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The evolution of climate change guidance for fluvial flood risk management in England

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Abstract

Floods are one of the biggest natural hazards to society, and there is increasing concern about the potential impacts of climate change on flood occurrence and magnitude. Furthermore, flood risk is likely to increase in future not just through increased flood occurrence but also through socio-economic changes like increasing population. The extent to which adaptation measures can offset this increased risk will depend on the level of future climate change, but there exists an urgent need for information on the potential impacts of climate change on floods, so that these can be accounted for by flood management authorities and local planners aiming to reduce flood risk. Agencies across the UK have been pro-active in providing such guidance for many years, and in refining it as the science of climate change and hydrological impacts has developed. The history of this guidance for fluvial flood risk in England is presented and discussed here, including the recent adoption of a regional risk-based approach. Such an approach could be developed and applied to flood risk management in other countries, and to other sectors affected by climate change.

Keywords

Adaptation, climate change projections, flood management, flood risk assessment, hydrological modelling

I Introduction

Flooding is a natural hazard that threatens lives and causes huge economic losses both in the UK and worldwide (Klijn et al. 2015). Recent events have served as timely reminders of our social and economic vulnerability, with the floods in central Europe in 2013 claiming 22 lives and costing an estimated €12bn (Munich Re 2013) and the winter 2013/14 floods in Britain estimated to have cost £1.3bn in England and Wales alone (EA 2016c). The sequence of recent flood events has led to inevitable questions about climate change, including the degree to which anthropogenic effects on the global climate are influencing extreme events (Kay et al. 2011c; Schaller et al. 2016) and what future climatic changes might mean for flood frequency and magnitude (Watts et al. 2015). There has been considerable research into the potential impacts of climate change for river flooding across Europe and beyond (e.g. Alfieri et al.

2015; Dankers et al. 2014; Roudier et al. 2016). The broad conclusion for Britain is that flooding is likely to increase, but with spatial variations because of local catchment characteristics as well as spatial differences in climatic changes (Bell et al. 2016; Kay and Jones 2012). Flood risk (the combination of occurrence and consequence) is also likely to increase in many parts of the world because of socio-economic changes like the increase in population, which affect exposure and vulnerability to floods (Arnell and Gosling 2016; Hirabayashi et al. 2013; Winsemius et al. 2016).

While efforts continue on climate mitigation, these findings explain why it is now widely accepted that society must be resilient against both climate variability and possible future climate change. The Climate Change Act 2008 made the UK the first country in the world to have a legally-binding long-term framework for both mitigation and adaptation to climate change, creating a framework for building and reinforcing the UK's ability to adapt to climate change. This included the requirement to produce a UK Climate Change Risk Assessment (CCRA) every 5 years; the first of these was published in 2012 (Defra 2012) and the second in January 2017 (Defra 2017). It also included the Adaptation Reporting Power; a mandate giving the government the power to require 'bodies with functions of a public nature' and 'statutory undertakers' to report on what they are doing to address the risks posed to their business by climate variability and change. At the same time it remains important that (adaptation) policy development is underpinned by robust scientific evidence, incorporating an appropriate representation of scientific uncertainty.

II The history of climate change guidance for fluvial flood risk

The Flood Estimation Handbook (Institute of Hydrology 1999) and subsequent updates (EA 2008; Kjeldsen 2007) present the national standard methods for estimating flood frequency curves for any site on the UK river network (gauged or ungauged). The methods are based on historic observational data, but assume that the underlying data series are stationary. It was recognised at a relatively early stage, at the beginning of the 1990s, that the emerging evidence on global warming and climate change could have an effect on flooding in the UK, presenting a threat to public safety. The immature nature of the science and associated (gross) uncertainty led the then UK Department for the Environment to invoke the Precautionary Principle and seek to take action to improve the UK's flood resistance and resilience (defined respectively as flood prevention, and minimising flood impacts and enhancing recovery; De Bruijn 2004). The limited scientific evidence at the time, based on modelling performed for the Thames and Severn catchments (Reynard et al. 1999), underpinned a set of (non-obligatory) guidelines for flood managers to include the effect of climate change in their decisions (MAFF 2001). This took the form of a sensitivity assessment incorporating a national percentage change in peak river flows of 20% to test the long-term effectiveness of flood management options over the following 50 years. Decisions would then be made, taking into account the results of the sensitivity testing and different investment timing strategies. The full text of the guidelines states:

> "In the view of the current uncertainty……. The sensitivity analysis of river flood alleviation schemes should take account of potential increases of up to 20% in peak flows over the next 50 years. … It will often be preferable to consider design options which allow the possibility of future incremental adaptation"

The initial scientific evidence was based on climate projections from the HadCM2 Global Climate Model, which pre-dated the UK Climate Impacts Programme (UKCIP; www.ukcip.org.uk). Subsequent analysis, funded by the Department for Environment, Food and Rural Affairs (Defra) and the Environment Agency (EA), applied the UKCIP02 climate projections (Hulme et al. 2002) to 10 catchments across Britain, for four emissions scenarios (Low, Medium-Low, Medium-High and High) (Reynard et al. 2004). As the majority of catchments and model runs showed changes in peak river flows of less than 20% up to the end of the 21st century, this work served to affirm the view that the 20% sensitivity allowance was relatively precautionary. Defra then issued guidance (Defra 2006) recommending that flood management options be assessed both with and without modifications to allow for the impacts of climate change, where the former assessment accommodated the 20% sensitivity allowance within the hydraulic design and subsequent cost-benefit analysis. Some case studies of application of the allowance are presented in Table 1, including one example where the 20% allowance was built-in immediately, one where this was not viable so resilience measures were used instead and one that applied phased implementation (Defra 2006). Similarly, while national planning policy for England since 2006 has steered development outside flood risk areas where possible, where development was located in flood risk areas it was required to be safe for its lifetime (DCLG 2012), including accounting for the impact of climate change using the allowance for fluvial flood risk (DCLG 2014).

Table 1 Case studies of application of the 20% sensitivity allowance for change in peak river flows under climate change.

Adaptation type	Description
Precautionary approach	In town C, the capacity of culverts under a trunk road in an urban area was increased to accommodate the 1 in 100 year flow and a possible increase in the flow by 20%. This decision was made because of the minimal cost of upsizing now, rather than the much higher costs of modification later, due to land acquisition and engineering complexity.
Adaptation approach	The impact of climate change was assessed using the 20% increase in flows in river P. However, defences could not be raised without raising the railway line, which was not economically viable. Therefore a decision was taken to: 1) bear the increased risk and accept that the standard of protection (now at 1 in 200 years) will reduce to 1 in 65 years in 50 years' time; 2) adapt to the climate change risk using non-structural methods that include resilience, and negotiate with Network Rail to implement their own precautionary measures. These measures included possible track raising or realignment if any major rail reconstruction work was contemplated during the next 50 years.
Adaptation approach: Smaller catchment	For a smaller river V, with steep upland valleys, sensitivity testing enabled comparison of changes in the relative strength of different options. A screen-out stage included broad sensitivity tests for climate change impacts using the allowances for peak river flows (20%) and peak rainfall intensity. This led to five options for further detailed appraisal, including some non-structural approaches: 1) wall height increase; 2) bypass channel; 3) large upstream storage; 4) moderate upstream storage with resilience measures; and 5) bypass channel with upstream storage. The benefits and costs for each option were appraised both with and without modification to accommodate climate change impacts, and the economic efficiency of the options was then compared: The preferred option was 4 with modification. Further sensitivity testing identified the optimal timing of investment for this option. In essence, the approach led to a resilient solution which allowed for future increases in upstream storage capacity, rather than just building existing defences higher now.
Adaptation approach: Large catchment	For large river X, a strategy considered £80m of work combining raising and strengthening defences with managed realignment to allow the estuary to spread into additional areas to reduce extreme flood events. This would also allow space for habitats to migrate inland and to counter the effects of coastal squeeze. A combination of solutions were sensitivity tested for climate change, including the 20% allowance.

The analysis of Reynard et al. (2004) included an investigation of whether the simulated changes in flows under climate change were related to the physical properties or location of the studied catchments. No definitive relationships could be shown from analysing only 10 catchments, but there were suggestions that properties like altitude and baseflow index could be influential, as could location. Due to (partial) dependence of catchment properties on location in Britain, it was not possible to identify whether differences in impact between catchments were due to spatial patterns in the climate change projections or catchment properties, or both. Thus a need was identified to extend the research to more catchments (a need backed up by the study of Kay et al. (2006), which applied Regional Climate Model (RCM) data to investigate the potential impacts of climate change on flood frequency for 15 catchments across Britain). Similarly, the need to continually update assessments using new climate projections and improved downscaling techniques was identified, along with the need to cover various sources of uncertainty, especially climate model uncertainty.

Thus further work was subsequently commissioned by the joint Defra/EA Flood and Coastal Erosion Risk Management (FCERM) R&D programme, with the aim of assessing the ongoing applicability of the 20% sensitivity allowance, and looking at how improvements in climate science (including the release in 2009 of the latest set of climate projections for the UK) and developments in catchment modelling could be incorporated into climate change allowances for peak river flows (Reynard et al. 2009). In particular, the national applicability of the 20% sensitivity allowance was to be assessed by modelling the impacts on peak flows for more catchments. This allowed consideration of the potential for regional variation, and the risk that applying a single national allowance could lead to over-/under-adaptation.

III The new risk-based approach

The 2009 UK Climate Projections (UKCP09) supported a risk-based approach to the potential impacts of climate change on river flows and flood peaks by providing probabilistic projections (Kay and Jones 2012), thus enabling selection of climate change impact allowances depending on levels of exposure or vulnerability. The UKCP09 projections were based on a complex set of modelling and statistical processing steps, resulting in a probabilistic representation of changes in a number of terrestrial climate variables for seven (over-lapping) 30-year time-slices and three emissions scenarios (Murphy et al. 2009). The projections are generally provided as sets of 10,000 equally likely (monthly, seasonal or annual) change factors, and are available for three spatial domains; i) boxes on a ~25x25km grid, ii) 16 administrative regions, iii) 23 river-basin regions. As the sets of change factors for different grid boxes are not spatially coherent they cannot be combined for application to larger areas, so the provision of river-basin region change factors enables consistent changes to be applied throughout a catchment.

Traditionally, climate change impact studies have used a top-down approach, whereby projections from climate models are used to drive impact models (e.g. Christierson et al. 2012; Kay and Jones 2012). However, such approaches become more onerous as ever-larger ensembles of climate model projections are produced (Fronzek et al. 2010), sometimes necessitating the selection of subsets of projections for impact modelling (e.g. Christierson et al. 2012; Ntegeka et al. 2014). Alternatives are to apply a bottom-up approach exploring the sensitivity of a system to climatic changes, or a combined sensitivity/projection-based approach, for example by overlaying climate projections on response surfaces produced by a sensitivity study. A big advantage of such combined approaches is the ease with which very large ensembles (e.g. from UKCP09) can be applied, or new assessments made when new projections are released (Wetterall et al. 2011). Combined sensitivity/projection-based approaches have recently been used in a number of studies: to assess risk of exceeding flow thresholds in various European basins (Weiß 2011), risk of high water levels in Nordic lakes (Wetterall et al. 2011), flood risk in Ireland (Bastola et al. 2011), and risks to a water supply system in Boston, USA (Brown et al. 2012).

A similar sensitivity/projection-based approach has been developed and applied to investigate the potential impacts of climate change on flood frequency in Britain (Reynard et al. 2009), using a sensitivity domain involving changes in rainfall mean and seasonality (Prudhomme et al. 2010). This was applied to 154 catchments in Great Britain, with the resulting response surfaces grouped into nine flood response types (Damped-Extreme, Damped-High, Damped-Low, Neutral, Mixed, Enhanced-Low, Enhanced-Medium, Enhanced-High, Sensitive) each represented by an average response surface (Prudhomme et al. 2013a). Decision trees were produced to enable estimation of response type from physical catchment properties (Prudhomme et al. 2013b).

This method was then applied to catchments across England and Wales, and combined with the UKCP09 projections for river-basin regions, to produce regional probabilistic distributions of the potential impacts of climate change on flood frequency, weighted by the number of catchments of each response type in the region (Kay et al. 2014a). The UKCP09 projections used were those for the medium emissions scenario for three time-slices — 2010-2039 (2020s), 2040-2069 (2050s) and 2070-2099 (2080s) — and also the low and high emissions scenarios for the 2080s, for each of twelve river-basin regions covering England and Wales (Figure 1). A similar approach was applied for Scotland (Kay et al. 2014b). The weighted distribution for each region (for a given time-slice and emissions scenario) accounts for the range of the UKCP09 projections in the region, and allows for uncertainty from the assumptions and simplifications necessary to apply the sensitivity-based approach (Kay et al. 2014c). The distributions for each response type in each region can also be used to look at variation in impacts between catchments (Figure 2), and allowance can also be taken of the use of average response surfaces for each response type, via use of standard deviation surfaces (Kay et al. 2014a,b). These distributions allow the development of a risk-based approach for climate change guidance by enabling the selection of impact percentiles, which can be chosen according to vulnerability, consequence, appetite for risk etc. The sets of regional distributions thus form the basis of new guidance for local planners and flood management authorities.

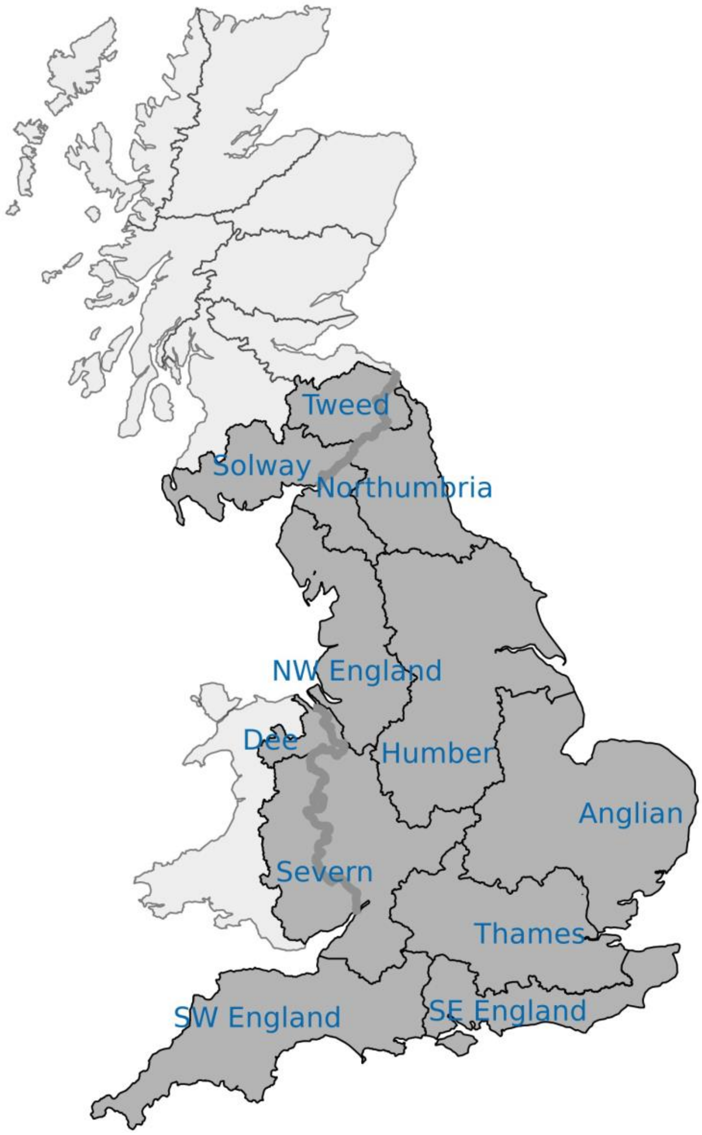

Figure 1 The eleven UKCP09 river-basin regions covering England (plus one solely covering Wales and seven solely covering Scotland). The Solway and Tweed regions are mainly in Scotland, with the England/Scotland border shown by a thick grey line, and the Dee and Severn regions cover parts of Wales, with the England/Wales border also shown by a thick grey line.

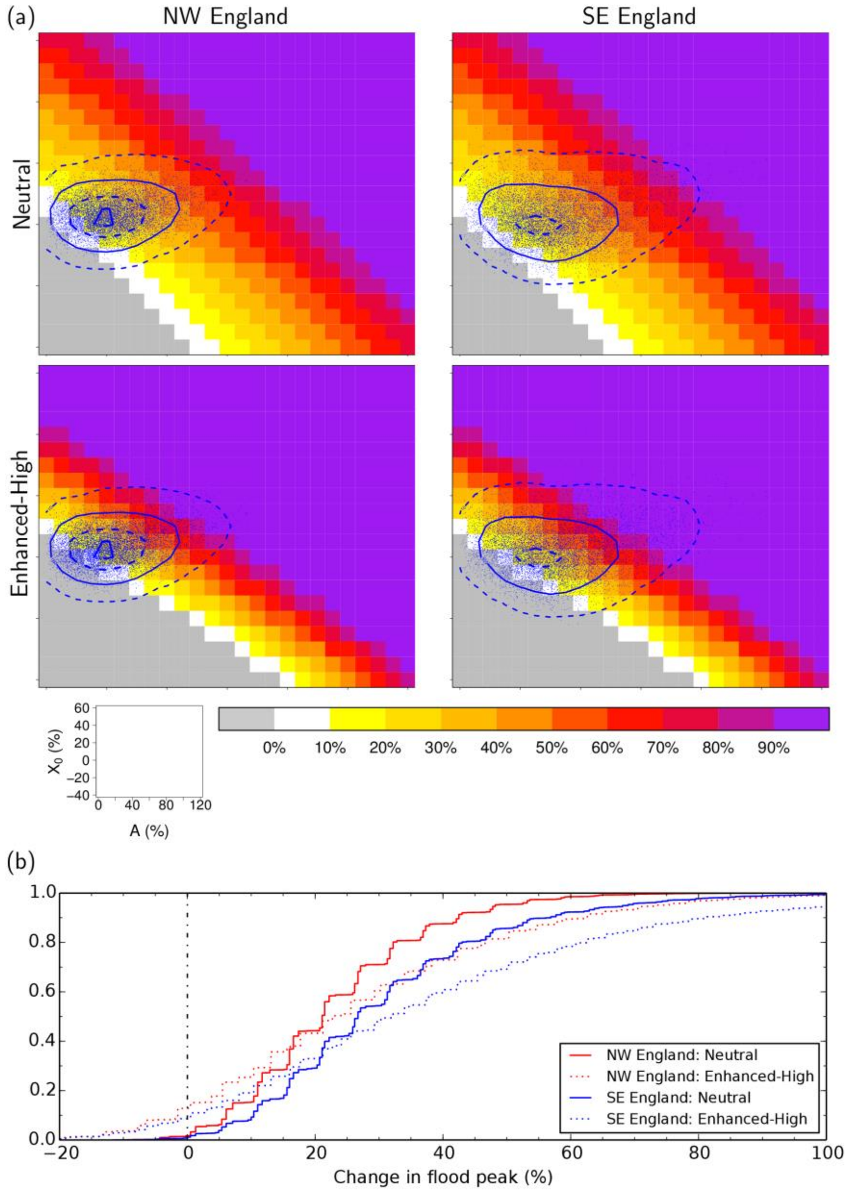

Figure 2 Example application of the combined sensitivity/projection-based approach: (a) Overlaying projections on response surfaces, for two response types (Neutral and Enhanced-High) and two UKCP09 river-basin regions (NW England and SE England). The sensitivity domain of changes in precipitation (see key, bottom-left) is defined by the harmonic mean X_0 (y-axis) and amplitude A (x-axis) via $X(t)=X_0+A\cos[2\pi(t-1)/12]$ for month t, using 5% intervals for both X_0 and A (Prudhomme et al. 2010). The percentage changes in flood peaks for each position on the sensitivity domain are shown by the coloured squares (see colour key, bottom-right), and the UKCP09 projections for the 2080s time-slice and medium emissions scenario are shown by the blue dots and contour lines. (b) Cumulative distribution functions, showing the corresponding percentage changes in flood peaks extracted from the response surfaces for the sets of UKCP09 projections. Percentage changes shown here are for 50-year return period flood peaks.

IV The new guidance

The EA issued new guidance for flood management authorities in England in 2011 (updated in 2016; EA 2016a), and guidance for flood risk assessments required under the planning system was issued in 2016 (EA 2016b). As the impact distributions vary by future time-slice and by river-basin region, the guidance is defined as a change in the 50-year return period flood peak for three time-slices (2020s, 2050s and 2080s) and for each of the eleven regions covering England (Table 2). The guidance for flood management authorities provides a set of five numbers (Lower, Central, Higher Central, Upper and H++) for each region and time-slice. The guidance for flood risk assessments is similar but does not provide the 'Lower' number. 'Central' is the 50^{th} percentile impact, while 'Lower', 'Higher Central' and 'Upper' represent the 10^{th}, 70^{th} and 90^{th} percentile impacts respectively; the *p*th percentile impact means that *p*% of the UKCP09 projections for that region and time-slice give a lower impact, while (*100-p*)% give a higher impact. The 'Lower', 'Central' and 'Upper' numbers thus represent the main range of estimated impacts of climate change on flood frequency from the UKCP09 projections, while 'Higher Central' provides an intermediate value that is more precautionary than 'Central' but not as precautionary as 'Upper'. The H++ numbers represent more extreme impacts and are derived from the 90^{th} percentile of the regional distributions for the Enhanced-High response type (see below). For the 2020s and 2050s all of the numbers are derived using the UKCP09 medium emissions scenario, but for the 2080s 'Lower' is from the low emissions scenario while 'Upper' is from the high emissions scenario, to make allowance for the greater uncertainty in future emissions for later time-slices. Figure 3 provides an example of the derivation of the guidance numbers, for two regions for the 2050s (medium emissions). Note that, for the Scottish border regions (Solway and Tweed), the guidance is derived from similar research for Scotland (Kay et al. 2011b, 2014b) rather than that for England and Wales (Kay et al. 2011a). Although the guidance issued by the EA only covers England, guidance is similarly available for Wales (Welsh Government 2016) and being derived by the devolved administration of Scotland (SEPA 2016). Note also that the guidance includes allowances for increases in the intensity of extreme rainfall and factors affecting coastal flooding (mean sea level, storm surge and wave height); these are derived from separate research and are not covered here.

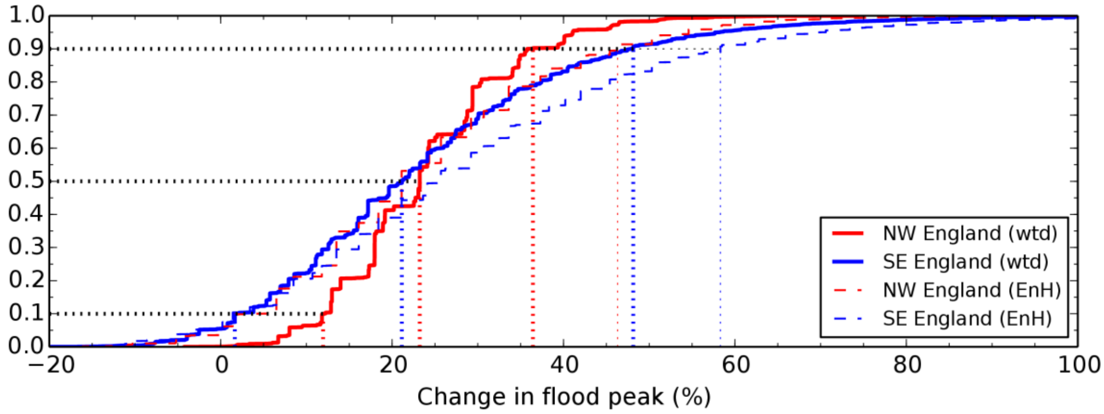

Figure 3 Example regional cumulative distribution functions (cdfs) for the percentage changes in flood peaks for two regions (NW England and SE England), showing both the weighted regional cdfs (solid lines) and the cdfs for the Enhanced-High response type (dashed lines). Also shown are dotted horizontal and vertical lines illustrating how to read off the impact corresponding to the required percentiles (10th, 50th and 90th) of each cdf, to select a range of allowances. Percentage changes shown here are for 50-year return period flood peaks, for the 2050s time-slice and medium emissions scenario.

H++ scenarios represent plausible but unlikely high-end impacts of climate change, which are useful for testing the sensitivity of adaptation options against a very extreme level of risk; an example of their development and application is for sea level rise within the Thames Estuary 2100 project (Ranger et al. 2013). As part of the second Climate Change Risk Assessment (CCRA2) the Adaptation Sub-Committee of the Committee for Climate Change commissioned a project to extend H++ scenarios to other variables, including temperature extremes and high and low rainfall and river flows. Thus H++ scenarios for high river flows were derived and presented in Chapter 6 of Wade et al. (2015), based on results from the same sensitivity/projection-based work used here (Kay et al. 2011a,b). These H++ scenarios represent high-end estimates of change in a type of catchment that is particularly sensitive to changes in climatic inputs: 'Enhanced-High' (Prudhomme et al. 2013a). Such catchments are more likely to occur in some river basin regions than others (Kay et al. 2011a, Figure 5.1) but they cannot currently be completely ruled out anywhere. The scenarios are provided as a range, with the lower end derived from the 90th percentile impact for the Enhanced-High response type, and provided for three time-slices (2020s, 2050s, 2080s) for each river-basin region, but the upper end provided only for the 2080s and for the UK as a whole (derived as the maximum of the 100th percentile impact). The CCRA2 lower-end H++ scenarios are those presented in Table 2, and for the 2080s they are on average about 20% greater than the 'Upper' numbers, but the CCRA2 upper-end H++ scenario is a 290% increase in flood peaks, which is significantly higher than anything in Table 2.

Table 2 Regional guidance for England, for three time-slices.

	2020s	2050s	2080s		2020s	2050s	2080s
Solway				**Tweed**			
H++	25	45	95	H++	20	35	75
Upper (90th)	20	30	60	Upper (90th)	20	25	45
Higher Central (70th)	15	25	30	Higher Central (70th)	15	20	25
Central (50th)	10	20	25	Central (50th)	10	15	20
Lower (10th)	5	10	10	Lower (10th)	0	5	5
NW England				**Northumbria**			
H++	25	45	95	H++	20	35	65
Upper (90th)	20	35	70	Upper (90th)	20	30	50
Higher Central (70th)	20	30	35	Higher Central (70th)	15	20	25
Central (50th)	15	25	30	Central (50th)	10	15	20
Lower (10th)	10	10	10	Lower (10th)	5	5	10
Dee				**Humber**			
H++	20	30	60	H++	20	35	65
Upper (90th)	20	30	45	Upper (90th)	20	30	50
Higher Central (70th)	15	20	25	Higher Central (70th)	15	20	30
Central (50th)	10	15	20	Central (50th)	10	15	20
Lower (10th)	5	5	5	Lower (10th)	5	5	10
Severn				**Anglian**			
H++	25	45	90	H++	25	40	80
Upper (90th)	25	40	70	Upper (90th)	25	35	65
Higher Central (70th)	15	25	35	Higher Central (70th)	15	20	35
Central (50th)	10	20	25	Central (50th)	10	15	25
Lower (10th)	0	5	5	Lower (10th)	0	0	5
SW England				**Thames**			
H++	25	50	105	H++	25	40	80
Upper (90th)	25	40	85	Upper (90th)	25	35	70
Higher Central (70th)	20	30	40	Higher Central (70th)	15	25	35
Central (50th)	10	20	30	Central (50th)	10	15	25
Lower (10th)	5	5	10	Lower (10th)	-5	0	5
				SE England			
				H++	30	60	120
				Upper (90th)	25	50	105
				Higher Central (70th)	15	30	45
				Central (50th)	10	20	35
				Lower (10th)	-5	0	5

The guidance for flood management authorities (EA 2016a) recommends that the Central estimate of change should be used to define the baseline risk over the lifetime of the decision. Upper and Lower estimates of change are provided alongside the Central estimate so that users can understand how greater or lesser change could affect the risk, and what options would be required to manage that range of risk. The concept was that users would plan for the Central option but use knowledge of the wider set of options to manage the fuller range of risk, to develop a more farsighted approach and hopefully a final option that is more robust to future climate change. For instance, planning for the Central estimate will be inadequate if greater change occurs, so users are encouraged to think about where additional measures should be taken immediately to avoid maladaptation, or look at where flexibility can be built into the plan to allow future flood managers to implement further adaptation if greater increases materialise. Examples would include building a flood defence with greater footings to allow for defences to be raised further in the future, and allow adequate access to the site for future adjustment of the flood scheme.

The guidance for flood risk assessments (EA 2016b) sets out which allowances should be used to assess the impact of climate change on flood risk according to the current flood zone and flood risk vulnerability classification of the proposed development. The assessment should be used to identify appropriate adaptations to ensure that the development meets planning policy in the National Planning Policy Framework (DCLG 2012) to be safe from flooding for its lifetime and not increase flood risk elsewhere. The fluvial flood zones considered are 2 (land having between a 1 in 100 and 1 in 1000 annual probability of river flooding), 3a (land having a 1 in 100 or greater annual probability of river flooding) and 3b (the functional floodplain), and the flood risk vulnerability classifications are ‘essential infrastructure’, ‘highly vulnerable’, ‘more vulnerable’, ‘less vulnerable’ and ‘water compatible’ (DCLG 2014). For example, for a Flood Risk Assessment (FRA) for ‘essential infrastructure’ planned in flood zone 3a, the guidance says to assess the Upper allowance, whereas for ‘more vulnerable’ development planned in flood zone 2 the guidance says to assess the Central and Higher Central allowances.

Nationally Significant Infrastructure Projects (NSIPs) defined in the Planning Act 2008 (as amended) (UK Government 2008) have to meet more specific policy requirements set out in a series of National Policy Statements (NPSs), including policies to ensure the infrastructure is resilient to future flood risk (and other climate and weather risks) due to climate change. NPSs have been produced, or are being produced, for NSIPs falling under energy, transport (including national networks, ports and airports), and water supply, waste water and hazardous waste (e.g. DECC 2011; DfT 2014). These NPSs include similar policies for taking account of the potential impacts of climate change, which can be summarised as:

- Apply, as a minimum, the emissions scenario that the UK’s Committee on Climate Change suggests the world is currently most closely following – and the 10%, 50% and 90% estimate ranges.
- Apply the high emissions scenario to safety critical elements of the infrastructure project. Some NPSs specify that the 50th percentile of the high emissions scenario should be applied in these cases.
- Be confident that there are not features of the design of the infrastructure project critical to its operation which may be seriously affected by more radical changes to the climate beyond that projected in the latest set of UK

climate projections, taking account of the latest credible scientific evidence, and that necessary action can be taken to ensure the operation of the infrastructure over its estimated lifetime. This policy requires consideration of the H++ scenarios.

V Discussion and conclusions

The provision of climate change allowances helps decision makers take account of climate change on future flood risk; without the allowances it would be extremely difficult for decision makers to do this for the large majority of developments. Despite the limitations of the original national 20% sensitivity allowance, it demonstrated very early uptake of climate change impact science by a key sector in the UK, recognising the potential impacts and providing adaptation advice for the relevant stakeholders and decision-makers. While now considered overly simplistic, the 20% allowance was relatively successful in achieving incorporation of climate change impacts into operational planning (Kuklicke and Demeritt 2016). More recent research has significantly improved understanding of the impact of climate change on flood peaks in England, so the new regional allowances are far more representative. These allowances have been available for decision makers since 2011 and were embedded in planning guidance in 2016. However, moving from a single national allowance (20%) to a range of allowances by river basin region has presented practical challenges. A practical issue is that the EA have floodplain modelling that includes the national 20% allowance for climate change for large parts of the country, which could be provided to decision makers. Such modelling is not yet available for the new climate change allowances, so developers and local planning authorities have to produce new modelling to understand how climate change allowances will affect floodplain extent and flood depths.

The provision of a range of allowances presents difficulties for decision-makers in terms of deciding the appropriate level of risk to adopt in flood design. Thus methods are needed for decision-making with uncertainty (Hall et al. 2012), with adaptation decisions being robust in the face of a range of possible future climates, rather than 'best' under a single future climate (Hallegatte 2009; Wilby and Dessai 2010). Hall et al. (2012) discuss various difficulties inherent in deciding the appropriate level of adaptation given current uncertainty, but state that these should not be obstacles to action and that "the decision-makers' toolkit needs to be equipped with a greater diversity of instruments, and their skills in deploying them need to be honed". One strategy for robust decisions is to implement plans progressively; a managed adaptive approach (Walker et al. 2013; Wilby and Keenan 2012). The timing and sequencing of actions in managed adaptive approaches is a key challenge, but regular evaluation and monitoring enable adjustments in response to emerging information on future risks.

Future work would refine (and ideally reduce the range of) the allowances. One issue is that the allowances are provided for each river-basin region, but the impact of climate change will inevitably vary between catchments within a region (sometimes significantly, depending on the response type of individual catchments relative to the dominance of alternative types within a region). Therefore in applying an average for a region there is a risk of over- or under-adaptation. The focus on regional allowances was partly necessitated by the fact that there is considerable uncertainty in the application of the decision trees and they are not readily applicable to ungauged catchments (Kay et al. 2014a), thus it was not considered appropriate to provide guidance that required estimation of the response type for a given location. A new project will take advantage of a new national-scale gridded hydrological model that can operate at a range of resolutions (Crooks et al. 2014). Applying the sensitivity-based approach with this model will thus provide modelled response surfaces for every river-point on the grid across Great Britain, which can be directly overlaid with climate change projections to estimate impact ranges for each location. In this way, a number of steps are removed from the existing approach (i.e. using decision trees to estimate response type and average response surfaces for each type), thus removing these additional sources of uncertainty. Note though that a number of other potential sources of uncertainty are not currently accounted for, including hydrological model structure and parameterisation.

However, the main cause of the wide range of allowances is the climate projections, and decision makers need to bear in mind that even probabilistic projections could underestimate total climate uncertainty and lead to sub-optimal decisions if applied too strictly (Hall 2006). Climate modelling uncertainty is potentially reducible (Deser et al. 2012), for example through improved process representation, but it is also possible that inclusion of new processes, or refinement of existing ones, could lead to greater uncertainty (Maslin and Austin 2012, Murphy et al. 2009 Section 2.5). Despite this, improved understanding of the controls on regional climate and on land-atmosphere feedbacks can only be an advantage (Wilby and Dessai 2010), as is the identification and understanding of sources of uncertainty in climate and impact models (Hallegatte 2009). A project is currently underway to upgrade the UKCP09 projections (UKCP18; Met Office 2016). When the updated probabilistic projections become available it will be necessary to investigate what they mean for changes in flood peaks; the use of the response surface approach should make this investigation relatively quick and easy to achieve. It will then be necessary to assess whether the guidance for flood management authorities and flood risk assessments also needs updating.

UKCP18 will also produce a set of very high resolution (<5km) RCM runs, designed to provide improved simulation of extreme weather events like convective summer storms. Recent research has shown that very high resolution (1.5km) RCM data, used to drive a gridded hydrological model, tends to project greater increases in flood peaks than use of equivalent 12km RCM data (Kay et al. 2015). However, more research is needed to investigate the robustness of this result, especially as the 1.5km RCM performed worse than the 12km RCM (driven by reanalysis boundary conditions) when data were used for modelling baseline flows. Research using the same RCM data has also shown increases in the intensity of heavy summer precipitation in the 1.5km RCM that are not seen in the 12km RCM (Kendon et al. 2014). Thus the very high resolution RCM runs from UKCP18 may provide better information about potential changes in intense rainfall, relevant for assessing impacts on surface water (pluvial) flood risk as well as river (fluvial) flood risk, and so could contribute to updated guidance on flooding and climate change. More information on how future changes in rainfall could develop (e.g. changes varying with intensity) may also suggest refinements to the two dimensions used to characterise rainfall changes in the sensitivity-based approach, as the sensitivity domain is necessarily a simplification of the temporal patterns of change (Kay et al. 2014c).

While the guidance discussed here, and the hydrological modelling and climate projections behind it, are specific to Britain, a similar approach could be developed and applied to flood risk management elsewhere. Although different countries adopt a range of different policies for flood risk management and the balance between structural and non-structural protection measures (Kreibich et al. 2015), most adaptation measures would benefit from improved understanding of the range of potential impacts of climate change on flood peaks, extents and depths. A similar approach could also be taken for other sectors affected by climate change, like drought management (Prudhomme et al. 2015). Whereas some factors determining the impacts of climate change will certainly differ between countries and between sectors, there are common factors, like the need to deal with uncertainty in climate change projections, thus there are likely to be useful lessons and techniques to be learnt from alternative studies.

A particular difficulty for adaptation is distilling the complexities of the science (including uncertainty) into information more directly usable by decision-makers, to enable fuller use of the available information. There are tensions between the scientific drive to highlight uncertainties and an institutional need for clear answers (Kuklicke and Demeritt 2016, Tang and Dessai 2012). Stephens et al. (2012) suggest that effective communication is a matter of getting the right balance between saliency, richness and robustness for different audiences. From a study of the use of climate projections for local adaptation planning, Lorenz et al. (2016) conclude that national-level steering is important and that guidelines on incorporation of climate projections within current planning processes should be provided, rather than requiring each local authority or planner to have independent capacity to integrate complex climate change projections themselves. Porter et al. (2015) show that investment to improve the quality and accessibility of climate information has developed the adaptive capacity of local authorities in Britain since 2003, but state that there are still barriers to adaptation. For adaptation to succeed, both the science of projecting climate change impacts, and the institutional capacity to respond to those projections, need to develop further.

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