Next generation exploration of UK future flood risks: High resolution climate, population and adaptation futures

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Abstract Under the Climate Change Act 2008 the UK Government is required to publish a Climate Change Risk Assessment (CCRA) every five years. In response to this requirement future flood risk across the UK is explored here under alternative climate change, population growth and adaptation policies through to the 2080s using an innovative emulation model (the Future Flood Explorer). The analysis highlights significant increases in flood risk with Expected Annual Damages rising from £2bn today to £2.7-3.0bn in the 2080s (depending upon associated population growth) given a 2oC rise in Global Mean Surface Temperature, and rising to £3.5-3.9bn given a 4oC rise. The contribution of climate change, population and individual adaptation measures to future changes in flood risk are, for the first time, disaggregated, providing insight to the most significant drivers and important responses. The results highlight that to manage risk effectively under a 2 or 4oC future, an enhanced whole system approach to adaptation is needed with action required from a broad range of stakeholders, from national level down to individual households and businesses.

1 Introduction

The importance of understanding future flood risk in the context of a range of future scenarios was perhaps first formalized as part of the seminal Foresight Future Flooding Studies (Evans et al, 2004a&b) and reinforced through the Climate Change Act 2008 that requires a UK-wide *Climate Change Risk Assessment* (CCRA) to be undertaken every 5 years with future risks (across multiple sectors including flood risk) assessed under a range of climate, socio-economic and adaptation futures.

This paper explores the assessment of future flood risks undertaken as part of the 3rd UK CCRA, based on the latest climate change projections (UK Climate Projections 2018; UKCP18), projections of population growth and alternative adaptation futures. The analysis is undertaken using an evolution of the innovative Future Flood Explorer (FFE), first developed to support the 2nd UK CCRA (Sayers et al, 2015, 2016). The insights from the analysis, and an exploration of the associated benefits and costs of individual adaptation measures as part of portfolio of policy responses, are presented alongside the underpinning climate, socio-economic and adaptation assumptions.

2 Overview of approach

The FFE (Sayers et al, 2015, 2020) provides an assessment of future flood risk from fluvial, coastal, surface water and groundwater sources. The approach takes account of flood defences where they exist, future climate change, population growth and the influence of a portfolio of adaptation policy measures. The high computational efficiency of the FFE allows multiple future scenarios to be explored across the UK. Here, this includes two climate change scenarios, representing a 2ºC and 4ºC rise in Global Mean Surface Temperature (GMST) by 2100; none, low and high population projections; and a wide-range of adaptation measures as part of three coherent adaptation portfolios – Figure 1. The drivers of changed are detailed in turn below.

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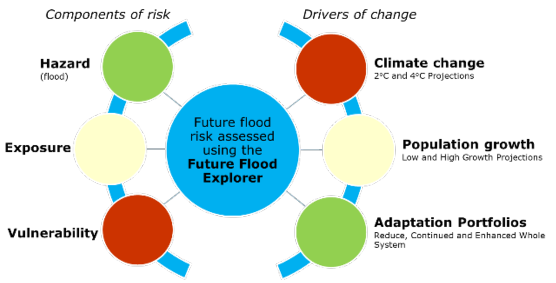
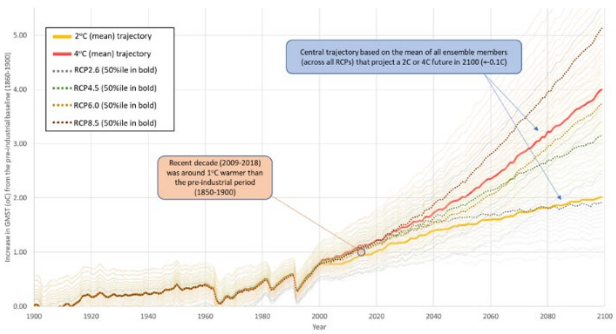


Figure 1. Overview of the structure of the analysis.

2.1 Influence of climate change on flood hazards

To provide a coherent understanding of the influence of climate change on the various flood sources the climate scenarios are framed using an increase in Global-Mean-Surface-Temperature (GMST). Two scenarios are considered; a 2°C and 4°C rise in GMST by 2100 (from pre-industrial times). This framing, although widely used (e.g. Sayers et al, 2015, Koks *et al,* 2020), does however present two difficulties.

1. ***There is no unique pathway to 2 or 4°C:*** Across the standard Representative Concentration Pathways (RCPs, van Vuuren *et al.,* 2011) many of the ensemble members from the UKCP18 Probabilistic Projections (Lowe et al, 2018) show an increase in GMST of 2° or 4°C by 2100. To avoid the overhead of modelling all of these futures, a mean of those members that project a rise of 2°C and 4°C (within a tolerance of +/-0.1 between 2090-2100 from a pre-industrial baseline) are used to construct two profiles of the rise in GMST with time – Figure 2.



Source from Sayers et al, 2020 using data from UKCP18 probabilistic projections

Figure 2. Rise in GMST to 2100

2. ***Not all sources respond only to temperature change:*** The approach to determining the influence of climate change on each flood source necessarily varies within the analysis to reflect the available underlying data from UKCP18 and constraints of analysis resource effort:

High-resolution changes in peak fluvial flows: All UKCP18 Probabilistic Projections that reach a 2 or 4°C rise in GMST **in or before** 2100 (from a pre-industrial baseline) are used in assessing the change in fluvial flows and associated extreme water levels on a 1km grid across the UK.

High-resolution changes in sea levels and coastal wave driven overtopping: The UKCP18 sea level projections used are based on the climate model simulations of the Coupled Model Inter-comparison Project Phase 5 (CMIP5, Taylor *et al.,* 2012) and additional analysis by Palmer *et al.,* (2018) that in-combination include the influence of oceanographic processes, gravitational and other adjustments due to ice melt and changes to terrestrial water storage as well as the elastic response of the land to the last de-glaciation to provide relative sea level rise estimates. rSLR estimates are then used Further processing is then used to assess the change in the standard of protection afforded by coastal defences using approach set out by Gouldby et al., 2017.

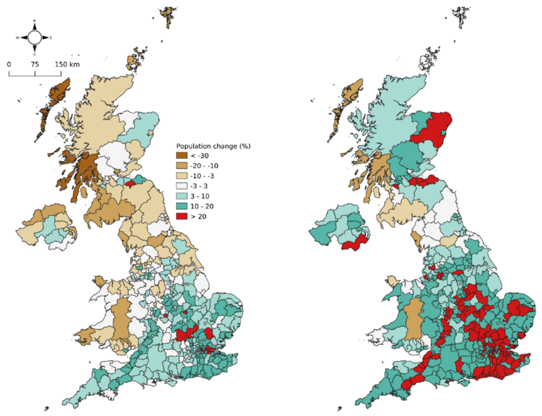
Changes in pluvial flooding driven by short duration rainfall intensity (< 6hours): Climate models are relatively poor at simulating short duration precipitation extremes (e.g. Kendon et al., 2014). This is primarily due to the relatively coarse resolution of climate models to date and their inability to capture important processes, such as convection. The development of finer-grid models remains in its infancy and data from the Met Office UKCP 2.2km climate model (Kendon et al., 2019) is yet to be fully mined. A combination of evidence is therefore used here to estimate the change in short duration rainfall intensity, including the Environment Agency guidance on climate allowances (Environment Agency, 2016a&b).

2.2 Influence of population growth

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

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

These changes (illustrated in Figure 3) translate into increased properties and population on the floodplain through the action of the spatial planning adaptation.



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

Figure 3. Population projection by UK Local Authority – 2080s

2.3 Influence of adaptation

It is widely recognised that flood risk is best managed through a portfolio of measures implemented through a continuous process of adjustment (e.g. Evans et al 2004a&b, Sayers et al., 2013,2014). The portfolio approach is also reflected here with nine individual Adaptation Measures (AMs) combined into three alternative Adaptation Portfolios (AP) that represent different levels of policy ambition:

- **No additional action:** Leading to **Reduced Whole System** (RWS) Adaptation: In the context of flooding, this does not mean taking no further action to maintain or improve flood defences for example, or assume that existing defence standards are maintained at present-day levels in all locations in all climate futures. Instead, the 'no additional action' baseline assumes adaptation to flood risk continues but investment in conventional defences fails to keep pace with climate change; there is limited take up of catchment-based or urban run-off measures; pressure for development and economic growth lead to continued new development on the floodplain; receptor (property) level flood resilience (PFR) continues to experience limited take-up amongst existing properties. There are several plausible reasons that may lead to such a situation. Other threats may become increasingly dominant in public funded priorities (translating to a reduction in the willingness to pay for flood risk management) or our collective capacity to promote and deliver flood risk management may wane as political and social capital is directed towards other priority issues.
- **Current objectives:** Leading to a continuation of **Current Levels of Adaptation** (CLA): The 'current objectives' policy response used here assumes flood risk management policies continue to be implemented as in the recent past whilst taking on board anticipated changes that are likely to result from recent changes in policy, such as the 25 Year Environment Plan and the National Planning Policy Framework in England, continued evolution of TAN15 in Wales, and National Planning Framework No. 4 in Scotland. These and similar documents are likely to encourage greater uptake of Natural Flood Management (NFM) and property flood resilience (PFR) measures than achieved in recent years and continue to encourage greater investment in FRM.
- **Current Objectives+:** Leading to an **Enhanced Whole System** adaptation (EWS): The 'current objectives+' scenario goes beyond the current implementation of policy to represent an 'Enhanced Whole System' (EWS) approach to adaptation. For example, investment in flood defence increases (including in more socially disadvantaged neighbourhoods) and land use planning policy is more successful in restricting development in the floodplain than currently achieved or anticipated. Awareness raising and a strengthening of building regulations and planning controls encourage greater receptor level resilience. Forecasting and warning systems develop with increased levels of sophistication, targeting those at risk more accurately than has been possible to date. Opportunities for more integrated planning and implementation are sought (e.g. Ministry of Housing, Communities and Local Government, MHCLG, 2018 and 2019, Welsh Government, WG, 2018) and, together with increasing momentum towards a 'net zero' emissions future, nature-based solutions are increasingly promoted and greater resilience delivered.

3 Projected future changes in flood risk

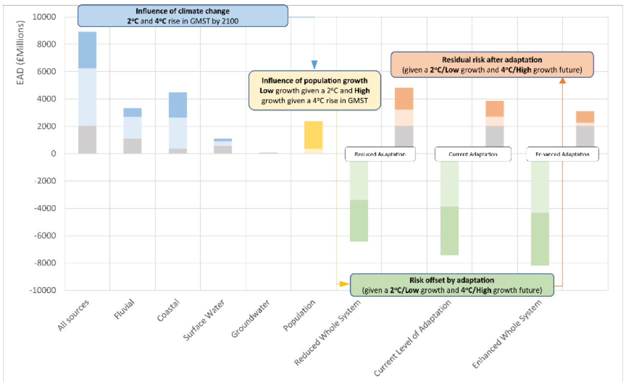
The analysis finds that assuming a continuation of Current Levels of Adaptation, Expected Annual Damages (EAD, including direct economic damage to residential and non-residential properties and associated indirect damages) are set to increase from present-day levels. Under a 2°C future EAD rises from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

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

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

~20% between a 2 and 4°C future. The influence of population varies with the projection of growth. Assuming low population growth the additional impact on risk is limited (although not insignificant, adding £364m to EAD), whereas high population growth has a much greater influence (adding ~£2.4bn to the EAD assuming a 4°C rise in GMST). By the 2080s the combination of a 4°C climate change and high population growth drives an increase of ~£9.2bn EAD in the absence of adaptation. The future is therefore bleak in the absence of adaptation and mitigation.

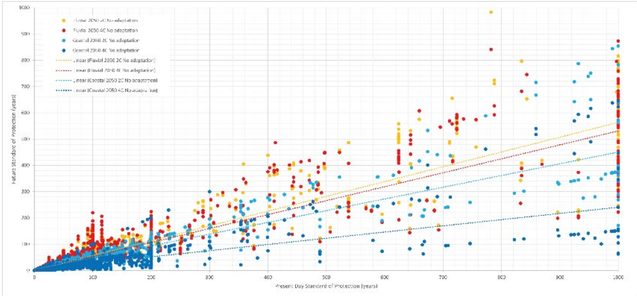
All three adaptation portfolios limit this increase. A continuation of Current Levels of Adaptation offsets ~£7.4bn of EADin the 2080s (under a 4°C future with high population growth) resulting in a net increase in risk of ~£1.8bn. An Enhanced Whole System (EWS) approach to adaptation offsets ~£8.2bn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



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

Figure 4 A disaggregation of the drivers of changes in risk by 2080s using the Future Flood Explorer – Expected Annual Damage (total)

Climate change also impacts the standard of protection afforded by flood defences. In the absence of any further adaptation the reduction in the standard of protection provided is significant. This reduction is most marked at the coast (see Figure 5). The impact of climate change on fluvial defences is more mixed with some areas experiencing a small increase in their effective standard of protection as peak flood flows reduce (reflecting the complex spatial pattern of future changes in peaks flows).



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

Figure 5 Impact of climate change on defence standards: 2050s assuming no adaptation

Catchment (natural) management provides a meaningful contribution to reducing the impact of climate change on conventional defence standards and reducing risk by limiting the the impact of more frequent floods on expected annual damages . The analysis suggests that investment in catchment management provides significant returns when combined with conventional flood defences (as here) across the UK. with a Benefit to Cost Ratio (BCR) of greater than ~20 across all portfolios. This reflects the comparatively low cost and an ability to meaningfully contribute to the management of more frequently occurring flood events that often drive EAD.

The analysis also provides a perspective on how risks are changing for the most socially vulnerable. In many rural towns and villages and smaller urban cities and towns the most socially vulnerable[a] are, on average, exposed to greater flood risk. For example, in some rural setting the present-day EAD is on average ~£150 per person (for those living in flood prone areas) but almost double this (~£280 per person) in the most socially vulnerable neighbourhoods (on average). In the future the most socially vulnerable, particularly in urban cities and towns, coastal areas and post-industrial cities experience disproportionate increases in risk, with the EAD per person increasing by a factor of 2.5 on average but by 2.8 in the most socially vulnerable neighbourhoods.

4 Conclusions

The innovative analysis provided by the Future Flood Explorer enables a consistent UK-wide assessment of future flood risk taking account of four sources of flooding, population growth and adaptation. The FFE has been shown to be a practical and credible approach that is fast to run enabling multiple futures to be explored. The analysis present here (using the latest climate projections form UCP18, population projections from Cambridge Econometrics and the detailed consideration of alternative adaptation policy portfolios) highlights:

[a] As defined by the 20% most socially vulnerable neighbourhoods according to the Neighbourhood Flood Vulnerability Index, NFVI, Sayers et al, 2016 and available via Oasis platform.

- **Sources of flood risk:** Fluvial flooding contributes the greatest to economic damages now and in the future but the relative contribution of both surface water and coastal flooding increases.
- **Changing standards of flood defences:** The reduction in the standard of protection afford by defences, in the absence of adaptation, is most marked at the coast. In fluvial settings most defences experience a reduction in standard but with significant spatial variation reflecting the complex spatial pattern of future changes in peaks flows.
- **Risk for agriculture:** The changing nature of habitats and the impact of climate change on agricultural damage responds to multiple variables not explicitly considered here (changes in the seasonality, salinity, chosen crops, local land management practice etc.). There is however an increase in exposure of agricultural land (Best and Most Versatile land) to frequent flooding (at least 1 in 30 years). The largest increases are projected in the agricultural heartlands of Lancashire and Northamptonshire as well as Bedfordshire, Cambridgeshire and Yorkshire. Flooding may also impact agricultural land in more marginal locations that have little (or no) Best and Most Versatile land. The impact on these more marginal lands (and associated activities and communities) is not considered here.
- **Systemic social flood disadvantage:** The most socially vulnerable experience the greatest level of disadvantage across the UK, – this is case today and in the future.
- **Spatial planning approaches:** The only adaptation response that acts to directly mitigate the influence of population growth is spatial planning; but spatial planning is always context specific. Many Local Authorities cannot avoid development in the floodplain whilst others have much more flexibility. The national planning framework needs to recognise this reality more directly and help locations that must build on the flood plain to do so in the context of a long-term plan to reduce risk and maintain safety. In some areas this may be by enforcing property level measures (for example in areas prone to fluvial flooding) but in coastal areas this is likely to mean a commitment to maintain appropriate long-term protection (together with an acceleration in cost that is likely to follow) or implement managed retreat (an adaptation option not explicitly considered here). Indecision today has the potential to lock-in risk for future generations.
- **Coastal and estuarine areas:** Many estuary and coastal urban areas are unable to avoid floodplain development. Coupled with relative sea level rise (rSLR) this leads to a major increase in coastal flood risk (the fastest growing of all hazards).
- **Catchment management provides a meaningful contribution to economic risk reduction:** The analysis suggests significant benefit to cost ratios based on economic benefits alone, noting that catchment management approaches also offer a wide range of co-benefits not considered here. The knowledge on the long-term performance of catchment management is however limited compared to the performance of conventional flood defences or planning measures. This lack of comparable knowledge should not be a barrier to appropriate use as a legitimate component of a portfolio response given the wide range of associated benefits but should be addressed.
- **Going beyond Current Objectives+:** Under all adaptation portfolios considered here, risks rise under a 2 and 4°C climate future. To maintain present-day risk levels constant to the end of the century continued innovation in adaptation approaches will be required. This may include, for example, greater effort towards making space for coastal and river dynamics within local and large-scale planning and development choices (including coastal realignment) as well as more integrated actions to address the increase in surface water flood risk.

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