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Assessing Future Flood Risk and Developing Integrated Flood Risk Management Strategies: A Case Study from the UK Climate Change Risk Assessment

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Abstract: As Earth's climate changes, individual nations must develop adaptation plans to respond to increasing or new climate risks. This study focuses on changing flood risk in England, UK, and examines the policy framework and actions that underpin England's adaptation from a flood risk management (FRM) perspective. Specifically, the flood risk projections that fed into the UK's Climate Change Risk Assessment were analysed alongside newly developed FRM adaptation portfolios that modified the flood risk projections to identify the potential of different measures to reduce Expected Annual Damages (EAD). The key findings indicate that: the range of EAD for all flood sources combined is projected to increase by 18–160% by the 2080s depending on the climate change, population growth and adaptation assumptions applied; adopting an enhanced adaptation approach presents an opportunity to manage much of the climate driven change in flood risk, particularly from river flooding; EAD from coastal flood risk shows the greatest increase relative to present day; and surface water flooding will become an increasingly more significant source of flood risk. Interpretation of the results in the context of the policy framework shows how greater coordination and integration of risk managers and interventions is required to improve adaptation planning.

Keywords: flooding; risk assessment; integrated flood risk management; England; policy; climate change

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1. Introduction

Flooding is one of the key climate change risks that societies face in the present day and into the future [1]. The insurance company Munich Re has estimated that flooding caused $90 billion of losses in 2021 with only 22% of that total covered by insurance [2]. However, vulnerability to flood risk can be reduced through long-term planning and adaptation. For example, the Thames Barrier in London, UK, has been in operation since 1982 and currently protects around 1.4 million people and property valued at over £321 billion [3]. Climate changes, resulting in sea level rise and changing weather patterns, though, mean that the Thames Barrier will not be effective for much longer and plans are in place to upgrade London's flood protection [3]. This measure has a clear costs-to-benefits case to support policy maker decisions, but other interventions do not have such a clear evidence base.

Considering these challenges, this paper examines the risk assessment and adaptation approaches used in England, UK, to assess future flood risk and to develop integrated flood risk management (FRM) strategies to address those risks.

1.1. The Climate Change Adaptation Framework in the UK

The UK's Climate Change Act 2008 [4] set out one of the world's first, legally binding national frameworks for reducing greenhouse gas emissions and adapting to climate change risks. On the risk management side, the Act requires Her Majesty's Government to conduct a Climate Change Risk Assessment (CCRA) every 5 years; these CCRAs have been published in 2012 [5], 2017 [6] and 2022 [7].

Following the CCRA being laid before Parliament, the government then prepares a National Adaptation Programme (NAP) that, according to the Climate Change Act, should manage the climate change risks identified in the CCRA. As such, NAPs were published in 2013 [8] and 2018 [9] with the third due to be published soon. These NAPs should outline specific adaptation actions relevant to each of the CCRA risks and the actions should be adequate to manage the magnitude of the changing risks.

Alongside the CCRA and NAP responsibilities for the government, the Act also created an independent scrutiny body now known as the Climate Change Committee (CCC). The CCC has two statutory responsibilities relevant to adaptation: it provides independent advice for the CCRAs; and it assesses the progress made by the government in managing climate change risk—i.e., scrutiny of the NAP—every 2 years. On the latter of these responsibilities, the CCC has consistently concluded that the first two NAPs have failed to adequately manage the climate change risks [10–13]. This failure applies to flood risk management as much as any other sector with, specifically, surface water flood risk being particularly poorly managed. For a more in depth discussion of the management of surface water flooding in England and the specific issues, see Russell and McCue [14].

As a whole, and based on the CCC assessments, it is not the case that the NAP presents an adequate, integrated strategy for FRM in a changing climate. Note that the 2018 NAP does include the update of the Environment Agency's National Flood and Coastal Erosion Management (FCERM) Strategy [15] as a NAP action, which does take a resilience-focused approach and a more integrated FRM strategy. However, the objectives embedded in the National FCERM Strategy are not part of the NAP.

Despite the issues with the NAP, the CCRA process has continued to develop through its iterations; see Brown et al. [16] and Warren et al. [17] for commentary on the step up from the 2012 CCRA to the 2017 CCRA. In particular, the independent advice from the CCC has become more in-depth and more central with each iteration: the CCC provided only advice and peer review for the 2012 CCRA Evidence Report [18], which was produced by a consortium led by a UK consultancy; for the 2017 CCRA, the CCC led the production of a comprehensive evidence report [19], which was supported by specially commissioned research projects; and the most recent 2022 CCRA saw an even more comprehensive, CCC led independent risk assessment [20] with a wider range of specifically commissioned research projects. As the identification and analysis of specific risks has evolved through time, it should have become increasingly urgent and (theoretically, if not politically) more straightforward for the NAP to identify the actions that are needed to manage the risks. However, this has not happened despite the in depth CCRA analyses of adaptation issues.

1.2. Flood Risk Analyses in the CCRA

The CCRAs have consistently identified flood risks amongst the most pressing present day and future hazards facing people, property, societies, infrastructure, and nature in the UK and that these risks require urgent management. However, and as described in Section 1.1, the identification of significant risk has not yet led to an adequate adaptation response in the NAP.

Moreover, this adaptation gap is particularly evident when considering flood risk: compared to many climate change risks, e.g., climate impacts on biodiversity, infrastructure, agriculture, supply chains, health, it is more straightforward to calculate flood risk because the areas susceptible are known (e.g., rivers, coasts, sewerage network), the drivers of the hazard are understood (e.g., precipitation changes, sea-level rise, urbanization) and the exposed populations and assets are well mapped [21–23]. Given this, each UK CCRA has involved the commissioning of a significant research project to make projections of future flood risk [24–26]. The most recent of these assessments [26] involved significant stakeholder engagement to develop three adaptation scenarios (i.e., FRM strategies) that reflect policies that are in place and planned, and that represent likely ambition for FRM in the future [27]. The aim of producing these adaptation scenarios was to apply them in the underpinning CCRA research project examining flood risk to understand the potential of adaptation interventions to reduce risk. For the current paper, these adaptation portfolios provide an opportunity to examine an informed compilation of integrated FRM approaches and to produce a detailed analysis of their impact in the context of the existing adaptation policy framework.

1.3. Aims and Structure

The overall goal of this paper was to assess the extent to which projected future flood risk can be managed by plausible FRM strategies. This was achieved by analysing the integrated FRM elements of the most recent climate change risk assessment [26] in England in more depth than in the underlying research report [26] or relevant CCRA chapter [28]. In particular, this included a novel breakdown of the impact of different FRM portfolios across the different sources of flood risk and a more complete examination of the contribution of the individual elements of those FRM portfolios. (Note that only England was considered in this analysis as it has the greatest flood risk of the four UK nations and to simplify the discussion of policies, which vary across the four UK nations.) This more granular analysis provides useful insights for other researchers, risk analysts, and policymakers, working on similar issues as many of the findings have generalisable implications.

The review and reflection on the climate change risk assessment and adaptation planning processes for an individual nation fills a significant gap in the literature, with notable previous studies taking a whole system risk/adaptation perspective for an individual nation [29] or examining high-level global patterns [30]. Furthermore, Adger et al. [29] also identified integrated risk assessments as a "frontier of climate change risk assessment" and, therefore, we advanced this field by focussing on risk assessment and adaptation strategy portfolios across a specific sector: flood risk management.

The specific aims of this study were to:

- Present the high-level findings from the future flood risk assessment that was conducted for the 2022 CCRA, including the impact of the population, global temperature, and adaptation scenarios that were used.
- Examine the integrated FRM strategies that were incorporated into the assessment.
- Discuss the lessons that can be extrapolated from the UK approach to climate change risk assessment and adaptation strategies more generally.

Section 2 (Materials and Methods) will give an overview of the methods used in Sayers et al. [26] that underpinned the 2022 CCRA and the process of engaging stakeholders to develop the integrated FRM scenarios along with the details of the integrated FRM scenarios. Section 3 (Results) presents the flood risk calculations across river, coastal and surface water flooding, and the impact of the FRM scenarios on those calculations. Section 4 (Discussion and Conclusions) examines the results in the context of increasing flood risk and the policy landscape, and conclusions are drawn.

2. Materials and Methods

This section presents the methods that were used to develop the two key datasets in this paper: the flood risk projections and the FRM adaptation scenarios.

2.1. Calculation of Future Flood Risk

The model used in Sayers et al. [26] to calculate future flood risk—known as the Future Flood Explorer, or FFE—takes a meta-modelling approach to producing flood risk projections. This method begins with the calculation of "impact curves" for the present day, which are constructed at a local scale using existing data on flood hazards, exposure, and vulnerabilities. The impact curves define the relationship between the severity of a flood, quantified by the return period, and the damage it causes, for which various damage metrics can be used. The FFE then applies scenarios of future climate change, population growth and adaptation changes to manipulate the impact curves to calculate how damage will change under those conditions. For example, in general climate change acts to modify the frequency of flooding, population growth increases (or decreases), exposure, and adaptation measures, reduce damages by either decreasing the damages for a given flood return period (i.e., reducing exposure or vulnerability) or by moderating the influence of climate change on the flood hazard.

Flood risk projections were produced for two periods: the "2050s" i.e., 2040–2069; and the "2080s" i.e., 2070–2099. The climate change scenarios look at the conditions in the UK under global temperature increases of 2 °C and 4 °C by 2100 [31]—these are the climate scenarios that were used in each of the two previous CCRAs [5,6]. The two population scenarios—low and high—are based on analysis commissioned for the CCRA [32] and relate approximately to a 2% and 42% increase in population by 2100 relative to 2016, respectively.

2.2. Developing Stakeholder Informed FRM Strategies

The adaptation strategies used in Sayers et al. [26] are central to the analysis here as they represent plausible future integrated FRM strategies. They are deemed plausible as the specific details of the different scenarios were developed with significant stakeholder input from policy officials from the UK Government and the devolved administrations in Scotland, Wales, and Northern Ireland. The discussions and written communication with these groups focused on the interpretation of current and possible future policy to deliver FRM interventions in nine areas (see Table 1). Within the limitations of the FFE structure, the details of the adaptation portfolios were agreed with the relevant policy officials. As well as making the research more robust, this process was of interest to the policy teams as they would ultimately have to use the CCRA results to inform the NAP actions that they would be drafting later. Overall, the adaptation scenarios were grouped together as:

- Reduced whole system (RWS)—assumes that recent FRM policy implementation continues but with a lower level of ambition.
- Current level of adaptation (CLA)—extrapolation of recent FRM policy implementation into the future with incorporation of anticipated policy changes; and
- Enhanced whole system (EWS)—as for CLA but interventions are implemented with a higher level of ambition.

The level or standard of deployment of individual FRM measures assessed to be in line with RWS, CLA and EWS are summarized in Table 1, and they are discussed in depth in the underlying CCRA research reports [26,27]. The impact of these measures on flood damage is then incorporated into the FFE calculations of future flood risk. The evidence underpinning the impact magnitude of each measure and how they are incorporated into the FFE has developed over a period of years [25,33,34] and is discussed in Sayers et al. [27].

Table 1. An overview of the individual adaptation measures developed in Sayers et al. [26] as plausible integrated FRM scenarios for England. These were informed by stakeholder engagement across the UK [27]. This table is summarized from Table 6.1 in Sayers et al. [26], where more details are included. All percentage changes are for the 2080s relative to present day unless otherwise stated.

Adaptation Measure	Reduced Whole System (RWS)	Current Level of Adaptation (CLA)	Enhanced Whole System (EWS)
Defences	Protection falls to 75% of present-day standards	Present-day standards are largely maintained	Protection standards are raised and cover new areas
Shoreline management	Shoreline adaptation remains largely unchanged	Some coastal realignment takes place to manage impacts	The Shoreline Management Plans [35] are implemented
Catchment management	Reversal in natural flood management (NFM) trends	NFM piloting followed by limited wider implementation	Successful NFM piloting leads to increased implementation

Table 1. *Cont.*

Adaptation Measure	Reduced Whole System (RWS)	Current Level of Adaptation (CLA)	Enhanced Whole System (EWS)
Sustainable urban drainage (SUDS)	Reversal of SUDS uptake: retrofit stops and implemented in only 30% of new developments	Limited SUDS retrofitting (~5%) with higher uptake in new developments (~50%)	Substantial SUDS take-up: 30% retrofit; 80% in new developments
Spatial planning	New developments in floodplains increases to ~15%	New developments in floodplains remains at ~12%	New developments in floodplains decreases to ~9%
Property flood resilience (PFR)	Limited take-up: 5% retrofit; 50% in new build	Steady take-up: 20% retrofit; 80% in new build	Substantial take-up: 30% retrofit; 95% in new build
Forecasting and warning	Differences between RWS, CLA and EWS scenarios are minimal. Overall, this is assumed to reduce damages by ~14% in all scenarios		
Insurance	Uptake drops after 2039 when the UK's flood re-insurance scheme (Flood Re) ends	A successful transition from Flood Re allows for current insurance levels to be maintained (CLA and EWS)	

The full suite of EAD results (plus other metrics) is available online [36] and are discussed in depth in Sayers et al. [26] and Kovats et al. [28]. In this paper, results from the FFE experiments are presented with a view to examining the impact of the different climate, population and adaptation scenarios for river, coastal and surface water flooding EADs. Groundwater flooding is not considered here because: (1) the damages from groundwater flooding are close to negligible on the national scale; and (2) the data underpinning the FFE calculations are not as robust as for river, coastal and surface water flooding. The damage metric of total (direct and indirect) Expected Annual Damages (EAD) is used as this metric is more straightforward to compare between sources of flooding.

3. Results

In this section, the results for EAD associated with the different climate change, population and adaptation scenarios outlined in Section 2 and for different sources of flooding will be presented.

3.1. All Sources of Flooding (River, Coastal and Surface Water)

Figure 1 shows the changes in EAD for all sources of flooding under the different scenarios considered in this analysis. Overall, these result show that EAD is set to increase in the future under all the scenarios examined here. There are no comparable studies to use as a point of reference for this result as research on projections of river, coastal and surface water flooding tend to only examine one flood source. (The UK Climate Change Risk Assessment cannot be used for comparison here as it uses the same data for its underlying calculations of flood risk change.) In Sections 3.2–3.4, however, we contextualise the results with relevant studies from the literature.

Relative to the present day, EAD could increase by more than 2.6 times (160% increase) by the 2080s (high population, 4 °C, RWS) or be limited to an 18% increase (low population, 2 °C, EWS). For the 2050s, these values are 1.9 times (90% increase) and 10% for the same scenarios. Further analysis of the impact of the different FRM portfolios is included in Section 3.5. Limiting the increase to close to present day EAD requires global climate change to be limited to 2 °C and for the most ambitious adaptation portfolio to be implemented.

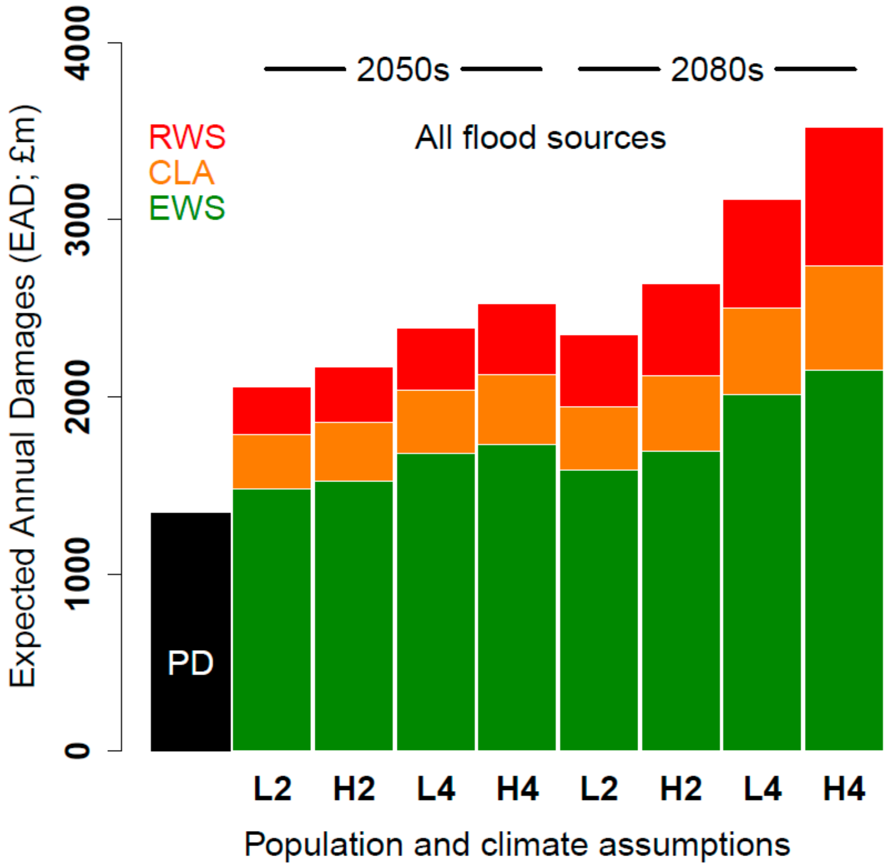

Figure 1. Stacked bar plot to show the impact of the different flood risk management (FRM) scenarios on expected annual damages (EAD), in £ millions, from river, coastal, and surface water flooding combined for present day (PD), the 2050s and 2080s. Several scenarios have been applied to the EAD calculations, which are indicated by the code along the *x*-axis. This code is a combination of the population assumption (L for low or H for high population growth, see Cambridge Econometrics [32]) and the climate change scenarios (2 °C or 4 °C by 2100, see Sayers et al. [31]). The bar colours relate to the FRM scenarios: EWS—Enhanced whole system adaptation (green); CLA—current level of adaptation (amber); or RWS—reduced whole system adaptation (red). The black bar labelled "PD" shows the present-day EAD.

3.2. River Flooding

Figure 2 presents the EAD changes for river flooding under the different scenarios examined here. The increase in flood damage is consistent with Ranasinghe et al. [37] who have projected an up-to 18% increase in river flood in Western Europe by 2100 and Arnell et al. [38] who calculate a median 21% increase in 10-year river flood events by the 2080s. These studies are not directly comparable but the sign of the change and order of magnitude of change are consistent with the results here.

River flooding makes up the largest part of the total present day flood EAD and the results show that it is possible to decrease EAD from river flooding into the future: under the 2 °C global climate change scenario, the EWS portfolio can reduce EAD by 7% or 2% for the low and high population scenarios, respectively, by the 2080s. This is a remarkable result and points to the potential of a strategic, integrated FRM approach to reduce risk. However, all outcomes for the CLA and RWS portfolios in the 2050s and 2080s point to an increase in EAD, which is as high as 100% under the high population, 4 °C global climate change and RWS assumptions.

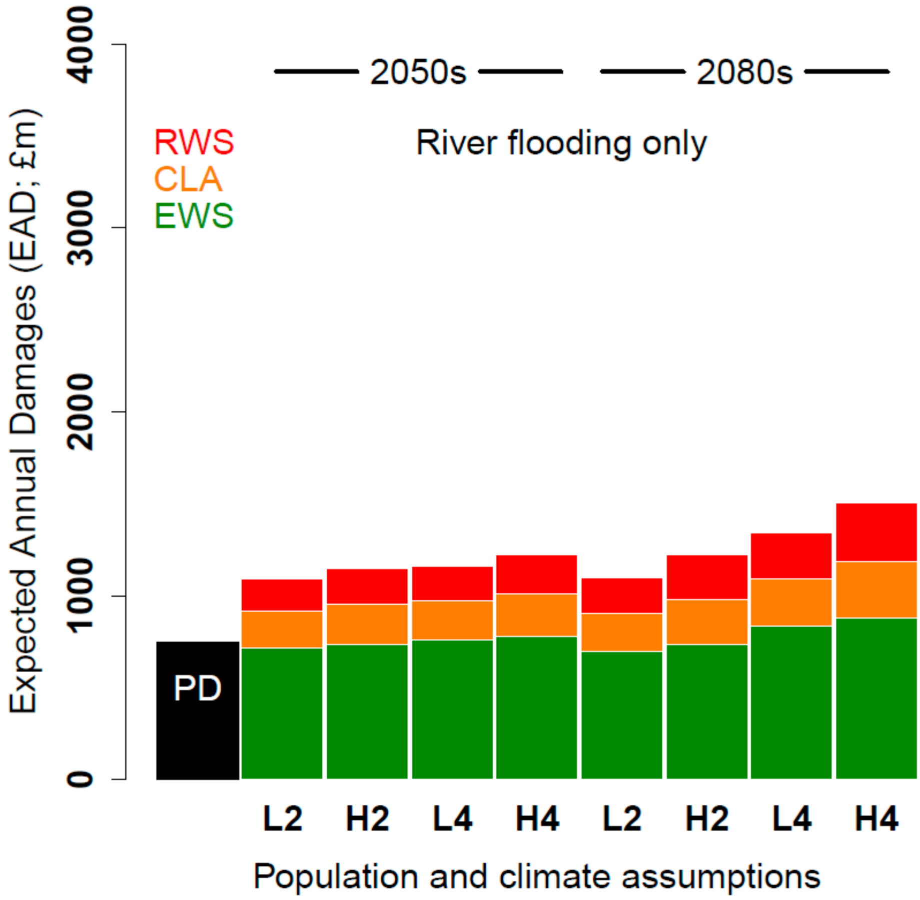

Figure 2. As for Figure 1 but for river flooding only. Note that the vertical scale is the same as Figure 1 for comparison.

3.3. Coastal Flooding

Figure 3 presents the EAD changes for coastal flooding under the different scenarios examined here. Coastal flooding makes up the smallest part of the total flood EAD for the present day but, particularly under high climate change/high sea-level rise scenarios, coastal flood damage makes up a larger proportion of overall flood EAD. This is consistent with Vousdoukas et al. [39] who have shown the potential for very large increases in coastal flood damages in Europe towards the end of the 21st Century e.g., up to two to three orders of magnitude increases.

The FFE results show that it is not possible to decrease EAD from coastal flooding in the 2050s or 2080s under any of the scenarios or FRM portfolios used (although this does not mean that it cannot be achieved, but does imply more ambitious, transformational adaptations may be needed than those envisaged within the study). The best-case scenario, under the 2 °C global climate change and low population growth with the EWS portfolio, can limit the EAD increase to 74% (37%) by the 2080s (2050s). At the other end of the scale, with 4 °C global climate change and high population growth using the RWS portfolio, the EAD increases by nearly five times by the 2080s i.e., a ~400% increase. This is the largest relative change identified under any of the flood source, future scenario and adaptation portfolio combinations examined.

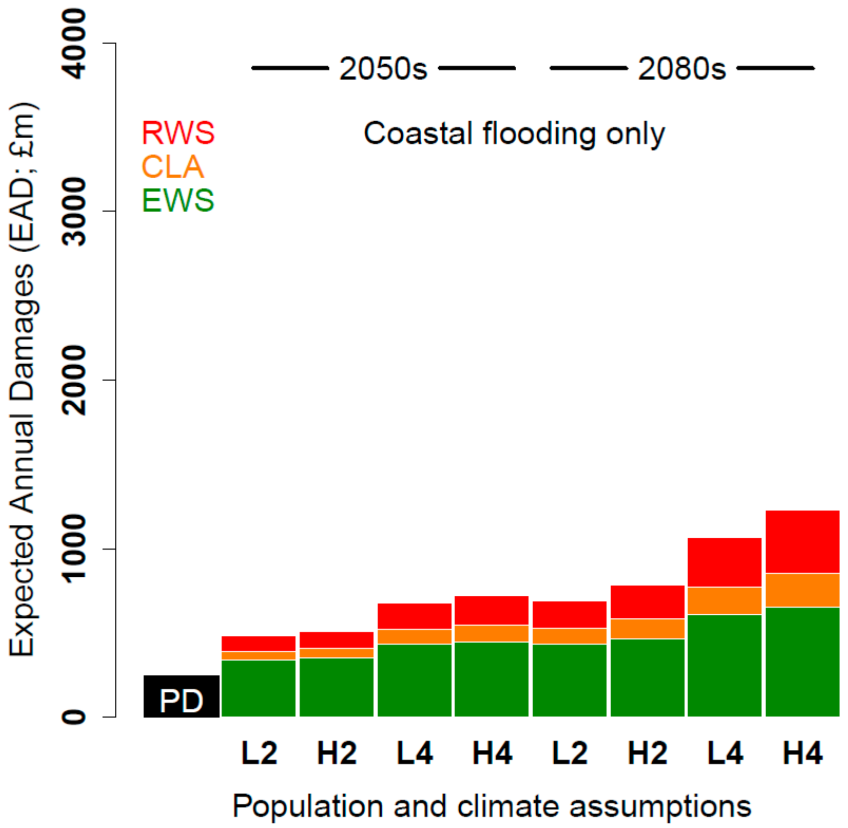

Figure 3. As for Figure 1 but for coastal flooding only. Note that the vertical scale is the same as Figures 1 and 2 for comparison.

3.4. Surface Water Flooding

Figure 4 shows the changes in EAD for surface water flooding under the different scenarios considered in this analysis. Before discussing any results, however, it must be noted that the short duration, high intensity convective rainfall that generally drives surface water flooding is difficult to model in the present day and even more challenging for the future [40]. The EAD projections produced by the FFE [26] used the best available projections of convective rainfall available at that time, e.g., [41] based on [42], but it should be noted that this is a developing field of research. The data used to drive the FFE climate change module, therefore, are much more uncertain for surface water flooding than for river or coastal flooding. It is possible that these results are a significant underestimate, which is much more likely than an overestimate given what is known about atmospheric moisture transport in warmer climates [43].

Nonetheless, using the data that are available, relative to the present day, EAD for surface water flooding shows the smallest increases in the future: EAD is shown to increase by a maximum of 2.3 times (i.e., a 130% increase) by the 2080s (high population, 4 °C, RWS) or be limited to an 34% increase (low population, 2 °C, EWS) by the 2080s. This is largely consistent with complementary studies: Papalexiou and Montanari [44], for example, showed that convective precipitation is likely to become more frequent and more intense in the 21st Century; and Rosenzweig et al. [45] described the processes whereby such changes would lead to increased surface water flooding. Given the uncertainty, though, it is difficult to say more about the consistency of these results with those of other research. Indeed, this points to the challenges that policy makers face in developing evidence-based adaptation strategies for surface water flood.

It is also evident that the FRM portfolios have the smallest impact on EAD of all the different sources of flooding in the future that were analysed here. This is the topic of discussion in Section 3.5 below.

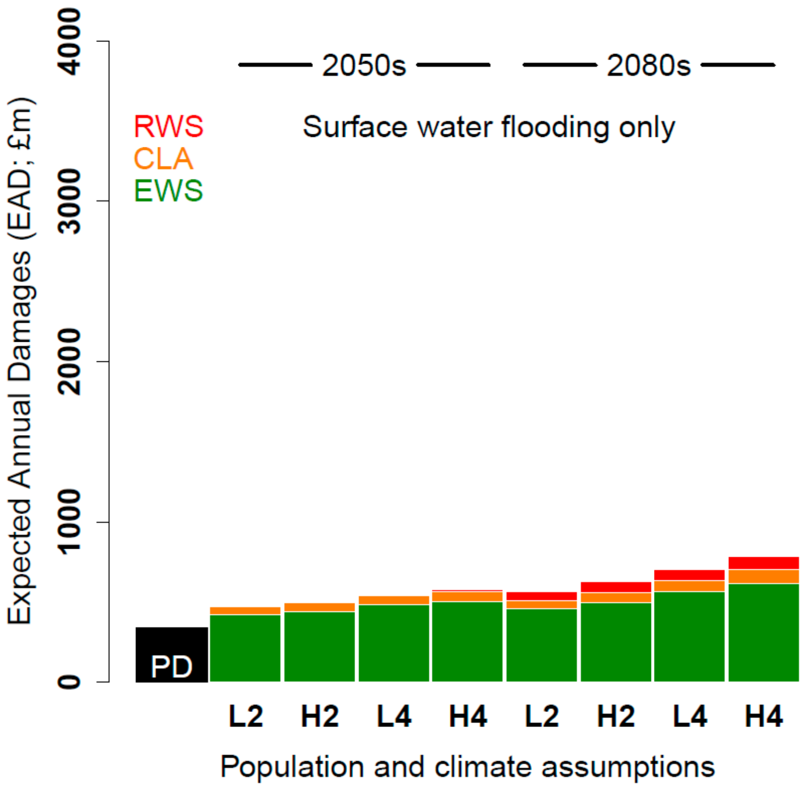

Figure 4. As for Figure 1 but for surface water flooding only. Note that the vertical scale is the same as Figures 1–3 for comparison.

3.5. Impact and Analysis of the RWS, CLA and EWS FRM Portfolios

Table 2 presents calculations of the EAD decreases driven by the FRM portfolios. Although the RWS portfolio is certainly not a "do nothing" scenario, it is used here as the counterfactual by which to compare CLA and EWS as it is, by consultation with the relevant policymakers, the lowest plausible level of FRM.

The most striking result is that the largest reductions for EAD are all for river and coastal flooding. As discussed in Sayers et al. [26], the reduction in EAD for river and coastal flooding reflects the dominant impact (and evidence base) of flood defences that prevent damage to properties built in flood prone areas. Naturally, increasing the flood risk and/or lowering the defence standards (as in the RWS portfolio) would increase damages. The CLA and EWS portfolios, therefore, can reduce the damages that grow under the RWS assumptions. Defences are generally not effective for surface water flooding events and, as seen in Figure 4 and Table 2, none of the three FRM portfolios has a large impact on the surface water flood damages as they increase with climate change and population growth.

Property level flood resilience (PFR) has a significant impact in reducing damages [26] and, therefore, needs to be considered more seriously in integrated FRM strategies. This is particularly the case in reducing damages to frequently flooded properties that are not protected by defences or other measures (i.e., residual risk). However, whilst PFR standards have been produced [46] and modelling studies are possible [47], there is currently very little evidence from deployment in real properties to understand the potential level of damage reduction [48]. This evidence base is urgently required to make decisions on deployment levels based on efficacy and empirically calculated cost-benefit ratios.

Sustainable urban drainage systems (SUDS) and improved drainage more generally play a key role in managing surface water flooding but, similar to the discussion of the drivers of surface water flooding in Section 3.4, more work is needed to refine the calculation of the benefits of drainage improvements.

Natural flood management (NFM), as part of catchment management, is shown to have significant potential within the FFE simulations to reduce damages. Although the evidence base for NFM opportunities is still developing [49] these initial results appear plausible. Nonetheless, these estimates will need to be revisited as our understanding and the evidence base improves. In particular, the areas where NFM can be efficiently and effectively deployed needs further consideration [26].

Table 2. Decrease in EAD (£ million and as a percentage), relative to RWS (reduced whole system adaptation), for the CLA and EWS portfolios for the different sources of flooding and population and climate scenarios. Values are shown in bold where they exceed a reduction of 33% or higher in the 2080s. CLA is current level of adaptation; EWS is enhanced whole system adaptation.

Flood Source and Scenario	CLA	EWS
All sources—Low—2 °C—2050s	269 (13%)	573 (28%)
All sources—High—2 °C—2050s	349 (15%)	711 (30%)
All sources—Low—4 °C—2050s	310 (14%)	643 (30%)
All sources—High—4 °C—2050s	401 (16%)	796 (32%)
All sources—Low—2 °C—2080s	408 (17%)	**765 (33%)**
All sources—High—2 °C—2080s	613 (20%)	**1105 (35%)**
All sources—Low—4 °C—2080s	519 (20%)	**946 (36%)**
All sources—High—4 °C—2080s	779 (22%)	**1371 (39%)**
River—Low—2 °C—2050s	173 (16%)	**375 (34%)**
River—High—2 °C—2050s	190 (16%)	**404 (35%)**
River—Low—4 °C—2050s	199 (17%)	**417 (36%)**
River—High—4 °C—2050s	218 (18%)	**450 (37%)**
River—Low—2 °C—2080s	192 (18%)	**401 (37%)**
River—High—2 °C—2080s	249 (19%)	**510 (38%)**
River—Low—4 °C—2080s	247 (20%)	**492 (40%)**
River—High—4 °C—2080s	320 (21%)	**626 (42%)**
Coastal—Low—2 °C—2050s	89 (18%)	142 (29%)
Coastal—High—2 °C—2050s	150 (22%)	**240 (36%)**
Coastal—Low—4 °C—2050s	102 (20%)	162 (32%)
Coastal—High—4 °C—2050s	171 (24%)	**271 (38%)**
Coastal—Low—2 °C—2080s	162 (23%)	**258 (37%)**
Coastal—High—2 °C—2080s	297 (28%)	**458 (43%)**
Coastal—Low—4 °C—2080s	206 (26%)	**324 (41%)**
Coastal—High—4 °C—2080s	376 (31%)	**575 (47%)**
Surface—Low—2 °C—2050s	8 (2%)	56 (12%)
Surface—High—2 °C—2050s	9 (2%)	66 (12%)
Surface—Low—4 °C—2050s	10 (2%)	64 (13%)
Surface—High—4 °C—2050s	12 (2%)	75 (13%)
Surface—Low—2 °C—2080s	54 (10%)	106 (19%)
Surface—High—2 °C—2080s	66 (9%)	136 (19%)
Surface—Low—4 °C—2080s	66 (11%)	130 (21%)
Surface—High—4 °C—2080s	83 (10%)	171 (22%)

Using spatial planning in conjunction with building regulations to manage flood risk is an essential element to consider even if it does not reduce existing risk. The route by which damages are avoided from this approach—i.e., not building properties in inappropriate locations—has a significant impact on the avoided damages associated with the adaptation portfolios. This approach has a very favourable cost–benefit ratio [50] and will become more important in the future: as population rises and more properties are built, the role of deciding where to put them becomes more difficult and will require more stringent building regulations (i.e., incorporation of SUDS and PFR into developments) to manage the risk.

Within the FFE experiments, forecasting and warnings were applied to reduce damages using evidence on potential effectiveness of such measures (see Table 1). Forecasting and warnings are clearly essential to reducing damages (and loss of life) from flooding and are required in effective integrated FRM strategies. Opportunities exist to improve the representation of such measures in different settings (for example relating the time to peak and local constraints on the opportunity to deliver and respond to a warning). Similarly, the impact of insurance within the FRM portfolios is included in the assessment of the Relative Economic Pain [33] but the interaction between insurance and other FRM adaptations may be important but is yet to be included.

4. Discussion and Conclusions

The analysis presented here is of interest for two specific reasons. First, the FRM actions outlined in England's NAP have been assessed as inadequate and, therefore, further analysis is required to identify the most effective routes to improve this situation—this are addressed in Section 4.1. Second, the analysis has more general lessons for integrated FRM approaches. These are discussed in Section 4.2.

4.1. Flood Risk Management Policy Development in Complex Governance Structures

As described in Section 1.1, The NAP for England was assessed by the CCC as not addressing the climate risks identified in the CCRA [10–13]. Specifically, on FRM, the second NAP was largely assessed to have no specific actions that would directly reduce flood risk [12] as most actions within the NAP related to organisational or procedural aspects of risk management and not risk reduction actions.

However, this does not mean that actions are not taking place or that they are not articulated somewhere. Indeed, whilst the CCC criticise the NAP actions as inadequately addressing the CCRA risks, England's progress in adapting to flood risk is assessed via many other policies, plans and strategies, and by the adaptations that are managed or that occur autonomously. For example, the CCC's "river and coastal flood alleviation" adaptation priority has always been assessed positively as significant sums of money are spent on FRM and this has historically had a large impact. Furthermore, the Environment Agency's National FCERM Strategy [15] has recently taken a long-term view of FRM and recognises the future risk associated with climate change. This is particularly true for river and coastal flood alleviation because the defences are generally well-developed technologies that are known to be cost effective.

Consequently, if actions are taking place regardless of the NAP, what is the purpose of the NAP? This is, of course, a question for policy officials and politicians but, from the analysis undertaken here, one good answer would be that it could focus on the integration of FRM actions and plans from different bodies. As discussed by Russell and McCue [14] and Benson et al. [51], the Flood and Water Management Act introduced in England in 2010 failed to "unify" many of the disparate responsibilities and authorities managing flood risk in the UK but the NAP could rectify some of this failure. For example, NAP actions could be set to achieve the managed realignment targets set out in the (non-statutory) Shoreline Management Plans, or to set targets for the uptake and retrofit of SUDS and PFR, or to impose limitations of the number of properties being built in areas of significant flood risk. In other words, where actions have been delayed or thought impossible because they span government departments, spatial boundaries, or risk management authorities, the NAP could provide an evidence-based direction for those difficult areas. This could include the development of the evidence base for emerging interventions, such as NFM or PFR, where greater understanding of the benefits could result in a strong case for the extent of their cost effective roll out.

4.2. Uncertainty in Integrated Flood Risk Management Measures

Looking beyond the UK, the method of developing plausible FRM portfolios with policymakers and the utilising them in flood risk projections provides useful insights for a wide group of flood risk analysts, professionals, and policymakers. Whilst the results for the UK are dominated by the impact of mature technologies on the best understood flood sources, a strategic FRM approach (e.g., Sayers et al. [52]) also highlights the elements of the mix that have potential should a more robust evidence base be forthcoming (e.g., PFR, NFM) and elements that have value but still need careful incorporation into a holistic plan (e.g., forecasting, warning, insurance).

It is also important to attempt to understand and value the co-benefits of all FRM approaches and incorporate these into the models that support policy decisions.

4.3. Conclusions

The key findings of this investigation are that:

- The range of EAD projections for all flood sources is projected to increase by between 18% and 160% by the 2080s depending on the assumptions applied on climate change, population growth, and adaptation actions.
- It is possible to reduce EAD from river flood risk by the 2080s.
- The EAD from coastal flood risk has the greatest potential to increase; and
- Adaptation actions have the least potential to impact surface water flood EAD.

More generally, this study found that the composition of an effective, national portfolio of FRM is difficult to identify, as efficient measures will vary from place to place. In addition, the evidence base used to underpin such strategies varies across approaches. At one extreme, conventional engineered defence, to protect assets from river and coastal flooding, have a strong evidence base to support significant investment in the maintenance of existing defences and the building of new defences in areas where flood risk and economic exposure can be shown to be high. Whereas FRM portfolios that deliver multiple benefits (through NFM) or rely upon homeowners acting (such as PFR) represent a more complex basket of measures to unpick. Calculations of present day and future risk from surface water flooding are also more difficult than for river or coastal flooding, which makes any cost-benefit arguments more challenging. Nonetheless, integration of different interventions is essential to manage flood risk to (politically and societally) tolerable levels and the analysis presented here contributes to this literature.

Delivering a portfolio FRM response, therefore, requires both the evidence base to continue to be improved and the process of decision making to be increasingly framed in a multi-criterion, long term, context that reflects uncertainty in the underlying evidence and in the future pathways of climate change and socio-economic factors and the full complexity of the adaptation choices.

At the level of physical process understanding, our ability to understand and assess surface water flood risk remains the most challenging of flood sources, as discussed in Section 3.4. Progress is being made in modelling and projecting the intense precipitation that drives surface water flooding [40] but this will take time to filter through to the improvement of flood risk models.

The next steps for this work, beyond the improvement of surface water flood risk calculation, are twofold: (1) the policy professionals working on FRM issues in the UK need to be re-engaged to ensure that the implications of their original input to this study is fully understood, which should refine FRM planning; and (2) the evidence supporting the impact of developing FRM approaches needs to be re-examined to ensure that they are equitably compared to more established approaches.

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