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CLIMATE CHANGE AND RIVER FLOODING: PART 2 SENSITIVITY CHARACTERISATION FOR BRITISH CATCHMENTS AND EXAMPLE VULNERABILITY ASSESSMENTS

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Short title: Characterising the sensitivity of British flood flows to climate change

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Abstract

This paper is the second of a series describing a scenario-neutral methodology to assess the sensitivity and vulnerability of British catchments to changes in flooding due to climate change. In paper one, nine flood sensitivity types were identified from response surfaces generated for 154 catchments. The response surfaces describe changes in 20-year return period flood peaks (RP20) in response to a large set of changes in precipitation, temperature and potential evapotranspiration. In this paper, a recursive partitioning algorithm is used to link families of sensitivity types to catchment properties, via a decision tree. The tree shows 85% success characterising the four sensitivity families, using five properties and nine paths. Catchment annual average rainfall is the primary partitioning factor, with drier catchments having a more variable response to climate (precipitation) change than wetter catchments and higher catchment losses and permeability being aggravating factors. The full sensitivity-exposure-vulnerability methodology is illustrated for two catchments: sensitivity is estimated by using the decision tree to identify the sensitivity family (and its associated average response surface); exposure is defined from a set of climate model projections and combined with the response surface to estimate the resulting impacts (changes in RP20); vulnerability under a range of adaptive capacity thresholds is estimated from the set of impacts. Even though they are geographically close, the two catchments show differing vulnerability to climate change, due to their differing properties. This demonstrates that generalised response surfaces characterised by catchment properties are useful screening tools to quantify the vulnerability of catchments to climate change without the need to undertake a full climate change impact study.

Keywords

Discriminant analysis; Sensitivity; Hydrological processes; Response surface; Flood risk; Vulnerability;

1. Introduction and background

With growing scientific consensus on global warming (IPCC, 2007a, b), research studies to investigate its potential impacts on ecosystems and adaptation strategies have multiplied (Wilby et al., 2009). The majority assess the impact of specific climate change scenarios - usually derived from Global/Regional Climate Model (G/RCM) projections - but when new model variants emerge such scenario-led impact studies also require updating.

A new approach to climate change impact assessment has recently emerged based on a 'bottom-up' approach aiming to identify the vulnerability of an environmental system to climatic risk (Pielke and Bravo de Guenni, 2004). The approach is based on a sensitivity analysis to derive response surfaces against which different adaptation thresholds can be evaluated, making it effectively 'scenario-neutral'. When included in an adaptation planning framework, the vulnerability assessment can be repeated with different sets of scenarios and adaptive capacity thresholds, providing the evidence necessary for decision makers (Wilby and Dessai, 2010).

By implementing the same fixed scenario-neutral sensitivity framework and generating the corresponding response surfaces for a range of catchments, variation in the 'climate-to-impact' signal of change can be systematically quantified for relevant impact variables, difficult in scenario-led approaches (Wilby et al., 2008). Recently, a scenario-neutral framework was developed to assess the sensitivity of flood peaks to climate change in Britain (Prudhomme et al., 2010), using a sensitivity domain comprising 4200 combinations of changes in precipitation (P), temperature (T) and potential evapotranspiration (PE). In part 1 (Prudhomme et al., submitted)this sensitivity framework was applied to 154 catchments using hydrological modelling, resulting in flood response surfaces illustrating changes in 2-, 10- and 20-year return period flood peaks for each catchment (Prudhomme et al., submitted, Section 2.4). Nine flood sensitivity types were shown to summarise the different ways in which the study catchments propagate the 'climate-to-flood' signal of change, each with a composite (average) response surface (Prudhomme et al., submitted, Section 3.2). These nine sensitivity types describe five main families of catchment flood responses found in Britain:

(i) Neutral. Percentage changes in flood peaks of similar magnitude to maximum monthly P percentage change;

(ii) Damped. Percentage changes in flood peaks of similar magnitude or generally lower than maximum monthly P percentage change. Flood regime relatively insensitive to small P increases;

(iii) Enhanced. Percentage changes in flood peaks of similar magnitude or generally greater than maximum monthly P percentage change. Flood regime affected even by small P increases;

(iv) Sensitive. Percentage changes in flood peaks very dependent on the precise characteristics of P changes – a small increase in P may lead to a much greater increase in flood peaks;

(v) Mixed. Percentage changes in flood peaks mixed (damped/neutral/enhanced) depending on magnitude and seasonal pattern of P changes. Catchments particularly affected by summer P increases.

Note that these names describe how flood peaks change relative to the maximum monthly P change; they do not describe how a catchment responds to P as an input.

Catchment properties influence streamflow generation processes and the response of river flows to change in climate (Fu et al., 2007). This paper investigates whether sensitivity types and catchment properties are linked, enabling such properties to be used to associate a sensitivity type, and corresponding composite response surface, to any catchment (including unmodelled or ungauged). This further enables an assessment of vulnerability for such catchments, without the need to undertake a full climate change impact study with a local impact model, by overlaying exposure and sensitivity. This sensitivity-exposure-vulnerability approach could thus be used as a screening tool for a large number of catchments (for example, the UK National River Flow Archive, www.ceh.ac.uk/data/nrfa, lists over 1400 catchments in Britain).

A decision tree approach is used to establish a characterisation of sensitivity types by catchment properties (Section 2). Section 3 describes the application of the full sensitivity-exposure-vulnerability approach and presents an example vulnerability assessment for two catchments, using composite response surfaces and sets of climate change scenarios, and illustrates how vulnerability and risk diagrams can help compare different adaptive capacity thresholds and catchment responses. Section 4 discusses the overall approach, with conclusions in Section 5.

2. Sensitivity characterisation

Relationships between flood sensitivity to climatic changes and catchment properties are investigated using a recursive hierarchical partitioning technique (Ripley, 1996). The decision trees resulting from this discriminant analysis are easy to interpret (Wei and Hsu, 2008) and can be adapted to expert knowledge approaches (Wang et al., 2009). Being non-parametric, they do not require assumptions on the distribution of the input data (Wang et al., 2009); advantageous for environmental data. Results are presented using the sensitivity for the 20-year return period flood peak (RP20).

2.1. Data

Nine sensitivity types were identified from the study catchments (Prudhomme et al., submitted); Damped-Extreme, Damped-High, Damped-Low, Neutral, Mixed, Enhanced-Low, Enhanced-Medium, Enhanced-High, Sensitive. Because the sample available for the Damped-Extreme type is too small (three catchments) to allow reliable characterisation, the corresponding catchments are removed from the sample, leaving eight types (151 catchments).

The sensitivity types emerged from analysing changes in flood peaks resulting from P change scenarios with a smoothed variation through the year, peaking in January (Prudhomme et al., submitted, Section 2.3). The effect of the month of the maximum P change was investigated by Kay et al. (2009) who found that for catchments with Damped types, the response surface may be either less damped or Neutral when peak P changes occur in autumn, while for catchments with Enhanced types the response surface may be further enhanced. When the peak P change occurs between February and mid-summer, the effect on changes in flood peaks is generally less. In order to integrate this variation in response surfaces due to the month of maximum P changes, and to address the issue of the small size of the groups for some types (which is a problem for the recursive partitioning algorithm), the remaining eight sensitivity types for RP20 are merged as follows: Neutral with Damped-High and Damped-Low; Enhanced-High with Enhanced-Medium and Enhanced-Low; Mixed and Sensitive remain unchanged. Four flood sensitivity families are thus used at RP20 (Neutral/Damped, Mixed, Enhanced, and Sensitive, in approximate order of increasing response variability).

Two main sources of catchment properties are available digitally in Britain: the Flood Estimation Handbook (FEH; Reed, 1999) and the National River Flow Archive (NRFA) Hydrometric Register (Marsh and Hannaford, 2008). After a preliminary analysis, a sub-selection of 27 FEH and NRFA properties is used in the discriminant analysis of sensitivity families, including information on catchment area, altitude, aspect and permeability (Supplementary Section 1).

2.2. Principles of decision trees and model complexity

A decision tree divides the space of possible observations (catchments) into sub-regions of the same category (sensitivity family) according to descriptors (catchment properties). It is an iterative approach: (i) The *root* is the top node (full sample); (ii) data at each node are split into two *branches* by binary tests (rules) to form two child nodes; (iii) a node becomes a *leaf* when no further split is possible or relevant; (iv) each leaf is associated with a probability for each sensitivity family; (v) a leaf is reached by following a set of rules (path). Decision trees thus enable the use of catchment metadata to assign a sensitivity family to a catchment (generally the family with the highest probability for the appropriate leaf). Imposing a maximum number of leaves or 'pruning' the tree by aggregating leaves are two common ways to reduce complexity. Cross validation, evaluation using contingency tables (Jolliffe and Stephenson, 2003) and expert judgment help define the final decision tree:

- At least one path/leaf attributing each sensitivity family;
- Each leaf should be as pure as possible, but if a leaf contains catchments from different families they should not have very different sensitivity;
- Paths should describe logical hydrological processes;
- The tree should not have too many small splits leading to a large number of leaves;

- Hit rate (family assigned by the decision tree the same as that simulated with the hydrological model) maximised, but misses (assigned family of lower response variability than simulated) minimised; false alarms (assigned family of higher response variability than simulated) are of lesser concern than misses. This does not take priority over the existence of a path for each sensitivity family and the logic of the hydrological processes.

The R freeware package `tree` and the commands (default options) `tree`, `cv.tree`, `prune.tree` and `predict.tree` are used.

2.3. Characterisation results

The discriminant analysis results in a decision tree (Table 1) that characterises the RP20 sensitivity families using nine paths and five catchment properties; standard average annual rainfall for 1961-1990 (SAAR, mm), catchment area (Area, km^2), northing of catchment outlet (North, GB national grid reference), percentage of high permeability bedrock (BHP, %) and mean annual loss (MAL, mm; the difference between mean annual rainfall and runoff). Two of the selected catchment properties, SAAR and MAL, are climatic variables which may change with time, therefore values are used for a specified period representing current conditions. The probability of each family is provided for each path (Table 1): paths are rarely associated with a highest probability of one but for most paths the majority of catchments generally belong to the same family (i.e. highest probability greater than 0.5). For each path an indicator of confidence in the highest probability family is also given, categorised as High (H), Medium (M), or Low (L). This indicator combines 'certainty' and 'robustness', where certainty is the difference between the two top probabilities for the path and robustness is the percentage of the original sample following the path (Supplementary Section 2).

Table 1. (place holder)

Performance of the decision tree is quantified using a contingency table (Jolliffe and Stephenson, 2003) which compares the simulated and assigned sensitivity families of the study catchments (Supplementary Table c). Overall, 85% of catchments are correctly classified, with 15% misclassified. Out of 6.6% false alarms, 4.6% have a higher response variability by only one category (e.g. simulated Neutral/Damped but assigned Mixed, or simulated Enhanced but assigned Sensitive). Out of 8.6% misses, 7.2% have a lower response variability by only one category.

River flow regime is known to be dependent on physical and climatic catchment properties; some sensitivity families are associated with several paths, showing that different combinations of catchment properties can represent catchments with similar response surfaces. The decision tree in Table 1 characterises the four sensitivity families associated with changes in RP20, but decision trees were also built for the nine sensitivity types for changes in 2- and 10-year return period flood peaks (RP2 and RP10; Reynard et al. (2009)). Using the decision trees that characterise the sensitivity type or family for the three flood indicators (RP2, RP10 and RP20) it is possible to highlight the dominant characteristics associated with each (Supplementary Table d). Two catchment properties are found to be key factors in the partitioning of the decision trees: SAAR (first split for all three indicators) and BHP. Area and the relative values of SAAR and MAL are also recurrent properties in many paths. MAL is particularly important for Mixed, Enhanced and Sensitive catchments, with Sensitive catchments associated with high MAL. This highlights that features of the annual water balance characterise a catchment's response to the climatic signal. In dry catchments, summer precipitation governs the build-up of soil moisture deficits which influences the recharge capacity and catchment saturation level of wetter seasons. These factors reflect the complex hydrological processes resulting in soil moisture variation generating higher variability in runoff coefficient than rainfall variation. Note however that these are guidelines only; a catchment does not necessarily have the same sensitivity type for all indicators, and more catchments have Damped types for higher frequency (e.g. RP2) than lower frequency (e.g. RP20) flood peaks. An extended hydrological discussion of sensitivity types/families is provided in Supplementary Section 3.

3. Vulnerability assessment using the scenario-neutral approach

The assessment of vulnerability to climate change from the scenario-neutral framework involves a three-stage process (Figure 1):

Stage 1 - **Sensitivity:** Determine the response of a catchment's flood regime to climate change.

Stage 2 - **Exposure:** Quantify the future climate change projections to which the catchment may be exposed.

Stage 3 - **Impacts and vulnerability:** Calculate the impacts (flood changes), by combining the sensitivity and exposure of the catchment. Compare the impacts to an adaptive capacity threshold (e.g. the maximum change against which the catchment is currently protected) to define catchment vulnerability.

Figure 1. (place holder)

This section describes these stages and presents example applications for two catchments.

3.1. Step-by-step methodology

Stage 1 - Sensitivity

A catchment's sensitivity type/family can be determined either through a modelling study using this sensitivity domain (Prudhomme et al., 2010) or from a flood sensitivity classification and characterisation using catchment properties (Section 2). The former analysis requires an impact model and is computationally demanding, but provides a catchment-specific response surface. The latter relies on the availability of certain catchment properties and is simple to implement, but links the catchment with a generic sensitivity type/family and its associated composite response surface, hence introducing additional uncertainty.

When no impact model exists for the considered catchment, the decision tree for changes in RP20 (Table 1) assigns one of four sensitivity families based on five catchment properties. Note that after the regrouping of eight sensitivity types into four families (Section 2.1), the Neutral composite response surface (and its standard deviation surface) is associated with the Neutral/Damped family and the Enhanced-High composite response surface (and its standard deviation surface) is associated with the Enhanced family, so that possible underestimation of changes in flood peaks using the response surfaces of sensitivity families is minimised.

Decision trees provide the probability for a catchment with a set of properties to belong to each of the four sensitivity families, and an indicator of confidence (High-H, Medium-M or Low-L) in the best-estimate. For larger catchments (Area>1000km^2) it is recommended that the confidence for the corresponding decision tree path be reduced by one level (H to M and M to L), as large catchments are less well represented by catchment-average properties. For paths associated with M or L confidence, it is recommended that all families associated with high probabilities are considered when undertaking the impact and vulnerability assessments. Similarly, if one (or more) of the properties for a given catchment is close to one of the thresholds in the decision tree, it is recommended that the families from the alternative path(s) are also considered. Considering several possible sensitivity families for a single catchment is a way to account for some of the uncertainty introduced by the classification and characterisation procedures.

Stage 2 - Exposure

The exposure relates to the climatic changes the catchment may be exposed to for a given time horizon. Future climate change projections (e.g. GCMs/RCMs) are possible ways to define the exposure of a catchment for a given future time horizon. The monthly change factors associated with climate model projections can be derived from time series representative of current and future climate time slices, possibly using the resampling methodology suggested in Prudhomme et al. (2010).

For consistency between exposure and the sensitivity domain of the response surfaces, the monthly climate change factors of the exposure are described as a mean annual change (X_0) and seasonal amplitude (A) by fitting a single-phase harmonic function. The two parameters (X_0, A) are expressed as the nearest multiple of 5% (the resolution of the sensitivity domain); the phase Φ is ignored as the sensitivity domain assumes $\Phi=1$ (January) (see Prudhomme et al., submitted, Section 2.3).

Stage 3 - Impacts and vulnerability

For any response surface, the impact of an exposure is the RP20 change corresponding to the scenario of the sensitivity domain that is most similar to the exposure (i.e. the exposure can be overlaid on the response surface). If changes in T are known, the response surface using the closest of the eight T/PE scenarios of the sensitivity domain could be considered.

Alternatively, impacts from all eight T/PE response surfaces can be considered, either separately or as an average. The latter approach is used here, as changes in T were shown to be generally much less important than changes in P (Prudhomme et al., submitted, Section 3.3).

When using a composite response surface, the uncertainty resulting from considering that surface instead of a modelled catchment response surface can be added by using the standard deviation (SD) surface associated with the composite surface (Prudhomme et al., submitted). Additional uncertainty, for example linked to hydrological model uncertainty (e.g. Bastola et al., 2011) or use of response surfaces instead of direct hydrological modelling under climate change (Kay et al., 2009), could also be investigated and included. Such uncertainty will be the subject of a future paper; in the following, only uncertainty due to use of composite response surfaces to represent a range of modelled response surfaces is considered.

Vulnerability is here defined as the degree to which a system is unable to cope with a certain change, using a given adaptive capacity threshold *C*. For individual catchments, the degree of vulnerability *v(C)* is the likelihood of a set of exposures resulting in an impact greater than *C*. For flood risk in Britain, an adaptive capacity *C* was (until recently) quantified as a 20% increase in flood peaks (Department for Environment Food and Rural Affairs, 2006).

3.2. Examples of implementation

The vulnerability assessment method is applied to two contrasting catchments: the Dove at Rocester Weir (NRFA catchment number 28008) and the Cole at Coleshill (NRFA 28066) both in the Midlands region of England (Table 2). The following assumes the catchments have not been modelled using the sensitivity framework (although they have).

Table 2. (Place holder)

Stage 1 - Sensitivity: Determine the flood response surface

Using their catchment properties (Table 2), the Neutral/Damped family is associated with the Dove at Rocester Weir (path 7 of Table 1; High confidence) and the Sensitive family is associated with the Cole at Coleshill (path 6 of Table 1; Medium confidence). Each composite response surface is assumed representative of the modelled catchment response surface; Figure 2 shows good similarity between the Dove local response surface and the Neutral composite surface (top) and between the Cole local response surface and the Sensitive composite surface (bottom). The standard deviation (SD) surfaces (Figure 2, right) provide information on the uncertainty associated with each composite response surface. Note the much larger SD associated with the Sensitive surface than the Neutral surface.

Figure 2. (place holder)

Stage 2 - Exposure: Determine the harmonic function parameters for the required climate change scenario(s)

Using monthly time series projections from CMIP3 obtained from the IPCC Data Distribution Centre (http://cera-www.dkrz.de/CERA/index.html) and the Program for Model Diagnosis and Intercomparison (PCMDI, http://www-pcmdi.llnl.gov), an ensemble of exposures is defined by fitting a single-phase harmonic function to monthly precipitation change factors for each projection as in Prudhomme et al. (2010) (Table 3). The exposures are defined for the 2080s time horizon (2071-2100).

Table 3. (Place holder)

Stage 3 - Impacts and vulnerability: combining flood sensitivity and exposure

The ensemble of exposures is translated to an ensemble of impacts, by extracting the percentage change from the appropriate response surface (and corresponding SD surface) for each exposure pair (A, X_0) (Table 3). For example, for the Dove the exposure ECHOG under A1B emissions represents an annual precipitation increase (X_0) of 15% and a seasonal amplitude (A) of 15%, which corresponds to an impact of +29% from the Neutral composite surface (Figure 2); considering the uncertainty in the composite surface to be quantified by twice the SD (2%), the impact range is 24–32% (28±2x2%). For the Cole, ECHOG under A1B has an RP20 impact range of -9–83% (37±2x23%).

For the Dove, 11 out of 45 scenarios (24%) have a composite RP20 change greater than the current 20% climate change allowance for England and Wales, rising to 16 scenarios (36%) when adding 2*SD. For the Cole, only 6 scenarios (13%) have a composite RP20 change greater than 20%, but this rises to 29 (64%) when adding 2*SD. Although the Cole belongs to the Sensitive family, compared with Neutral/Damped for the Dove, this does not automatically imply that the catchment is more vulnerable to change; it depends on the scenarios being considered and where these lie on the different response surfaces (see Figure 2 for the differences in alignment and band width of these surfaces).

This example shows that two catchments geographically close to each other but with different catchment properties can have different impacts under the same exposure due to their different sensitivity to precipitation changes, and have different uncertainty associated with the estimated impacts also due to their different sensitivity and to the representativeness of the composite response surface. As a consequence, the vulnerability to the same adaptive capacity threshold *C* also varies; a national allowance (here *C*=20%) leaves some catchments more vulnerable than others. Figure 3 shows vulnerability curves (i.e. vulnerability to different *C*) for the two example catchments, derived using the impacts from Table 3. Catchments which are geographically distant could also have very different exposures, due to the geographical variation of climate model projections, leading to potentially differing vulnerability even for catchments with similar sensitivity (not shown).

Figure 3. (place holder)

4. Discussion

The methodology presented in this two-part series of papers is based on a number of assumptions and a relatively large amount of information – but is still limited in a number of ways. A number of these limitations relate to the sensitivity framework's use of monthly change factors (smoothed using a single-harmonic function) applied to baseline climate data and used to drive a hydrological model; these are discussed in Part 1 (Prudhomme et al., submitted). Further caveats associated with the methodology are discussed below.

The flood sensitivity classification (Prudhomme et al., submitted) and characterisation (Section 2) were established using relatively natural catchments, hence with limited urbanisation or water management practices. This means that the resulting decision trees are not necessarily suitable for catchments where water bodies significantly attenuate river flow, or with a relatively large urbanised area (where infiltration might be reduced and runoff proportionally larger than in non-urbanised areas). Also, one of the catchment properties that proved necessary to characterise sensitivity families is Mean Annual Loss (MAL), as calculated for the UK Hydrometric Register. However, unlike the rainfall indicator SAAR, its definition is based on the period of flow record rather than a standard time period. This could be an issue as the period of flow record is different for every catchment (varying between over 100 years to less than 10 years) and MAL is likely to be non-stationary as trends in water usage are incorporated. Further work is required on the role of superimposed catchment losses or gains, combined with other catchment properties, on flood hydrology, and whether alternative properties could be found to replace MAL.

A snowmelt module was used as a pre-processor on the precipitation data in the hydrological modelling to allow for the influence of snowfall and subsequent melt on runoff. However, the derived decision trees (for RP2, 10 and 20) do not include properties which directly relate to influence of snow on changes to flood peaks. This probably reflects the fact that snowmelt-affected peaks do not dominate the flood regime of the modelled catchments, though many catchments include snowmelt events in their POT series. Supplementary Table d shows which sensitivity types can include decreases in flood peaks due to precipitation as snow and subsequent gradual melt. Such catchments may show variation in response surface with temperature scenario. In other climatic regimes properties relating to snowmelt could have more widespread impact on changes to flood peaks (e.g. Köplin et al., 2012).

Finally, the complete scenario-neutral framework and its implementation for vulnerability assessment are based on two generalisations, both associated with their own uncertainty. First, using the composite response surface of a given sensitivity type/family as a proxy for the catchment response surface will inevitably modify any impact estimate. Second, the flood sensitivity estimation method relies on how well catchment properties summarise the complex hydrological processes, and how many catchments of each sensitivity type/family are represented by the study sample. While uncertainty associated with both generalisations has been investigated, and recommendations made when high uncertainty has been identified, the application of the complete regionalised methodology cannot be considered equivalent to an in-depth, detailed climate change impact study based on local modelled impacts from a large range of exposures.

5. Conclusions

This two-part series of papers has described the development of a scenario-neutral framework that can be used as a powerful tool to assess the vulnerability to climate change exposure against an adaptive capacity threshold. While the overall methodology was implemented for the impacts of climate change on peak river flows in Britain, it could be transferred to any environmental system for which an impact model can be applied and drivers of change (e.g. climate, land-use or population changes etc.) expressed relatively simply.

Following the definition of vulnerability suggested by IPCC (2007a), the method is based on a three-stage procedure defining sensitivity, exposure, and vulnerability relative to an adaptive capacity. Using a sensitivity domain guided by, but not limited to, climate model projections, the method enables the assessment of the response of catchments to an extensive range of possible exposures. Three novel elements have been introduced within the scenario-neutral framework and explicitly integrated into the vulnerability assessment procedure for the first time:

- Climate change exposure. The uncertainty in climatic change signal as simulated by GCMs and RCMs is known to be large, especially for P, which is particularly influenced by the spatial scale of climate models and large climate variability. When climate variability is considered in estimating the mean monthly signal of changes, the range of estimates in the change factors can also be very large. Prudhomme et al. (2010) showed that in the UK, a single-phase harmonic function could summarise in three parameters the possible mean monthly change factors that would be obtained when considering climate variability.
- Sensitivity to seasonality of change. In hydrology, the length and associated total P of wet and dry seasons is important for hydrological processes as generated runoff depends not only on P but also on the soil capacity to absorb more water. The study of the response of different catchments to different seasonal patterns of changes –

from uniform throughout the year to a large difference in magnitude between wetter and dryer periods – has demonstrated the role of seasonal change and its necessity in sensitivity studies in hydrology.

- Characterisation of flood sensitivity to climate change. The study of the flood sensitivity of 154 catchments across Britain to climate change has shown that the physical and climatic properties of catchments can discriminate their capacity to 'damp' or 'enhance' the climate change signal. The resulting characterisation, based on five catchment properties, enables the assignment of a flood sensitivity family for changes in 20-year return period flood peaks to any catchment in Britain with the appropriate properties, without the need to undertake a systematic sensitivity analysis. This, in turn, enables easy impact and vulnerability assessments. The characterisation has been demonstrated here for 20-year return period flood peaks, but has also been determined for 2- and 10-year return periods (Reynard et al., 2009).

Combining these three features has delivered a scenario-neutral framework offering a powerful screening tool (similar to the 'risk screening' tier mentioned by Dessai et al., 2005) to rapidly estimate the impacts resulting from a set of exposures and to quantify the associated vulnerability for different adaptive capacity thresholds. Such analyses can be rapidly updated when any new sets of climate change projections are released, without the need to undertake a complex sensitivity study or top-down impact analysis, which is a real advance as it greatly reduces the computing load after the initial study.

Because the framework is applicable to any catchment in Britain, vulnerability assessments can be readily made for a range of scales (from local to national) but also targeted to different sensitivity types/families or catchment properties, highlighting more vulnerable sets of catchments. Once the response surface of each catchment in an area of interest is available, impacts can be estimated by combining the climate change exposure of each catchment with its response surface, and vulnerability under a range of adaptive capacities can be assessed. When numerous scenarios of exposure and catchments are considered, an overall vulnerability assessment (risk level) can be made for the area of interest (regional or national) by counting the proportion of cases when the resulting impact is above a certain adaptive capacity threshold *C*. This enables the development of climate change allowances by region or sensitivity type/family, instead of a national allowance.

Note however that the sensitivity analysis presented here does not replace complex climate change impact analysis. For catchments less represented by the study sample (large water body area, heavily urbanised), those showing high variability of flood response to precipitation change (e.g. enhanced and sensitive families) and those associated with a lower confidence level and high uncertainty, it is recommended to undertake a full local climate change impact analysis. Later papers will assess the uncertainty associated with the full approach, and present national and regional vulnerability assessments for Britain.

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CLIMATE CHANGE AND RIVER FLOODING: PART 2 SENSITIVITY CHARACTERISATION FOR BRITISH CATCHMENTS AND EXAMPLE VULNERABILITY ASSESSMENTS

Christel Prudhomme, Alison L. Kay, Sue Crooks, Nick Reynard

Tables:

Table 1. Schematic of the decision tree for RP20 and, for each path, the probability associated with each flood sensitivity family and the confidence level for the highest probability family (in bold)

Decision tree schematic						Path #	Flood sensitivity family of path	Confidence level	Probability for flood sensitivity family: Neutral/ Damped	Mixed	Enhanced	Sensitive	Size of leaf (number of elements from sample)
SAAR ≤ 969.5	MAL ≤ 500.5	MAL < 403.5				1	Neutral/ Damped	M	**0.80**	0.20	0.00	0.00	10
		MAL ≥ 403.5	BHP < 73.5	BHP ≤ 4.5		2	Enhanced	H	0.11	0.22	**0.67**	0.00	18
				BHP > 4.5	SAAR ≤ 858	3	Mixed	H	0.00	**0.90**	0.10	0.00	21
					SAAR > 858	4	Neutral/ Damped	L	**0.50**	0.17	0.33	0.00	6
			BHP ≥ 73.5			5	Enhanced	H	0.09	0.00	**0.82**	0.09	11
	MAL > 500.5					6	Sensitive	M	0.00	0.00	0.27	**0.73**	11
SAAR > 969.5	North ≤ 403275	Area < 781.09				7	Neutral/ Damped	H	**0.91**	0.09	0.00	0.00	23
		Area ≥ 781.09				8	Mixed	L	0.00	**0.57**	0.43	0.00	7
	North > 403275					9	Neutral/ Damped	H	**1.00**	0.00	0.00	0.00	45

Table 2. Description and catchment properties of two contrasting example catchments (from Marsh and Hannaford, 2008)

NRFA ID	River	Gauging station	Description	Area km^2	North	BHP %	SAAR mm	MAL mm
28008	Dove	Rocester Weir	Predominantly upland catchment with headwaters draining Millstone Grit and Carboniferous Limestone while lower reaches are Permian and Triassic Sandstones and Triassic Limestones, with some superficial deposits within river valleys. Land use is predominantly moorland and pasture	401	339750	8	1020	445
28066	Cole	Coleshill	Substantially urbanised catchment. Underlying geology: mercia mudstone with extensive coverings of Boulder clay and glacial sand and gravel	120	287500	0	723	508

Table 3. Exposure and associated impact for the Dove at Rocester Weir and the Cole at Coleshill, using a multi-model and multi-emission ensemble of projections for the 2080s. Exposure is defined by harmonic function parameters (*A*, *X_0*, *Φ*) fitted to the median of resampled monthly precipitation change factors for the most appropriate GCM grid cell for each catchment, for 17 CMIP3 GCMs and three SRES emissions scenarios (see Prudhomme et al., 2010). Impact on RP20 is given as the percentage change defined from the composite response surface (Chg) with associated uncertainty due to use of composite response surfaces to represent a range of modelled response surfaces (standard deviation SD).

		Dove at Rocester Weir (NRFA 28008): Neutral					Cole at Coleshill (NRFA 28066): Sensitive				
Emissions scenario	GCM	Exposure			Impact RP20 (%)		Exposure			Impact RP20 (%)	
		A	*Xo*	*Φ**	Chg	SD	*A*	*Xo*	*Φ**	Chg	SD
A1B	BCM2	31.8	3.8	1.9	32	3	23.6	7.5	1.1	32	22
A1B	CGMR	8.2	12.1	10.5	18	2	8.2	12.1	10.5	13	18
A1B	CNCM3	34.2	-8.4	1.3	20	3	31.2	3.9	0.8	20	18
A1B	CSMK3	1.9	1.0	10.7	-2	2	1.9	1.0	10.7	-25	12
A1B	ECHOG	15.4	14.6	1.3	28	2	15.4	14.6	1.3	37	23
A1B	GFCM20	23.7	-5.4	1.0	16	2	23.7	-5.4	1.0	-17	13
A1B	GFCM21	17.6	-1.9	0.9	16	2	39.1	-7.3	1.3	1	15
A1B	HADGEM	14.5	-6.2	1.3	6	2	14.5	-6.2	1.3	-27	12
A1B	INCM3	10.2	5.6	1.9	13	2	10.7	5.6	1.9	-4	15
A1B	IPCM4	5.6	-5.5	3.2	-3	2	5.6	-5.5	3.2	-34	11
A1B	MIMR	10.0	9.9	2.9	18	2	20.6	3.7	1.6	7	16
A1B	MPEH5	0.7	15.0	11.4	15	2	0.7	15.0	11.4	20	20
A1B	MRCGCM	11.3	3.7	4.8	13	2	6.9	6.5	11.3	-8	14
A1B	NCCCSM	20.6	-12.5	0.9	5	2	20.6	-12.5	0.9	-34	11
A1B	NCPCM	11.7	1.7	1.5	7	2	11.9	6.3	2.0	-4	15
A2	BCM2	39.0	13.1	1.2	54	4	28.6	12.3	1.4	39	23
A2	CGMR	15.6	15.4	11.1	29	2	15.6	15.4	11.1	38	23
A2	CNCM3	50.0	-9.1	1.3	36	3	36.1	1.4	1.0	10	16
A2	CSMK3	2.5	8.7	1.4	14	2	2.5	8.7	1.4	7	17
A2	ECHOG	20.8	14.1	1.1	12	2	20.8	14.1	1.1	45	25
A2	GFCM20	30.4	-9.6	1.1	15	3	30.4	-9.6	1.1	-25	12
A2	GFCM21	19.1	-2.4	0.78	16	2	41.0	-9.1	1.5	-14	13
A2	GIER	28.7	2.6	1.9	32	3	28.7	2.6	1.9	20	18
A2	HADCM3	37.1	-3.2	1.4	26	3	37.1	-3.2	1.4	-5	14
A2	HADGEM	16.6	-6.0	0.4	6	2	16.6	-6.0	0.4	-27	12
A2	INCM3	12.8	7.3	1.6	17	2	12.8	7.3	1.6	1	16
A2	IPCM4	11.2	-4.4	0.8	1	2	11.2	-4.4	0.8	-31	11
A2	MIMR	5.6	11.3	1.3	14	2	18.1	2.8	1.1	7	16
A2	MPEH5	11.4	12.9	9.2	24	2	11.4	12.9	9.2	31	22
A2	MRCGCM	7.3	6.5	4.7	8	1	9.9	12.4	0.3	13	18
A2	NCCCSM	27.1	-17.9	0.4	-1	3	27.1	-17.9	0.4	-49	9
A2	NCPCM	10.0	-0.2	2.8	7	2	9.8	5.8	1.3	-4	15
B1	BCM2	29.1	9.4	1.5	38	3	24.2	4.8	1.4	13	17
B1	CNCM3	27.7	-3.0	1.2	21	3	24.3	3.8	1.1	13	17
B1	CSMK3	6.3	3.8	1.1	8	1	6.3	3.8	1.1	-8	14
B1	GFCM20	9.4	1.3	0.8	7	2	9.4	1.3	0.8	-18	13
B1	GFCM21	6.2	-0.7	0.8	2	2	18.9	-5.4	1.0	-22	12
B1	GIER	12.2	2.7	1.4	13	2	12.2	2.7	1.4	-4	15
B1	HADCM3	24.0	1.9	1.0	21	2	24.0	1.9	1.0	-3	15
B1	INCM3	7.8	4.0	2.5	13	2	7.8	4.0	2.5	-4	15
B1	IPCM4	4.1	3.0	5.8	8	1	4.1	3.0	5.7	-8	14
B1	MIMR	6.1	9.2	8.5	14	2	7.8	3.4	2.4	-4	15
B1	MPEH5	2.1	9.4	3.6	10	2	2.1	9.4	4.0	3	16
B1	MRCGCM	3.3	-1.9	4.6	2	2	9.2	3.4	11.1	-4	15
B1	NCCCSM	5.2	-6.5	1.6	-3	2	5.2	-6.5	1.6	-34	11

**Φ* given as month number, for information only: The impact is calculated assuming *Φ*=1 (January)

Figures:

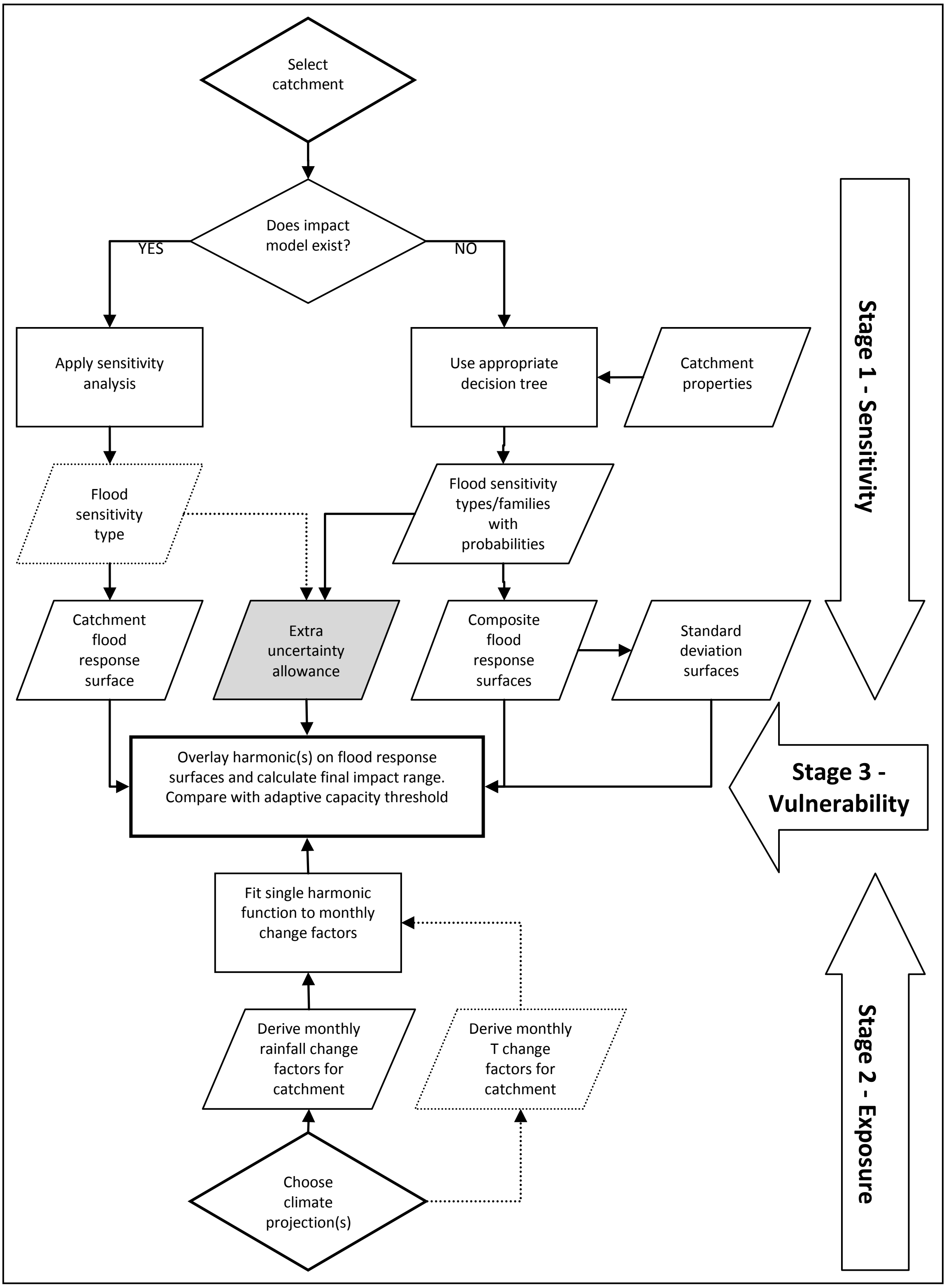

Figure 1. Flow chart describing the steps required for defining the vulnerability of a catchment's flood regime compared to an adaptive capacity threshold. The grey box is not fully implemented here.

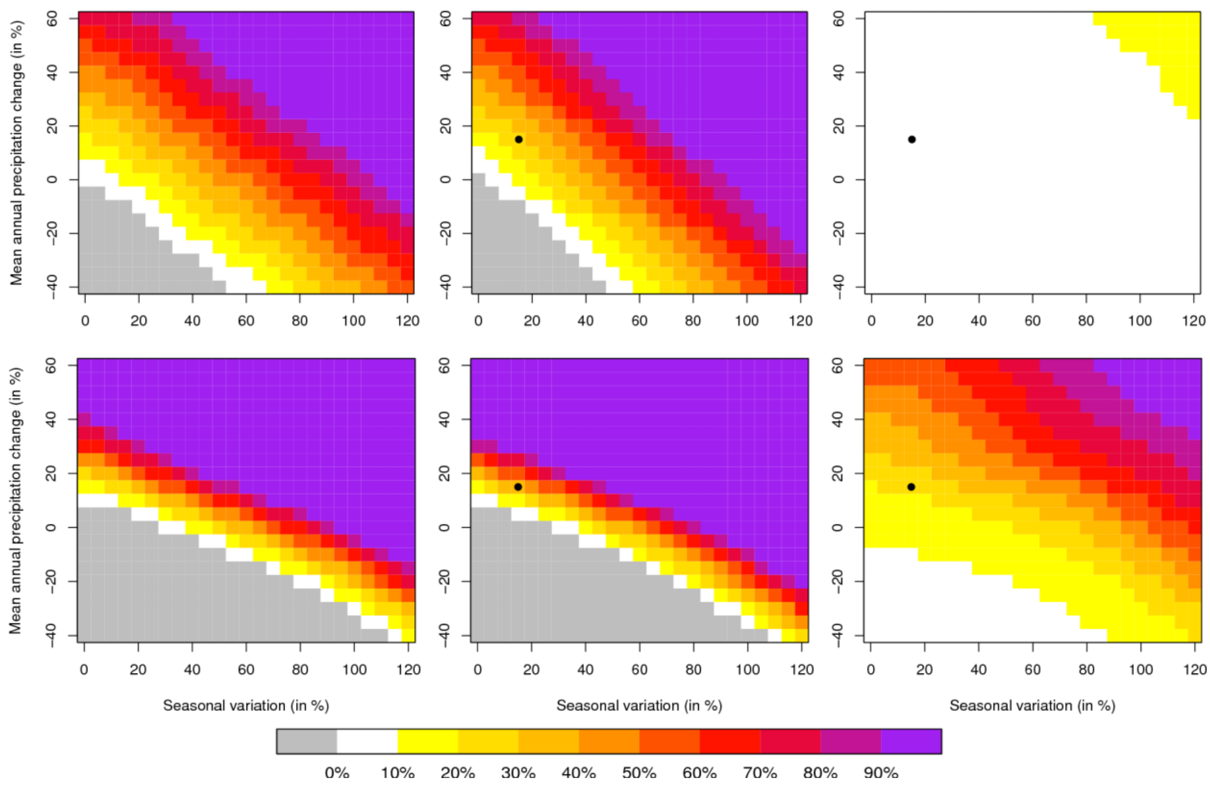

Figure 2. Response surfaces showing the change in 20-year return period flood peaks for the Dove at Rochester Weir (top) and the Cole at Coleshill (bottom) obtained from local catchment modelling (left) and using the decision tree (centre; Neutral composite for the Dove, Sensitive for the Cole). Also shown is the standard deviation (SD) surface associated with each composite response surface (right). Overlaid on each composite and SD surface is a black dot indicating the location of the ECHOG A1B scenario (*A*=15%, X_0=15%; see Table 3).

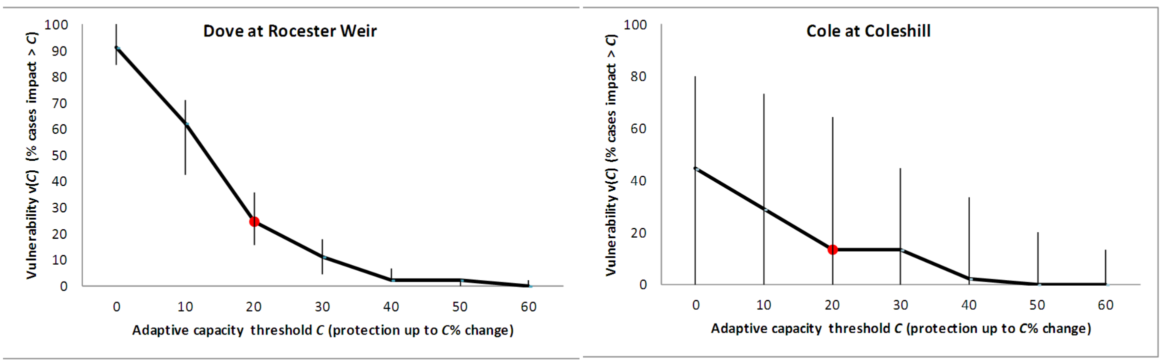

Figure 3. Vulnerability diagram for different adaptive capacity thresholds (*C*) for the Dove at Rochester Weir (left) and the Cole at Coleshill (right). Thick black line constructed from impact defined from exposure and composite response surface (Chg from Table 3); Uncertainty due to use of composite response surfaces to represent a range of modelled response surfaces (using Chg±2*SD) is shown as vertical bands for each C. Red symbol shows the vulnerability associated with the adaptive capacity C=20%

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Climate change and river flooding: part 2 sensitivity characterisation for British catchments and example vulnerability assessments

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Supplementary material

1. Catchment properties considered

Two main sources of catchment properties are available digitally in Britain for a comprehensive number of catchments; the Flood Estimation Handbook (FEH; Reed (1999)) and the National River Flow Archive (NRFA) Hydrometric Register (Marsh and Hannaford, 2008). The FEH provides a CD-ROM containing digital descriptors for over four million UK catchments that drain an area of at least 0.5 km^2 (Bayliss, 1999). The Hydrometric Register is a catalogue of UK river flow gauging stations holding summary hydrometric and spatial statistics for over 1,500 river basins. Thirty eight properties are available for each catchment. After preliminary analysis, a sub-selection of FEH and NRFA catchment properties (Table a) is included in the discriminant analysis of flood sensitivity families. The selected FEH properties include physical (e.g. AREA, DPSBAR and ALTBAR) and locational (e.g. EAST and NORTH) properties which are constant over time, climatic and related wetness properties (e.g. SAAR, PROPWET and SMDBAR) which may vary over time (through natural variation or climate change), and land related properties (e.g. the three urban properties) which may change with time. Where properties may change then the values used are for a stated reference period, 1961-1990 for climatic properties and 2001 for land use, so that change in flood frequency is relative to the current conditions. The Hydrometric Register properties, MARu and MAL, are not available for a standard reference period but for the period of observed flow record, used as representative of current conditions.

Some additional statistics were also considered, to evaluate whether the sensitivity is influenced by the seasonality in the hydroclimatology of the catchments. Three variables were derived from the time series data for the case study catchments (Table b). Summer.PE provides a measure of the average dryness of a catchment during the summer and therefore the impact of changing soil moisture deficit on flood potential during the autumn. The value of Summer.PE indicates how much changes in summer rainfall and PE are likely to impact on flood frequency. A value much greater than 1.0 indicates that autumn flood potential is unlikely to be affected by climate change (autumn floods will still be readily generated). Similarly autumn flood potential will be little changed with a Summer.PE value much smaller than 1.0 (autumn floods unlikely to be generated). However, if the ratio is close to 1.0 then changes to summer rainfall and PE will impact on the generation of floods during the following months, with implications for changes in flood frequency. POT1 is the sample corresponding to the Y highest independent daily flood peaks that have been recorded in the daily flow series, where Y is the number of years of available flow records. The POT1-type variables evaluate if the season of the main peak floods in the baseline has a significant influence on the sensitivity family. As the largest increase in rainfall is assumed to occur in winter, if the majority of baseline flood peaks occurred in winter then the increase in flood discharge may be greater than if the majority of peaks occurred in the summer (see Prudhomme et al., submitted, for details of the P change scenarios).

Table a. Catchment properties considered for the analysis

			FEH catchment properties		
Acronym	**EAST**	**NORTH**	**AREA**	**BFIHOST**	**DPLBAR**
Variable	Easting of catchment outlet (in GB national grid)	Northing of catchment outlet (in GB national grid)	Catchment drainage area (km^2)	Base flow index derived using the HOST classification	Index describing catchment size and drainage path configuration (km)
Acronym	**DPSBAR**	**FARL**	**PROPWET**	**SAAR**	**SPRHOST**
Variable	Index of catchment steepness	Index of flood attenuation due to reservoirs and lakes	Index of proportion of time soils are wet	1961-90 standard period average annual rainfall (mm)	Standard percentage runoff derived using the HOST classification (%)
Acronym	**ALTBAR**	**ASPBAR**	**ASPVAR**	**LDP**	**RMED**
Variable	Mean catchment altitude (m above sea level)	Index representing the dominant aspect of catchment slopes	Index describing the invariability in aspect of catchment slopes	Longest drainage path (km)	Median annual maximum rainfall (mm)
Acronym	**SMDBAR**	**URBEXT**	**URBCONC**	**URBLOC**	
Variable	Mean soil moisture deficit defined by MORECS for 1961-90 (mm)	Index of fractional urban extent	Index of concentration of urban and suburban land cover	Index of location of urban and suburban land cover	
			UK Hydrometric Register catchment properties		
Acronym	**MEAN ANN RUNOFF (MARu)**	**BEDROCK HIGH PERMEABILITY (BHP)**	**BEDROCK MODERATE PERMEABILITY (BMP)**	**BEDROCK VERY LOW PERMEABILITY (BVLP)**	
Variable	Depth of water over the catchment equivalent to the mean annual flow (mm)	Proportion of the catchment underlain by rock formations of high permeability	Proportion of the catchment underlain by rock formations of moderate permeability	Proportion of the catchment underlain by rock formations of low permeability	
Acronym	**MEAN ANNUAL LOSS (MAL)**	**GEN HIGH PERMEABILITY (GHP)**	**GEN LOW PERMEABILITY (GLP)**	**MIXED PERMEABILITY (MP)**	
Variable	Difference between mean annual catchment rainfall and mean annual catchment runoff (mm)	Proportion of the catchment underlain by superficial deposits of generally high permeability	Proportion of the catchment underlain by superficial deposits of generally low permeability	Proportion of the catchment underlain by superficial deposits of mixed permeability	

HOST is the Hydrology of Soil Types classification system (Boorman et al., 1995)
MORECS is the Met Office Rainfall and Evaporation Calculation System (Thompson et al., 1982)

Table b. Additional catchment properties

Acronym	Summer.PE	POT1.3m	POT1.2m
Variable	Average annual ratio between rainfall and potential evaporation for the 6 month period April to September	Proportion of POT1 peaks observed in 3-month periods (NDJ, FMA, MJJ, ASO)	Proportion of POT1 peaks observed in 2-month periods (DJ, FM, AM, JJ, AS, ON)

Preliminary analyses showed that these additional properties could be selected in some paths, but overall performance was only marginally different from paths which only used FEH and Hydrometric Register properties. Thus it was decided not to use these statistics as they would not be easily available for catchments not included in the study.

2. Decision trees

A decision tree divides the space of possible observations (catchments) into sub-regions of the same category according to descriptors (catchment properties). A category can be a flood sensitivity type or family; the latter are used in the description below. Decision trees thus enable the assignment (in probabilistic terms) of a sensitivity type/family to a catchment from a set of metadata for the catchment.

For each path an indicator of confidence is calculated that combines how certain the highest probability estimate is with how robust it might be, where these concepts are defined as:

- **Certainty** of the probability estimate, measured by the difference between the two top probabilities for the path. A large difference indicates that the great majority of the catchments following the path are from the same family, and it is very likely that a new catchment with properties consistent with that path would have the same family. Conversely, a nil/small difference reflects that, when following the path, the two top families are equally/near-equally likely.
- **Robustness** of the probability estimate, measured by the percentage of the original sample following the path. For a large group, the highest probability is unlikely to change much if one catchment is added or removed from the sample; for a small group, the addition or removal of one catchment might significantly change the probability values, and even change the order of the top categories.

The product of certainty and robustness is an indication of the confidence in the sensitivity family associated with the highest probability. Values (in %) range from 0 (when the two top priorities are identical) to a hypothetical maximum of 100 (if the whole sample belongs to the same category and there is a single leaf). Thresholds of 2 and 5 were chosen to flag Low, Medium and High confidence levels. High confidence is thus given to estimates with high certainty and high robustness, while Low confidence is given to estimates with low certainty and/or low robustness, as a slightly different sub-sample might have resulted in completely different 'recommended' categories using the same path.

The contingency table is a way to quantify the performance of a decision tree (Jolliffe and Stephenson, 2003). The contingency table of the decision tree identified to characterise the sensitivity families for changes in RP20 (Table c) shows a relatively high hit rate (family assigned by decision tree equal to that simulated using hydrological model) of 85%.

Table c. Contingency table associated with the decision tree identified to characterise the sensitivity families for changes in RP20. Cells in the diagonal (bold) show the number of catchments correctly assigned to a sensitivity family by the decision tree; cells below the diagonal show false alarms (assigned family more sensitive than simulated); cells above the diagonal show misses (assigned family less sensitive than simulated).

		Simulated sensitivity family			
		Neutral/ Damped	Mixed	Enhanced	Sensitive
Assigned sensitivity family	Neutral/Damped	**77**	5	2	0
	Mixed	0	**23**	5	0
	Enhanced	3	4	**21**	1
	Sensitive	0	0	3	**8**

3. Hydrological discussion

River flow regime is known to be dependent on physical and climatic catchment properties and this paper investigates whether catchment properties can characterise a catchment's flood response to climatic changes. Although this paper presents the decision tree characterising the four sensitivity families (groups of sensitivity types) for changes in RP20, the nine sensitivity types are used for changes in RP2 and RP10 (2- and 10-year return period flood peaks) and decision trees were built to characterise the types for these flood indicators (see Reynard et al., 2009). Using the decision trees that characterise the sensitivity type or family for the three flood indicators (RP2, RP10 and RP20) it is possible to highlight the dominant characteristics associated with each sensitivity type (Table d).

The characterisation of sensitivity families established in this paper highlights that the annual water balance in a catchment (i.e. how different/similar mean annual rainfall, SAAR, and mean annual losses, MAL, are) is critical in shaping how the catchment responds to changes in the climate, as it characterises the catchment's capacity to respond to the climatic signal and to generate proportionally smaller or larger changes in flood peaks than the imposed P changes. This is consistent with work in Austria by Merz and Blöschl (2009) who found larger variability of the runoff coefficient of dry catchments (where mean annual P and mean annual losses are of similar magnitude) than of wet catchments (where mean annual P is greater than mean annual losses). For dry catchments, the seasonality of the water balance is an aggravating factor - those with a 'critical' summer water balance have some of the most sensitive sensitivity types/families. While summer might not be the main flood-generating season in most parts of Britain, it is important for the annual flood regime in some catchments as the balance of summer precipitation and losses (mainly through evaporation) governs the build-up of soil moisture deficits in the warmer and drier months; subsequently this influences the time when infiltration and groundwater recharge begin and the catchment saturation level of later seasons. These complex hydrological processes result in soil moisture variation generating higher variability in runoff coefficient than rainfall variation (Merz and Blöschl, 2009). This is consistent with work by Sivapalan et al. (2005) in Austria, who identified seasonality in P and evaporation as governing the generation of floods through their effects on antecedent conditions.

Table d. Dominant catchment properties for the nine flood sensitivity types

Sensitivity type	Dominant properties
Damped-Extreme	Medium to high SAAR, possible snowmelt influence, flood events have summer predominance
Damped-High	Generally high SAAR, possible snowmelt influence, generally low permeability (short memory), flood events mainly not in winter (Dec – Feb)
Damped-Low	Medium to high SAAR, water balance not affected by change, generally low permeability
Neutral	Generally high SAAR, water balance not affected by change, low to medium permeability, flood events mainly in winter
Mixed	Generally low SAAR, summer water balance important, low to medium permeability
Enhanced-Low	Low to medium SAAR, not high permeability
Enhanced-Medium	Low SAAR, generally low-lying, not high permeability
Enhanced-High	Low to medium SAAR, generally high permeability but also low permeability with critical summer water balance
Sensitive	Low to medium SAAR, high Mean Annual Loss, summer water balance very sensitive to change, medium to high permeability

For definitions of SAAR, Mean Annual Loss and permeability see Table a; permeability refers to bedrock permeability

After catchment wetness, bedrock permeability is the next dominant property in the decision tree divisions. Merz and Blöschl (2009) found that land use, soil type and geology did not seem to exert a major control on runoff coefficients but suggest that hydraulic conductivity could provide a better correlation. Bedrock permeability properties were selected in the decision trees in preference to permeability of superficial deposits or BFIHOST and SPRHOST (properties based on the HOST classification). This suggests that it is the permeability of the substrate which is important rather than the specific geological or soil type. Catchments with low permeability are relatively less variable in how flood peaks change in response to change in P than those with higher permeability. There is greater linearity in the relationship between change in P and change in flood peak in catchments with low permeability than catchments with high permeability. This is because catchments with high bedrock permeability benefit from groundwater storage, and changes to the amount of water stored affect outflow from storage over periods from seasons to years. Thus the impact of change can be cumulative. Conversely, catchments of low bedrock permeability do not have groundwater storage and therefore lack the capacity for the wetness/dryness of one year to affect the river flow of following years. The relationship between catchment bedrock permeability and sensitivity type might be counter-intuitive as high permeability is often interpreted as meaning greater resilience to climate variability – and by extension to its change. But climate variability is short-term variation, during which high permeability catchments do not respond as rapidly as low permeability catchments, whereas climate change is long-term allowing the persistence of change to have relatively more impact on the flood characteristics of catchments with high bedrock permeability.

As mentioned above, the influence of seasonal water balance and catchment properties on streamflow generation is well known, but this is the first time (to the knowledge of the authors) that their role in shaping the (quantified) response of flood flows to climatic changes has been systematically evaluated for an extensive range of climate scenarios and catchments. The work shows that the non-linearity of the rainfall-runoff transformation and the propagation of the climate-to-flood change signal can be estimated with some degree of success by a set of climatic and physical catchment properties. Up to now, the role of the catchment in its response to climatic change has often been implicit and less investigated in climate change impact and adaptation studies than the climate change signal itself (see for example Kay et al., 2009; Veijalainen et al., 2010; Vidal and Wade, 2009). This deficiency was recognised by Ntelekos et al. (2010), but while they clearly identified the major role the level and type of urbanisation has on the sensitivity of an area to climatic changes, they did not attempt to formally link the response of a catchment to its physical (and non physical) characteristics and only evaluated the impact of a few scenarios (derived from climate models) on flooding. As most studies are based on few catchments, generalising their results is problematic, and the mixed results obtained in climate change impact studies cannot be systematically explained as they reflect a '*complex interplay between downscaled climate change scenario(s) and regional variations in catchment properties*' (Wilby et al., 2008). The scale (both in terms of the number of scenarios and number of catchments) of the sensitivity analyses undertaken by Prudhomme et al. (submitted) made possible the quantification of the variety of catchment's responses to climatic changes in Britain and the link between these responses and catchment properties – and by extension, to the main hydrological processes of the catchments. These results approach a formalised categorisation of 'impact of changes on hydrological processes' as attempted empirically for land use changes by Bronstert et al. (2002) and Wilby et al. (2008). The role of different processes shaping the response of a system to climatic change is unlikely to be relevant only to river flooding. For example, the importance of landscape and feeding mechanisms of wetlands (rain, river or groundwater feeding) might impact on the response of wetlands to changes in climatic patterns, hence enabling generalisation of their possible sensitivity to climate change using the systematic approach developed here.

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