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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: FD2020
2. Project title: Regionalised impacts of climate change on flood flows
3. Contractor organisation(s):
   CEH Wallingford
   Crowmarsh Gifford
   Wallingford
   Oxfordshire
   OX10 8BB
4. Total Defra project costs (agreed fixed price): £ 236683
5. Project: start date .... 01 October 2005
   end date .... 30 November 2009

6. It is Defra's intention to publish this form.
   Please confirm your agreement to do so...**YES** ☒ **NO** ☐

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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

See attached file

Executive summary

The primary objective of FD2020 ‘Regionalised impacts of climate change on flood flows’ was to assess the suitability of the October 2006 FCDPAG3 guidance on climate change[1]. This guidance requires an allowance of 20% to be added to peak flows for any period between 2025 and 2115 for any location across Britain. This guidance was considered precautionary and its derivation reflected the evidence available at that time. FD2020 has been designed to increase this evidence base and the research findings suggest that regional, rather than national, guidelines for changes to peak flows due to climate change might be more appropriate.

The majority of climate change impact analyses are scenario-led using the outputs from one or more Global (GCM) or Regional Climate Models (RCM). There are two main weaknesses of this approach. First, a full understanding of the inter-relationships between climate changes, catchment properties and changes in flood flows cannot be obtained. Second, no insight is gained into what might occur if something happens other than the exact projections of the climate model-based scenarios, so that when new scenarios are released, new impact studies have to be performed. This implies that any policy derived from this scenario-led evidence is equally time-limited. To overcome this issue, this project took a different approach, basing the methodology on a wide-ranging sensitivity analysis, and as such is **scenario-neutral** and not dependent on any one set of climate change scenarios. The approach investigates catchment response to changes in climate by imposing the same changes to a set of catchments across Britain. This allows those catchments that respond in a similar manner to be grouped together, or “regionalised”, into flood response types. To ensure the results are robust, and any subsequent policy guidance long-lasting, the framework has been designed to investigate changes in climate that encompass current knowledge of future climate change available from the GCMs of IPCC Fourth Assessment Report and RCM used to derive the suite of UKCP09 products.

The method allows any catchment, including those not modelled as part of this project, to be allocated to a flood response type according to its catchment properties, and hence its vulnerability to climate change assessed. The research has also provided a range of other catchment, and scenario-specific tools, for assessing the **risk** of change in peak flows, and these are illustrated in this report.

The research has led to a number of key findings in relation to the project objectives. First, the catchment-based analysis suggests that the current allowance can no longer be considered precautionary as a change of 20% does not encompass the majority of catchment changes in flood flows. Second, there is strong evidence that catchment response to climate change (in terms of change in flood flows) is influenced by catchment properties. This implies that a single national allowance for climate change might not be appropriate and that more “regionalised” allowances, depending on catchment type, could be developed.

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[1] www.defra.gov.uk/environment/flooding/policy/guidance/project-appraisal.htm

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
    - the scientific objectives as set out in the contract;
    - the extent to which the objectives set out in the contract have been met;
    - details of methods used and the results obtained, including statistical analysis (if appropriate);
    - a discussion of the results and their reliability;
    - the main implications of the findings;
    - possible future work; and
    - any action resulting from the research (e.g. IP, Knowledge Transfer).

See attached file

1 Science Objectives for project FD2020

1.1 Project context and objectives

Current guidance on incorporating the impact of climate change on peak river flows in flood management decision-making is enshrined in the FCDPAG3 supplementary note, 2006[1]. This guidance presents a nationally uniform allowance of 20%, static beyond 2025 and described as precautionary.

The aim of this project is to provide additional scientific evidence against which the validity of the current guidance can be assessed and the possibility of developing new regionalised climate change guidelines for flood management can be explored.

In particular, the project aimed to:

- Investigate the impact of climate change on a number of catchments in England and Wales to assess the suitability of the FCDPAG3 20% climate change allowance for river flood flows given the developments in science;
- Investigate a number of catchments' response to climate change to identify any national variation such that the FCDPAG3 allowance could be regionalised. The term regionalised is not limited here to location but could equally be a function of any of the catchment characteristics;
- Investigate the uncertainty in understanding changes to future river flood flows from climate change.

2 Methodology

The majority of climate change impact analyses use the outputs from one or more Global (GCM) or Regional Climate Models (RCM), meaning that the resulting impacts are only valid until a new generation of GCM and RCM results become available. This implies that any policy set on the basis of this scientific evidence is equally time-limited. To overcome this issue, this project took a different approach basing the methodology on a wide-ranging sensitivity analysis and hence allowing this approach to be **scenario-neutral**, and not dependent on any one set of climate change scenarios. This approach investigates the catchment response to changes in climate by imposing the same scenarios of change to a set of catchments across Britain, hence allowing those catchments that respond in a similar manner to be grouped together ("regionalised"). To ensure the results are robust and any resulting policy guidance long-lasting, the framework has been designed to investigate changes in climate that encompass current knowledge of future climate available from the IPCC AR4 and UKCP09 products.

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[1] www.defra.gov.uk/environment/flooding/policy/guidance/project-appraisal.htm

While this method allows any catchment (including those not modelled in this project) to be allocated to a group, and hence its vulnerability to climate change assessed, it also provides a range of other catchment and scenario-specific tools for assessing the **risk** of change in peak flows.

The methodology developed follows a relatively simple concept, shown schematically in Figure 1. The same climate change drivers are imposed on all of the 155 modelled catchments and the response of peak flows to these changes analysed, initially, on a catchment basis. This provides a wealth of information that can afterwards be compared to individual, or multiple GCM/RCM projections. Thereafter, these catchment flood regime responses (called flood response patterns) are categorised (or grouped) according to their similarity in terms of the climate-driven flood responses as opposed to geographic "regions". Four indicators of change in flooding were chosen for the analysis, these being the change in the magnitude of daily flood peak of the 2-year, 10-year, 20-year and 50-year return period events (i.e. the change in magnitude of the flood that would be expected to recur, on average, every 2, 10, 20 or 50 years). For each of these indicators, all catchment responses are analysed and characterised according to their flood response pattern. Key families of flood responses are distinguished and relationships with the catchment's characteristics identified, leading to a catchment characteristic-based "regionalisation".

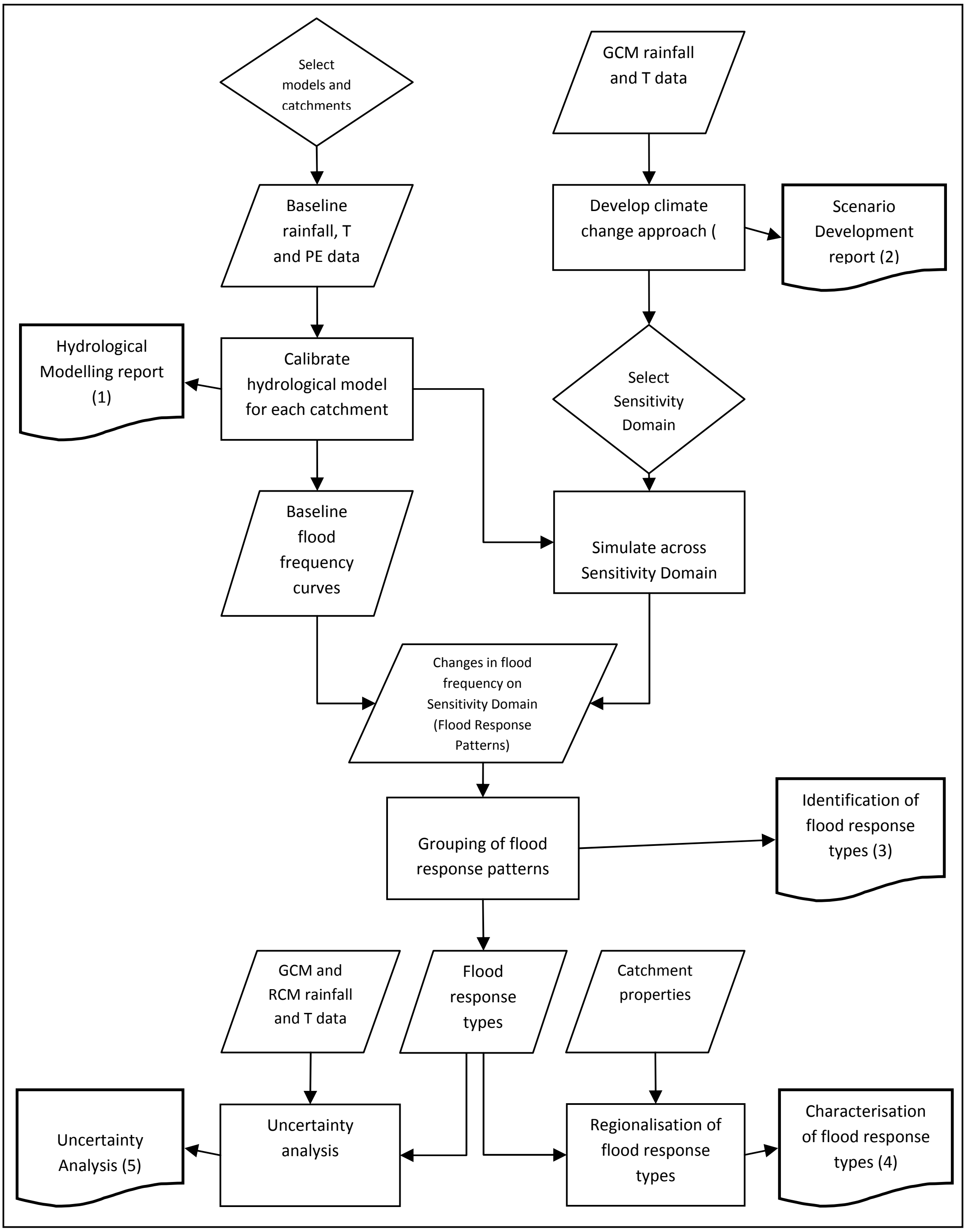


Figure 1 Schematic of project FD2020

2.1 Hydrological Modelling

The hydrological modelling tasks within this project provide the fundamental building blocks for the subsequent analysis of the potential impacts of climate change on flood flows, and the regionalisation of those impacts. It was therefore essential that the models are set up and calibrated as robustly as possible. In particular, the inclusion of snowmelt within the models was considered crucial, given the project’s aim to *regionalise* the impacts of climate change on flooding, as the winter flow regime of upland catchments can be considerably affected by snowfall and snowmelt, even in the UK, and changes in temperature will almost certainly alter the balance between snowfall and rainfall processes in such catchments in the future.

In total, 154 catchments across Britain were modelled. There are 120 catchments modelled with a lumped conceptual hydrological model, the Probability Distributed Moisture (PDM) model and 35 (generally larger) catchments with a semi-distributed hydrological model (CLASSIC), with one catchment being modelled using both models, so there are 155 sets of calibration results presented. The final calibrations include the use of a snowmelt module, which has been applied with a fixed set of module parameters for all catchments, to avoid an arbitrary decision on which catchments are affected. The hydrological models with the snowmelt module require input time-series of precipitation, potential evaporation and temperature to simulate mean daily flow. Overall, model performance improved when the snowmelt module is applied.

The calibrated models were used to simulate baseline time series of mean daily flows from which a set of independent flood peaks is extracted for each catchment. For the majority of catchments there was a good comparison between flood frequency curves fitted to the observed and modelled mean daily flood peak data sets. Reasons are identified where there are considerable differences between the observed and modelled curves.

The final calibrated parameter sets were used in the next part of the project: the application of a large, regular set of perturbations to observed precipitation time-series, alongside a smaller set of (linked) perturbations to temperature and PE time-series, to investigate the relative sensitivity of different catchments to the potential range of climate change.

2.2 Climate scenario approach

The objective was to develop a methodology to evaluate the **vulnerability** of catchment flood regimes to climate change. This required the identification of a range of climate change scenarios for a comprehensive, yet manageable evaluation of future river flood flows, which was guided by, but not limited to, current projections of climate changes. This methodology also characterises the climatic change **hazard**, for comparison with catchment vulnerability to change.

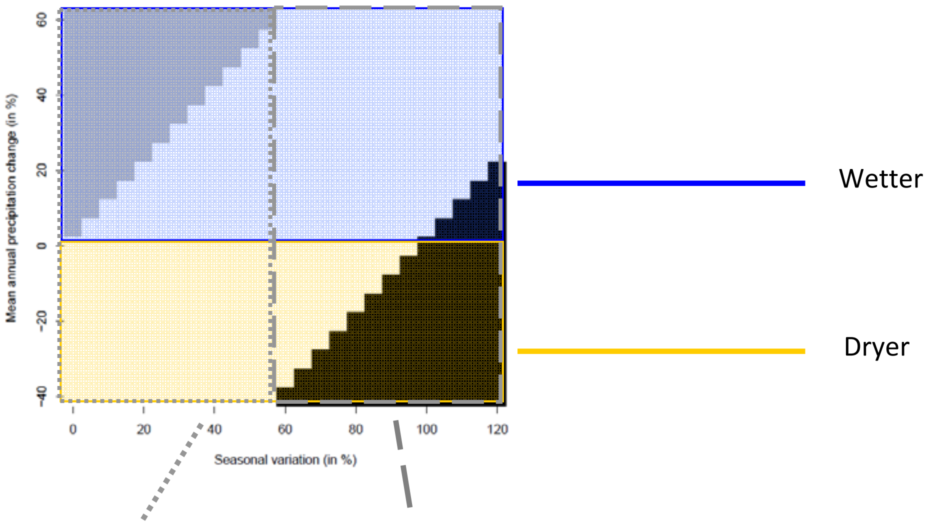
Projections from 17 GCMs, for three emission scenarios were analysed for all land cells over Britain to calculate monthly factors of climate changes. It emerged that it is possible to describe the seasonal pattern of monthly change factors using a single harmonic function defined in terms of the mean annual change, the maximum monthly change and the month in which this maximum occurs. The monthly changes in precipitation almost always show a peak in winter, while for temperature the peak could occur at any time of year.

For rainfall, the month of maximum change is fixed to January, so that the sensitivity framework can be reduced to a two-dimensional space defined by changes in mean annual rainfall (from an annual reduction of 40% to an annual increase of 60%) combined with changes in rainfall seasonality (from 0% to 120%). Using the harmonic formulation, this represents 525 smoothed monthly precipitation scenarios for rainfall (allowing for 5% increments of change in both the mean annual rainfall and the seasonality), built to incorporate all current projections of future climate for any location in Britain. For temperature, eight scenarios were selected and corresponding PE scenarios evaluated.

For each catchment, the eight warming scenarios (temperature and corresponding PE changes) are each used in combination with the 525 precipitation scenarios to create an **8-member ensemble** (one member per warming scenario) of climate-driven changes in a chosen flood indicator. For interpretation the result from each ensemble member is displayed in a 2-dimensional space for each analysed indicator, as shown in Figure 2 and Figure 3:

- Y-axis: Mean annual change; the bottom half part of the diagram represents an overall decrease in the mean annual precipitation (drier climate); the top half of the diagram represents an overall increase in the mean annual precipitation (wetter climate) (Figure 2).
- X-axis: Maximum season change; the left part of the diagram represents scenarios where changes in the winter and in the summer are not very different (no change in the precipitation seasonal pattern); the right part of the diagram represents scenarios where changes in winter are much larger than changes in the summer (increased seasonality with wetter winters and drier summers). This can be interpreted as intensification in the seasonal cycle (Figure 2).

For some rainfall scenarios, precipitation increases in all months, including in the summer (high mean rainfall change combined with a low seasonal variation): these are highlighted in grey in the top left of Figure 2. For others, the summer rainfall is reduced to nil (low mean annual change combined with high seasonal variation, leading to factors lower than -100% for some summer months). These scenarios are highlighted in black in the bottom right of Figure 2.



Low seasonality High seasonality

Figure 2 Scenario characteristics of the sensitivity domain

Each diagram contains 525 squares, each corresponding to a different precipitation scenario (or inter-annual change pattern). A schematic of the space with its corresponding monthly precipitation scenarios is given in Figure 3.

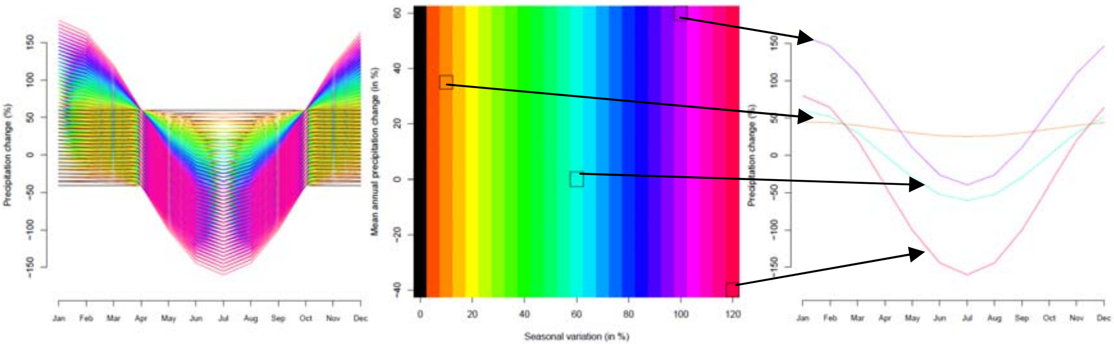


Figure 3 Construction of the sensitivity domain and corresponding inter-annual change scenarios

2.3 Defining the vulnerability: Identification of key flood response types

In the scenario-neutral approach developed in the project, the vulnerability of a catchment is characterised in two steps: firstly, the response of the flood regime to a range of climatic changes is simulated and analysed for similarity, and secondly the major flood responses are characterised according to catchment properties. This section describes the first of these steps. The changes in flood peak for 154 catchments across Britain were modelled according to a comprehensive framework of 4,200 patterns of change in rainfall, temperature and potential evaporation (PE).

The formulation of the harmonic functions leads to ‘smoothed’ monthly percentage change factors, which are used to produce alternative climate series. These climate time series are input to the hydrological model to generate river flow time series which are compared with the simulated baseline series. Changes in the magnitude of flood peaks of 2, 10, 20 and 50-year return period (i.e. the flow that would be expected to occur, on average, once every 2, 10, 20 or 50 years) were selected as the indicators of change in the flood regime. The percentage changes in these flood indicators are representative of the response of the catchment to a variety of different climates and hence describe the vulnerability of the flood regime to changes in climate.

The analysis of all the individual catchment flood response patterns resulted in the identification of nine flood response types for all flood indicators, shown in Figure 4. They can be described by five main families of behaviour: Neutral catchments, for which the changes in flood peak magnitude are of similar magnitude to the maximum change in monthly rainfall; Damping catchments, which are relatively resilient to small changes in rainfall; Enhancing catchments, which are relatively vulnerable to small changes in rainfall; Mixed catchments, which are both vulnerable and resilient to changes in rainfall, depending on the magnitude and seasonal pattern of the rainfall changes; and Sensitive catchments, which are very vulnerable to almost any increase in rainfall. The nine key flood response types fully describe the range of responses in the flood regime to climate change in Britain. Hence they characterise the vulnerability of a catchment’s flood regime to changes in climate.

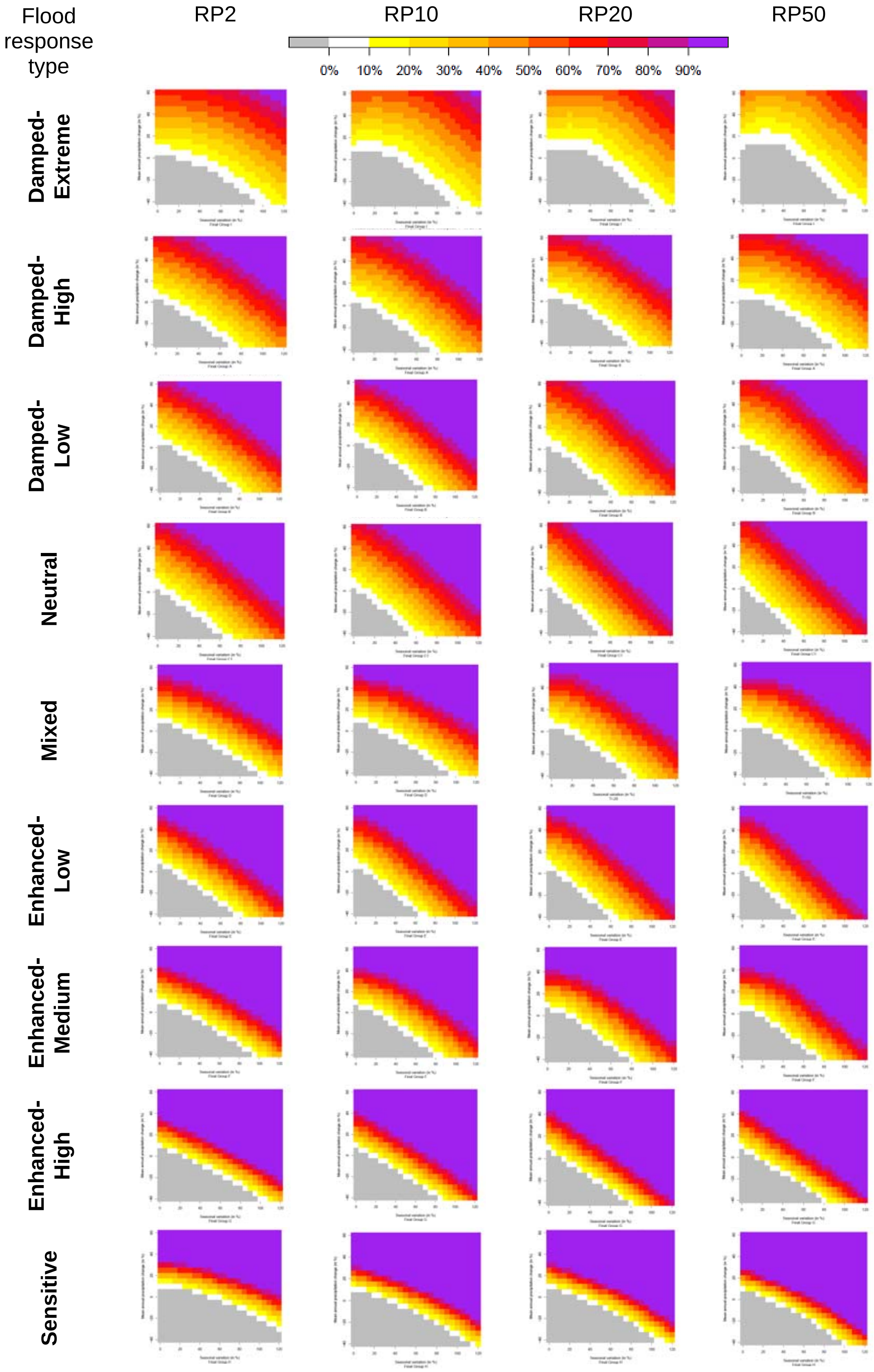


Figure 4 Key flood response patterns (averaged over the eight T/PE scenarios) for the nine flood response types, for the four flood indicators

2.4 Defining the vulnerability: Regionalising the key flood response types

This section describes the second step of the assessment of the vulnerability of a catchment's flood regime to climatic change. This is achieved by identifying the relationships between catchment characteristics (geographic, geologic or climatic) and the vulnerability of the flood peaks of a catchment to changes in the climate.

Nine flood response types representing the vulnerability of British catchments to climate change were identified; one group was removed from the analysis as it was made of only three of the study catchments, hence too few for a reliable model to be built. This left eight flood response types to characterise. Using a hierarchical partitioning technique and digital catchment descriptors from the Flood Estimation Handbook and the Hydrometric Register databases, a decision tree was identified for each indicator to discriminate between the flood response types. Nine descriptors in total were used in the four decision trees including mean annual rainfall, area, northing and easting, elevation, and measures of bedrock permeability and catchment losses by abstraction and evaporation.

At the 2-year return period level, all eight flood response types could be discriminated. For changes in the 20- and 50-year return period floods, the flood response types had to be merged into four main categories before they could be discriminated by the catchment characteristics. This merging was also necessary to ensure that uncertainty due to the impact of seasonality in rainfall change was fully incorporated into the flood response types.

For the most enhancing catchments (i.e. where the changes in flood peak are proportionally much greater than the maximum changes in rainfall), the difference between the mean annual rainfall and the losses in the catchment was found to be an important discriminatory factor. For changes in higher return period floods, mean annual rainfall was found to be less critical. Wetter catchments were found to be in general less enhancing than drier catchments. Large catchments seem to be slightly more difficult to classify, suggesting they might not be fully represented by single value descriptors which smooth out spatial variations important in the response of the river to climatic changes.

2.5 Uncertainty Analysis

This section describes the analysis undertaken to assess the potential level of uncertainty, due to various assumptions and simplifications necessary to develop the project's 'scenario-neutral' approach to regionalisation. The main aim of the uncertainty analysis is to assess whether values extracted from the flood response patterns will consistently over- or under-estimate the impact of climate change scenarios. The uncertainty analysis thus addresses the following factors:

1. Assumptions made for sensitivity framework development;
2. Use of a fitted harmonic instead of monthly factors;
3. Use of the simple delta change method of downscaling;
4. Natural variability.

Due to the number of factors investigated, the analysis is performed on a small subset of catchments, chosen to be as representative as possible of the nine flood response types found in

Great Britain. There is one catchment modelled with the PDM (at a daily time step) for each of the nine flood response types, for which the full uncertainty analysis is performed. In addition, there are four catchments modelled with CLASSIC (at a daily time step), representing four of the flood response types, for which a subset of the analysis is performed.

The results show that the level of uncertainty from different factors varies significantly between catchments. For some catchments the overall level of uncertainty varies little with return period, whilst for others it increases / decreases with return period. The four CLASSIC catchments show a similar pattern of uncertainty to that for the corresponding PDM catchments. However, each of the CLASSIC catchments has a higher level of uncertainty than its corresponding PDM catchment. This probably reflects the larger catchment area of the CLASSIC catchments.

Generalising the catchment results to their flood response types suggests that 'Neutral' catchments will have the lowest level of uncertainty and 'Sensitive' catchments will have the highest level of uncertainty, as shown in Table 1. The different levels of uncertainty for the different catchment types are compatible with the underlying climatological and hydrological differences between their flood response types.

Table 1 Suggested extra uncertainty allowances (and their multiplication factors for larger catchments), by response type and flood return period

Flood response type:	RP2	RP10	RP20	RP50
Damped-Extreme	10	11	11	11
Damped-High	**8**	11	12	16
Damped-Low	**8**	**6**	**7**	**8**
Neutral	**3**	**3**	3	3
Mixed	**16**	**13**	**11**	**10**
Enhanced-Low	**7**	**6**	7	**8**
Enhanced-Medium	**12**	**12**	15	18
Enhanced-High	**14**	**12**	**9**	6
Sensitive	**20**	**20**	**20**	**20**
If Area > 2000km^2	x1.0	x1.3	x1.7	x2.1

Numbers in bold are those to be used with (merged) key response patterns, when a catchment's response type is estimated from catchment properties. Note that, where flood response types are merged (outlined squares), the middle uncertainty allowance is applied.

Numbers not in bold are only required for use with modelled catchment response patterns.

Despite the small number of catchments investigated here, the fact that the results are physically reasonable, and the similarity of the results for comparable PDM and CLASSIC example catchments, gives confidence in the extension of the results to catchment type.

3 Application of the methodology

The FD2020 concept and methodology allows the rapid estimation of the change in daily peak flows (for the 2-, 10-, 20- or 50-year return periods) under any climate change scenario (or set of scenarios), for any catchment in Britain where the set of catchment characteristics are available. The method involves a three-stage process.

- **Vulnerability:** Determine the vulnerability of a catchment flood regime to climate change, defined by a set of 4,200 changes for four flood indicators, organised in a flood response pattern following a strict analytic framework
- **Hazard:** Determine the hazard from future climate change projections, defined from a single-phase harmonic function summarising the seasonal variation in monthly climate change factors
- **Risk:** Determine the risk of flood change as the combination of vulnerability and hazard, defined as the change in the flood indicators corresponding to one of the 4,200 scenarios of the flood response pattern the closest to the characteristics of the hazard. Extra change can be added to incorporate uncertainty from Table 1 (above).

3.1 Worked example

This section presents a worked example for one of the case study catchments, but assumes that its response type is unknown and therefore needs to be derived from catchment properties. The following is a step-by-step guide of the use of the FD2020 project method, described above.

Site number: 02001 (Helmsdale at Kilphedir)

Catchment descriptors (Table 5.2 explains the descriptors):

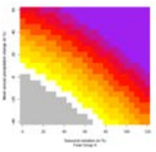
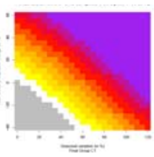
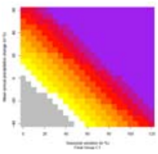
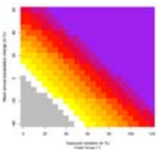
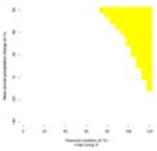
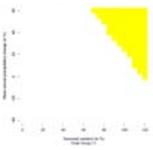
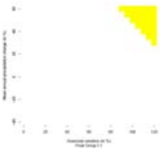
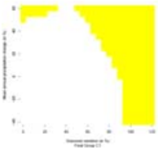
NORTH	918250	SAAR	1117	BHP	0
EAST	299700	ALTBAR	214	BVLP	99
AREA	552.96	BFIHOST	0.324	MAL	366

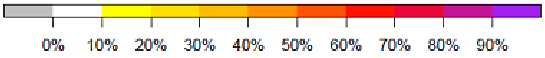
Stage 1 - Vulnerability: Find the key flood response pattern representative of the catchment

Using the decision trees and the catchment descriptors above, the probability that the catchment falls into the different flood response types can be calculated for all four flood indicators, with associated confidence levels. Results for the Helmsdale at Kilphedir are summarised below.

				Probability of flood response types							
Flood indicator	Catchment properties relative to thresholds	Path number	Confidence level	Damped-H	Damped-L	Neutral	Mixed	Enhanced-L	Enhanced-M	Enhanced-H	Sensitive
RP2	SAAR ≥ 969.5; AREA ≤ 847.795; NORTH ≥ 171175	11	**H**	**0.79**	0.02	0.19	0	0	0	0	0
RP10	SAAR ≥ 969.5; AREA ≤ 680.86	11	**H**	N/A	0.33	**0.67**	0	0	0	0	0
RP20	SAAR ≥ 969.5; NORTH ≥ 403275	9	**H**	N/A	N/A	**1.00**	0	N/A	N/A	0	0
RP50	SAAR ≥ 969.5; ALTBAR ≤ 245.5; AREA ≤ 781.09	7	**H**	N/A	N/A	**0.91**	0	N/A	N/A	0.09	0

Once the flood response type with the highest probability has been identified, the corresponding key flood response pattern can be used as proxy for the catchment flood response pattern for each flood indicators. The standard deviation pattern of the flood response type provides information on the uncertainty associated with the key flood response pattern. This is summarised below.

	RP2	RP10	RP20	RP50
Flood response type	Damped-High	Neutral	Neutral	Neutral
Key flood response pattern (averaged over 8 T/PE scenarios)				
Standard deviation pattern (over 8 T/PE scenarios)				



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

The quantification of the hazard is achieved by fitting a single-phase harmonic function to monthly change factors:

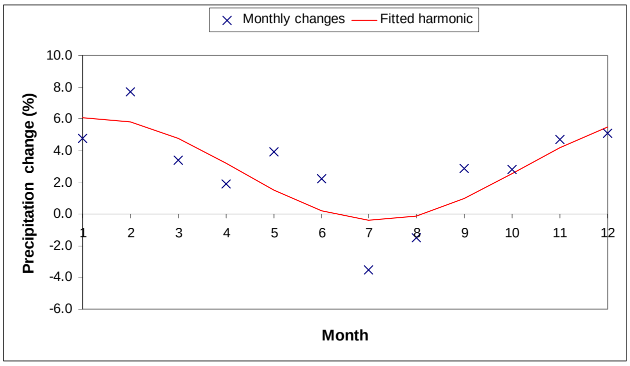
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Target scenario	4.8	7.7	3.4	1.9	3.9	2.2	-3.5	-1.5	2.9	2.8	4.7	5.1
Smoothed (via single harmonic function)	6.1	5.8	4.8	3.2	1.5	0.2	-0.4	-0.1	1.0	2.5	4.2	5.5

Actual fitted harmonic:

Mean (X_0) = 2.87%

Amplitude (A) = 3.26%

Phase (Φ_{month}) = 1.2



Nearest response pattern harmonic (5% intervals):

Mean = 5%

Amplitude = 5%

Phase = 1 (as only January modelled)

Stage 3 - Risk: Estimate flood changes combining the hazard (climate change scenario(s)) with the catchment vulnerability (key flood response pattern) and add any required uncertainty allowance.

By identifying the mean annual change and (semi-)amplitude used to establish the vulnerability that is most similar to the hazard, the risk may be quantified as the corresponding flood indicator change. Uncertainty in the representation of the key flood response pattern, as characterised by the standard deviation, can be added. Also the extra uncertainty allowances resulting from the methodological assumptions can also be added. A summary of the risk and its associated uncertainty is given for the four flood indicators below.

	RP2	RP10	RP20	RP50
Flood response type	Damped-High	Neutral	Neutral	Neutral
Key flood response (floodr)	6	7	8	8
Standard deviation (sd)	3	2	1	4
Resulting range (floodr +- 2sd)	0 to 12	3 to 11	6 to 10	0 to 16
Extra uncertainty allowance (euc)	8	3	7	8
Final range (floodr +- 2sd + euc)	8 to 20	6 to 14	13 to 17	8 to 24
Modelled response type	Damped-High	Damped-High	Damped-High	Damped-High
Modelled flood response (floodr_mod)	3	3	3	2
Extra uncertainty allowance (euc_mod)	8	11	12	16
Final value (floodr_mod+euc_mod)	11	14	15	18

For this example, given the choice assumed (target scenario, uncertainty due to the internal variability of the response types and additional uncertainty) the final ranges of change in the 20-year return peak flows can be read from the table above as an increase of between 24 to 28%.

This worked example also generated a response type for each of the four return periods with High confidence. It is likely that this would not be case for many examples, given the probabilities associated with alternative response types and the potential robustness of the associated probabilities to changes in the catchment sample. In order to incorporate these factors, and to minimise possible underestimation in the changes in peak flows, Table 2presents some practical recommendations on what course of action might be taken under a range of circumstances that may arise when applying the methodology.

Table 2 Practical suggestions for predicting the response type of a catchment's flood regime from its descriptors.

Priority order	Test		Action	Change in flood peak (impact)	Uncertainty considered
1	Is the target catchment area greater than 1,000 km^2 ?	Yes	Reduce the confidence level by one for all results: Medium for predicted High confidence; Low for predicted Medium confidence		Large catchments slightly less well represented by single value descriptors
		No	Keep all confidence levels as estimated		
2	Are the characteristics of the target catchment within 5% of a threshold?	Yes	Follow both paths		
3	Has the Path been estimated with a High confidence?	Yes	Use the predicted response type with the highest probability	Estimated from the flood response pattern (FRP)	
4	Has the Path been estimated with a Medium confidence?	Yes	Consider predicted response types with the two highest probability	Use the largest of a) the estimate from the FRP of highest probability; b) the estimate from FRP of the most vulnerable level of the two	Misclassification
5	Has the Path been estimated with a Low confidence?	Yes	Consider **all** predicted response types	Consider range given by a) the average of all estimations for all likely FRP, weighted according to their probability; b) the estimate from FRP of the most vulnerable level of all	Misclassification

The data available to drive the hydrological models used in FD2020 restricted the choice of flood indicators. Relatively short record lengths meant that nothing more extreme than the 50-year return period could be used with any degree of confidence. It is acknowledged that (changes in) peak flows at the 100-year return period are important, but the science does not support the generation of results for this flood indicator. To develop such results, the changes for the 50-year return period would have to be extrapolated out to 100 years, with additional uncertainty added to reflect this crude extrapolation. This was not something within the scope of FD2020 and would need additional research to be able to quantify such changes and the associated uncertainty.

3.2 Risk of change in peak flows from current climate projections

The impacts obtained from the catchment flood response patterns for 154 catchments can be used to quantify the changes for the four flood indicators for individual climate change scenarios. Single phase harmonic functions are fitted to the specific monthly climate change factors (with or without climate variability) derived from climate model output. Then the mean annual change and the (semi-)amplitude are compared to the 525 scenarios of the sensitivity framework. The scenario from the framework that is most similar to the single-harmonic parameters is selected as representative of this climate model scenario. The corresponding change in peak flows from the appropriate flood response pattern is the estimate of the impact of this scenario on a specific flood indicator.

The maps in Figure 5 summarise the results for the 16 AR4 GCMs for the four flood indicators. For each flood indicator, each climate model scenario (for the 2080s under the A1B emissions scenario) has been associated with the most similar rainfall scenario from the flood response pattern for each of the 8 T/PE scenarios, resulting in sets of changes in flows for 16*8 GCMs. From each set, these changes are ordered and the 10th, 50th and 90th percentiles have been extracted and plotted. The maps presented illustrate results for the A1B emissions scenario and for the 2080s time-slice, but the risk of changes in flood flows associated with different climate hazards from alternative scenarios could be considered and summarised in the same way. It should be noted that these maps purely summarise the values obtained from the catchment flood response patterns. They do not include any extra uncertainty allowance.

The maps suggest that the current FCDPAG3 recommendation of a 20% sensitivity allowance for climate change is still relatively good when considering the median (50th percentile) from the latest sets of climate change scenarios (for the 2080s under the A1B emissions scenario). Very few catchments have a median change over 20%, but many catchments have the 90th percentile change above 20%.

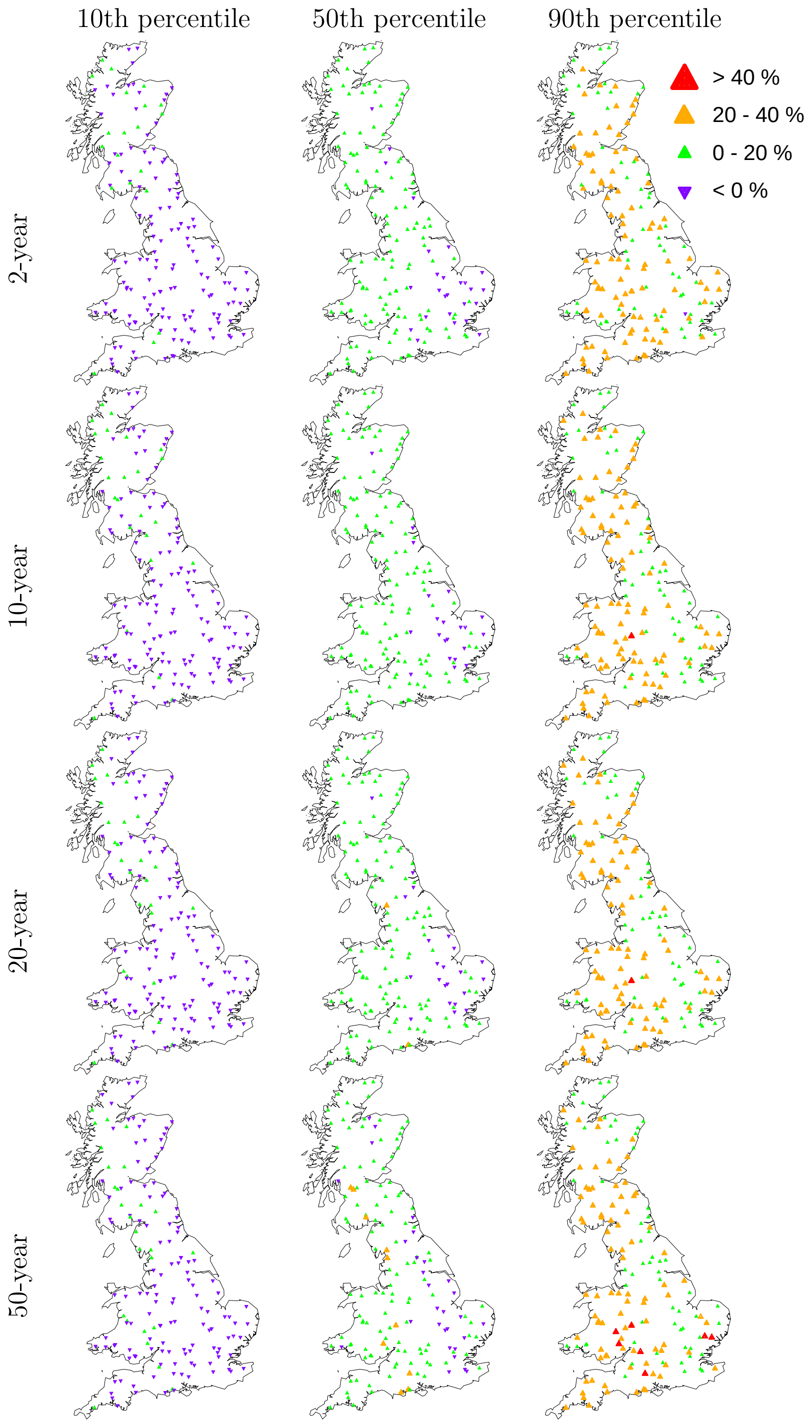


Figure 5 Summary of impacts read from the catchment response patterns (for all 8 T/PE scenarios, not including any extra uncertainty allowance) for 16 GCMs used in the IPCC fourth Assessment Report (IPCC-AR4) (2080s, A1B emissions

3.3 Resilience of the catchments to the 20% allowance

From the limited set of considered catchments and climate change projections, it is possible to assess the ‘risk’ of peak flows exceeding a given threshold: for example, the 20% allowance recommended by the FCDPAG3 guidance. The impacts from the 16 AR4 GCMs (for all 8 temperature / PE scenarios) were analysed, and the proportion of cases exceeding a given threshold calculated for each of the 154 catchments.

Figure 6 shows the results obtained for a set of climate change allowances chosen at 10% intervals between 0% and 100% (for the 20-year return period). Each cross represents the response of one of the tested catchments. The 10th, 30th, 50th (median), 70th and 90th percentiles are also indicated for each threshold value.

This graph shows the median (solid line) decreasing quickly as the allowance is increased. Looking particularly at the 20%, a catchment on the median line would have around 15% of the 16 AR4 GCM scenarios with an impact greater than 20%, however half of all modelled catchments fall above this median line. Alternatively, the level of risk could be selected and the allowance determined from there. For example, only 10% of the 16 AR4 GCM scenarios are permitted to exceed an allowance. Next the number of catchments (of the 154) that are permitted to exceed this value is also set at 10% (i.e. the 90th percentile of catchments of the sample, highlighted by upper dotted lines). Now the allowance may be determined by reading across from the y-axis and down to the x-axis, this case being about 27%.

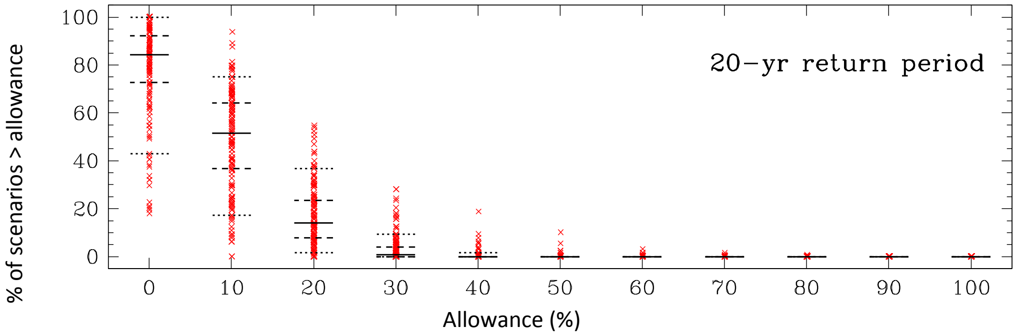


Figure 6 Evaluation of the resilience of allowance thresholds from the study catchments for 16 AR4 GCMs (2080s, A1B emissions scenario). Each cross for a given value of the allowance represents the results for one catchment. The 50th, 30th and 70th, and 10th and 90th percentiles (solid, dashed and dotted lines respectively) are shown for each value of the allowance.

4 Assessment of results against objectives

4.1 Objective 1: How appropriate does the existing guidance remain given the new modelling within FD2020?

Previous research leading to the development of FCDPAG3 guidance on climate change in 2006 was based on the hydrological modelling of just 10 river catchments across Great Britain, under selected climate change scenarios derived from a limited number of global and regional climate models. This project has extended the modelling approach to 154 catchments, as well as developed a new, scenario-neutral method to facilitate the development of regionalised guidance. It is important therefore that the existing 20% guidance is assessed against the new results from the catchment modelling exercise of FD2020.

Sections 3.2 and 3.3 above described the use of the catchment-specific information from the project, rather than the regionalised information. It is this information that currently can be used to assess the resilience of the current 20% in the light of this new modelling work, until a full nationwide assessment of vulnerability and hazard has been done. The maps in Figure 5 show this allowance to be relatively robust for the 2080s when considering the median (50^{th} percentile) from the climate change scenarios. However, the maps also show that there is a 10% chance (according to the 90^{th} percentile of the 16 AR4 GCM) that, by the 2080s, flood changes will be greater than 20% for the majority of the 154 considered catchments

Furthermore,

Figure 6 shows that for 20-year return flows a catchment on the median line would have around 15% of the 16 AR4 GCM scenarios with an impact greater than 20%. This means that half of all modelled catchments, which fall above this median line, have more than 15% of scenarios exceeding 20%, up to a worst case catchment where 60% of the GCM scenarios produce changes above 20%.

4.2 Objective 2: What evidence is there to support the development of regionalised climate change guidance?

The analysis of the response patterns and development of the nine response types clearly shows the need to distinguish between catchment types. The different types respond very differently to a given change in climate depending upon a wide range of catchment-specific characteristics as can be seen in Figure 4. The science presented in FD2020, and the categorisation of nine response types, points very clearly to the need for regionalised climate change allowances to help avoid potential over, or under, adaptation to climate change.

4.3 Objective 3: How does the uncertainty analysis undertaken within FD2020 inform new regionalised guidance?

The uncertainty analysis within this project was designed to test the assumptions made during the development of the scenario-neutral, sensitivity method, and illustrated the varying degrees of uncertainty from a range of sources. Furthermore, the varying levels of uncertainty for each of the nine catchment response types provide additional evidence of the need to incorporate some uncertainty information into the final set of guidance material. The worked example provides an illustration of how the methodology developed within FD2020 could be applied, and includes uncertainty bands, dependent upon which of the response groups the “target” catchment falls into.

5 Implications of the findings and future work

FD2020 has produced results providing evidence that the existing 20% guidance can no longer be considered as precautionary and should be refined. Furthermore there is good evidence to suggest that any new guidance should be “regionalised” in nature, taking account of the different responses of catchments, dependent upon their catchment characteristics, to changes in climate. To this end FD2020 has also produced a methodology for determining a change in peak flows (for the 2-, 10-, 20- or 50-year return periods) for any catchment in Great Britain where the set of catchment characteristics are available.

The list below describes a few ideas that would lead to the delivery of some new outputs, based on the FD2020 approach, to aid further decision making in this field:

- National evaluation of the **vulnerability** levels of the flood regime, using the catchment properties and paths obtained in the FD2020 project;
- National evaluation of the climate change **hazard**, using latest climate projections (including GCM, RCM and UKCP09 scenarios);
- National evaluation of the **risk** of change in the flood regime, obtained by overlaying national vulnerability and hazard maps. This could include specific evaluation of risk using the UKCP09 scenarios.

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

REYNARD, N.S., CROOKS, S.M., KAY, A.L., PRUDHOMME, C., Donovan, B., Hardy, K. and Wilby, R.W. (2009). *Regionalisation of climate impacts on flood flows to support the development of climate change guidance for Flood Management.* Proceedings of 44th Defra Flood & Coastal Risk Management Conference, Telford, UK, June/July 2009, 12pp.