Surface water Future risk and investment needs

Report prepared for the National Infrastructure Commission

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EXECUTIVE SUMMARY

Background

Across England, surface water flood risk is significant and projected to increase with climate change and development. The management of surface water flooding currently involves multiple organizations from the public and private sectors. In the recent past their collective investment in surface water flood management (SWFM) has been around £279 million per year. This study explores the scale of the continued investment that will be needed to address SWFM as the climate and the population changes.

Actions to reduce surface water flooding are also complex and multiple. Some measures, such as Sustainable Drainage Systems (SuDS), offer opportunities to deliver wider benefits (improved amenity, biodiversity, water quality, *etc.*) but they are not a silver bullet as their use is constrained in terms of space and the reduction in risk that they can achieve. Conventional drainage infrastructure (including piped networks) offers fewer wider benefits but nonetheless is likely to remain an important component of the SWFM portfolio of actions. Even with these and other measures, surface water flooding is likely to continue to occur. Incorporating measures to address this residual flood hazard (designing for exceedance) is an important consideration today and is likely to remain so in the future.

This analysis explores the relationship between investment and surface water flood risk through to 2100, with a focus on the residual risks that may exist by the 2050s and the investment need for the period from present day (2022) to 2050.

Approach

The Future Flood Explorer (FFE) framework is used to provide an estimate of future surface water flood risk and investment requirements within England. The analysis extends the approach used in the third UK Climate Change Risk Assessment, CCRA3 (Sayers *et al.,*2020) to include the last climate change projections (using recently available outputs from the Convection Permitting Model (CPM), a range of surface water management adaptation measures and their associated cost.

Two climate futures (a 2^{o}C and 4^{o}C rise in Global Mean Surface Temperature (GMST) by 2100 relative to pre-industrial times) and three population projections (none, low and high) are combined with 15 alternative surface water adaptation portfolios to explore the relationship between national investment in SWFM infrastructure and changing risk. Each portfolio incorporates the following measures in varying degrees:

- SuDS for new developments as well as retrofitting surface water storage and infiltration measures.
- Below ground conveyance, including modifying piped network capacity.
- Exceedance measures, including modifying surface flow pathways and property level measures.

No consideration is given to the influence of non-structural measures, such as improved forecasting and warning or awareness raising *etc.*

Attenuating surface water flooding has the potential to reduce combined sewer overflow (CSO) discharges. This is captured through a reduced cost associated with CSO improvements. This reduced cost is only accrued where SuDS measures are implemented.

Key messages

The national (England) analysis finds that:

#1 Return of investment – Reduction in economic damage

The analysis suggests an investment of ~£29bn provides a positive Net Present Value (NPV) return given a 2°C climate future and no population change, rising to ~£39bn in a 4°C and high population growth future. This represents an increase of 3.3 to 4.5 times on recent expenditure. The investment that achieves a maximum NPV (a notional economic optimum given the study constraints) varies between ~£9bn given a 2°C climate future and no population change and ~£12bn given a 4°C and high population growth future. This is based on consideration of reductions in economic flood damage achieved and real investment in capital and operational expenditure through to the 2050s.

#2 Opportunity for, and significance of, wider benefits from source-led adaptations

The inclusion of the value of wider benefits (air quality, amenity, carbon sequestration, *etc.*) into the economic analysis significantly increases the case for investment in surface water flood management using SuDS based portfolios; adding ~£0.6bn of benefits. These benefits do not accrue through conventional piped drainage responses.

#3 Investment in conventional piped drainage will be needed to supplement source-led SuDS

SuDS offer an important contribution to national surface water risk reduction. For real investments up to ~£5bn (by the 2050s) investments in SuDS accounts for around 20% (or more) of the national optimised investment portfolio. As investment levels increase, the return on investment slows and pathway-led (piped drainage) portfolios become increasingly selected to reduce risk. This highlights an 'effectiveness' limit to the source-led approaches and the need for supplementary pathway-led portfolios to deliver high standards of protection. This reflects inherent limitations on the performance of SuDS but also constraints of space (limiting the implementation of SuDS in some urban locations).

#4 Urban areas contribute most to surface water flood risks and have the greatest investment need

The majority of surface water flood risk is in urban areas and urban areas dominate the projected investment need (accounting for ~90% of the project investment regardless of the future or investment level). This reflects the greater population in urban areas and influence of impermeable urban surface on run-off.

#5 Not all surface water flooding can be eliminated, designing for exceedance is an important principle

The management of surface water flooding is not analogous to fluvial flooding. Protection against surface water flooding cannot be achieved through increased capacity in SuDS and piped drainage alone (as could be notionally argued in the case of providing a higher standard fluvial flood defence). Designing for exceedance (to address the residual flood hazard) is a central aspect of surface water management and such measures are considered as part of each portfolio. No consideration is given here to their implementation as a standalone action in those locations not identified for investment in broader drainage improvement. Exceedance measures are likely to be an important response in these areas, quantifying their benefits is outside of the scope of this study.

#6 Opportunity for, and importance of, adopting a more strategic and integrated approach to surface water management

Adopting a strategic approach to planning investments offers cost savings. This includes adopting city wide and catchment wide planning responses to reduce the costs, conservatively considered to offer cost savings of ~5-10%. More strategic action also offers opportunity to reduce flood risk whilst simultaneously reducing the costs of addressing storm overflows (CSOs). Assuming CSO cost savings accrue only in those locations where SuDS led portfolios are selected as part of the national optimised activities, the present value of the cost saving peaks at ~£4bn given a £20bn real (undiscounted) investment through to 2050s. The analysis indicates a greater opportunity to take advantage of SuDS led flood management approaches and hence CSO cost savings given a 2°C compared to 4°C future. In all futures considered, as the national investment level increases, piped drainage responses increasingly dominate the selected portfolios. Consequently, the CSO cost saving reduces.

#7 Lack of confidence in present day surface water flood risk

There is significant uncertainty in present day surface water flood risks and the number of properties impacted by surface water flooding. The central estimate of economic damage from surface water flooding from the Environment Agency's Long-term Investments Scenarios 2019 (~£1.25bn per year and ~3m properties) are used here to calibrate the present-day estimates within Future Flood Explorer (FFE) tools. These estimates are significantly greater than those presented in the Climate Change Risk Assessment (CCRA3) and are presented with caution given the difficulties in estimating surface water flood risks and the Environment Agency's ongoing efforts to improve these estimates (as part of the National Flood Risk Assessment 2). The FFE does not seek to determine present day risks from first principles but to emulate estimate assessments and then project the influence of change (in climate, population and adaptation). As the present-day assessments are refined, these are likely to modify the projected investment needs.

#8 A need to better understand uncertainties in costs and the performance of adaptation measures

The analysis presented covers a wide range of issues. All are uncertain. Uncertainties in climate and population growth are addressed using alternative futures. Uncertainties in the cost of adaptation measures and their performance are addressed using 'best estimates'. These are based on direct evidence where possible or judgements made by the project team with a supporting rationale. A structured sensitivity analysis has not been possible within the constraints of this project but is recommended to identify those aspects of the analysis that have the greatest influence on the case for investment. Such a study would be difficult, but possible, and add considerably to the state of knowledge and help better direct future investment.

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LIST OF ABBREVIATIONS

AEP	Annual Exceedance Probability
AM	Adaptation Measure
AP	Adaptation Portfolio
B£ST	Benefits EStimation Tool – valuing the benefits of blue-green infrastructure
CapEx	Capital expenditure
CCRA	Climate Change Risk Assessment
CPM	Convection Permitting Model
CSO	Combined Sewer Overflow
DWMP	Drainage and Wastewater Management Plans
EA	Environment Agency
FCERM	Flood and Coastal Erosion Management
FFE	Future Flood Explorer
NIC	National Infrastructure Commission
NOx	Nitrogen Oxides
NPV	Nett Present Value
OpEx	Operational expenditure
PV	Present value
PVb	Present value benefits
PVc	Present value costs
RCP	Representative Concentration Pathway
SOx	Sulphur Oxides
SPL	Sayers and Partners LLP
SSP	Share Socio-economic Pathway
SuDS	Sustainable Drainage Systems
SWFM	Surface Water Flood Management
SWM	Surface Water Management
TotEx	Total expenditure (CapEx and OpEx)
WAAD	Weighted Annual Average Damage
WaSC	Water and Sewerage Company
uFMfSW	Updated Flood Map for Surface Water
UKCP18	United Kingdom Climate Programme 2018

1.0 INTRODUCTION

1.1 Aims and Objectives

This report explores the relationship between:

- **Investment in surface water flood management**

and

- **Surface water flood risk**

And how this relationship is influenced by

- **Climate change and population growth**

The analysis uses and extends the Future Flood Explorer (FFE) used in support of the UK Climate Change Risk Assessment (CCRA3) flood projections (Sayers *et al.,*2022) to better represent adaptation to manage surface water flood risks and their costs. Climate change projections have been updated to include available high-resolution outputs from the UKCP18 Convection Permitting Model (CPM, Chan *et al.,*2022). Due to the constrained programme of this study no other changes to underlying data used in support of the CCRA have been incorporated.

1.2 Target audience

This report is written for the National Infrastructure Commission (and professional bodies). Efforts have been made to ensure the report can be read as a standalone document. The drafting assumes knowledge of the context of the project commission.

1.3 Report Structure

The report is structured as follows:

- **Chapter 2 – Context and main assumptions** – sets out the flood hazards, future drivers of risk, and the reporting scales used.
- **Chapter 3 – Benefits – Adaptation portfolios and measures** – presents the approach to the assessment of avoided risk and the wider benefits associated with SWFM activities.
- **Chapter 4 – Cost – Adaptation costs and who pays** – presents the approach to the assessment of adaptation costs.
- **Chapter 5 – Results - Return on investment** – presents the decision rules used to determine the preferred mix of adaptations and resulting Net Present Value and associated changes in the properties at risk.
- **Chapter 6 – Conclusions** – presents summary conclusions. No effort is made to recommend action (as this will be determined by the NIC). Recommendations for future research and further studies are included.
- **Chapter 7 - References**

Detailed appendices are provided on some aspects of the method to maintain readability of the report. These include:

- **Appendix A** – Recent expenditure and outcomes
- **Appendix B** – Review of how different SuDS affect run-off
- **Appendix C** – Representation of individual adaptation measures
- **Appendix D** – Existing expenditure: Private and public
- **Appendix E** – Cost functions

Green boxes are used to illustrate issues and evidence.
Blue boxes are used to highlight important assumptions or constraints.

2.0 CONTEXT AND MAIN ASSUMPTIONS

2.1 Background

The NIC was established in 2015 to provide the Government with impartial advice on major long-term infrastructure challenges. Its objectives are to support sustainable economic growth across all regions of the UK, improve competitiveness and improve quality of life. Support for climate resilience and the transition to net zero carbon emissions by 2050 are also central objectives. As part of this remit, the Government has asked the NIC to explore the investment required to appropriately manage surface water flooding (SWF) in England and make recommendations to Government.

The NIC commissioned Sayers and Partners (SPL) to provide the evidence to support this process, including evidence on the changing surface water risks and the costs and benefits of action.

Note:

Economic v wider benefits: The NIC was asked to consider reducing the risk of surface water flooding, so the model was optimised to focus investment choices on economic damage (direct property damage and associated indirect damage). Wider benefits that may differentiate the preferred approach to adaptation are not included the optimisation but those accrued are estimated and presented as part of the final cost benefit calculation. This constraint is reflected in the analysis presented.

Surface water risk is difficult to determine in detail: Surface water flooding modelling and associated risk assessment (and how these change with time) is complex. National assessments of surface water flooding are less mature, and in some ways more complex, than equivalent analysis of fluvial or coastal risks. This includes the granularity required to understand and model surface water processes, including making assumptions about detailed issues of drainage, kerb heights and the nature of the urban fabric (is it a hedge or is it a wall?). Such issues are difficult to include in the most detailed local studies and very difficult in broader scale models. Although every effort is made to base the assessment presented here on evidence, the calculation is novel and necessarily involves various assumptions (as highlighted throughout). The report should be read in this context.

2.2 Temporal and spatial reporting scales

2.2.1 Appraisal and reporting periods

The analysis covers the present day (2022) to 2100.

- **Appraisal period:** Costs and benefits over the appraisal period (2022-2100) are discounted using standard Treasury discount rates to determine the Present Value (PV). The results are used to compare the performance of alternative adaptation portfolios and determine the preferred approach at any given location (using decision rules as detailed later in Chapter 5). Costs and benefits are assessed in ten yearly steps and interpolated to yearly values to support the assessment of PV.
- **Real investment period**: The NIC has set an investment window that covers the period from the present-day to the 2050s. A sum of undiscounted costs through to the 2050s is reported here as the 'real' investment cost.
- **Risk comparison periods:** The change in risk is reported by comparing present-day and future risks in the 2050s given different climates, populations, and investment levels.

2.2.2 Reporting exposure to surface water flooding

The number of properties exposed to surface water flood hazards is reported using three standard bands:

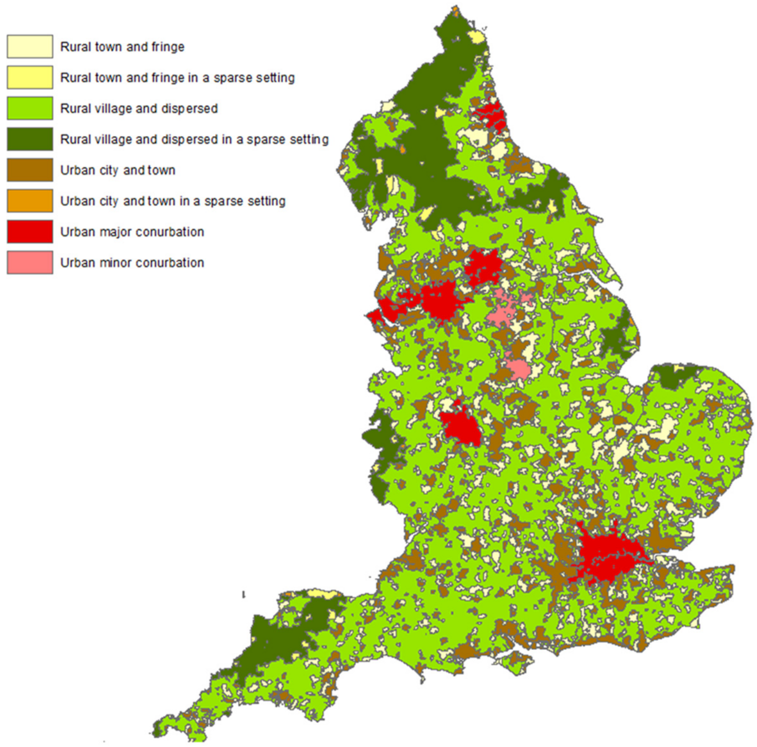
- **High chance of flooding:** More likely than 1/30 Annual Exceedance Probability (AEP, notionally equivalent to an average return period of more frequent than 1in30 years).

- **Medium chance of flooding**: Between 1/30 and 1/100 AEP (notionally equivalent to an average return period of between 1in30 to 100 years).
- **Low chance of flooding**: Less likely than 1/100 AEP (notionally equivalent to an average return period of less frequent than 100 years).

2.2.3 Reporting geographies

Two geographies are used to report the results (both risk and cost):

- **National:** covering all of England.
- **Settlement type:** covering eight categories of urban and rural settings as defined by ONS using a combination of metrics (as set out by Bibby and Brindley, 2013). These are mapped in Figure 2-1 and their relative importance in terms of the number of properties exposed to flooding is shown in Table 2-1.



Source: Authors based on data from Bibby, P. & Brindley, P. (2013)

Figure 2-1 Settlement types – Urban to rural

Table 2-1 Present-Day - Number of residential properties exposed to surface water flooding by settlement type

Settlement type	Residential properties exposed to flooding – Present day	
	High (More frequently than 1in30 years, on average)	**Moderate** (More frequently than 1in100 years, on average)
Rural town and fringe	24,700	58,806
Rural town and fringe in a sparse setting	1,386	3,219
Rural village and dispersed	18,731	37,632
Rural village and dispersed in a sparse setting	1,664	3,241
Urban city and town	139,317	349,100
Urban city and town in a sparse setting	671	1,511
Urban major conurbation	130,834	348,084
Urban minor conurbation	8,284	22,811
Total	**325,587**	**824,404**

2.3 Flood hazards

The analysis focuses on surface water flooding driven by short duration rainfall events (typically < 6 hours).

Note:

Present-day hazards: Data on surface water flood hazards from the Environment Agency surface water hazard mapping (embedded within Risk of Flooding from Surface Water, RoFSW) are assumed to be representative of the present-day. This provides information on areas prone to surface water flooding more frequently than 1in30 years, 1in100 years and 1in1000 years on average and are based on underlying modelling driven by a range of storm durations to determine the hazard maps. The hazard data (with a resolution of 2m) does not therefore represent a single storm event but the chance of surface water flooding at a location.

Present-day 1in1,000-year surface water hazard map defines the limit of the flood prone area, today and in the future: It is assumed climate change and adaptation influence the probability of flooding within this area but does not change the limits of this area. The ongoing 'Plausible Extremes' project (personal communication Sayers and the Environment Agency) identifies that a 20% increase in rainfall can increase the number of properties exposed to flooding more frequently than 1in1000 years on average. Such rare events have limited influence on the risk but nonetheless should be considered for inclusion in future studies.

Surface water flooding is assumed to be uncorrelated to coastal or fluvial flooding: The Environment Agency estimates that 660,000 properties are at risk from flooding both from rivers, the sea, and surface water. 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 and can be considered in isolation without double counting. No explicit consideration is given to the changing conditions of tide or fluvial locking of surface water discharges.

2.4 Flood risk

The analysis focuses on two quantifications of risk as set out below.

2.4.1 Direct damage

Direct damage to residential properties and non-residential properties are based on the Weighted Annual Average Damages (WAAD) approach adjusted to reflect the findings of the analysis of surface water damages within the Environment Agency's Long-Term Investment Scenarios (Environment Agency, 2019). The Agency's analysis suggests a significant increase in the assessment of present-day surface water risks compared with previous estimates and this is carried forward here.

2.4.2 Indirect and intangible damage

Indirect damages are assumed to be 70% of the direct residential damages. This includes the following aspects:

- 11% uplift to account for indirect losses associated with emergency services and provision of temporary accommodation (applied to residential losses only);
- 16% uplift to account for indirect losses for risk to life and physical injury;
- 43% uplift to account for indirect losses for impacts on infrastructure, transport, schools, and leisure.

Intangible damages associated with mental health impacts are reflected through a further uplift of 20% applied to the direct (residential) damages. This approach reflects that used in the CCRA3 (Sayers *et al.,*2020, where additional references are given).

Note

The values used to adjust for indirect and intangible impacts refer to flooding in general and are assumed appropriate for surface water.

2.5 Adaptation benefits – Assessment scope

Three forms of benefit are considered to accrue from adaptation: avoided risk, wider benefits accrued, and the reduction in costs to address CSOs. The approach to assessing each category of benefit is discussed below.

2.5.1 Avoided risk

Flood risk avoided is used as the primary indicator of economic benefit. The risk avoided is determined by comparing the Expected Annual Damage (EAD) with and without adaptation.

An evolution of the Future Flood Explorer (FFE, Sayers *et al.,*2016, 2022) is used here to provide this estimate. The FFE uses the surface water hazard mapping produced by the Environment Agency to develop an understanding of present risks and manipulates that understanding through metamodeling approaches to assess how these change given climate and population change and adaptation.

The present-day hazard data necessarily includes various assumptions and uncertainties (outside of the scope here to explore). This data is, however, scrutinized and validated by local Environment Agency teams (to different degrees in different locations), and updated where locally detailed modelling is available (Environment Agency, 2019, Defra, 2021c). The FFE combines this data with receptor data sets to establish a series of Impact Curves (IC) at the scale of 'Census Calculation Areas' (CCAs). A CCA represents a further sub-division of a 1kmx1km Calculation Area using the boundaries of the Lower (layer) Super Output Areas (LSOAs). This helps ensure each CCA represents a coherent social geography. The ICs are then manipulated to represent change at this scale.

The FFE manipulates these ICs to understand the influence of future change on risk. The estimates from the Environment Agency (2019) are taken as the best available present day estimates. These latest estimates are significantly higher than previous estimates (although remain highly uncertain given the inherent difficulties in assessing surface water risks). This reflects the Agency's further analysis of past events (including the 2013-14 events) to determine the average property damages caused by surface water flooding and consequently estimate present-day EAD. The FFE has therefore been recast to faithfully emulate the present-day risks as presented by the central estimate from the Environment Agency (Table 2-2).

Table 2-2 Comparison of present risks - FFE and published data

Properties (Number)	**Environment Agency[1]**	**FFE (for the NIC)**
High (more frequent than 1in30 years, on average)	326,000	325,747
Medium (between 1in30-1in100 years on average)	499,000	498,977
Low (less frequent than 1in100 years, on average)	2,348,000	2,349,121
Total	3,173,000	3,173,845
Damage (£)	**Environment Agency[2]**	**FFE (for the NIC)**
Expected Annual Damage (central)	1,239,000,000	1,260,045,555

It is not possible to compare future changes in flood risk projected by the FFE directly. Instead, the confidence in future estimates is gained using accepted inputs (of climate and population change) and credible representations of adaptation and showing how these project future changes in risk (see below and later chapters).

Note:

Importance of the present-day estimates of risk – The estimates of present-day risks are of central importance to deciding the return on investment. The current estimates of present-day risk are significantly higher than those presented in CCRA3 for surface water flooding and recognised as significantly uncertain. It is beyond the scope here to reassess present day risks (noting that these are being revised in detail as part of the ongoing update to the National Flood Risk Assessment). Changing the quantum of the risk to be managed will impact the investment case and the scale of investment that can be justified. Sensitivity analysis should be considered to explore this relationship in a future assessment (beyond the scope here). This context should be considered in viewing the investment results presented here.

Changed estimates in present day surface water risks - The understanding of surface water risks is less well-founded than coastal or fluvial sources. The Environment Agency's most recent estimates of surface water risks are significantly greater than previously or than those reported in the CCRA3. The decision was taken here to reflect the Agency's revised present-day estimates (and damage and properties flooded) as the best available and update the baseline within FFE to align with these values. This means direct comparison of absolute values of risks, present and future, with previous studies (such as CCRA3) is not possible because of this change in the present-day baseline. The comparison of the changes in risk – with and without adaptation, and given different future climate and population, remains a valid comparison to make (although this is out of scope here).

Surface water the most difficult flood source to model - National surface water hazard maps are being extensively revised through the National Flood Risk Assessment 2 programme to refine and extend the available data (although uncertainties will remain). The current availability of only three return periods (particularly the absence of the mapping of more frequent return periods) and limited information on local drainage networks necessarily constrains the accuracy of the meta modelling approach for surface water when compared with fluvial or coastal flooding. The approach, therefore, draws upon expert judgement from across the project team supported by a review of literature and practice on the performance of surface water adaptations (although recognising the limitations and focus of the commission). Further validation of the approach, beyond the scope of this commission, is recommended.

[1] Flood and coastal erosion risk management report: 1 April 2020 to 31 March 2021 - GOV.UK (www.gov.uk)

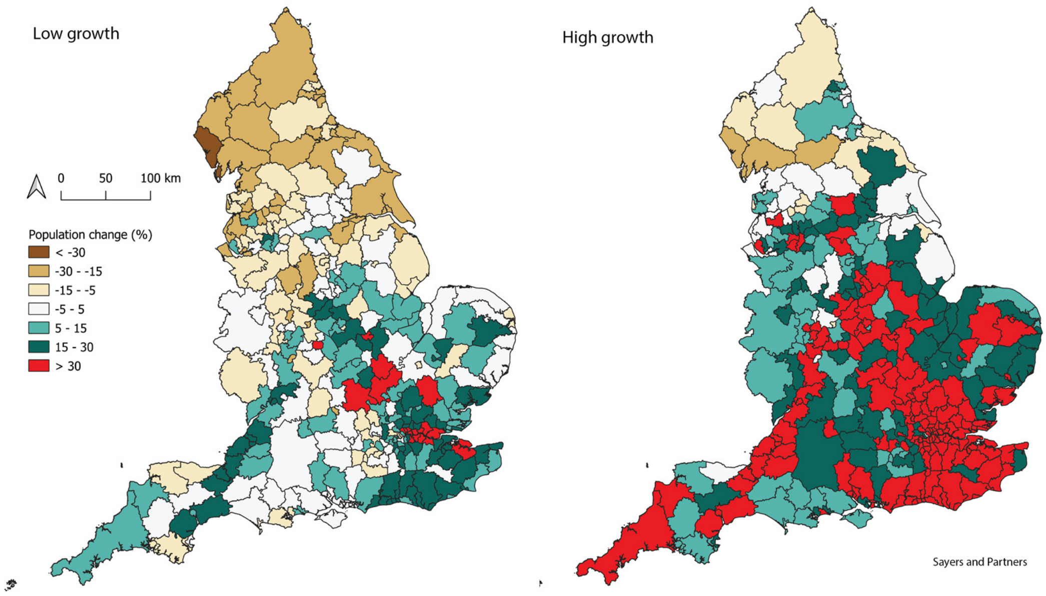
[2] Environment Agency (2019). Long Term Investment Scenarios: Additional Analysis. Topic 13 technical report Progress in knowledge since LTIS 2014 – Surface Water. Unpublished.

Population change

Three projections of population growth are used:

- **High growth** (Cambridge Econometrics, 2019 - Figure 2-2)**:** 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 21 million from 2022. 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 dependants aged between 0-15 is also slightly higher in the high scenario, reflecting higher birth rates.
- **Low growth** (Cambridge Econometrics, 2019 - Figure 2-2)**:** 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 ~68 million in 2100, an increase of just under 1 million from 2022 and leads to an older age structure (with over 65s accounting for 36% of the population, compared with 29% in the central scenario).
- **No change:** In addition to the growth projections a third *'no population growth'* future is considered. Within this scenario the present-day population distribution remains unchanged.

The demand for new residential properties is assumed to reflect a combination of population growth and average household occupancy. The central projections of household occupancy at a local authority scale are taken from Cambridge Econometrics (2019) and applied to translate the population growth in each projection to a local development demand. In the case of no growth, it is assumed there is no demand for new housing.



Left: Change given low population growth. **Right**: Change given high population growth. Source data: Cambridge Econometrics (2019).

Figure 2-2 Projected population change by Local Authority (2019 boundaries) – England, Present day to 2080s

Note:

Reused projections: The projections used here are those used within the CCRA3 analysis without modification (beyond correction for the change in Local Authorities' boundaries since publication) and do not link explicitly to a single Shared Socio-economic Pathway (SSP).

No consideration of non-residential development: Population growth is assumed to influence residential development only.

Urban creep: No consideration is given to urban creep (i.e., the increase of imperviousness in existing urban areas over time). Adaptations to existing areas however are considered (increasing green space) as detailed later (see Chapter 3).

Climate change

Two climate scenarios are used. Each is defined by an increase in Global-Mean-Surface-Temperature (GMST) by 2100 from pre-industrial times. The first reflects a 2°C rise and the second a 4°C rise. The Convection Permitting Model (CPM - 2.2km UKCP18) outputs for 2050s and 2070s is used here to determine the climate change driven influence on short duration rainfall intensity (Chan *et al,* 2021 and in review). The CPM data provides uplifts in rainfall intensity on a 5km grid. The data is provided for a range of return periods and critical durations (1, 3, 6, 12 and 24 hours) and for the 50% and 95% values driven by Representative Concentration Pathway 8.5 (RCP 8.5).

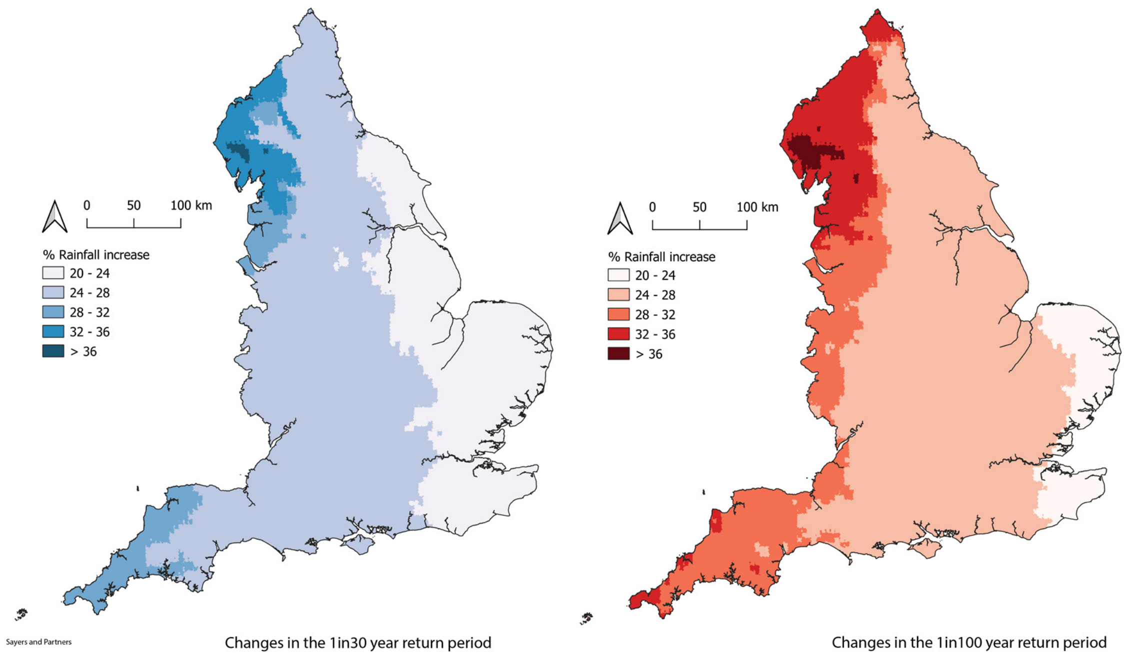
The UKCP18 uplifts are presented relative to a 1981-2000 baseline for two time horizons (Figure 2-3). Assuming the rainfall change to be independent of time and dependent on temperature change, these results are used as the basis of interpolating a full range of climate responses. To understand the time profile of change (between some future time and the present-day) the projections are associated with GMST rise (using the UKCP18 probabilistic projections, as set out in Sayers *et al.,*2020). Once a GMST value is assigned, the CPM outputs are then integrated to provide an uplift for any given rise in GMST (assuming a zero uplift in 1990). This enables the FFE to determine the change in rainfall for any year and climate future (defined by a rise in GMST by 2100).

Note:

Storm duration - An average uplift based on the 3- and 6-hour duration storms CPM outputs is adopted here.

Update from CCRA3 (Sayers et al, 2020) - This analysis replaces the data on changes in short duration rainfall used in CCRA3 that predates the publication of the CPM outputs.

Fluvial and coastal boundary conditions are assumed unchanged: Surface water flows may be restricted by downstream fluvial and tidal water levels. This is assumed unchanged here.



Left: Uplift in the 1in30 year return period rainfall (mm/hr) by the 2080s from baseline period (1981-2000) assuming a 4oC GMST rise by 2100 (from pre-industrial times). The uplifts are based on an average of the <3 and <6-hour critical storm duration.
Right: The equivalent plot showing the increase in the 1in100 year return period rainfall (mm/hr) by 2080s.
Source data: Chan et al, 2021.

Figure 2-3 Change in the 1in30 and 1in50 year return period intense rainfall by the 2080s assuming a 4°C climate future (increase from baseline 1981-2000)

2.5.2 Wider benefits of SuDS and their value

The National (England) Planning Policy Framework (NPPF, Ministry of Housing, Communities and Local Government, 2021, 2022) was significantly strengthened in July 2018, with revised planning practice guidance in August 2022, to improve the focus on the multifunctional benefits of SuDS as part of any development. Coupled with publication of the 25-Year Environment Plan (HM Treasury, 2018) and the stated aim of net biodiversity gain, Local Authorities will increasingly be required to prioritize multi-functional SuDS (given space and geological constraints) and discouraged from adopting mono-functional approaches that have limited environment benefits (such as geo-cellular storage or urban tanks, Melville-Shreeve *et al.,*2018). Defra is reviewing how best to implement Schedule 3 of the Flood and Water Management Act 2010 and is expected to announce the findings of its review in Autumn 2022. If it is implemented, then this is expected to put in place statutory standards for the construction of SuDS on new developments and make the connection of surface water to foul sewers conditional on the approval of a developer's approach to SuDS.

The range of additional benefits provided by SuDS, if properly considered, can be significant in range and value, including for example:

- **Air quality:** Trees and vegetative SuDS can play an important role in absorbing airborne pollution (e.g., NOx, SOx and particulates), reducing the risks of and impacts from air pollution, particularly in urban areas.
- **Amenity**: spaces used to create storage SuDS can provide opportunities for other uses when dry. For example, in the Manor Fields Park area in Sheffield, a 100-year overflow detention pond is also used for community events.[3]
- **Biodiversity:** Green infrastructure provides habitats for flora and fauna.
- **Carbon sequestration:** Trees and vegetative SuDS absorb carbon dioxide and help mitigate climate change through sequestration of greenhouse gases.
- **Health:** SuDS provide improved physical and mental health outcomes for those with a view of or improved access to green space.

Information that underlies the B£ST tool (CIRIA, 2019) is used to value the wider benefits provided by SuDS based adaptations. This information has been translated to value per property protected from flooding by SuDS schemes (Table 2-3). This data is then used in the FFE to value the wider benefits associated with different adaptation. It is assumed that no wider benefits are accrued given investment in conventional pipe drainage or other non-SuDS measures.

Table 2-3 Valuing wider benefits of SuDS based adaptations

Benefit category	Assumptions	£ benefit per property protected *		
		Lower	Used	Upper
Air quality	0.012 ha of SuDS (e.g., rain garden) and 24 medium trees per ha	3.80	7.60	10.20
Amenity	240 beneficiaries (60 people per ha over 4ha)	23.90	71.80	143.60
	Low monetary value for street greening selected (e.g., 'small trees')			
	Values related to increased property prices are not included			
Biodiversity	Land use changes to 'improved grassland'	0.20	0.50	1.00
Carbon sequestration	Annualized benefit over 40-year period for 24 medium trees	0.40	1.00	1.80
Health**	Central value used for physical health benefit	0.20	0.50	1.10
	Low value for emotional health benefit	5.60	22.50	50.50

*Assuming 24 properties per hectare
**Assuming 2 properties (4 adults) per 1ha catchment receive a benefit, i.e., 16 adults over 4ha intervention area

[3] Home (manorfieldspark.org)

Note

Benefit delivery: It is assumed here that SuDS are designed in a way that delivers these benefits. This should be the case through recent revisions to National Policy and Planning Framework that requires SuDS for major new development to provide, where possible, multi-functional benefits. This objective across all SuDS is recognised as a 'hopeful' assumption given evidence suggests (Melville-Shreeve *et al.,*2018) source control and attenuation are often delivered using concrete or plastic tanks with throttled outlets, or with runoff conveyed via pipes to collecting ponds. These approaches tend to offer limited (or even no) additional benefits. It is however assumed that with strengthening guidance (*e.g.*, Schedule 3 in England of the Flood and Water Management Act 2010, as now being promoted by Defra) future investment in SuDS will provide wider benefits in addition to flood risk reduction.

Central estimates: Programme constraints meant the analysis here focuses on central estimates. Low and upper values could be readily explored in future analysis.

2.5.3 Reduction in CSO costs

Surface water from around 62% of properties drains to combined sewerage systems, where it mixes with foul sewage (Personal communication – Richard Ashley and Brian Smith, formerly of Yorkshire Water). Surface water from the remainder of properties drains to surface water sewers, or to no public sewers at all, for example where drained directly to soakaways. When rainfall exceeds the capacity of a combined sewer may be exceeded and excess water is discharged (referred to as a Storm Overflow event or, as used here, a Combined Sewer Overflow, CSO). When this occurs, untreated sewage may be discharged to rivers, lakes, or the sea. Although there is considerable variation across England in the frequency of CSO discharges, they are typically driven by very frequent events (often associated with rainfall events that occur 5 to 10 times a year, or even more frequently (The Rivers Trust, 2022). The events that typically drive surface water flooding are much less frequent (i.*e.,* once a year or less frequently). In this context it is assumed that adaptations aimed at addressing CSO discharges have limited influence on flood hazards. Actions taken to reduce flood hazards that include retrofit SuDS to manage existing risks are likely to reduce CSO discharges.

Box 2-1 Storm overflows and surface water flood management - An opportunity for joined up management

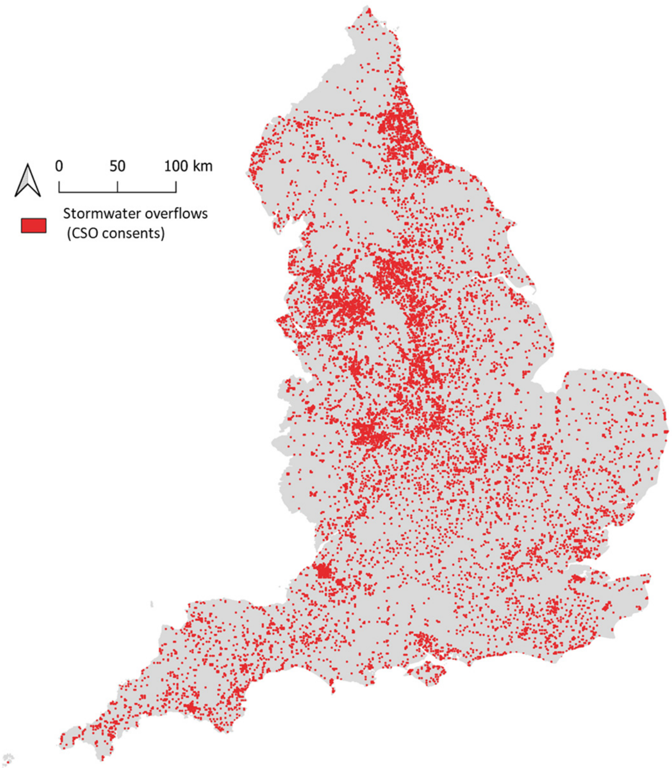
There are few examples of schemes where investments in urban surface water management enhancements have set out to simultaneously better control flooding and sewer overflows for water quality control. Most projects aim to manage one or the other. Nevertheless, there are numerous published examples of successful investments that have delivered both flood risk reductions and controlled sewer overflow spills. Many of these are in the USA where there has been a long history of wet weather control programmes aimed mainly at prevention of receiving water pollution. With the growing utilisation of nature-based systems using both blue and green infrastructure for surface water control, it has become apparent that, in many instances, these are more cost-effective than the conventional built infrastructure used for urban drainage enhancements comprising below ground pipes and tanks. Unfortunately, there are drawbacks to using nature-based options because of the difficulties of retrofitting in dense urban spaces. These are frequently often not of a size to cope with the largest rainfall events and evidence now suggests that combinations of green and grey infrastructure systems provide the most robust, and likely to be more resilient, means of managing surface water in urban areas. Policies and planning in urban areas for hazards including flooding, water pollution and lack of water resources need to encompass the widest possible integration of systems and services, rather than focusing on drainage in isolation. Only in this way can the challenges of future climates and societal change be coped with at affordable costs.

The Government recently committed water companies to investing £55.96bn[4] through to 2050 to tackle the issue of CSOs (Defra, 2022). It is assumed that investment in surface water flood management through SuDS-led adaptation acts to reduce the required investment in CSOs, with a

[4] Toughest targets ever introduced will crack down on sewage spills - GOV.UK (www.gov.uk)

cost saving of £55 per property protected from flooding. This has been derived by dividing the annualized investment in CSOs (determined by £55.96bn divided by 26 years, £2.24bn), further divided by the number of properties within the associated surface water flood prone area (assumed to be 62% of the total number of properties, 3,123,762 * 0.62 = 1.93m), yielding a cost per property of £717.

It is assumed that 25% of this potential reduction is achieved (£289 per property) in those areas that adopt a SuDS led approach to flood risk management (as determined through the decision rule here, see later) and have experienced CSOs in the past, as determined by the consented discharges database (Environment Agency, 2022). If these two conditions are satisfied the cost reduction per property is assumed to be accrued for all flood prone properties within that CA. The year-by-year savings are not monitored. Instead, a PV saving per property is calculated for the period 2022 to 2050 (the same period as the Defra CSO investment analysis). This saving is recorded separately as part of the investment assessment (see Chapter 5).



Source: Based on Environment Agency consents, Environment Agency, 2022

Figure 2-4 Storm overflows – Consents

Note:

It is assumed that any spend to reduce CSOs alone has no influence on flooding and hence no influence on SWFM benefits or the case for SWFM investment.

To be successful, SuDS are typically applied widely around an area of flood damages to achieve sufficient attenuation/losses of surface water. SuDS actions are therefore assumed to benefit CSO spill reduction (if CSOs are present).

No CSO cost saving is accrued in those areas where piped drainage led portfolios are implemented. This reflects the increase in conveyance associated with these portfolios, and consequently little relief is provided to offset CSO costs. It is assumed the CSO costs remain unchanged in this case.

2.6 Adaptation costs

2.6.1 Included costs

To determine the cost of adaptation four categories are considered:

- **Capital costs** (CapEx) – an estimate of the outturn capital expenditure associated with initial implementation of the measure. This encompasses costs relating to consultation, design, and preliminary assessments.
- **Operational cost** (OpEx) – an estimate of the annual operational expenditure reflecting the cost of operation, maintenance, and periodic renewal. These costs could be incurred by highways authorities, local authorities, water companies or others involved in or responsible for operation and maintenance (see Section 5).
- **Carbon cost** – an estimate of the carbon costs, including construction (embodied) and operational carbon in tonnes, with carbon emissions valued using government guidance and extrapolated to 2100.[5]
- **Support costs** – costs incurred each year which do not directly progress a scheme (including improvements of existing functions and payment for additional benefits, such as improved operator access, walkways *etc.*). These activities are assumed to incur costs that are not captured by the other three categories and are assumed to be £29.4mn per year (see later in Section 4). These costs are assumed to be fixed (i.e., they do not rise in line with higher investment scenarios). Whilst it could be argued that these support costs would rise with investment in flood risk reduction measures, any such rise is likely to be at a lower rate of increase than the increase in investment directly addressing flood risk.

2.6.2 Excluded costs

In determining the cost of adaptation **no** consideration is given to:

- **On-costs** – No consideration is given to the potential increase in downstream costs, for example increased treatment costs associated with increased conveyance of flows through the piped network.
- **Land purchase costs** – It is assumed that owned land is utilised, or measures are implemented with the agreement of landowners.
- **Construction disruption**: some measures, such as piped drainage improvements, are often associated with significant disruption during construction. These impacts are excluded here.
- **Transfer payments** – In line with HM Treasury Green Book guidance, VAT and other withholding taxes are excluded as these represent transfers and have no net impact at a societal level.
- **Residual asset values and benefits** – Returns on investments within the appraisal period are assumed to accrue benefits within the appraisal period (*i.e.,* through to 2100). After this period, it is assumed that the asset continues to perform and accrue benefits. Residual asset values and residual benefits that may be accrued beyond 2100 are excluded.
- **Optimism bias –** The cost functions are derived from out-turns (see Chapter 4). Given this basis, an optimism bias is not applied, and the central estimate within the cost functions used.
- **Affordability –** As instructed by the NIC no consideration is given to affordability and investments are assumed to take place from day one and then further adaptation takes place in response to future change. This creates a bias within the NPV calculations that heightens the influence of costs and diminishes the influences of benefits.
- **Resources and capacity building:** Investment in resources, skills, and capacity within Lead Local Flood Authorities and Risk Management Authorities (and industry more broadly) to assess and

[5] Valuation of greenhouse gas emissions: for policy appraisal and evaluation - GOV.UK (www.gov.uk)

manage surface water risk. This investment will need to be supported with capacity and capability to deliver.

Note:

Cost accounting assumptions: All costs are updated to latest (2022) prices using GDP deflators from government.[6] Future costs are converted into Present Values by discounting at rates recommended by government, 3.5% per year initially, falling to 3% from year 31 and 2.5% from year 76.[7]

2.6.3 Influence of climate change

Climate change is likely to influence both the OpEx and CapEx costs in a way that may increase costs of delivering improvements and maintenance in a changed climate. This may increase the costs by 10-20% for every 1 degree rise in GMST from the present day but little evidence has been found to support this directly. Within the analysis climate change includes the number of properties at risk and type of portfolio needed to reduce risk (as within the FFE climate change influences the performance of the various measures and portfolios, see Chapter 3). Nonetheless if may be argued that additional costs may be incurred. As agreed with the NIC, these are excluded from the analysis here but may be introduced as part of the post analysis.

2.6.4 Influence of settlement type

The costs of adaptation are modified according to the context of implementation as defined by the eight settlement types (urban to rural) introduced earlier (section 2.2.3). This results in higher implementation costs in urban areas compared with rural areas reflecting the increased difficulties of undertaking work. In some instances, especially piped drainage, this is countered by an assumed shorter length of pipe typically associated with an urban property compared with a rural property. This is detailed in Chapter 4.

2.6.5 Opportunity for savings through strategic planning

The basis of the cost functions largely draws on evidence from local projects. As planning and actions continue to become more integrated and more strategic, it is likely that cost savings will be possible. This is accounted for here through two considerations as below.

Savings through integrated planning

Surface water management involves multiple actors (Table 2-4). Individually and collectively these organisations act to implement a portfolio of measures that respond to national and local flood risk management policies, planning regulations and guidance such as the Environment Agency's Flood and Coastal Erosion Risk Management Strategy, the Water Industry Strategic Environmental Requirements (WISER); The Water Industry National Environment Programme (WINEP): as well as Drainage and Wastewater Management Plans (DWMPs). As a more integrated approach is adopted there may be opportunities for cost savings. One such opportunity is reflected here in the reduction in CSO costs that may be accrued in those areas adopting SuDS leading to adaptations to manage flood risk (the CSO savings as described earlier).

Saving through strategic planning

By adopting larger scale planning domains (catchment, town or even city) there is an opportunity for a more strategic approach to adaptation. If appropriately implemented this may offer an opportunity to reduce costs from those determined from local, rather piecemeal, studies. Findings

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[6] HM Treasury (2022) https://www.gov.uk/government/statistics/gdp-deflators-at-market-prices-and-money-gdp-march-2022-quarterly-national-accounts

[7] HM Treasury (2022) The Green Book (2022) - GOV.UK (www.gov.uk)

from the recent Cloud-to-Coast EC Interreg initiatives suggest savings may be significant, suggesting the potential to increase benefit cost ratios by a factor of 2 (Sayers *et al.,*2022). A conservative assumption (based on the judgement of the project team) is made here that a more strategic approach is adopted and yields a cost saving of:

- 10% in urban areas
- 5% in rural areas

The reduction in opportunity in rural areas reflects the more limited ability to adopt a strategic perspective in the context of surface water flooding in an existing rural setting.

Table 2-4 Public and private sources of investments

Context of investment	Overview of activities
Public investment (defined here as delivery promoted and controlled by public sector bodies)	
Flood and Coastal Erosion Management (FCERM)	England-wide scheme managed on a 6-year programme by the Environment Agency. Open to Lead Local Flood Authorities (LLFAS) and drainage authorities to initiate and lead projects.
Local Levy	A levy charged upon all residents and businesses within the boundary of a Drainage Board's district, and on Local Authorities serving that district. Used for operational and capital spend on land drainage.
Highways including National Highways (formerly Highways England), County, District and Unitary local authorities	Responsible for the construction and maintenance of highways and land up to the highway curtilage. This included the effective drainage of highways. The Designated Funds Programme is available to fund wider schemes including highways SuDS and natural flood management.
Lead Local Flood Authorities	Unitary and County Councils act as Lead Local Flood Authorities under the Flood and Water management Act 2010.
Private investment (defined here as delivery promoted and controlled by private sector bodies – including regulated bodies)	
Water and sewerage companies	Collection and treatment of wastewater from homes and businesses. Surface water drainage of properties and highways (via highway drainage connections), either using separate surface water systems or combined sewers.
Private landowners	Provision and maintenance of drainage to drain private buildings, hard-standing and agricultural land. Common law responsibilities to not adversely impact neighbouring land.
Railways	Construction and maintenance of drainage to effectively drain railway tracks, stations, sidings *etc.* Rights of connection to rivers and public sewers.
Private developers	Provision of SuDS schemes associated with new and redevelopment activities.

3.0 BENEFITS – ADAPTATIONS PORTFOLIOS AND MEASURES

3.1 Introduction

It is widely accepted that flood risk is best managed through a portfolio of measures (Evans et al, 2004a&b, Sayers et al, 2014, 2022). A range of individual Adaptation Measures (AMs) that relate to the management of the sources and pathways of surface water flood hazards and their impact on receptors is considered (using the source-pathway-receptor framework set out in Sayers *et al.,*2002). These individual adaptations are combined into alternative Adaptation Portfolios (APs) with each representing a different approach to managing risk; from focusing on conventional piped drainage to one that focuses on sustainable drainage.

The individual measures and their collective performance as part of a portfolio are represented within the FFE. This representation takes account of the local context of implementation. For example, the space available to implement storage ponds, underlying geology that may constrain the use of swales, and the scale of the available grey space (roads, car parks *etc.*) available for conversion to more green space (swales *etc.*) are all considered in translation of the AMs to their local representations. Spatial variations in the rainfall intensities and influence of climate change are also represented and influence the spatial pattern of changing flood risk and the future drainage capacity needed to manage flood hazards.

Through this representation the FFE can assess the change in risk and hence the benefits that different approaches may typically accrue at a local scale. This does not imply the assessment is credible at a local scale. The detail of the local context and the necessarily simplified representation of the influence of adaptation mean results are only credible at aggregated scales and are most suited to understanding the change in risks at aggregated scales of interest here (i.e., national and settlement type).

The range of individual AM and how they are combined into alternative APs is elaborated below.

3.2 Adaptation Measures

A range of individual AMs are considered, namely:

- **Source measures** – to *slow the flow*: Adaptation measures that influence the source of flood waters act to slow the production of run-off during a storm (by slowing the flow through infiltration or storage, or both). This, in turn, reduces the flood hazard. SuDS are considered here as the primary 'source' adaptation. There are however many SuDS options that can be applied at a range of scales. For the purposes of the assessment SuDS measures are grouped into three categories:
    - New build
    - Retrofit infiltration
    - Retrofit storage

  This characterisation builds upon a broader review of the literature and practical guidance applied to SuDS and their performance (Appendix B).

- **Below ground pathway measures –** to *convey the flow*: Adaptation measures that convey run-off away from an area also influence the flood hazard. These measures are predominantly represented by the piped drainage network.
- **Exceedance measures** – to *manage residual flood water:* surface water flooding occurs *en route* to the infrastructure put in place to manage it and the peak intensity a storm can often overwhelm even well-designed infrastructure (Fratini *et al.,*2012). Designing for exceedance (when the collective capacity of the source and below ground pathway measures are exceeded) is central to sound management of the surface water (as reinforced in the CIRIA guidance, Digman *et al.,*2014). This includes, for example, taking measures to guide surface water flows to

minimize impacts (referred to here as surface pathways) and/or to take measures to reduce impacts given a receptor is flooded (e.g., property level measures).

These individual adaptation measures are illustrated in Figure 3-1. The implementation of each measure within the FFE is discussed in Appendix C. Their combination in portfolio is discussed in the following section.

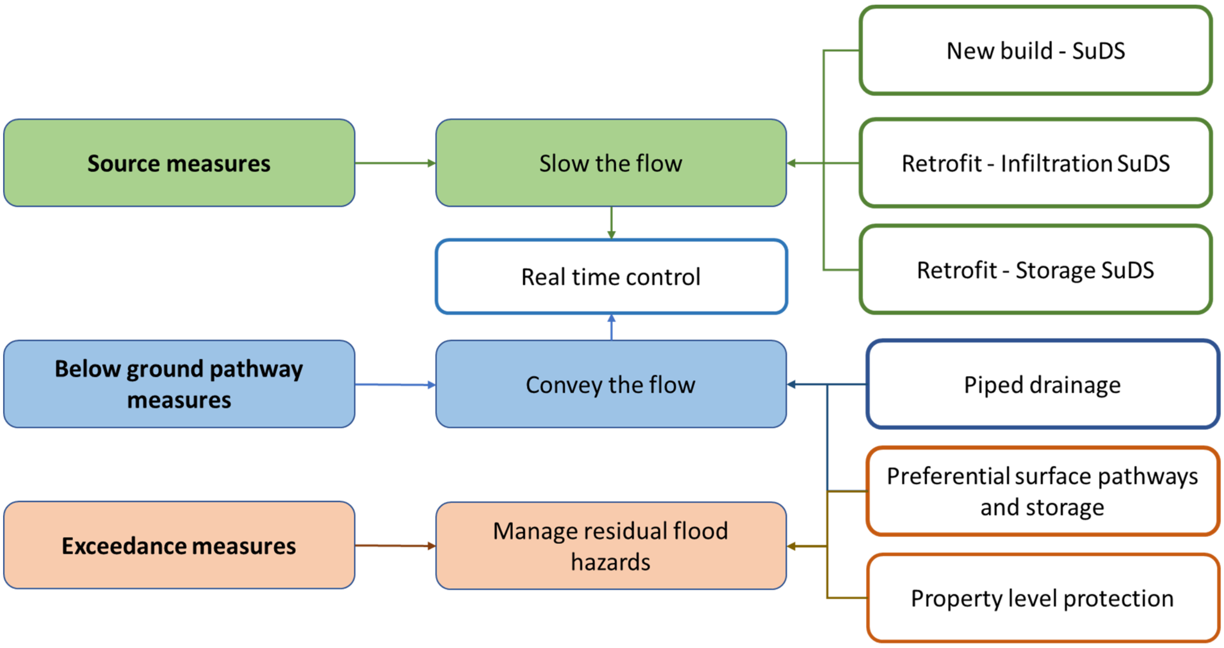


Figure 3-1 Adaptation measures – Surface water flood hazard management

Note

The focus of this study is investment in infrastructure to reduce the chance of flooding and by extension associated impacts and risk. No consideration is given to broader measures associated with non-structural activities including:

Improved forecasting and warning: There is no national surface water forecasting and warning system, despite the recognised expectation for exceedance. Forecasting and warning, including for short duration intense rainfall, is however continuously improving and will be a crucial part of the surface water management response, offering opportunities to reduce damages and disruption associated with flooding. This potential has not been included here.

Spatial planning: Spatial planning can have a powerful influence on future risk by moderating the influence of development. Population growth is assumed here to drive an increase in the demand for residential properties. The location of new development is assumed to be influenced by spatial planning, reflecting the limited consideration of surface water flood hazards within existing planning regulations. Where the population is projected to decrease the risk also decreases proportionally.

Property level measures to reduce damage given flooding: The use of concrete floors, changing electrical wiring *etc.* are other opportunities to reduce the damage given a property is flooded. These costs and benefits are excluded here. Passive property scale protection (to prevent flood waters entering a property) through local engineered and pathway modification is included.

3.3 Adaptation Portfolios

The individual adaptation measures are combined into a series of portfolios to be evaluated within FFE (Figure 3-2). Fifteen portfolios are assessed. Each portfolio is constructed from an alternative perspective; including six source-led portfolios (that focus on SuDS with more minor effort given to piped drainage responses), six below ground pathway led approaches (that focus on piped drainage with less effort given to SuDS) and three more balanced approaches. The scale of ambition associated with each adaptation measure within each portfolio is illustrated in Table 3-1. These qualitative statements are translated to quantified representations in the FFE at a local scale (taking account of various local constraints, such as the available space, the rural and urban context *etc.*) using the relationships set out in Appendix C.

The APs are used within FFE to develop a 'data cube' of possible adaptations, their cost, and their associated influence on surface water flood risk for each calculation area within the FFE. These results are then mined to determine the preferred adaptations for a given level of investment using the decision rules discussed later in Chapter 5.

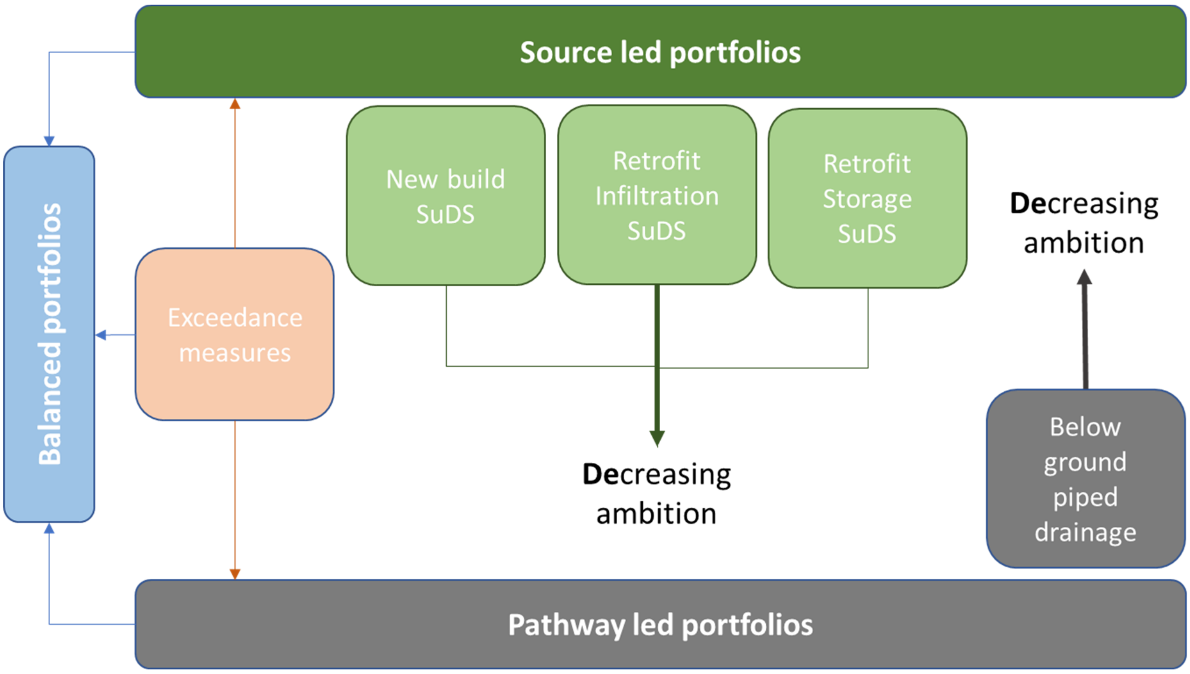


Figure 3-2 Adaptation portfolios – Framework for combining individual measures

Note:

Order of implementation: To determine the cost and performance of each measure within the portfolio consistently between portfolios, the individual measures within each portfolio are implemented in the same order with the FFE. The adopted order is as follows: first, new build SuDS (if new development takes place), followed by infiltration SuDS, storage SuDS and then piped drainage, real time control and lastly the exceedance measures (above ground pathways and property measures).

Table 3-1 Summary adaptation portfolios and individual measures

	Portfolio name and ambition														
	Source led (SL)						Balanced (HB)			Pathway led (PL)					
Adaptation measure	SL-0	SL-1	SL-2	SL-3	SL-4	SL-5	HB-1	HB-2	HB-3	PL-5	PL-4	PL-3	PL-2	PL-1	PL-0
New build - SuDS	VH	VH	H	M	L	VL	L	M	H	M	M	L	VL	-	-
Retrofit - Infiltration SuDS	VH	H	M	L	VL	VL	VL	L	M	L	L	VL	VL	-	-
Retrofit - Storage SuDS	H	H	H	H	M	M	L	M	H	H	M	L	VL	-	-
Below ground pathways - Piped drainage	VL	VL	VL	VL	M	M	H	H	H	H	H	VH	VH	EH	UH
Real time control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Exceedance measures - Surface pathways	VL	VH	H	M	M	L	L	M	H	M	M	L	L	-	-
Exceedance measures - Residual protection	VL	VL	VL	VL	L	L	M	M	M	M	M	H	H	VH	UH

Where:
EL = Extremely Low ambition
VL = Very Low ambition
L = Low ambition
M = Moderate ambition
H = High ambition
VH = Very High ambition
EH = Extremely High ambition
UH = Ultra High ambition
Yes = The measure is included in all portfolios in the same way

4.0 COSTS – ADAPTATION COSTS AND WHO PAYS

Both the costs of adaptation and who pays are addressed. The approach to each is summarised below and detailed in supporting Appendices.

4.1 Existing investment in surface water flood management

An estimated £279.6mn is invested annually in SWFM by a range of organisations (Table 4-1). This estimate reflects the spend that can be reasonably attributed to flood risk reduction activities and excludes investments in more routine actions to remove blockages, collapses, or overload of sewers due to growth (as detailed in Appendix A). The ongoing Flood and Coastal Resilience Innovation Programme (FCRIP) and the water company Green Economic Recovery funding are considered to be temporary programmes of investment, but are included following consultation with NIC.

Across the Environment Agency and water companies, 10% of present-day investment is assumed to be associated with activities that do not directly reduce flood risk. For Local Authorities, it is assumed that 20% of their investment is not directly focused on risk reduction. This differential reflects the lack of reporting of local authority expenditure on 'flood defence and land drainage;' and no consistent annual or periodic reporting describing the activities and outcomes achieved from these budget lines. By contrast, the objectives and outcomes of present-day investments undertaken under Flood and Coastal Erosion Risk Management (FCERM), by the water companies and by National Highways, are well documented. This leads to an estimate of £32.3mn per year spent on activities not directly leading to risk reduction.

Table 4-1 Existing expenditure by organisation

	CapEx (£mn)	**OpEx** (£mn)	**TotEx** (£mn)	% not directly associated with flood risk reduction	Annual spend (in addition to adaptation costs) - £mn
FCERM: Government Investment	52.0	0.0	52.0	10%	5.2
FCERM: Contributions from other parties	1.7	0.0	1.7	10%	0.2
Defra core retained budget	3.0	0.0	3.0	10%	0.3
Environment Agency Flood and Coastal Resilience Innovation Programme (FCRIP)	7.0	0.0	7.0	10%	0.7
Highways England: Designated Funds Programme	11.2	0.0	11.2	10%	1.1
Local Authority Revenue Account	21.4	21.4	42.8	20%	8.6
Water and Sewerage Companies (WaSCs): Business Plans	121.7	8.6	130.3	10%	13.0
WaSCs: Green Economic Recovery	31.6	0.0	31.6	10%	3.2
Total	**249.5**	**30.0**	**279.6**		**32.3**

4.2 Existing private public split

As agreed with the NIC the analysis apportions investments between two groups of measures:

- **Group 1 investments:** Sub-surface measures (piped drainage) and real time control.
- **Group 2 investments:** Infiltration SuDS; Storage SuDS; exceedance measures and new build SuDS.

This provides flexibility for a post analysis distribution of possible funding mechanisms to be undertaken by the NIC. To aid these post analysis considerations the indicative split between public and private funding and the associated with each adaptation measure (and the evidence used to inform this split) is presented in Appendix D.

Note:

The FFE does enable the investment splits to be tracked and the total private and public costs associated with measure within a portfolio to be estimated. Given the constraints of the project here it was agreed not to use this capability.

4.3 Cost functions

The cost of implementing each adaptation measure (e.g., piped drainage, new build SuDS *etc.*) is assessed using a series of top-down cost functions. Each function is described in a similar way based on the estimate of the properties protected. This enables the cost of each adaptation to be rapidly, but credibly, assessed in the FFE.

The cost functions for each adaptation measure, together with the supporting evidence, are set out in Appendix E. A wide range of evidence and information sources are used, including water company costs, Environment Agency research and publications (e.g., Environment Agency, 2015), SPON's Civil Engineering and Highway Works Price Book, academic literature, CIRIA, and previous projects/work undertaken by the authors (as detailed in Appendix E).

5.0 RESULTS - RETURN ON INVESTMENT

5.1 Overview

Assuming recent investment levels persist through to the 2050s (2022-2055), the associated real investment (non-discounted) would be £10.2bn. This section explores the return on investment given higher and lower levels of investments. To do so it is assumed investment is based on rational risk-based choices, with those portfolios yielding the greatest return on investment at a given location implemented first (see the decision rule below). The resulting value of the investment is presented together with a breakdown by settlement type and the distribution of the portfolio choices as investment levels increase (see Sections 6.3 and 6.4).

5.2 Decision rules

The decision rules used to allocate a given scale of national investment maximise the return on that investment through a simple pairwise optimisation as follows:

Step 1 – The Net Present Value (NPV) and Benefit Cost Ratio (BCR) for each alternative Adaptation Portfolio is estimated for each Calculation Area (CA) based on the estimated costs and benefits throughout the appraisal period (to 2100). Costs and benefits in future years are discounted using Treasury Green Book discount rates.

Step 2 – For a given level of national investment (the target investment), the NPV is maximised by ranking each adaptation portfolio (AP) as implemented at a local scale (i.e., CA) by BCR, from highest to lowest. The AP and CA combination with the highest BCR is implemented first, followed by the second highest and so on. For each first encounter of a CA, the NPV, PV Cost (PVc) and PV Benefits (PVb) are accrued. For each subsequent encounter of a CA, the previously encountered AP is replaced if the subsequent AP achieves a greater reduction in Expected Annual Damage (EAD) than the previously encountered AP (for that CA). The cumulative PVc, PVb and NPV are updated accordingly. This process continues until all available adaptations have been assessed or the target national PV Investment (PVi) is exceeded. Residual risks (properties that continue to be flooded) are also tracked through this process.

The process focuses on benefits derived from avoided property related flood damage. The process is however repeated twice, once including and once excluding wider benefits. The results for each are drawn upon in the following sections (although the focus remains on avoided risk).

Note:

Climate and population growth scenario: The process is applied to each future separately. No attempt is made to provide a robust allocation of investment.

Counterfactual: The avoided risk reflects a comparison of the future risk with and without adaptation. Here the ‘without’ case assumes no improvement in drainage capacity and no take-up of SuDS for new development.

Affordability or funding source: Neither play a part in the optimisation process. This results in spend being incurred early in the appraisal period. An affordability constraint could be readily applied in the FFE as part of a future analysis.

Reality of investment choices: No attempt is made here to reflect the reality of the existing allocation process (as it occurs in practice) – i.e., the rules the Environment Agency or Water Companies may use to decide where and when to invest (that may not be solely risk based).

Timing of investment: A lack of affordability limits and optimization in time (only in space) means the presented NPV are likely to be lower than would be the case if investment was optimized in time. Including the ability to optimize in time could be introduced to the FFE to support future analysis. The impact on the NPV is difficult to determine but could be significant.

5.3 National – Return on investment and residual risks

5.3.1 National return on investment - Maximised Net Present Value

Optimised return - Based on economic damage reduction only

The return on investment in adaptation (as expressed through Net Present Value, NPV) rises sharply up to a real investment (*i.e.*, not discounted) through to the 2050s to around ~£5bn regardless of the climate and population future (Figure 5-1). The real investment yielding maximum return (defined by the peak NPV) does however vary with the future scenarios, ranging from ~£9bn assuming a 2°C, no population change future (slightly higher than a continuation of present-day expenditure, equivalent to a spend of ~£8.2bn), increasing to ~£13bn assuming a 4°C, high population growth future. The peak of NPV return is much flatter in the case of the 4°C high population growth, with limited reduction in NPV as spends increase to ~£20bn.

Net positive return – Based on economic damage reduction only

The NPV remains positive (greater than zero) for real investments of around £29bn (assuming a no population growth, 2°C future) rising to £39bn (assuming a high population growth, 4°C future).

Optimised return - Based on economic damage reduction and wider benefits

The return on investment increases significantly when the wider benefits associated with SuDS are included (Figure 5-2). SuDS based adaptations provide amenity, air quality, biodiversity, carbon sequestration, and health benefits as well as a reduction in the cost of addressing CSOs (where relevant). Including these wider benefits increases the optimised return (defined by the real investment at the peak NPV) to between ~£9 and 10bn assuming a 2°C, no population growth future, and up to ~£15bn (with a relatively flat peak) assuming a 4°C, high population growth future.

The contribution of wider benefits and CSO cost savings change as the real investment increases. For real investments of up to ~£20bn (by 2050s) these additional benefits are primarily associated with CSO cost savings. This is likely to reflect the dominant use of source-led portfolios (based on SuDS) within the optimised national investments. SuDS based portfolios, where selected, act to attenuate flows and are assumed to reduce the storm overflows. As real investment levels increase, pathway-led portfolios (that focus more on conveying flows through piped drainage) are increasingly selected as the preferred approach (based on economic damage benefits only) and hence offer progressively less in terms of CSO cost savings (Figure 5-3).

Net positive return – Based on economic damage reduction and wider benefits

The NPV remains positive (greater than zero) for real investments of up to ~£29bn (assuming a no population growth, 2°C future) rising to £39bn (assuming a high population growth, 4°C future).

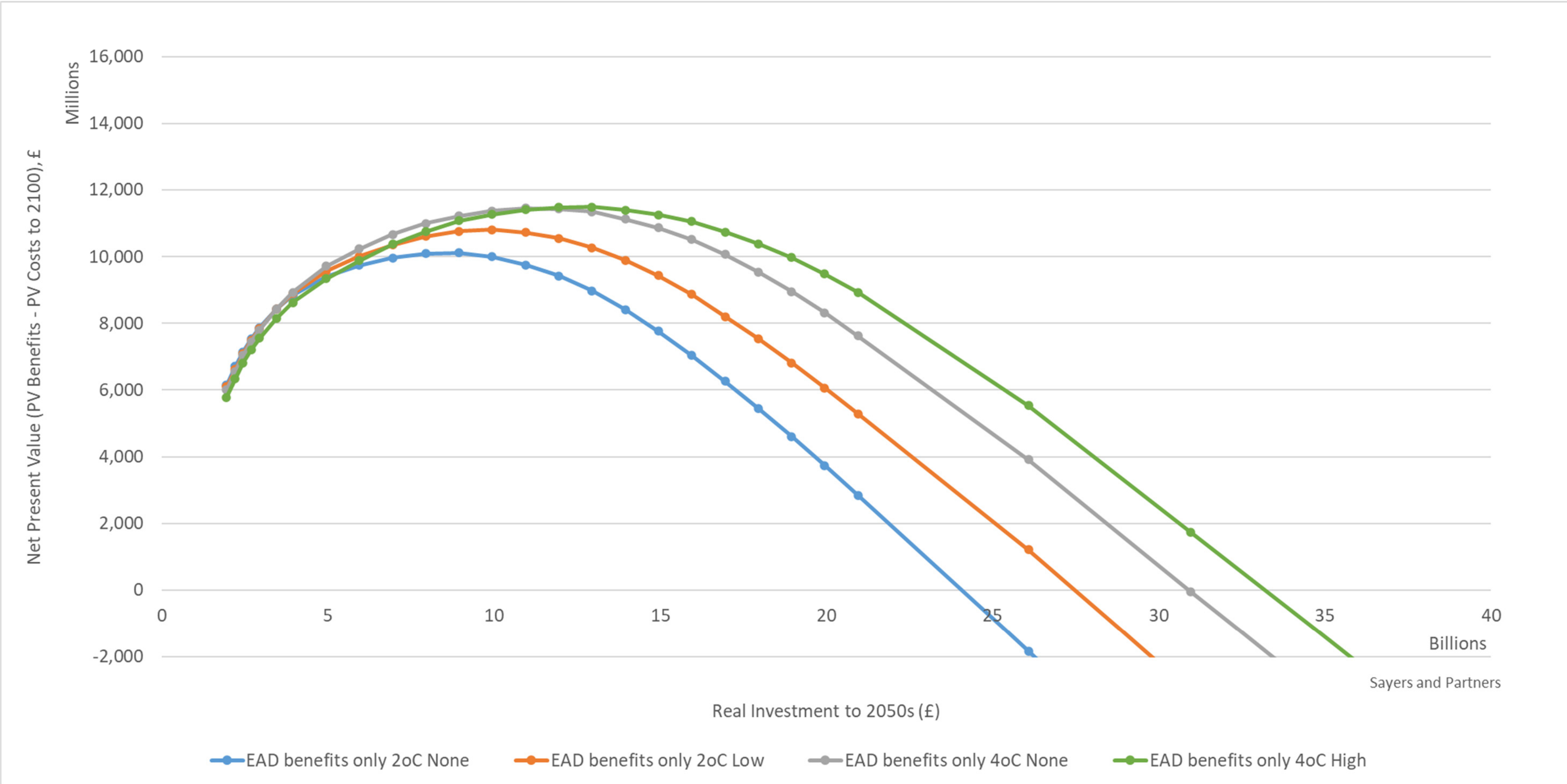


Figure 5-1 National return on investment - Maximised Net Present Value (based on economic damage reduction only)

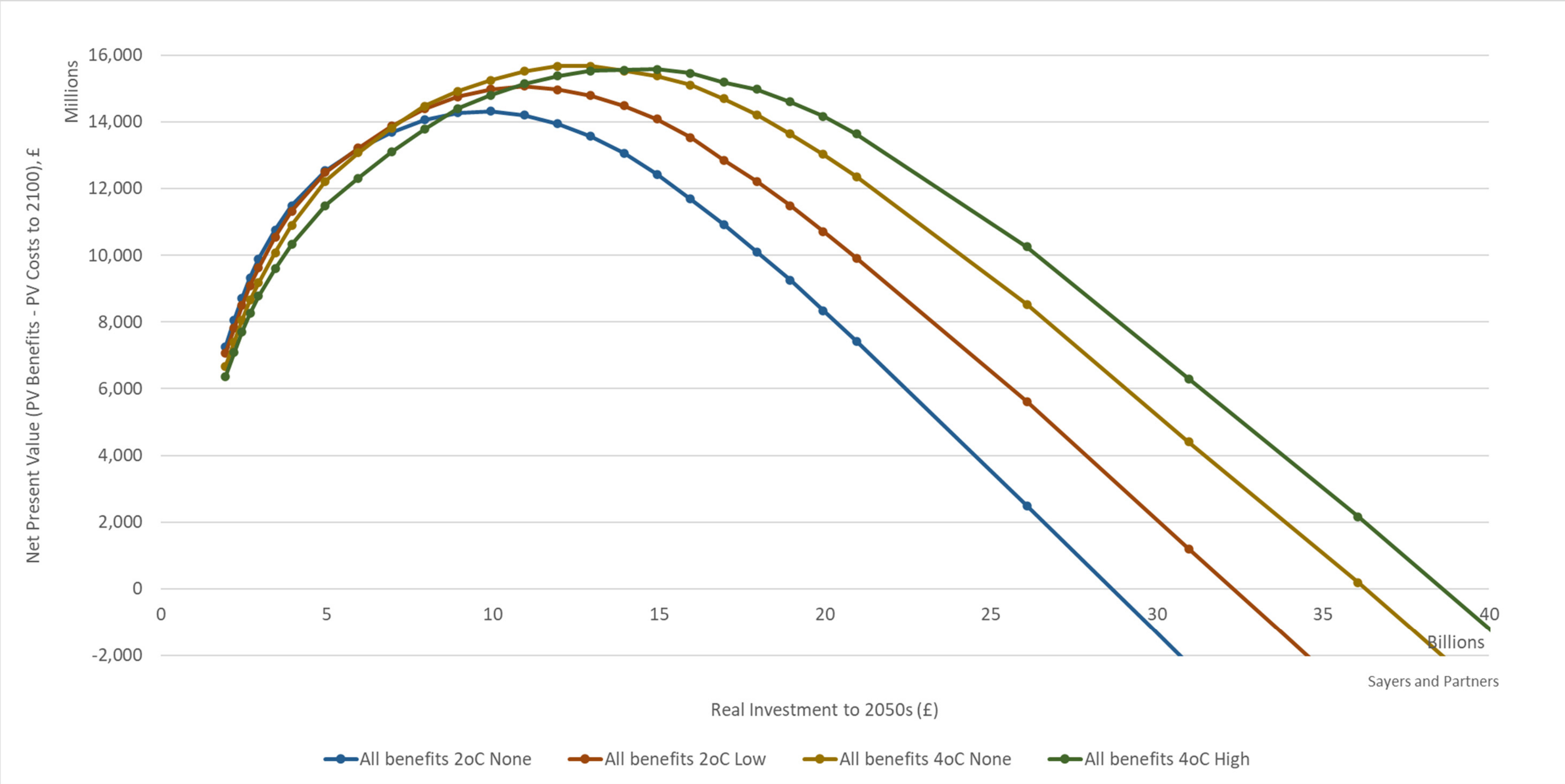
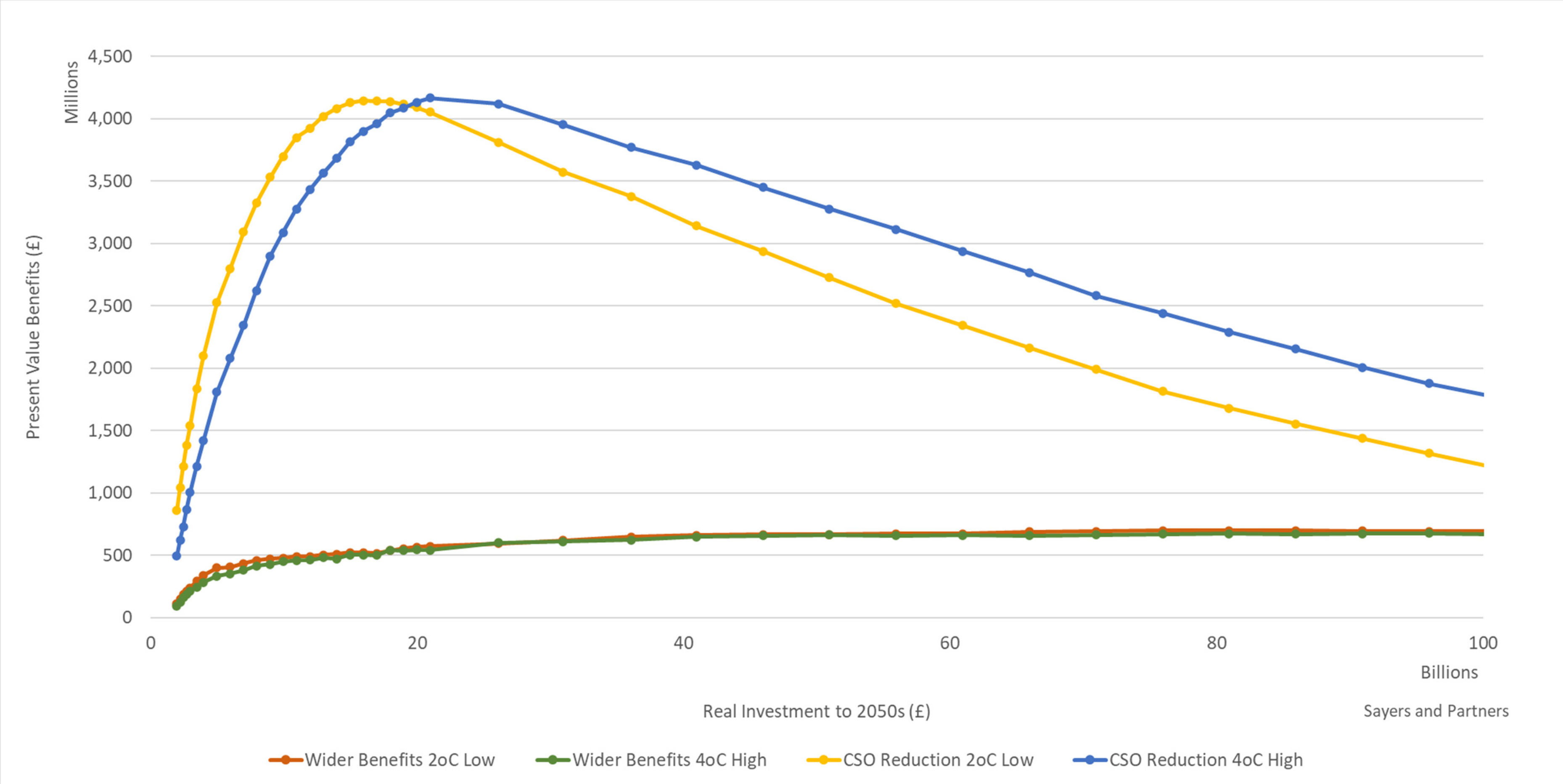


Figure 5-2 National return on investment - Maximised Net Present Value (based on damage reduction and wider benefits, including CSO cost savings)



Note: 2°C low population growth, and 4°C high population growth futures only.

Figure 5-3 National return on investment – contribution of wider benefits and CSO cost savings to the maximised Net Present Value

5.3.2 Split of capital, operation, and carbon expenditure

Capital expenditure increasingly dominates as the real investment increases (Figure 5-4). Operational costs remain around 8% of the total costs up to an investment level of ~£2bn (through to 2050s) before falling to <1%. This reflects the preference given to the source-led portfolios as part of nationally optimised response given lower levels of spend (and hence higher maintenance costs). As the real investment increases, the optimisation process increasingly selects pathway-led portfolios with much lower associated on-going maintenance costs as investment levels increase.

5.3.3 Split by source-led and pathway-led adaptation portfolios

Source-led portfolios offer an important contribution to national surface water risk reduction at lower levels of national expenditure (Figure 5-5). For real investments up to ~£5bn (by the 2050s) investments in SuDS accounts for around 20% (or more) of the national investment. As investment levels increase, the return on investment slows (as seen earlier in Figure 5-1) and pathway-led (piped drainage) portfolios become increasingly selected to reduce risk. This highlights an 'effectiveness' limit to the source-led approaches and the need for supplementary pathway-led portfolios to deliver high standards of protection from surface water flooding where required. This reflects inherent limitations on performance of SuDS but also constraints of space (limiting the implementation of SuDS in some urban locations). To deliver higher levels of risk reduction, source-led portfolios require complementary exceedance measures to be in place.

5.3.4 Spatial distribution of optimised investment

The spatial distribution of a national optimised investment of £35bn, indicative of the maximum real investment to the 2050s yielding a positive return (*i.e.* NPV greater than zero), is given in Figure 5-6. The pattern of investment is similar in both a 2°C low population growth and a 4°C high population growth future. This reflects the concentration of expenditure within urban areas in all futures considered here (a finding echoed in later discussion in Section 5.4).

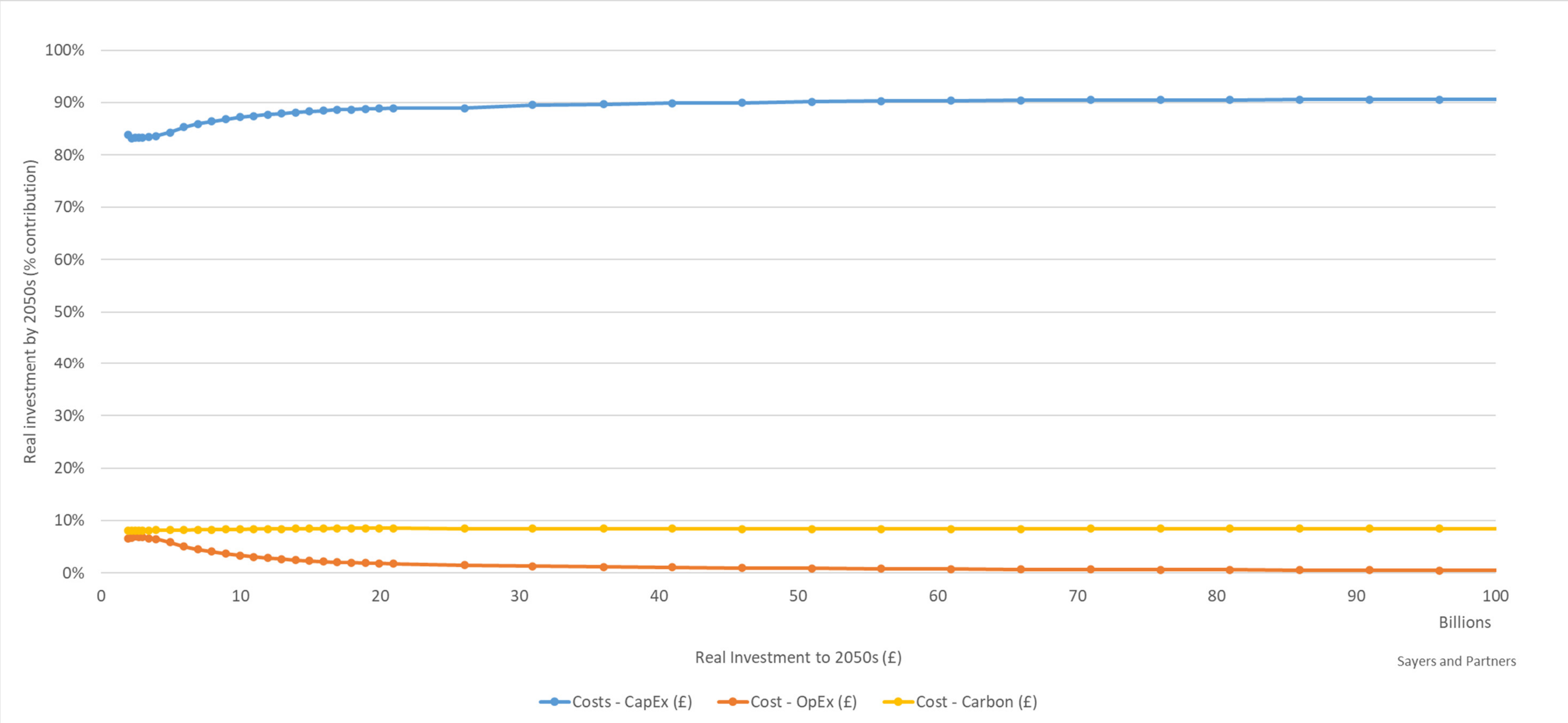
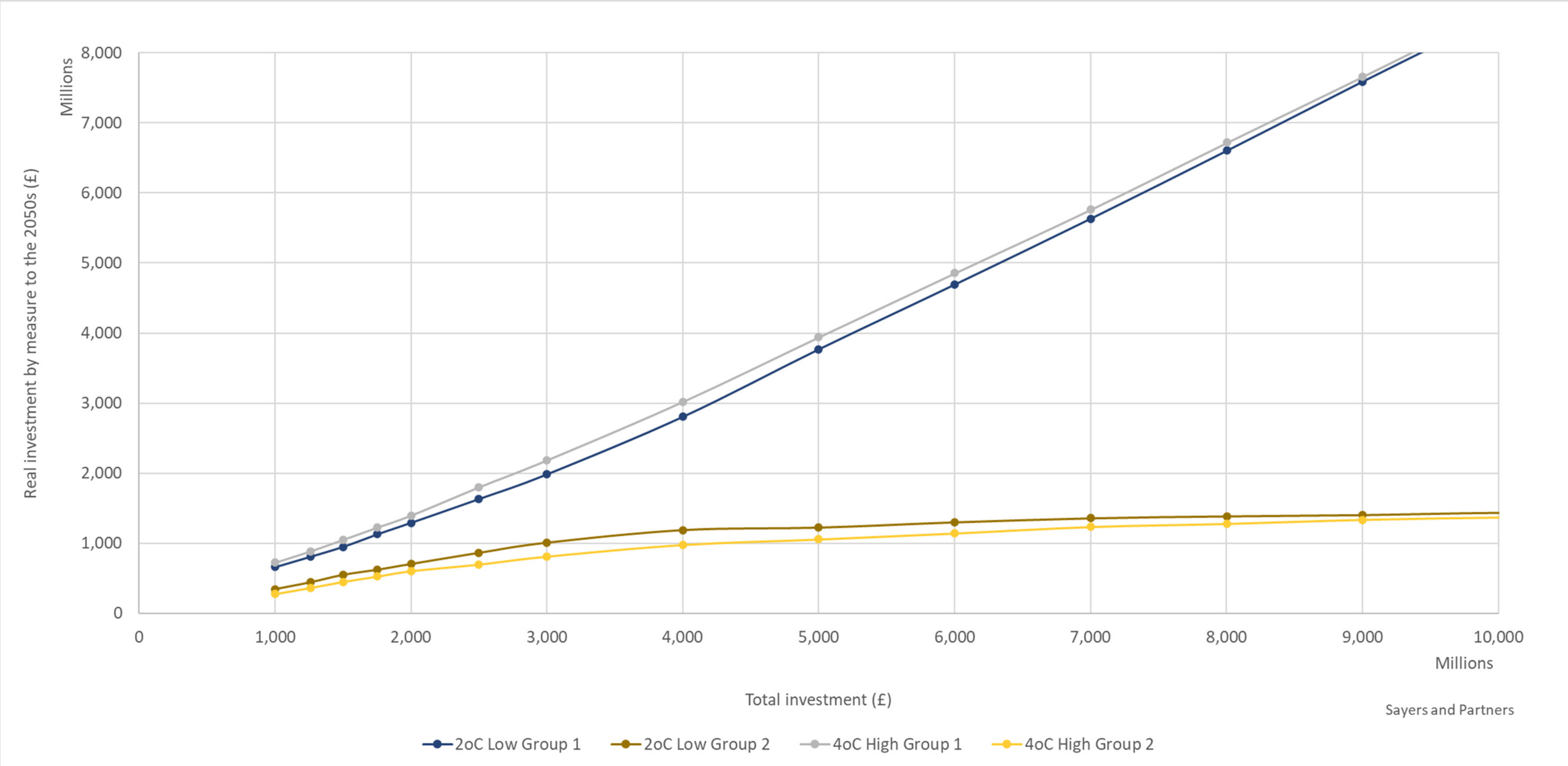
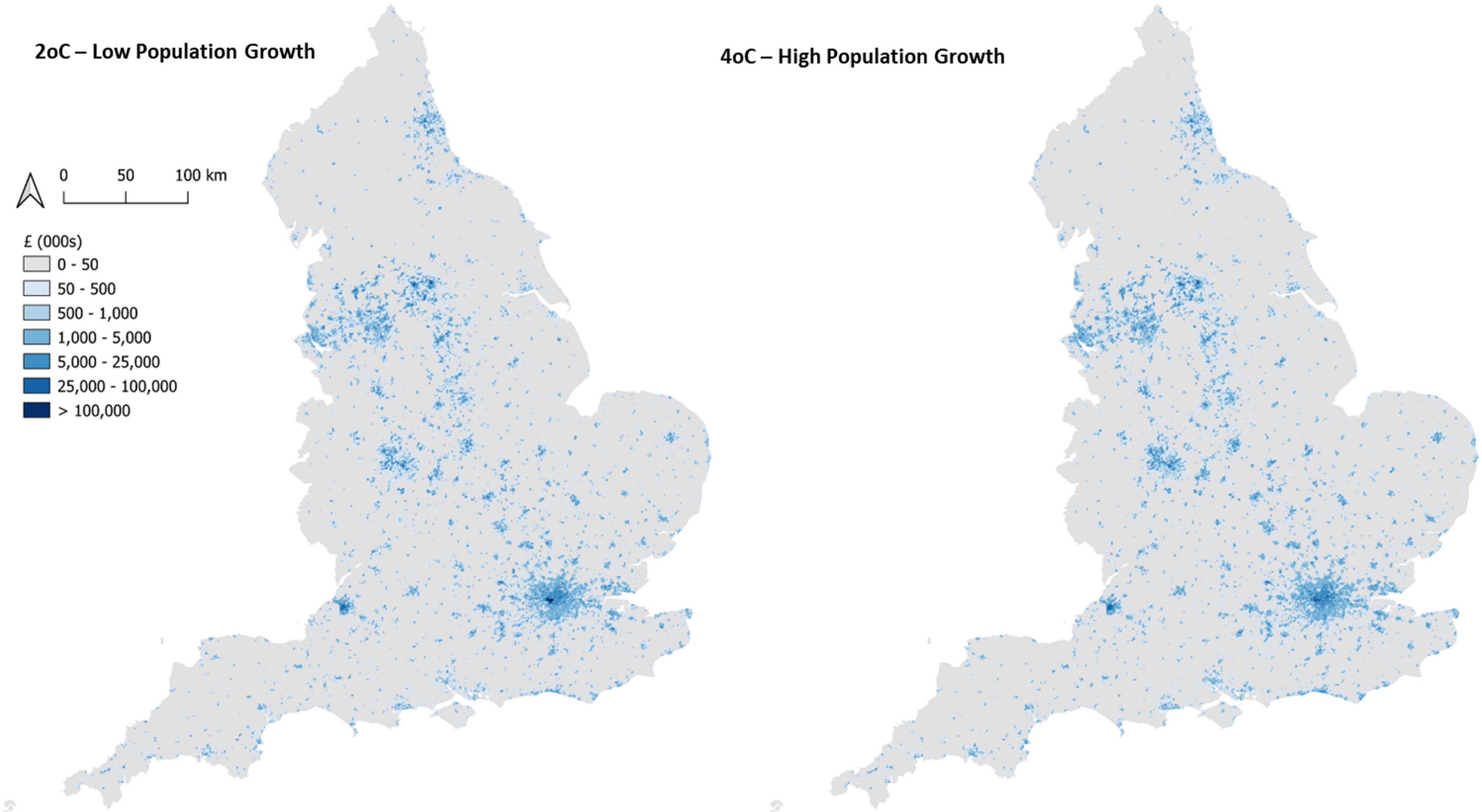


Figure 5-4 National investment – Real investment to 2050s (% contribution of expenditure on capital, operational and carbon)



Group 1 investments refer to Sub-surface measures (piped drainage) and real time control.
Group 2 investments refer to Infiltration SuDS; Storage SuDS; surface pathways; exceedance measures and new build SuDS.

Figure 5-5 National investment – Real investment to 2050s – Indicative distribution by grouped measures



Left - 2°C low population growth future. Right – 4°C high population growth future

Figure 5-6 Spatial distribution of optimised investment of £35bn (real investment) – 2°C – Low Population growth and 4°C - High Population Growth

5.3.5 Residual Expected Annual Damage by the 2050s

The Expected Annual Damage (EAD) associated with surface water flooding rapidly reduces as the real investment increases to ~£20bn in all future climate and population growth scenarios considered here (Figure 5-7). The reduction is largest in a 4^{o}C high population growth future (reducing from a projected risk of ~£1.6bn by the 2050s in the absence of adaptation to ~£0.58bn) and smallest in 2^{o}C no growth future (reducing from £1.3bn to ~£0.45bn). As the real investment increases the incremental reduction in EAD diminishes.

5.3.6 Properties protected and remaining at risk

Exposed to flooding, 1in30 years, on average

The number of properties protected up to a 1in30 year standard (i.e., exposed to flooding that occurs less frequently than 1in30 years, on average) largely mirrors the reduction in EAD (Figure 5-8). The number of properties projected to experience frequent flooding (more frequent than 1in30 years on average) reduces significant as real investment increases to ~£20bn; the reduction in the number of properties exposed to flooding then slows as real investment extends to £100bn (through to the 2050s). This reflects the difficulty in providing full protection from surface water flooding at any given location (regardless of adaptation efforts) and the significant expenditure that would be required to adapt all locations (as not all locations receive investment based on economic rules used as part of the national £100bn investment).

Exposed to flooding, 1in100 years, on average

The number of properties protected up to a 1in100 year standard (i.e., exposed to flooding that occurs less frequently than 1in100 years, on average) rapidly declines as real investment to the 2050s increases to ~£20bn (Figure 5-9). Continuing to reduce the number of properties exposed to infrequent flooding becomes increasingly difficult and a significant number of properties remain exposed regardless of the investment in adaptation. This pattern is reflected across all climate and population future considered here but most evident given a 4^{0}C high population growth future, with over 400,000 properties remaining exposed to flooding more frequently than 1in100 years, on average, despite a real investment of £100bn by the 2050s.

Exposed to flooding, annual average

As real investment increases, the reduction in the annual average number of properties exposed to surface water flooding by the 2050s varies significantly in the different futures considered here (Figure 5-10). The number of properties exposed given limited investment in adaptation (~£2bn by the 2050s) is projected to reach 200,000 given a 4^{o}C high population growth future by the 2050s. As investment increases to ~£20bn (to 2050s) the annual average number of properties flooded reduces rapidly, although remains much higher given a 4^{o}C high population growth future compared to the future scenarios considered here. This highlights the importance of continuing to mitigate climate change and to improve planning controls as part of a broader response to surface water flooding (although neither are considered here).

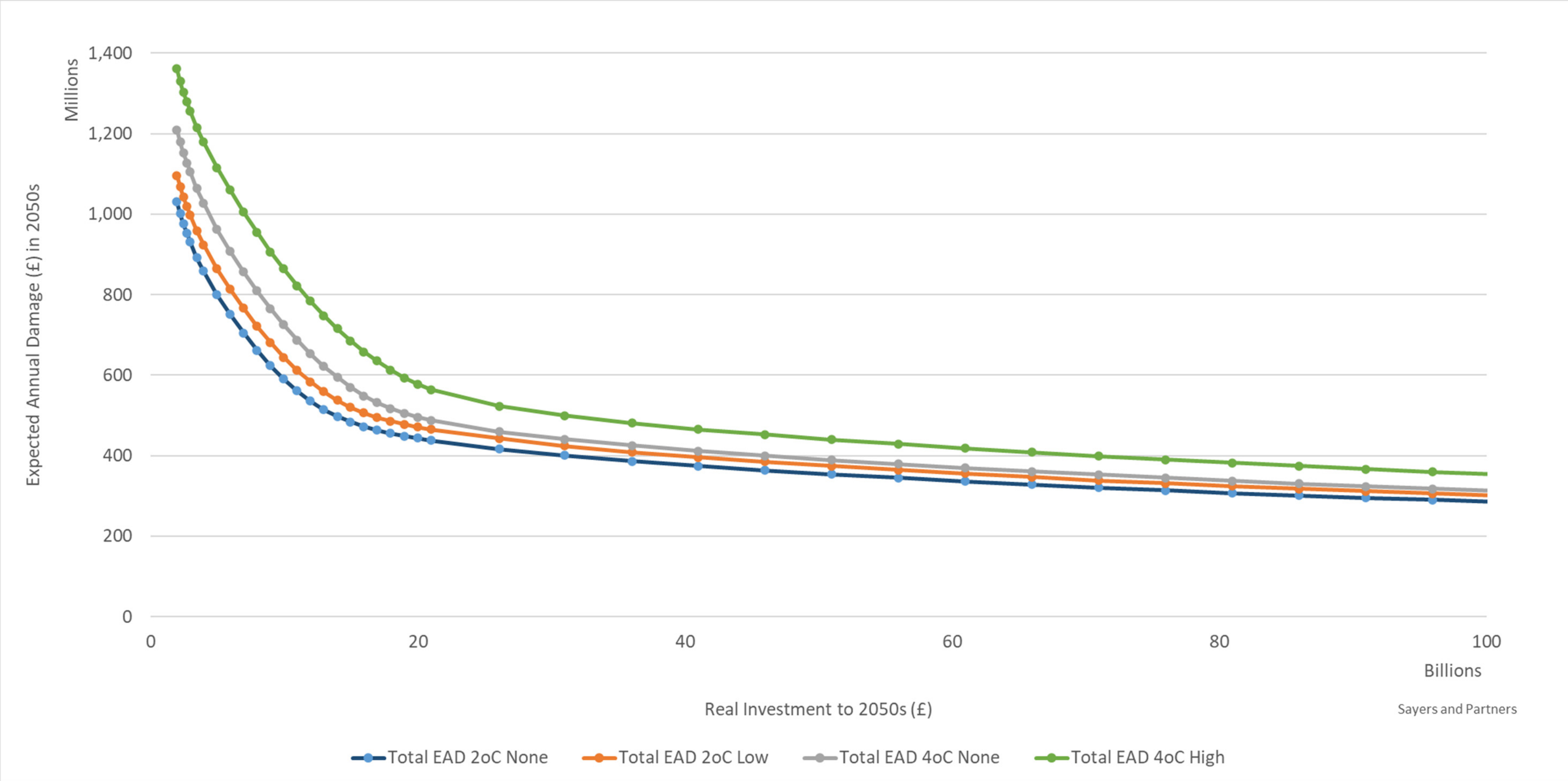


Figure 5-7 National return on investment – Expected Annual Damage by the 2050s

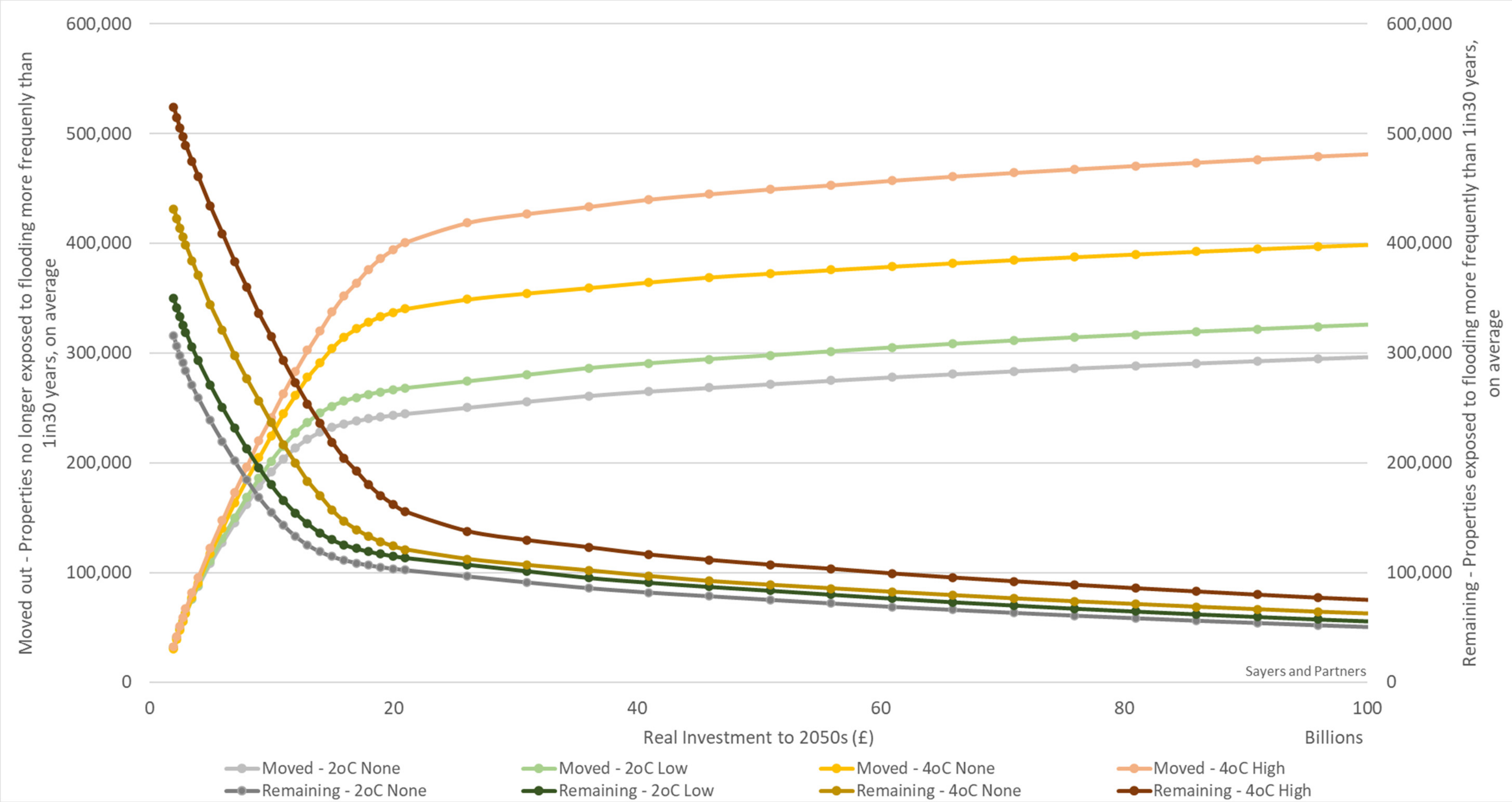


Figure 5-8 National return on investment – Properties protected and remaining at risk – Exposed to flooding, equal to or more frequently than 1in30 years, on average

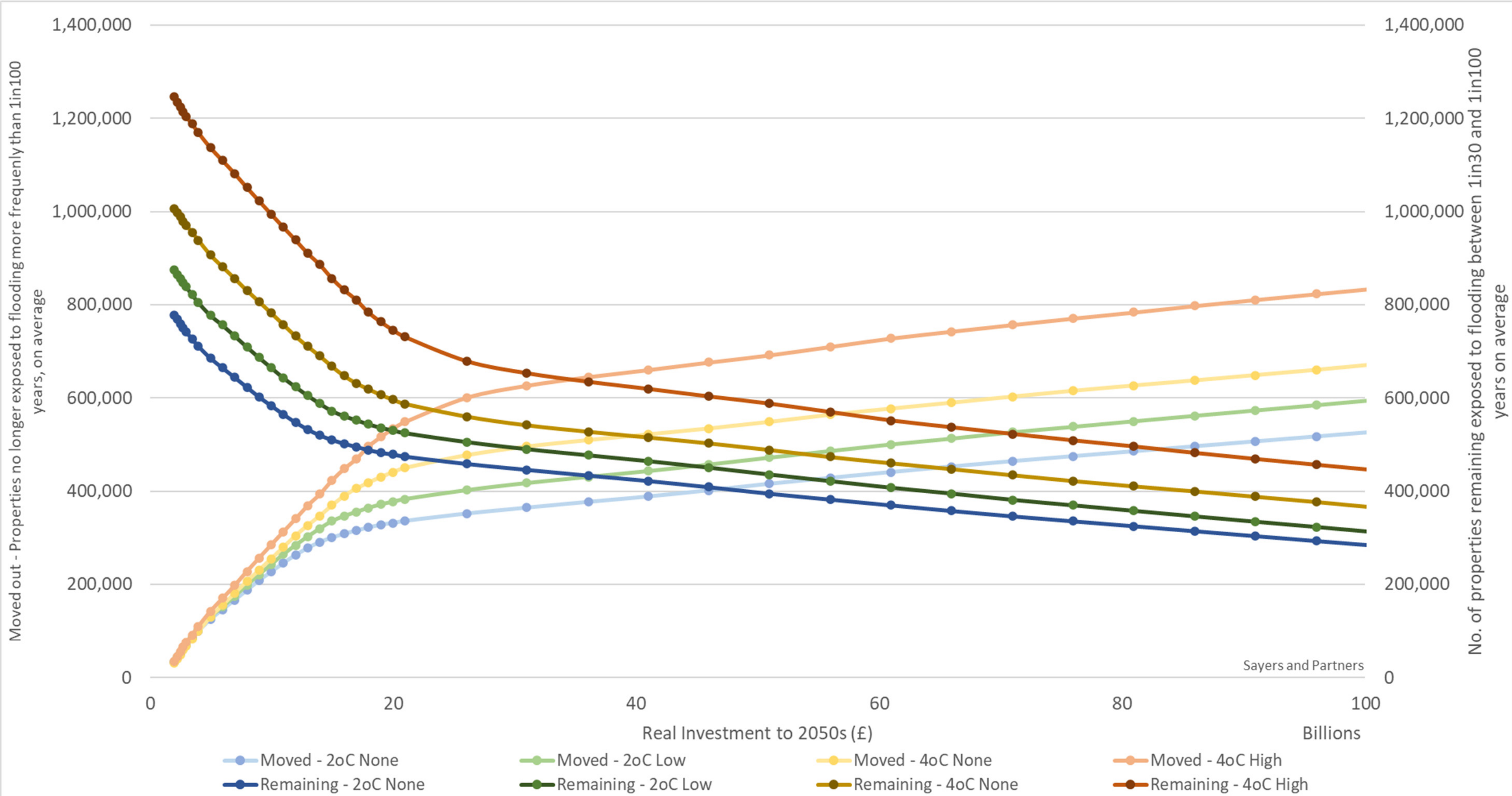
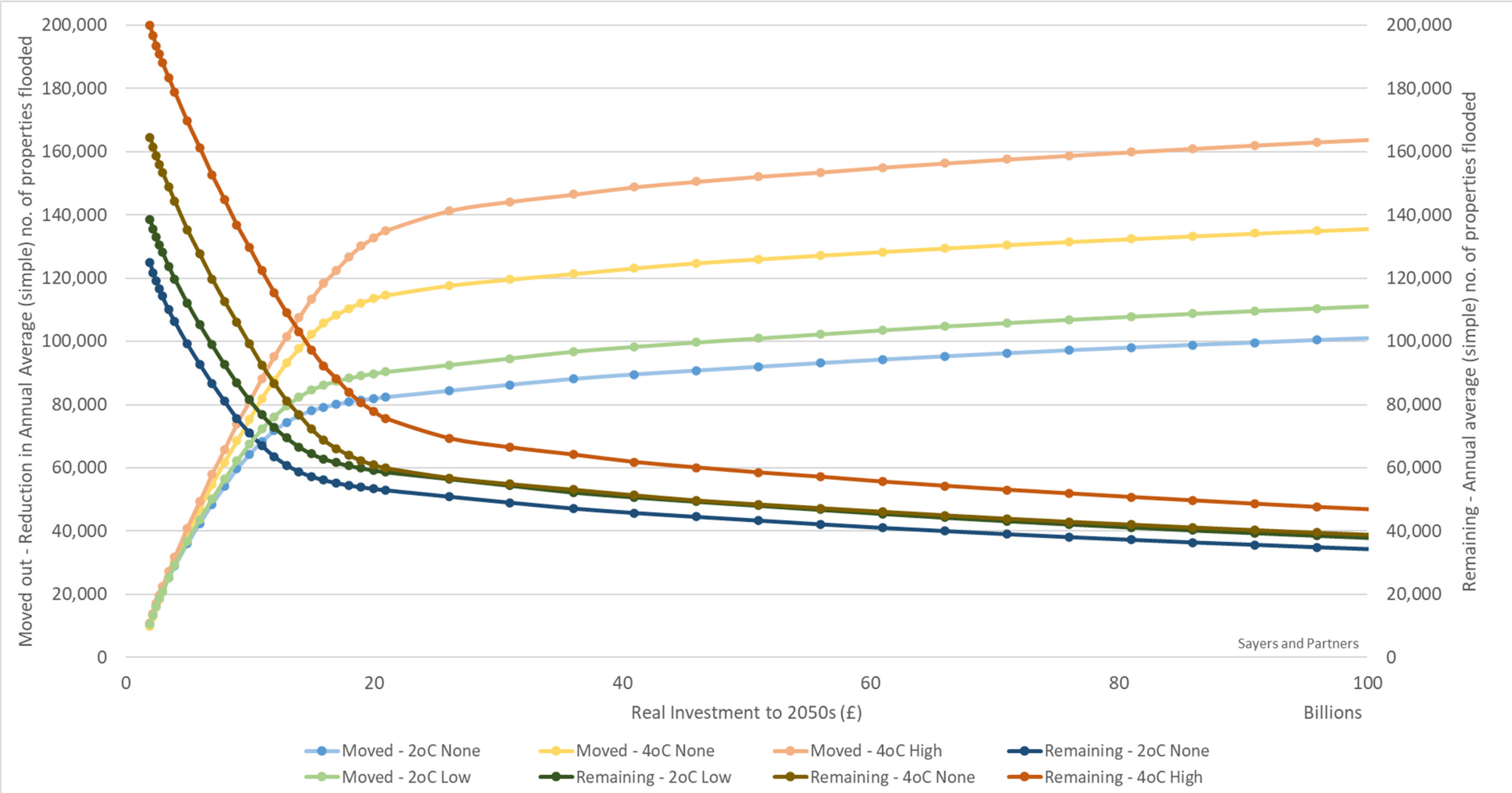


Figure 5-9 National return on investment – Properties protected and remaining at risk – Exposed to flooding, equal to or more frequently than 1in100 years, on average



Note: 'Simple' annual average refers to the annual average determined based on properties in bands following optimisation.

Figure 5-10 National return on investment – Properties protected and remaining at risk – Annual Average No. of properties flooded

5.4 Settlement type - Return on investment and residual risks

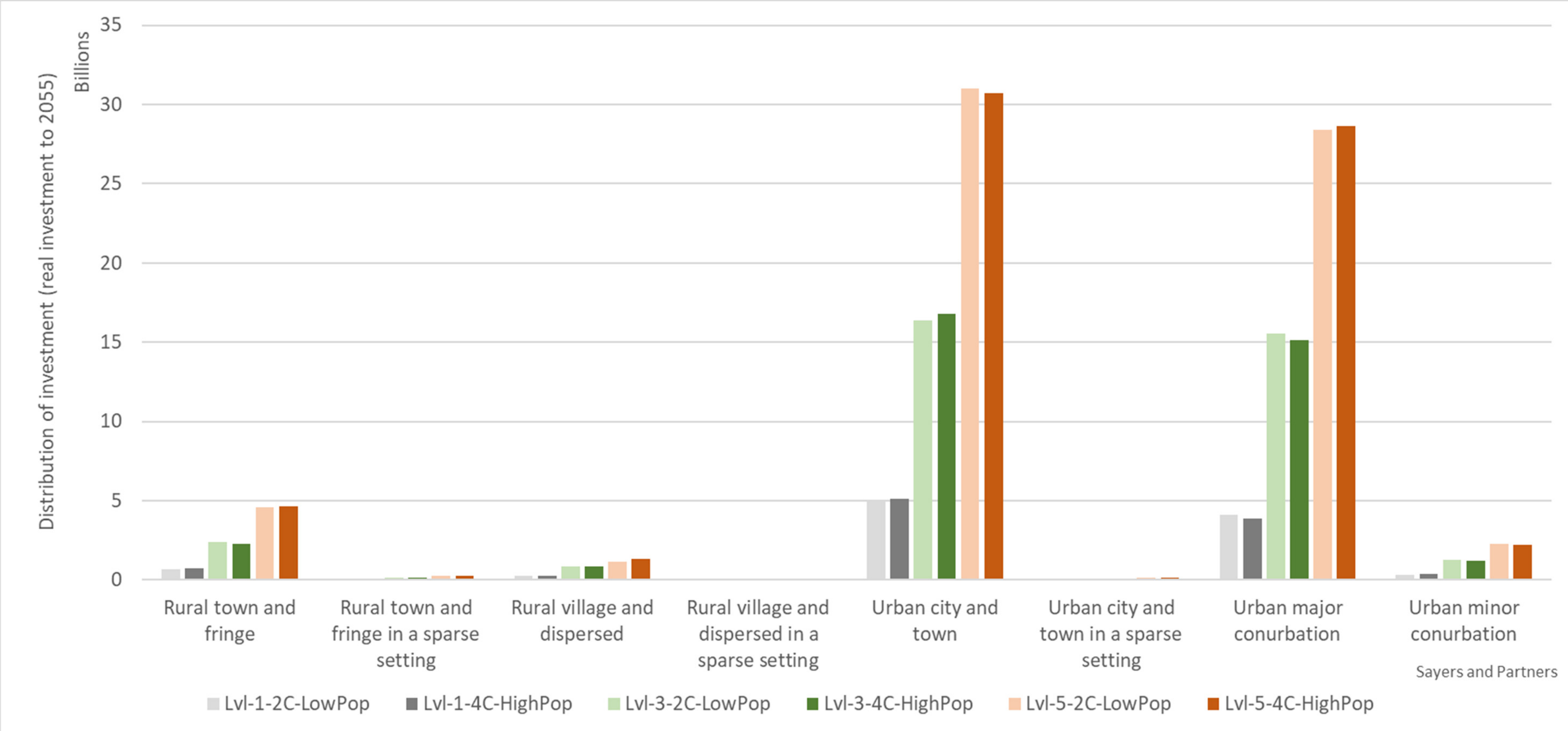
The lens of settlement type is used to explore the relationship between investment and risk in more detail. Six discrete national levels of investment are considered (Table 5-1). These represent an expenditure similar to a continuation of present-day levels (~£10bn real investment to 2055), a level close to the optimised national investment from the analysis presented in earlier sections (~£20bn), and a series of higher investment levels.

Table 5-1 Discrete exploratory real investment levels

Real Investment (£bn) - 2022 to 2055	
Level 1	10
Level 2	20
Level 3	35
Level 4	50
Level 5	65
Level 6	80

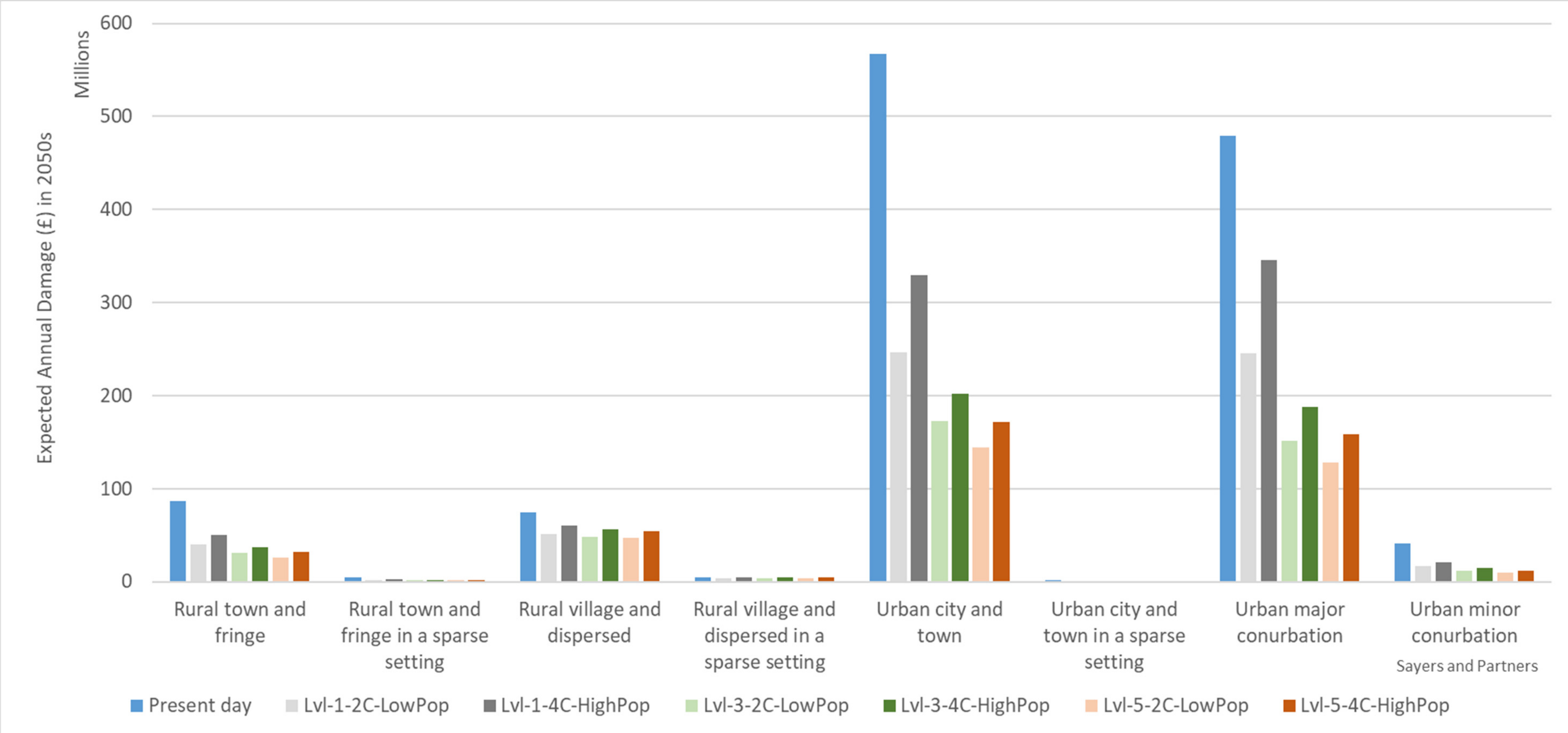
Note: Levels 1, 3 and 5 used in the following charts

Most investment is in urban settlement types, regardless of the national level of spend or future (Figure 5-11). This reflects the concentration of surface water risks in those areas (Figure 5-12). The EAD is significantly reduced given £10bn (level 1) investment and continues to decrease (but more slowly) as spend increases. The number of properties that remain exposed to surface water flooding highlights that a continuation of current levels of investment is unlikely to reduce risks by the 2050s below those experienced today, and in a 4°C high population growth future the number of properties exposed to flooding increases (Figure 5-13 and Figure 5-14).



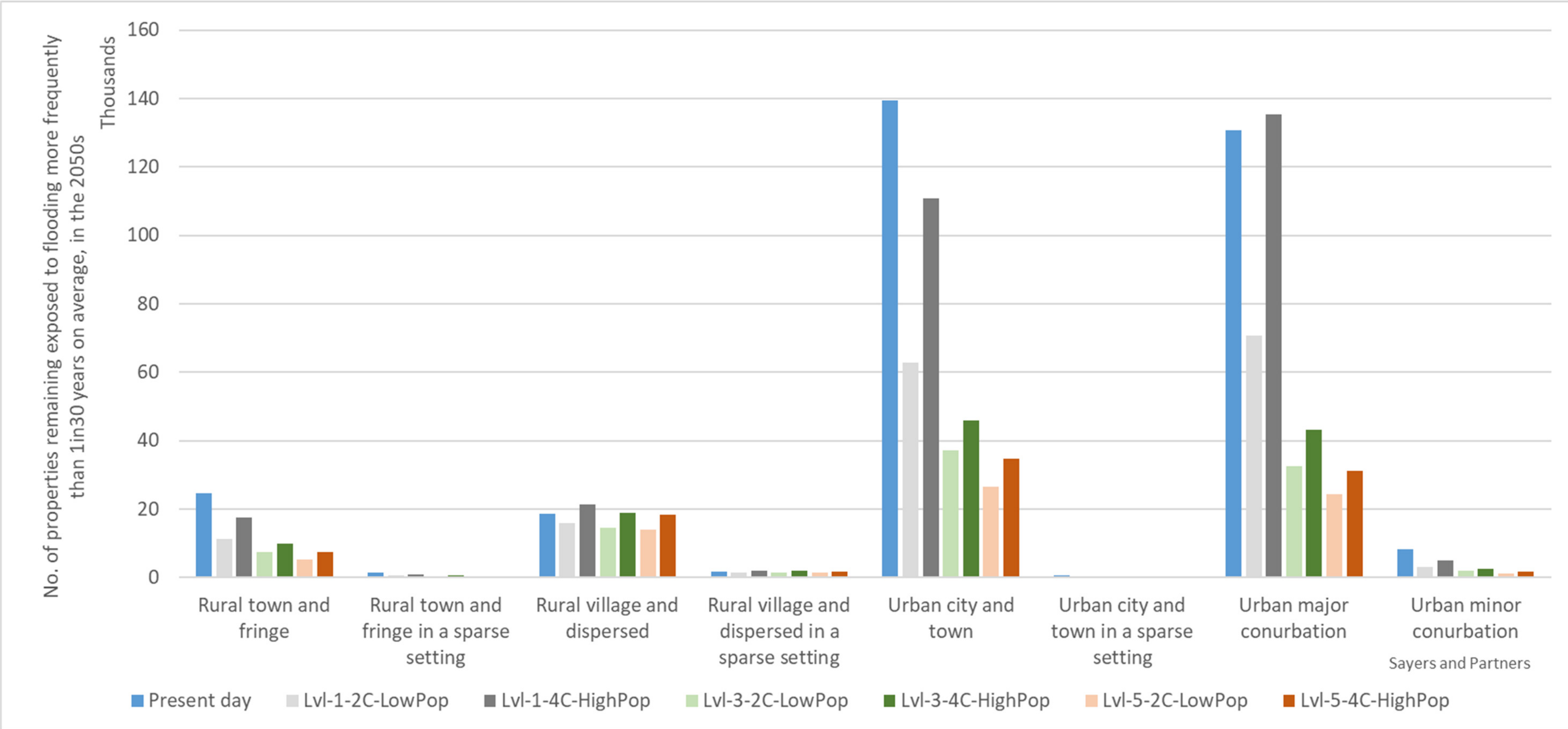
Lighter shading - 2ºC low population growth future. Darker shading – 4ºC high population growth future. Different colours reflect different investment Levels 1 (~£10bn), 3 (~£35bn), and 5 (~£65bn)

Figure 5-11 Distribution of investment – By settlement type given increasing levels of real investment to 2050s



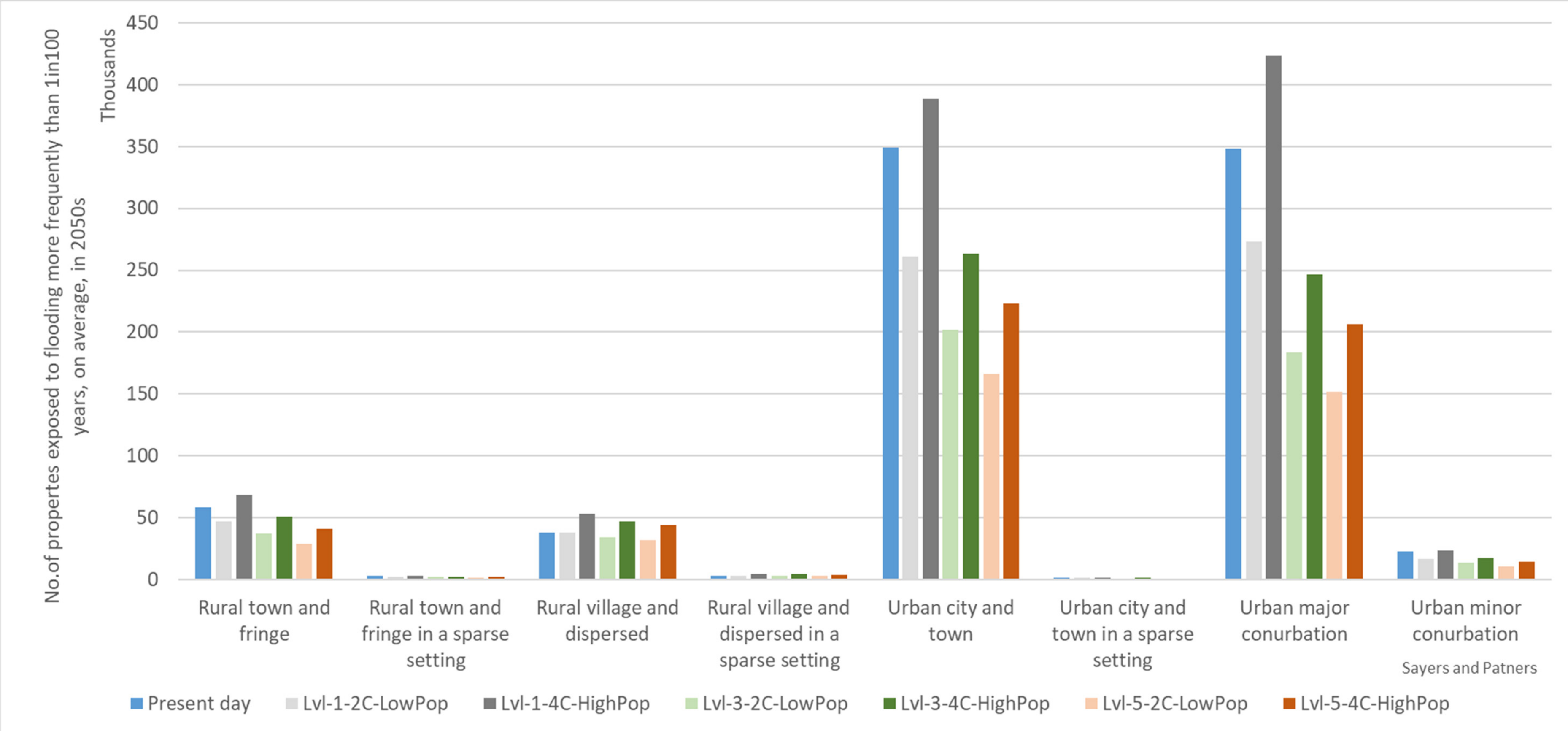
Blue – Present day. Lighter shading - 2°C low population growth future. Darker shading – 4°C high population growth future. Different colours reflect different investment Levels 1 (~£10bn), 3 (~£35bn), and 5 (~£65bn)

Figure 5-12 Distribution of residual risks – Expected Annual Damage as real investment to 2050s increases



Blue – Present day. Lighter shading - 2°C low population growth future. Darker shading – 4°C high population growth future. Different colours reflect different investment Levels 1 (~£10bn), 3 (~£35bn), and 5 (~£65bn)

Figure 5-13 Distribution of residual risks – No. of properties exposed to flooding more frequently than 1in30 years, on average



Blue – Present day. Lighter shading - 2°C low population growth future. Darker shading – 4°C high population growth future. Different colours reflect different investment Levels 1 (~£10bn), 3 (~£35bn), and 5 (~£65bn)

Figure 5-14 Distribution of residual risks – No. of properties exposed to flooding more frequently than 1in100 years, on average

6.0 CONCLUSIONS

6.1 Caveats

Approach to recommendations

No conclusions are drawn regarding the acceptability, affordability, or organisation of the actions needed. The analysis focused on presenting future changes in surface water risk and the influence of alternative levels of national investment in adaptation, climate and population growth on those risks.

Importance of present-day estimates of risk

The FFE makes no attempt to assess present day flood risk from first principles but uses estimates provided by the Environment Agency. For this study, the present-day estimates of surface water flood risks are drawn from the Environment Agency's most recent assessment undertaken in support of LTIS 2019. The LTIS analysis is not a formal reassessment of surface water risk but does represent the best available existing assessment. It is also noted that the estimate of present-day surface water flood risk used within the UK CCRA3 is much lower. The difficulty and uncertainty associated with estimating surface water risks is acknowledged by the Environment Agency and highlighted as an area requiring further development. It is also recognised that the present-day risk is the focus of ongoing developments as part of the next generation National Flood Risk Assessment (NaFRA2). The analysis presented here should be revisited once this data is available.

6.2 Conclusions

The analysis suggests an investment of ~£29bn provides a positive net present value return given a 2°C climate future and no population change, rising to ~£39bn in a 4°C and high population growth future. This represents an increase of 3.3 to 4.5 times on recent expenditure. This is based on consideration of reductions in economic flood damage achieved and real investment in capital and operational expenditure through to the 2050s.

Below these headline figures several conclusions can be drawn from the analysis, namely:

Opportunity for, and significance of, wider benefits from source-led adaptations

The inclusion of the value of wider benefits (air quality, amenity, carbon sequestration, *etc.*) into the economic analysis significantly increases the case for investment in surface water flood management using SuDS based portfolios; adding ~£0.6bn of benefits. These benefits do not accrue through conventional piped drainage responses.

Investment in conventional piped drainage will be needed to supplement source-led SuDS

SuDS offer an important contribution to national surface water risk reduction. For real investments up to ~£5bn (by the 2050s) investments in SuDS accounts for around 20% (or more) of the national optimised investment portfolio. As investment levels increase, the return on investment slows and pathway-led (piped drainage) portfolios become increasingly selected to reduce risk. This highlights an 'effectiveness' limit to the source-led approaches and the need for supplementary pathway-led portfolios to deliver high standards of protection. This reflects inherent limitations on the performance of SuDS but also constraints of space (limiting the implementation of SuDS in some urban locations).

Urban areas contribute most to surface water flood risks and have the greatest investment need

The majority of surface water flood risk is in urban areas and urban areas dominate the projected investment need (accounting for ~90% of the project investment regardless of the future or investment level). This reflects the greater population in urban areas and influence of impermeable urban surfaces on run-off.

Not all surface water flooding can be eliminated, designing for exceedance is an important principle

The management of surface water flooding is not analogous to fluvial flooding. Protection against surface water flooding cannot be achieved through increased capacity in SuDS and piped drainage alone (as could be notionally argued in the case of providing a higher standard fluvial flood defence). Designing for exceedance (to address the residual flood hazard) is a central aspect of surface water management and such measures are considered as part of each portfolio. No consideration is given here to their implementation as a standalone action in those locations not identified for investment in broader drainage improvement. Exceedance measures are likely to be an important response in these areas, quantifying their benefits in these areas is outside the scope of this study.

Opportunity for, and importance of, adopting a more strategic and integrated approach to surface water management

Adopting a strategic approach to planning investments offers saving. This includes adopting city wide and catchment wide planning responses to reduce the costs, conservatively considered to offer saving of ~5-10%. More strategic action also offers the opportunity to reduce flood risk whilst simultaneously reducing the costs of addressing storm overflows (CSOs). Assuming CSOs cost savings to accrue only in those locations where SuDS led portfolios are selected as part of the national optimised activities, the present value of the cost saving peaks at ~£4bn given a £20bn real (undiscounted) investment through to 2050s. The analysis indicates a higher opportunity to take advantage of SuDS led flood management approaches and hence CSO cost savings given a 2^{o}C compared to 4^{o}C future. In all futures considered, as the national investment level increases, piped drainage responses increasingly dominate the selected portfolios. Consequently, the CSO cost saving reduces.

6.3 Assessment recommendations

Continue to improve present day estimates of surface water flood risk

There is significant uncertainty in present day surface water flood risks and the number of properties impacted by surface water flooding. This reflects the significant challenges in assessing surface water risks and the need for continued effort (in research and practice) to better understand and model surface water flooding and associated risks.

Continue to improve our understanding of the uncertainties in costs and the performance of adaptation measures

The analysis presented covers a wide range of issues. All are uncertain. Uncertainties in climate and population growth are addressed using alternative futures. Uncertainties in costs of adaptation measures and their performance are addressed using 'best estimates'. These are based on direct evidence where possible or judgements made by the project team with a supporting rationale. A structured sensitivity analysis has not been possible within the constraints of this project but is recommended to identify those aspects of the analysis that have the great influence on the case for investment. Such a study would be difficult, but possible, and add considerably to the state of knowledge and help better direct future investment.

Timing of investment

The analysis presented provides a spatial optimization of investment. No consideration is given to optimization in time. This means that the presented NPVs are likely to be lower than would be the case if investment was optimized in both space and time. The ability to optimize in time and constrain the optimization using affordability considerations could be introduced to the FFE to support future analysis. The impact on the NPV is difficult to determine but could be significant.

Results validation and updated to the present-day risk

The publication of DWMPs during development of this report could provide a source of sense-checking / validation to the FFE results. This would require access to (unpublished) modelling results and structured analysis to compare results. As has been discussed in this report, the approach adopted is appropriate for analysis at aggregated spatial scales and does not seek to replicate or replace the detailed planning and analysis process at a local scale (although various local constraints and contexts are included). For this reason, any comparison exercise should be undertaken at a regional scale, preferably using DWMP results from at least three water companies, to identify the impact of different methodologies on results. Even at this scale, care will be needed to ensure a common decision basis is used (i.e., as imposed by the NIC on this study), the same inputs of climate and population projections are applied, *etc.* For example, the DWMPs are focused on a single flooding metric, the number of properties at risk from internal sewer flooding in a 1 in 50-year rainfall event. It would be reasonable to expect some degree of spatial correlation between these plans and the results presented here but significant effort would be needed to provide a meaningful and useful comparison. False comparisons would be easily made.

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APPENDIX A. RECENT EXPENDITURE OUTCOMES AND TRENDS

A.1 Existing expenditure

An estimated £279.6 million is invested annually in SWFM by a range of organizations (Table A1-1). This estimate reflects the spend that can be reasonably attributed to flood risk reduction activities, and excludes investments in more routine actions to remove blockages, collapses, or overload of sewers due to growth, as these investments are considered to be focused on maintaining serviceability rather than specifically targeting at flood risk reduction.

Available evidence from water companies is largely based on AMP6 (Asset Management Programme). It is difficult to determine if this period is typical of investment levels as there is little reliable evidence prior to 2015. The current AMP7 period has more focus on pollution and environmental targets with a slightly lower focus on flooding than previous plans, AMP4 (2005-10) and AMP5 (2010-15). The AMP6 levels are therefore considered a reasonable indicator, albeit potentially high estimate of water company spend.

Note:

Water companies issued their draft Drainage and Wastewater Management Plans (DWMPs) during the preparation of this study, but after this analysis of existing expenditure was prepared. The DWMPs present portfolios of future investment scenarios, so, as a follow-up to this study, a review of DWMPs and a comparison of their findings with the outputs of the FFE is recommended.

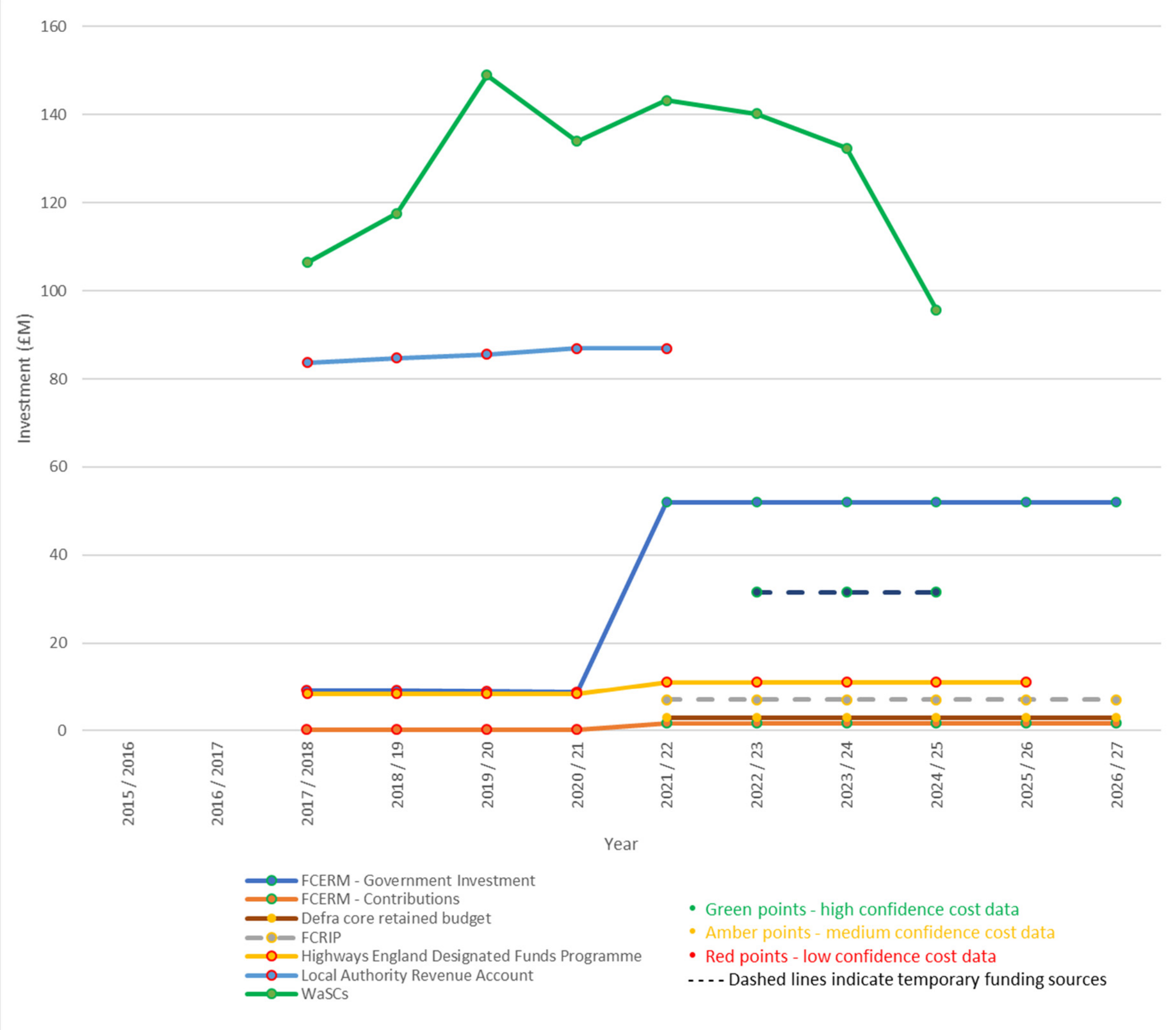
The Flood and Coastal Erosion Risk Management (FCERM) programme for 2021-2027 (£5.2bn for all flood risks) is double the previous programme investment (£2.6bn over 2015-2021). The 2021-2026 plan (Defra, 2021a) aims to better protect 336,000 properties, of which 34% (114,000) will be properties at risk from surface water flooding. Increasing investment in addressing surface water flood risk is a Defra priority (Defra, 2021c).

Appendix Table A.1-1 Annual investment in surface water flood management – Existing (~2021)

Source	Annual Investment (2021 baseline, £M)	Confidence score	Temporary source?	Narrative and sources
Flood and Coastal Erosion Risk Management (FCERM): Government Investment	CAPEX 52.0 OPEX 0.0 **TOTEX 52.0**	High	No	Calculated as 6% of the total FCERM programme (£5.2M) spread over six years. The 6% is the percentage of total spend in the current programme that has been assigned to surface water schemes, which are specifically identified. A step-change in the level of investment in surface water schemes is identified compared to the previous 2015-2021 programme, although data for this earlier programme is less certain because surface water schemes were only identifiable by their scheme name, and the total value of all projects in the data available exceeded the £2.6 billion total programme. Defra, 2021a, 2022 and Environment Agency 2017, 2022
FCERM: Contributions from other parties	CAPEX 1.7 OPEX 0.0 **TOTEX 1.7**	High	No	This is based on forecast contributions for existing surface water schemes in the FCERM programme, which collectively add 48% extra funding to the central government funding of those schemes. So, to estimate the value of contributions across the whole 6-year FCERM programme, 48% on top of the total £52M investment from central government (see row above) comes to £25M. However, the National Audit Office found that only 7% of partnership funding during 2015-2020 was from the private sector (National Audit Office, 2020). The remaining 93% comes from the public sector, and it was considered that this is likely to almost entirely come from Local Authority Revenue funding for flood risk and drainage (see investment line below). Therefore, to avoid double counting this funding, only £1.7 (7% of £25M) is included here. (Department of Levelling Up, Housing & Communities 2022, National Audit Office, 2020)
Defra core retained budget	CAPEX 3.0 OPEX 0.0 TOTEX 3.0	Med	No	Defra retains a small portion of its funding for flood and coastal erosion risk management for ad hoc projects. This is known as the core Defra retained budget and expenditure amounted to £5.9 million in 2021-22. Of this we have assumed a 50% allocation (£3 million) to surface water schemes.
Flood and Coastal Resilience Innovation Programme (FCRIP)	CAPEX 7.0 OPEX 0.0 **TOTEX 7.0**	Med	Yes	Based on seven funded projects which are predominantly surface water (Northamptonshire, NE Lincolnshire and S Yorkshire, Southend, Suffolk and Norfolk, Slough, East Sussex, and Devon. Programmes runs 2021/22 to 2026/27. (Defra / Environment Agency 2021). Following discussion with NIC, this source is included in the calculation of total annual funding, although it is a temporary programme with no commitment to be continued beyond 2027. (Defra, 2022b).
Highways England: Designated Funds Programme	CAPEX 11.2 OPEX 0.0 **TOTEX 11.2**	Low	No	Based on identified Designated Funds investment in flood risk management in the 2015 to 2020 plan (£42M or 6% of total £675M fund) factored up to 6% of the £936M 2020-2025 fund. The Designated Funds Programme is designed to provide benefits beyond the core construction and maintenance of highways, including benefits to road safety, the environment,

				and local communities. (Highways England, 2020, 2021)
Local Authority Revenue Account	CAPEX 21.4 OPEX 21.4 (split is assumed) **TOTEX 42.8**	Low	No	Spend has been consistently recorded since 2013/14 for: • Defence against flooding • Land drainage and related work (excluding levy / Special levies) • Land drainage and related work - Levy / Special levies However, there is no national or local reporting of how this investment was spent. The value is an average of the values for 2017-18 to 2021/22 and has been nominally reduced by 50% to account for assessed spend on ordinary watercourses and potential overlap with the FCERM contributions from other parties. (HM Government, 2022 and Department of Levelling Up, Housing & Communities 2022)
Water and Sewerage Companies (WaSCs): Business Plans	CAPEX 121.7 OPEX 8.6 **TOTEX 130.3**	High	No	Based on water company Business Plan tables averaged for years 2018/19 to 2024/25. Investment in sewer flooding is understood to be lower during the current AMP7 funding period compared with previous periods (especially AMP4 and AMP5), although investment totals for these periods have not been identified. Note that our analysis has excluded Welsh Water, which serves some catchments in England, but includes Severn Trent Water, which serves a similar sized area of Wales. (Company business plans, 2019)
WaSCs: Green Economic Recovery	CAPEX 31.6 OPEX 0.0 **TOTEX 31.6**	High	Yes	A one-off fund (2022/23 to 2024/25) to boost green investment following the Covid-19 pandemic. Most of the investment in surface water management is the Severn Trent Water programme of SuDS retrofit in Mansfield, with additional from South West Water. (OfWAT, 2021). Following discussion with NIC, this source is included in the calculation of total annual funding, although it is a temporary programme with no commitment to be continued beyond 2025.
TOTAL (£m) *excluding* temporary sources	**CAPEX 211.0 OPEX 30.0 TOTEX 241.0**			
TOTAL (£m) *including* temporary sources	**CAPEX 249.5 OPEX 30.0 TOTEX 279.6**			

CapEx = Capital Expenditure. OpEx = Operational Expenditure. TotEX = Total Expenditure



Sources: Based on sources referenced in Table A.1

Appendix Figure A.1-1 Sources of investment, adjusted to 2021 baseline

Some investment and outcomes have not been identified or are deliberately excluded:

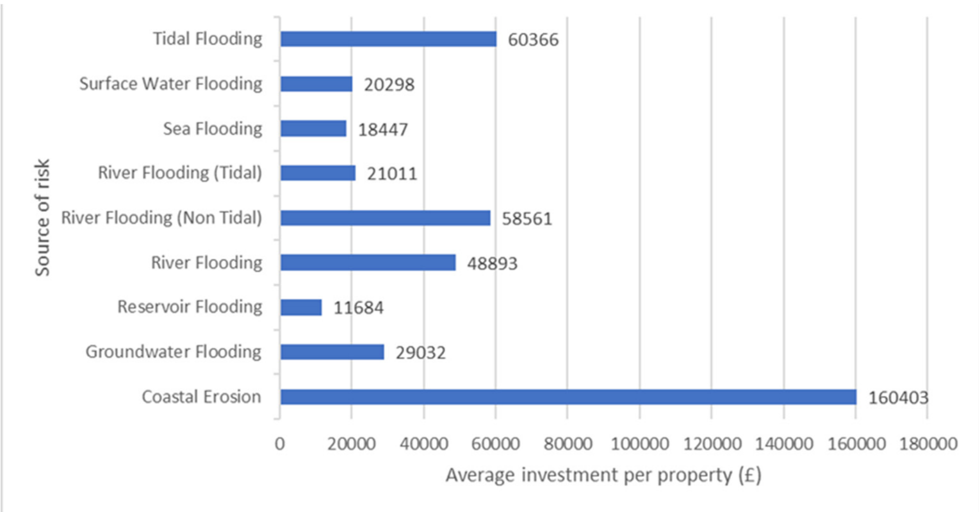
- Following discussion with NIC, temporary programmes of investment are included in the calculation of baseline annual investment. These include the Flood and Coastal Resilience Innovation Programme (FCRIP) and the water company Green Economic Recovery funding.
- Local authority highway drainage functions. In total, local authorities (not including National Highways and Transport for London) were forecast to spend £608M on highway “structural maintenance” and £630M on "environmental, safety and routine maintenance” in 2021-2022 (HM Government, 2022). Analysis of a sample of local authority budgets and annual reports could not isolate specific spend on highways drainage and flood risk, however it is considered that the vast majority of this spend will be to construct and maintain effective drainage of the highway itself, and not to reduce flood risk to others. On this basis, spend on highways drainage is required to meet obligations of the highway authority, in a similar way to any large public or private landowner (for example the NHS) might spend on building and maintaining surface water drainage to drain its own buildings and hard-standing areas. For this reason, highway authority spend on drainage has been excluded.
- Network Rail. No flooding-specific targets or investment lines were identified in the current Delivery Plan 2019-2024 (Network Rail, 2018). As with highway drainage, most of the investment in railway drainage is to ensure the effective and safe provision of railway services.

- Development sector. Investment in surface water drainage as part of housing or employment development is considered to be solely for the purpose of enabling that development to provide suitable levels of surface water flood mitigation to the site, and not to increase risk to others. Private sector contributions to FCERM schemes are considered covered under the "contributions" identified above.

A.2 Outcomes

There is no single set of outcome measures that are applied to all sources of investment in surface water flood risk management. Overall, outcome measures break down into HM Government approaches bases on Treasury rules (e.g., FCERM business cases, Multi-Coloured Manual) and market-based approaches applied in the water industry based on customer willingness-to-pay for enhanced services.

Within the current FCERM programme, surface water schemes have spent or intend to spend £20.3k per property, which compares favourably with investment in tidal and fluvial flooding and coastal erosion (Appendix Figure A.1-1). Note that schemes where the number of benefitting properties was set at zero or one were excluded from this analysis.



Appendix Figure A.2-1 FCERM 2021-2027 average investment per property by source of risk

Benefit-cost ratios are not readily available for the current FCERM programme to compare surface water schemes with other sources of flooding, however the average BCR for the 2015-2021 FCERM programme for all sources of flooding was 8. A 2011 study for Defra (Maslen Environmental, 2011) reviewed four surface water flood studies which had appraised a range of surface water measures as having BCRs of 0 to 4, with just one solution in one location having a BCR of 6.4. Anecdotally, based on experience developing FCERM appraisals, it is not uncommon for potential surface water schemes to not progress due to not being able to demonstrate a cost-beneficial solution, often because of relatively low numbers of properties protected and shallower flood depths compared to coastal or fluvial flooding.

Attempt was made to calculate an average investment per property from water company programmes, by dividing total budget (from business plan table App1) by the numbers of properties (table WWS2) where risk is reduced (Table AA). This gives unreliable results (including one negative cost per property) due to the mix of hydraulic and other causes, incident-based and risk-based interventions reported by water companies and indicates how the diversity of reporting measures employed by the companies makes comparison of outcomes and costs per property difficult to compare (even resulting in negative spends in some instances, emphasising the limited reliability and clarity within the published numbers).

Appendix Table A.2-1 Cost per property based on WaSC AMP7 risk reduction targets

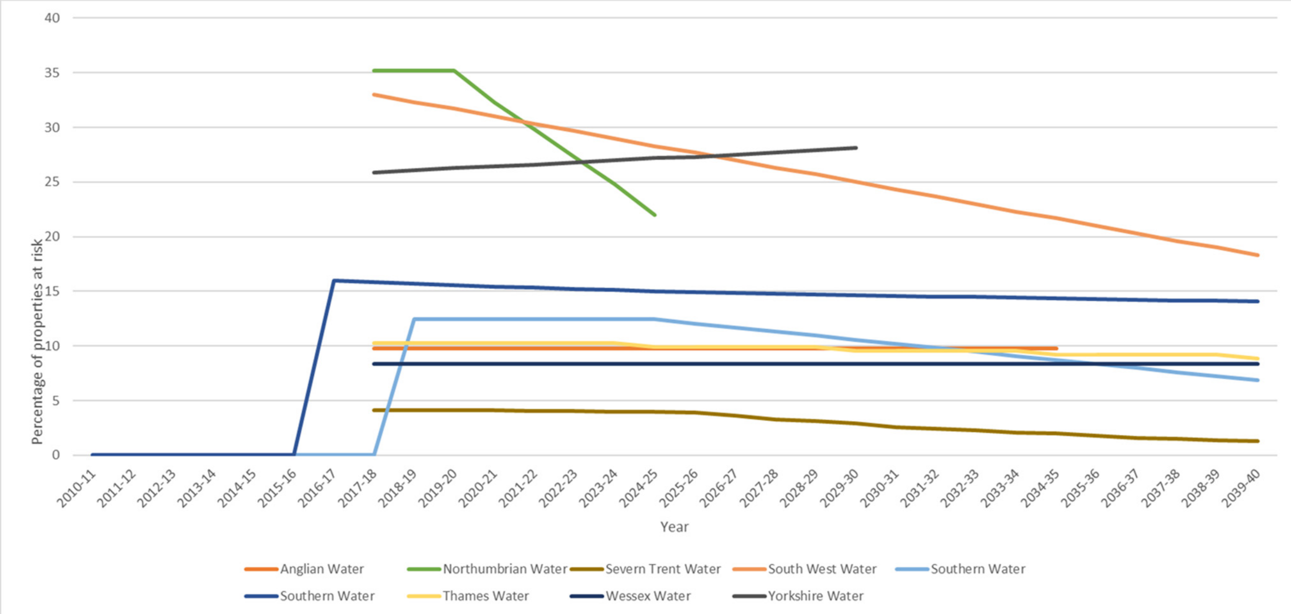
Organisation	Funding Total (£M)	AMP7 Reduction in internal sewer flooding incidents per annum	AMP7 Reduction in external sewer flooding incidents per annum	AMP7 Reduction in properties at risk of sewer flooding in a storm	Cost per property (£M)
Anglian Water	53.2	110	250	0	0.1479
Northumbrian	86.0	134	906	169853	0.0005
Severn Trent Water	140.8	76	295	6386	0.0208
South West Water	22.2	33	685	26156	0.0008
Southern Water	16.0	125	1517	0	0.0097
Thames Water	135.1	250		32604	0.0041
United Utilities	102.3	1150	1643	11222	0.0073
Wessex Water	84.8	31		0	2.7105
Yorkshire Water	41.5	240	1191	-19872	-0.0022
England	682.0	2150	6487	226348	0.00301

A.3 Trends

The analysis has identified several recent trends and new areas of focus in the realm of surface water management:

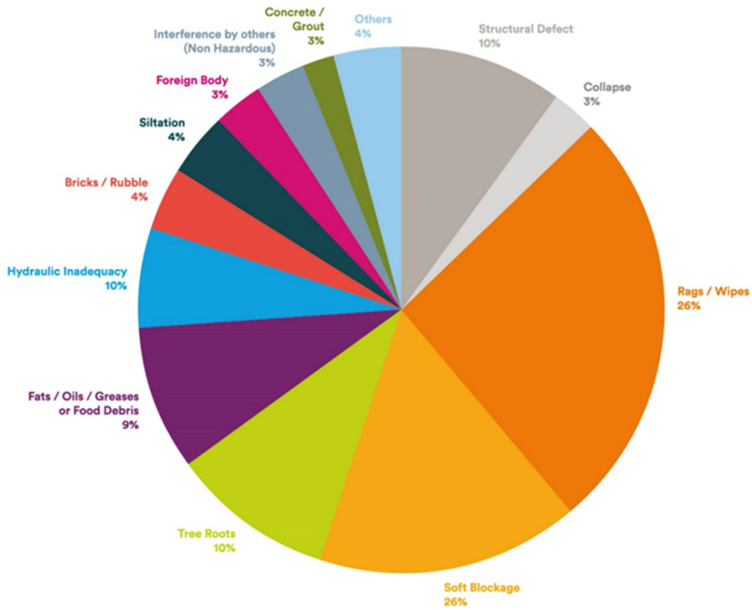
- **Funding for innovation.** During the current period, the Flood and Coastal Resilience Innovation Programme (FCRIPS) and the water company Green Economic Recovery have increased investment in innovative approaches to managing surface water flood risk by around £39M per year. Additionally, the OfWAT Innovation Fund (OfWAT, 2022) is funding pilot projects including smart water communities, sewer defect detection using Artificial Intelligence (AI) and autonomous wastewater catchments. Combined, these three initiatives have significantly increased the focus on innovation in the water and flood risk management sectors.
- **SuDS and surface water separation**. Within their AMP7 business plans, several of the companies have targets and Outcome Delivery Incentives (ODIs) relating to separation of surface water from combined sewerage systems. The scope of these remains moderate (in terms of hectares removed), except for Severn Trent Water's Green Economic Recovery funded programme to provide 58,000m^3 of SuDS storage in Mansfield by 2025, estimated to be 60% of the storage required in Mansfield by 2050. The scale of this programme is transformative when compared to the mainly very small-scale SuDS retrofit projects previously undertaken by water companies and LLFAs.
- **Risk-based approaches.** Within the water companies, there is now an increased focus on manging flood risk, rather than simply reducing the number of incidents per year. Incident based targets are highly weather-dependent. Between 2000-2001 and 2009-2010, incidents fluctuated between 4,000 to 9,000 per year (OfWAT, 2011). In 2020-2021 there were 6,079 incidents (Water UK, 2022), suggesting no significant downturn over the intervening period. Companies are now required to report the number of properties at risk of internal sewer flooding in a 1 in 50-year storm event, following a consistent methodology (OfWAT, 2019). Companies reported between 4% and 35% of properties were at risk in 2019-2020, suggesting inconsistencies in their application of the assessment method. Northumbrian Water proposed a

programme of risk reduction over AMP7, but this was rejected by OfWAT and at appeal by the Competition and Markets Authority (CMA). Figure YY indicates the wide range of company assessments both of current risk and the future trajectory of risk.



Appendix Figure A.3-1 Properties at risk in a 1 in 50-year storm

- **Fewer large schemes.** Water companies report that there are fewer large sewer flooding schemes in their current programmes, reflecting that the hotspots of multiple properties at risk have been addressed in previous AMPs. This is another reason why surface water separation is likely to achieve greater attention as it is better suited to addressing scattered risk around urban areas. There is also an increase focus on other sources of sewer flooding which account for most incidents (Figure ZZ).



Appendix Figure A.3-2 Sources of sewer flooding incidents, United Utilities

APPENDIX B. REVIEW OF HOW DIFFERENT SuDS AFFECT RUN-OFF

B.1 Introduction

This Appendix provides a brief review of UK relevant literature on how different types of SuDS affect storm runoff. The aim is to provide a summary for each SuDS type on how it can enable runoff reduction (to support an updated representation in the FFE, as detailed later in Appendix C).

A range of SuDS types have been identified and situated within a spatial framework relevant to the NIC archetypes being used – being three variable levels of development scale: i) property, ii) road, iii) neighbourhood. The various SuDS considered in this review have been placed according to the spatial level of service they are typically applied to (Table B.1-1). Where a type of SuDS application varies across scales it is placed accordingly – such as permeable paving, which can vary from the scale of a driveway at a property, to a road within a housing estate.

Appendix Table B.1-1 SuDS types: archetypes and scales

<table>
<tr><th>Property</th><th>Road</th><th>Neighbourhood</th></tr>
<tr><td>Green Roof</td><td>Permeable Paving</td><td>Detention pond</td></tr>
<tr><td>Soakaway</td><td>Raingarden</td><td>Retention pond</td></tr>
<tr><td>Bioretention</td><td></td><td>Wetland</td></tr>
<tr><td>Rainwater harvesting</td><td colspan="2">Swale/Filter strip/Filter drains</td></tr>
<tr><td>Soakaway</td><td colspan="2">Infiltration trench/basin</td></tr>
</table>

In this review, runoff coefficient is meant volumetrically with respect to a storm event and does not consider release through infiltration or other media after the storm event: i.e., total runoff volume during the event as a fraction of total input volume during the event. Peak flow coefficient is the peak flow rate at the outlet of the SuDS compared to a “no SuDS” case.

Furthermore, a value for indicative runoff coefficients will only be provided for source runoff control SuDS, essentially green roofs, and permeable paving. This is because these are the only type of SuDS for which such values are available - and which do not form part of a wider treatment train. All other SuDS are highly dependent on hydraulic design and site conditions and generally expected (under ideal conditions) to mitigate runoff up to the greenfield runoff rate (typically up to the 1 in 100-year event). This is evident in the UK SuDS manual, which only mentions the runoff coefficient with respect to either the rational method and literature values for surfaces including permeable paving and green roofs.

The review will also include some indication regarding the scale of coverage, and scale of uptake, for SuDS in the UK in both new developments and retrofitting. Data for this will come from the recent UK Government report on the application and effectiveness of planning policy for Sustainable Drainage Systems (Ministry of Housing, 2018).

B.2 Green Roofs

B.2.1 Retention capacity vs runoff coefficient

This report proposes considering a green roof's retention capacity in preference to its runoff coefficient. This is because runoff coefficients vary with storm depth: a roof may be able to retain a 20 mm storm, but much less of a 200 mm storm. This means that runoff coefficients vary with storm duration, return period and, because of spatially varying depth-duration-frequency relationships, location in the UK. Conversely, maximum retention capacity is linked to physically measurable or estimable characteristics and does not vary with storm duration, return period or physical location.

There are four main factors that affect a green roof's maximum retention capacity as discussed below.

B.2.2 Vegetation

The role of vegetation in stormwater retention is unclear: Monterusso *et al.,* (2004), Van Woert *et al.,* (2005) and Dunnett *et al.,* (2008) cumulatively indicate that several species could provide, at worst, no retention capacity. However, taller, and wider plants intercept more rainfall, as do plants with hairy or waxy leaves (Nagase & Dunnett 2012). Succulents, which were often chosen by default for thinner and less expensive roofs, tend to capture less water than grasses and forbs (Lundholm et al 2010).

Based on these references, vegetation could be assumed to provide zero retention in a typical, low-cost extensive green roof, and a small amount of retention in a more expensive roof design.

B.2.3 Substrate

Green roof substrate has a wilting point and field capacity. A substrate's maximum retention capacity is equal to the field capacity, minus the wilting point, multiplied by the substrate layer depth. Hence, it scales linearly with layer thickness.

The difference between field capacity and wilting point can vary greatly between substrates, although values determined through FLL (2008) methodology are commonly around 0.33±0.10 (Bengtsson *et al.,* 2004, Poë *et al.,* 2015, Wang *et al.,* 2021). The pressure-plate method more commonly used for soils often gives lower values, but FLL values are believed to be more representative of green roof behaviour (Poë *et al.,* 2015). Values derived for soils (e.g., Roehr & Kong 2013) are usually too low as green roof substrates are designed to outperform soils for volumetric water holding capacity.

Limited research has focused on the evolution of substrate water holding capacity with age. Getter *et al.,* (2007) reported that their green roof's water holding capacity almost doubled after five years in use. De-Ville *et al.,* (2017) reported smaller increases in water holding capacity for brick-based and LECA substrates (~22% and ~34%); only LECA was statistically significant at 5%.

From these references, the maximum water holding capacity of a new substrate is typically about 30-35% of the substrate's depth and may be more for aged substrate.

B.2.4 Drainage layer

Drainage layers come in many forms, including granular, plastic, and fibrous layers. Granular and some plastic drainage layers tend to have zero or near-zero water storage capacity. Plastic drainage layers can also be moulded to store water. Typical maximum capacities for moulded plastic layers are 3-7 mm for those used in extensive green roofs (e.g., ZinCo Floradrain FD 25, Bauder DSE 20, Lindum Roofdrain), and 12+ mm for intensive roofs (e.g., ZinCo Floradrain FD 60, Bauder DSE 60). As the drainage layer is separated from the substrate by a filter, the risk of collecting substrate and hence retention capacity reducing in the long-term should be small. Fibrous layers may have maximum capacities of 3-6 mm depending on their choice of material; Voyde et al., (2010) reported

4.7 mm for coconut coir. Protection mats are normally used underneath plastic and granular drainage layers; these can have some water storage capacity if they are fibrous (~3 mm). Some green roofs, usually shallower ones, do not use drainage layers but normally still use protection mats.

B.2.5 Antecedent rainfall and evapotranspiration

A green roof's maximum retention capacity is controlled by physical properties, summarized above. However, not all of this is available at any given time. Maximum retention is achieved when the plants and substrate are at wilting point and the drainage layer storage is empty. Hence, green roofs tend to have higher available retention capacity for a particular storm when evapotranspiration is high and rainfall before the storm is low, such as in summer, in drier climates, and following warm, sunny days. Less ideal circumstances give lower retention capacity. Very poor circumstances may not allow any retention.

B.2.6 Converting from retention capacity to runoff coefficient

Using the information above, an extensive green roof system with succulent plants, 80 mm of substrate and a fibrous protection mat might have a total water storage capacity of 30 mm. Its lowest runoff coefficient, achieved under dry and warm antecedent weather, would be $(x - 30)/x$, where x is the depth of the storm of interest in mm. A 6-hour, 100-year storm varies from 50.6 to 168.1 mm across Great Britain, with a median of 69.0 mm, so the "dry and warm day" runoff coefficient of this roof would vary from 0.407 to 0.822, depending on location, with 0.565 being a typical value. An intensive roof, with a mix of plant species, 200 mm of substrate, a moulded plastic drainage layer and a fibrous protection mat might have a total water storage capacity of 75 mm, so the "dry and warm day" runoff coefficient of this roof would be zero across large parts of the UK, and 0.554 under the largest 6-hour, 100-year storm. However, under extremely unfavourable circumstances, the runoff coefficient could still approach one.

B.2.7 Runoff and Peak runoff reductions – Green Roofs

Method 1: literature review – studies reporting per-event performance in detail

Appendix Table B.2-1 Runoff coefficients across various roof types

Roof design	Max storage estimate	Runoff coefficient (50 mm rainfall event)	Runoff coefficient (100 mm rainfall event)
Extensive with Sedum species, 80 mm brick substrate and drainage board[1]	25 mm	0.50-1.00	0.75-1.00
Extensive with rockery species mix, 70 mm rockery substrate and drainage board[2]	*35 mm*	*0.30-1.00*	*0.65-1.00*
Semi-intensive with herbaceous plants, 140 mm peat and sand substrate, granular drainage layer[3]	60 mm	0.00-1.00	0.40-1.00
Roof garden with lawn or perennial plant mix, 200 mm brick and organic substrate, drainage board[4]	*136 mm*	*0.00-1.00*	*0.00-1.00*

1: doi.org/10.1016/j.jhydrol.2011.10.022
2: zinco-greenroof.co.uk/sites/default/files/2021-12/ZinCo_Extensive_Green_Roofs_0.pdf
3: doi.org/10.3390/w12010090
4: zinco-greenroof.co.uk/sites/default/files/2020-03/ZinCo_Intensive_Green_Roofs.pdf

Note that italicized grey lines are manufacturers estimates and seem high.

Lower runoff coefficients are appropriate for summer events in drier areas (i.e., low rainfall and high evapotranspiration before the event), higher runoff coefficients are appropriate for winter events in wetter areas (i.e., higher rainfall and low evapotranspiration before the event). Where the maximum storage is larger than the rainfall event, the range of conditions under which the runoff coefficient is zero is increased. Note that nominal 50 mm and 100 mm events have different return periods depending on their duration and location within the UK.

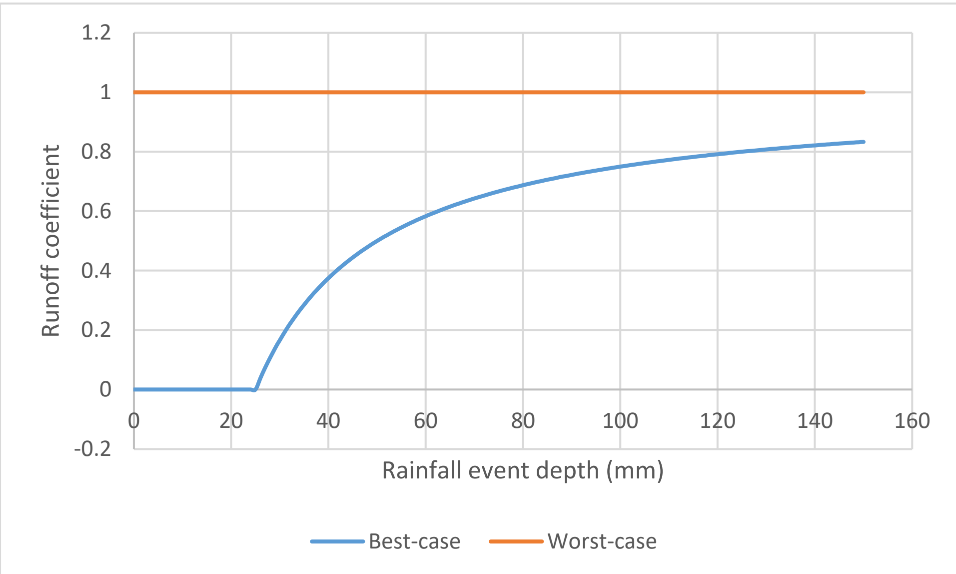
Method 2: equation based on review paper

doi.org/10.1016/j.resconrec.2021.105577 : Review of 1948 events across 73 papers. Global scope, but "average" numbers seem reasonable in context of Reference 1 above (conducted in Sheffield).

Average: For an average rainfall event depth of 31.5 mm, substrate depth of 113 mm, roof area of 74.7 m^2 and slope of 3.9%, mean runoff coefficient is 0.378 and mean peak flow coefficient is 0.307. The box on the boxplot isn't explained, but, for runoff coefficient (peak flow coefficient), ranges from approximately 0.06 to 0.65 (0.06 to 0.52), with a horizontal line across the width of the box at approximately 0.34 (0.23). Points outside the box take the full range of 0-1 for runoff coefficient and 0.004-1 for peak flow coefficient.

Sensitivity: For a 1% increase in event depth, mean runoff coefficient reduces by 0.142% and mean peak flow coefficient by 0.0827. For a 1% increase in substrate depth, mean runoff coefficient increases by 0.1% while the relationship with mean peak flow coefficient is not significant.

Relations with slope and area were small and complex, respectively.



Best case: warm and dry summer with sunshine leading up to the event.
Worst case: cold and wet winter, with rain leading up to the event.

Note: As roof depth, species complexity and/or drainage layer storage increases, the best-case runoff coefficient of zero can be achieved for larger storms, while the worst-case runoff coefficient of one becomes more and more difficult to achieve

Appendix Figure B.2-1 Runoff coefficient for low-cost, low-weight green roof

B.3 Permeable Paving

Permeable paving is designed to reduce localised runoff and provide a route for rainwater to locally infiltrate into substrate below. The joints between paving blocks are filled with sand or other loose substrate to allow water to percolate downwards. The primary role is to reduce runoff volume and promote hydrograph attenuation.

It can be deployed at the property scale – most evident in the form of a block paved driveway and paths. It can also be used to replace roads and pavement in residential areas.

The runoff coefficient – as defined by runoff from the surface during a storm event – has been shown to vary considerably based on type of paving, location, and storm intensity.

Permeable paving is suitable for both retrofit and new build – however replacing existing roads and pavement would be an expensive retrofit. They are generally a good choice for new developments due to the possibility to reduce storm runoff into storm drains.

Pervious pavements can be used in most ground conditions and can be sited on waste, uncontrolled or non-engineered fill, if necessary with a liner, where the design allows for differential settlement (Woods Ballard *et al.,*2015). In areas with low permeability there will be limited or no infiltration to media below that which is installed on site for local sub-surface storage,

B.3.1 Runoff and Peak runoff coefficients

A minimum value of 2500 mm/h (for new pavements) is considered reasonable for a pavement surface to be considered pervious in respect of surface water management (Woods Ballard *et al.,*2015). Runoff coefficients range from 0.1 – 0.7, depending on rainfall intensity, joint width, and materials (https://www.mapc.org/resource-library/fact-sheet-permeable-paving/). BS standards (BS 8515:2009) assume a runoff coefficient of 0.6 for permeable pavement made of concrete blocks. Marchioni & Becciu (2015) undertook a synthetic review of experimental results for permeable paving in urban areas across wider literature, and found that runoff coefficients vary considerably (0.0 – 0.45) based on type and location. A detailed study from the US across a range of permeable paving types suggest runoff reductions vary between 46% and 98% compared to traditional systems (Alam *et al.,*2019). In comparison to conventional asphalts, permeable and porous pavements provide more effective peak flow reductions (up to 42%) and longer discharging times (Scholz and Grabowiecki, 2007)

The evidence suggests large variance in runoff reductions and runoff coefficients observed on permeable paving, but little detail on how this resposne varies with rainfall.

B.4 Rainwater Harvesting

Rainwater harvesting (RWH) involves collecting rainwater runoff from various surfaces - such as roofs and other impermeable areas – to then be stored and treated (where required) to be subsequently used as a supply of water. RWH systems are designed to a specific level of service, which may address water supply only or additionally surface water management (Woods Ballard *et al.,*2015). These are systems that are much larger than standard water butts and have specific design and application specifications in the UK (e.g., BS 8515:2009+A1:2013 Rainwater harvesting systems. Code of Practice).

B.4.1 Runoff and Peak runoff reductions

The performance of RWH systems is simply a function of the area from whch runoff is collected, the runoff coeffient of that surfacer and avaiulable storage. The design rainfall depth can be any value. However, site runoff volumetric control criteria are often linked to the 1 in 100 year, 6-hour event, which tends to be of the order of 60 mm in the UK. Unless the RWH system can be designed to guarantee to capture all events without overflowing (which is very unlikely), RWH systems cannot be assumed to contribute to a reduction in peak flow rate on a consistent basis, and therefore site conveyance design should not assume that any flow rate reduction is achieved (Woods Ballard *et al.,*2015).

B.5 Infiltration (storage) systems

Infiltration systems are designed to promote infiltration of surface water runoff into soils and ground below. There does not seem to be any specific limitation on using such systems in less permeable soils or in groundwater areas but the SuDS manual recommends a minimum depth of 1m between the base of any systems and maximum likely groundwater level (Woods Ballard *et al.,*2015). They are suitable for managing runoff from small areas if development and can also be retrofitted but will require permits for sites with potentially high pollution loads such as industrial areas. Infiltration contributes to reducing runoff rates and volumes while supporting baseflow and groundwater recharge processes. The rate at which water can be infiltrated depends on the infiltration capacity (permeability) of the surrounding soils.

There are many different types of drainage component that can be used to facilitate infiltration. **Soakaways** are engineered excavations filled void-forming materials facilitating temporary storage of water before infiltration to below ground. Other systems can be thought of more as green in appearance and have more co-benefits. **Infiltration trenches** are linear soakaways. **Infiltration basins** are flat-bottomed, shallow landscape depressions that store runoff enabling infiltration into the subsurface soils and some evaporation after the event – they also provide valuable microhabitats.

Bioretention systems are shallow landscaped depressions which are typically under drained and rely on engineered soils, enhanced vegetation and filtration to remove pollution and reduce runoff downstream (UNaLab, 2020). They are aimed at managing and treating runoff from frequent rainfall events rather than the larger rare events which would be bypassed via an overflow. A rain garden is the main type of such systems and is a kind of garden that primarily serves as area for water control (storage and infiltration) on a small-scale especially in urban areas. Rain gardens are established in artificial surroundings and catches water runoff from roofs, roads and other (sealed) surfaces. Storm water runoff is drained into rain gardens, where it is stored for a certain period, and infiltrates either into the ground soil or flows into the sewage system. A certain amount of water is taken up and transpired by plants. They are a cost-effective retrofit option, due to their flexibility in size and detailing which can be integrated within existing landscaped areas.

B.5.1 Runoff and Peak runoff reductions

The performance of infiltration systems is dependent on the infiltration capacity of the surrounding soils and the depth to groundwater. The SuDS manual provides typical infiltration coeffients that range from 3E-2 m/s in good infiltation media such as gravel, to as low as 3E-9 m/s in poor media such as Clay (Woods Ballard *et al.,*2015). It is necessary to design storeage of water on site or in the infiltration unit to allow time for it to soak away.

SuDS manual guidance indicates: 'Infiltration systems should be designed to manage storms up to the design standard of service required for the contributing catchment area: this could be the 1:10 or 1:30 year storm, or larger. As discharge criteria from a development site are usually based on a 1:100 year event plus an allowance for climate change, the performance of infiltration systems under such conditions needs to be known. For ease of design, and to minimise the occurrence of surface flooding within the development, this may result in the soakaways being designed to manage the 1:100 year event (plus climate change allowance).' This suggests any use of such systems should consider the runoff coeffient to be effectevley zero up to the 100 year event during a storm event – such that runoff from the wider development remains at the greenfield runoff rate. The discharge should also be managed to half empty in the follwing 24 hours or longer – based on wider system assessment.

Bioretention is only for managing smaller rainfall events, and larger rainfall events may bypass the system via an overflow. There are no clear guidelines on how much runoff they therefore manage or produce. In general they should produce no runoff in smaller events – but exact rates will vary with media and area/depth of the system. Given they are not supposed to take up large areas and are more for multiple benefits including pollutant removal, rather than than flood reduction per se, it is perhaps best to envisage them as packaged with other systems as part of measures to reduce runoff to greenfield rates.

B.6 Infiltration (conveyance) systems

As per infiltration (storage) systems these conveyance systems are designed to promote infiltration of surface water runoff into soils and ground below - while also maintaining some conveyance of runoff from impervious areas to other areas and replacing engineered channels.

Infiltration contributes to reducing runoff rates and volumes while supporting baseflow and groundwater recharge processes. The rate at which water can be infiltrated depends on the infiltration capacity (permeability) of the surrounding soils. There does not seem to be any specific limitation on using such systems in less permeable soils or in groundwater areas – except that the attenuation/infiltration potential is reduced (Woods Ballard *et al.,*2015). They are suitable for managing runoff from small areas if development and can also be retrofitted but will require permits for sites with potentially high pollution loads such as industrial areas.

Swales are shallow, broad vegetated channels that store and/or convey runoff and remove pollutants- often forming part of the wider treatment train and can be designed to promote infiltration where soil and groundwater conditions allow. Swales can replace conventional pipework as a means of conveying runoff, and the use of adjacent filter strips and/or flow spreaders can also remove the need for kerbs and gullies (Woods Ballard *et al.,*2015). The inclusion of check dams or berms installed across the flow path can temporarily pond runoff to increase infiltration and decrease flow velocity.

Filter strips are graded, and sloping strips of grass or vegetation designed to treat runoff from adjacent impermeable areas by promoting sedimentation, filtration, and infiltration. Filter strips facilitate low levels of infiltration so present minimal groundwater pollution risks.

Filter drains are shallow trenches filled with stone/gravel that create temporary subsurface storage for the attenuation, conveyance and filtration of surface water runoff (Woods Ballard *et al.,*2015). They work best when incorporated into a treatment train and should be used in conjunction with other SuDS components.

B.6.1 Runoff and Peak runoff reductions

The performance of infiltration (conveyance) systems is dependent on the infiltration capacity of the surrounding soils, slope and the depth to groundwater.

Swale design is based on an open channel design that balances storage, treatment and infiltration during small storms with the need for peak flow conveyance during larger events. Peak flow control design and assessment of the surface storage volume can be determined by using standard hydraulic assessment. Infiltration contributions should only be included for dry or enhanced swales, where slopes are < 1.5%. The swale should have adequate capacity to convey and/or store the design return period event. Swales are not assumed to provide a reduction in volume of runoff for the rare 1:100 year, 6 hour event, but if infiltration rates from the system are deemed to be significant for this scale of event, then this should be explicitly accounted for by the design (Woods Ballard *et al.,*2015).

Sheet flow across filter strips is not usually controlled, and in this situation no reduction in peak flow is included within design calculations. And do not provide significant infiltration during large storm events, so they do not contribute to volumetric reductions during design storms.

Filter drains can help to manage peak flows by naturally limiting rates of conveyance through the filter medium, and also by providing attenuation storage which fills when the rate of flow at the outlet is controlled. Design and assessment of the surface and subsurface storage volumes can be determined using standard hydraulic assessment – but no specific values or guidelines with respect to flows of certain RP are provided.

As per other smaller more localised measures that do not generally make up a significant area within either a new or a retrofitted development – consider part of wider measures to meet greenfield runoff rates. Actual runoff coefficients would be defined on a case-by-case basis related to their sixing, location, soils, and slope. This suggests it would be best to assume they form part of wider measures intended to ensure greenfield runoff rates and to enable many other co-benefits for water quality and biodiversity.

B.7 Ponds, Basins & Wetlands

B.7.1 Detention basins

Detention basins are designed to detain water only. They are dry at the start of an event, gain water during an event, then return to dry some time after the end of the event, temporarily storing water but ultimately releasing it as runoff. The runoff coefficient of a detention basin is therefore 1 – runoff that flows in also flows out, though potentially over a much longer time than if it weren't there.

B.7.2 Infiltration basins

Infiltration basins are designed to infiltrate water, avoiding runoff. They "should be designed to manage storms up to the design standard of service required for the contributing catchment area" (The SuDS manual, section 13.4: Woods Ballard *et al.,* 2015), implying a runoff coefficient of 0, even for extreme storms (that are not closely preceded by another extreme storm or a series of storms). Peak flow coefficient is also 0, as there is no outflow.

B.7.3 Ponds and wetlands

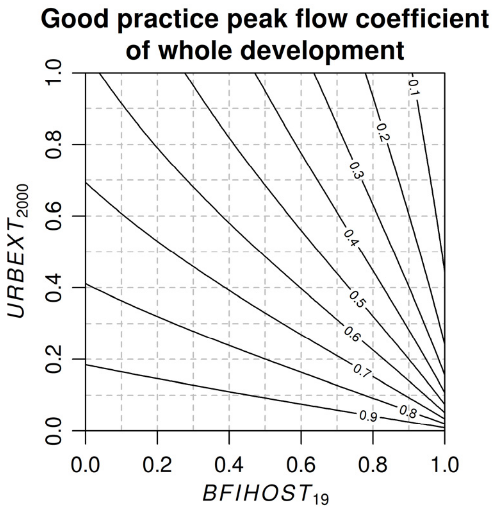
Ponds contain a permanent pool. If the water level at the start of an event is below the outlet level, then the difference in volume between the water level and the outlet can be stored. Relating this to a runoff coefficient depends on the pond's area, upstream area, and rainfall event depth. Assuming that the pond area is typically 3-7% of upstream area (Farming and Water Scotland 2021), a water level 15-30 mm below the outlet is required to store 1 mm of rainfall. Based on typical UK evaporation rates, we can assume that a pond's runoff coefficient is practically 1. In fact, the SuDS manual, section 23.4.4, states that ponds and wetlands "do not normally contribute to volumetric control of runoff".

B.8 Peak runoff coefficient for whole-development SuDS management train

Ponds, basins, and wetlands are often used as the final stage in a SuDS management train. Hence, they are designed to "finish" what was "started" earlier in the train. So, the performance of a pond/basin/wetland by itself is highly dependent on the quantity, quality and size of the SuDS devices positioned before it. It is perhaps better to think of the performance of the entire neighbourhood SuDS management train than any neighbourhood control in isolation.

The SuDS manual, section 3.3, defines "good practice" for extreme events as when post-development volumes and peak flow rates do not exceed greenfield volumes and peak flow rates for the 100-year return period event. Given the rarity of the 100-year event (1% chance per year), the volume and peak outflow from a neighbourhood SuDS control might never exceed greenfield conditions.

The peak flow coefficient is therefore the greenfield runoff rate divided by the urbanised runoff rate. The urban adjustment factor in the FEH statistical method is the inverse of this: urbanised runoff rate divided by greenfield runoff rate. It is based on $BFIHOST_{19}$ (a measure of ground permeability) and $URBEXT_{2000}$ (a measure of proportion of urbanisation) and is constant for all return periods. The peak flow coefficient, i.e., inverse of the urban adjustment factor, is plotted below as a function of $BFIHOST_{19}$ and $URBEXT_{2000}$.



Appendix Figure B.8-1 Peak flow coefficients for whole developments - by BFIHOST and URBEXT.

Peak flow coefficients for specific $BFIHOST_{19}$ and $URBEXT_{2000}$ values are tabulated below.

Appendix Table B.8-1 Peak flow coefficients for specific BFIHOST19 and URBEXT2000

$URBEXT_{2000}$	$BFIHOST_{19}$		
	0.3	**0.5**	**0.8**
0.2	0.85	0.80	0.63
0.5	0.68	0.59	0.37
0.8	0.55	0.45	0.24

As stated earlier, this is not the peak flow coefficient of the neighbourhood-scale SuDS device (e.g., the pond) by itself, but the peak flow coefficient of the neighbourhood-scale SuDS device plus the entire upstream drainage network discharging into it. The peak flow reduction given by the neighbourhood-scale SuDS device is therefore the difference between the greenfield runoff rate and the reduced rate of runoff resulting from the upstream property-scale and street-scale SuDS devices.

Note that the greenfield runoff volume and rate are the *maximum* allowed by good practice. Developments are allowed to release runoff at even lower rates, although it should be noted that there may be an extra cost and potentially no incentive to achieving additional voluntary peak flow rate reductions. However, in permeable areas, an infiltration basin may be no more expensive or difficult to install than a detention basin but may reduce peak flows and volume beyond what is required by good practice.

B.9 Exceptions

In rare cases where controlling to greenfield runoff volumes is unachievable, two alternatives are permitted. 1) excess flows above greenfield are restricted to 0.2 m^3/s per km^2 of development, but volumes released up to greenfield are allowed to reach greenfield rates. 2) all runoff from the 100-year event is restricted to the greater of 0.2 m^3/s per km^2 of development or the mean annual flood peak rate. For case 1, the above plot applies, if greenfield rates exceed 0.2 m^3/s per km^2 of development. For case 2, peak flow coefficients depend on return period.

B.10 Scale of coverage, and scale of uptake, for SuDS in the UK

The review undertaken by Government on the application and effectiveness of planning policy for Sustainable Drainage Systems (Ministry of Housing, 2018) examined the extent to which national and local planning policy has been successful in encouraging the take-up of sustainable drainage systems in new developments. The review looked at how national planning policies for SuDS are reflected in local plans and the uptake of SuDS in major and minor new housing developments and commercial/mixed-use developments. 80% of all adopted and 95% of emerging local plan policies reflected the requirements of the written ministerial statement that SuDS are to be provided in all major new developments wherever this is appropriate. Just over 80% of all adopted local plans included SuDS policies that go further than national policy expectations (e.g., SuDS required for all developments regardless of location and scale).

No national picture on the actual current coverage of SuDS was available in the literature and sources analysed. Nor a national picture on retrofitted SuDS or by a specific SuDS type. This lack of national data would likely be in part due to the lack of a complete database or flood assets register – which was normally required under Section 21 of the Flood and Water Management Act 2010 (for lead local authorities). Reviewing progress in 2019 HR Wallingford identified the need for recording SuDS information and for mapping (Smith and Reaney, 2019) and that progress towards such a national picture was still underway.

APPENDIX C. REPRESENTING ADAPTATION MEASURES

The Future Flood Explorer (Sayers et al, 2015, 2020) has been extended here to better represent surface water flood management adaptations within the same metamodeling framework as previously used for the UKCCRA3 (Sayers at al., 2020). The approach to representing these changes is set out below.

C.1 Rainfall characterisation

A national picture of extreme rainfall is the starting point for representation of risk, climate change, population growth and adaptation in the FFE. The FFE uses rainfall derived from the FEH web service (which implements the FEH 2013 rainfall model) for each of 10 River Basin Districts (RBDs - Appendix Figure C.1-1); as the rainfall is a point estimate, this is defined for a representative point within the RBD coinciding with the centroid of the polygon. For those RBDs that cover parts of Wales or Scotland as well as England the choice point is moved to be within England.

Appendix Figure C.1-1 River Basin Districts with representative points shown in red

The results for a 3-hour 1% AEP rainfall (used here for illustration, the rainfall model predicts a range of durations and AEPs) are given in the table below. These show significant variation across the country, and that the driest regions (e.g., Anglian) do not necessarily have the lowest extreme rainfalls.

Appendix Table C.1-1 hour 1% AEP rainfalls for the representative points for each RBD

River Basin District	Representative Point	3-hour 1% AEP Rainfall (mm)
Anglian	Ely	71
Severn	Hereford	58
Dee	Chester	60
Northwest	Preston	49
Northumbrian	Newcastle	67
Southeast	Horsham	58
Humber	Doncaster	48
Solway Tweed	Carlisle	54
Southwest	Exeter	53
Thames	Slough	63

C.2 Runoff characterisation

Surface water flooding depends on runoff, rather than rainfall *per se* (although these are related). A simple model of runoff generation is required to turn rainfall into runoff and thus understand the effects of urbanisation, adaptation, population growth *etc.* on flooding. Within the FFE runoff is calculated on a Census Calculation Area (CCA) basis (as introduced in Chapter 2).

For each CCA an estimate is made of the present-day area of 'green' space (assumed to be 'rural' land cover portion) and 'grey' space (assumed to be 'urban' land cover portion). As development takes place (due to population growth) and adaptation choices implemented these proportions change. As they change, different runoff generating characteristics are applied to each of these land cover types as summarized in Table C2-1. Rural areas have a 40% runoff coefficient applied as a nationally representative average. Urban areas (which themselves will include a lot of permeable surfaces such as parks and gardens) have a higher runoff coefficient, plus the effects of the drainage system (assuming a 12 mm/hr drainage capacity which may change as part of the adaptation measures applied). A SuDS landcover type is also introduced that has a rural type of runoff coefficient but still benefits from the action of the drainage system, so will generate lower runoff than either the urban or rural landcover types.

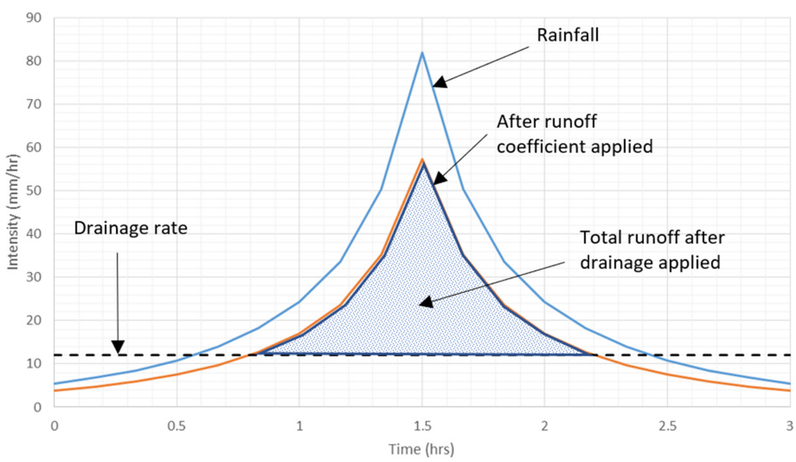
Appendix Table C.2-1 Summary of runoff characteristics for the land cover types defined in each CCA

Land cover type	Runoff coefficient	Drainage rate (present day) *
Rural	40%	None
Urban	70%	12 mm/hr
SuDS	40%	12 mm/hr

* The 12 mm/hr figure is changed in some adaptation scenarios to represent investment in stormwater drainage.

Based on these values, runoff is calculated as illustrated in Figure C2-1. The rainfall for the relevant CCA is multiplied by the FEH summer storm profile, 3-hour duration[8] to give a hyetograph. This is then multiplied by the runoff coefficient, and excess runoff above the drainage rate gives the total runoff. For CCAs with multiple landcover types, runoff is calculated for each of these, and the area weighted average used for the CCA.

Appendix Figure C.2-1 Schematic of runoff calculation based on summer storm profile, runoff coefficient and drainage rate

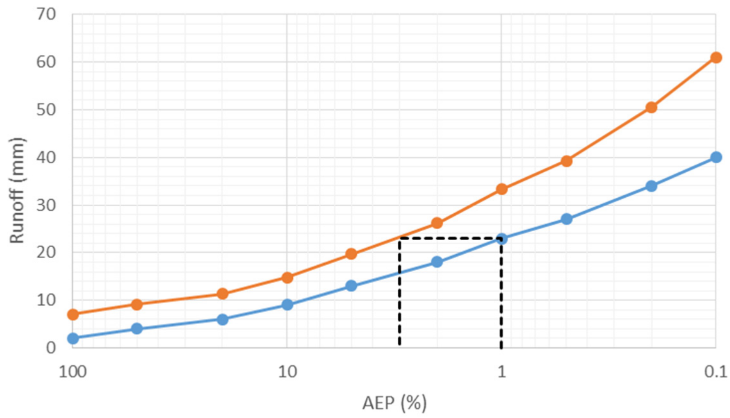


[8] There is no nationally available information on surface water critical storm durations, so a representative 3-hour figure is used everywhere

C.3 Representing climate change

The rainfall and runoff models described in the preceding sections enable the FFE Impact Curves (ICs) to be modified in response to climate change, population growth and adaptation. The impact curves are first defined for the present day, giving, for example, the number of properties affected across a range of return periods as present in the hazard data (as introduced earlier in Chapter 2 and detailed in Sayers *et al.,*2020).

To illustrate how the ICs are manipulated with the FFE to represent climate change consider, for example, an impact with an Annual Exceedance Probability (AEP) of 1%. Under an increase in rainfall due to climate change, this impact may become more likely. To calculate how much more likely (or in some instances less likely), runoffs for various AEPs are calculated from RBD rainfall and the runoff model for present day and with a rainfall climate change uplift applied calculated (as illustrated in Appendix Figure C.3-1). The 1% AEP runoff for present day is 23mm, and under future climate (using the uplift from the CPM model outputs, see Chapter 2) the AEP for this runoff increases, say, to 3%. This point in the Impact Curve is therefore moved from 1% AEP to 3% AEP; other points are treated in the same way to give a future impact curve where the effects of climate change are reflected in the increased probability of these impacts occurring. The future runoff curve is calculated using uplifted rainfall, population, adaptation measures (e.g., SuDS) allowing all these effects to be represented in the future Impact Curve for each CCA.



Appendix Figure C.3-1 Runoff for present day (blue) and future (orange) used to calculate change in AEP

C.4 Representing population growth

Using the rainfall and runoff models to adjust impact curves enables the effects of population growth to be represented, via two effects. Firstly, population growth leads to an increase in the number of properties and hence the number of receptors subject to the surface water flood hazard. Secondly, an increase in the number of properties (changing the nature of an area away from rural and towards urban) increases runoff and hence the surface water hazard, increasing risk to existing properties.

The first effect is represented simply by uplifting the impacts in line with the increase in the number of residential properties, calculated from the increase in population and factoring in changes in occupancy (if occupancy reduces for example because of an aging population, then more properties are needed even when population stays the same). The second effect of increasing runoff is represented as described in the previous section, calculating the future runoff using an increased urban proportion in a CCA.

Note

No consideration is given to changes in non-residential properties in response to future growth.

C.5 Representing adaptation

C.5.1 New Build - SUDS

Representation in the FFE

New build SuDS are represented by modifying the proportion of urban area in a CCA to reflect the impact of SuDS on runoff. The adaptation is parameterised by as a single uptake (which can be specified as varying with epoch and settlement type) which represents the number of new residential properties where SuDS are adopted.

The percentage uptake is used to modify the proportion of urban, rural and SuDS areas within each CCA, as shown in the example in Appendix Table C.5-1. In this example, there are 1900 residential and 300 non-residential properties within the CCA, and the urban area covers 30% of the total CCA area. A population change of +15% and a projected reduction in household occupancy of 3% means that the number of residential properties will increase by 18.6%; it is assumed that the number of non-residential properties will stay the same. The total number of properties in the CCA therefore increases by 16%. Including the breakdown of residential and non-residential properties in this way means that the method accounts for different types of urban area, with residential areas undergoing more development than business or industrial areas in response to population change.

If there is no uptake of SuDS, then the increase in properties of 16% will produce a future urban extent of 34.8%, and this will be reflected in the runoff calculations used to generate the future impact curve. With an uptake of 50% for new properties, then the urban area will increase to only 32.4%, and areas fitted with SuDS will represent 8% of the total area. The new urban, rural and SuDS areas are used in the runoff calculation used to modify the impact curve probabilities for future epochs.

Appendix Table C.5-1 New build SuDS example calculations with no uptake and a 50% uptake

Population change	+15%	Example scenario (for a given CCA)	
Occupancy change	-3%		
Properties change	+18.6%		
Landcover	**Present Day**	**Future – no SuDS uptake**	**Future with 50% SuDS uptake**
Residential properties	1900	2253	2253, 176 with SuDS
Non-residential properties	300	300	300
Urban	30%	34.8%	32.4%
SuDS	0	0	8.0%
Rural	70%	65.2%	59.6%

Assumed ambition

The review undertaken by Government on the application and effectiveness of planning policy for Sustainable Drainage Systems (Ministry of Housing, 2018) examined the extent to which national and local planning policy has been successful in encouraging the take-up of sustainable drainage systems in new developments. The review looked at how national planning policies for SuDS are reflected in local plans and the uptake of SuDS in major and minor new housing developments and commercial/mixed-use developments. 80% of all adopted and 95% of emerging local plan policies reflected the requirements of the written ministerial statement that SuDS are to be provided in all major new developments wherever this is appropriate. Just over 80% of all adopted local plans included SuDS policies that go further than national policy expectations (e.g., SuDS required for all developments regardless of location and scale). It is not known, however, if these conditions were implemented or those implemented will be maintained. It is also recognised that permitted developments (patios, driveways, extensions) are excluded from this process and unlikely to incorporate SUDS.

Consequently, there is no national picture on the actual current coverage of SuDS was available in the literature and sources analysed. Nor a national picture on retrofitted SuDS or by a specific SuDS type. This lack of national data is likely in part due to the lack of a complete database or flood assets register – which is normally required under Section 21 of the Flood and Water Management Act (for lead local authorities). Reviewing progress in 2019 HR Wallingford identified the need for recording SuDS information and for mapping and that progress towards such a national picture was still underway.[9]

Given this context the take-up rates for new build SuDS are assumed to vary from <15% to 75% (Appendix Table C.5-2). The present-day values are only provided for context and assumed to represented in the present-day hazard data, and therefore are not applied in the FFE.

Appendix Table C.5-2 New development SUDS: % of all new development implementing effective SUDS

Ambition	Present Day	2080s
Very Low	15%	30%
Low	30%	45%
Moderate	45%	60%
High	60%	75%
Very High	75%	90%

C.5.2 Retrofit - Infiltration SUDS

Representation in the FFE

Infiltration SuDS refers to the retrofitting of measures to attenuate flows by encouraging infiltration (and associated storage) at a range of scales, including:

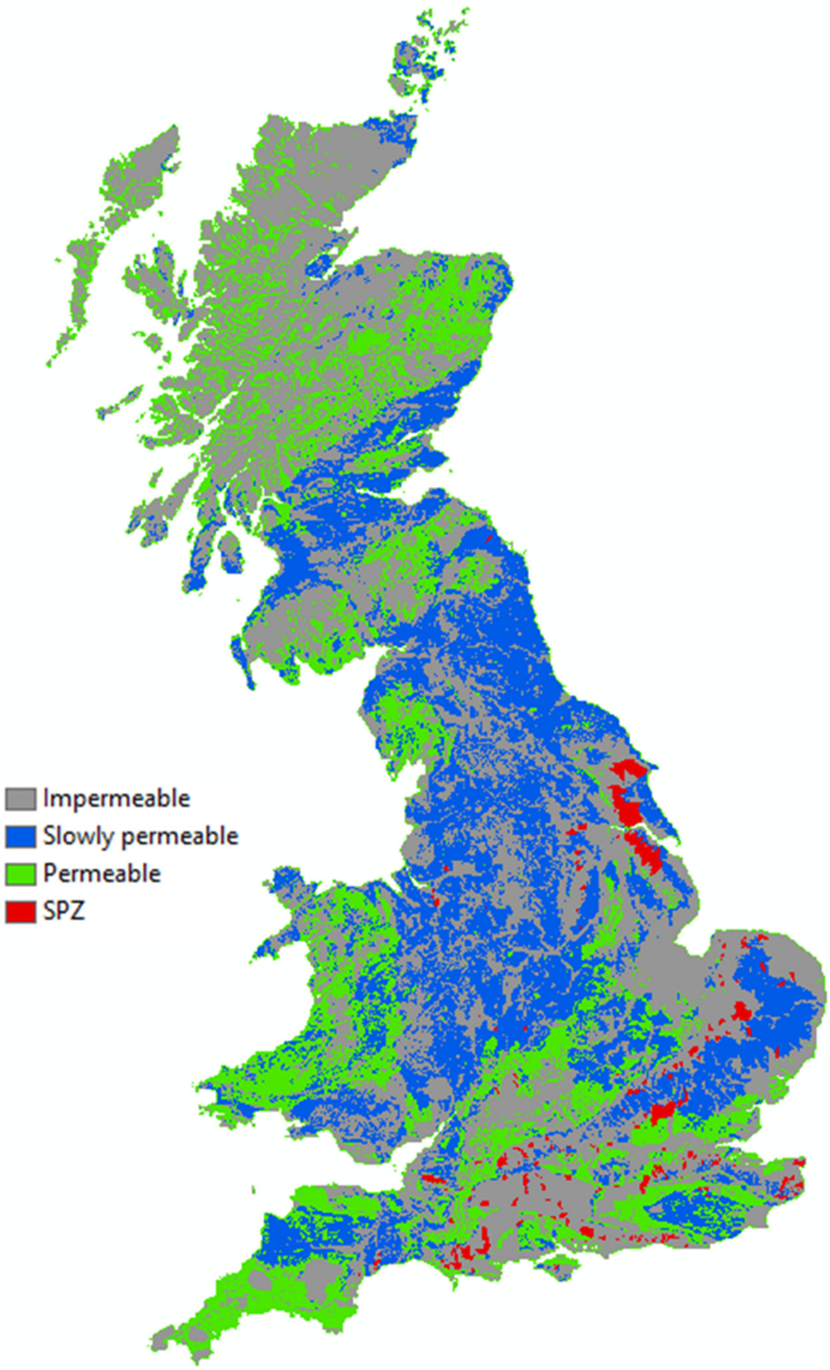
- **Property scale -** Green roofs, soakaways, permeable drives, and patios *etc.*, and possibly trenches for larger premises, applied to residential and non-residential properties. Storage of rainwater is becoming more popular at property scale especially as summer rainfalls decrease and dwellers use barrels for garden irrigation, in some instances by discounted costs of purchase through sewerage undertakers. For the analysis present here these storage activities that are considered part of the property infiltration measures.
- **Street scale –** Swales, and permeable road surfaces, linear infiltration trenches
- **Neighbourhood** scale - rain gardens, permeable car parking and other grey space, infiltration basins and bioretention ponds

These measures are parameterised through four uptake values, covering residential properties, non-residential properties, roads, and carparks. The uptakes are applied only in areas identified as suitable for SuDS as defined by CEH Wallingford using the SPH HOST values to define potential suitability of soils for infiltration SuDS, as:

- Impermeable areas – assumed **not** suitable
- Slowly permeable – assumed suitable
- Permeable – assumed suitable
- Source (water) Protection Zones (SPZ) – assumed **not** suitable

The geography of these zones is illustrated in Appendix Figure C.5-1.

[9] Smith, B. and Reaney, P. (no date) ‘SuDS asset register and mapping Review of current status and recommendations.



Source: CEH Wallingford, HOST (Boorman et al, 1995)

Appendix Figure C.5-1 Soil class based on defined permeability

The assumed uptakes values (see the following section) are used to modify the proportion of urban, rural and SuDS areas within the CCA (in addition to the changes from new build SuDS described in the previous section), as illustrated in Appendix Table C.5 3. In this example CCA, there are 410 properties or 31.5% of the total with SuDS retrofitted. All buildings occupy 22% of the CCA area (30% urban extent less 5% for road and 3% for carparks), so the 31.5% with SuDS fitted represent 6.93% of the CCA area. When combined with SuDS fitted to roads and carparks this gives a total area of 8.65% with SuDS fitted, with a corresponding decrease in urban (non-SuDS area). Rural proportion stays the same. The updated urban, SuDS and rural areas are used to calculate future runoff and hence modify the impact curves.

Appendix Table C.5-3 Example of retrofit infiltration SuDS

Landcover	Present Day	SuDS retrofit uptake	Number/area with SuDS fitted
Residential properties	1000	35%	350
Non-residential properties	300	20%	60
Urban excluding roads and carparks	22%		6.93%
Roads	5%	10%	0.5%
Carparks	3%	30%	0.9%
Changing nature of the CCA			
Urban	30%		21.35%
SuDS	0%		8.65%
Rural	70%		70%

Assumed ambition

Despite the continued focus on improving infiltration within existing urban areas in planning guidance (e.g. Woods Ballard *et al.,*2015) the take up of retrofit SuDS remains low although increasing as the significance of surface water flooding and associated benefits of SuDS (beyond flood management) are all likely to drive increased used. A range of take up values are there used within the analysis as set out below.

Appendix Table C.5-4 Retrofit – Infiltration SUDS: % conversation of existing impermeable areas

Ambition	Present Day	2080s
Very Low	5%	8%
Low	10%	30%
Moderate	15%	56%
High	30%	60%
Very High	50%	68%

Note: No explicit distinction is made between urban and rural settings within the take-up assumptions. The distinction is however captured through the assessment of existing impermeable area.

C.5.3 Retrofit – Storage SuDS

Representation in the FFE

Many of the measures introduced as 'infiltration SuDS' above also provide some degree of storage. In many instances the storage is often 'retained' their capacity to attenuate runoff at the time of rainfall event is available is often limited. This adaptation measure therefore focuses neighbourhood scale storage schemes (*e.g.,* retention ponds which tend to serve several buildings or streets).

Retention basins are designed to be dry for most of the time, enabling rainfall runoff to be temporarily stored and downstream flood peaks attenuated. Given space, detention basins offer an opportunity to significantly reduce storm run-off, however in many settings available space to retrofit storage is limited. Two primary considerations are therefore considered:

- **Design standard of protection in years** – Translated to a performance capacity in mm/hr using the rainfall intensity equivalent to the design return period (given the present-day climate to avoid assuming unrealistic alignment between climate change and action). This is defined regionally using a <3-hour storm duration. This definition assumes the detention basin exists across the calculation domain and is therefore reduced according to locally available green space. With less available green space the implementation of storage is less.
- **Performance during events above and below standard** – An equivalent Standard of Protection (SoP) is assigned to the basin but with an effectiveness that varies with storm return period (in years) to reflect a reduction in effectiveness with increasing severity of a storm. This is assumed to be 100% for return periods less than or equal to the design standard, reducing to 0% for all storms with a return period greater than the twice the design standard.

These parameters are combined to give a modified drainage rate as illustrated in Appendix Table C.5-5, with the increase in drainage rate representing the benefit of installing the storage scheme. For a given storm magnitude, the 3-hour rainfall and average intensity is calculated for the appropriate RBD. The total effectiveness for that storm magnitude is the product of the green space proportion for that CCA, uptake (this is generalised so that 50% take-up reduces the effect for all CCAs, rather than being applied to 50% of CCAs), and the effectiveness by storm magnitude (relative to SoP). The increase in effective drainage rate produced by storage SuDS is given by:

$$mm/hr\ Reduction = (Rainfall\ Intensity - Drainage\ Rate\ ) \times Total\ Effectiveness$$

The example given in the table shows that the increase in effective drainage rate is zero for small storms; these are well within the capacity of the drainage system and so storage is not required. For larger storms, the storage starts to become effective, with the biggest increase in drainage rate for storms of magnitude equal to the SoP. For even bigger storms, storage is overwhelmed and gives little or no benefit in terms of increased effective drainage.

Appendix Table C.5-5 Example of calculation of storage SuDS impact on effective drainage rate

Green space	30%	Example context of the CCA			
Uptake	100%				
Drainage rate	12mm/hr				
Effectiveness by storm magnitude					
<=100% SoP	1				
101-150% SoP	0.5				
151-200% SoP	0.25				
>200% SoP	0				
Influence on drainage rate					
Return period (years)	3hr rainfall (mm)	3hr intensity (mm/hr)	Effectiveness by RP	Total effectiveness	Increase in effective drainage rate (mm/hr)
5	30	10	1	0.3	0
10	38	13	1	0.3	0.3
100	71	24	0.25	0.075	0.9
1000	111	37	0	0	0

Assumed ambition

The variation in design standard assumed across the range adaptation ambitions are set out in Appendix Table C.5-5. For all it is assumed 50% of total available area is considered (see above).

Appendix Table C.5-6 Retrofit – Storage SuDS: Design standard (years) based on the equivalent <3-hour rainfall (mm/hr)

Ambition	Standard (years, given present day climate)
Very Low	10
Low	30
Moderate	50
High	100
Very High	200

Note: No explicit distinction is made between dense or less dense urban or rural settings. The distinction is however captured through the assessment of existing green space.

C.5.4 Below ground pathways – Piped drainage

Representation in the FFE

Many existing networks are recognised as at capacity and providing increased capacity within the pipe drainage network is likely to play a significant role in future investments. Conventional responses to overloaded drainage systems typically entail increasing pipe storage, providing localised storage tanks and/or pumping.

The adaptation to the piped drainage is expressed as a present-day Standard of Protection (SoP) for each future year and settlement type (and varies for the adaptation scenario being modelled). The specified SoP is converted to an equivalent mm/hr drainage capacity using a relationship between the drainage rate and the design standard of the drainage network (in years) – as shown in Appendix Table C.5-7. The numbers in this table have been derived using the same Monte Carlo approach which was used to generate the 12 mm/hr default drainage rate figure but modified to use a specific design SoP rather than a range. This gives an approximate lookup between SoP and drainage rate.

Appendix Table C.5-7 Lookup table between SoP and drainage rate by river basin district

	Return Period (years) and associated drainage rate (mm/hr)					
RBD	10	20	30	50	75	100
Anglian	13	17	19	23	25	28
Severn	11	14	16	19	21	23
Dee	11	14	16	19	21	23
Northwest	13	17	19	23	25	28
Northumbria	10	12	14	16	18	20
Southeast	11	14	16	19	21	23
Humber	11	14	16	19	21	23
Solway Tweed	10	12	14	16	18	20
Southwest	11	14	16	19	21	23
Thames	13	16	18	21	23	25

Source: Environment Agency – Nafra2 Monte Carlo analysis – unpublished.

To illustrate the implementation with the FFE consider, for example, a proposed adaptation to provide a drainage capacity of 1 in 30 years for the Northwest RBD. This will be implemented as a drainage capacity of 19mm/hr.

Within the FFE it is assumed that pipe drainage is only implemented if other measures (within a given portfolio) to slow the flow (i.e., SUDS measures) are unable to achieve the required standard. To do so, this drainage capacity is set as a minimum drainage rate; if the effective drainage rate produced by storage SuDS and surface pathways is larger than the mm/hr rate specified by the piped drainage SoP, then this is not reduced.

Assumed ambition

A range of standards are considered (Appendix Table C.5-8). These are specific in terms of the present-day climate. This avoids linking adaptations implemented now to perfect knowledge about future climate change. The standards set below may therefore reduce with time.

Appendix Table C.5-9 Sub-surface pathways: Design standard (years) assuming a <3 hour during storm

Ambition	Present Day (mm/hr)	Target standard (1inx years, present day climate)
Extremely Low		5
Very Low		10
Low		15
Moderate	10-12	20
High		30
Very High		50
Extremely High		100
Ultra High		200

C.5.5 Real-time control

SMART city initiatives and pervasive monitoring is increasingly emerging as important component of asset management and the water sector is at the vanguard of this process (e.g., Pathirana *et al.,*2021). Real time monitoring supports dynamic control of assets that can be effective in improving operational efficient of both SuDS and piped drainage infrastructure. 'Smart' rainwater barrels and the use of outlet flow control on ponds or below ground storage tanks, for example, are all emerging to support the performance of SuDS schemes. To be successful pervasive instrumentation is needed to monitor flow rates and levels across the drainage network to ensure that the peak flows from the various branches of the drainage network do not arrive at downstream points simultaneously.

Representation in the FFE and scale of ambition

Within the analysis here it is assumed that real time control increases the performance of drainage network. The improvement in performance is implemented by increasing drainage capacity provided (the sum of the source and pathway measures outlined above) by a percentage. The enhancement applied varies according to the severity of the rainfall event (described by its return period in years), with the greatest opportunity for improvement applied to the more frequent storms and reducing to no enhanced in extreme events (Appendix Table C.5-10). The evidence for these values is limited and based on judgment of the authors. Given real time control is not the central focus here, these values are not differentiated by the scale of the ambition.

Appendix Table C.5-10 Real time control: Assumed improvement in capacity

Storm return period (years)	Percentage increase in effective capacity (applied to mm/hr)
<10	0.10
25	0.09
50	0.08
100	0.03
>100	0.00

Note:

It can be readily imagined that real time control will play an increasing part in water management at local catchment scale. Such measures will increasingly offer opportunities to improve performance of existing assets and reduce maintenance costs (enabling better targeting). As yet, there are few UK examples of larger scale control, although some significant trials are emerging (Newcastle Smart City)[10]. Advanced exemplars do exist internationally, in Japan for example, such active control has been effective at keeping installation costs down in urban areas (Maeda et al, 2005) and RTC is seen as highly cost-effective for CSO control in Canada (Jean *et al.,*2021).

[10] https://www.newcastle.gov.uk/our-city/smart-thinking-smart-city

C.5.6 Exceedance – Surface pathways

Representation in the FFE

The CIRIA guidance provides details of measures that may be used, including raising or lowering of roadside kerbs, to allow water to pass or to constrain the flow to move to a planned safer route. Subtle changes in ground surface slope, provision of localised SuDS (to disrupt the phasing of peak flows) and relevelling can all be used to manage surface flow pathways. The design and effectiveness of such measures will be highly context specific (and various case studies are illustrated in the CIRIA guidance).

The effects of modification of surface pathways (e.g., engineering the urban environment to steer water away from receptors) is represented in the same way as storage SuDS. Green space is used to parameterise effectiveness in the same way as for storage, as this is a useful proxy for the space available to manage surface water pathways. The increase in effective drainage rate is applied on top of the increase from storage SuDS. The additional drainage capacity is determined based on an assumed maximum design standard (30-year equivalent rainfall) moderated by the available green space.

Assumed ambition

The implementation ambition is differentiated by the degree of assumed take-up (Appendix Table C.5-11). In all case the associated standard s assumed 1in30years (based on present day climate) and implemented as outlined above.

Appendix Table C.5-11 Surface pathways: % take-up (by area of available green space)

Ambition	Present Day	2080s
Very Low	0%	10%
Low	5%	15%
Moderate	10%	20%
High	15%	25%
Very High	20%	30%

Note: No explicit distinction is made between dense or less dense urban or rural settings. The distinction is however captured simplicity through the assessment of existing green space.

Note:

Although competition between land uses, e.g., to maintain traffic movements versus maintain flow pathways could be an issue associated with implementation this is not considered here.

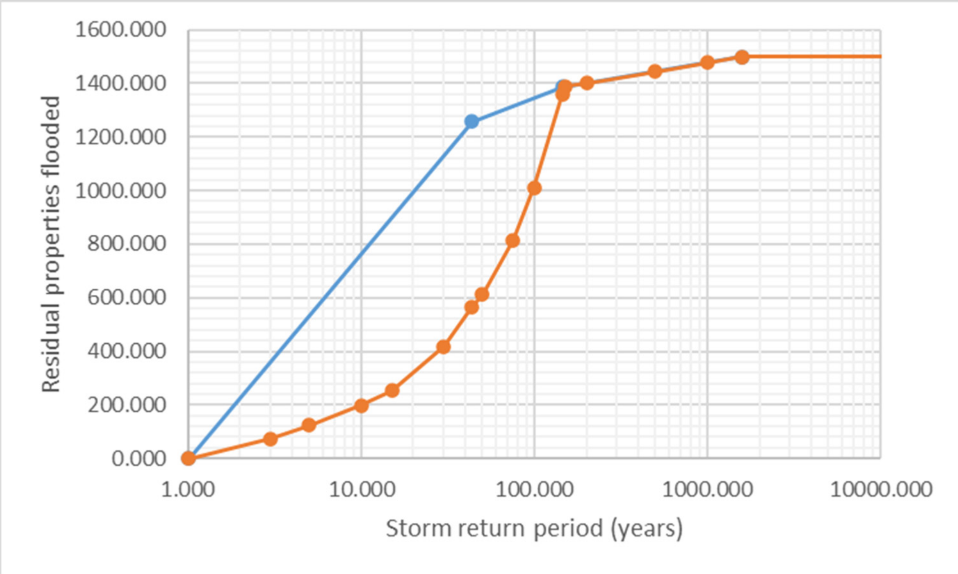
C.5.7 Exceedance – Residual exceedance measures

Representation in the FFE

There are numerous guidance documents for property level measures. For example, CIRIA (Kelly *et al.,*2021) sets out comprehensive guidance in a UK context. The understanding of owner responsibility has gained ground in recent decades and both house dwellers and commercial or industrial premise owners and users are more and more realizing the need to take measures where necessary. There are numerous measures from resistance to water ingress to building design to facilitate simple and fast post-flood recovery. It would be expected that uptake of such measures will continue to gain ground as flood risks and impacts increase into the future.

The focus here is on measures taken to avoid surface water entering a property and other additional actions to manage the residual hazard; rather than reduction in damage that may be achieved through measures to reduce the cost of damage. A residual property resilience standard is applied after implementation of all other measures within a portfolio. This is implemented simply by modifying the Impact Curve to proportionally reduce the number of residual properties that may experience internal flooding. Various measures could be implemented to achieve this outcome, from raising property thresholds to more local protection (garden walls and the property measures for non-residential properties).

A 'soft' implementation is assumed. This means the impact of the exceedance measures reduce some but not all residual impacts. For those AP associated with a higher standard a greater number of properties at residual risk (after all other levers) are assumed protect (as illustrated in the figure below). The 'soft' standard applied reflect the target standard of the portfolio. Given a target standard of below 1in30 years, it is assumed 30% of residual properties are projected up to this standard. For a target standard of 1in100 years it is assumed that 90% of the residual properties at high risk are protected.



Appendix Figure C.5-2 Example of the residual resilience measure - Assuming a resilience target of 1in200 years

Assumed ambition

A range of ambition levels are assumed as set out below that reflect the overall ambition of the portfolio (Appendix Table C.5-12). In portfolios that target a lower standard of protection the assumed effectiveness of the exceedance measures is assumed also to be lower. This provides a coherent focus on hazard management (noting that an exceedance only portfolio is not considered nor are internal measures that could be taken to reduce the damage, given internal flooding).

Appendix Table C.5-12 Target residual exceedance standard (years)

	Exceedance protection to properties		
	Protection to properties in 1in30 year band	Protection to properties in 1in30 to 1in100 year band	Protection to properties >1in100 years
Very Low	27%	0	0
Low	65%	0	0
Moderate	90%	0	0
High	90%	35%	0
Very High	90%	72%	0
Extremely High	90%	90%	0

APPENDIX D. EXISTING EXPENDITURE: PRIVATE v PUBLIC

The split between public and private investment for the individual measures is estimated based on understanding of present-day practices. Water company investment is classed as private.

D.1 New build - SuDS

The split of public vs private spend on new build SuDS is based on author's experience, no specific data was identified on this aspect.

Appendix Table D.1-1 2 New build SuDS - Public v private split

Capital	Spilt	Rationale
Public (%)	20%	NPPF and Defra Non-Statutory Standards require SuDS to be implemented on all new developments. Site drainage is at the cost of the developer. Split based on an assumption of public vs private sector development.
Private (%)	80%	
Revenue		
Public (%)	40%	A higher percentage of public sector spend has been allowed for revenue compared to capital, to account for SuDS built by private developers but adopted and maintained by local authorities.
Private (%)	60%	

D.2 Retrofit - Infiltration SuDS

There is insufficient data to identify spend, but author experience from schemes and observations of the usage of permeable surfacing indicates that the majority being laid is in private rather than public spaces.

Appendix Table D.2-1 Public v private split – Infiltration SUDS

Capital	Spilt	Rationale
Public (%)	20%	WaSCs are not generally investing in infiltration SuDS, as, except for soakaways, these are not considered to be adoptable sewerage assets. However, there is considerable private investment when for example gardens are paved or repaved. The removal of permitted development rights for paving of front gardens has increased uptake of permeable paving surfaces. Some, but not all, local authorities will adopt permeable paving on highways.
Private (%)	80%	
Revenue		
Public (%)	20%	Revenue spend is assumed to follow the same split as capital, as there is no mechanism for public bodies to adopt SuDS built by private investment.
Private (%)	80%	

D.3 Retrofit -Storage SuDS

For storage SuDS, the single £86M Green Economic Recovery investment by Severn Trent Water is considered too far outweigh investment from FCERM.

Appendix Table D.3-1 Public v private split – Storage SUDS

Capital	Spilt	Rationale
Public (%)	20%	Of the current (2021-27) FCERM surface water schemes, approximately £1M assigned to schemes mentioning "SuDS" or "sustainable" in their title. This is likely to under-estimate public spend on storage SuDS but, compared to £86M private investment identified for Mansfield alone (for a range of SuDS), most of the investment is within the private sector, in particular from WaSCs.
Private (%)	80%	
Revenue		
Public (%)	20%	Revenue spend is assumed to follow the same split as capital, as there is no mechanism for public bodies to adopt SuDS built by private investment.
Private (%)	80%	

D.4 Below ground pathways - Piped drainage

For below-ground drainage, private sector investment by water companies and develops dominates spend.

Appendix Table D.4-1 Public v private split - Conventional piped drainage

Capital	Spilt	Rationale
Public (%)	10%	Almost all investment in new or enhanced piped drainage is undertaken by water companies and private landowners and developers (including railways). This would include piped highway drainage on new roads within housing estates. The remaining 10% represents public sector investment in new or enhanced pipe drainage on culverted watercourses and public highways.
Private (%)	90%	
Revenue		
Public (%)	20%	Public revenue spend is considered to be a slightly larger proportion than for capital, due to a large legacy of culverted watercourses and highway drainage.
Private (%)	80%	

D.5 Real time control

At present we are not aware of any examples of real-time control being applied, in the surface water arena, by public bodies.

Appendix Table D.5-1 Public v private split – Real time control

Capital	Spilt	Rationale
Public (%)	0%	Whilst real-time control is in common usage to manage coastal and main-river flooding, we have not identified any examples of its usage by LLFAs or other public bodies to manage surface water flooding, although this might be one area of innovation that the FCRIP schemes will consider. By contrast this is an area of significant and growing investment by water companies (e.g., Thames Water aiming for up to 200,000 sensors by 2025).
Private (%)	100%	
Revenue		
Public (%)	0%	Revenue spend is assumed to follow the same split as capital.
Private (%)	100%	

D.6 Exceedance - Surface pathway modification

There is no hard evidence available for spend on flow exceedance measures, however it is known that most of these measures are implemented in highways and other public spaces.

Appendix Table D.6-1 Public v private split – Surface pathways

Capital	Spilt	Rationale
Public (%)	80%	Split based on the general split of responsibilities between public and private bodies. However, there is a trend towards increase WaSC (private sector) investment in above-ground solutions, now that swales, basins, ponds and bioretention features are considered to be adoptable sewers.
Private (%)	20%	
Revenue		
Public (%)	80%	Revenue spend is assumed to follow the same split as capital.
Private (%)	20%	

D.7 Exceedance – Residual resilience measures

Residual resilience measures could be delivered through various mechanisms, most notably property level protection. This is an area where there is ongoing public investment, but there is also private investment.

Appendix Table D.7-1 Public v private split – Property level

Capital	Spilt	Rationale
Public (%)	50%	This is an area of significant uncertainty. Of the current (2021-27) FCERM surface water schemes, approximately £0.6M is assigned to schemes mentioning “resilience” in their title. This is likely to substantially under-estimate public spend on PFR. There is also significant investment in PFR from various private sector sources including individual householders, insurers, utility companies (protecting critical assets) etc.
Private (%)	50%	
Revenue		
Public (%)	50%	Revenue spend is assumed to follow the same split as capital.
Private (%)	50%	

APPENDIX E. COST FUNCTIONS

E.1 New build - SuDS

E.1.1 Capital cost

The capital cost of new build SuDS is calculated as follows:

Capital cost (new build SuDS) =

*No. of new properties protected by SuDS * average cost per property protected * climate factor*

where:

Number of properties protected is defined by the change in the annual average number of properties flooded in the same way as for piped drainage.

Average cost per property protected is based on work undertaken by the Welsh Government (2016) and is shown in the table below.

Appendix Table E.1-1 Cost function and evidence - CapEx New build SuDS

Development size (no. units)	Cost per property (£, 2021 prices)		
	Central	Lower	Upper
<50	11,523	1,198	59,883
>50	4,678	287	13,657

E.1.2 Operational cost

The operational cost of new build SuDS is based on the same source and is shown in the table below. The evidence around smaller developments (<50 units) is more limited, whilst the more extensive evidence around larger developments (>50 units) leads to a greater range of values.

Appendix Table E.1-2 19 Cost function and evidence - OpEx New Build SuDS

Development size (no. units)	Cost per property (£ per year, 2021 prices)		
	Central	Lower	Upper
<50	35.6	35.6	35.6
>50	34.7	27.9	48.3

The evidence suggests that the operational costs of SuDS are significantly higher than for piped drainage (see later), reflecting the additional and ongoing maintenance requirements of above ground solutions (e.g., pond clearing, grass mowing, replanting).

E.1.3 Carbon cost

The carbon cost of new build SuDS is calculated as:

Carbon cost = carbon emissions per £ spent on adaptation (tonnes) * cost per tonne

where:

carbon emissions per £ spent on adaptation (tonnes) is based on multiple sources, most notably:

- SOEP (Defra, 2021b), which provides a central value of 98,300 kgCO_2e per unit (ha) of area managed by SuDS.
- SuDS for Roads (2013), which provides estimates of the whole-life carbon associated with various SuDS features, the average of which is 0.4 total kgCO2e per £ (min 0.08, max 0.66).

These estimates are combined to produce an estimate of the carbon emissions per £ spent on adaptation as shown in the Table below.

Appendix Table E.1-3 Carbon emissions per £ spent on adaptation – New build SuDS

	Cost per property (£, 2021 prices)		
	Central	Lower	Upper
Typical carbon emissions	0.000209	0.000049	0.000343

The estimates of whole-life carbon associated with SuDS are lower than those for piped drainage for the Central and Lower estimates, and slightly higher for the Upper estimate. This is in line with expectations, and reflects the greater uncertainty associated with the evidence for SuDS.

E.2 Retrofit - Infiltration SuDS

E.2.1 Capital cost

The capital cost of storage SuDS is calculated as follows:

Capital cost =

*No. of existing properties protected by SuDS * cost per property protected * climate factor*

where:

Number of properties protected is defined as above.

Cost per property protected is defined based on an extensive review of evidence sources, including

- London strategic SuDS pilot study (Arcadis, 2020)
- Environment Agency (2015) Cost estimation for SuDS
- Johnson & Geisendorf (2019)
- Ossa-Moreno et al (2017)

The cost per property estimates are shown in the table below. Costs in rural areas are estimated to be 64% of the urban cost reflecting the relative ease of construction.

Appendix Table E.2-1 Cost function and evidence - CapEx Storage SuDS

Assumed components	Capital cost per property (£, 2021 prices)		
	Central	Lower	Upper
Bioretention	496	397	596
Street trees	4,728	3,782	5,673
Green roof	56	54	61
Planters	755	604	906
Typical cost	**5,980**	**4,793**	**7,246**

E.2.2 Operational cost

The operational cost of retrofitting storage SuDS is derived from the same sources as above and is shown in the table below.

Appendix Table E.2-2 Cost function and evidence - OpEx Storage SuDS

Assumed components	Operational cost per property (£ per year, 2021 prices)		
	Central	Lower	Upper
Bioretention	2.0	1.3	2.1
Street trees	46.8	37.8	56.7
Green roof	0.9	0.7	1.1
Planters	7.6	6.1	9.2
Typical total	**57.8**	**45.9**	**68.4**

E.2.3 Carbon cost

The carbon cost is calculated in the same way as for new build SuDS and use the same carbon emissions per £ spend on adaptation.

E.3 Retrofit - Storage SuDS

E.3.1 Capital cost

The capital cost of infiltration SuDS is calculated in the same way and using the same rates as for storage SuDS.

E.3.2 Operational cost

The operational cost of infiltration SuDS is calculated in the same way and using the same rates as for storage SuDS.

E.3.3 Carbon cost

The carbon cost is calculated in the same way as for new build SuDS and use the same carbon emissions per £ spend on adaptation (see earlier).

E.4 Below ground pathways - Piped drainage

E.4.1 Capital cost

The capital cost of piped drainage is calculated as follows:

Capital cost =

*No. of properties with improved protection * length of pipe per property * cost of raising per km (based on the target capacity standard) * climate factor*

where:

Number of properties protected is defined as above.

Length of pipe per property is derived from figures provided by water companies, which suggest that 62.5% of sewers by length receive surface water. This is applied to the number of properties served, resulting in 14.9 metres of surface water pipe per property in urban areas (on average) and 18.6 metres of pipe/property in rural areas.

Cost of raising the conveyance capacity of 1km of pipe is derived from various sources of evidence (Table E4-1). The costs shown are for urban areas. Costs in rural areas are based on the same sources and are estimated at 64% of the urban cost. It is noted that some of the evidence is derived from sources published some time ago, but they remain the best available.

Appendix Table E.4-1 Cost function and evidence - Piped drainage

Context	Cost per km (£, 2021 prices)			Source
	Central £	Lower £	Upper £	
New build - upto1in30	709,284	571,174	1,142,655	Central (Webber, 2019) Lower (Environment Agency, 2015) Upper (SPON)
New build - more than 1in30	709,284	571,174	1,130,291	
Retrofit – engineered design standard upto1in30	1,107,803	886,243	1,329,363	Babtie (2003), Lower/Upper values based on -/+ 20% to reflect inherent variability and uncertainty
Retrofit- engineered design standard more than or equal to 1in30	8,560,293	6,848,235	10,272,353	

The evidence suggests there is a significant increase in the cost of retrofitting piped drainage systems beyond the 1 in 30-year design standard. This may simply be a function of the limited evidence or may reflect the need to upgrade the system to achieve higher standards in each location (e.g., the associated increase in capacity across the existing network). It is assumed here that evidence is reasonable and increasing capacity beyond 1in30 years adds significant cost.

Although validation is difficult, the cost functions above are broadly consistent with estimates from other sources. For example, the central value for retrofit up to 1 in 30 translates to £75,162 per property in urban areas. In AMP7, around £150.8m of funding was allocated to flood risk reduction, protecting 1,727 properties. This equates to around £87k per property, slightly higher than the figure above, probably because it includes actions taken to address hydraulic and other causes of flooding (that may entail a higher cost per property).

E.4.2 Operational cost

The operational cost of piped drainage is calculated as follows:

Operational cost (piped drainage) =

*Pipe length (km) * PipecostOpex (£/km) * number of properties protected * climate factor*

Where the *Number of properties protected is defined as above.*

PipecostOpex is based on Webber *et al.,*(2019), which provides estimates of £0.13 and £0.17 per m for a drainage upgrade of +12 mm/hr (broadly 1 in 10-year standard) and +24 mm/hr (broadly 1 in 30-year) respectively, assuming a 450-mm-diameter pipe laid under an urban highway as shown in the table below.

Appendix Table E.4-2 Cost function - OpEx Subsurface pathways (piped drainage)

	Cost per km per year (£ per year, 2021 prices)		
	Central	Lower	Upper
Typical total	4.79	1.48	6.27

E.4.3 Carbon cost

The carbon cost of piped drainage is calculated as follows:

Carbon cost (piped drainage) =

*carbon emissions per £ spend on adaptation (tonnes) * cost per tonne*

where

Cost per tonne – uses the same values as earlier

Carbon emissions (tonnes) per £ spend on adaption is based on a range of sources, including Thames Tideway, SuDS for Roads, Environment Agency reports, Defra's Storm Overflows Evidence Project (SOEP), academic literature and carbon databases. The SOEP (Defra, 2021b) suggests a central value of 249 kgCO_2e per unit (m^3) of network storage (range 212 to 286 kgCO_2e per unit). This is based on a 'typical' storage tank arrangement, with a storage volume of 900m^3 located within 100m of the combined sewer. Jato-Espino *et al.,* (2022), which provides an estimate of 500 kgCO_2e per functional unit for a traditional approach to drainage systems (including excavation, sand bedding, backfilling, pipe, manhole, storm drain, pump), with the functional unit being the processing of 1 m^3 of stormwater over 50 years. This suggests the carbon emissions associated with conventional drainage are slightly higher than those associated with SUDS. This is reflected in the carbon emissions per £ spend as set out in the table below.

Appendix Table E.4-3 Carbon emissions per £ spent on adaptation – Sub-surface pathways (piped drainage)

	Cost per property (£, 2021 prices)		
	Central	Lower	Upper
Typical carbon emissions per £ spend	0.000240	0.000178	0.000302

E.5 Real time control

Real time control is assumed to reduce the cost of capital and operational investment in conventional piped drainage. A reduction in the cost of the piped drainage is assumed net of the cost of implementation by RTC. This only applies to piped drainage and not to other interventions.

E.5.1 Capital cost

Capital cost saving (RTCcapex) =

*Capital cost (piped drainage) * efficiency saving*

Where

Capital cost (piped drainage) is based on the capital cost function for piped drainage set out previously.

The *efficiency saving* is assumed to be 5% of the capital cost, with a range of 1% (lower) to 10% (upper).

E.5.2 Operational cost

The operational cost saving is estimated in the same way as the capital cost saving, i.e., a net 5% saving on the operational cost estimate for piped drainage.

E.5.3 Carbon cost

The carbon cost saving is estimated in the same way as the capital cost saving, i.e., a net 5% saving on the carbon cost estimate for piped drainage.

E.6 Exceedance measure - Surface pathway modification

E.6.1 Capital cost

The capital cost of above ground (exceedance) measures is calculated as follows:

Capital cost (aboveground) =

No. of properties protected * cost per property protected * climate factor

Where:

Number of properties protected is defined in the same way as previously.

Cost per property protected is derived largely from the case studies featured in CIRIA (2014), although it is noted that limited evidence exists, and is shown in the table below.

Appendix Table E.6-1 Cost function and evidence – Surface pathways

	Cost per property (£, 2021 prices)		
	Central	Lower	Upper
Typical cost (regardless of details of action taken)	667	534	800

E.6.2 Operational cost

There are no available estimates of the operational cost associated with above ground (exceedance) measures. These are therefore assumed to be the same as infiltration SuDS in the cost function.

E.6.3 Carbon cost

The carbon cost is calculated in the same way as for new build SuDS and use the same carbon emissions per £ spend on adaptation.

E.7 Exceedance – Residual resilience measures

Residual resilience measures could be delivered through various mechanisms, most notably property level protection or local protection measures. The cost will depend on how these are delivered. The assumption made here is the costs of implementing residual resilience measures are in line with the average cost of protecting a property within the associated CA. This approach is applied to the Capital, Operational and Carbon.