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LETTER

An assessment of the potential for natural flood management to offset climate change impacts

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Abstract
Natural Flood Management (NFM) aims to work with natural processes to reduce flood risk, and can potentially contribute to integrated flood risk management (alongside engineering solutions) by providing landscape-based resilience to climate change impacts. Here, two approaches are used to assess the extent to which NFM could offset the impacts of climate change on floods in Great Britain. The first looks at specific catchments where there is quantitative evidence for the effect of NFM measures on peak flows. The second takes a broad-brush national view, assuming two potential levels of NFM reductions in peak flows. Both approaches use flood impacts derived from climate change projections for a range of future time-slices and emissions scenarios. The results show that NFM measures are much less likely to be able to offset the impacts of climate change for later time-slices and for higher emissions scenarios, but also that the chance of offsetting the impacts of climate change in any individual catchment will depend on its type (how sensitive it is to climatic changes) and its location (due to spatial variation in climatic changes). Confounding factors in the analysis include any time lag associated with the NFM reduction in peak flows, and different effects of NFM on peak flows of different return periods. It is also unclear whether there is any relationship between a catchment's type and its practical potential for implementing NFM, or the level of peak flow reduction that NFM could achieve; any such relationship could be critical in determining the overall potential for NFM to offset climate change impacts in different catchments. Although the focus here is Great Britain, a similar approach could be applied internationally.

1. Introduction

The ambition of Natural Flood Management (NFM) is to work with natural processes to reduce the risk of flooding, while simultaneously restoring or enhancing aspects of the natural environment (Lane 2017). NFM measures operate across a range of scales and cover a multitude of land- and river/floodplain-based approaches, including: increasing infiltration (e.g. innovative soil management practices), slowing the flow (e.g. instream log jams), and enhancing water storage (e.g. floodplain restoration and pond creation) (Dadson *et al* 2017, Lane 2017). Application of NFM is part of policy in the UK (SEPA 2015, Cabinet Office and Defra 2016), attracting significant government investment (ca 15 million by Defra in 2016). NFM is well aligned with the current focus of flood risk management in the UK (EA 2017), which looks at the catchment scale, adopts both non-structural measures (including NFM) and structural measures (e.g. traditional flood defences) and engages stakeholders to identify optimal solutions.

In the UK, flood risk management takes a long-term strategic view, which includes assessing the potential impacts of climate change. For example, the Environment Agency in England has published their long-term investment scenarios study (LTIS; EA 2014), which provides an economic assessment of future flood and coastal erosion risk management for 2015–2065. Following the widespread flooding that took place in England in June/July 2007, the UK government commissioned a review of flood defences which noted that increasing future flood risk cannot be met by building larger and larger flood defences (Pitt 2008). NFM contributes to integrated flood risk management by providing landscape-based resilience to climate or land-management changes instead of, or alongside, engineering solutions. By engaging and empowering local stakeholders, NFM plays an important role in delivering Defra's 25-year environment plan (England 2018), and in meeting the priorities of the Well-being of Future Generations (Wales 2015) Act, and it is likely to be a key approach to delivering post-brexit agri-environment schemes.

Although there is growing public and stakeholder interest in NFM, there is a lack of consistent evidence for its efficacy, and quantitative prediction of downstream reductions are uncertain especially in large catchments and for large floods (Dadson *et al* 2017). Without improvement in our understanding of either benefits or potential limitations, progress in the use of NFM will continue to be constrained and potentially ineffective (Dixon *et al* 2016). However, should NFM prove effective in reducing flood risk it may usefully contribute to integrated flood risk management by future-proofing flood risk solutions, providing resilience to climate change.

Two approaches are used here to assess the extent to which NFM can offset the impacts of climate change. The first approach looks at specific catchments for which there is quantitative evidence of the effect of NFM measures on peak flows. The second approach takes a broad-brush national view, assuming two potential levels of NFM reductions in peak flows to assess differences in the extent to which these might offset climate change in different types of catchment, in different parts of the country. Both approaches use flood impacts derived from climate change projections for a range of future time-slices and emissions scenarios. The data and methods are described in section 2, with results in section 3, and discussion and conclusions in sections 4 and 5 respectively.

2. Data and methods

This section presents a review of evidence of the effect of NFM measures on peak flows in British catchments (section 2.1), and describes the source of data on the potential impacts of climate change on flood peaks (section 2.2). Then the methods for assessing the potential for NFM to offset climate change impacts are presented, for both the catchment-based and national-scale analyses (section 2.3).

2.1. Effect of NFM measures

The potential effect of NFM was considered by reviewing current evidence and collating key contextual information. The Environment Agency's NFM Evidence Base was the primary source of evidence (EA 2017). A table was assembled (supplementary section 1.1 is available online at stacks.iop.org/ERL/14/044017/mmedia) including the following fields:

- Source of evidence*
- NFM construction date
- Location*
- Catchment characteristics*
- NFM type*
- NFM details
- NFM size
- Effect on soil water retention and runoff
- Effect on flooding*
- Seasonal effect
- Magnitude of flood affected
- Effect lag
- Effect on sediment transport
- Wider benefits
- Whether modelled or observed*
- References

A subset of this information is provided in supplementary table S1 (only for the starred* fields and catchments in Great Britain), and figure 1 presents maps summarising supplementary table S1 by effect on peak flows, and by whether the results were from observed or modelled data. Information for many of the above fields in combination is important in supporting an assessment of NFM effectiveness. For instance, the effect of NFM on a flood peak must be considered with respect to the flood magnitude and catchment size.

Over 40 quantitative studies are available (from the UK and elsewhere), but more than 75% are based on model results, and most relate to small catchments; ~55% are smaller than 50 km^2 and over 70% are smaller than 100 km^2. Also, more than a third of studies report the effect of combinations of NFM measures, and although the exact positions and spatial extent/magnitude of NFM interventions in an upstream catchment may be very important they were not captured. No attempt has been made to check the quality of the evidence reported.

While important information has been collated, it was a challenging exercise as diverse information (with varying levels of detail) is reported by authors. For instance flood magnitude is not always presented as a standardised metric such as return period, but in depths of rainfall, largest in a given month or qualitatively as a 'large' or 'small' events. The study locations which do have quantitative evidence of the effect of NFM measures on reducing peak flows have been used in the catchment-

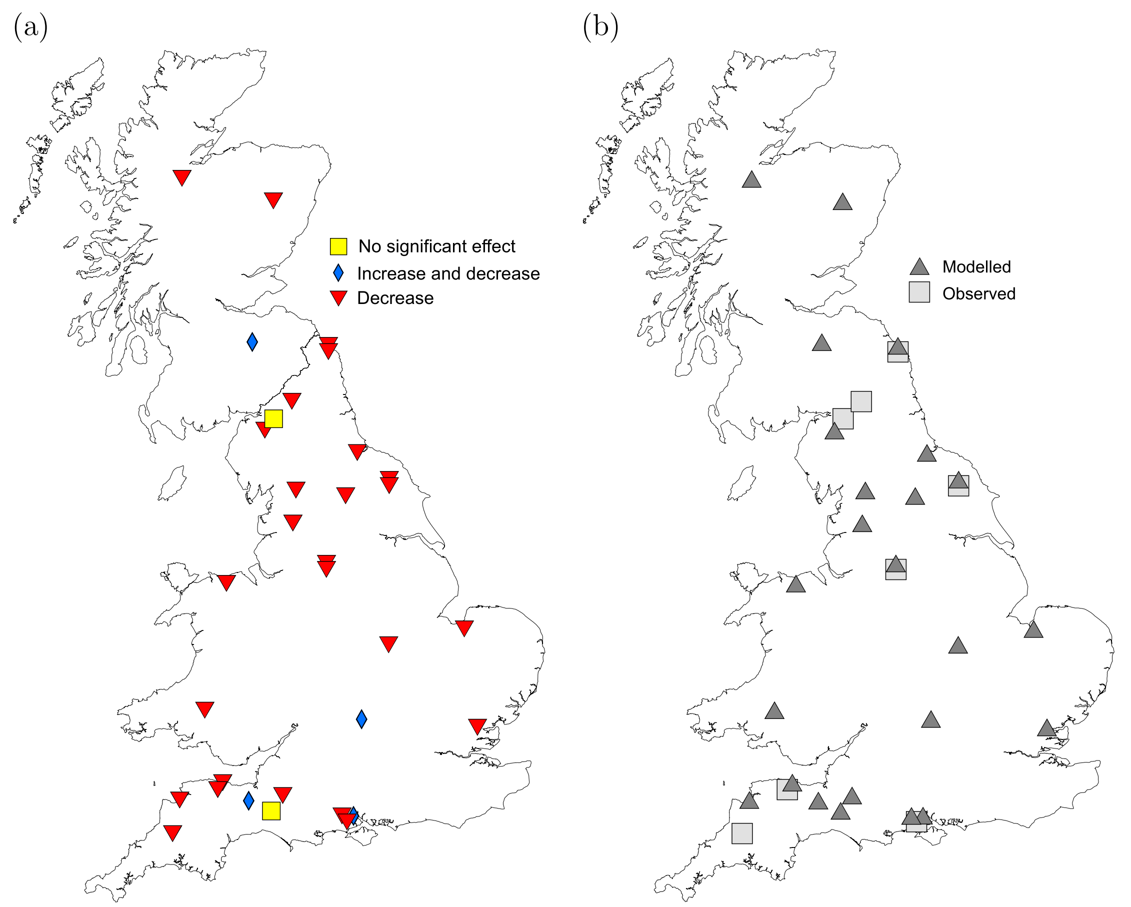

Figure 1. Maps summarising the studies listed in supplementary table S1 by (a) the effect they showed on peak flows and (b) whether they were based on observed or modelled data.

based assessment of the extent to which NFM can offset the impacts of climate change (section 2.3).

2.2. Impacts of climate change on flood peaks

Agencies across the UK have been providing guidance on the impacts of climate change on flooding for many years, refining the guidance as the science of climate change and hydrological impacts has developed (Reynard *et al* 2017). The latest guidance (EA 2016a, 2016b, SEPA 2016, Welsh Government 2016) was based on research which developed a sensitivity-based approach to climate change impacts, by looking at changes in peak flows corresponding to a set of prescribed changes in climatic inputs (precipitation, temperature and potential evaporation) (Prudhomme *et al* 2010). The advantage of such an approach to climate change is that the resulting response surfaces can be readily combined with sets of climate change projections, to rapidly estimate the potential range of impacts on peak flows. The ease of application of this sensitivity-based approach (described briefly below, with more detail in supplementary section 1.2) makes it ideal for use here.

The sensitivity-based approach identified nine 'flood response types'—Damped-Extreme, Damped-High, Damped-Low, Neutral, Mixed, Enhanced-Low, Enhanced-Medium, Enhanced-High, Sensitive (Prudhomme *et al* 2013a)—each associated with representative (average) 'flood response surfaces' illustrating the sensitivity of flood peaks (of given return periods) to climatic changes (supplementary figure S1). The Neutral response type shows peak flow changes similar to the precipitation changes, while Damped types show flow changes generally smaller than the precipitation changes, and Enhanced types show flow changes that are often larger than the precipitation changes. Flow changes for the Mixed and Sensitive types are more dependent on the specific seasonality and magnitude of precipitation changes.

The representative flood response surfaces were then combined with the UKCP09 probabilistic climate change projections for river-basin regions (Murphy *et al* 2009). These consist of 10 000 equally likely sets of monthly changes in climatic variables, and include data for 19 river-basin regions covering the majority of GB—North Highland, West Highland, North-East Scotland, Argyll, Tay, Clyde, Forth, Solway, Tweed, North-West England, Northumbria, Dee, Humber, West Wales, Anglian, Severn, Thames, South-East England, South-West England. The projections for various combinations of future time-slice and emissions scenario (2020s Medium, 2050s Medium, and 2080s Low, Medium and

Table 1. NRFA gauging stations identified close to a number of locations with quantitative evidence of the effect of NFM measures on reducing peak flows, along with their estimated flood response types and the river-basin region they are located within.

ID[a]	NRFA station number	River@location	Area (km^2)	Estimated flood response type	River-basin region	Notes
1b_ED	42 003	Lymington@Brockenhurst	99	Mixed	SE England	Gauge north of Lymington
12_ED	27 056	Pickering Beck@Ings Bridge	68	Mixed	Humber	Gauge short distance downstream of Pickering
24a_ED	76 011	Coal Burn@Coalburn	1.5	Neutral	Solway	Gauge at site
5_LR	39 021	Cherwell@Enslow Mill	551	Enhanced	Thames	Gauge downstream of study site
10_LR	71 015	Dunsop@Footholme Flume	25	Neutral	NW England	Gauge at site
12b_LR	27 059	Laver@Ripon	87	Enhanced	Humber	Gauge at furthest downstream point of river
14_LR	06 008	Enrick@Mill of Tore	106	Neutral	North Highland	Gauge near site

[a] From supplementary table S1.

High), were processed and overlaid on the representative flood response surfaces, and corresponding sets of flood impacts extracted (Kay *et al* 2014a, 2014b). Here the impacts on 50 year return period flood peaks are used, as the current Environment Agency guidance on climate change and flood peaks is based on these values (Reynard *et al* 2017).

In addition, decision trees were derived to enable estimation of the flood response type of a catchment from its physical catchment properties (e.g. average annual rainfall and permeability; Prudhomme *et al* 2013b). These decision trees were applied to each catchment in the National River Flow Archive (NRFA; nrfa.ceh.ac.uk), to provide information on the spatial distribution of flood response types across Britain (Kay *et al* 2014a, 2014b; supplementary figure S2). Extra uncertainty allowances were also derived for each response type (Kay *et al* 2014c). These enable correction of mean bias when extracting impacts from the response surfaces, which is necessary due to the assumptions and simplifications required for the sensitivity-based approach.

2.3. Assessing the potential for NFM to offset climate change impacts

The catchment-based analysis uses the available quantitative information (section 2.1). Locations are selected (from supplementary table S1) which have quantitative evidence of the effect of NFM measures on reducing peak flows, and for which a nearby NRFA gauging station can be identified (table 1 and figure 2). For each of the NRFA stations, the catchment's estimated flood response type is obtained (section 2.2), along with the UKCP09 river-basin region within which it is located (table 1).

For each catchment in table 1, the impacts of climate change on 50 year return period peak flows are estimated as explained in section 2.2, by selecting the sets of impacts for the appropriate flood response type and river-basin region (including use of the extra uncertainty allowances). The potential for NFM to offset the impacts of climate change is then assessed, by finding the percentage of the 10 000 UKCP09 projections which give impacts less than the potential NFM reduction in peak flows (e.g. if NFM could reduce peak flows by 10%, the percentage of UKCP09 projections which produce a change in 50 year return period peak flows of +10% or less is selected). This is done for each combination of future time-slice and emissions scenario. An example of reading the percentage of projections from the cumulative distribution of peak flow impacts is shown in figure 3. The results are presented in section 3.1.

To extend the catchment-based results to the national scale, two levels of NFM reductions in peak flows are selected (section 3.2). Each of these levels is applied in turn, to calculate (for each river-basin region, each flood response type, and each combination of future time-slice and emissions scenario) the percentage of the UKCP09 projections which give impacts less than the potential level of reduction in peak flows from NFM. The results are presented in section 3.2.

3. Results

3.1. Catchment-based

The potential for NFM measures to offset climate change impacts on peak flows for each catchment (table 1) are given in table 2, alongside the quantitative information on the potential reduction in peak flows from NFM (supplementary table S1). Note that two sets of results are given for catchment 42 003, where data are available for two separate NFM scenarios.

Table 2 shows significant variation between catchments, due both to the variation in the NFM peak flow reduction itself, and variation in the impacts of climate change (by both flood response type and spatial location). However, NFM measures are less likely to be able to offset the impacts of climate change for later time-slices and for higher emissions scenarios; in only

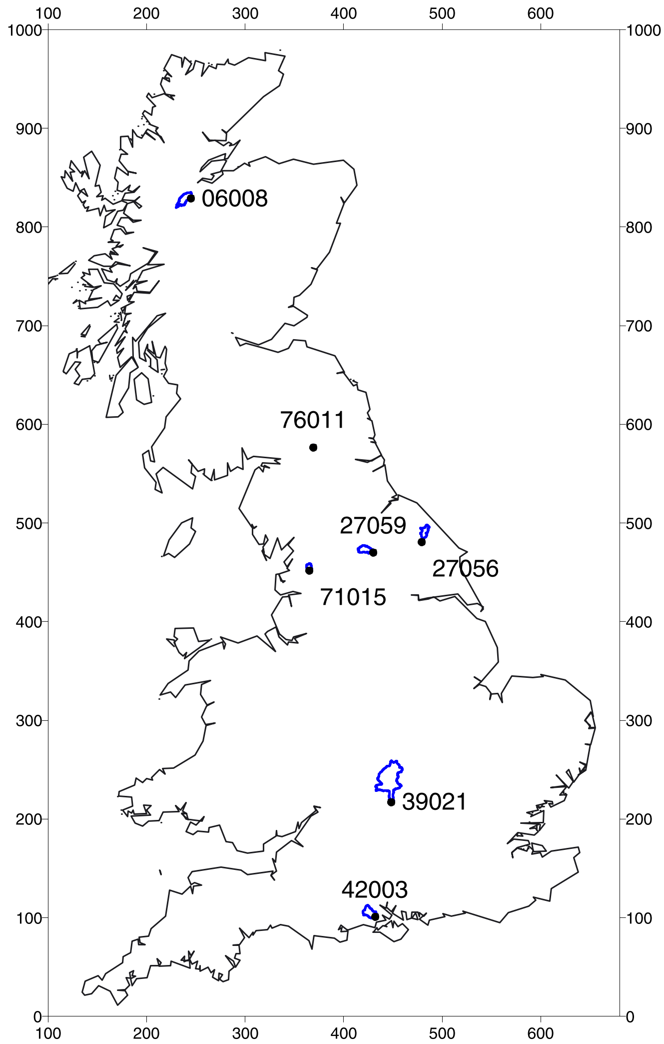

Figure 2. The NRFA catchments corresponding to locations which have quantitative evidence of the effect of NFM measures on reducing peak flows (table 1). The outer box shows the GB national grid coordinates (km).

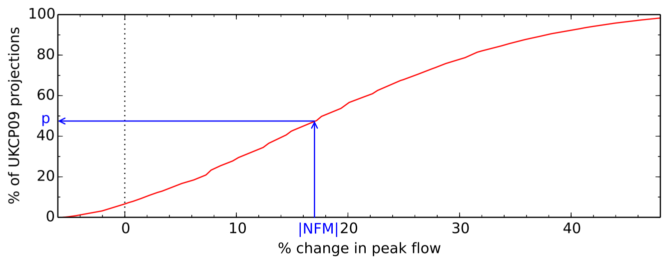

Figure 3. Example cumulative distribution function of the percentage change in peak flows from UKCP09 probabilistic projections (red curve), showing how to read off the percentage of the projections, p, which give impacts less than or equal to the potential NFM reduction in peak flows |NFM| (blue arrows).

one catchment (27 056) could NFM succeed in offsetting more than 50% of the possible range of impacts from UKCP09 probabilistic projections for the 2080s time-slice under the High or Medium emissions scenarios.

It should be noted that there is varied information on the return period of peak flows for which the stated reduction from NFM applies, and in some cases this is not available at all. In each case the results of the climate change assessment in table 2 assume that the stated NFM reduction applies for 50 year return period peak flows, but the results may be misleading if the reduction only applies to much lower return periods (as could be the case for catchment 39 021 for example) or indeed if it applies at much higher return periods (as for catchment 06 008). In the latter case, if a

Table 2. The potential for NFM to offset climate change impacts on peak flows in selected catchments. Catchments and time-slices/emissions scenarios where there is less than a 50% chance of NFM measures offsetting climate change impacts are highlighted in bold. Note that, for some catchments, information is not available on the return period corresponding to the NFM reduction in flood peaks, but in each case the climate change assessment assumes that the NFM reduction applies for 50 year return period peak flows.

			Percentage of UKCP09 projections giving impacts $<$ |NFM peak flow reduction|				
NRFA station number	Potential NFM peak flow reduction (% decrease)[a]	Return period of potential NFM peak flow reduction (years)[a]	2020s Medium	2050s Medium	2080s Medium	2080s Low	2080s High
42 003	6	100	**32**	**18**	**11**	**12**	**8**
42 003	19	33.33	89	60	**40**	**49**	**28**
27 056	15–20	Not available	95	86	67	77	51
76 011	5–20	$<$100[b]	94	64	**44**	59	**22**
39 021	10–15	2–10	71	**42**	**26**	**34**	**15**
71 015	7	3–53	**6**	**1**	**1**	**1**	**0**
27 059	1–2	100	**43**	**22**	**12**	**13**	**6**
06 008	0.8	200	**6**	**1**	**1**	**2**	**0**

[a] From supplementary table S1 (where a range of peak flow reductions is given, the upper value was used).

[b] 0% reduction at 100 year return period.

higher reduction than 0.8% applies for 50 year return period peak flows for catchment 06 008, then the potential for NFM to offset climate change would be higher. In the former case, if a lower reduction than 15% applies for 50 year return period peak flows for catchment 39 021, then the potential for NFM to offset climate change would be lower. Similarly, for catchment 76 011 it is unclear exactly what return period the stated 20% peak flow reduction applies to, but the data source does state that the effect decreased with increasing event size and was lost at the 100 year return period, so the results assuming that the 20% reduction applies to 50 year return period peak flows may overstate the potential for NFM to offset climate change in this catchment.

3.2. National-scale

The two selected levels of NFM reductions in peak flows used for the national-scale analysis are 5% and 20%. Using information from table 1, the latter value has been applied nationally to represent a possible upper end of the potential for NFM measures to reduce peak flows, while the former represents a potentially more widely-realisable effect.

The potential for NFM to offset climate change impacts on peak flows in each river-basin region is shown in figure 4 for an NFM reduction of 5%, and in figure 5 for an NFM reduction of 20%. Each individual map presents the percentage of the UKCP09 probabilistic projections which give impacts less than or equal to the NFM reduction level, for catchments of a particular response type and for one time-slice and emissions scenario. Note that, for some response types at some time-slices/emissions scenarios, there is a non-zero percentage of UKCP09 projections which give decreases, rather than increases, in flood peaks (supplementary figure S3); these are included in figures 4 and 5, thus boosting the percentages (as can be seen in the example distribution in figure 3).

The national results echo the catchment results, in that they show that NFM measures are less likely to be able to offset the impacts of climate change for later time-slices and for higher emissions scenarios. They also clearly show how the chance of offsetting the impacts of climate change in any individual catchment will depend on its flood response type (e.g. the chance in a catchment with a 'Mixed' flood response type could be better than that in an 'Enhanced-Low' catchment). Alternatively, the national results for NFM reductions in peak flows of 5% and 20% (figures 4 and 5) could be interpreted as highlighting that much higher levels of NFM would be required to offset the impacts of climate change for later time-slices and higher emissions scenarios, particularly in some types of catchment.

4. Discussion

Several factors are not accounted for within the analyses of section 3. One of these is any time lag associated with the stated NFM reduction in peak flows. For example, for catchment 42 003 the stated 6% reduction in 100 year return period peak flows (table 2) relates to afforestation and applies 25 years post-planting (supplementary table S1). Thus the results for the 2020s time-slice may over-state the potential for NFM to offset climate change in this catchment as the 6% reduction would not have been achieved by then. Similarly, if the trees were to result in a greater decrease in flood peaks over longer periods post-planting then the results for the later time-slices may under-state the potential for NFM to offset climate change in this catchment.

For the national-scale analyses, it cannot be assumed that catchments of every response type are present in every river-basin region. Some regions, particularly those to the west and north of Britain, are dominated by the

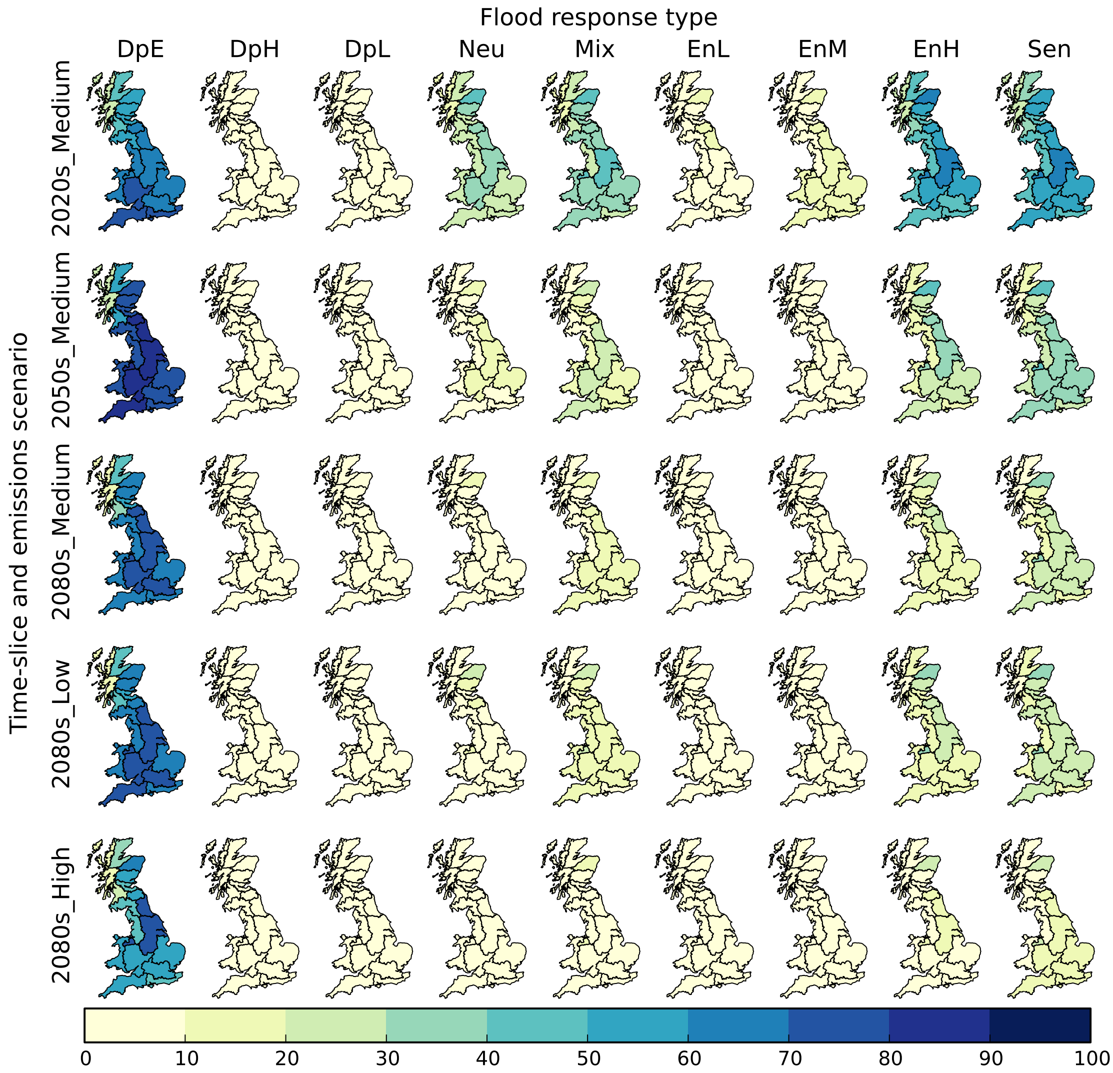

Figure 4. The percentage of the UKCP09 probabilistic projections which give impacts less than or equal to a potential NFM reduction in 50 year return period peak flows of 5%, for five combinations of future time-slice and emissions scenario (top to bottom; 2020s Medium, 2050s Medium, 2080s Medium, 2080s Low, 2080s High) and for each of the nine response types (left to right; Damped-Extreme, Damped-High, Damped-Low, Neutral, Mixed, Enhanced-Low, Enhanced-Medium, Enhanced-High, Sensitive).

Neutral response type at the 50 year return period, while other regions have more of a mix of response types, including Neutral, Mixed, Enhanced and Sensitive in the south and east of England and Neutral, Mixed and Damped in eastern Scotland (supplementary figure S2). However, this spatial distribution relies on the decision trees derived to estimate response types of NRFA catchments from catchment properties, which are not definitive as they only identify the most likely response type in each case, based on the limited set of modelled catchments (Prudhomme *et al* 2013b). Research is currently underway applying the sensitivity-based approach using a national-scale grid-based model, to provide modelled response surfaces for every river-point across Great Britain, thus avoiding the need to use decision trees to estimate a catchment's flood response type.

It is also unclear whether there is any relationship between a catchment's flood response type and its practical potential for implementing NFM measures, or the level of peak flow reduction that NFM could achieve. Any such relationship could be critical in determining the overall potential for NFM to offset climate change impacts in different catchments. The recently published National Strategic NFM Opportunity Maps (EA 2017) indicate opportunities for several types of NFM measures (floodplain reconnection, runoff attenuation features, and tree planting) and are usefully quantified against national averages. These could enable an evaluation of the NFM potential in catchments of different response types.

5. Conclusions

In the UK, NFM interventions designed to retain more water in the landscape or slow-down conveyance are still being assessed in terms of their effect on downstream flood risk. Through reviewing published evidence the complexities inherent in predicting the flood response of UK catchments to various NFM

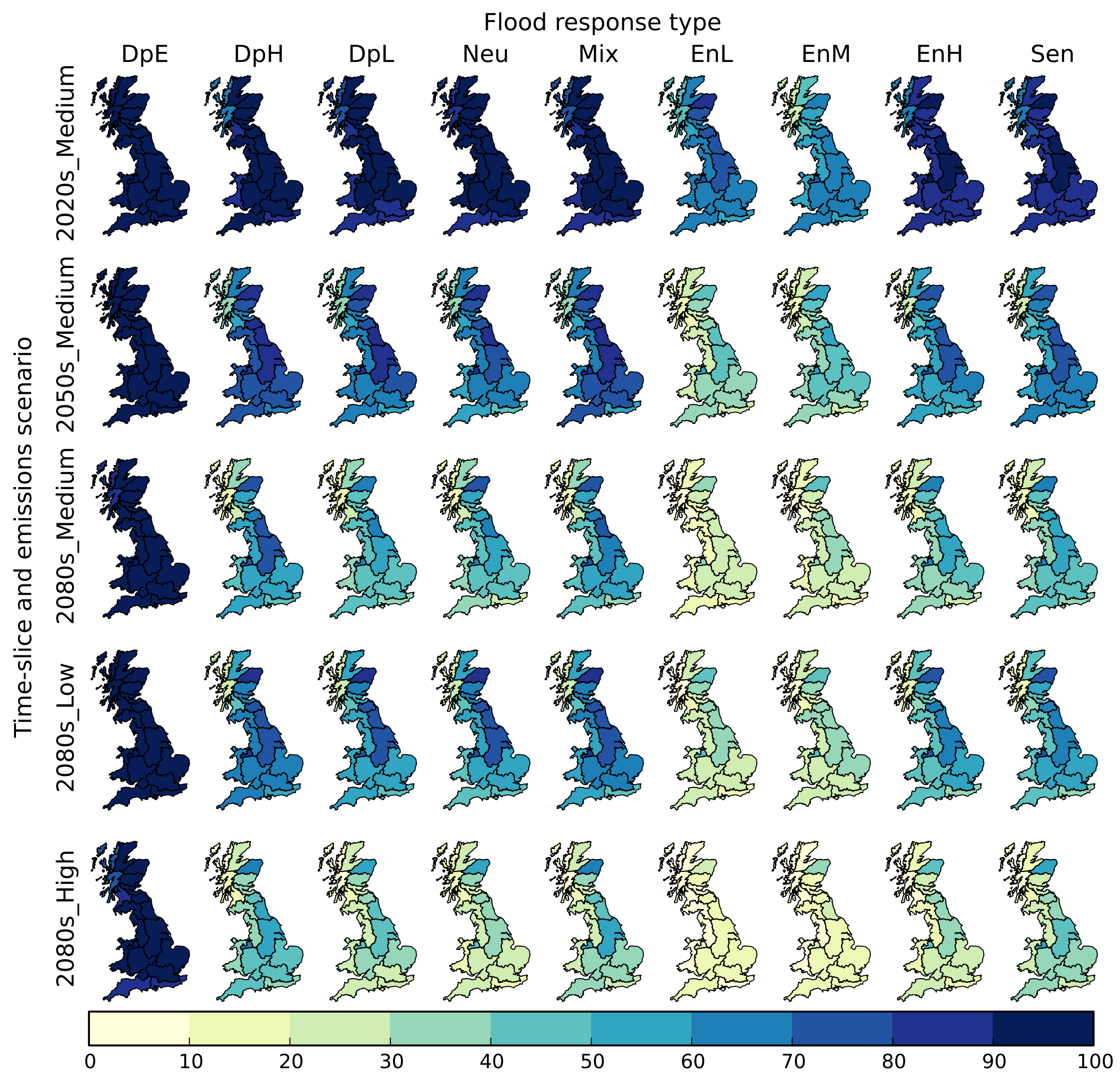

Figure 5. As figure 4, but assuming that NFM can achieve a reduction in 50 year return period peak flows of 20%.

interventions were identified. Existing evidence suggests that interventions are likely to be most effective in smaller catchments, where they may effectively hold back or slow runoff from short periods of intense rainfall. However, if rainfall is prolonged then interventions may not have sufficient capacity. Interventions are likely to be effective at larger scales only if they are applied widely across headwater catchments, however potential synchronisation of flood waves should then be taken into account (Hankin *et al* 2017).

Further research is needed to enhance the evidence base for NFM, and should focus on evaluating the effectiveness at a range of catchment scales and event magnitudes. It is also vital that contextual information is reported in a standardised way. Furthermore, most studies providing evidence for a reduction of peak flows are model-based (section 2.1); there is an urgent need for observational evidence to validate these findings. The publication of National Strategic NFM Opportunity maps now allows the practical implementation of NFM to be considered. On-the-ground implementation of NFM may also be limited by issues associated with land ownership, liabilities and challenges associated with funding. However, the wider benefits should also be considered.

Just as for planning of traditional flood defences (EA 2016a), planning of NFM interventions needs to take account of potential future changes in peak river flows as well as historical flows. The methodology presented in this paper quantifies the potential effectiveness of NFM for offsetting increases in peak river flows related to climate change, under the UKCP09 climate projections. The assumed NFM peak flow reductions used here are based on the limited available evidence and should be refined as results of current monitoring activities are delivered. The results at both catchment and national scales show significant variation between catchments. They also show that NFM measures are more likely to be able to offset the impacts of climate change for earlier time-slices and for lower emissions scenarios, although this assumes that there is no time lag associated with the NFM reduction in peak flows (contrary to what would be expected in the case of afforestation for example). For the national-scale analysis, two possible levels of reduction in peak flows by NFM (5% and 20%) are analysed for 50 year return period peak flows, but as published evidence reviews suggest that NFM is likely to be more effective at reducing peak flows of lower return periods, the chance of offsetting the impacts of climate change could be greater for lower return period peak flows (e.g. $<$10 years).

Although unlikely to be a panacea, NFM measures can play a role in mitigating flood risk and adapting to climate change, alongside traditional flood defences and other evolving measures such as property level protection. NFM planning should also consider potential effects on low flows/droughts, which are themselves expected to worsen under climate change (e.g. Kay *et al* 2018). While there are limitations to the evidence presented here, this paper presents a novel method for evaluating the potential of NFM to offset the impacts of climate change on peak flows, and when the evidence base is enhanced a more robust assessment will be possible. Although the focus here is Great Britain, a similar approach could be applied elsewhere.

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