation of policy (and recently introduced policy) to represent a higher level of ambition as part of an ‘Enhanced Whole System’ (EWS) portfolio approach to adaptation. For example, investment in flood defence increases (including in more socially disadvantaged neighbourhoods) and land use planning policy is more successful in restricting development in the floodplain than currently achieved or anticipated. Awareness raising and a strengthening of building regulations and planning controls encourage greater receptor level resilience. Forecasting and warning systems develop with increased levels of sophistication, targeting those at risk more accurately than has been possible to date. Opportunities for more integrated planning and implementation are sought and momentum towards a ‘net zero’ emissions future increases (e.g. as presented for England in the 25 Year Environment Plan and the National Planning Policy Framework, MHCLG, 2019), Planning Policy Wales (WG, 2018)). Together this leads to an increased role for nature-based approaches, including catchment management, coastal realignment, and update of Sustainable Urban Drainage systems (SUDS).

By adopting an Enhanced Whole System approach to adaptation, flood risks are projected to change:

- **Increase in risks are more limited:** With an EWS approach to adaptation, increases in future flood risks are significantly reduced when compared to continuing the Current Level of Adaptation (CLA); Expected Annual Damages (direct and indirect) rise to £3.1bn by the 2080s under a 4°C high population growth future. This is £0.8bn less than under the CLA assumption.
- **Systemic disadvantage is reduced:** An adaptation portfolio of enhanced responses reduces risk in both rural and urban settings, including for the most socially vulnerable. This is most notable in smaller *urban cities and towns* with the rise in Expected Annual Damages per person lessened from £189 (under an CLA approach) to £162 by the 2080s in a 4°C high population growth future.

8.4 Cross-cutting adaptation challenges and issues

- **Sources of flood risk:** Fluvial flooding contributes the greatest to economic damages now and in the future but the relative contribution of both surface water and coastal flooding increases.

Groundwater flooding remains a relatively small contribution to national risk (but will be important locally).

- **Risk for infrastructure and flood defences:** Category A and B infrastructures see a large increase in exposure driven by surface water and fluvial and coastal flood sources. The reduction in the standard of protection afforded by defences, in the absence of adaptation, is most marked at the coast. In fluvial settings most defences experience a reduction in standard, but in some areas climate change acts to increase the effective standard provided. This reflects the complex spatial pattern of future changes in peak flows, that in some cases (particularly under the 4°C future) reduce.
- **Risk for habitats and agricultural:** The changing nature of habitats and the impact of climate change on agricultural damage responds to multiple variables not explicitly considered here (changes in the seasonality, salinity, chosen crops, local land management practice etc.). There is however an increase in exposure of agricultural land (Best and Most Versatile land) to frequent flooding (1 in 30 years return period or more frequent). The largest increases are projected in the agricultural heartlands of Lancashire and Northamptonshire as well as Bedfordshire and Cambridgeshire and Yorkshire. Flooding may also impact agricultural in more marginal locations that have little (or no) Best and Most Versatile land. The impact on these more marginal lands (and associated activities and communities) is not considered here.
- **Systemic flood disadvantage:** The most socially vulnerable experience the greatest level of disadvantage in Northern Ireland, Wales, and Scotland – this is the case today and in the future. When considered through the lens of Relative Economic Pain the difference between the risk faced by the more and less socially vulnerable is significant. This reflects in part low income levels, but also levels of insurance take-up; an issue that will need to be addressed in the transition planning for Flood Re.
- **Spatial planning approaches:** The only adaptation response that acts to directly mitigate the influence of population growth is spatial planning; but spatial planning is always context specific. Many Local Authorities cannot avoid development in the floodplain whilst others have much more flexibility. The national planning framework needs to recognise this reality more directly and help locations that must build on the flood plain to do so in the context of a long-term plan to reduce risk and maintain safety. In some areas this may be by enforcing property level measures (for example in areas prone to fluvial flooding) but in coastal areas this is likely to mean a commitment to maintain appropriate long term protection (together with an acceleration in cost that is likely to follow) or implement managed retreat (an adaptation option not explicitly considered here). Indecision today has the potential to lock-in risk for future generations.
- **Coastal and estuarine areas:** Many estuary and coastal urban areas are unable to avoid floodplain development. Coupled with relative sea level rise (rSLR) this leads to a major increase in coastal flood risk (the fastest growing of all hazards). Exposure to flood risk can be managed by (i) avoiding locating new development in flood-prone areas (where this is possible), and/or (ii) realigning the urban landscape to reduce the number of people and properties that occupy floodable land (this could include localised land raising).
- **Catchment management provides a meaningful contribution to economic risk reduction:** Investment in catchment management provides significant returns when combined with conventional flood defences (as here) across the UK. The Benefit to Cost Ratio (BCR) of the catchment management measures is strong across all portfolios. The BCR reduces as the scale of adaptation ambition increases (as expected) but is always greater than ~20. This reflects the comparatively low cost and an ability to meaningfully contribute to the management of more

frequently occurring flood events that often drive Expected Annual Damages (based on economic benefits alone, noting that catchment management approaches also offer a wide range of co-benefits not considered here). The knowledge on the long-term performance of catchment management (and Natural Flood Management) is however limited compared to the performance of conventional flood defences or planning measures. This lack of comparable knowledge should not be a barrier to appropriate use as a legitimate component of a portfolio response given the wide range of associated benefits but should be addressed.

- **Going beyond Current Objectives+:** Under all adaptation portfolios considered here, risks rise under a 2 and 4°C climate future. To maintain present-day risk levels constant to the end of the century continued innovation in adaptation approaches will be required. This may include, for example, greater effort towards making space for coastal and river dynamics within local and large scale planning and development choices (including coastal realignment) as well as more integrated actions to address the increase in surface water flood risk.

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APPENDIX A. Supporting datasets

See separate file.

APPENDIX B. Risk metrics

See separate file.

APPENDIX C. Climate change projections

See separate file.

APPENDIX D. Individual adaptation measures: Representation in the FFE

See separate file.

APPENDIX E. Present-day comparisons

See separate file.

APPENDIX F. Supporting results

See separate file and associated spreadsheet of results at Local Authority scale (available on request).