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CLIMATE CHANGE AND RIVER FLOODING: PART 1 CLASSIFYING THE SENSITIVITY OF BRITISH CATCHMENTS

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Abstract:	Effective national and regional policy guidance on climate change adaptation relies on robust scientific evidence. This two-part series of papers develops and implements a novel scenario-neutral framework enabling an assessment of the vulnerability of flood flows in British catchments to climatic change, to underpin the development of guidance for the flood management community. In this first part, the sensitivity of the 20-year return period flood peak (RP20) to changes in precipitation (P), temperature (T) and potential evapotranspiration (PE) is systematically assessed for 154 catchments. A sensitivity domain of 4,200 scenarios is applied combining 525 and 8 sets of P and T/PE mean monthly changes, respectively, with seasonality incorporated using a single-phase harmonic function. Using the change factor method, the percentage change in RP20 associated with each scenario of the sensitivity domain is calculated, giving flood response surfaces for each catchment. Using a clustering procedure on the response surfaces, the 154 catchments are divided into nine groups: flood sensitivity types. These sensitivity types show that some catchments are (very) sensitive to changes in P but others buffer the response, while the location of catchments of the same type does not show any strong geographical pattern. These results reflect the range of hydrological processes found in Britain, and demonstrate the potential importance of catchment properties (physical and climatic) in the propagation of change in climate to change in floods, and so in characterising the sensitivity types (covered in the companion paper).
Response to Reviewers:	We have edited the text in the introduction as requested by the editor.

Response to reviewers comments on "CLIMATE CHANGE AND RIVER FLOODING: PART 1 CLASSIFYING THE SENSITIVITY OF BRITISH CATCHMENTS"

We would like to thank the editor and Reviewer for helpful comments. Our response to these comments is provided below.

Editor:
The manuscript requires only minor revisions at this point. Please consider the comments of the one reviewer (below) and also the reviews and comments on the second manuscript in preparing the revisions to this manuscript. In particular, we recommend incorporating a clear explanation of why higher-frequency variability has been ignored (very clear in the response to reviews) in this manuscript, and referring readers of the second manuscript to the explanation in this manuscript. In addition, please either change the acronyms FST, FRS and FSF used in both manuscripts (issue raised by a reviewer of the second manuscript) or do not use them at all. It is unfortunate, but the letters are too similar and make the manuscripts difficult to follow. See Reviewer #2's comments on manuscript 2. Other specific editing suggestions are made below.

A paragraph has been added at the end of this paper, explaining why the sensitivity framework has been set-up and implemented as it has (e.g. not including changes in higher-frequency variability), and that future work will investigate enhancements to the method. We hope this is sufficient - we will refer to it from Paper 2. The acronyms FRS, FST and FSF have been removed, with the terms 'response surface', 'sensitivity type' and 'sensitivity family' used instead.

Reviewer #3:
General
I would like to thank the authors for the revision of the paper and the response to my comments. The paper is now almost suitable for publication in Climatic Change. Some minor comments on the response of the authors are given below and need to be addressed by the authors.

20. It is still not clear to me how the goodness-of-fit of the generalised pareto distribution for the peak-over-threshold series has been tested and what the results were.

The method of fitting a GPD to POT data is the standard method recommended in the UK. Further details of fitting flood frequency curves to the POT series for observed river flows and flows simulated using historic climate data are given in Crooks et al (2009); see Section 2.1, where text on model calibration and performance has been edited.

31. This is an example where it is not really satisfying for a reader to see that the explanation is given in another (although companion) paper.

Some text has been added; also see response to 32 below.

32. I would like to advise the editor to remove this part and leave some more space for e.g. explanation of relationships between catchment characteristics and FSTs.

The summary has been reduced slightly, but we feel it is useful to the reader to have some element of summary here, to act as a reminder of key points, help put results in context, and set the scene for the companion paper. We feel it would be premature to add much more explanation of relationships between catchment properties and sensitivity types here, as that is the focus of the following paper (This aspect has been made clearer).

33. This outlook to future work can be included in the discussion/ conclusions.
OK, this outlook has been added.

Editor's specific comments:
Pg 4, ln 50-3 Problems with the references. Please check for this issue throughout the manuscript

pg 7, ln 27-30 "not attempt" - "no attempt"?
OK

pg 11, ln 45 It would help to add a short phrase describing why people use Taylor diagrams
A phrase has been added.

pg 11, ln 51-55 The key finding is the internal variability being smaller than the external variability. We'd prefer not to put phrases in italics, so try to reword these sentences to stress the key points without relying on the italics.
OK; see response below.

pg 12, ln 1-13 This (and the previous) paragraph are very dense with acronyms and jargons and the key points will be lost on most readers. Consider trying to rewrite. The next paragraph (Section 3.4) is similar yet much easier to follow.
The two paragraphs in Section 3.3b have been edited, and are hopefully more readable now.

pg 12, ln 38-42 "As it is..." sentence is awkward and contains some typos
This sentence has been deleted.

pg 12, ln 51-54 "In winter"... this point is not entirely intuitive. Why couldn't a sharp spike in P generate a flood, given that PE is low?
This sentence has been rewritten, and the meaning is hopefully clearer now.

Check the manuscript for typos; there are several incidences of capitalized plurals (S not s) and additional punctuation.
OK

CLIMATE CHANGE AND RIVER FLOODING: PART 1 CLASSIFYING THE SENSITIVITY OF BRITISH CATCHMENTS

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Short title: Sensitivity of British flood flows to climate change

Revised for Climatic Change, February 2013

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Abstract

Effective national and regional policy guidance on climate change adaptation relies on robust scientific evidence. This two-part series of papers develops and implements a novel scenario-neutral framework enabling an assessment of the vulnerability of flood flows in British catchments to climatic change, to underpin the development of guidance for the flood management community. In this first part, the sensitivity of the 20-year return period flood peak (RP20) to changes in precipitation (P), temperature (T) and potential evapotranspiration (PE) is systematically assessed for 154 catchments. A sensitivity domain of 4,200 scenarios is applied combining 525 and 8 sets of P and T/PE mean monthly changes, respectively, with seasonality incorporated using a single-phase harmonic function. Using the change factor method, the percentage change in RP20 associated with each scenario of the sensitivity domain is calculated, giving flood response surfaces for each catchment. Using a clustering procedure on the response surfaces, the 154 catchments are divided into nine groups: flood sensitivity types. These sensitivity types show that some catchments are (very) sensitive to changes in P but others buffer the response, while the location of catchments of the same type does not show any strong geographical pattern. These results reflect the range of hydrological processes found in Britain, and demonstrate the potential importance of catchment properties (physical and climatic) in the propagation of change in climate to change in floods, and so in characterising the sensitivity types (covered in the companion paper).

Keywords

Flood risk; climate-runoff sensitivity analysis; climate change factors; seasonality; response surface; climate elasticity of streamflow

1. Introduction

With a growing scientific consensus on global warming (IPCC, 2007a, b), national and local authorities have started to account for possible climate change impacts in their policy planning. In England and Wales, flood management appraisal guidance has been issued by the UK Government's Department for Environment Food and Rural Affairs (Defra). Until recently this required all flood management plans to include, within a sensitivity analysis, an increase of up to 20% in peak river flows over the next 50 to 100 years for any catchment, making no allowance for regional variation in climate change or catchment properties (see http://www.defra.gov.uk/environ/fcd/pubs/pagn/climatechangeupdate.pdf).

Typically, the science basis for flood risk policy has been dominated by conventional "top-down" (scenario-led) approaches (Figure 1, left). Such impact and adaptation assessments for climate change involve three steps (Prudhomme et al., 2010): (i) scenarios describing future climate are derived from Global Climate Models (GCMs); (ii) these scenarios are input to impact models to provide estimates of future consequences; (iii) adaptation responses are invoked to mitigate risks or realise benefits. Difficulties in accessing multi-model projections and an inability of some users to increase computing load often result in climate change impact assessments being made for a limited number of sites based on a limited number of global or regional climate models (RCMs).

Such scenario-led approaches have a number of limitations:

(i) By definition, scenarios are subsets of all possible outcomes (Pielke and Bravo de Guenni, 2004): one GCM/RCM output only provides a single representation of a future large-scale climate;

(ii) GCM/RCMs may not adequately represent the regional and local climate, particularly the characteristics of extremes (e.g. Frei et al., 2006);

(iii) Results from multi-scenario analyses provide an indication of uncertainty through a range of potential future changes, but generally have no associated probabilities and therefore make risk-based decision-making and policy development difficult;

(iv) Streamflow response to climate variability and change is non-linear (Mosley and McKerchar, 1992) and there may be tipping points resulting in significant flow changes that fall outside the future climate represented by GCM/RCMs;

(v) The dynamics by which climate and catchments interact are complex with response of river flow to change in precipitation conditioned by catchment properties (Fu et al., 2007) and influenced by changes in rainfall intensity, frequency, seasonality and total, as well as evapotranspiration, soil moisture and temperature (Mosley and McKerchar, 1992). A single set of GCM/RCM outputs may not increase our understanding of how these variables interact.

In the last few years, a new scenario-neutral paradigm in climate change impact analysis has emerged (Figure 1, right) where sensitivity to the entire spectrum of environmental threats, including climate change, is first assessed before the future likelihood of such scenarios is tested. This approach combines:

1. *Sensitivity*: the degree to which a system is affected by changes in certain variables (e.g. by changes in climate);
2. *Exposure*: the projected change in variables that could affect the system (e.g. the climate change scenarios); and
3. *Adaptive capacity*: the ability of a system to adapt to changes (Lindner et al., 2010).

Figure 1. (place holder)

Mastrandrea et al. (2010) suggests that combining 'top-down' approaches with 'bottom-up' analyses (e.g. identifying impact thresholds) is necessary to bridge the gap between climate-impact research and adaptation policies. Moreover, integrating knowledge on sensitivity and exposure from probabilistic projections (e.g. UKCP09. Jenkins et al., 2009) results in a probabilistic assessment of impacts, addressing one of the main weaknesses of sensitivity analyses identified by Wilby et al. (2009). Once the framework is in place, risk assessments can be performed and adaptation strategies evaluated (e.g. Sharma and Bharat, 2009).

Sensitivity testing of water resources based on mean annual changes in climate has been reported by Fu et al. (2007) and Yu et al. (2010) while Bastola et al. (2011) and Weiß (2011) included seasonal changes but most considered few catchments and/or scenarios. In contrast, and for the first time a scenario-neutral framework has been applied here to many catchments and typical catchment responses to climatic changes identified and characterised, so that vulnerability to climate change can be readily assessed, even for ungauged catchments. Two research questions are addressed:

- Does the sensitivity of flood flows to climate change vary across Britain? (this paper)
- Does the sensitivity of flood flows to climate change depend on catchment properties? (Prudhomme et al., submitted)

This paper implements the sensitivity framework of Prudhomme et al. (2010) to generate flood response surfaces to climatic change for 154 catchments across Britain. The analysis is shown here for changes in the magnitude of the 1 in 20-year flood peak (or 20-year return period flood peak, RP20 hereafter), as this is typically used for flood risk policy, but the framework has also been applied to other flood frequencies, RP2 and RP10, which showed similar response surfaces (Reynard et al., 2009). Note that changes in daily precipitation patterns are not included mainly due to the lack of skill in modelling daily precipitation fields by GCMs at the time of the analysis. Thus the results only reflect the implications of changes in monthly precipitation on the calculated flood peaks and not any changes in the intensity and frequency of daily precipitation extremes other than those implied by applying monthly change factors to an observed baseline of daily precipitation.

2. Data and methods

The sensitivity framework is implemented on 154 catchments in Britain, representative of the range of catchment properties and climatic variability in the country. For each catchment a hydrological model is run with different climatic inputs defined according to the same sensitivity domain, and changes in RP20 are calculated.

2.1. Hydrological models

Two hydrological models are applied: the Probability Distributed Model (PDM, Moore, 2007) is used for 120 (generally) smaller catchments, and the Climate and Land-use Scenario Simulation In Catchments (CLASSIC) model (Crooks and Naden, 2007) is used for 35 (generally) larger catchments; one catchment is simulated by both models. The PDM is a lumped rainfall-runoff model with three conceptual stores (soil moisture, fast flow and slow flow). A simplified version of the full PDM is used to reduce the problem of equifinality

(Beven and Freer, 2001) and allow automatic calibration. CLASSIC is a semi-distributed grid-based rainfall-runoff model with three main modules (soil moisture accounting, drainage and channel routing) and semi-automatic calibration. As snow plays a determinant role in climate-to-flow response in mountainous areas and can affect UK upland catchments a snowmelt module (Bell and Moore, 1999) is used as a pre-processor for the precipitation inputs, to improve simulation of snowmelt influenced river flow and allow for possible changes in the split between snowfall and rainfall. Different objective functions are used within the calibration procedure, as appropriate to the role of the parameter, including fit of observed and simulated flood frequency curves. To ensure integrity of calibration hydrological model performance was manually assessed for each catchment. Catchments were only included in the sensitivity modelling if they satisfied performance criteria, particularly for simulation of high flows, though a few with lower performance were tracked through the analyses to identify if performance affected the results. Details on models, catchments, calibration and performances are in Crooks et al. (2009).

2.2. Data

Calibration data are provided by the UK National River Flow Archive (NRFA), Environment Agency and Scottish Environment Protection Agency (river flow) and UK Met Office (precipitation). The majority of catchments have at least 30 years of good quality data with a maximum period from January 1961 to December2001. Point precipitation data are used to generate catchment/grid-average precipitation (P) using the Triangle method (Jones, 1983). Gridded monthly potential evapotranspiration (PE) based on the Penman-Monteith equation (Monteith, 1965) is from the UK Met Office Rainfall and Evaporation Calculation System (MORECS) (Hough et al., 1997; Thompson et al., 1982) and distributed uniformly within the month. Gridded daily minimum and maximum temperature (T) are from the UK Met Office (http://www.ukcip.org.uk/). Corresponding altitudes are from a Digital Terrain Model (Morris and Flavin, 1990).

2.3. Sensitivity domain

a) Background

For a sensitivity analysis to provide useful insights into the response between a driver (here climate) and an impact variable (here flood peaks) the domain must describe the major aspects influencing the variable. Sensitivity testing of water resources has so far been limited to two-dimensional analyses where responses of combined changes in mean annual P and T (e.g. Yu et al., 2010) or changes in mean annual P and PE (Liu and Cui, 2011) are investigated.

However, P and T seasonality is known to influence streamflow generation, as it controls antecedent conditions (Ziervogel et al., 2010). Elsner et al. (2010) suggested that considering only mean annual change might mask important inter-annual processes and result in different impacts, as for snowpack in Washington State (USA). In Britain, hydrological processes have strong seasonality, with the recharge season (when water stores fill) and spring (when evaporative losses increase with the start of the growing season) being pivotal to determine the annual water balance. Any changes in climatic characteristics during these seasons are therefore likely to affect streamflow generation in the following months and years.

Prudhomme et al. (2010) showed that decadal and intra-annual climate changes in P and T from CMIP3 outputs (Covey et al., 2003) can be smoothed by a single-phase harmonic function, with a peak in January for P (January or August for T). This enforces symmetry on changes in the transitional seasons of autumn and spring. Alternative smoothing procedures, not imposing symmetry, are possible, but Prudhomme et al. (2010) showed no evidence that the seasonal pattern of change is significantly different from that described by a single-harmonic function. The analysis of Bosshard et al. (2011) confirms the need to smooth change factors in some way, to reduce sampling artefacts caused by natural variability, though they apply a spectral smoothing technique to the annual P and T cycles before calculating change factors, rather than directly smoothing the change factors. Some smoothing was also used for the UK Climate Impacts Programme’s sets of monthly change factors UKCIP02 (Hulme et al., 2002).

While previous studies suggest that scenario-neutral, sensitivity-based analyses provide a step forward for assessment of climate change impacts, particularly when including changes in seasonality, they cover few catchments and/or few climate projections and no attempt is made to regionalise responses. Changes in the frequency and intensity of wet days are very important for fast responding catchments, as their flood-generation processes are sub-daily. However, current GCMs and RCMs are not yet able to simulate well sub-monthly precipitation characteristics in regions such as Europe, in particular high intensity daily and sub-daily precipitation (Kjellstrom et al., 2010). Therefore changes in rainfall frequency/intensity at the sub-monthly scale were not considered.

b) Definition

Here, the sensitivity domain developed by Prudhomme et al. (2010) is used, as summarised below. Monthly changes in P and T are defined by the single-harmonic function

Equation 1 $$X_t = X_0 + A\cos\left(\frac{2\pi}{12}(t-\Phi)\right)$$

where X_t is the value at time t (month number), X_0 is the arithmetic mean, A is the amplitude and Φ is the phase (time of year the maximum occurs, in months). The type of variation dominating the curve is revealed by the size of the amplitude A (hereafter referred to as 'seasonality'). P changes are represented as percentages, while T changes are in °C.

For P, the phase was fixed to correspond to January (Φ=1). Sets of pairs (X_0, A) then define the 2-dimensional P sensitivity domain and are used in Equation 1 to derive the corresponding X_t (monthly percentage changes in P; Supplementary Figure a): X_0 varies between -40% and +60% and A between 0% and +120%, each by increments of 5% (a total of 525 P scenarios). Note that some combinations lead to no precipitation occurring in summer or to increases in summer precipitation.

As streamflow and flood regimes are less sensitive to T and PE than to P, the number of T scenarios – and associated PE scenarios – is restricted to eight (Supplementary Table a), and Equation 1 is used to derive monthly T changes. Associated PE changes are estimated using the T-based equation of Oudin et al. (2005) with the Central England Temperature series (http://www.cru.uea.ac.uk/~mikeh/datasets/uk/cet.htm) as the baseline.

2.4. Implementation

For each of the 4,200 combinations of monthly P and T/PE change factors of the sensitivity domain, synthetic catchment climate time series (P, T and PE) are generated using the ‘change factor’ method (e.g. Hay et al., 2000) with the historical catchment climate time series. For each catchment, the impact model is run using each set of synthetic climate series as driving data, producing corresponding synthetic daily river flows.

Following Prudhomme et al. (2003) a generalised pareto distribution (Naden, 1992) is fitted to peaks-over-threshold POT2 series (Bayliss and Jones, 1993), independently for the baseline daily flows (i.e. those simulated using historical climate time series) and synthetic daily flows, to estimate percentage changes in the magnitude of 20-year return period flood peaks (RP20). In addition, the elasticity of flood flows (i.e. “proportional change in streamflow divided by the proportional change in a climate variable” Schaake, 1990) is used to aid understanding of the non-linearity of the rainfall-runoff processes. The elasticity of RP20 is calculated as the ratio between RP20 change and January P change, and provides information on the influence of winter P changes on the flood regime (while January is the month of maximum P change, by construction, December and February will experience the second highest P changes of the year). Elasticity values higher (lower) than 1 indicate a change in RP20 greater (smaller) than that of January P. Elasticity provides a way of normalising the percentage changes in RP20; P in other months could be used, when the values of elasticity would be different but the general pattern would be the same.

Flood response surfaces are generated for each T/PE scenario separately and describe changes in RP20 and elasticity of RP20. Graphical representation consists of 3-dimensional diagrams with X_0 (changes in mean annual P) on the y-axis, A (reflecting the seasonality of P changes) on the x-axis and changes in RP20 or elasticity of RP20 as colour gradients (Supplementary Figure b).

3. Flood response to climate change in Britain: flood sensitivity types

3.1. National picture for Britain

Response surfaces for all 154 catchments (Supplementary Figure c) show great similarity for RP20 changes: changes in flood magnitude decrease with a decrease in mean annual P when the seasonal variation is small; changes in flood magnitude gradually increase when both mean annual P and seasonality increase; changes in flood magnitude can be very large for large changes in mean annual P and/or seasonality. In contrast, the elasticity of RP20 shows more variability throughout Britain. Elasticity varies with changes in mean annual P but also has a strong relationship with the seasonality of P changes. This links with the different rainfall-runoff processes that occur in different seasons in Britain. The 154 response surfaces show that this variation is not uniform from catchment to catchment.

3.2. Identification of flood sensitivity types

Typical flood sensitivities are investigated through a clustering analysis of the response surfaces of the 154 catchments (RP20 changes for all P and T/PE combinations together) based on a hierarchical agglomerative clustering algorithm with Euclidian distance as the dissimilarity measure and the Ward algorithm (function `agnes` of the package 'cluster' of the statistical software R). This is similar to the clustering analysis of Köplin et al. (2012), who grouped catchments in Switzerland according to their hydrological response (changes in mean monthly flows) to a small set of climatic changes (derived from 10 GCM/RCM combinations).

To avoid extreme P scenarios (not projected to occur in Britain with current climate models Prudhomme et al., 2010) overly influencing the analysis, only responses from scenarios with *A* up to 80% are considered (although the full extent is displayed in the response surfaces). Three catchments are *a priori* excluded from the analysis as they showed different sensitivity to climate change than the rest of the catchments but could not be systematically discriminated by the clustering algorithm due to their limited sample size. As they show similar sensitivity to each other, these three catchments are considered a separate group. Eight groups are identified for the remaining 151 catchments. To avoid too many small groups being formed, a two-stage process is used; first four groups are produced then the two largest are further divided.

The resulting nine groups (eight from the clustering analysis, plus one (Damped-Extreme) from the excluded catchments) represent nine typical flood sensitivity types to climatic change, named Damped-Extreme, Damped-High, Damped-Low, Neutral, Mixed, Enhanced-Low, Enhanced-Medium, Enhanced-High and Sensitive. These are briefly characterised across the range of P changes in Table 1 and shown schematically in Supplementary Figure d. Composite (or average) response surfaces are calculated for each sensitivity type (Figure 2):

- Composite RP20 change: mean of RP20 change (arithmetic mean for each of the 525 P changes of the sensitivity domain, over all T/PE scenarios and all catchments of that type);
- Composite elasticity of RP20: mean of elasticity of RP20 (calculated as above for each of the 525 P changes of the sensitivity domain);
- Standard deviation of RP20 change: standard deviation of RP20 change (calculated as above for each of the 525 P changes of the sensitivity domain) — a measure of spread within a sensitivity type.

Table 1. (place holder)

Figure 2. (place holder)

The composite response surfaces (Figure 2a) are ordered according to the width and shape/curvature of the percentage change bands, from Damped-Extreme (widest bands) to Sensitive (narrowest bands). The width of the bands illustrates how sensitive a type is to mean P changes. The names of the sensitivity types describe how flood peaks change relative to the maximum change in P and not how a catchment responds to P as an input per se. The Neutral response type has the most linear relationship of the nine types between change in P and change in flood peak; width of the bands in approximately straight lines (Figure 2a), with an elasticity of around 1.0 for most of the surface (Figure 2b) is illustrative of the linear relationship.

3.3. Robustness of flood sensitivity types

The robustness of the sensitivity types is assessed by investigating the influence of the T/PE scenarios, and the internal and external variability of each type.

a) Influence of T/PE scenarios on flood response to climate change

The variability of response surfaces for a catchment due to different T/PE scenarios is found to be much smaller than that between catchments (Supplementary Figure e), confirming the lesser role of T/PE variability compared to P variability in controlling high flow and flood variability in Britain. The degree of response surface variation between T/PE scenarios varies between catchments/types though, as it depends on the relative values of P and PE, which determine whether all the precipitation is used to satisfy the evaporative demand or if there is enough water for infiltration (filling up of catchment water stores) or to contribute to streamflow (and possibly flood) generation.

b) Internal and external sensitivity type variability

The variation in response surfaces of catchments with the same sensitivity type (internal variability) is compared to that of catchments with different sensitivity types (external variability) using Taylor diagrams, designed to summarise how well patterns match each other (Taylor, 2000). Figure 3a uses each composite response surface in turn as the reference pattern, and compares all the catchment response surfaces (for a single T/PE scenario) to that reference , where the symbol colour/shape indicates the sensitivity type of each catchment. For each sensitivity type, the similarity between catchment response surfaces is good and the spread around the reference is small compared with that for all response surfaces: internal variability is much smaller than external variability. Thus the sensitivity types are homogeneous and each composite response surface is significantly different from the others, confirmed by comparing the composite surfaces in a Taylor diagram (Figure 3b).

Figure 3 also illustrates that Damped types show the least variability within response surfaces (smallest pattern standard deviations). As the climate change signal is damped (Figure 2) the variation in RP20 changes is smaller. Conversely, Enhanced types show high variability within their response surfaces, also associated with larger internal variance (wider range of response surfaces of the same type). The variability of Mixed and Neutral types is between that of Damped and Enhanced. The Sensitive type shows the largest response surface variability and the largest internal variance.

Figure 3 (place holder)

3.4. Interpretation of the flood sensitivity types

Figure 4 shows the sensitivity types of the 154 catchments plotted to the catchment outlet locations. The location of sensitivity types across Britain does not show any strong geographical pattern, although some features emerge: Catchments associated with a Damped type are generally found in the west and north-east, while those with a Neutral type are often located in the west. Catchments with a Mixed type are found in most parts of Britain except in western Scotland and catchments with an Enhanced type are generally found in the south-east.

Figure 4. (place holder)

The differentiating factors between the nine sensitivity types can be understood in terms of climatology, including seasonality and natural variability of climatic variables, combined with hydrological processes in the catchment; the main factors are discussed briefly below. The relationship between sensitivity types and catchment properties is the focus of the companion paper.

a) Water balance

The seasonality of the hydrological water balance between incoming P and outgoing losses (mainly through evaporation and water usage) provides the background which determines whether a ‘precipitation event’ is sufficient to generate a flood. In winter (Dec–Feb) inputs generally greatly exceed losses; the sign of the water balance is not affected by changing P and PE so, on average, flood potential is not changed. However, in the remainder of the year changes in P and PE may change the sign of the water balance, with consequent effects on flood potential. Catchments sensitive to changes in the seasonal water balance are more influenced by T/PE scenario seasonality and tend to belong to the Mixed or Enhanced types.

b) Catchment memory

The response between P and runoff is determined by catchment properties such as topography, soil type and geology. These properties determine the water storage capacity and lag between P and river flow, or the catchment ‘memory’. With a short memory catchment (e.g. an upland catchment with impermeable bedrock and little storage), changes in the water balance have influence over a limited time, such as hours or days, whereas for a long memory catchment (e.g. a catchment with permeable bedrock such as chalk), changes to the water balance, through changes in stored water, may be evident over months, or even years. Catchments with short memory tend to be Damped or Neutral types, while those with long memory tend to be Enhanced-High or Sensitive types. Note that the analysis undertaken here only concerns precipitation changes at the monthly scale, not sub-monthly patterns, which are more important for short-memory catchments.

c) Natural variability

The future climate series have been created using the change factor method applied to observed P, T and PE. The sequencing and time of year of extreme rainfall events in the observed data series, inherent within natural variability of the climate, may have an effect on the resultant change in frequency of the associated flood events.

d) Frequency of floods in baseline time series

The mean and coefficient of variation of the observed and modelled POT2 series for each catchment are analysed to investigate whether the characteristics of the sampled flood peaks (controlled by the baseline climate time series) are linked to sensitivity type. No marked difference is found in the dispersion between the nine sensitivity type and no systematic bias appears in the reproduction of the daily flood peak variability for particular types. Thus the sensitivity types identified for the study catchments are not related to flood history, hence are a reliable description of catchment (albeit modelled) behaviour under climatic change.

4. Discussion and conclusion

This paper describes the first part of a novel methodology using a scenario-neutral framework. The method quantifies catchment flood response to climatic change using the same sensitivity analysis for 154 British catchments, and aims to provide scientific evidence to policy makers regarding the expected range of impacts that could occur in different catchments. Changes in 20-year return period flood peaks (RP20) are simulated for each catchment, for a sensitivity domain comprising 525 sets of precipitation (P) changes combined with eight sets of temperature/potential evapotranspiration (T/PE) changes including changes in both mean annual magnitude and seasonality of the climate.

For each T/PE scenario, flood response surfaces for changes in P are generated for each of the 154 catchments, describing the associated change in RP20 and the elasticity of RP20 (ratio of change in RP20 over the January P change). These show that:

- There is a large variation in response surfaces across catchments. The same climate change scenario can result in very different changes in flood peaks, and some catchments are much more sensitive to climatic (particularly P) change than others. This is important for long-term planning, as adaptation measures could be more appropriate in some catchments than others. Note that changes in high intensity precipitation are not investigated.
- Changes in RP20 and elasticity of RP20 are strongly linked to the seasonality of climatic changes. Note that January is winter in Britain; generally wet and when most recharge occurs. A phase (month of largest P increase) occurring in a dry season is likely to result in different responses. While Fu et al. (2007) showed that elasticity varies with mean annual P change, they did not study the effect of seasonality of changes. These results demonstrate that undertaking impact studies using only mean annual P changes might underestimate flood magnitude changes. Moreover, traditional elasticity analyses aiming to understand the non-linearity of streamflow generation processes, based on combining mean annual P and T changes only, might be less efficient to describe and understand climate-catchment dynamics than a sensitivity analysis where seasonality is explicitly considered. This could also be the case for other sectors.
- The variation in response surfaces generated with different T/PE scenarios for a catchment is generally small compared to the variation in response surfaces between different catchments. This confirms the relatively low importance identified by Zheng et al. (2009) of T/PE compared to P for streamflow and flood generation processes, and

that for flood impact studies in Britain, analyses using more P than T/PE scenarios are appropriate.

- The range of response surfaces found for the 154 study catchments in Britain can be classified into nine flood sensitivity types, describing five main behaviours: Neutral, with elasticity of RP20 close to 1; Damped, with elasticity of RP20 often less than 1; Enhanced, with elasticity of RP20 often greater than 1 for increases in mean P; Mixed, where elasticity of RP20 strongly depends on the magnitude and seasonality of P changes; and Sensitive, where the flood regime is very impacted by even small P changes. While some differences in elasticity of streamflow to climate for different catchments have been identified in other parts of the world it is often not clear whether this is characteristic of general hydrological processes or the result of specific local conditions in those catchments. Only a systematic analysis over a large number of catchments can identify if similarities in catchment response exist, as shown here for floods in Britain and by Köplin et al. (2012) for mean monthly flows in Switzerland (where seven response types were identified).
- The nine sensitivity types identified in Britain do not show any strong geographical pattern, although weak north/south and west/east divides are shown for some types. This is likely to be related to the strong influence of catchment physical properties, such as soil, geology, land use, aspect and geomorphology, and some influence of the climate (in particular the seasonal difference between P and PE). While hydrological science identified long ago the difference in hydrological processes in catchments with different properties, this difference has, until very recently, not been systematically investigated regarding how it modifies the rainfall-change-to-flood-change signal. The analysis of Köplin et al. (2012) demonstrates the influence of properties including slope and altitude on changes in mean monthly flows in Switzerland. An analysis of sensitivity types and catchment properties could provide information on the level of influence of different properties on flood changes in Britain.

In the companion paper (Prudhomme et al., submitted) a discriminant analysis is used to characterise catchments with similar sensitivity types based on catchment properties. This allows any catchment with available catchment property information to be associated with a response surface without the need for a full sensitivity analysis using an impact model. This could prove extremely useful in the context of vulnerability.

The scenario-neutral sensitivity framework applied here uses monthly change factors (smoothed by a single-harmonic function) applied to baseline data series, so does not change the sub-monthly variability or temporal sequencing of the baseline data. This is deliberate as it guarantees that the same set of climate change signals is imposed on all catchments, enabling more robust classification (and characterisation - see part 2, Prudhomme et al. submitted) of the sensitivity of flood flows to climatic change. Introducing sub-monthly changes would add further dimensions to the sensitivity domain and make classification and subsequent application more difficult. Similarly, although using a weather generator (e.g. Bastola et al. 2011) would introduce changes in variability and temporal sequencing, it would also introduce inconsistency (noise) in the response surfaces, hampering robust classification. For this first implementation of a generalised scenario-neutral methodology for climate change impact and vulnerability assessment, the method was kept as simple as possible. Despite this, we believe that the information provided by the response surfaces is very valuable for understanding catchment behaviour under climate change and can be used to inform policy makers. Future work will investigate how best to enhance the sensitivity framework methodology, as well as validating the sensitivity type classification by modelling further catchments.

5. Acknowledgements

The work presented was funded by Defra and the Environment Agency for England and Wales (FD2020 ‘Regionalised impacts of climate change on flood flows‘) with additional contribution from the NERC-CEH Water science programme. They are all gratefully acknowledged. The development of the science benefited from helpful support from the project managers (Karl Hardy, Ella Thomason and Bill Donovan) and fruitful discussions with Prof. Rob Wilby and review by Prof. Nigel Arnell and Prof. Howard Wheater. Data were from CMIP3, CERA, IPCC-DDC, FEH and the UK National River Flow Archive. The views expressed are those of the authors and not of the funding organisations.

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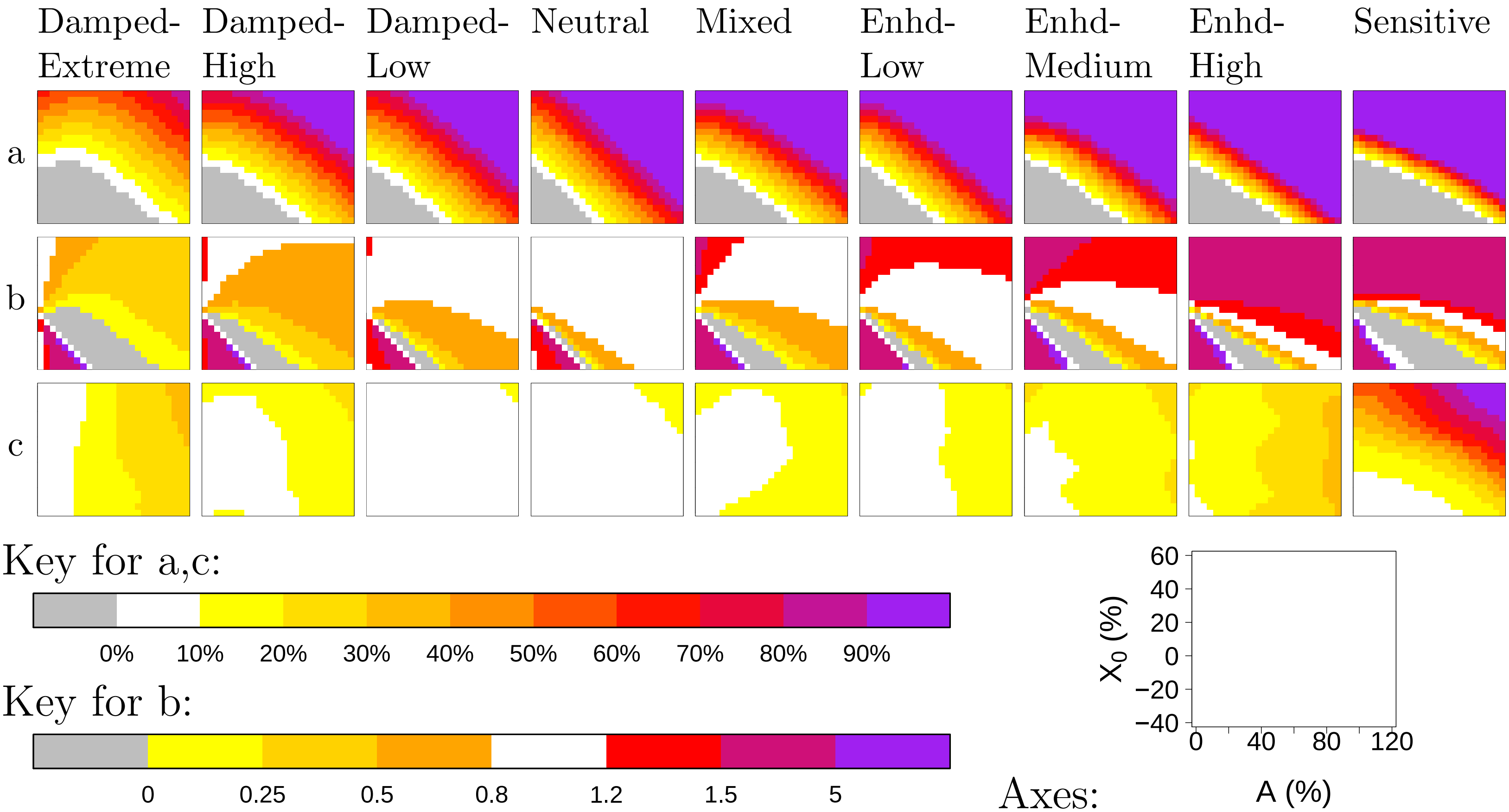
Figure 2


Damped-Extreme
Damped-High
Damped-Low
Neutral
Mixed
Enhd-Low
Enhd-Medium
Enhd-High
Sensitive
a
b
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Key for a,c:
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
Key for b:
0
0.25
0.5
0.8
1.2
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Axes:
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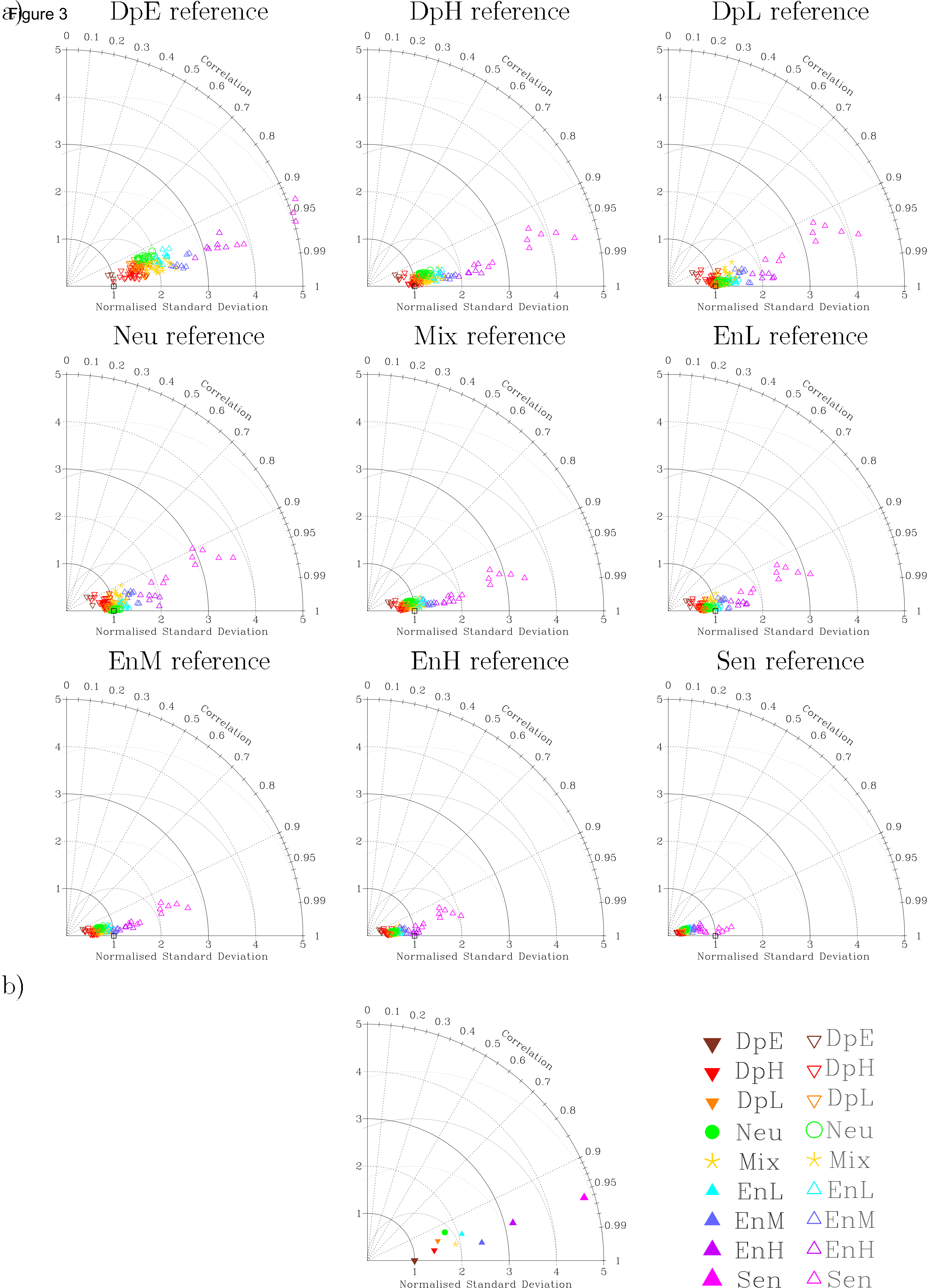
A (%)

Figure 3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0.7
0.8
0.9
0.95
0.99
1
Normalised Standard Deviation
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2
3
4
5
b)
DpE
DpH
DpL
Neu
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EnL
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Sen
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CLIMATE CHANGE AND RIVER FLOODING: PART 1 CLASSIFYING THE SENSITIVITY OF BRITISH CATCHMENTS

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Tables :

Table 1. Summary description of changes in RP20 for the nine flood sensitivity types found in Britain

Flood sensitivity type (shorthand)	Signal description	Increase in mean annual P with increase in summer P	Increase in mean annual P with decrease in summer P	Decrease in mean annual P with increase in winter P	Decrease in mean annual P with decrease in all months
Neutral (Neu)	Neutral	Similar	Similar	Similar or lower	Decrease
Damped-Low (DpL)	Slightly damped	Similar or higher	Similar or lower	Lower or much lower	Decrease
Damped-High (DpH)	Very damped	Similar or higher	Similar or lower	Much lower or decrease	Decrease
Damped-Extreme (DpE)	Extremely damped	Similar or lower	Much lower	Much lower or decrease	Decrease
Enhanced-Low (EnL)	Slightly enhanced	Higher	Similar or higher	Similar or lower	Decrease
Enhanced-Medium (EnM)	Enhanced	Much higher	Similar or higher	Lower or much lower	Decrease
Enhanced-High (EnH)	Very enhanced	Much higher	Similar to much higher	Lower to decrease	Decrease
Sensitive (Sen)	Sensitive	Much higher	Much lower to much higher	Much lower or decrease	Decrease
Mixed (Mix)	Mixed	Higher or much higher	Similar or lower	Much lower or decrease	Decrease

Similar – percentage increase in flood peak of similar magnitude to maximum monthly percentage increase in P (elasticity of RP20 to January P from 0.8 to 1.2)

Lower – percentage increase in flood peak lower than maximum monthly percentage increase in precipitation (elasticity of RP20 to January P from 0.5 to 0.8)

Much lower – percentage increase in flood peak much lower than maximum monthly percentage increase in precipitation (elasticity of RP20 to January P from 0 to 0.5)

Higher – percentage increase in flood peak higher than maximum monthly percentage increase in precipitation (elasticity of RP20 to January P from 1.2 to 1.5)

Much higher – percentage increase in flood peak much higher than maximum monthly percentage change in precipitation (elasticity of RP20 to January P greater than 1.5)

Decrease – percentage decrease in flood peak

Summer – change in at least one month from May to September

Winter – change in at least one month from November to March

Change in P derived from single-phase harmonic function with peak in January

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Figure 1. Schematic of climate change impact studies: top-down, scenario-led approach (left) and bottom-up, scenario-neutral framework (right)

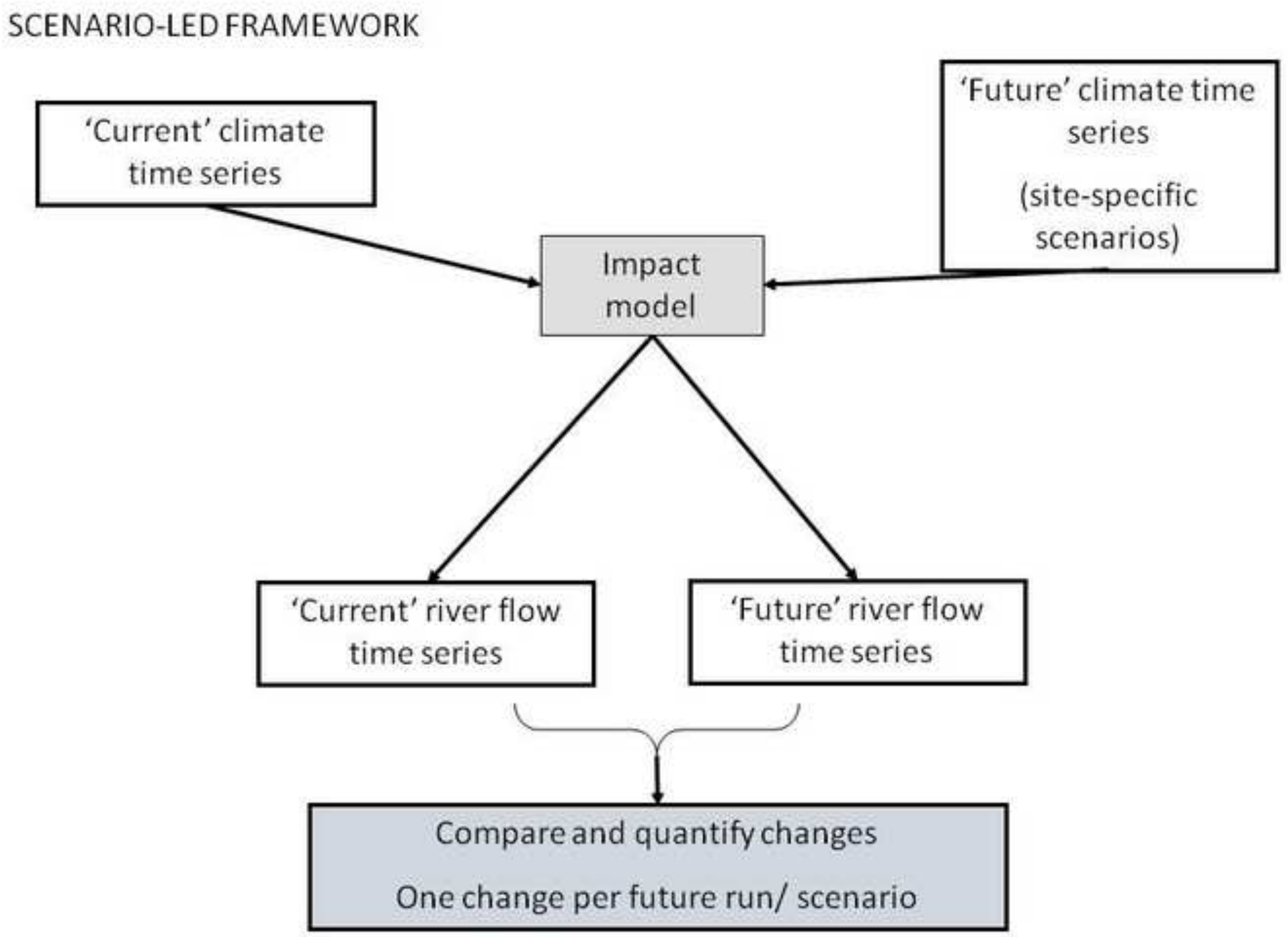
Figure 2. Composite flood response surfaces associated with flood sensitivity types of British catchments: (a) RP20 change; (b) elasticity of RP20; (c) standard deviation of RP20 change. Graphical representation consists of 3-dimensional diagrams with changes in mean annual P (X_0) on the y-axis and changes in A (reflecting the seasonality of P changes) on the x-axis (see axes diagram, bottom-right), with the third dimension shown by the colour gradient (see colour keys, bottom-left).

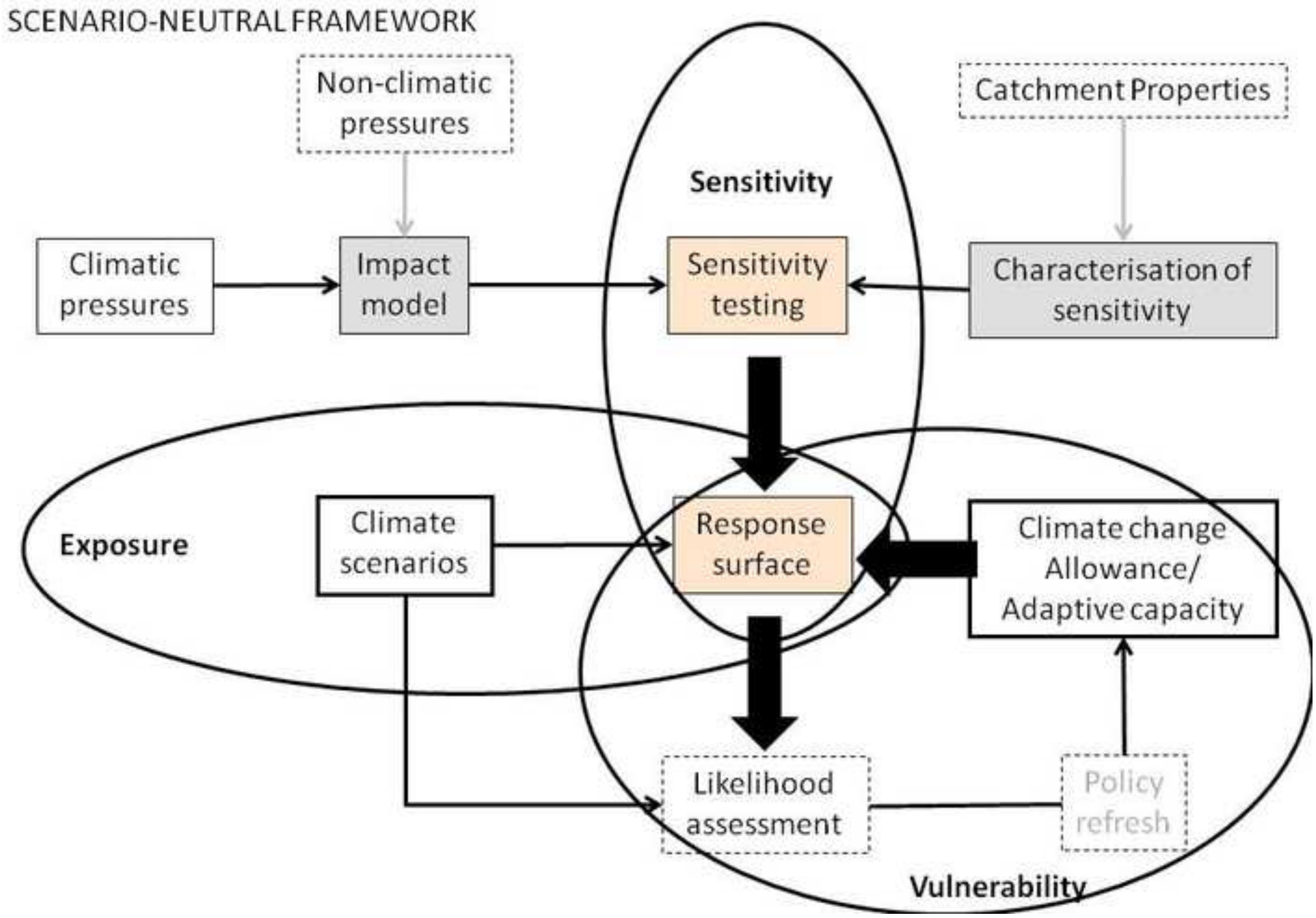
Figure 3. Taylor diagrams comparing, for RP20 change, a) each catchment flood response surface (for the Medium Aug T/PE scenario; coloured symbols) with each composite response surface as reference (black square); b) each composite response surface with the Damped-Extreme (DpE) composite response surface as reference

Figure 4. Flood sensitivity types of the study catchments for RP20

Table 1. Summary description of changes in RP20 for the nine flood sensitivity types found in Britain

Manuscript Part 2


SCENARIO-LED FRAMEWORK
'Current' climate time series
'Future' climate time series
(site-specific scenarios)
Impact model
'Current' river flow time series
'Future' river flow time series
Compare and quantify changes
One change per future run/ scenario


SCENARIO-NEUTRAL FRAMEWORK
Non-climatic pressures
Catchment Properties
Sensitivity
Climatic pressures
Impact model
Sensitivity testing
Characterisation of sensitivity
Exposure
Climate scenarios
Response surface
Climate change Allowance/ Adaptive capacity
Likelihood assessment
Policy refresh
Vulnerability