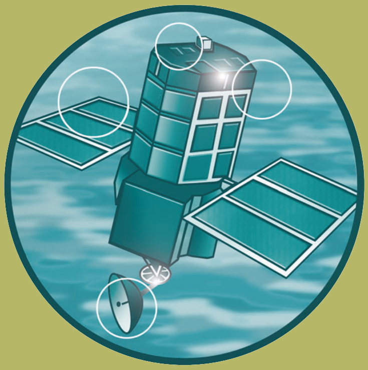
Joint Defra/EA Flood and Coastal Erosion
Risk Management R&D Programme

Regionalised Impacts of Climate Change on Flood Flows

R&D Technical Report FD2020/TR



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Joint Defra/EA Flood and Coastal Erosion Risk
Management R&D Programme

Regionalised impacts of climate change on flood flows

R&D Technical Report FD2020/TR

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Statement of use
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. 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.

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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

FAST TRACK BOXES

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1. Introduction

FAST TRACK BOX

Section 1: Introduction

Current guidance on incorporating the impact of climate change on peak river flows in flood management decision-making is enshrined in the FCDPAG3. 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.

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.

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.

After this introductory section, the report is divided into seven further sections. Section 2 presents the hydrological modelling and the study catchments. Section 3 describes how the climate change scenarios were derived. Then the definition and identification of the vulnerability of a catchment flood regime to climate change is described (Section 4) and its regionalisation from catchment properties using decision trees presented (Section 5). The uncertainty in the scenario methodology is assessed in Section 6, with Section 7 presenting worked examples of how to apply the concept and a final discussion in Section 8.

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The FCDPAG3 guidance on climate change[1] requires all flood management strategies and schemes to allow for climate change by incorporating a "national precautionary sensitivity range" for peak river flows of up to 20% over the next 100 years. This guidance makes no allowance for regional variation in climate change or catchment type because the underpinning science has not been able to resolve the spatial distribution of climate change impact on flood flows with enough confidence to set policy regionally. The overall objective of project FD2020 *Regionalised impacts of climate change on flood flows* is to provide the science base on which such "regional" policy can be developed.

1.1 Background

Typically, the science basis for setting policy in this area has been climate change impact assessments for a limited number of catchments using the outputs of one or more global (GCM) or regional climate models (RCM), described as climate change scenarios. These data are either used directly, through downscaling, or to perturb the climate data that drive a calibrated catchment model so that change to river flows under future climates may be derived. Scenario-led approaches have a number of limitations:

- The GCM / RCM output only provides a single representation of a (baseline and) future large-scale climate
- The RCM may not adequately represent the regional and local climate, and particularly the characteristics of extremes needed for modelling peak flows
- The results from multiple scenario analyses provide an indication of uncertainty through a range of potential future changes. They have no associated probabilities and therefore make decision-making and policy development difficult, tending to lead to a precautionary reaction to gross uncertainty
- Catchment response to climate and climate change is non-linear and there may be thresholds that could result in a significant change to river flows that may fall outside the future climate represented by the GCMs /RCMs. This is very important information for a policymaker, in terms of both the size and timing of future changes in flows
- The dynamics by which the climate and catchments interact are complex. Changes in rainfall intensity, frequency, seasonality and total, as well as evapotranspiration, soil moisture and temperature will all influence river flows. A single set of GCM / RCM outputs will only represent one set of these changes and may not increase our understanding of how these variables interact

The research community is tackling the first three bullet points in a number of ways. For example, the latest generation of climate change scenarios for the UK (UKCP09) have been produced as probability density functions (pdfs), derived from perturbed parameter experiments of the Hadley Centre RCM (and the optional use of a stochastic weather generator). These data could, in turn, be used to drive catchment models and would provide pdfs of change in peak

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

flows. In contrast, the scenario-led approaches cannot address the fourth point as, by definition, they are restricted to a limited number of existing projections.

Considering the fifth point in more detail, Kay *et al.* (2006) undertook a climate change experiment with an RCM (HadRM3H) to provide estimates of changes in flood frequency between the 1970s and 2080s for 15 catchments across Britain. This experiment showed that despite decreases in annual average rainfall in all but one catchment, eight show an increase in flood frequency at most return periods whereas two show substantial decreases. They suggest that the fact that flood frequency can increase, despite an overall decrease in rainfall, implies a marked change in the distribution of rainfall, either in terms of the probability of rainfall events and/or its seasonal cycle. Decreases in flood peaks are shown for a number of the catchments in the south and east of England, despite an increase in winter mean and extreme rainfall. Increased summer and autumn soil moisture deficits are thought to be the reason for this. Other catchments, further north or west, show an increase in flood peaks, in some cases of over 50% (for the 50-year recurrence interval flow). The issue being addressed by FD2020 is how to develop a fuller understanding of climate change / catchment dynamics over Britain.

Finally, scenario-led approaches are based on many assumptions and large uncertainties remain. For example, changes in the inter-annual and inter-decadal variability of climate, and the assumption that the future climate lies somewhere within the space described by the scenarios, and even if this final assumption were correct, uncertainty remains about precisely when such changes might occur.

1.2 The FD2020 approach

The key objectives of FD2020 were:

- 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 flows given the developments in the science since 2002
- Investigate a number of catchments' response to climate change to identify any potential similarities such that the FCDPAG3 nationwide 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 flows from climate change

To achieve these objectives the FD2020 project took a very different approach to the standard scenario-led assessments. Rather, it follows a **scenario-neutral** framework which 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, or "regionalised".

The method separates the climate change that a catchment may be exposed to **(the hazard)** from how the catchment responds (in terms of changes in peak flows) to changes in the climate **(the vulnerability)**. By then combining current understanding of climate change likelihood (the 'hazard') with the vulnerability of a given catchment, it is possible to evaluate the **risk** of changes in peak flows.

This analysis aims to identify if different catchments react differently in terms of changes in their flood regime to the same set of climatic changes (i.e. the property of a catchment determines its response to climate changes) or if there is a uniform response across Britain (i.e. the changes in the flood regime of a catchment are purely due to the magnitude of imposed climate changes). A full vulnerability evaluation is possible by defining a comprehensive sensitivity framework of changes to the mean and seasonality of precipitation and temperature and modelling the flood response of each catchment within this fixed framework.

Within this methodology, the project is not simply undertaking a large, multi-catchment, multi-scenario climate change impact analysis, it is exploring the dynamics of the relationships between climate change impacts on peak flows and catchment characteristics in a 'scenario neutral' way. To ensure the results are robust and any resulting policy guidance long-lasting, the sensitivity framework has been designed to investigate changes in climate that more than encompasses the current knowledge of future climate change from the new scenarios available from the IPCC Fourth Assessment Report and UKCP09 products.

The methodology developed follows a relatively simple concept, shown schematically in Figure 1.1. 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".

This methodology allows an estimation of the impact of climate change on the flood regime of any catchment that has not been modelled within this project, using:

- the flood response pattern for the unmodelled catchment's regionalised group defined from its characteristics
- climate change scenarios (GCMs, RCMs, UKCP09, or any scenarios produced in the future) which are projected for the catchment.

Specific scenarios associated with very large changes can be identified and used to provide a policy-maker with the potential probability of that change in flows occurring. It is also possible to identify, for different future time horizons, the evolution of the likelihood of change under different scenarios. This provides information which could be used as a basis for decisions and / or policy for the management of such catchments under future climate change.

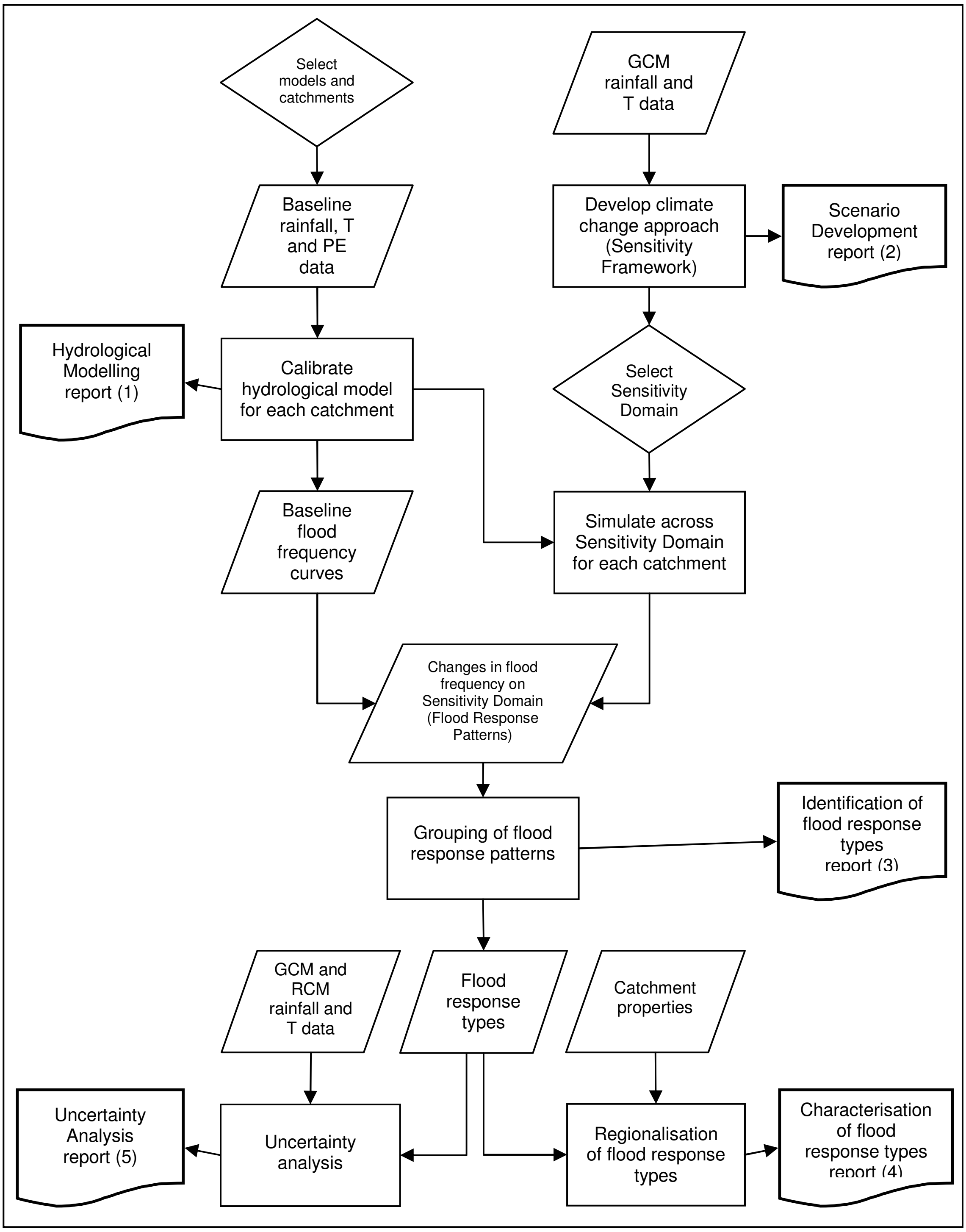

Figure 1.1 Schematic of project FD2020.

1.3 Vulnerability, hazard and risk

The methodology developed in the project has been designed to build on three key concepts inherent to climate change impact assessments:

- The vulnerability. This is the description of how flood indicators (2-year, 10-year, 20-year, 50-year return period flows) change in response to a change in climate. The sensitivity framework tested 4,200 possible different climate scenarios, summarised in eight regionalised flood response patterns. The vulnerability is specific to each catchment (Section 4).
- The hazard. This is the projected change in the climate. In this project, we have summarised the hazard in a simple 3-parameter function (the single-phase harmonic). This is specific to the climate projections (Section 3).
- The risk. This is the combination of the vulnerability and the hazard such that two catchments with a similar vulnerability to change might have very different risk if the projected changes in precipitation are different.

1.4 Products and deliverables

The conceptual methodology developed and the products generated within this project provide powerful tools to rapidly evaluate the impact of a large range of rainfall and temperature scenarios (potential hazard) on the flood regime of any catchment in Britain (vulnerability). Using these tools, two specific questions essential to the development of climate change adaptation policy can readily be assessed:

- **What is the impact of a specific hazard on the flood regime of a catchment?** This is similar to a traditional impact study resulting from the modelling of specific climate change scenario(s) on a catchment, requiring the existence of a hydrological model appropriate for flood study for that catchment. The FD2020 concept allows this question to be answered without undertaking additional hydrological modelling, by identifying the vulnerability of the flood regime of a catchment from just its characteristics. This follows the extensive modelling and regionalisation study presented in this report, and the use of this vulnerability pattern to find the response of the catchment to a specific climate change scenario. Section 7.4.1 presents the results of a climate change impact study for the 154 catchments across Britain under 16 GCM and 11 RCM scenarios
- **What is the likelihood that a threshold change in a flood indicator will be exceeded under climate change and by which time horizon?** While this is a fundamental question for policymakers for designing new allowances for climate change, traditional impact studies cannot easily provide an answer without significant computational resources, as they are based on a top-down approach where specific scenarios result in specific changes. A bottom-up approach is necessary, where all the possible scenarios are identified, and compared to current knowledge of

climate change to evaluate their likelihood. This can only be achieved through a comprehensive sensitivity study. While the FD2020 project has only evaluated impacts resulting from seasonal changes in the climate and ignored both changes in the inter-annual and intra-monthly variability, its framework does provides a tool for such assessments. An example of how to exploit the FD2020 framework to evaluate the likelihood of threshold exceedance is showed in Section 7.4.2

1.5 Report structure

The report is divided into eight sections, including this introductory section and a final discussion (Section 8). Section 2 presents the hydrological modelling and the study catchments. Section 3 describes how the climate change scenarios were derived, and the modelling framework of the project. Following this the definition and identification of the vulnerability of a catchment flood regime to climate change is described (Section 4) and its regionalisation from catchment properties using decision trees presented (Section 5). The uncertainty in the scenario methodology is assessed in Section 6, while Section 7 presents worked examples of how to apply the FD2020 concept.

2. Hydrological models, catchments and calibration

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Section 2: Hydrological models, catchments and calibration

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 is 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.

This section describes the hydrological models (their structure and data requirements) and details the 154 catchments to be modelled across Britain. There are 120 catchments modelled with the PDM (a lumped conceptual hydrological model), and 35 (generally larger) catchments with CLASSIC (a semi-distributed hydrological model), 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 improves when the snowmelt module is applied.

The calibrated models are 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 is 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 are 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. The development and method of application of this set of perturbations is described in the next section.

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To understand the change to river flows driven by changes to the climate, the current or baseline flow regime for each catchment has to be determined. Thus it was necessary to develop a set of models, for a representative number of catchments across England, Wales and Scotland, which accurately reproduce the relationship between the baseline climate and catchment characteristics. More detail on aspects of the project summarised in this section can be found in Milestone Report 1 (Crooks *et al.* 2009).

Many previous studies of the impact of climate change on river flows and flood frequency in Britain have ignored the role of precipitation falling as snow, and of subsequent snowmelt. However, given that this project aims to *regionalise* the impacts of climate change on flooding, it was considered important to include these processes as the winter flow regime of upland catchments can be considerably affected by snowfall and snowmelt, even in the UK (e.g. Archer 1981; Ferguson 1984), and changes in temperature will almost certainly alter the balance between snowfall and rainfall processes in such catchments in the future.

2.1 Hydrological models and the snowmelt module

Two hydrological models were selected for use in the project:

- the Probability Distributed Model (PDM; Moore 1985, 2007), which is a lumped conceptual model, and
- the Climate and Land-use Scenario Simulation In Catchments (CLASSIC) model (Crooks and Naden 2007), a semi-distributed, grid-based model

Both are conceptual rainfall-runoff models developed for continuous simulation of river flow across the complete flow range. They incorporate soil moisture accounting processes, the primary component of non-linearity between rainfall and runoff, and routing procedures for converting effective rainfall (rainfall minus evaporative losses) to runoff. Smaller catchments are modelled with the PDM, which requires inputs of catchment-average rainfall and potential evaporation (PE), with flow data for calibration. Larger catchments are modelled with CLASSIC which requires gridded inputs of rainfall and PE, normally at a daily time-step, as well as land-use, soil and digital terrain data.

A complication with the catchments to be modelled with the PDM is that some have hourly data available, whilst the majority have daily data. The inclusion of catchments with daily data improves the spatial coverage of Britain as well as allowing the use of longer records, whilst the use of hourly data is more appropriate to capture the response of smaller, hydrologically-responsive catchments. Daily data are not used for catchments with an area less than 50 km^2. Here, the hourly (daily) PDM catchments have been calibrated and run at the hourly (daily) time-step. However, the impact of the climate change scenarios for the hourly PDM catchments is assessed on the flood frequency curve derived from daily mean flows, for consistency with the CLASSIC and daily PDM catchments.

2.1.1 PDM description

The PDM is typical of the relatively simple model structures that nevertheless can be applied effectively across the UK. It is based on conceptual stores, and represents non-linearity in the transformation from rainfall to runoff by using a probability distribution of soil moisture storage. This determines the time-varying proportion of the catchment that contributes to runoff, through either ‘fast’ or ‘slow’ pathways. The full PDM has a number of different formulations, but the version used here is simplified to allow automatic calibration for the majority of catchments. The reduction in the number of parameters is useful in limiting the problem of equi-finality, where a number of quite different parameter sets can result in very similar model performance. A brief description of the model and its remaining parameters is given below, along with a diagram illustrating its conceptual structure (Figure 2.1).

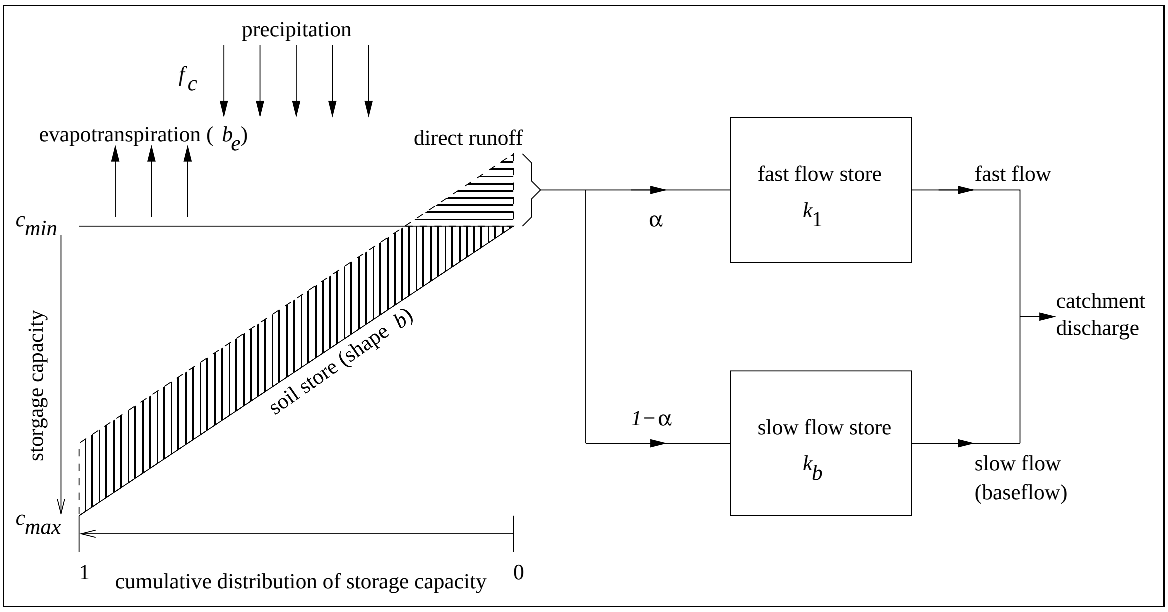

Figure 2.1 The conceptual structure of the version of the PDM rainfall-runoff model applied in the project.

Rainfall inputs to the soil store are first multiplied (at each time step) by a rainfall factor f_c. A value of f_c different to 1 can be used to allow for errors in rainfall inputs (e.g. bias in the calculated catchment average rainfall due to the location of raingauges) or to compensate in cases where there is significant loss or gain of water across the catchment boundary via subsurface pathways. The soil store is depleted through evaporation, with content of the store determining the proportion of the potential evaporation that actually occurs (via a function parameterised by b_e; the higher the value of b_e, the faster the approach of actual evaporation to its maximum (potential) level as the soil store fills). The distribution of the soil storage capacity can be described, in the full PDM, by any of a number of specified functions, but a Pareto distribution is the most widely used in practice and this is applied here. The shape of this distribution is parameterised by b, with the minimum capacity of any point within the soil store given by the parameter c_{min}, usually taken as zero, and the maximum capacity of any point given by the parameter c_{max}. The value b=1 gives a uniform distribution (that is, an equal proportion of soil stores of all depths between c_{min} and c_{max}) whereas a value $b<1$ means that there is a lower proportion of shallower soil stores compared to deeper soil stores.

The soil store then generates direct runoff from a varying proportion of the catchment area, depending on how full it is. It is generally assumed, in the full PDM, that the direct runoff (overflow) from the soil store is routed through a fast flow store ([near-] surface storage), and that downward drainage from the soil store is routed through a slow flow store (groundwater storage). An alternative formulation, used here, is to assume that a proportion α of the direct runoff goes to the fast flow store, whilst $1-\alpha$ goes to the slow flow store. The value of α can be estimated using soils data. Both fast and slow routing systems can be represented by a number of types of storage reservoir in the full PDM, but in this case a linear fast flow store and a cubic slow flow store are assumed. The time constants of the stores are k_1 and k_b respectively. The catchment discharge is produced from a combination of fast flow (surface runoff) and slow flow (baseflow).

2.1.2 CLASSIC description

The semi-distributed continuous simulation rainfall-runoff model CLASSIC was developed for estimating the impacts of climate and land use change in large catchments and was initially tested on the Thames, Severn and Trent drainage basins (Crooks *et al.* 1996). It has been further developed and used in the earlier climate change impact studies (Reynard *et al.* 1998, 2001). A schematic of the model structure is shown in Figure 2.2; details of the model and how the parameters operate within the model structure are given in Crooks and Naden (2007).

The model, which comprises three component modules, is applied on a grid framework with climatic inputs of rainfall and PE to each grid square. The components are a soil water balance module to determine effective rainfall, a drainage module, and a simple channel routing module. The soil water balance module operates as a soil moisture accounting system characterised by two parameters, the total depth of water available to vegetation and the percentage of this depth from which evaporation occurs at the potential rate. When the soil moisture deficit (SMD) exceeds this depth, loss of water is determined by an exponential relationship between PE and SMD (Calder *et al.* 1983).

The hydrologically effective rainfall generated by the soil water balance module forms the input to the drainage module in which the water is held in storage reservoirs. Soils overlying permeable substrata are modelled with a one-component store, outflow from which is determined by a time parameter; soils overlying substrata with no significant underlying aquifer are modelled with two component stores, representing quick and slow flow, operating in parallel. These stores each have time parameters to determine their rates of outflow, with a further parameter determining the proportion through the quick store. Urban areas have a separate water balance and drainage module, and the total grid square outflow is given by the sum of the outflows from each storage reservoir operating within a particular grid square.

The routing module convolves the grid square outflow with a measure of the catchment channel network (the network width function) determined from a DTM (Digital Terrain Model). This is further convolved with a routing function with two parameters, for wave velocity and a coefficient of diffusion. Individually routed grid square flows are summated to provide the total flow at the simulation site, normally a gauging station.

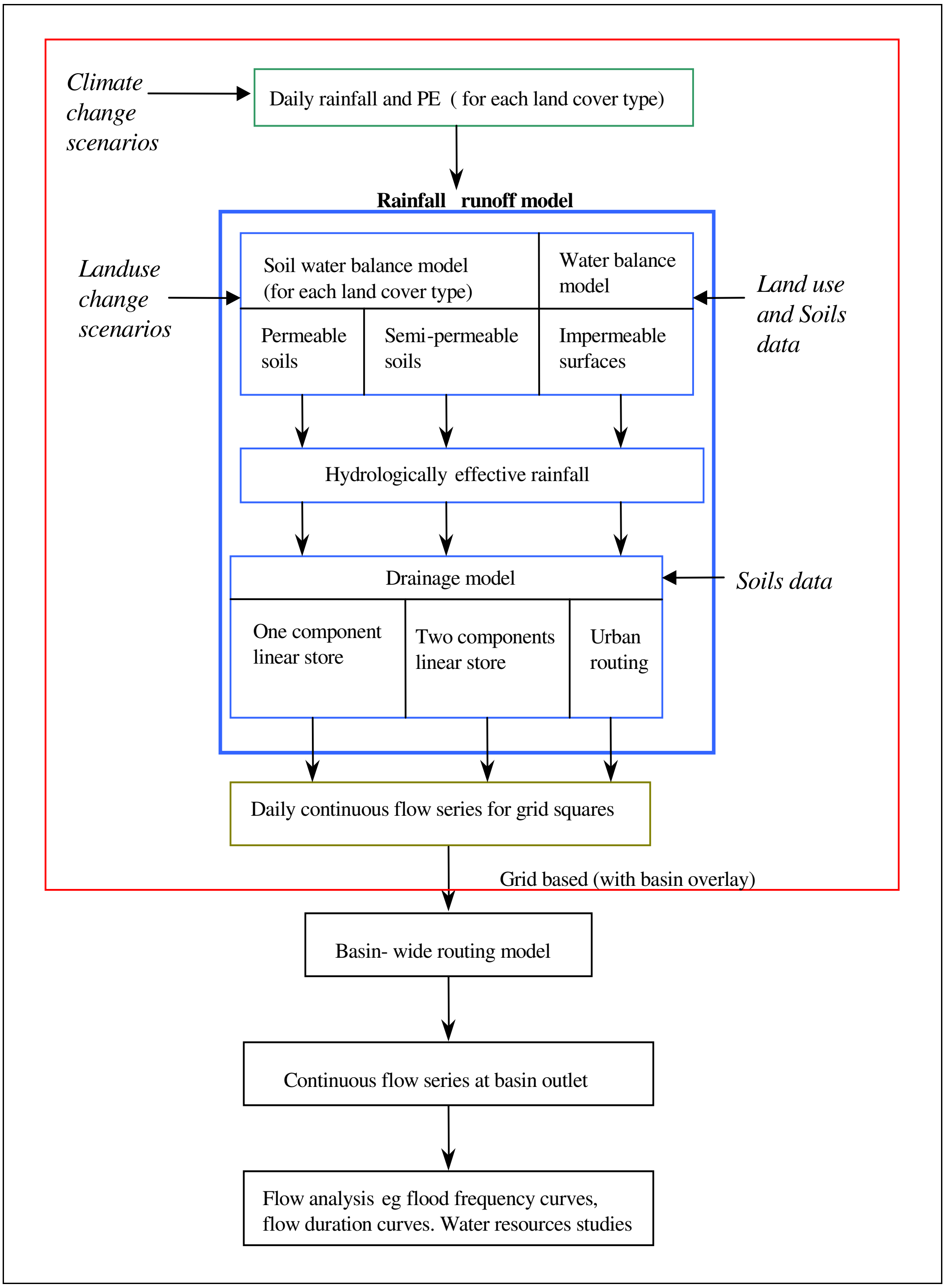

Figure 2.2 Conceptual structure of the semi-distributed hydrological model, CLASSIC.

The grid square size is catchment-specific, depending on area and the variation of climatic and physiographic conditions within the catchment. The model is normally run at a daily time step using grid square averages of observed daily rainfall (Gannon 1995) and MORECS monthly PE, divided equally into daily values, to simulate mean daily flow.

2.1.3 Snowmelt module

A snowmelt model was required which was appropriate for all catchments and could be calibrated using only temperature and elevation data. Its main purpose is to improve timing in upland areas between precipitation and runoff. A snow module, devised by Bell and Moore (1999) particularly for improved snowmelt forecasting in Britain using the PDM, was adapted to use with both the PDM and CLASSIC hydrological models. The module is essentially used as a pre-processor for the rainfall inputs to the hydrological models, meaning that input of water is delayed if precipitation occurs as snow. The version employed uses a simple temperature-related snow store and melt rate with eight parameters, including threshold temperatures for determining whether precipitation is rain or snow and melt of accumulated snow, a melt factor and time constants for release of melt from snow-pack storage (see Milestone Report 1, Crooks *et al.* 2009).

Although the effect of snowfall is greatest in upland catchments, particularly in the north and east of Britain, it was decided that the snowmelt module should be included when modelling every catchment. This avoided the need to make a prior judgement on catchments which would/would not be affected, and maintained consistency of methodology, but necessitated the sourcing of historical time-series of temperature across Britain to use within the snowmelt module for each catchment.

2.2 Catchments

Catchments were selected with acceptable quality data to provide a good coverage both geographically and of physical catchment properties. Table 2.1 lists the 74 catchments modelled with the PDM with daily data, Table 2.2 the 46 catchments modelled with hourly data, also with the PDM, while the 35 catchments modelled with daily data with CLASSIC are listed in Table 2.3. In total 154 catchments have been modelled, with one catchment being modelled using both the PDM and CLASSIC meaning there are 155 sets of catchment modelling results. Each table includes the catchment number (according to the National River Flow Archive), the river name and location name of the flow gauging station, the catchment area, the 1961-1990 standard average annual rainfall ($SAAR_{61-90}$) and the baseflow index (BFI). The catchment outlets and boundaries are shown on the maps in Figure 2.3.

Table 2.1 Details of the PDM daily catchments

Catchment Number	River	Location	Catchment Area (km^2)	SAAR$_{61\text{-}90}$ (mm)	BFI
02001	Helmsdale	Kilphedir	551.4	1117	0.48
04005	Meig	Glenmeannie	120.5	2145	0.26
06008	Enrick	Mill of Tore	105.9	1294	0.32
07002	Findhorn	Forres	781.9	1064	0.41
08004	Avon	Delnashaugh	542.8	1111	0.56
10002	Ugie	Inverugie	325.0	812	0.64
13001	Bervie	Inverbervie	123.0	890	0.56
13005	Lunan Water	Kirkton Mill	124.0	771	0.52
14001	Eden	Kemback	307.4	799	0.62
16003	Ruchill Water	Cultybraggan	99.5	1889	0.30
17005	Avon	Polmonthill	195.3	989	0.41
19011	North Esk	Dalkeith Palace	137.0	907	0.52
20001	Tyne	East Linton	307.0	713	0.52
21023	Leet Water	Coldstream	113.0	671	0.35
22001	Coquet	Morwick	569.8	850	0.45
27007	Ure	Westwick Lock	914.6	1118	0.39
27021	Don	Doncaster	1256.2	799	0.56
27043	Wharfe	Addingham	427.0	1383	0.33
27049	Rye	Ness	238.7	839	0.68
28015	Idle	Mattersey	529.0	650	0.79
28066	Cole	Coleshill	130.0	722	0.44
30017	Witham	Colsterworth	51.3	642	0.50
31002	Glen	Kates and King St Brs	341.9	608	0.59
32003	Harpers Brook	Old Mill Bridge	74.3	623	0.49
33012	Kym	Meagre Farm	137.5	585	0.26
33019	Thet	Melford Bridge	316.0	620	0.78
33029	Stringside	Whitebridge	98.8	629	0.85
34003	Bure	Ingworth	164.7	669	0.83
34006	Waveney	Needham Mill	370.0	594	0.47
36005	Brett	Hadleigh	156.0	580	0.46
37001	Roding	Redbridge	303.3	606	0.39
37031	Crouch	Wickford	71.8	572	0.30
38003	Mimram	Panshanger Park	133.9	656	0.94
39069	Mole	Kinnersley Manor	142.0	795	0.39
39105	Thame	Wheatley	533.8	644	0.63
40011	Great Stour	Horton	345.0	747	0.70
42012	Anton	Fullerton	185.0	773	0.96
43005	Avon	Amesbury	323.7	745	0.91
43007	Stour	Throop	1073.0	861	0.67
44002	Piddle	Baggs Mill	183.1	943	0.89
45005	Otter	Dotton	202.5	976	0.53
47007	Yealm	Puslinch	54.9	1410	0.56
47008	Thrushel	Tinhay	112.7	1143	0.39
48003	Fal	Tregony	87.0	1210	0.68
50002	Torridge	Torrington	663.0	1186	0.39
50006	Mole	Woodleigh	327.5	1306	0.47
52010	Brue	Lovington	135.2	867	0.47
53009	Wellow Brook	Wellow	72.6	998	0.62
54008	Teme	Tenbury	1134.4	841	0.57
54018	Rea Brook	Hookagate	178.0	756	0.51
54025	Dulas	Rhos-y-pentref	52.7	1269	0.37
55029	Monnow	Grosmont	354.0	955	0.59
58005	Ogmore	Brynmenyn	74.3	1976	0.49
61001	Western Cleddau	Prendergast Mill	197.6	1275	0.65
64001	Dyfi	Dyfi Bridge	471.3	1834	0.38
65006	Seiont	Peblig Mill	74.4	2278	0.40
66011	Conwy	Cwm Llanerch	344.5	2055	0.28
67009	Alyn	Rhydymwyn	77.8	969	0.40
68001	Weaver	Ashbrook	622.0	731	0.53
68005	Weaver	Audlem	207.0	719	0.50
69040	Irwell	Stubbins	105.0	~1405	0.44
73005	Kent	Sedgwick	209.0	1732	0.46
75017	Ellen	Bullgill	96.0	1110	0.49
76014	Eden	Kirkby Stephen	69.4	1483	0.24

Catchment Number	River	Location	Catchment Area (km^2)	SAAR$_{61-90}$ (mm)	BFI
78003	Annan	Brydekirk	925.0	1351	0.44
79002	Nith	Friars Carse	799.0	1460	0.39
79003	Nith	Hall Bridge	155.0	1505	0.27
81002	Cree	Newton Stewart	368.0	1760	0.27
83005	Irvine	Shewalton	380.7	1228	0.26
84012	White Cart Water	Hawkhead	234.9	1314	0.35
85003	Falloch	Glen Falloch	80.3	2842	0.17
94001	Ewe	Poolewe	441.1	2273	0.65
95001	Inver	Little Assynt	137.5	2211	0.64
97002	Thurso	Halkirk	412.8	1057	0.46

Table 2.2 Details of the PDM hourly catchments

Catchment Number	River	Location	Catchment Area (km^2)	SAAR$_{61-90}$ (mm)	BFI
03003	Oykel	Easter Turnaig	330.7	1895	0.23
07001	Findhorn	Shenachie	415.6	1219	0.36
07004	Nairn	Firhall	313.0	940	0.45
10003	Ythan	Ellon	523.0	826	0.73
12007	Dee	Mar Lodge	289.0	1335	0.45
21013	Gala Water	Galashiels	207.0	930	0.52
21017	Ettrick Water	Brockhoperig	37.5	1733	0.34
22006	Blyth	Hartford Bridge	269.4	696	0.35
23011	Kielder Burn	Kielder	58.8	1199	0.34
24005	Browney	Burn Hall	178.5	743	0.51
25006	Greta	Rutherford Bridge	86.1	1128	0.22
27051	Crimple	Burn Bridge	8.1	856	0.31
28008	Dove	Rocester Weir	399.0	1021	0.62
28039	Rea	Calthorpe Park	74.0	781	0.47
28046	Dove	Izaak Walton	83.0	1096	0.79
29001	Waithe Beck	Brigsley	108.3	690	0.85
30004	Lymn	Partney Mill	61.6	685	0.65
36008	Stour	Westmill	224.5	589	0.43
36010	Bumpstead Brook	Broad Green	28.3	589	0.23
38007	Canons Brook	Elizabeth Way	21.4	601	0.41
38020	Cobbins Brook	Sewardstone Road	38.4	616	0.26
39007	Blackwater	Swallowfield	354.8	707	0.67
39017	Ray	Grendon Underwood	18.8	622	0.17
39037	Kennet	Marlborough	142.0	772	0.94
39073	Churn	Cirencester	84.0	854	0.89
40005	Beult	Stile Bridge	277.1	690	0.24
42008	Cheriton Stream	Sewards Bridge	75.1	889	0.97
45003	Culm	Wood Mill	226.1	971	0.53
54027	Frome	Ebley Mill	198.0	827	0.87
54034	Dowles Brook	Oak Cottage, Dowles	40.8	715	0.40
54090	Tanllwyth	Tanllwyth Flume	0.9	2425	0.30
55008	Wye	Cefn Brwyn	10.6	2453	0.31
55013	Arrow	Titley Mill	126.4	962	0.55
57005	Taff	Pontypridd	454.8	1830	0.47
57006	Rhondda	Trehafod	100.5	2184	0.41
58006	Mellte	Pontneddfechan	65.8	1979	0.38
60002	Cothi	Felin Mynachdy	297.8	1551	0.44
60003	Taf	Clog-y-Fran	217.3	1420	0.56
74001	Duddon	Duddon Hall	85.7	2265	0.29
79005	Cluden Water	Fiddlers Ford	238.0	1423	0.38
81006	Minnoch Water	Minnoch Bridge	141.0	1993	0.28
84030	White Cart Water	Overlee	111.8	1367	0.32
86001	Little Eachaig	Dalinlongart	30.8	2341	0.23
90003	Nevis	Claggan	76.8	2913	0.26
93001	Carron	New Kelso	137.8	2615	0.26
96001	Halladale	Halladale	204.6	1102	0.26

Table 2.3 Details of the CLASSIC catchments

Catchment Number	River	Location	Catchment Area (km^2)	SAAR$_{61-90}$ (mm)	BFI
08006	Spey	Boat O Brig	2861.2	1122	0.60
11001	Don	Parkhill	1273.0	891	0.69
12002	Dee	Park	1844.0	1113	0.53
12003	Dee	Polhollick	697.0	1231	0.46
15006	Tay	Ballathie	4587.1	1463	0.64
21009	Tweed	Norham	4390.0	996	0.53
23001	Tyne	Bywell	2175.6	1044	0.38
24009	Wear	Chester le Street	1008.3	885	0.47
27003	Aire	Beal Weir	1932.1	987	0.52
27007	Ure	Westwick Lock	914.6	1118	0.39
27009	Ouse	Skelton	3315.0	914	0.46
27041	Derwent	Buttercrambe	1586.0	765	0.69
28022	Trent	North Muskham	8231.0	761	0.65
33026	Bedford Ouse	Offord	2570.0	609	0.47
33035	Ely Ouse	Denver Complex	3430.0	587	0.48
39001	Thames	Kingston	9948.0	719	0.64
39008	Thames	Eynsham	1616.2	749	0.68
39016	Kennet	Theale	1033.4	782	0.87
39081	Ock	Abingon	234.0	658	0.63
40003	Medway	Teston	1256.1	762	0.41
43021	Avon	Knapp Mill	1706.0	840	0.90
47001	Tamar	Gunnislake	916.9	1259	0.46
53018	Avon	Bathford	1552.0	850	0.59
54001	Severn	Bewdley	4325.0	924	0.53
54057	Severn	Haw Bridge	9895.0	807	0.58
55002	Wye	Belmont	1895.9	1231	0.46
55023	Wye	Redbrook	4010.0	1038	0.54
60010	Tywi	Nantgaredig	1090.4	1595	0.46
62001	Teifi	Glan Teifi	893.6	1377	0.54
67033	Dee	Chester Bridge	1816.8	1208	0.50
69037	Mersey	Westy	2030.0	1081	0.57
71001	Ribble	Samlesbury	1145.0	1348	0.34
72004	Lune	Caton	983.0	1529	0.32
76007	Eden	Sheepmount	2286.5	1214	0.49
84013	Clyde	Daldowie	1903.1	1170	0.46

2.3 Data

Daily mean flow and raingauge data are available from the National Water Archive, held at CEH Wallingford. The daily raingauge data are used to make catchment-average daily rainfall, using the Triangle Method of Jones (1983), for input to the PDM, and to make gridded rainfall inputs for CLASSIC. Daily rainfall data are available for all catchments from January 1961; daily mean flow data, required for calibration, have a variety of starting times; the earliest date selected is 1961, compatible with the rainfall data, the latest date is 1994.

For the hourly PDM catchments, hourly flow and raingauge data previously obtained from the Environment Agency and Scottish Environmental Protection Agency, are used. The raingauge data are processed to provide catchment-average hourly rainfall. Most hourly data begin in 1985, with the latest in 1993. The end date for all daily and hourly raingauge and flow data is December 2001.

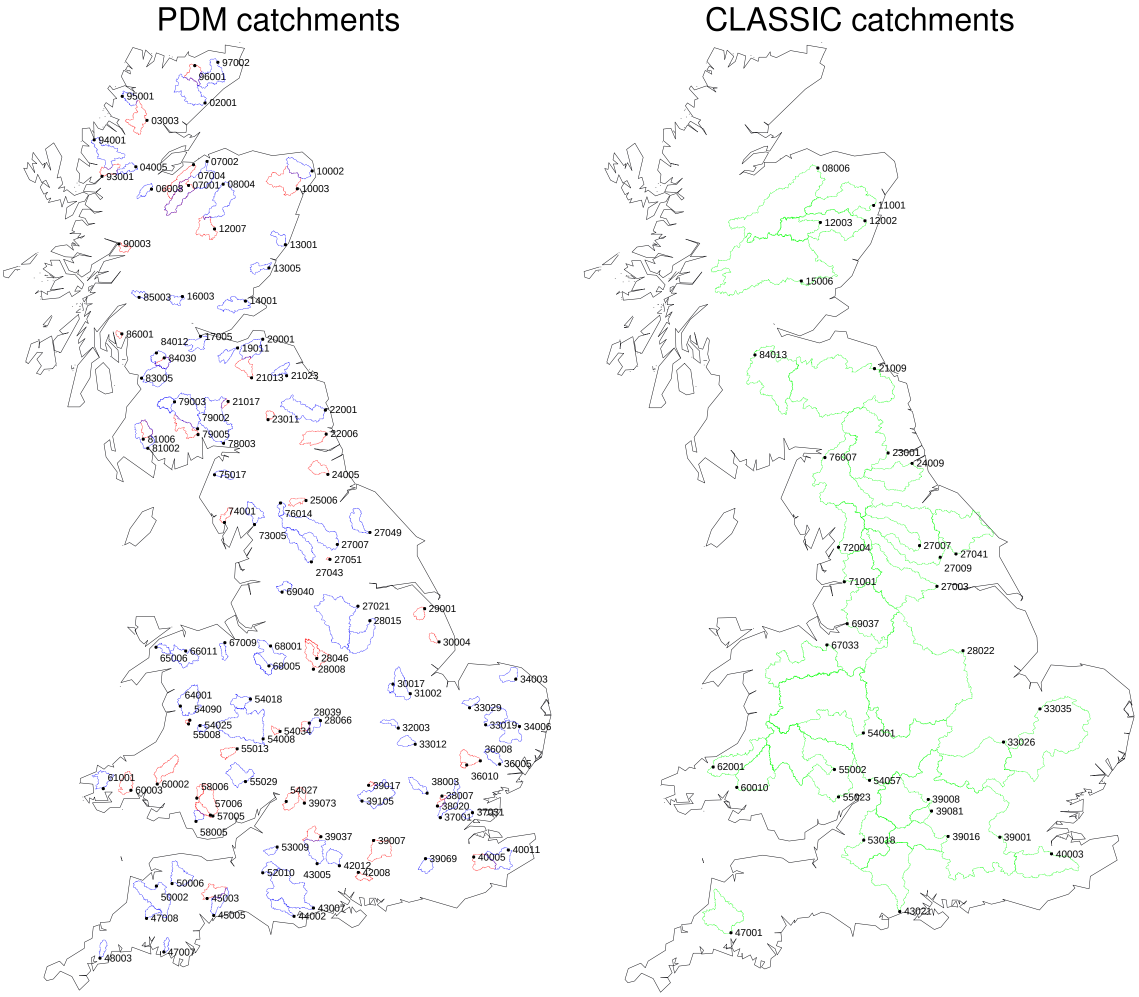

Figure 2.3 PDM and CLASSIC catchment outlets and boundaries (PDM hourly – red, PDM daily – blue, CLASSIC – green).

MORECS (Meteorological Office Rainfall and Evaporation Calculation System) monthly data (Thompson *et al.* 1982; Hough *et al.* 1997) are used to provide catchment potential evaporation (PE) inputs for the PDM and gridded PE inputs for CLASSIC. These data are based on the Penman-Monteith equation for PE (Monteith 1965) and are available from 1961 as average values for 40 km × 40 km grid squares across Britain. For a catchment modelled with the PDM, weighting the PE data for each MORECS grid square by the proportion of the catchment in that square, and then summing over the squares, produces the monthly PE data for that catchment. Gridded PE for CLASSIC is obtained by interpolation from the MORECS grid onto the appropriate catchment grid. For each model, the monthly values are then disaggregated equally down to the required input time-step.

Time-series of daily minimum and maximum temperature data for the period 1960 to 2006 have been produced by the Met Office as one of the UKCP09 products, on a 5km grid over the UK. These data, which are estimates of the temperature at the centre of each 5km x 5km grid box, have been used as input to the snowmelt module for the PDM and CLASSIC. Altitudes, not available with the temperature data, are taken from the corresponding points (grid box centres) within the IHDTM (Morris and Flavin 1990), which has a 50m horizontal resolution.

Use of the temperature data for the PDM involves the selection of the temperature grid-box in the centre of the catchment, for which the minimum and maximum temperature time-series are extracted for the required period. For CLASSIC the temperature grid boxes are superimposed on the modelling grid boxes and a weighted average temperature and altitude determined for a model grid box. For CLASSIC grid boxes covering the periphery of a catchment, if the centre of a superimposed temperature grid box lies outside the catchment boundary, then temperatures are determined from an adjacent in-catchment grid box to provide continuity of temperature decrease with altitude around the boundary.

For catchments modelled at a daily time-step, a mean daily temperature time-series is calculated as the average of the minimum and maximum temperature for each day (09:00 to 09:00). For catchments modelled at an hourly time-step, an hourly temperature time-series is constructed using a sine curve approximation, assuming that the maximum and minimum temperatures occur at 2pm and 2am respectively.

2.4 Calibration

Calibration is the process of setting model parameter values which reproduce the characteristics of catchment rainfall-runoff response across the spectrum of hydrological conditions. Generally, calibration is achieved by comparing simulated flows with observed flows, with the difference between them taken as a measure of model performance. Probably the most universally used objective function in hydrological modelling is the model efficiency of Nash and Sutcliffe (1970). A Nash-Sutcliffe value of 1 indicates a perfect fit, whilst a negative value indicates that the fit is worse than that of the mean value. The aim in this project is to obtain a Nash-Sutcliffe value of at least 0.6 for mean daily flows, at least 0.8 for 30-day mean flows and an overall volume error of less than 10%. These target objective function values were selected for the project based on ones which have been used to indicate a satisfactory fit between observed and modelled hydrographs (Wilby 2005, Hellebrand and van den Bos 2008) Additional objective functions are used during the calibration of the models.

All available data for each catchment have been used in the calibration to include as wide a range of hydrological conditions as possible and help ensure that the choice of data period is not a factor in the following impact analysis. The mean data length for calibration is 34 years for the PDM daily catchments, 17 years for the PDM hourly catchments and 36 years for the catchments modelled with CLASSIC. Catchments were first calibrated without the snowmelt module and an initial assessment made of model performance. This assessment allowed the identification of catchments which required investigation into reasons for poor calibration. Following the acquisition of the temperature data a final calibration and assessment were undertaken. A set of constant values for the parameters in the snowmelt module, which could be used for all catchments, was determined during testing of the model.

The most important part of calibration, particularly when a hydrological model is used to assess the impact of climate change on a flow regime, is confidence in the overall modelled relationship between precipitation and runoff. The integrity of the calibration procedure in the hydrological modelling is essential for meaningful interpretation of climate change impacts. The procedure followed has endeavoured to ensure that calibrations are based on good quality data (or reasons known for anomalies) and that derived parameter values represent stable catchment rainfall-runoff processes. Stationarity of catchment characteristics and model parameters is assumed in all flow simulation. Uncertainty affects all aspects of the modelling process including data accuracy of both climate and flow data, data periods used for calibration, spatial and temporal representation of hydrological processes and model structure and calibration. Aspects of modelling uncertainty are discussed in Milestone Report 5 (Kay *et al.* 2009a).

2.4.1 PDM calibration

Parameter values for the catchments modelled with the PDM are either pre-determined or obtained by automatic calibration. It is not advisable to calibrate all parameters using the automated routine because of interdependence between some of the parameters. Four parameters are assigned fixed values or are calculated from catchment properties. Values for two parameters – the relationship between potential and actual evaporation, b_e, and the distribution of soil moisture stores, b – are assigned following sensitivity modelling. Britain is divided into two regions (South and East or North and West) with set values of b_e and b derived for each region. The rainfall adjustment factor, f_c, is set at 1 for all catchments (i.e. no adjustment to rainfall), while the value of α, the split between the fast and slow flow stores, is set as 1-BFIHOST (FEH catchment characteristic for the base flow index derived from soil classes).

An automatic calibration routine (Calver *et al*. 2005) is then used to calibrate the remaining three parameters – c_{max}, k_1 and k_b. The calibration is a three stage process using different objective functions for each parameter. The first stage starts from random values for these parameters and calibrates in the order c_{max}, k_1, k_b; the second stage begins with the optimal values from the first stage and re-calibrates in the order c_{max}, k_b, k_1. The final stage recalibrates k_1 using an objective function based on the fit between the observed and modelled flood frequency curves. This last stage may cause a deterioration in the objective function values for the fit over the whole time series, given by the differences in objective function values between stage two and three of the calibration. A visual assessment of observed and modelled hydrographs and flood frequency curves is made to ensure that overall model performance is not unduly compromised by adjustment in the value of k_1.

Assessment of the calibration results identified catchments which required further investigation. One particular subset was 11 catchments with a high proportion of baseflow, generally with a value of BFIHOST ≥ 0.75, for which the automated routine did not perform well. These catchments were then manually calibrated using an interactive version of the PDM resulting in improved objective function values. Reasons for poor calibration were identified for other catchments, including catchment history, data quality and parameter values, and manually calibrated where appropriate.

After inclusion of the snowmelt module and assessment of the calibrations, five catchments still have unexplained poor objective function values. Three of these are upland catchments in Scotland where sub-daily timing of precipitation and temperature may be critical in good flow simulation and two have unknown reasons. All catchments are included in further analyses and treated in the same way as the other catchments but the calibration performance is considered in the interpretation of later results.

2.4.2 CLASSIC calibration

A major consideration when calibrating a hydrological model for large UK catchments is that gauged flow is rarely natural runoff. In most catchments flow is affected by water utilisation within the catchment and many have river regulation and transfers of water into or out of the catchment. Therefore, direct calibration to minimise differences between gauged and simulated flow, particularly in the low flow range, may not be appropriate. A few catchments have naturalised flow series which allow direct comparison between observed and modelled flows. A semi-automated calibration procedure has been devised for CLASSIC to assign grid square parameter values without calibration against observed flows.

The grid-square parameter values for the soil water balance and drainage modules are initially determined automatically from the topography, main land use groups and soil types. Those in the soil water balance module may be adjusted if comparison with observed flows indicates that the water balance has a consistent bias. The catchment routing parameters are normally determined by automated calibration with observed flow data with manual adjustment to improve the fit of the flood frequency curve, if appropriate. Thus, within a large catchment, grid square parameter values are the same regardless of the downstream location of the point on the river at which the flow is simulated, while the routing parameter values are specific to the location. Therefore, although the total number of parameter values to be set is comparatively high (one set per grid square), the resulting parameter space is physically and spatially consistent. The model can be used to simulate flows at ungauged locations, or gauging stations with limited or poor quality flow data, by estimating the routing parameters from catchment area and average channel slope.

Calibration performance is assessed by the three objective function values (Section 2.4) and visual comparison of observed and modelled hydrographs, flow duration curves, flood frequency curves and seasonal pattern of average monthly flow.

2.5 Hydrological model performance and flood frequency

Full details of hydrological model performance and objective function values are given in Milestone Report 1 (Crooks *et al.* 2009). Model performance improves for nearly all catchments when including the snowmelt module as runoff for all catchments is affected by snowmelt at some time during the baseline period, but for a few the impact on discharge rates is minimal. However, its inclusion is vital for timing of runoff in upland catchments.

A major criterion in the calibration of the hydrological models is to achieve a good similarity between frequency of observed and modelled peak discharges. The peaks-over-threshold (POT) method has been used to analyse the time-series of observed and modelled mean daily flows to provide flood data series. An average of 2 peaks per year has been used (POT2) to provide a more complete picture of the flood history than is achieved with only 1 peak per year but without including many minor flood events. Having sufficient peaks to adequately define the flood frequency pattern is particularly important for many of the catchments with hourly data, which have less than 20 years of data.

A Generalised Pareto Distribution is fitted to each POT2 series using the technique of probability weighted moments (Naden 1993) to produce a flood frequency curve. A flood frequency curve relates flood peak magnitude to the frequency with which that magnitude or greater is likely to occur. The frequency may be expressed in terms of the return period (RP) for a flood magnitude and is defined as the average time period between discharges exceeding that magnitude. All flood peak magnitudes, observed and modelled, used in the project are for mean daily flows even if the flows have been modelled at an hourly time step. Examples of observed and modelled flood frequency curves are given in Figure 2.4 for six catchments with contrasting hydrological response characteristics, which also illustrates some of the reasons for differences between observed and modelled flows (Table 2.4).

Table 2.4 Characteristics of catchments with flood frequency curves in Figure 2.4

Catchment number	Area (km^2)	SAAR (mm)	BFI	Comments
07004	313	940	0.45	Upland catchment, snow in winter, extrapolation of rating curve, NE Scotland
37001	303	606	0.39	Urban development, extrapolation of rating curve, S E England
39008	1616	749	0.68	Bypassing of gauging station, S Central England.
43005	324	745	0.91	Groundwater catchment, good high flow rating, S England
54001	4325	924	0.53	Diverse catchment, ultrasonic gauge, Central Wales
73005	209	1732	0.46	Flashy, responsive catchment, NW England.

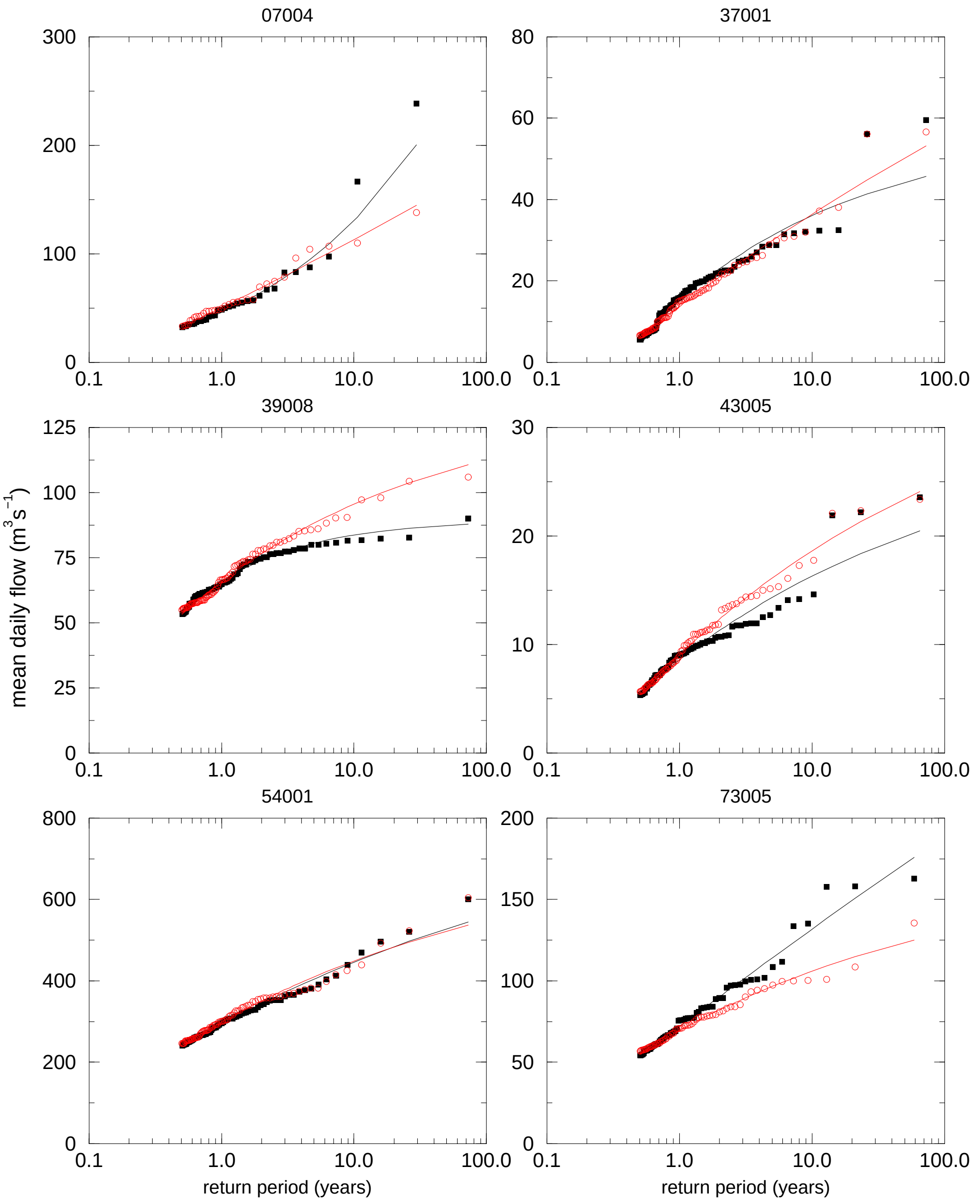

Figure 2.4 Observed (black) and modelled (red) flood frequency curves for six catchments. Fitted curves (solid lines), observed mean daily flow peaks (black squares), modelled mean daily flow peaks (red circles)

A dimensionless statistic used to compare data series is the coefficient of variation, cv, defined as the ratio between the standard deviation and mean of the series. The coefficient of variation is a measure of the relative range, or dispersion, of the series. Therefore comparison between values of cv for the observed and modelled POT2 series for each catchment indicates how well the modelled flood peaks reproduce observed variation in daily flood peak response. Comparative values of the mean and coefficient of variation for the observed and modelled POT2 series are plotted in Figure 2.5.

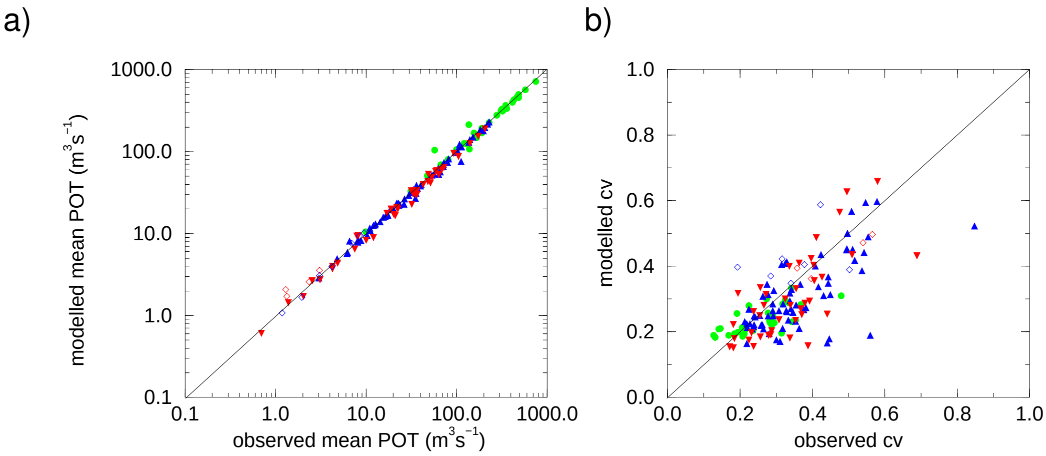

Figure 2.5 Comparison between observed and modelled values of a) the mean and b) the coefficient of variation (cv) of the POT2 series, for catchments modelled with the daily PDM (blue triangles), the hourly PDM (red triangles) and CLASSIC (green circles). Groundwater catchments are indicated by open diamonds of the appropriate colour

Of the six observed and modelled flood frequency curves shown in Figure 2.4 the catchment with the highest modelled cv is 37001 (0.597 modelled, 0.578 observed) where the runoff from urban areas contributes to the high variation in flood response. The lowest cv is for 39008 (0.184, 0.132) where the flood response is often constrained by the slow response from the substantial groundwater component of flow. Groundwater catchments often have a low flood range but under exceptional conditions high floods may be generated, as for 43005 (0.378, 0.406). Large catchments generally have a low flood peak range compared to the mean flood discharge (e.g. 54001, 0.208, 0.216).

Flood frequency curves from modelled flows are the basis of the analysis to determine impacts of climate change on daily peaks. Within the provisos outlined in this section regarding data measurement and spatial and temporal modelling issues, the modelled flow response for each catchment is considered appropriate for assessing impacts of change in precipitation and temperature on flood frequency. Uncertainty from choice of sampling method and fitting a frequency curve has not been included in subsequent analyses as the same methods of sampling and curve fitting are used throughout. It is the difference between the baseline and scenario flood frequency curves that is the indicator of change.

The calibrated models were run with 41 years of precipitation and PE data (1961 – 2001) for all catchments run with daily data and with the longest available data series (ending in 2001) for the catchments run with hourly data. These modelled flows are the baseline mean daily flows to which simulated flows from alternative climate scenarios are compared. Flood frequency analysis of the baseline mean daily flows provides the POT2 flood series and baseline flood frequency curves used in the project to develop the regionalised response to climate change.

3. Definition of climate change scenarios and sensitivity framework

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Section 3: Definition of climate change scenarios and sensitivity framework

This section describes the rationale and development of the climate change scenarios used in this project. The objective was to develop a methodology to evaluate the **vulnerability** of catchment flood regimes to climate change. This requires 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.

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. 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 IPCC Fourth Assessment Report and UKCP09 products.

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.

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To characterise the full vulnerability of a catchment's flood regime to climatic change, it is essential that the scenarios capture the range of potential climatic changes expected to occur in Britain, including the large GCM (Global Climate Model) uncertainty. This would allow the conclusions of the vulnerability assessment (resulting from the modelling exercise and regionalisation study) to be as robust as possible, and to provide a sound and long-lasting science-base for subsequent policy guidance to the flood management community.

The assessment of climate change on catchment flood regimes traditionally involves the use of a scenario describing the future climate (sometimes downscaled and bias-corrected) from a set of climate model runs under specific emission scenarios, run through a continuous river flow simulation model to provide estimated future flow series. Comparison between future and baseline flow series determines the potential impact due to climate change on specific indicators, for example representative of the flood regime.

Previous climate change studies relied on projections from only a few global (GCM) and regional (RCM) climate models, and thus could only capture a very limited part of the GCM uncertainty. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4) now provides data from 17 GCMs, all considered equally plausible representations of future climates, and thus as many of them as possible should be considered in any impact study for a fuller assessment of the uncertainty due to climate modelling. This is rarely done systematically for a large number of scenarios and catchments.

In addition to the use of a limited number of GCMs, traditional impact studies are usually closely linked to a specific version of each GCM, to the assumed greenhouse gas emission scenarios, and to the time horizons of the projections. This deterministic approach does not allow for progress in the formulation and parameterisation of GCMs, their spatial resolution, or in the emission scenarios, to be incorporated in a straightforward manner. New impact studies would be necessary for every new model version.

This project has developed a new way of investigating the response of catchments to rainfall and temperature change. Instead of defining monthly change factors, as is traditionally done, seasonal patterns of change in climatic variables are described by a single harmonic function built from a range of monthly factors of change incorporating climate variability to characterise the climatic change hazard.

Current GCMs provide information on monthly mean changes, but the range of projections is wide and varies by region, and impacts on flood flows are also varied. In order to separate the variation in the flood response due to catchment properties from that due to climate drivers (specifically precipitation, temperature and potential evaporation), it is necessary to impose the same climate driver changes to a range of catchments over Britain to characterise their vulnerability to climatic changes. This is best achieved through a sensitivity framework. The resulting analysis of the response of catchments to multiple changes in the climate thus accounts for the large uncertainty due to GCM outputs, but also captures seasonal variability in the changes. The chosen sensitivity domain must thus capture all the uncertainties in rainfall and temperature expected from climate modelling. The sensitivity domain provides a benchmark to create many climate scenarios used to simulate the flood regime under changed climate conditions. To keep the computing load manageable, (i) changes in potential evaporation (PE) are estimated from a temperature-based formula (Oudin *et al.* 2005) and (ii) the 'change factor' method was chosen to create the alternative climate time series, using a single harmonic formulation to smooth the seasonality of the monthly factors: the observed catchment precipitation, temperature and potential evaporation (PE) time series are modified according to monthly percentage change factors (Fowler *et al.* 2007). These alternative climate time series are then run as input to hydrological models to derive changes in selected flood indicators.

This section first presents a new way to define climate change factors (Section 3.1). The results of a nationwide analysis of current climate change projections in Britain are then presented (Section 3.2), followed by the sensitivity framework used in the project to define catchments vulnerability (Section 3.3) and the associated limitations (Section 3.4) . The section concludes explaining how to derive the climate change hazard (Section 3.5) and the risk from the combination of hazard and vulnerability (Section 3.6). More detail on aspects of the project summarised in this section, including key assumptions, can be found in the Milestone Report 2 (Prudhomme and Reynard 2009).

3.1 Definition of climate change scenarios

Monthly time series projections from 17 GCMs following three emission scenarios used for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR4) were 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).

For all models, time series for all grid cells covering Britain were extracted, and monthly averages calculated for the control run (20C3M, assuming an increase in the $C0_2$ level as observed in the 20th century – for each GCM, this is the 'reference' baseline climate) and the future runs. Table 3.1 presents the emission scenarios considered but fuller information on the GCMs can be found in the Milestone Report 2 (Prudhomme and Reynard 2009).

Table 3.1 Emission scenarios considered. More detail in IPCC (2000)

Emission scenario	Detail	No GCM exp.
20C3M	Climate of the 20th Century experiment. Generally runs from ~1850 to present. Control run for SRES emission scenarios A1B, A2 and B1 experiments	17
SRA1B	Future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. SRES A1B assumes a balance across all sources of technology (fossil intensive and non-fossil energy source). Experiments run from conditions from the end of 20C3M until 2100, then with fixed CO2 levels to 720 ppm and continue to run to 2200	16
SRA2	Very heterogeneous world. The underlying theme is self-reliance and preservation of local identities, with continuously increasing of global population. Technological changes are slower and more fragmented that in other storylines. Experiments use the end of the 20C3M experiment as their initial condition.	17
SRB1	Convergent world with the same population projection as A1, but with rapid changes in economic structures towards a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity but without additional climate initiatives. Experiments run from conditions from the end of 20C3M until 2100, then with fixed CO2 levels to 550 ppm and continue to run to 2200	14

The percentage factors of change were derived in three separate steps. Illustrations are given for changes in precipitation for two contrasting regions of Britain: the north, for 57.3º N and 3.75º W (Scotland, in the Caingorns) and the south, for 51.6º N and 0º (England, near London).

Step 1: monthly averages

For each GCM run and each grid cell, 20-year monthly averages are calculated from the monthly time series for the following periods (time slices):

- 1951-2000 for the control (20C3M emission run)
- 2071-2100 for the future (SRA1B, SRA2 and SRB1 emission runs)

To maintain the year-to-year structure, the averages are calculated from 20 consecutive years within the time slices. It means that 31 averages are calculated for the 20C3M run, and 11 averages are calculated for the future runs. Calculating different averages is a way of accounting for the climate variability in both baseline and future time horizons.

Step 2: monthly changes

The standard procedure used to estimate future monthly changes is to calculate the difference between a 30-year future time slice (for the 2080s, 2070-2099) and a baseline / control run time slice, generally 1961-1990 (see TAR factors http://www.ipcc-data.org/). In this project, we have calculated the difference between any future and any control (expressed as percentage of the control), i.e. for combinations between 20-year sub-periods within the baseline and future time slices using a resampling technique. In this way, it is possible to incorporate the uncertainty due to the current and future climate variability in the possible changes, which would not be possible from using single 30-year time-slices (see Milestone Report 2, Prudhomme and Reynard 2009). For each future GCM and emission run and each grid cell, this results in a range of monthly factors all equally representative of possible changes between the baseline climate and the 2080s climate. Figure 3.1 illustrates these ranges (or variations due to climate variability in control and future climate) using a box-plot representation, where the first (i.e. 25% values are below), second (i.e. median) and third quartiles (i.e. 25% values are above) in the changes, corresponding to a particular GCM scenario and grid cell, are summarised graphically for each month. Note the month-to-month variability in the ranges.

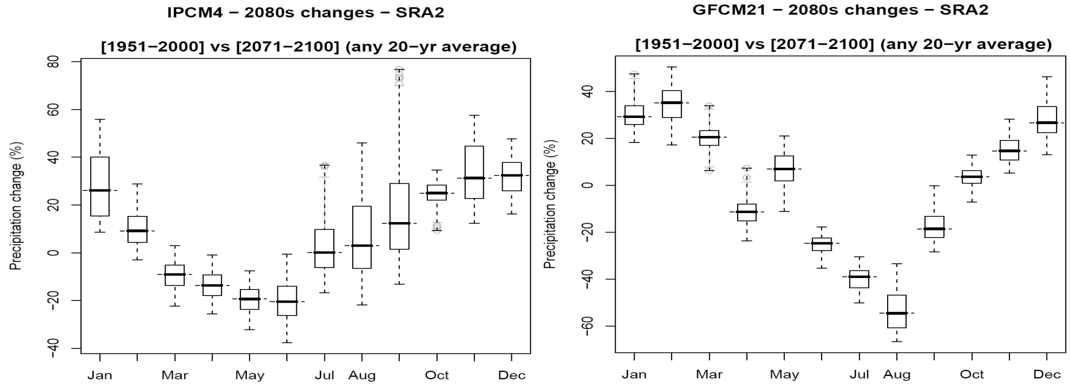


Figure 3.1a Factors of change for outputs for a Northern cell based on any future 20-year average within [2071-2100] compared to any resampled 20-year average from within [1951-2000] (box plots and circles: first, second and third quartiles: rectangle; 1.5 times interquartile range: whiskers; outliers: circles) (continue next page)

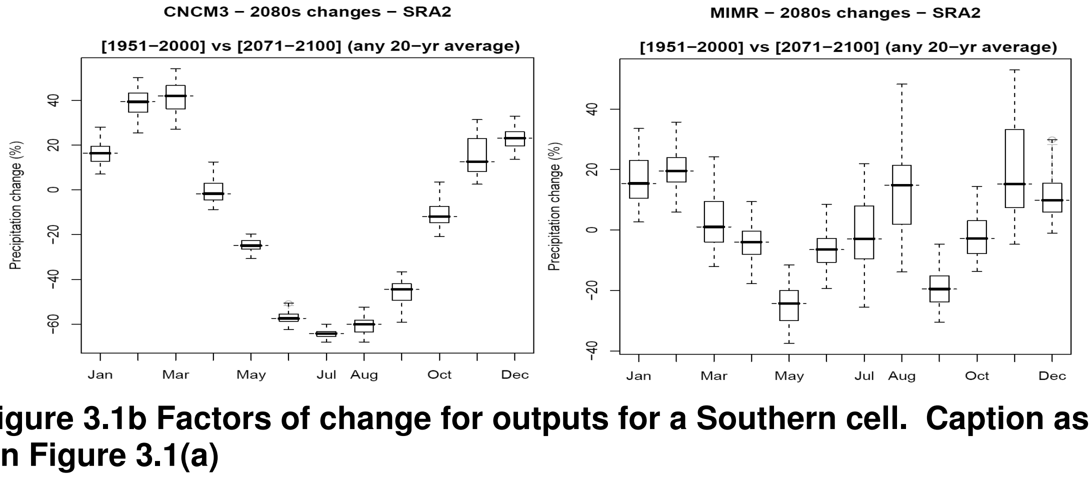


Figure 3.1b Factors of change for outputs for a Southern cell. Caption as in Figure 3.1(a)

Step 3: Intra-annual changes: single-phase harmonic function

Figure 3.1 shows a seasonal variation in the monthly changes, with any of the values within the box plots showing changes all equally probable. Figure 3.2 shows a single-phase harmonic function fitted to the monthly median of changes of Figure 3.1: for the great majority of the months, the harmonic function runs through the box plots, and thus represents accurately possible future changes. The changes from month-to-month vary smoothly, from a high in the winter, to a low in the summer and not randomly from month-to-month. For some scenarios, the difference between the maximum and the minimum changes is large (e.g. CNCM3, Figure 3.1b left graph), while other scenarios indicate a very small variation in the seasonality of changes: (e.g. MIMR, Figure 3.1b right).

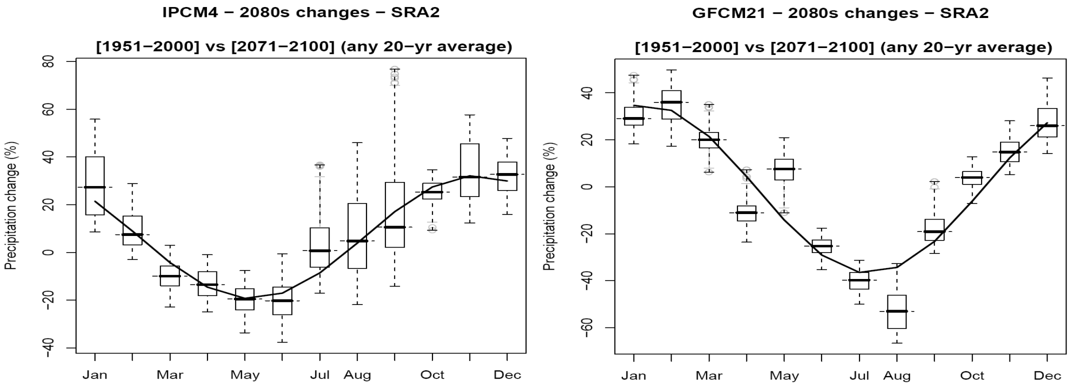


Figure 3.2a Same as Figure 3.1a but with a single harmonic function fitted to describe the factors of change

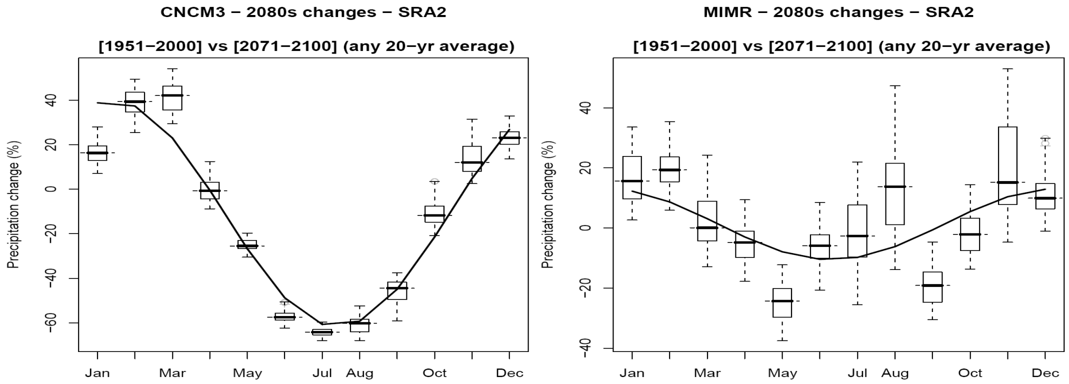


Figure 3.2b Same as Figure 3.1b but with a single harmonic function fitted to describe the factors of change

Three parameters are necessary to fully describe a single-phase harmonic function that summarises a 12-monthly annual pattern:

- The phase. This is the month of the maximum (peak) change
- The mean annual change. This is the overall average of the pattern
- The semi-amplitude. This is the difference between the maximum (peak) change and the mean annual change. This is called here 'seasonal variation' or 'change in seasonality'

The expression of a single-phase harmonic function for an annual cycle is:

$$X(t) = X_0 + A \cos\left(\frac{2\pi t}{12} - \Phi_{rad}\right)$$

with X_0 the mean annual change, A the (semi-)amplitude of the harmonic, Φ_{rad} the phase of the harmonic (in radian), t is the month (1 for January, 12 for December) and $X(t)$ is the value of the change for the month t (from Wilks 2006). The relationship between the phase in months, Φ_{month}, and the phase in radians, Φ_{rad}, is given by:

$$\Phi_{rad} = \frac{2\pi\Phi_{month}}{12}.$$

The single-phase harmonic function is a powerful tool to summarise seasonality of changes in climate in Britain, with simple, easy to understand parameters.

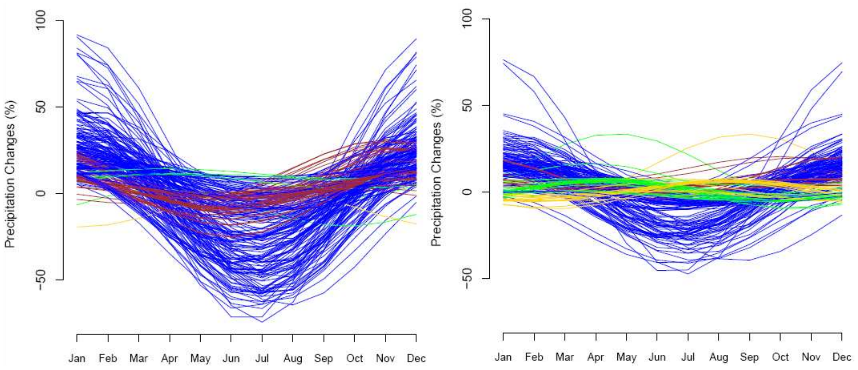
In this project, there are two main advantages of using the monthly pattern described by a single-phase harmonic function over the traditional fixed monthly changes:

1. The traditional (fixed) monthly changes quantify only one possible set of climate changes and are very dependent on the specific times slices used for their computation. They do not account for any climate variability. The harmonic functions are here fitted on a range of possible monthly factors including baseline and future climate variability
2. A sensitivity analysis on the monthly factors would entail a 12-dimension analysis for rainfall * 12 dimension for temperature/PE (i.e. 144 dimension analysis). The single-phase harmonic reduces the analysis to a 3-dimension for rainfall * 3-dimension for temperature/PE (i.e. 9 dimension). This is much more manageable.

3.2 National analysis of climate change scenarios

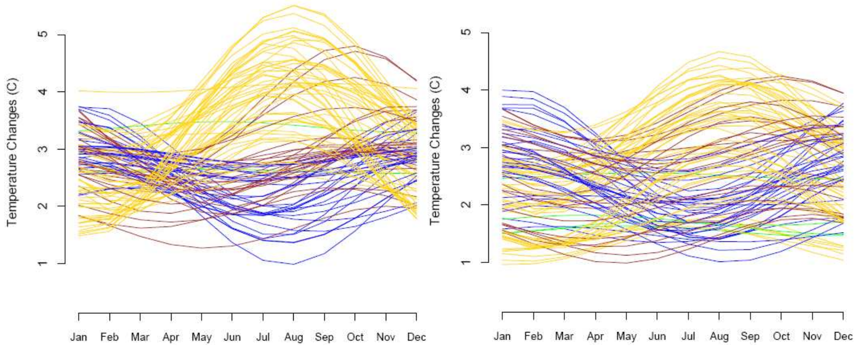
The factors of change for all GCM & emission scenarios combinations, for all grid cells over the UK were calculated for the 2080s, and a single-phase harmonic function fitted on all the changes for precipitation (Figure 3.3) and temperature (Figure 3.4). The season of maximum change is colour-coded.

The national analysis showed that for precipitation, the harmonic function generally peaks in winter for all emission scenarios, while the range in mean annual change is large. For temperature, there is no distinct season of maximum change, with both winter and summer equally projected. No significant correlation was found between change in precipitation and temperature patterns (Milestone Report 2, Prudhomme and Reynard 2009). This resulted in defining two sensitivity frameworks for the project, one for precipitation and one for temperature (Table 3.2) that can be combined independently. Because the effect of the warming pattern on the flood regime is smaller than that of change in rainfall pattern, the number of temperature scenarios was restricted to eight. However, both precipitation and temperature sensitivity frameworks describe a range of possible scenarios larger than currently suggested climate model projections.



SRA2 SRB1

Figure 3.3 Fitted single-phase harmonic functions of monthly precipitation changes (in %) from all available GCM experiments for land cells in Britain under SRA2 and SRB1. Season of maximum change: blue - winter (DJF); green - spring (MAM); yellow - summer (JJA); brown - autumn (SON)



SRA2 SRA1B

Figure 3.4 Fitted single-phase harmonic functions on monthly temperature changes (in degree Celsius) from all available GCM experiments for land cells in Britain under SRA2 and SRB1. Season of maximum change: blue - winter (DJF); green - spring (MAM); yellow - summer (JJA); brown - autumn (SON)

Table 3.2 Sensitivity framework for precipitation and temperature

	Phase	Mean annual change	Seasonality	Scenarios
Precipitation	January	-40% to 60%	0 to +120%	All combinations by increments of 5% Total: 525 scenarios
Temperature	January and August	1.5° 2.5° 4.5°	1.2° 1.8° 1.6°	Low-Jan and Low-Aug Medium-Jan and Medium-Aug High-Jan and High-Aug
	None	0.5°; 4.5°	0°	Low-/High-Non-Seasonal (NS) Total: 8 scenarios

3.3 Vulnerability to climate change: Sensitivity framework

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 (see Section 4). To facilitate the interpretation, results from each ensemble member are displayed in a 2-dimensional space for each analysed indicator:

- Y-axis: Mean annual change; the bottom half part of the diagram represents an overall decrease in the mean annual precipitation (dryer climate); the top half of the diagram represents an overall increase in the mean annual precipitation (wetter climate) (Figure 3.5).
- 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 dryers summers). This can be interpreted as intensification in the seasonal cycle (Figure 3.5).

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 3.5. 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 3.5.

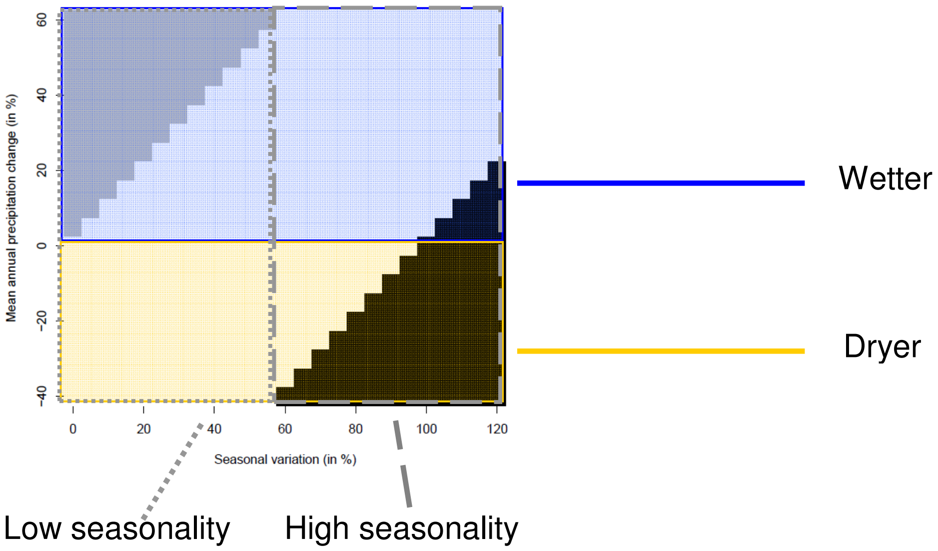


Figure 3.5 Scenario characteristics of the sensitivity domain

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 3.6.

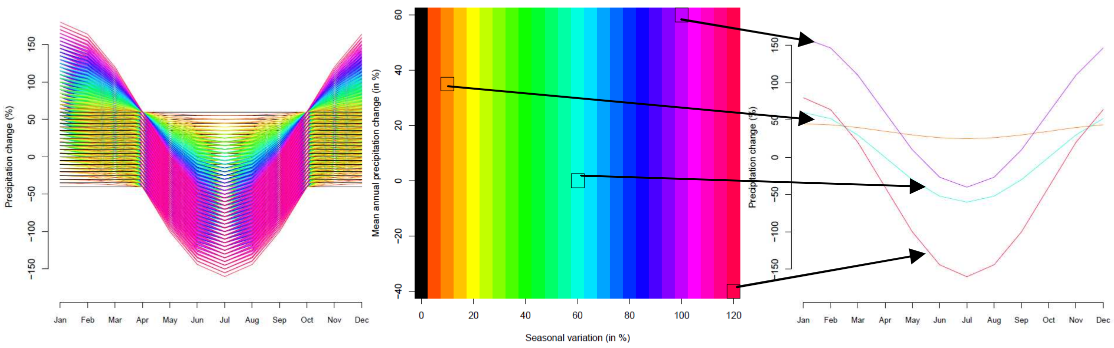


Figure 3.6 Construction of the sensitivity domain and corresponding inter-annual change scenarios

3.4 Limitations of the vulnerability characterisation

The construction of the sensitivity framework and its use to assess changes in flood indicators is not free from assumptions. These constrain the space, primarily to limit the number of runs of the hydrological models, to **4200 for each catchment**. These assumptions are listed below:

- winter peak in change to precipitation
- winter peak always centred on January
- symmetry between summer and winter variance from mean, no change to inter-monthly rainfall pattern

- no consideration of different extreme events outside the data used in calibrating the hydrological models (due to the use of the perturbation method)
- precipitation is a greater driver of change in peak flows than temperature, so the temperature domain change is limited to eight scenarios only
- the extremities of the temperature space are sampled to ensure that the resulting impacts capture the full range of possible values

The effects of some of these limitations on the resulting impacts have been assessed in the uncertainty analysis reported in Section 6.

3.5 Climate change hazard

The climate change hazard is linked to our understanding of how the climate might evolve in the future. It depends on current climate change projections and any associated probabilities. In order to incorporate the uncertainty due to the modelling of the climate, it is important to evaluate the climate change hazard from a range of climate change projections, ideally from different climate models and emission scenarios. The likelihood or probability of specific projections can also be used to evaluate the hazard.

In the FD2020 project, climate change scenarios have been summarised in smoothed monthly climate change factors using a single harmonic function, using the 3-step technique presented in Section 3.1 as follows:

- Calculate the range of possible monthly climate change factors for a given time horizon by considering different possible baseline and future monthly averages, for example derived from 20-year periods within longer baseline and future time slices. All the climate change factors (difference between future and baseline monthly averages) are equally representative of possible climate change, and their range demonstrates the climate variability included within the climate modelling
- Calculate the median monthly change and fit a single-phase harmonic function on these median values. The harmonic function represents a smoothed set of monthly factors, each as likely as any of the multiple monthly change factors

3.6 Climate change risk

In FD2020, catchment flood regime vulnerability is assessed by quantifying the changes in four flood indicators under a set of fixed (525) rainfall and (8) T/PE changes, resulting in eight ‘flood response patterns’ (see Section 4 for more detail). Defining the risk as the change associated with a particular hazard (i.e. comparing the hazard with the vulnerability) requires finding the pre-fixed scenarios of the sensitivity framework which are the most similar to the hazard. To do this the hazard must be expressed in the same form as used for the sensitivity domain. That is a single harmonic function should be fitted to each set of monthly changes in rainfall and T to estimate the mean annual and seasonal changes (see Section 3.5). There are two elements to consider in this comparison: the change in rainfall and the change in T/PE:

- For T/PE changes, only eight pre-fixed scenarios are tested in the FD2020 framework. The characteristics of the eight scenarios can be compared to the harmonic function parameters of the temperature changes and the most similar in terms of mean annual change, seasonal change and phase selected. The sensitivity framework quantifying the changes in flood peak of that particular T/PE scenario (one of the 8-ensemble members tested) is the one to consider as representative of that particular hazard
- It is also possible to consider all of the 8-ensemble member changes, either using their ensemble mean or their range. This is because changes in T/PE are not as important as changes in rainfall for flood regime changes (see Section 6 for more details) and because it is easier to derive probabilistic assessments of changes from a single reference vulnerability
- For rainfall changes, round the mean annual and (semi-)amplitude parameters of the fitted harmonic function to the nearest 5%. Rounding up the parameters provides conservative estimates of flood changes
- The rounded rainfall hazard corresponds to a single combination of one of the 'seasonal change' percentages (equivalent to the (semi-)amplitude parameter, presented in the x-axis of the sensitivity diagram of Figure 3.6) and one of the mean annual change percentages (presented in the y-axis of the sensitivity diagram)
- The change in the chosen flood indicator resulting from this particular climatic change hazard is the response of the selected ensemble member (single, or mean) for the corresponding pre-fixed rainfall scenario

4. Identification of flood response types for Britain

PREVIOUS FAST TRACK BOX ON PAGE 25

Section 4: Identification of flood response types for Britain

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) defined in Section 3, using the hydrological models developed in Section 2.

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. 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. These 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.

NEXT FAST TRACK BOX ON PAGE 51

This section presents the first part of the regionalisation procedure, which aims to identify the vulnerability of the flood regime of a catchment to climatic changes, and identify key flood response patterns found in Britain from a pool of 154 catchments. The second part of the regionalisation, which aims to characterise the vulnerability using catchment properties, is described in Section 5.

The sensitivity framework put in place is scenario-neutral as it does not rely on a particular climate model projection but considers the impact of a range of possible rainfall and warming scenarios. For Britain, this range is described by 525 rainfall scenarios combined with eight warming scenarios (including PE scenarios, this gives a total of 4,200 scenarios, see Section 3). Using these scenarios, 4,200 river flow time series are generated for each catchment and indicators of change in flood frequency derived for each series. The flood indicators selected for analysis are the percentage change in the magnitude of the 2-year, 10-year, 20-year and 50-year return period flood peaks, labelled RP2, RP10, RP20 and RP50, describing the flow that would be expected, on average, once every 2, 10, 20 and 50 years). It is the 4,200 changes for each of the flood indicators which define the vulnerability of the catchment and which are grouped according to similarity of response pattern.

This section first presents how the sensitivity framework and analysis of changes in the flood indicators are grouped into flood response patterns (Section 4.1). These patterns have then been characterised, for Britain, as nine flood response types (Section 4.2). This is followed by a discussion on the hydrology of the flood response types (Section 4.3) and their variation (Section 4.4), before concluding with the geographic distribution of the response types for the 154 modelled catchments in the project (Section 4.5). More detail on aspects of the project summarised in this section can be found in the Milestone Report 3 (Prudhomme *et al.* 2009a).

4.1 Flood response patterns

Using the sensitivity framework described in Section 3 (summarised in Table 3.2), for each catchment, the hydrological models established in Section 2 were run with alternative synthetic climate time series to produce synthetic river flow series. These are compared with the simulated baseline series to determine statistics of change. The synthetic climate time series were generated using the change factor (sometimes termed “delta change”) method of downscaling, where observed climate daily values representative of the ‘baseline’ are modified proportionally by a monthly climate change factor to create ‘future’ climate time series. The monthly climate (rainfall and T/PE) change factors used were derived from each element of the sensitivity framework, i.e. smoothed monthly percentage change factors calculated using the single-phase harmonic function with a January phase for each of the 525 rainfall scenarios and eight sets of harmonic function values for T/PE, described in Section 3.

For each flood indicator, the eight warming scenarios (temperature and corresponding PE changes) were each run in combination with the 525 precipitation scenarios to create an 8-member ensemble response surfaces (one member per warming scenario). Results are displayed in a 2-dimensional space for a given flood indicator, as shown for one T/PE scenario in Figure 4.1. On the left, the changes in the flood indicator (here changes in the 20-year daily flood peak) are represented, colour-coded according to the magnitude of changes: this is the flood response pattern, as it represents the response of the catchment to climatic changes on its flood regime. On the right, the percentage changes in flood magnitude are divided by the maximum percentage change in rainfall (sum of the (semi-)amplitude and mean annual change) to highlight the non-linearity in the rainfall-runoff transformation. This is the ratio response pattern, as it represents the ratio between flood and rainfall changes and highlights for which scenarios the rainfall changes are damped/enhanced by the catchment (i.e. whether the changes in flood peak are proportionally lower/similar/greater than the maximum rainfall change). Both diagrams provide two different illustrations of how a catchment's flood regime responds to climatic changes. It is the underlying information in the flood response pattern, percentage changes in flood magnitude associated with a given rainfall/T/PE scenario, which is analysed in the grouping procedure. In the rest of the document, 'flood response pattern' is used to describe both the changes in flood magnitude obtained using the sensitivity framework and their graphical representation. There are four eight-member flood response patterns for each catchment (one per flood indicator).

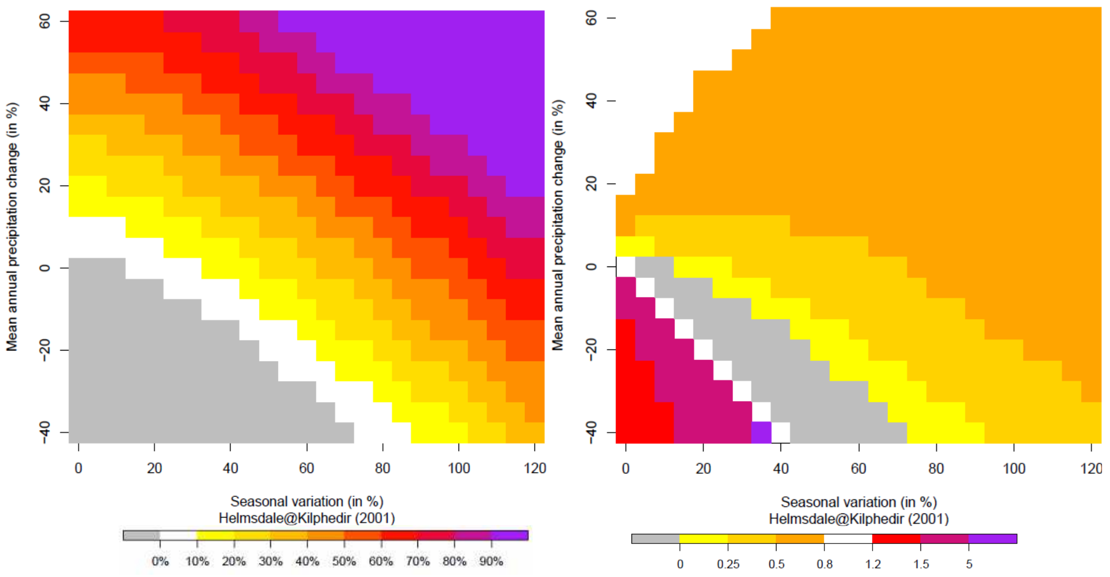


Figure 4.1 Example flood response pattern (left) and ratio response pattern (right) for changes in 20-year flood peak for the Helmsdale @ Kilphedir with the Medium-Aug temperature/PE scenario (maximum rainfall change in January)

4.2 Flood response types

The set of eight flood response patterns was derived for each catchment and then grouped according to their similarity, using a hierarchical clustering technique (see Milestone Report 3, Prudhomme *et al*. 2009a, for details of the grouping methodology). For any catchment, the analysis of all the flood and ratio responses showed that the spread between the ensemble members (i.e. different warming scenarios for the same 525 rainfall scenarios) is much smaller than the spread between different ensembles (i.e. representing the response of different catchments). This confirms that, when analysing change in the flood regime, the variation due to a change in the temperature pattern is not as important as that due to a change in rainfall. For each flood indicator, the identification of the key flood response patterns across Britain was achieved by considering together the eight members as representative of a catchment response. The identification of the key flood response patterns was performed independently for each flood indicator.

This procedure resulted in the identification and definition of nine flood response types for Britain within five families: Neutral, Damping, Enhancing, Mixed and Sensitive. An effort was made in the interpretation of the results so that similar response surfaces belong to the same overall type across the different indicators. The nine response types are presented schematically in Figure 4.2, in which discrete boundaries between types should be considered as dividing a continuum. Flood response types are positioned relative to each other to represent the change in vulnerability to flooding from increase in rainfall, so that the least vulnerable type is on the left of the figure and the most vulnerable on the right.

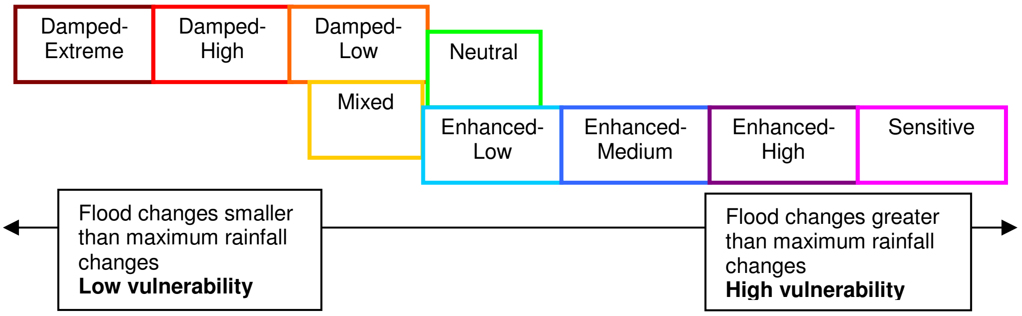


Figure 4.2 Schematic of the nine flood response types

The response types are listed in Table 4.1, with brief descriptions of change in flood peak for four categories of change in mean annual and seasonal precipitation. The flood and ratio response patterns for each response type and each of four flood indicators are shown in Figure 4.3 and Figure 4.4 respectively. The variability of response patterns within each response type, as measured by the standard deviation and coefficient of variation, has also been calculated for each response type (Figure 4.5 of Milestone Report 3, Prudhomme *et al*. 2009a).

Table 4.1 Summary description of changes in flood peaks for the nine flood response types of Britain from 154 catchments

Response type	Signal description	Increase in mean annual rainfall with increase in summer* rainfall	Increase in mean annual rainfall with decrease in summer* rainfall	Decrease in mean annual rainfall with increase in winter** rainfall	Decrease in mean annual rainfall with decrease in all months
Neutral	Neutral	Similar	Similar	Similar or lower	Decrease
Damped L	Slightly damped	Similar or higher	Similar or lower	Lower or much lower	Decrease
Damped H	Very damped	Similar	Similar or lower	Much lower or decrease	Decrease
Damped E	Extremely damped	Lower	Much lower	Much lower or decrease	Decrease
Enhanced L	Slightly enhanced	Higher	Similar or higher	Similar or lower	Decrease
Enhanced M	Enhanced	Much higher	Similar or higher	Lower or much lower	Decrease
Enhanced H	Very enhanced	Much higher	Similar to much higher	Lower to decrease	Decrease
Sensitive	Sensitive	Much higher	Much lower to much higher	Much lower or decrease	Decrease
Mixed	Mixed	Higher or much higher	Similar or lower	Much lower or decrease	Decrease

Similar – percentage increase in flood peak of similar magnitude to maximum monthly percentage increase in precipitation (ratio of 0.8 to 1.2)
Lower – percentage increase in flood peak lower than maximum monthly percentage increase in precipitation (0.5 to 0.8)
Much lower – percentage increase in flood peak much lower than maximum monthly percentage increase in precipitation (0 to 0.5)
Higher – percentage increase in flood peak higher than maximum monthly percentage increase in precipitation (1.2 to 1.5)
Much higher – percentage increase in flood peak much higher than maximum monthly percentage change in precipitation (more than 1.5)
Decrease – percentage decrease in flood peak

***Summer** – at least one month from May to September
****Winter** – at least one month from November to March
Change in rainfall derived from harmonic function with peak in January and trough in July

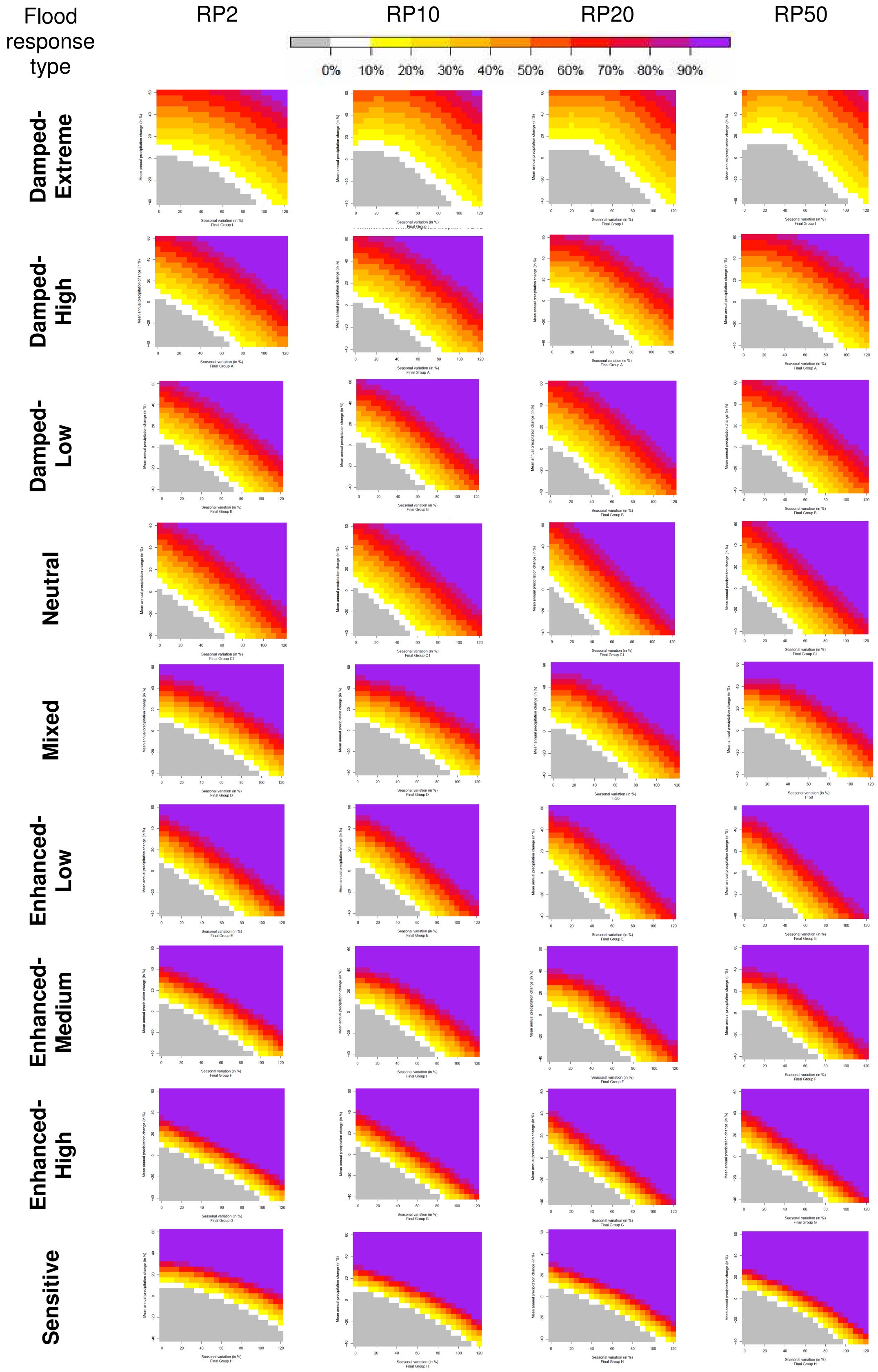


Figure 4.3 Key flood response patterns (averaged over the eight T/PE scenarios) for the nine flood response types, for the four flood indicators

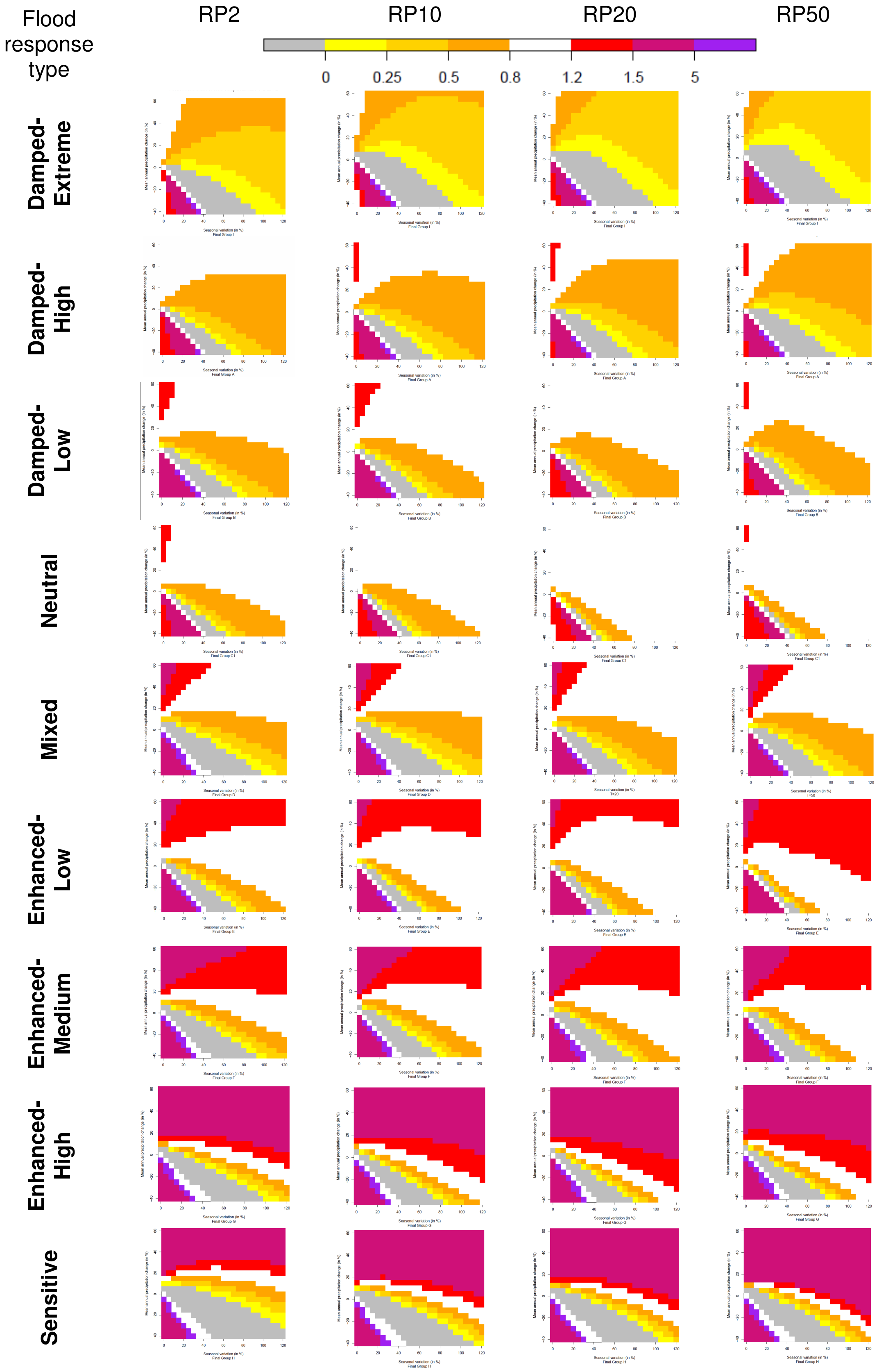


Figure 4.4 Ratio response patterns (averaged over the eight T/PE scenarios) for the nine flood response types for the four flood indicators

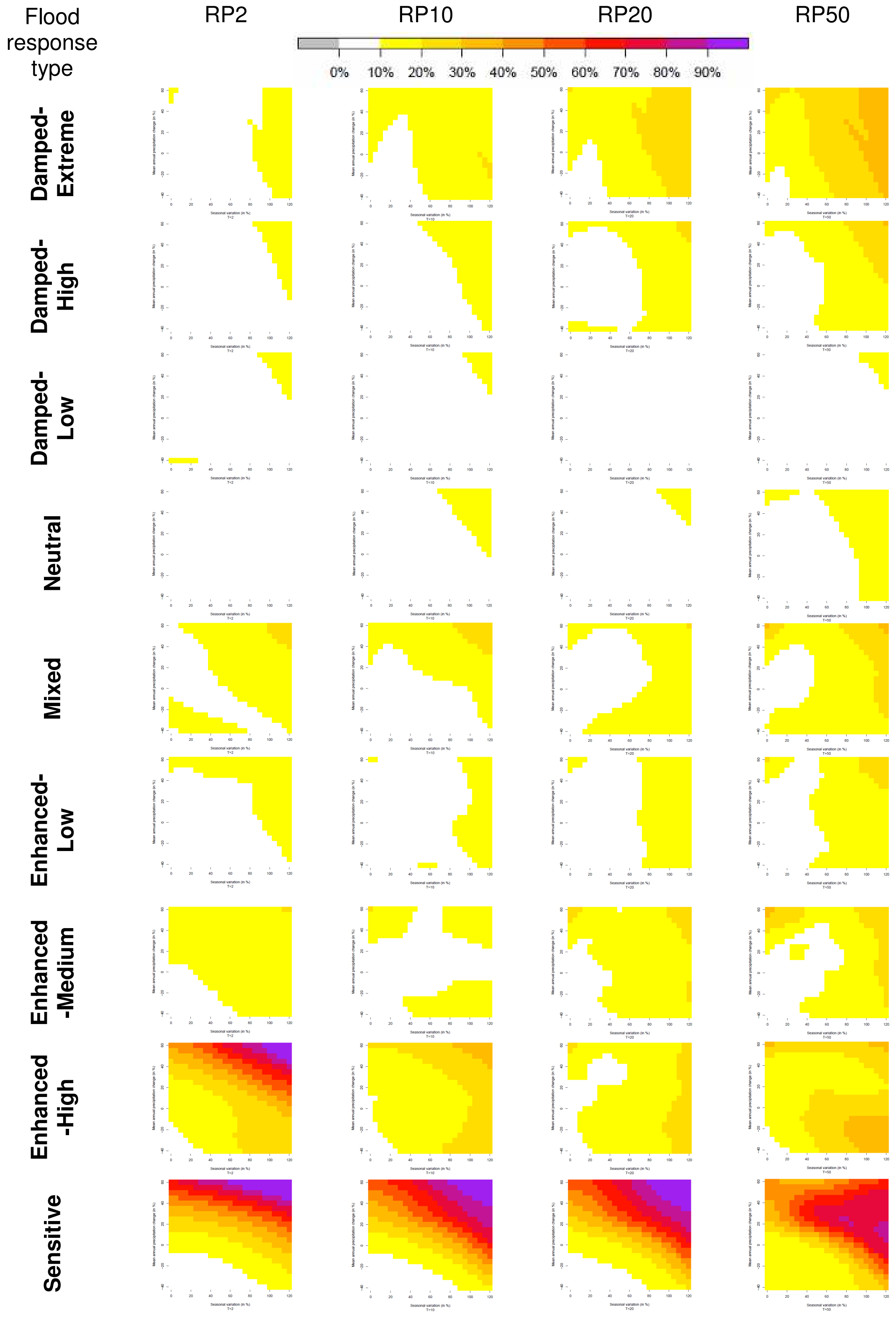


Figure 4.5 Standard deviation of key flood response patterns (over the eight T/PE scenarios) for the nine flood response types for the four flood indicators

4.3 Hydrology of flood response types

The differentiating factors between the nine identified flood response types can be understood in terms of climatology, seasonality, catchment hydrology and natural variability. As it is the impact of changing the climate which is being investigated, it follows that the balance between climatological parameters is of major importance to future changes in frequency of rainfall-runoff response.

a) Water balance

The seasonality of the hydrological water balance between incoming precipitation (P) and outgoing losses, mainly through evapotranspiration (PE) and water usage, provides the background which determines whether a ‘precipitation event’ is sufficient to generate a flood. In the winter (Dec – Feb) inputs generally greatly exceed losses and therefore the balance is not unduly affected by changing P and PE. On average, the flood potential is not changed. However, in the remainder of the year the water balance may be considerably altered by changes in P and PE with consequent effects on the flood potential.

b) Catchment memory

The rate of response between rainfall and runoff is determined by catchment properties such as permeability, soil type and slope. These properties determine the lag between rainfall and river flow or the ‘memory’ of the catchment. With a short memory catchment changes in the water balance impact over only a limited time, such as hours or days. Whereas for a long memory catchment changes to the water balance may be evident over months, or even years.

c) Natural variability

The future climate series have been created using the factor of change method applied to observed precipitation, temperature and PE. The sequencing and time of year of extreme rainfall events in the observed data series, inherent with natural variability of the climate, may have an effect on the resultant change in frequency of the associated flood events. This aspect is considered further in Section 5 (regionalisation of the key flood response patterns) and Section 6 (uncertainty analysis).

d) Frequency of floods

Four flood indicators have been selected for analysing the impacts of climate change: changes in the magnitude of the 2-year, 10-year, 20-year and 50-year return period daily peak flows. Floods, typical of different return periods, may tend to occur at different times of the year and have different causative factors (e.g. cyclonic/convective rainfall or snowmelt). Therefore, when the impact of the three factors described above combine, it is to be expected that changes to current flood frequency may not be of the same magnitude, or direction, across all return periods. For example, an increase in mean annual rainfall of 5% with 10% seasonality could result in a decrease in the 2-year return period peak but an increase in the 20-year event.

The specific characteristics of the four factors described above for each of the flood response types form the subject of Section 5.

The choice of the baseline time series used in the catchment analyses, and in particular the variability in the peak flows within the baseline for each catchment, could potentially influence the quantified vulnerability. As discussed in Milestone Report 1 (Crooks *et al.* 2009), the time period for the flood peak data series is governed by the length of the observed flow series and is therefore not the same for all catchments. Also, differences between observed and modelled values of the mean flood discharge and coefficient of variation may be attributable to a number of data measurement factors.

This was tested by evaluating whether there is any relationship between the flood response type and the characteristics of the sampled flood peak data series. To do this the mean and coefficient of variation (cv) of the observed and modelled POT2 series for each catchment were analysed according to their flood response type. The results are shown in Figure 4.6 for two flood indicators, RP10 (left) and RP50 (right).

Generally, catchments of Enhancing type are associated entirely with low mean flood discharge (maximum of 100 m^3s^{-1} for enhanced medium, high and sensitive), while there is no distinct characteristic for the Damping catchments (Figure 4.6 top). There is a shift in the flood response type of catchments with the largest mean POT2 from Damping type for RP10 towards a more Enhancing type (Mixed, Neutral and Enhanced low) for RP50. When looking at the dispersion of POT2 series, there is no marked difference between the nine flood response types (Figure 4.6 bottom). Note that apart for the three Damped Extreme catchments (brown, left hand side) where the modelling underestimates the observed dispersion in POT2 series, there is no systematic bias in the reproduction of the daily flood peak variability for any particular flood response type and family. Therefore, the flood response type for a catchment is not related to flood history.

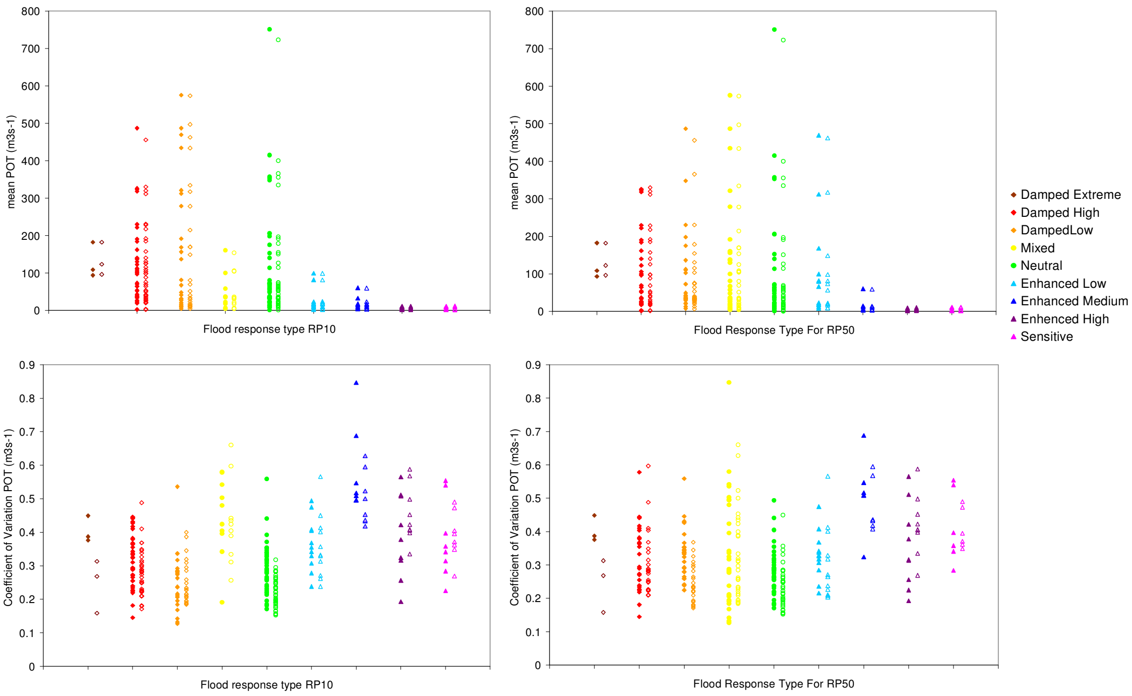


Figure 4.6 Mean (top) and coefficient of variation (bottom) of POT2 series according to the flood response types for RP10 (left) and RP50 (right). Filled symbols are for observed POT series, open symbols for modelled POT series

4.4 Variability in the key flood response patterns

4.4.1 Effect of warming scenarios on the key flood response patterns

Although the eight temperature/potential evaporation (T/PE) ensemble members have been combined in each key flood response pattern, the differences in PE between them do have a small impact on the seasonal water balance. The degree to which the water balance is impacted depends on the relative values of precipitation and PE. Thus for the Neutral flood response type (Figure 4.7 left), there is little difference with phase and value of the temperature increase while for the Enhanced High flood response type (Figure 4.7 right), there is a noticeable difference with both phase and temperature change (e.g. size and shape of the grey, or purple, areas which represent the scenarios leading to a reduction, or increase of more than 90%, in the flood peak magnitude). The Damped Extreme pattern also shows a variation with change in temperature (not shown). More detail can be found in Section 6.

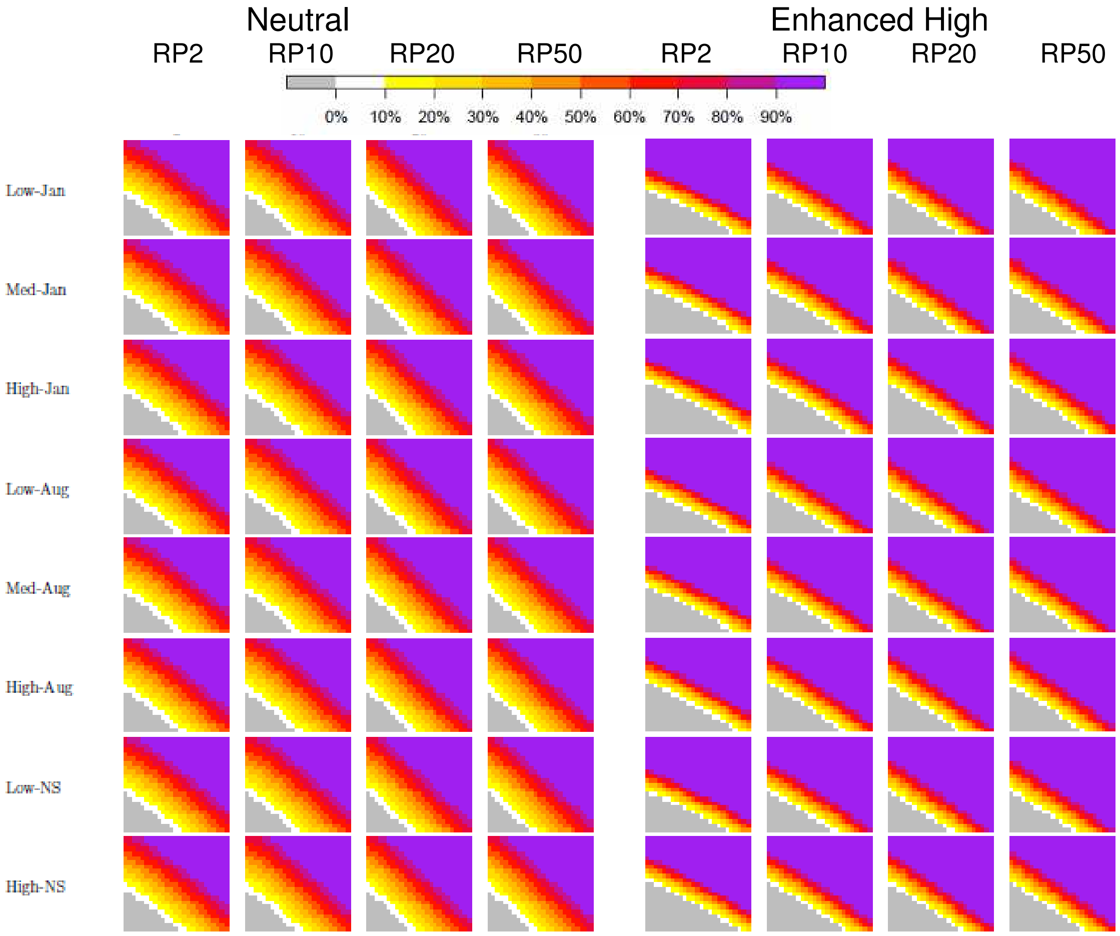


Figure 4.7 Flood response patterns for the eight T/PE ensemble members for Neutral (left) and Enhanced H (right) for the four flood indicators

4.4.2 Intra- and inter-variability of the nine flood response types

The flood response types identified for Britain synthesise in nine groups the range of changes in flood peak due to changes in the climate found for 154 catchments. Each type is represented by a key flood response pattern defined as the composite patterns made by the arithmetic mean of all flood response patterns from all T/PE scenarios from all catchments of that type. The key flood response patterns are then analysed to evaluate:

- Whether each key flood response pattern is homogeneous, i.e. the spread within the group is not too large
- Whether each key flood response pattern is significantly different from the others, i.e. the difference between all the key flood response patterns is larger than the difference between a catchment flood response pattern and its key flood response pattern

The similarity of two flood response patterns can be quantified in terms of their correlation and their standard deviation, and Taylor diagrams were one of the tools used for the analysis (see Milestone Report 3, Prudhomme *et al.* 2009a, for details). These showed that, generally, the spread around the key flood response patterns is small compared with the spread of all flood response patterns: *the internal group variability is much smaller than the external group variability*. This is an indication that the groups are homogeneous and each flood response pattern is significantly different from another.

Damped key flood response patterns are representative of catchments with lesser variability. As they dampen the climate change signal to flood, the variation in the changes in flood magnitude is small. At the opposite end, Enhanced key flood response patterns are characterised by larger internal variance in their pattern: changes in flood magnitude are large. The variability of Mixed and Neutral patterns is between that of Damped and Enhanced patterns. The Sensitive patterns show the largest intra-group variability.

The variability in the catchment flood responses is larger for low return periods than for higher return periods in particular for the Enhanced High and Sensitive flood responses. This means that it is not necessary to discriminate as many flood response types for high return periods as it is for low return periods, and few flood response types are representative of the majority of the catchment flood responses.

4.5 Geographical location of flood response types

There is no strict geographical pattern in the location of the flood response types through Britain (Figure 4.8) but some important features emerge:

- Different key flood response patterns can be associated with the same catchments for different flood indicator: the symbols in the maps show different geographical patterns
- There is no geographical region associated with only one flood response type: a characterisation of the flood response type cannot be done on a purely geographical basis
- Damping patterns (down triangles) are generally found in the west and in the north for low return period, but move eastward for RP20 and RP50
- The Neutral pattern (circles) is found in Scotland, Wales and the west of England
- The Mixed pattern (stars) is found in most parts of Britain for RP2, while it is found mostly in south and east of England at RP50
- Enhancing patterns (up triangles) are generally found in the southern part of the country (and principally in England), but a few catchments in Wales and Scotland are also found at higher return period

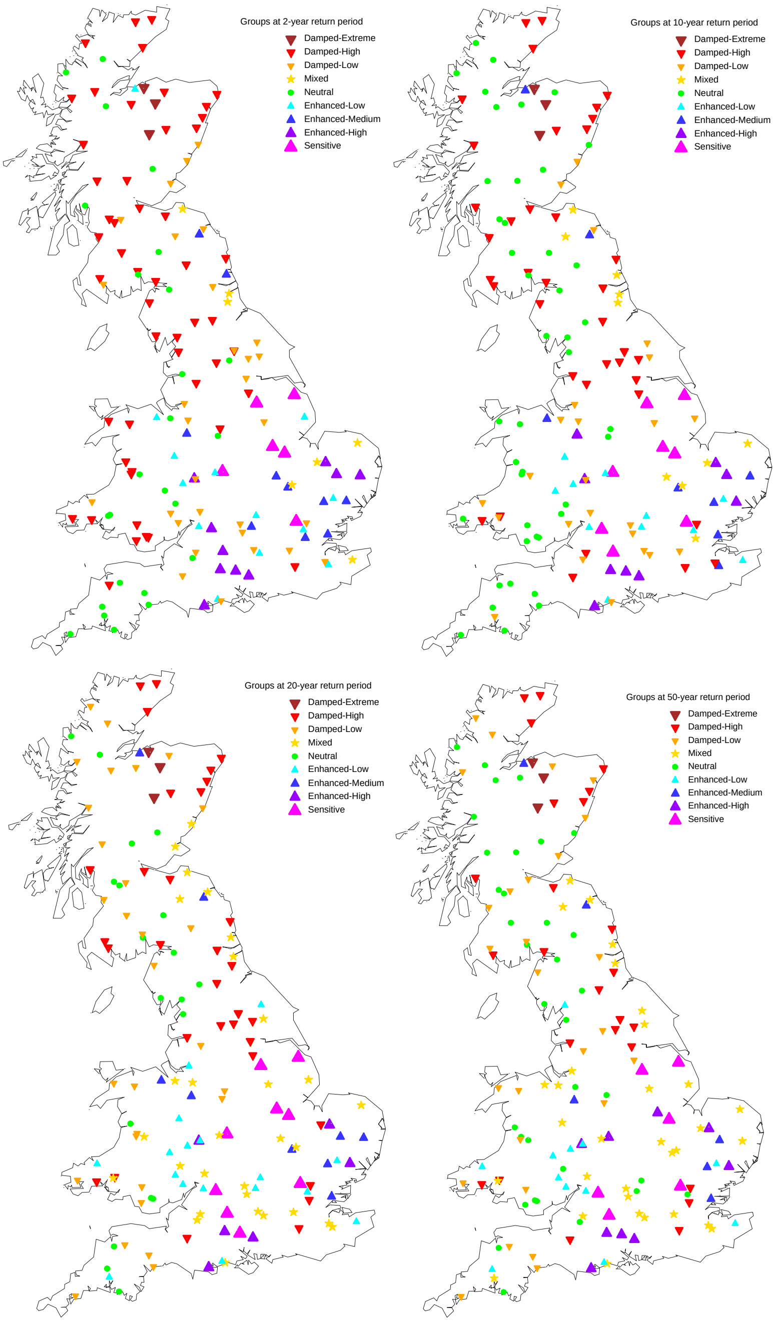


Figure 4.8 Flood response types associated with the 154 modelled catchments for RP2, R10, RP20 and RP50 (maximum rainfall change in January)

5. Regionalising the flood response types

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Section 5: Regionalising the 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 insure 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.

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In the scenario-neutral approach developed in the project, the vulnerability of a catchment is characterised in two steps: firstly, the response surfaces of a set of catchments to a range of climatic changes are simulated and analysed for similarity, and secondly the key flood responses are characterised according to catchment properties.

This section describes the second step of the vulnerability assessment in which relationships were investigated between catchment characteristics (geographic, geologic or climatic) and the vulnerability of the catchment flood regime to changes in climate. The work follows the identification of nine flood response types for catchments in Britain (Section 4), after a comprehensive 'scenario-neutral' sensitivity study based on 4,200 patterns of changes in rainfall, temperature and potential evaporation (Section 3).

A total of nine flood response types corresponding to nine key flood response patterns were identified for each flood indicator, represented by five main 'families' of catchments. These are listed with brief descriptions in Table 4.1 and presented schematically in Figure 4.2. The key flood response patterns (averaged over the 8 T/PE scenarios) for each flood response type and each of four flood indicators are shown in Figure 4.3.

The aim of this section is to find links between the flood response type of a catchment and its catchment properties. Once such 'regional' relationships have been established, they can be used to assign a flood response type to any catchment for which the relevant catchment properties are available. In other words it will be possible to assess the potential change in flood peak due to climate change from its key flood response pattern without the need to undertake a full climate change impact study.

This section summarises the methodology used to assign a flood response type to a catchment from its physical characteristics (Section 5.1) and presents the data used (Section 5.2). The decision trees obtained for the four flood indicators are then presented (Section 5.3) and discussed in terms of their performances (Section 5.4) and the hydrological characteristics associated with each flood response type (Section 5.5). More detail on aspects of the project summarised in this section can be found in the Milestone Report 4 (Prudhomme *et al.* 2009b).

5.1 Method: hierarchical recursive partitioning and decision trees

The hierarchical partitioning method (also called recursive partitioning) was used to associate a set of catchment descriptors with a flood response (or vulnerability) type in the form of sets of rules, or decision trees. Decision trees have also been used to characterise UK rivers into ecological types from their physical characteristics (Acreman *et al.* 2008) and for seasonal forecasting of low summer flow in the river Thames (Wedgbrow *et al.* 2005).

Decision trees are defined by a set of binary rules (here, based on catchment characteristics) which divide the original sample (the catchments) into a number of categories (the flood response types). The decision trees were derived using the set of codes from the R freeware package `tree`. The terminology of decision trees can be summarised by:

- The *root* is the top node and includes all samples to be classified
- Data at each node are split into two *branches* according to binary tests, or rules, leading to the formation of two further nodes
- A node becomes a *leaf* when no further split is possible or relevant
- A node is pure if it contains only catchments with the same flood response type, and then becomes a leaf
- An impure node can either be further divided, or become a leaf if it contains too few catchments
- A leaf is reached by following a set of partitioning rules, called a path
- Each leaf has associated ‘flood response type probabilities’: the probability that a catchment following a path to a leaf belongs to a given flood response type
- The flood response type associated with a leaf is that with the highest probability

The final decision trees were chosen according to qualitative and quantitative evaluations:

- There should be at least one leaf (or path) for all flood response types
- The flood response type probabilities of the leaves should be as distinct as possible, i.e. one flood response type probability should be much higher than the others, rather than several flood response types with similar probability
- If a leaf contains catchments with different flood response types, they should have flood response types of the same family, e.g. they should all be from the damping family rather than some from damping and some from the enhancing families
- The paths should describe logical hydrological processes
- The tree should not have too many splits leading to a large number of leaves
- The method should maximise the number of catchments correctly classified, but minimise the number of catchments classified with a more damping type than observed
- Each tree is compared with trees of other return periods so that selected trees use a common pool of descriptors, to increase readability and reduce complexity

5.2 Data

5.2.1 Flood response types for the four flood indicators

The nine flood response types, identified in Section 4, emerged from analysing changes in flood peaks from rainfall change scenarios with a smoothed variation through the year, peaking in January. The impact of the month of the maximum rainfall change was investigated by Kay *et al.* (2009a) which showed that for catchments in the Damping family, the flood response pattern may be either less Damping or Neutral when peak changes in rainfall occur in the autumn, while for catchments in the Enhancing family the flood response pattern may be more Enhancing. When the peak rainfall change occurs between February and mid-summer, the effect on changes in flood peaks is generally less. This impact is particularly applicable for RP20 and RP50 (see Section 6 for more detail).

Because only three catchments were classified as Damped Extreme, they could not be discriminated and were not included in the analysis, leaving 151 modelled catchments for the analysis. The implication of this simplification is discussed in Milestone Report 4 (Prudhomme *et al.* 2009b).

In order to integrate the variation in the flood response type due to the month of maximum rainfall change, and to address the issue of under-representation of some flood response types in the sub-sample of 152 patterns (151 catchments, but one catchment is modelled using both the PDM and CLASSIC) per flood indicator, the remaining eight flood response types were merged as shown in Table 5.1.

Table 5.1 Combination of flood response types for higher return periods, along with the name of the key flood response pattern to be applied for each combination

Flood response type	Combination of flood response types (with key flood response pattern to be applied) for:			
	RP2	RP10	RP20	RP50
Damped-Extreme	Damped-Extreme	Damped-Extreme	Damped-Extreme	Damped-Extreme
Damped-High	Damped-High	Damped-Low	Neutral	Neutral
Damped-Low	Damped-Low			
Neutral	Neutral	Neutral		
Mixed	Mixed	Mixed	Mixed	Mixed
Enhanced-Low	Enhanced-Low	Enhanced-Low	Enhanced-High	Enhanced-High
Enhanced-Medium	Enhanced-Medium	Enhanced-Medium		
Enhanced-High	Enhanced-High	Enhanced-High		

This merging of flood response types for higher return periods is entirely compatible with the conclusions of the type variability, where lower variability in the key flood response patterns was found at high return periods (see Section 4.4).

A decision tree was developed independently for each flood indicator.

5.2.2 Catchment descriptors

Two main sources of catchment descriptors are available digitally in Britain for a comprehensive number of catchments and were used in this project, along with hydroclimatic catchment properties derived for the study catchments:

- The Flood Estimation Handbook (FEH) catchment descriptors database. They are regrouped in a CD-ROM containing digital descriptors for over four million UK catchments that drain an area of at least 0.5 km^2. Nineteen of these descriptors were considered in the project
- The hydrometric registry entries. The hydrometric register is a catalogue of river flow gauging stations in the UK holding summary hydrometric and spatial statistics for over 1,500 river basins, available in paper and digital format (Marsh and Hannaford 2008). Eight descriptors were considered in the project
- Hydroclimatological information. Three variables were derived from catchment PE and seasonality of daily flood peaks and considered in the project

5.3 Decision trees

Nine catchment descriptors were found to be necessary to characterise the flood response types for all four indicators, as summarised in Table 5.2. Depending on the flood indicator, different partition rules were necessary to achieve total discrimination of the flood response types. To ensure consistency in the decision trees and address the merged response types in an appropriate manner, some expert judgment was used to finalise the decision trees (see Milestone Report 4, Prudhomme *et al.* 2009b, for details). The number of paths and overall performance of the selected tree model for each indicator are given in Table 5.3. Not surprisingly higher model performance is achieved with fewer groups.

The selected decision trees (Figure 5.1) and associated probabilities (Table 5.4) are given for each flood indicator in the next pages. In Figure 5.1, the paths are colour-coded according to the flood response type with the highest probability. Some flood response types can be categorised by several paths: this shows that different combinations of catchment descriptors might represent catchments with similar flood change response to climate change.

Table 5.2 Catchment descriptors used in the decision trees to determine flood response types

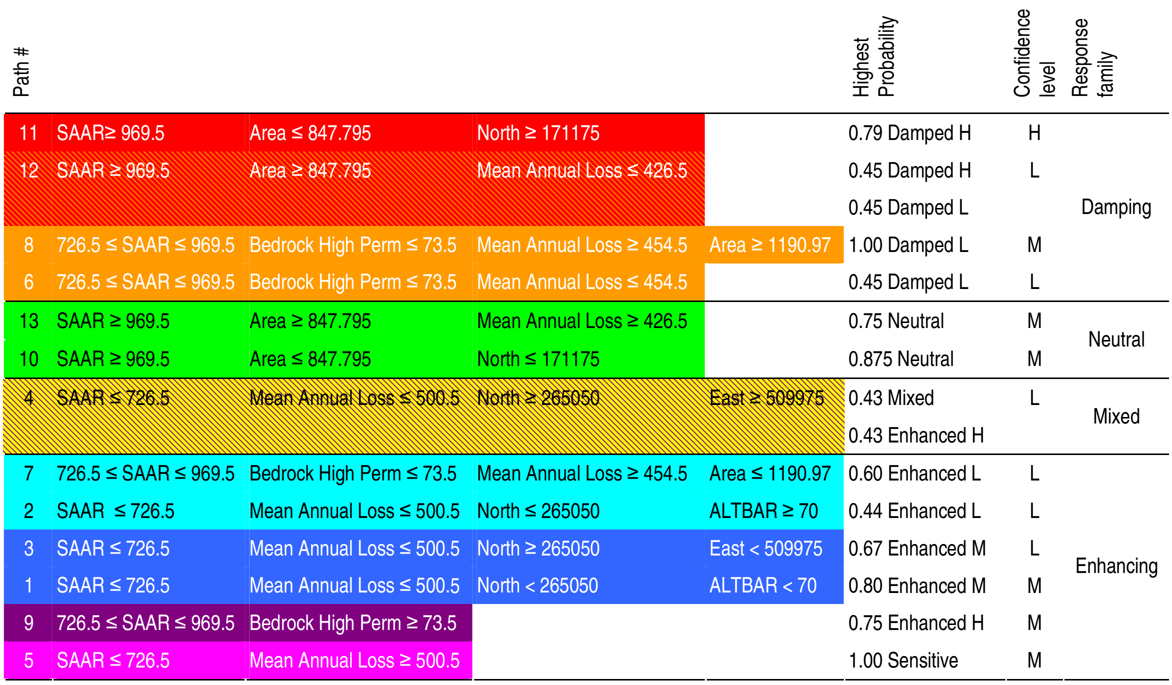
Descriptor		RP2	RP10	RP20	RP50
SAAR (FEH)	1961-90 standard period average annual rainfall (mm)	Y	Y	Y	Y
Area (FEH)	Catchment drainage area (km^2)	Y	Y	Y	Y
ALTBAR (FEH)	Mean catchment altitude (m above sea level)	Y	Y		Y
BFIHOST (FEH)	Base flow index derived using the HOST classification		Y		
North (FEH)	Northing of catchment outlet (in GB national grid)	Y	Y	Y	
East (FEH)	Easting of catchment outlet (in GB national grid)	Y			
Bedrock High Permeability (BHP) (Hydrometric Register)	Proportion of the catchment underlain by rock formations of high permeability (%)	Y	Y	Y	Y
Bedrock Very Low Permeability (BVLP) (Hydrometric Register)	Proportion of the catchment underlain by rock formations of low permeability (%)				Y
Mean Annual Loss (MAL) (Hydrometric Register)	Difference between mean annual catchment rainfall and mean annual catchment runoff (mm)	Y		Y	Y

Table 5.3 Summary statistics of tree performance

Flood indicator	Number of groups	Number of leaves	Number of descriptors	Tree performance (%)
RP2	8	13	7	68
RP10	7	12	6	68
RP20	4	9	5	85
RP50	4	9	6	83

While decision trees summarise neatly the main relationships between catchment descriptors and the vulnerability of the flood regime of a catchment to a range of climatic changes, they are probabilistic assessments and all the flood response types with a non-nil probability should also be considered. In a decision tree, each path (leading to a leaf) is associated with a probability of belonging to one of the flood response types to be discriminated. Most paths are not associated with a probability of one, i.e. do not contain catchments of a single flood response type. However, the majority of catchments generally belong to the same flood response type (given in column 3 of Table 5.4). A confidence level associated with the flood response type with the highest probability is also given, combining how certain the probability estimate is with how robust it might be. More details on the confidence level estimation are given in Milestone Report 3 (Prudhomme *et al.* 2009a). The level of confidence should be taken into consideration when using the decision tree to assess the vulnerability to climate change of a catchment's flood regime. The use of probabilities and confidence levels is explained through a set of worked examples in Section 7.

5.3.1 Decision tree and associated probability for RP2



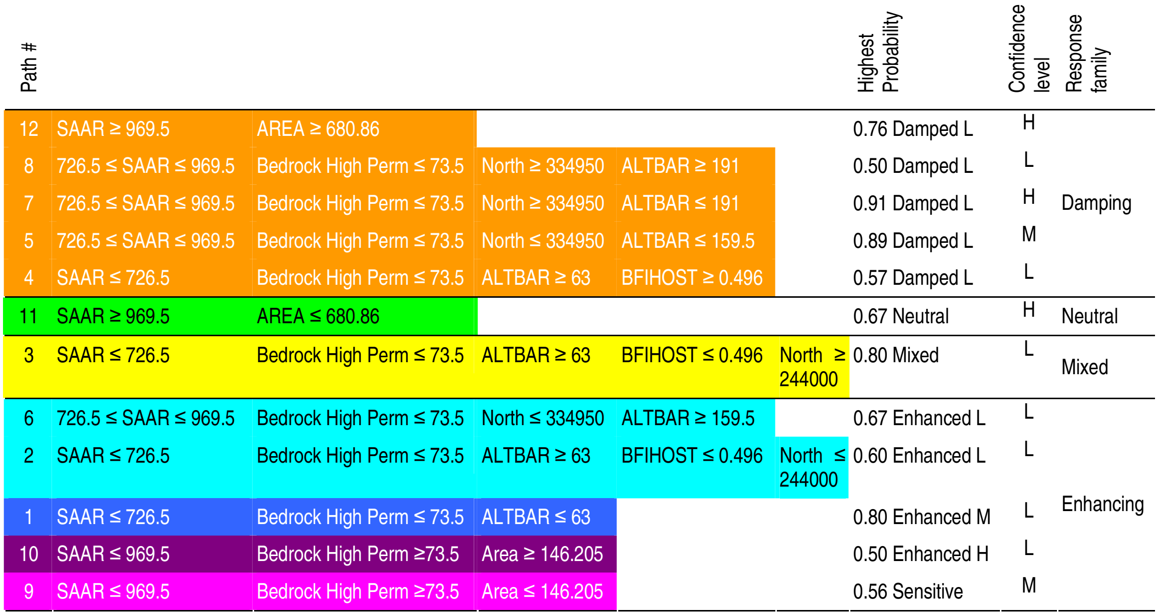
Path #					Highest Probability	Confidence level	Response family
11	SAAR≥ 969.5	Area ≤ 847.795	North ≥ 171175		0.79 Damped H	H	Damping
12	SAAR ≥ 969.5	Area ≥ 847.795	Mean Annual Loss ≤ 426.5		0.45 Damped H	L	
					0.45 Damped L		
8	726.5 ≤ SAAR ≤ 969.5	Bedrock High Perm ≤ 73.5	Mean Annual Loss ≥ 454.5	Area ≥ 1190.97	1.00 Damped L	M	
6	726.5 ≤ SAAR ≤ 969.5	Bedrock High Perm ≤ 73.5	Mean Annual Loss ≤ 454.5		0.45 Damped L	L	
13	SAAR ≥ 969.5	Area ≥ 847.795	Mean Annual Loss ≥ 426.5		0.75 Neutral	M	Neutral
10	SAAR ≥ 969.5	Area ≤ 847.795	North ≤ 171175		0.875 Neutral	M	
4	SAAR ≤ 726.5	Mean Annual Loss ≤ 500.5	North ≥ 265050	East ≥ 509975	0.43 Mixed	L	Mixed
					0.43 Enhanced H		
7	726.5 ≤ SAAR ≤ 969.5	Bedrock High Perm ≤ 73.5	Mean Annual Loss ≥ 454.5	Area ≤ 1190.97	0.60 Enhanced L	L	Enhancing
2	SAAR ≤ 726.5	Mean Annual Loss ≤ 500.5	North ≤ 265050	ALTBAR ≥ 70	0.44 Enhanced L	L	
3	SAAR ≤ 726.5	Mean Annual Loss ≤ 500.5	North ≥ 265050	East < 509975	0.67 Enhanced M	L	
1	SAAR ≤ 726.5	Mean Annual Loss ≤ 500.5	North < 265050	ALTBAR < 70	0.80 Enhanced M	M	
9	726.5 ≤ SAAR ≤ 969.5	Bedrock High Perm ≥ 73.5			0.75 Enhanced H	M	
5	SAAR ≤ 726.5	Mean Annual Loss ≥ 500.5			1.00 Sensitive	M	

Figure 5.1a Schematic of partition rules for RP2 with associated highest probability and confidence level; coloured according to corresponding flood response type (hashed if highest probability equal for two types)

Table 5.4a Probability attached to each assigned flood response type and confidence levels for the highest probability (bold) for RP2.

			Probability of flood response type								
Path #	Size of leaf (number of elements from the sample)	Flood response type of path	Damped-H	Damped-L	Neutral	Mixed	Enhanced-L	Enhanced-M	Enhanced-H	Sensitive	Confidence level
1	5	Enhanced-M	0	0	0	0	0.20	**0.80**	0	0	**2 M**
2	9	Enhanced-L	0	0.33	0	0	**0.45**	0.22	0	0	0.71 L
3	6	Enhanced-M	0	0	0	0.17	0	**0.66**	0.17	0	1.93 L
4	7	Mixed	0	0	0	**0.43**	0.14	0	**0.43**	0	0 L
5	6	Sensitive	0	0	0	0	0	0	0	**1.00**	**3.95 M**
6	20	Damped-L	0.35	**0.45**	0.10	0.10	0	0	0	0	1.31 L
7	10	Enhanced-L	0	0.40	0	0	**0.60**	0	0	0	1.31 L
8	6	Damped-L	0	**1.00**	0	0	0	0	0	0	**3.95 M**
9	8	Enhanced-H	0	0	0	0.125	0.125	0	**0.75**	0	**3.29 M**
10	8	Neutral	0.125	0	**0.875**	0	0	0	0	0	**3.95 M**
11	48	Damped-H	**0.79**	0.02	0.19	0	0	0	0	0	**18.95 H**
12	11	Damped-H	**0.45**	**0.45**	0.10	0	0	0	0	0	0 L
13	8	Neutral	0	0.25	**0.75**	0	0	0	0	0	**2.63 M**
Original category size			51	30	25	7	13	10	10	6	

5.3.2 Decision tree and associated probability for RP10



Path #						Highest Probability	Confidence level	Response family
12	SAAR ≥ 969.5	AREA ≥ 680.86				0.76 Damped L	H	Damping
8	726.5 ≤ SAAR ≤ 969.5	Bedrock High Perm ≤ 73.5	North ≥ 334950	ALTBAR ≥ 191		0.50 Damped L	L	
7	726.5 ≤ SAAR ≤ 969.5	Bedrock High Perm ≤ 73.5	North ≥ 334950	ALTBAR ≤ 191		0.91 Damped L	H	
5	726.5 ≤ SAAR ≤ 969.5	Bedrock High Perm ≤ 73.5	North ≤ 334950	ALTBAR ≤ 159.5		0.89 Damped L	M	
4	SAAR ≤ 726.5	Bedrock High Perm ≤ 73.5	ALTBAR ≥ 63	BFIHOST ≥ 0.496		0.57 Damped L	L	
11	SAAR ≥ 969.5	AREA ≤ 680.86				0.67 Neutral	H	Neutral
3	SAAR ≤ 726.5	Bedrock High Perm ≤ 73.5	ALTBAR ≥ 63	BFIHOST ≤ 0.496	North ≥ 244000	0.80 Mixed	L	Mixed
6	726.5 ≤ SAAR ≤ 969.5	Bedrock High Perm ≤ 73.5	North ≤ 334950	ALTBAR ≥ 159.5		0.67 Enhanced L	L	Enhancing
2	SAAR ≤ 726.5	Bedrock High Perm ≤ 73.5	ALTBAR ≥ 63	BFIHOST ≤ 0.496	North ≤ 244000	0.60 Enhanced L	L	
1	SAAR ≤ 726.5	Bedrock High Perm ≤ 73.5	ALTBAR ≤ 63			0.80 Enhanced M	L	
10	SAAR ≤ 969.5	Bedrock High Perm ≥73.5	Area ≥ 146.205			0.50 Enhanced H	L	
9	SAAR ≤ 969.5	Bedrock High Perm ≥73.5	Area ≤ 146.205			0.56 Sensitive	M	

Figure 5.1b as Figure 5.1a for RP10

Table 5.4b Same as Table 5.4a for RP10, for the merged flood response types

Path #	Size of leaf (number of elements from the sample)	Flood response type of path	Probability of flood response type							Confidence level
			Damped-L	Neutral	Mixed	Enhanced-L	Enhanced-M	Enhanced-H	Sensitive	
1	5	Enhanced-M	0	0	0.20	0	**0.80**	0	0	1.97 L
2	5	Enhanced-L	0.20	0	0.20	**0.60**	0	0	0	1.31 L
3	5	Mixed	0	0	**0.80**	0	0	0	0.20	1.97 L
4	7	Damped-L	**0.57**	0	0	0	0	0.29	0.14	1.29 L
5	9	Damped-L	**0.89**	0	0	0.11	0	0	0	**4.61 M**
6	6	Enhanced-L	0.17	0.17	0	**0.66**	0	0	0	1.93 L
7	11	Damped-L	**0.91**	0.09	0	0	0	0	0	**5.93 H**
8	10	Damped-L	**0.50**	0	0.30	0	0.20	0	0	1.31 L
9	9	Sensitive	0	0	0	0	0.22	0.22	**0.56**	**2.01 M**
10	10	Enhanced-H	0	0	0.10	0.30	0	**0.50**	0.10	1.31 L
11	54	Neutral	0.33	**0.67**	0	0	0	0	0	**12.1 H**
12	21	Damped-L	**0.76**	0.24	0	0	0	0	0	**7.18 H**
Original category size			63	43	10	11	8	9	8	

5.3.3 Decision tree and associated probability for RP20

Path #				Highest Probability	Confidence level	Response family
9	SAAR ≥ 969.5	NORTH ≥ 403275		1.00 Neutral	H	Neutral
7	SAAR ≥ 969.5	NORTH ≤ 403275	Area ≤ 781.09	0.91 Neutral	H	
4	858 ≤ SAAR ≤ 969.5	403.5 ≤ Mean Annual Loss ≤ 500.5	4.5 ≤ Bedrock High Perm ≤ 73.5	0.50 Neutral	L	
1	SAAR ≤ 969.5	Mean Annual Loss ≤ 403.5		0.80 Neutral	M	
3	SAAR ≤ 858	403.5 ≤ Mean Annual Loss ≤ 500.5	4.5 ≤ Bedrock High Perm ≤ 73.5	0.90 Mixed	H	Mixed
8	SAAR ≥ 969.5	NORTH ≤ 403275	Area ≥ 781.09	1.00 Mixed	M	
5	SAAR ≤ 969.5	403.5 ≤ Mean Annual Loss ≤ 500.5	Bedrock High Perm ≥ 73.5	0.82 Enhanced H	H	Enhancing
2	SAAR ≤ 969.5	403.5 ≤ Mean Annual Loss ≤ 500.5	Bedrock High Perm ≤ 4.5	0.67 Enhanced H	H	
6	SAAR ≤ 969.5	Mean Annual Loss ≥ 500.5		0.73 Sensitive	M	

Figure 5.1c as Figure 5.1a for RP20

Table 5.4c Same as Table 5.4b for RP20

Path #	Size of leaf (number of elements from the sample)	Flood response type of path	Probability of flood response type				Confidence level
			Neutral	Mixed	Enhanced-H	Sensitive	
1	10	Neutral	**0.80**	0.20	0	0	**3.95 M**
2	18	Enhanced-H	0.17	0.17	**0.67**	0	**5.92 H**
3	21	Mixed	0	**0.91**	0.09	0	**11.33 H**
4	6	Neutral	**0.50**	0.17	0.33	0	0.67 L
5	11	Enhanced-H	0.09	0	**0.82**	0.09	**5.28 H**
6	11	Sensitive	0	0	0.27	**0.73**	**3.32 M**
7	23	Neutral	**0.91**	0.09	0	0	**12.4 H**
8	7	Mixed	0	**1.00**	0	0	**4.60 M**
9	45	Neutral	**1.00**	0	0	0	**29.6 H**
Original category size			81	30	32	9	

5.3.4 Decision tree and associated probability for RP50

Path #					Highest Probability	Confidence level	Response family
9	SAAR ≥ 969.5	ALTBAR ≥ 245.5			1.00 Neutral	H	Neutral
7	SAAR ≥ 969.5	ALTBAR ≤ 245.5	Area ≤ 781.09		0.91 Neutral	H	
1	SAAR ≤ 969.5	Bedrock High Perm ≤ 73.5	Mean Annual Loss ≤ 427.5		0.76 Neutral	H	
8	SAAR ≥ 969.5	ALTBAR ≤ 245.5	Area ≥ 781.09		0.44 Mixed	L	Mixed
2	SAAR ≤ 858	Bedrock High Perm ≤ 73.5	Mean Annual Loss ≥ 427.5	Bed V L Perm ≤ 75	0.875 Mixed	H	
5	SAAR ≤ 969.5	Bedrock High Perm ≥ 73.5	Mean Annual Loss ≤ 493.5		1.00 Enhanced H	H	Enhancing
4	SAAR ≤ 969.5	Bedrock High Perm ≤ 73.5	Mean Annual Loss ≥ 427.5	Bed V L Perm ≥ 75	0.54 Enhanced H	L	
3	858 ≤ SAAR ≤ 969.5	Bedrock High Perm ≤ 73.5	Mean Annual Loss ≥ 427.5	Bed V L Perm ≤ 75	0.50 Enhanced H	L	
6	SAAR ≤ 969.5	Bedrock High Perm ≥ 73.5	Mean Annual Loss ≥ 493.5		0.56 Sensitive	L	

Figure 5.1d as Figure 5.1a for RP50

Table 5.4d Same as Table 5.4b for RP50

Path #	Size of leaf (number of elements from the sample)	Flood response type of path	Probability of flood response type				Confidence level
			Neutral	Mixed	Enhanced-H	Sensitive	
1	17	Neutral	**0.76**	0.235	0	0	**5.87 H**
2	24	Mixed	0.04	**0.875**	0.04	0.04	**13.2 H**
3	6	Enhanced-H	0.33	0.167	**0.50**	0	0.79 L
4	11	Enhanced-H	0.36	0.09	**0.54**	0	1.30 L
5	10	Enhanced-H	0	0	**1.00**	0	**6.58 H**
6	9	Sensitive	0	0.11	0.33	**0.56**	1.36 L
7	22	Neutral	**0.91**	0	0.09	0	**11.87 H**
8	9	Mixed	0.33	**0.44**	0.22	0	0.65 L
9	44	Neutral	**1.00**	0	0	0	**28.9 H**
Original category size			87	32	27	6	

5.4 Assessment of the decision trees

Each decision tree was evaluated according to the number of well-classified and misclassified catchments, summarised below and in Table 5.5:

- The proportion of catchments classified correctly is always greater than 50%, ranging from 67.5% for RP10 to 84% for RP20
- When misclassified, 7.7% to 14% of catchments have a predicted flood response type more Enhancing than observed by one category (using Figure 4.2): e.g. observed Damped Medium but predicted Damped Low, or observed Enhanced Low and predicted Enhanced Medium. This number is reduced to none to 7% for a jump of two categories (e.g. observed Enhanced Low and modelled Enhanced High)
- The total percentage of ‘false alarms’ (catchments classified with more Enhancing flood response type than observed) ranges from 8.4% (RP20) to 20% (RP10)
- For ‘misses’, (catchments classified with a more Damping flood response type than observed) 5.8 to 7.1% of catchments are classified with a type less Enhancing by one category: e.g. observed Damped Medium but modelled Damped High, or observed Enhanced Low and modelled Mixed
- The total percentage of ‘misses’ ranges from 6.5% (RP20 and RP50) to 15% (RP2), always smaller than the ‘false alarms’
- There is no flood response type consistently associated with lower confidence level across all four flood indicators
- Generally, Neutral is assigned most with high confidence
- Groups sizes less than 10 catchments for Mixed and Enhanced types at RP2 and RP10 contribute to the lower confidence levels for those indicators
- Overall, 88% of the catchments are classified correctly in the either the Damping or Enhancing families over the four flood indicators (i.e. no switch across the Neutral/Mixed line of Figure 4.2): the decision trees are able to characterise the observed variation in catchments’ flood response to climatic changes between different return periods
- Catchments misclassified for three indicators or more generally have some alteration in their natural flow (i.e. flood response to change might not be well represented by the catchment characteristics), or have descriptor values close to the splitting rules (i.e. other classification could be possible)
- Large catchments seem to be slightly more difficult to classify. This would suggest that the response of the flood regime of large catchments to climate change might not be fully represented by single value descriptors as they would smooth out spatial variations important in the response of the river to climatic changes.

Table 5.5 Summary of misclassification statistics

	No. in correct flood response type	No. in ‘higher’ flood response types False alarms			No. in ‘lower’ flood response types Misses		
		1	2	>2	1	2	>2
RP2	105	12	11	1	11	10	2
RP10	104	22	8	1	10	1	6
RP20	129	13	0	0	10	0	0
RP50	126	15	1	0	9	1	0

1, 2 and >2 are the number of types (as Table 5.1) between the observed flood response type and that predicted using Figure 5.1. Ordering levels of vulnerability as in Figure 4.2

5.5 Hydrological characteristics of flood response types

As outlined in Section 4.3, the differentiating factors between the nine flood response types can be understood in terms of the interaction between four main features of catchment hydrology and climatology, namely the water balance, catchment memory, natural variability and frequency of flood event. The fact that different decision trees and paths are required for the four indicators shows that a catchment may not exhibit the same response to climate change for all flood events. This is because floods typical of a 2-year return period frequency may have very different characteristics and causes, and response to change, to 50-year events. A catchment may, but may not, have a single flood response type to change. However, the values of the catchment descriptors in Figure 5.1 show two rules which are common to all four flood indicators. The first split always uses SAAR with a value of 969.5 mm and a Bedrock High Permeability of 73.5% occurs in all trees (2nd level split for RP10 and RP50). These two catchment descriptors are the key factors in the partitioning of the decision tree. Area is the other descriptor used for all indicators.

The importance of the relative values of SAAR (rainfall) and Mean Annual Loss (a measure of water losses in the catchment, for example from evaporation) can be summarised by:

- Balance between SAAR and Mean Annual Loss is important for Mixed, Enhancing and Sensitive catchments
- Sensitive catchments have high Mean Annual Loss
- SAAR less critical at higher return periods
- Damped-High catchments have high SAAR

Guidelines for hydrological and climatological characteristics for each flood response type are given in Table 5.6 but flood response types do not have definitive boundaries applicable to all indicators.

Table 5.6 Dominant characteristics for the nine flood response types

Flood response type	Dominant characteristics
Damped-Extreme	Medium to high SAAR, water balance affected by snowmelt, flood events have summer predominance
Damped-High	Generally high SAAR, water balance in spring may be affected by snowmelt, 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

One catchment descriptor which is not included in the decision trees but which may cause the predicted flood response type to be unrepresentative is URBEXT, the index of fractional urban extent. Eight catchments out of the 154 have more than 10% of the catchment area urbanised, with the highest value of 33% (Rea at Calthorpe, 28039). There is no evidence from the results that the predicted flood response types for these catchments are inconsistent with those from the selected catchment descriptors. However, it is assumed in the hydrological modelling of future climate change that catchment descriptors and model parameter values are stationary, which may not apply to urban catchments. Also effects of rainfall on urban catchments are very variable depending on the precise nature of the storm-water drainage. Therefore, caution should be used when applying the methodology to catchments with a high urban extent particularly if the urban area is close to the point of interest on a river.

6. Uncertainty analysis

PREVIOUS FAST TRACK BOX ON PAGE 51

Section 6: 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. The different levels of uncertainty for the different catchment types are compatible with the underlying climatological and hydrological differences between their flood response types.

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.

NEXT FAST TRACK BOX ON PAGE 79

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. More detail on aspects of the project summarised in this section can be found in Milestone Report 5 (Kay *et al.* 2009a).

6.1 Background and aims

The 'scenario neutral' approach of the project (Section 3) required that the monthly changes in precipitation and temperature suggested by current GCMs were distilled down into a 'simple' sensitivity framework, using single harmonic functions (i.e. annual sine-curves with a single peak and trough). This resulted in a sensitivity framework of 4200 scenarios (525 precipitation x 8 temperature / potential evaporation (T/PE), summarised in Table 3.2). These 4200 scenarios were then applied to baseline catchment time-series using the delta change method of downscaling, and run through the catchment hydrological models. This resulted in the production of response patterns, representing the response of each catchment to the prescribed sets of changes in rainfall and T/PE in terms of the percentage change in flood peaks at four return periods (2, 10, 20 and 50 years), where the modelled change under each scenario is colour-coded. Points can then be superimposed on the flood response patterns for a given catchment, to indicate the precipitation scenarios suggested by specific global and regional climate models (GCMs and RCMs). An example of such a flood response pattern, with points representing different GCMs and RCMs, is shown in Figure 6.1.

When points representing different climate change scenarios (from GCMs or RCMs) are superimposed on the flood response patterns for a particular catchment, various simplifications are applied. For data from a given climate model, for a given grid box (chosen according to the catchment location), firstly a set of monthly changes in precipitation is calculated (which can be done in a number of different ways), then a sine-curve (single harmonic function) is fitted to those 12 monthly values. It is two of the parameters of that harmonic function (the mean and the amplitude) which determine the position of the corresponding point on the response pattern. The phase of the fitted harmonic is ignored, since the flood response patterns all correspond to a January peak change in precipitation. Also ignored is what that particular climate model says about other changes in precipitation, like intensity changes. In addition, no account is taken of how well the single harmonic function fits the 12 monthly values. Similarly, what that particular climate model says about changes in monthly temperature can be ignored, and the point superimposed onto the composite flood response patterns (from the average of all eight of the applied T/PE scenarios). Alternatively, a single harmonic function could be fitted to the 12 monthly values derived for changes in temperature, and the point only superimposed onto the response pattern corresponding to the closest of the eight T/PE scenarios. These are some of the factors which are addressed as part of the uncertainty analysis.

Essentially, the uncertainty analysis aims to address the questions:

1. Due to the assumptions and simplifications necessary for the sensitivity framework methodology, will values extracted from the flood response patterns consistently over- or under-estimate the impact of climate change scenarios?
2. If so, can guidance be given on the level of this potential bias, according to catchment type and flood return period?

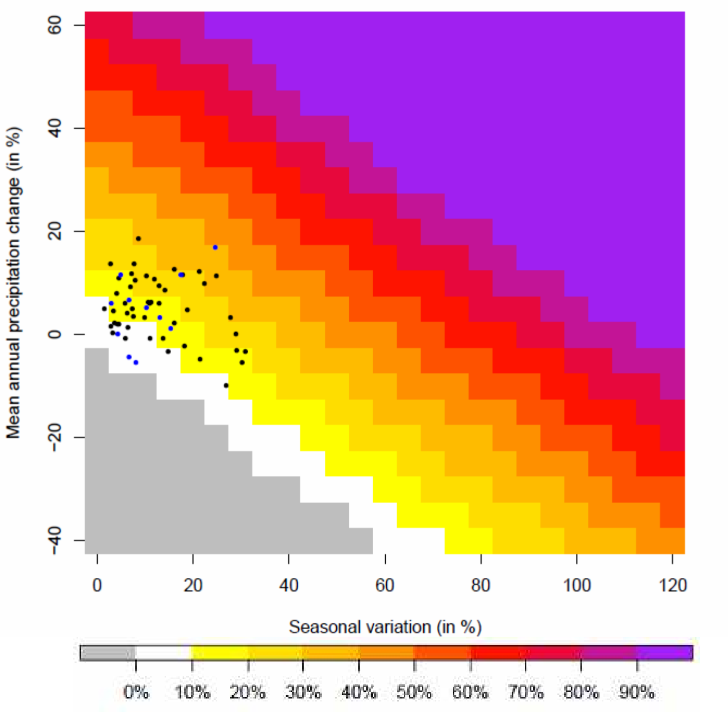


Figure 6.1 Example flood response pattern, showing the percentage change in the flood peak with a 20-year return period for one catchment under one T/PE scenario. Grey areas show scenarios with a decrease in the flood peak, other colours show an increase (in 10% increments, see key). The points superimposed on the response pattern indicate the locations of particular GCM (black) and RCM (blue) scenarios.

6.2 Approach

The factors addressed are:

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.

6.2.1 Catchment choice

Due to the number of factors investigated, the analysis is performed on a small subset of catchments. For each of the nine flood response types (Section 4), a catchment modelled with the PDM at a daily time step was chosen. Preference was given to daily PDM catchments to maintain consistency of methodology across all the response types. A CLASSIC catchment was chosen in addition to the daily PDM catchment where possible (there are not CLASSIC catchments with all response types). The full uncertainty analysis is performed for each of the chosen PDM catchments, with a subset of that analysis performed for the chosen CLASSIC catchments, to investigate the effect of some of the sources on uncertainty on larger catchments. The PDM catchments thus selected within each flood response type are given in Table 6.1, with the additional CLASSIC catchments given in brackets.

Table 6.1 Chosen PDM (*CLASSIC*) catchment for each flood response type.

Flood response type	Catchment number	Flood response type	Catchment number	Flood response type	Catchment number
Damped-Extreme	07002 (-)	Neutral	47007 (*76007*)	Enhanced-Medium	21023 (-)
Damped-High	02001 (*27009*)	Mixed	34003 (*33026*)	Enhanced-High	43005 (-)
Damped-Low	14001 (*39001*)	Enhanced-Low	54008 (-)	Sensitive	38003 (-)

6.2.2 Alternative response patterns

One of the main assumptions within the sensitivity framework is that precipitation is a greater driver of flooding than temperature, thus only eight temperature (T) scenarios were applied (with their corresponding PE scenarios). This assumption could be tested by applying a larger number of T/PE scenarios. However, the results using the existing scenarios suggest this is not necessary, as there are relatively small differences in the flood response patterns for most catchments across the eight existing scenarios (Figure 4.7 and Appendix A of Milestone Report 5, Kay *et al.* 2009a). As most of the tested scenarios were chosen towards the extremes of the likely domain of change suggested by current GCMs, any other likely scenario would be intermediate to the existing ones and thus very unlikely to result in significantly different response patterns.

The other main assumption within the sensitivity framework is that the peak precipitation change occurs in January. To demonstrate the effect of this assumption, alternative response patterns were produced for the nine example PDM catchments, with the peak precipitation change taken to occur in each alternative month in turn. That is, for each catchment and for each of the 8 T/PE scenarios, the same set of 525 precipitation scenarios was applied but with different phases, resulting in a set of 11*8 alternative response patterns which are compared to the original 8.

6.2.3 Alternative application of scenarios

The key question remaining is: what difference is there likely to be between the results for a given GCM/RCM scenario when the parameters of its fitted single harmonic function are used to extract the impact from a response pattern and the impact if that same scenario was applied in a less simplified way, with hydrological modelling? For instance, if a set of monthly changes in precipitation, T and PE is derived from GCM data and applied to the baseline precipitation, T and PE series (respectively) for a catchment, and the resulting perturbed series used to drive the hydrological model and derive a new flood frequency curve, the impact (i.e. difference from the baseline flood frequency curve) is likely to differ to some extent from that extracted from the response patterns, due to the sensitivity framework's use of smoothed monthly changes and assumption of a January precipitation peak. Table 6.2 gives details of the alternative modelling of scenarios applied, using the sets of GCM and RCM data described below.

Both the GCM and RCM data used are for baseline and 2080s time-slices, with the A1B emissions scenario for the latter. The GCMs applied are those from the IPCC 4th Assessment report, of which there are 16 in total: BCM2, CGMR, CNCM3, CSMK3, ECHOG, GFCM20, GFCM21, HADCM3, HADGEM, INCM3, IPCM4, MIMR, MPEH5, MRCGCM, NCCCSM, NCPCM (see Table 5.1 of Milestone Report 2, Prudhomme and Reynard (2008), for details). The RCMs applied are those of the perturbed parameter ensemble produced by the Met Office Hadley Centre as part of UKCP09 (Murphy *et al.* 2009). There are 11 RCM runs in total, each of which should be interpreted as a plausible realisation (there are no weights attached to any of the ensemble members).

6.2.4 Application of RCM time-series data

The last row in Table 6.2 refers to the direct use of time-series data, taken from the UKCP09 RCM ensemble, to drive the hydrological models. For each ensemble member, the required data were available for two time-slices. The first (Baseline) time-slice runs from 1 January 1961 to 30 December 1990 and the second (Future) time-slice runs from 1 January 2070 to 30 November 2099 and is available for the A1B SRES emissions scenario (IPCC 2000). The RCM grid box size is approximately 25 km x 25 km over Britain. For each grid box, hourly precipitation is available directly, daily PE from the land-surface is derived from daily RCM open-water PE using the method described in Kay *et al.* (2008), and daily minimum and maximum temperature are available (for application of the snowmelt module). See Milestone Report 5 (Kay *et al.* 2009a) for details on how the RCM grid box data are used to drive the catchment hydrological models.

When RCM data are used to drive one of the hydrological models, the changes in a given flood indicator are assessed by comparing the results for the Baseline and Future time-slices (assuming approximate stationarity within each time-slice), rather than by comparing the result using the Future time-slice to an observed baseline. This is because there may be bias in the RCM data. Also, the Baseline and Future time-slices for a given RCM ensemble member are kept together, as any bias may differ between ensemble members.

Table 6.2 The alternative applications of GCM and RCM scenarios, including how they are applied for precipitation, temperature and PE, what assumption they help to address, and the notation used for the GCM- and RCM-based results.

Precipitation	Temperature (T) and Potential Evaporation (PE)	What assumption / simplification does it address	Notation for sets of climate model scenarios (2080s, A1B emissions)	
			16 AR4 GCMs	11 UKCP09 RCMs
Response pattern harmonic (multiples of 5% for mean and amplitude; January peak)	8 T harmonics and associated PE changes		*gcm_rpat*	*rcm_rpat*
Actual single harmonic (fitted to median monthly changes below)	As above	Response pattern use of a January precipitation peak (and nearest 5% for mean and amplitude)	*gcmharm*	*rcmharm*
Actual double harmonic (fitted to median monthly changes - below)	As above	Response pattern use of rotational symmetry between winter and summer changes in precipitation	*gcmharm2*	*rcmharm2*
Monthly changes (medians of range from 20-year sub-periods - below)	Associated monthly T and PE changes	Use of smoothed monthly changes (via single harmonic function) rather than actual monthly changes	*gcm20med*	*rcm20med*
Range of monthly changes (for 20-year sub-periods in baseline and future time-slices)	As above	Use of a single set of monthly changes (the 12 median values) rather than a range of possible sets	*gcm20*	*rcm20*
Alternative monthly changes (for fixed 30-year baseline and future time-slices)	As above	Use of the ‘standard’ set of 12 monthly changes, for comparison with sets above	*gcm30*	*rcm30*
Climate model time-series (Baseline and Future)	Climate model time-series (Baseline and Future)	Uncertainty due to the use of the delta change method	N/A	*rcm_tseries*

6.2.5 Natural variability and other factors

In order to try to put the modelled climate change impacts into context, a simple and pragmatic method of exploring the effect of natural variability is applied, based on resampling of the baseline rainfall data following the method of Kay *et al.* (2009b). There, only rainfall data were resampled. Here, due to the inclusion of the snowmelt module, rainfall and temperature are resampled together, to maintain the dependence between winter temperature and precipitation (and thus snowfall). For a catchment, a set of 101 resampled rainfall and temperature series are thus produced, with resampling in 3-month blocks. The hydrological model is then run, and the required flood statistics derived, with each new set of input data. The differences between these sets of flood statistics and those derived using the baseline (non-resampled) input series are then calculated. These differences are then ordered, for each statistic, and the median and the upper and lower 95% bounds extracted (that is, the 51st, 3rd and 99th of the 101 ordered values). This range, when compared to values suggested by different scenarios of climate change, helps to put the latter into context, as it can be seen whether climate change is likely to result in changes in flooding within or beyond the potential range of natural variability.

Uncertainty due to the choice of emissions scenario is not covered in the uncertainty analysis, as other research has consistently shown that emissions uncertainty is smaller than GCM uncertainty (e.g. Kay *et al.* 2009b, Prudhomme and Davies 2009, Wilby *et al.* 2006, Wilby and Harris 2006, Cameron 2006). Likewise, hydrological modelling uncertainty, whether from hydrological model structure or parameterisation, is not specifically addressed within the uncertainty analysis as other research has suggested that it is smaller than GCM uncertainty (Kay *et al.* 2009b, New *et al.* 2007, Wilby and Harris 2006, Booij 2005). However, the similarity of the results for catchment 27007 (the Ure at Westwick Lock) when modelled both with the PDM and CLASSIC — two very differently structured and parameterised hydrological models — gives some confidence that hydrological modelling uncertainty is not likely to be a major factor (see Section 2.6 of Milestone Report 5 (Kay *et al.* 2009a)).

6.3 Results

6.3.1 Alternative response patterns

Examples of alternative response patterns, using the regular grid of 525 mean and seasonal precipitation changes with the phase in each month from January through to December, are shown in Figure 6.2a, for each of the chosen PDM catchments (for the flood peak with a 20-year return period, under the Medium-Aug T/PE scenario). These demonstrate that, when the peak change occurs between February and mid-summer, rather than January, the effect on flooding is generally less, whereas if the peak change occurs in autumn or earlier in winter the effect can be greater. The exception to this occurs for catchment 07002 (Damped-Extreme), where the impact on flooding is greater if the peak change occurs between spring and autumn rather than in winter. This difference is probably mainly due to the effect of snowfall / snowmelt, but also partly due to the distribution of peaks within the baseline.

It must be recalled, when looking at the results in Figure 6.2a, that not all peak months for precipitation change are equally likely under current scenarios of climate change. As shown in Figure 6.2b, January is the peak month for precipitation change for over 35% of AR4 GCM scenarios, and peaks during the period December-February account for nearly 70% of all scenarios over Britain, while peaks in October and November correspond to 13% of the scenarios. However, the potential differences in impacts if the peak precipitation change occurs in a month other than January are taken into account in the Regionalisation part of the project (Section 5), in order to make the results less dependent on what is currently suggested by GCMs (Milestone Report 4, Prudhomme *et al.* 2009b).

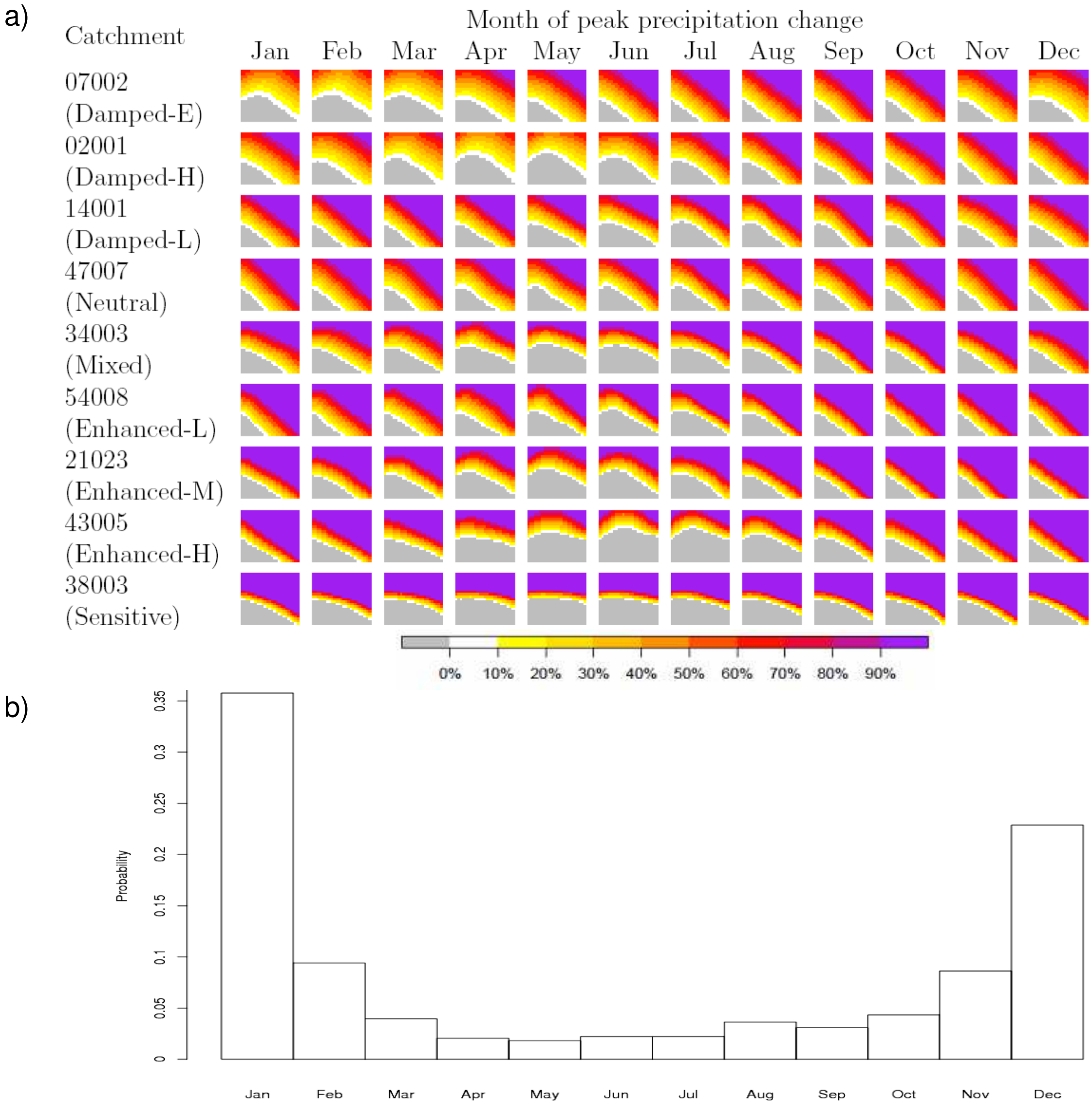


Figure 6.2 a) Example flood response patterns for the nine PDM catchments showing the difference when the peak rainfall change is taken in each month from January to December (left to right), for percentage change in the flood peak with a 20-year return period (under the Medium-Aug T/PE scenario). b) Likelihood of month of peak rainfall change from current (AR4) GCMs over Britain.

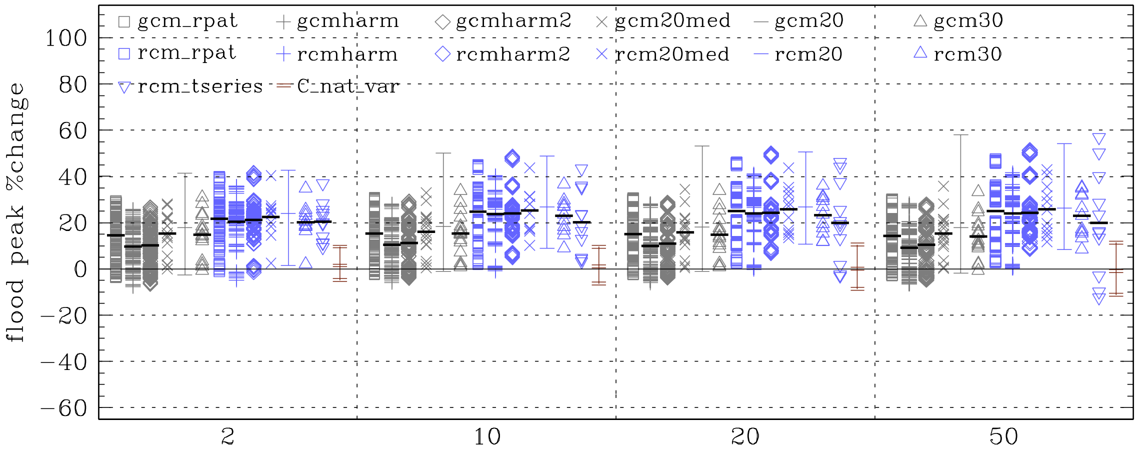
6.3.2 Alternative application of scenarios

Examples of the results for three of the PDM example catchments, with different response types (Neutral, Damped-High and Enhanced-High), are shown in Figure 6.3 for each of the four flood indicators. The figure key uses the terminology given in Table 6.2. Figures for all of the catchments in Table 6.1 can be found in Appendix B of Milestone Report 5 (Kay *et al.* 2009a). The results demonstrate the differing range of climate model uncertainty, and range of natural variability, according to catchment response type. However, the most important consideration is any difference in the averages from each alternative set of results relative to the means from the values extracted from the response patterns, as any consistent differences here would represent a first-order bias in use of the response patterns. Any difference in the spread of the results from the sets of climate scenarios would be a second-order bias.

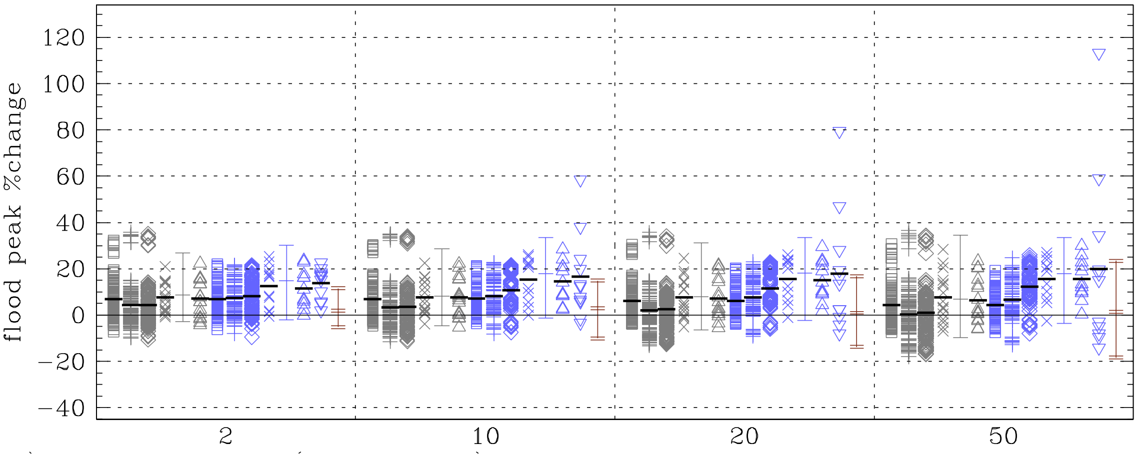
Figure 6.4 summarises, for the nine PDM example catchments, the average values from the different sets of results (Table 6.2) using the sets of GCM- and RCM-based scenarios. The results show that the level of uncertainty (that is, the difference from the mean value extracted from the response pattern) for different factors varies significantly between catchments, with the maximum difference not always being due to the same alternative set of results. Table 6.3 summarises the maximum differences of any of the alternative means from their respective response pattern means in Figure 6.4. This shows that some catchments (e.g. 38003, Sensitive) show a greater overall shift in impact under any of the alternatives than do other catchments (e.g. 47007, Neutral). For some catchments the overall level of uncertainty varies little with return period, whilst for others it can increase or decrease.

For the four CLASSIC catchments, only the RCM time-series results (and the range of current natural variability) are compared to the values extracted from the response patterns. Table 6.4 summarises the differences between the mean from the use of the RCM time-series and the mean of the values extracted from the response patterns, for the four CLASSIC catchments. They show a similar pattern of uncertainty to that for the PDM catchment of the same response type (cf. Table 6.3). However, the CLASSIC catchments tend to have higher levels of uncertainty, probably reflecting their larger catchment area.

47007 (Neutral)



02001 (Damped-High)



43005 (Enhanced-High)

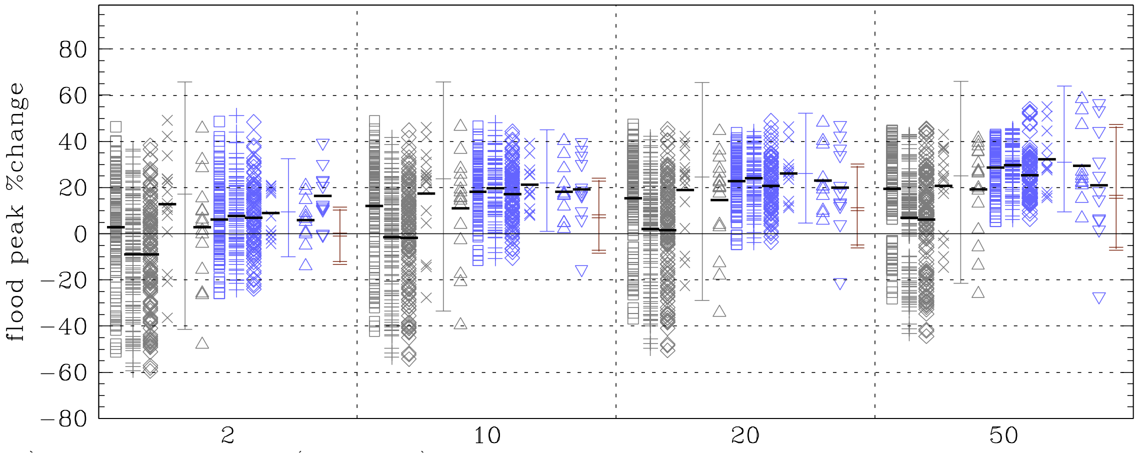


Figure 6.3 Example results from the uncertainty analysis for three PDM catchments, of three different response types, under GCM-based (grey) and RCM-based (blue) scenarios. The key notation is explained in Table 6.2. Also shown is an estimate of the median and 95% bounds of current natural variability (C_nat_var; brown)

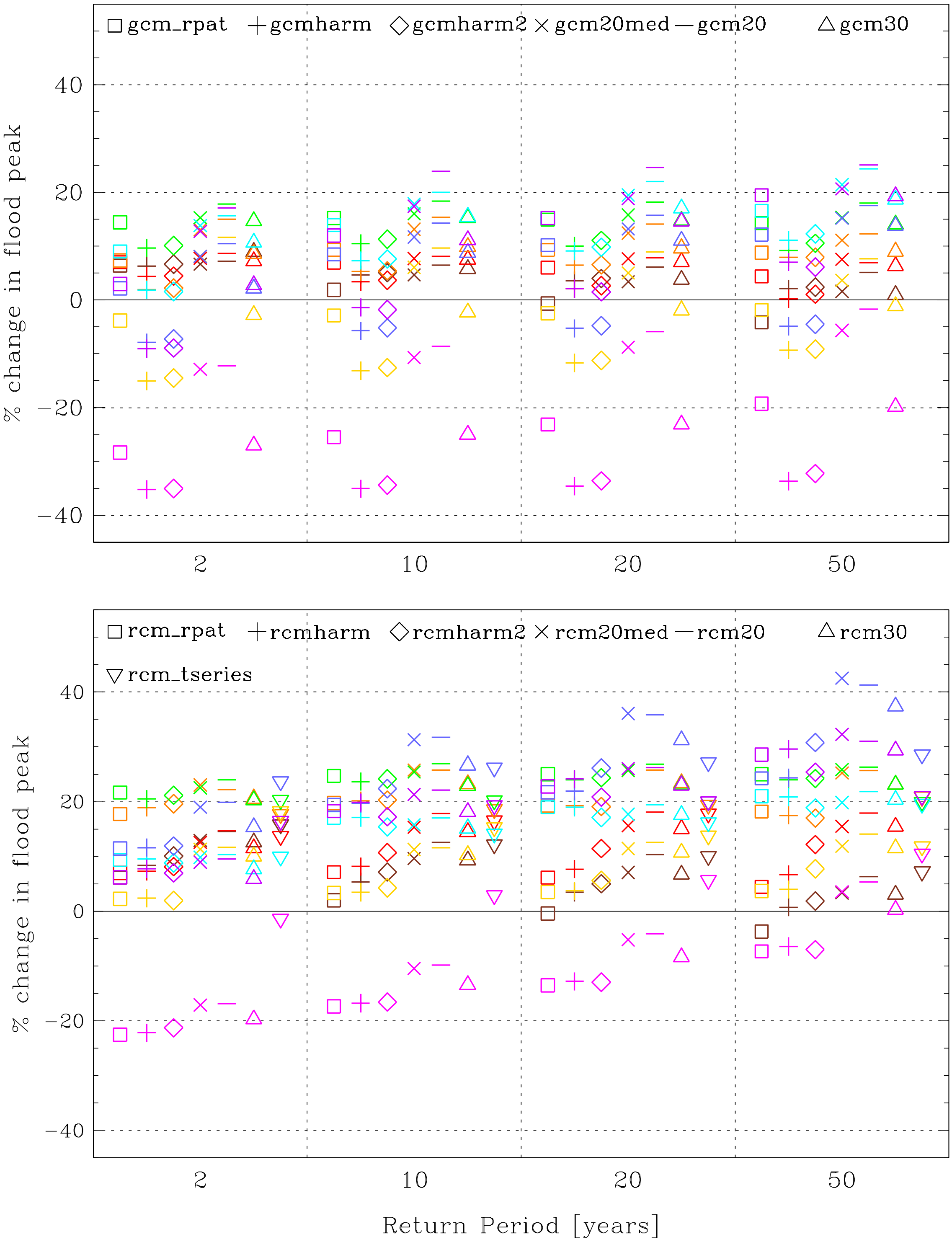


Figure 6.4 Graphs summarising the average (mean or median) values from the different sets of results (key notation given in Table 6.2), for GCM-based scenarios (top) and RCM-based scenarios (bottom). The results are coloured by catchment / response type (Table 6.1): 07002 (Damped-Extreme; brown), 02001 (Damped-High; red), 14001 (Damped-Low; orange), 47007 (Neutral; green), 34003 (Mixed; gold), 54008 (Enhanced-Low; cyan), 21023 (Enhanced-Medium; blue), 43005 (Enhanced-High; purple), 38003 (Sensitive; magenta).

Table 6.3 The maximum difference (%) between the mean from alternative options and the mean of the values extracted from the flood response patterns (*gcm_rpat* for GCM-based results and *rcm_rpat* for RCM-based results in Figure 6.4), for each of the PDM example catchments at each of the four return periods.

PDM catchment (flood response type)	Return period [years] 2	10	20	50
07002 (Damped-E)	10	11	11	11
02001 (Damped-H)	8	11	12	16
14001 (Damped-L)	8	6	6	8
47007 (Neutral)	3	3	3	4
34003 (Mixed)	16	13	11	10
54008 (Enhanced-L)	7	6	7	8
21023 (Enhanced-M)	12	12	14	18
43005 (Enhanced-H)	14	12	9	6
38003 (Sensitive)	21	20	19	18
Mean	11	10	10	11

Table 6.4 The difference (%) between the mean from the use of the RCM time-series and the mean of the values extracted from the response patterns, for each of the CLASSIC example catchments at each of the four return periods.

CLASSIC catchment (flood response type)	Return period [years] 2	10	20	50
27009 (Damped-H)	4	13	18	26
39001 (Damped-L)	5	9	12	17
76007 (Neutral)	4	5	7	10
33026 (Mixed)	9	15	21	30
Mean	6	11	15	21

6.3.3 Direct use of the RCM ensemble time-series

When the ensemble of RCM time-series data are used directly to drive the hydrological model, the mean change at each return period is generally similar to that obtained from some of the tested delta change methodologies. The main exception to this is catchment 38003 (Sensitive), where the mean from direct use of the RCM ensemble data is much larger than the mean from any of the delta change alternatives, especially at lower return periods. For a number of catchments, the full range from the direct use of RCM ensemble data is much larger than the range from any of the delta change alternatives, especially at higher return periods. However, it is not always the same RCM ensemble member which gives the larger increases, so these are seemingly not closely related to the parameter settings within the ensemble member.

An inspection of the flood frequency curves from simulations for the Baseline and Future RCM time-slices suggests that the larger increases are due to the pairing of differently shaped flood frequency curves; a flattening baseline curve with an ever-increasing future curve can lead to very large increases at higher return periods. Note that the RCM baselines are not meant to exactly reproduce the climate in the baseline period, but are simply one representation of what could have occurred in that period, just as the Future time-slice is one representation of what could occur in that period (under given assumptions on emissions etc). That is, *both* time-slices are affected by the presence of natural variability.

Considering the range of results from the use of the RCM time-series ensemble as representing climate change plus natural variability helps to explain their expanded range relative to that from use of the delta change methods (which do not include natural variability). This is because, under a given RCM ensemble member in a given period, natural variability could act in the same direction as climate change, thus reinforcing its apparent effect in that period, or act in the opposite direction, thus reducing its apparent effect in that period (see discussion in Section 2.2 of Murphy *et al.* 2009). Add to this the fact that the Baseline, as well as the Future, time-slice includes natural variability, and it is clear how the range of changes can appear to be much wider using this method. The estimate of the potential range of current natural variability provided can be used to help put the RCM time-series ensemble results into context with the delta change results.

6.3.4 Natural variability

For each catchment, an estimate of the potential range of current natural variability is provided, to help put the potential impacts under climate change into context. For some catchments the potential climate change impacts on flood peaks (for the 2080s) hardly ever exceed the potential range that could occur just through natural variability of the current climate (e.g. 43005, Enhanced-High). For other catchments there is a distinct upwards shift in impacts under climate change, in comparison to the range of natural variability (e.g. 47007, Neutral).

There is considerable similarity in the results, relative to natural variability, between the four CLASSIC catchments and their corresponding (in terms of response type) PDM catchments (see Table 6.1). This suggests that this result is a real feature of catchment type that can be carried through to the response types, at least for these four response types.

However, it cannot be assumed that a catchment is ‘safe’ from the impacts of climate change just because there is not an upward shift relative to natural variability, as the catchment may not be sufficiently protected against natural variability in itself. This could particularly be the case if the potential range of natural variability is very large (e.g. for ‘Enhanced’ or ‘Sensitive’ catchments) or if the observed record for the catchment is not all that representative of what could generally be expected of the catchment.

It should also be remembered that the resampling methodology used here to estimate the range of current natural variability is a pragmatic method used to investigate a very complex issue. As such it does not cover the full range of contributing factors, for instance changes in maximum daily rainfall, and thus the full range of natural variability is likely to be larger for all catchments, and perhaps proportionally more so for some types of catchment compared to others. In addition, natural variability may itself alter under climate change.

6.4 Discussion

A number of assumptions and simplifications were necessary to develop the project's 'scenario neutral' approach to regionalisation of climate change impacts on flood flows. These constraints facilitated the production of 'flood response patterns' representing the vulnerability of a given flood indicator for a catchment to a particular set of changes in precipitation, temperature and PE. In order to assess the potential level of uncertainty from a number of these assumptions and simplifications, various alternative delta-change methods, as well as direct use of time-series data from an RCM ensemble, have been applied to a small subset of catchments.

The results from these alternatives methods, under given GCM/RCM scenarios, have been compared to values extracted from the flood response patterns for those scenarios. This comparison shows that different catchments can have different causes of uncertainty (that is, the differences in comparison to the flood response pattern results occur at different stages in the uncertainty analysis). Perhaps more importantly, some catchments have an overall higher potential level of uncertainty than other catchments. Furthermore, some catchments have a similar level of uncertainty across all four of the return periods investigated, whereas others have a level of uncertainty which increases/decreases with return period.

By generalising the catchment results to their response types, it is possible to say something about the potential level of uncertainty for different types of catchment. For instance, a catchment classified as 'Neutral' will have quite a low level of uncertainty (as will catchments classified as 'Damped-Low' or 'Enhanced-Low'), while a catchment classified as 'Damped-High' or 'Mixed' is likely to have a higher level of uncertainty, and a catchment classified as 'Sensitive' is likely to have the highest level of uncertainty. The different levels of uncertainty for the different catchment types are compatible with the underlying climatological and hydrological differences between their response types (Milestone Report 4, Prudhomme *et al.* 2009b).

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. The next step is to develop guidance on what level of uncertainty to allow, according to response type and return period. The potential effect of catchment area on the level of uncertainty will also have to be borne-in-mind.

7. Application of the FD2020 methodology

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Section 7: Application of the FD2020 methodology

This section describes several ways in which the FD2020 methodology and supporting catchment information can be used to provide evidence for assessing the suitability of climate change allowances for flood management.

The application of the methodology is illustrated through two worked examples, taking two of the modelled catchments, but treating them as if they were unmodelled. The first is for a catchment where the confidence attached to the prediction of the flood response type is high, the second being an example of when this confidence is lower. The examples take a step-by-step approach to determining the catchment vulnerability, comparing it with the climate hazard and determining the resultant risk of change in peak flows, with uncertainty.

In addition, the applications of some tools are illustrated using the catchment-specific information, allowing national-level risk assessments, in particular addressing two policy-relevant questions: What is the impact of a specific climate scenario (hazard) on the flood regime of a catchment? What is the likelihood that a threshold of change will be exceeded under climate change? These tools are illustrated through maps of catchment impacts obtained from the catchment flood response patterns and graphs showing catchment impacts against given climate change allowances for 16 AR4 GCMs and 11 RCMs (for the 2080s time horizon and the A1B emissions scenario).

Finally there is a discussion of how this methodology can be extended to unmodelled and ungauged catchments to provide a fully national assessment.

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7.1 Outline

This project has developed a concept and methodology for 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.

Stage 1 - Vulnerability: Determine the vulnerability of a catchment flood regime to climate change
Stage 2 - Hazard: Determine the hazard from future climate change projections
Stage 3 - Risk: Determine the risk of flood change as the combination of vulnerability and hazard

The **vulnerability** is defined by a set of 4,200 changes for four flood indicators, organised in a flood response pattern following a strict analytic framework.

The **hazard** is defined from a single-phase harmonic function summarising the seasonal variation in monthly climate change factors.

The **risk** is 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.

If the required catchment happens to be one that has been modelled within the project, then the modelled flood response patterns can be used. Otherwise some catchment descriptors must be determined and used to assign a flood response type to the unmodelled catchment, and the corresponding key flood response patterns used as proxy for the actual catchment flood response pattern. The flow chart in Figure 7.1 presents the application of the methodology for a specific flood return period, for modelled and un-modelled catchments. The addition of uncertainty is described in Section 7.2, and some worked examples are provided in Section 7.3. Different exploitation of the FD2020 methodology and concept are presented in Section 7.4 (for the project catchments) and Section 7.5 (for un-modelled catchments), including how to undertake a national assessment of flood risk due to climate change and how to evaluate the resilience of British catchments to a set of flood change threshold allowances.

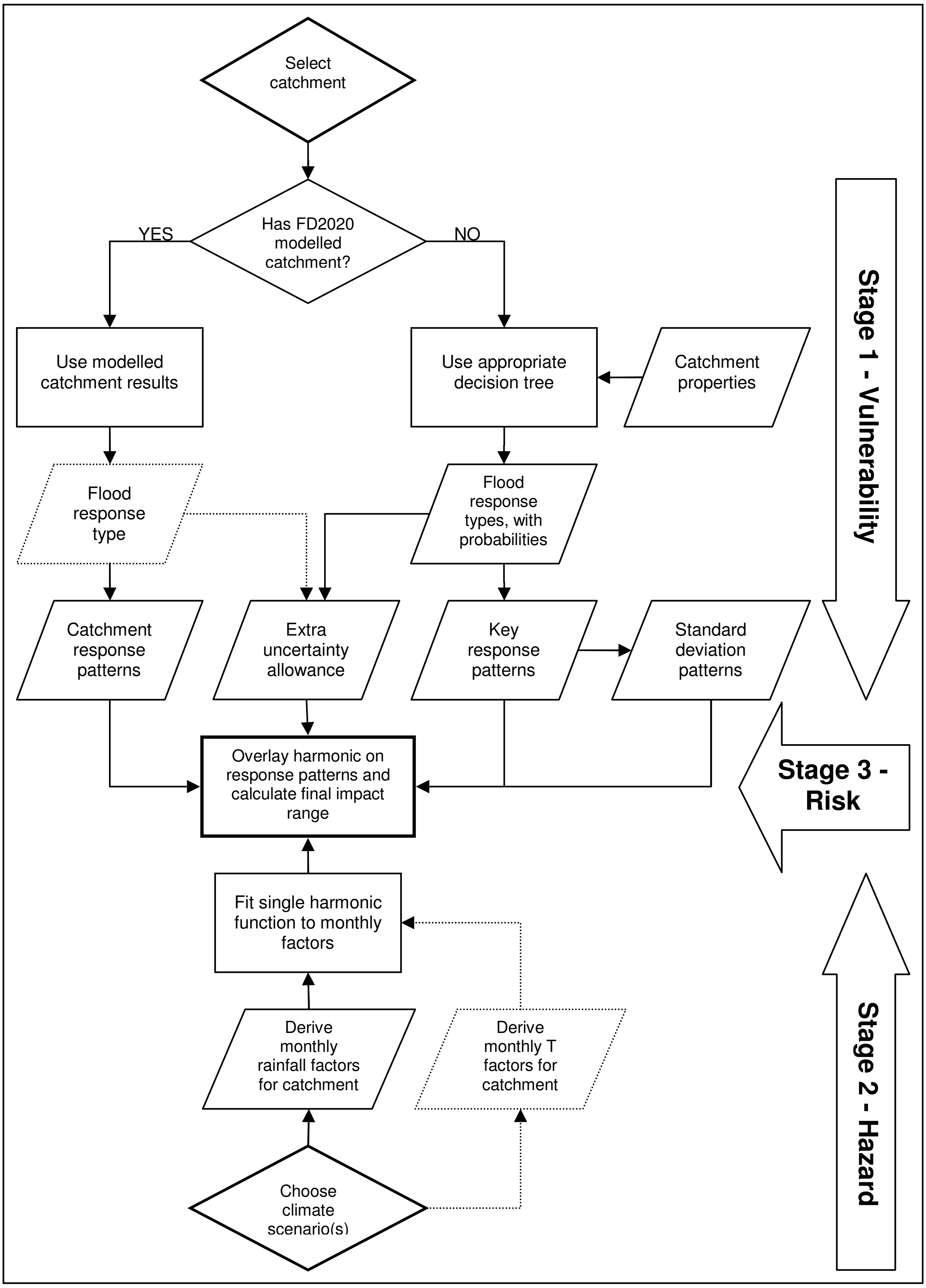


Figure 7.1 Flow chart describing the steps required for the application of the FD2020 methodology for a given flood return period

7.2 Uncertainty

There are two main sources of uncertainty to consider when using key flood response patterns as proxy for evaluating flood changes:

- Uncertainty due to the representation of the catchment flood response pattern by a composite key flood response pattern
- Uncertainty due to the assumptions and simplifications necessary for the ‘scenario neutral’ approach involving single-phase harmonic function scenario definition and delta change downscaling method.

The first uncertainty can be quantified using the standard deviation (sd) pattern (Section 4.2) associated with each flood response type alongside the flood response patterns to determine a range of possible impacts for a given catchment, climate scenario and flood indicator. Assuming flood response patterns of the same type to be normally distributed, adding or subtracting 1 sd would account for around 68% of the variation in the flood response pattern distribution, and 2 sd would account for around 95% of the variation in the distribution.

The second uncertainty would need extra allowances according to response type and flood return period. Based on the work presented in Section 6 and Milestone Report 5 (Kay *et al.* 2009a) suggested allowances are summarised in Table 7.1. Where response types are merged (see Section 5.2.1), it is suggested that the medium-level of uncertainty allowance should be applied within each merged set, as some but not all of the sources of uncertainty are accounted for in the merging. For catchments with area above 2000 km^2, changes should be multiplied by factors of 1.0, 1.3, 1.7 and 2.1 at the 2-, 10-, 20- and 50-year return periods respectively.

Table 7.1 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.

Considering both uncertainties, estimates for the range of flood changes can be given as:

$$\begin{array}{c}\text{Value from}\\ \text{flood}\\ \text{response}\\ \text{pattern}\end{array} \pm \lambda \begin{array}{c}\text{Value from}\\ \text{standard}\\ \text{deviation}\\ \text{pattern}\end{array} + \begin{array}{c}\text{Extra}\\ \text{uncertainty}\\ \text{allowance}\end{array}$$

where a value of $\lambda=1$ would give the approximate 68% range (assuming a normal distribution), and $\lambda=2$ would give the approximate 95% range.

To use a key flood response pattern as proxy to estimate changes in flood indicators for an un-modelled catchments, there are two possibilities:

- The key flood response pattern is the average of the 8-ensemble member flood response pattern of all modelled catchments of the corresponding flood response type. These are the key flood response patterns presented in Section 4.
- The key flood response pattern is the average of a single ensemble member flood response pattern of all modelled catchments of the corresponding flood response type. The choice of the relevant ensemble member (corresponding to one of the eight T/PE scenarios considered in the project) will be made according to a specific scenario of temperature change.

Whilst the first approach is more straightforward, the second may be more appropriate for some flood response types, where the influence of different T/PE scenarios on the flood response is significant. The use of the flood response pattern averaged across the eight T/PE scenarios with the associated standard deviation pattern covers the uncertainty introduced by ignoring the specific temperature changes suggested by a given climate scenario. If it is important to reduce uncertainty as much as possible, it is recommended that a single-ensemble member flood response pattern and its associated sd is used for flood change estimates. This single pattern would be chosen for the similarity of its temperature scenario with one of the eight T/PE scenario considered in the project.

7.3 Worked examples

This section illustrates the application of the methodology by way of two worked examples. The first is for a catchment where the confidence attached to the prediction of the flood response type is high, the second being an example of when this confidence is lower. In applying this methodology, demonstrated in these worked examples, a number of decisions are required, including what to do when the confidence in the estimated response type is not high. Table 7.2 presents some practical recommendations on what course of action might be taken under a range of circumstances that may arise when applying the methodology.

Table 7.2 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

7.3.1 Worked example 1: High confidence level

Site number: 02001 (Helmsdale at Kilphedir)
Catchment descriptors (Table 5.2 explains the descriptors):

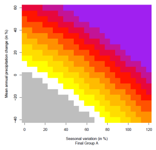
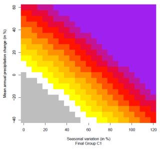
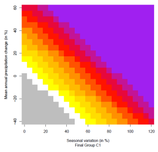
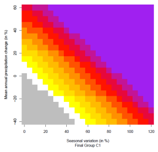
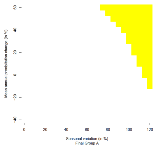
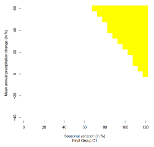
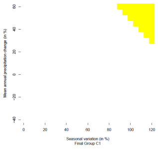
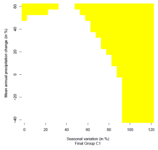
NORTH	918250	SAAR	1117	BHP	0
EAST	299700	ALTBAR	214	BVLP	99
AREA	552.96	BFIHOST	0.324	MAL	366

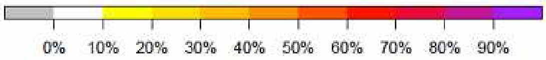
Stage 1 - Vulnerability: Find the key flood response pattern representative of the catchment

Using the decision trees (Section 5) 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.

Flood indicator	Catchment properties relative to thresholds	Path number	Confidence level	Probability of flood response types							
				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 using the formula:

$$X(t) = X_0 + A \cos\left(\frac{2\pi}{12}(t-\Phi_{month})\right)$$

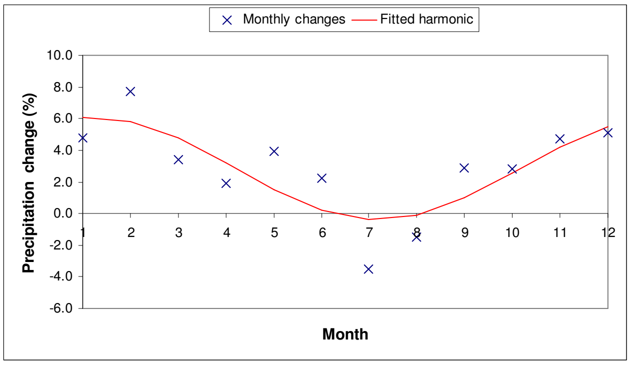
with X_0 the mean annual change, A the (semi-)amplitude of the harmonic, Φ_{month} the phase of the harmonic (in months), t is the month (1 for January, 12 for December) and $X(t)$ is the value of the change for the month t (from Wilks 2006).

The monthly change factors can be derived from a number of resamples using the methodology suggested in Section 3, or be based on the difference between a single baseline and a single future time slices. Illustration of the smoothing through a single-harmonic function is given below.

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 (see 7.2 and Table 7.1) can 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

7.3.2 Worked example 2: Lower confidence level

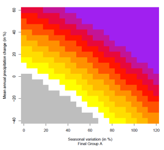
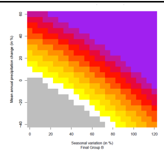
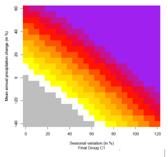
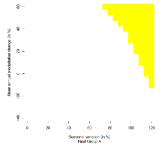
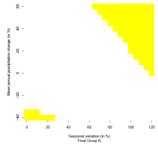
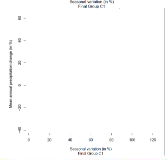
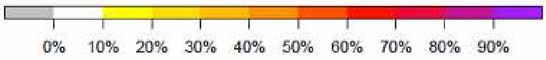
See Section 7.3.1 for detailed explanation of the implementation of the 3-step methodology.

Site number: 15006 (Tay at Ballathie)
Catchment properties (Table 5.2 explains these properties):

NORTH	736600	SAAR	1424	BHP	0
EAST	314700	ALTBAR	411	BVLP	83
AREA	4586.82	BFIHOST	0.473	MAL	301

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

				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 MAL ≤ 426.5	12	L	**0.45**	**0.45**	0.10	0	0	0	0	0
RP10	SAAR ≥ 969.5 AREA ≥ 680.86	12	**H**	N/A	**0.76**	0.24	0	0	0	0	0
RP20	SAAR ≥ 969.5 NORTH ≥ 423275	9	**H**	N/A	N/A	**1.00**	0	N/A	N/A	0	0
RP50	SAAR ≥ 969.5 ALTBAR ≥ 245.5	9	**H**	N/A	N/A	**1.00**	0	N/A	N/A	0	0

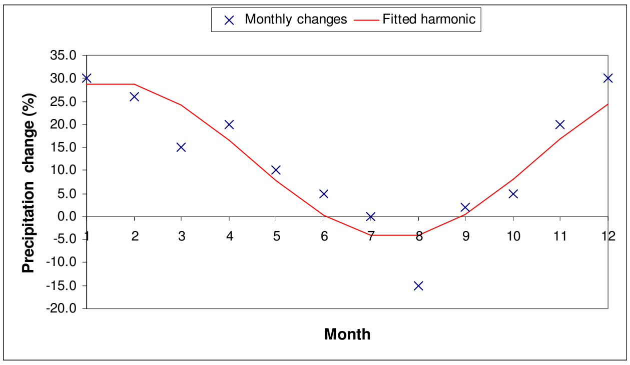
Flood response type	Damped-H	Damped-L	Neutral
Key flood response pattern (averaged over 8 T/PE scenarios)			
Standard deviation pattern (over 8 T/PE scenarios)			
			

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

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) = 12.33%
Amplitude (A) = 16.99%
Phase (Φ_{month}) = 1.5

Nearest response pattern harmonic (5% intervals):
Mean = 10%
Amplitude = 15%
Phase = 1 (as only January modelled)



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

*Changes (%) for RP2 for each of the possible key flood response patterns with addition of uncertainty from the standard deviation patterns and the extra uncertainty allowances (*Table 7.1*)*

	Flood response type			Modelled response (Neutral)
	Damped-H	Damped-L	Neutral	
Flood response (floodr)	17	17	21	25
Standard deviation (sd)	4	4	2	N/A
Resulting range (floodr +- 2sd)	9 to 25	9 to 25	17 to 25	N/A
Extra uncertainty allowance (euc)	8	8	3	3
Final range (floodr +- 2sd + euc)	17 to 33	17 to 33	20 to 28	28

7.4 National assessment of change in flood risk from climate change, from modelled catchments

The conceptual framework developed and the products generated within this project are powerful tools enabling the rapid assessment of the impact of a large range of rainfall and T/PE scenarios (potential hazard) on the flood regime of any catchment in Britain (vulnerability). Using these tools, two questions of relevance to climate change adaptation policy can be easily assessed:

- **What is the impact of a specific climate scenario (hazard) on the flood regime of a catchment?** This is similar to a traditional impact study resulting from the modelling of specific climate change scenario(s) on a catchment. The FD2020 method estimates this without recourse to further hydrological modelling. This is done by identifying the vulnerability of the flood regime of a catchment from its catchment properties, following the extensive modelling and regionalisation exercise presented in this report. This vulnerability pattern is then used to find the response of a catchment flood regime to a specific climate change scenario.
- **What is the likelihood that a threshold of change will be exceeded under climate change?** While this is a fundamental question for policymakers seeking to develop allowances for climate change, traditional impact studies cannot easily provide an answer without significant computational resources, as they are based on a top-down approach where specific scenarios result in specific changes. A bottom-up approach is necessary, where all the possible scenarios are identified, and compared with current knowledge of climate change to evaluate their likelihood. This can only be achieved through a comprehensive sensitivity framework. While the FD2020 project has only evaluated impacts resulting from seasonal changes in the climate and ignored both changes in the inter-annual and intra-monthly variability, its framework does provide a comprehensive tool for such threshold assessments. An illustration of how the FD2020 method and results can be used to evaluate the likelihood of threshold exceedance is given in Section 7.4.2

7.4.1 Evaluation of climate change impact on flood indicators

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 7.2 and Figure 7.3 summarise the results for the 16 AR4 GCMs and 11 UKCP09 RCMs respectively (Section 6.2) 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, and 11*8 RCMs. From each set, these changes are ordered and the 10th, 50th and 90th percentiles have been extracted and plotted. Note that these percentiles are not directly comparable to similar percentiles presented in UKCP09 (for example the changes in annual and seasonal precipitation in Figure 4.10 of Murphy *et al*. 2009) as no emulator has been applied to expand the ensemble: the results are based only on the 16 GCMs (Figure 7.2) and 11 RCMs (Figure 7.3). The maps presented here 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 the extra uncertainty allowance described in Section 7.2.

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%, particularly for the set of GCM impacts. The set of RCM impacts shows more catchments with a median percentage change above 20% than the set of GCM impacts, probably because of the greater change in seasonality of precipitation suggested by the Hadley Centre RCM. However, many catchments have the 90th percentile change above 20%, both for GCM and RCM scenarios, suggesting that the current 20% sensitivity allowance can no longer be considered precautionary. This is especially the case if the extra uncertainty allowances of Section 7.2 are included (maps not shown).

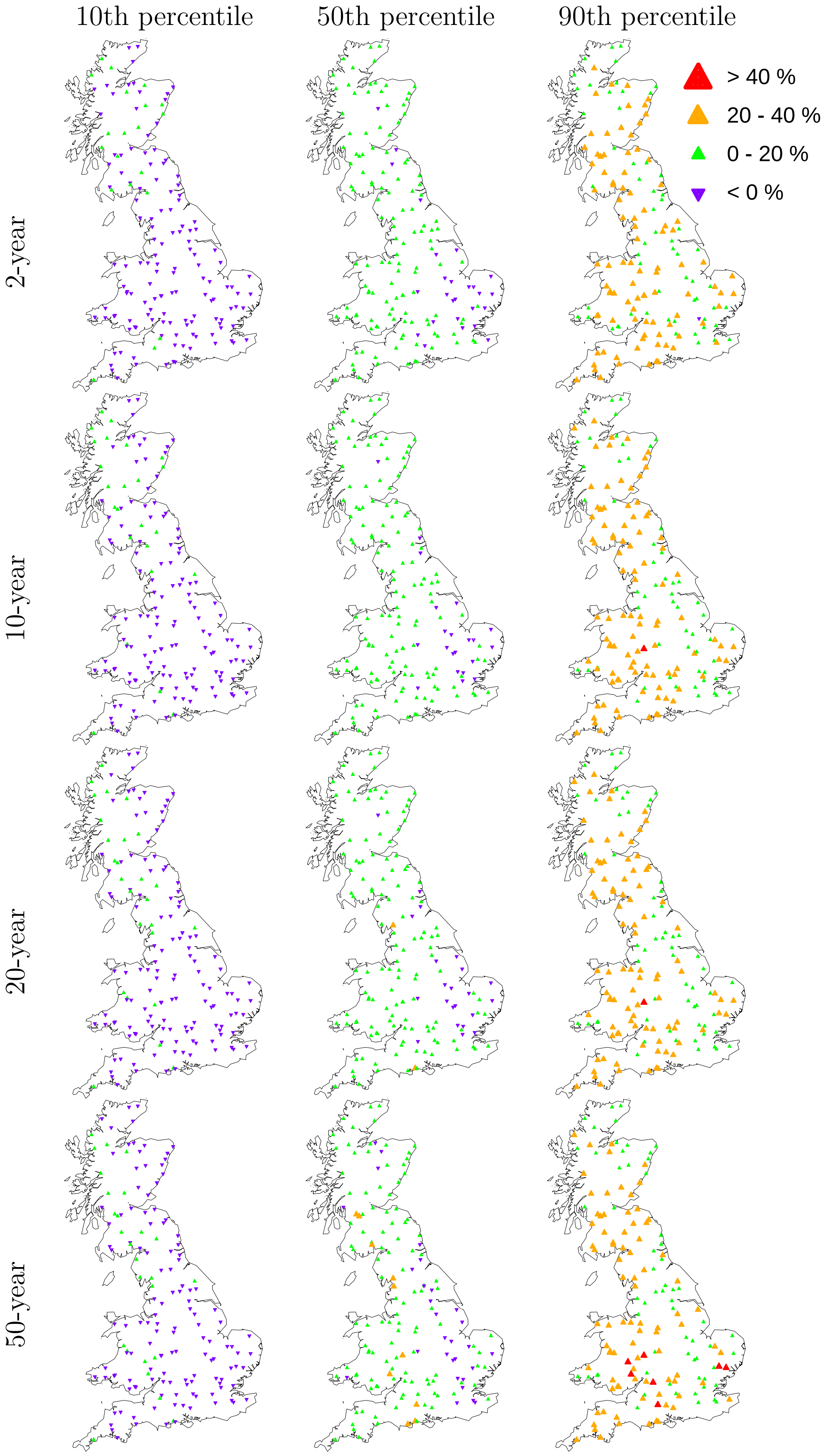


Figure 7.2 Impacts obtained from the catchment flood response patterns (for all 8 T/PE scenarios, not including the extra uncertainty allowance) for 16 AR4 GCMs (2080s, A1B emissions scenario). Values on the left show the return period of the flood level assessed

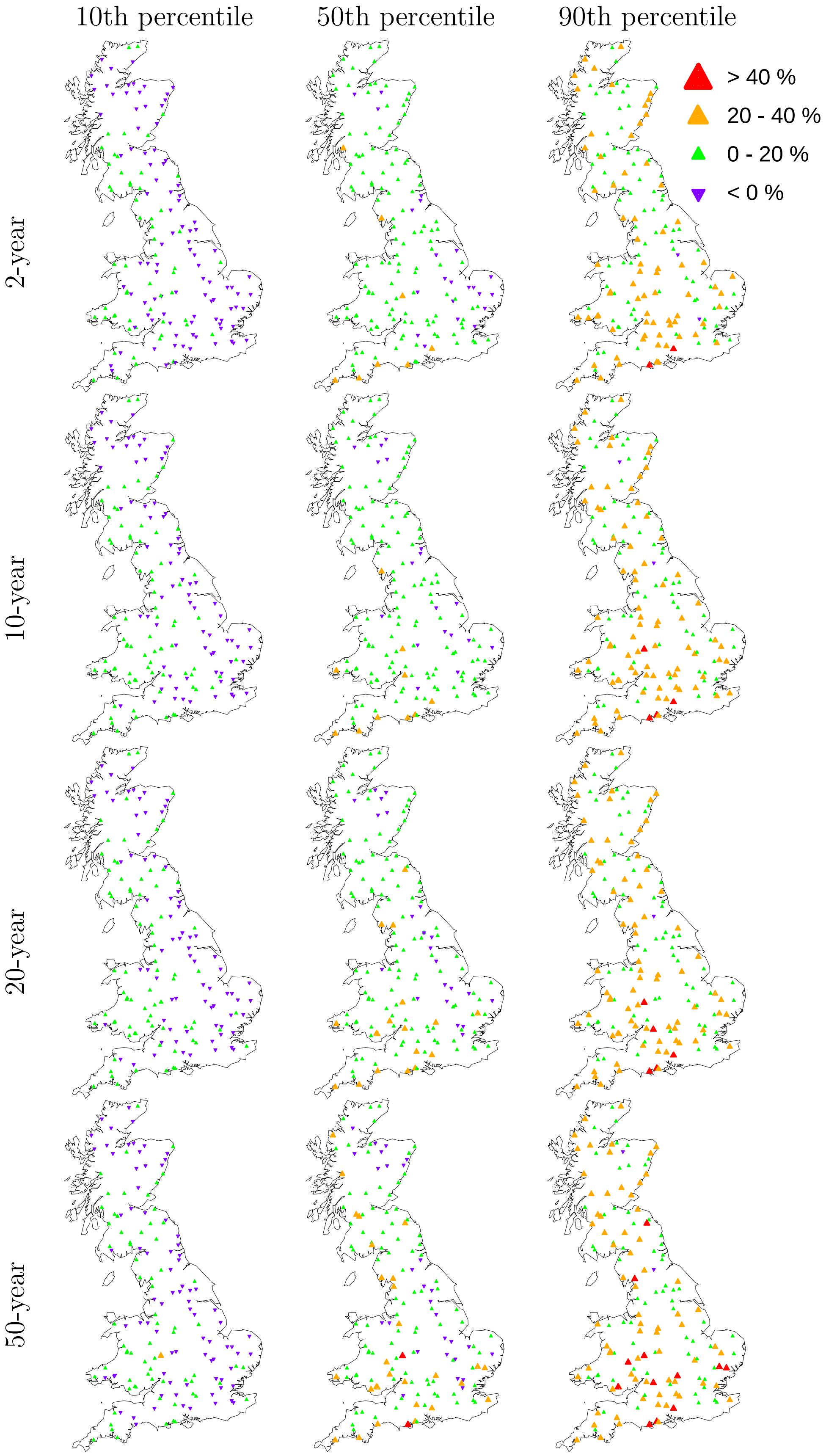


Figure 7.3 Same as Figure 7.2 but for 11 UKCP09 RCMs

7.4.2 Assessment of the probability of threshold exceedance

The modelling framework on which the flood response types and their corresponding key flood response patterns are built results in the quantification of flood changes from 4,200 different scenarios of rainfall and T/PE change. Using the flood response patterns (either obtained from modelling of the flood regime of a catchment, or approximated from the catchment descriptors and assigned flood response type) it is possible to quickly identify the sets of scenarios generating flood changes greater/lower than a given threshold. Combining this information with current understanding of the climate change hazard, it is possible to estimate the proportion of scenarios in each category, i.e. the risk of exceeding a threshold of change in flood peaks due to climate change. By repeating this process, it is possible to compare the risk of exceeding alternative thresholds. This provides a powerful tool for policy-makers, allowing the analysis of the resilience of catchments to climate change for any number of possible allowances.

The analysis can be done on a national basis, as presented in Figure 7.4 and Figure 7.5, or regionally. In Figure 7.4 (16 AR4 GCMs) and Figure 7.5 (11 UKCP09 RCMs), the sets of impacts obtained from the flood response patterns for each catchment (for all 8 T/PE scenarios) are summarised in terms of their exceedance of a given set of climate change allowances (chosen at 10% intervals between 0% and 100%) for the four flood indicators. That is, for a given catchment, flood indicator and set of climate change scenarios, the proportion of considered climate change scenarios that are greater than *X*% is calculated, where *X* is 0, 10, 20, …100. These proportions are plotted against the allowance *X* on the graphs in Figure 7.4 and Figure 7.5, with each cross for a given value of *X* representing one of the 155 project modelled catchments. The 10th, 30th, 50th (median), 70th and 90th percentiles over these catchments are also indicated for each value of *X*.

Looking at the median (solid) line in these graphs (i.e. with half the catchments plotted above this line and half plotted below) the level of risk falls off quickly (at all four return periods) as the allowance is increased. For instance, under the set of GCM scenarios (Figure 7.4), for half of the modelled catchments, around 50% of climate change scenarios generate an impact greater than that 10% allowance, whereas only around 15% of scenarios generate an impact greater than 20% (the current national allowance). If the allowance is taken as 30%, practically no scenarios result in impact greater than this threshold for half of the catchments. Similar conclusions apply to the set of RCM scenarios (Figure 7.5). However, there are a number of catchments where the decrease in risk with increasing allowance is much slower (the points above the median line), particularly when considering changes in higher return period flows, and under the RCM scenarios. Using this type of assessment it is possible to make an informed decision for new allowances after deciding on the level of risk that is acceptable:

i. What proportion of catchments is to be protected?
ii. What proportion of climate change scenarios are permitted to exceed the allowance

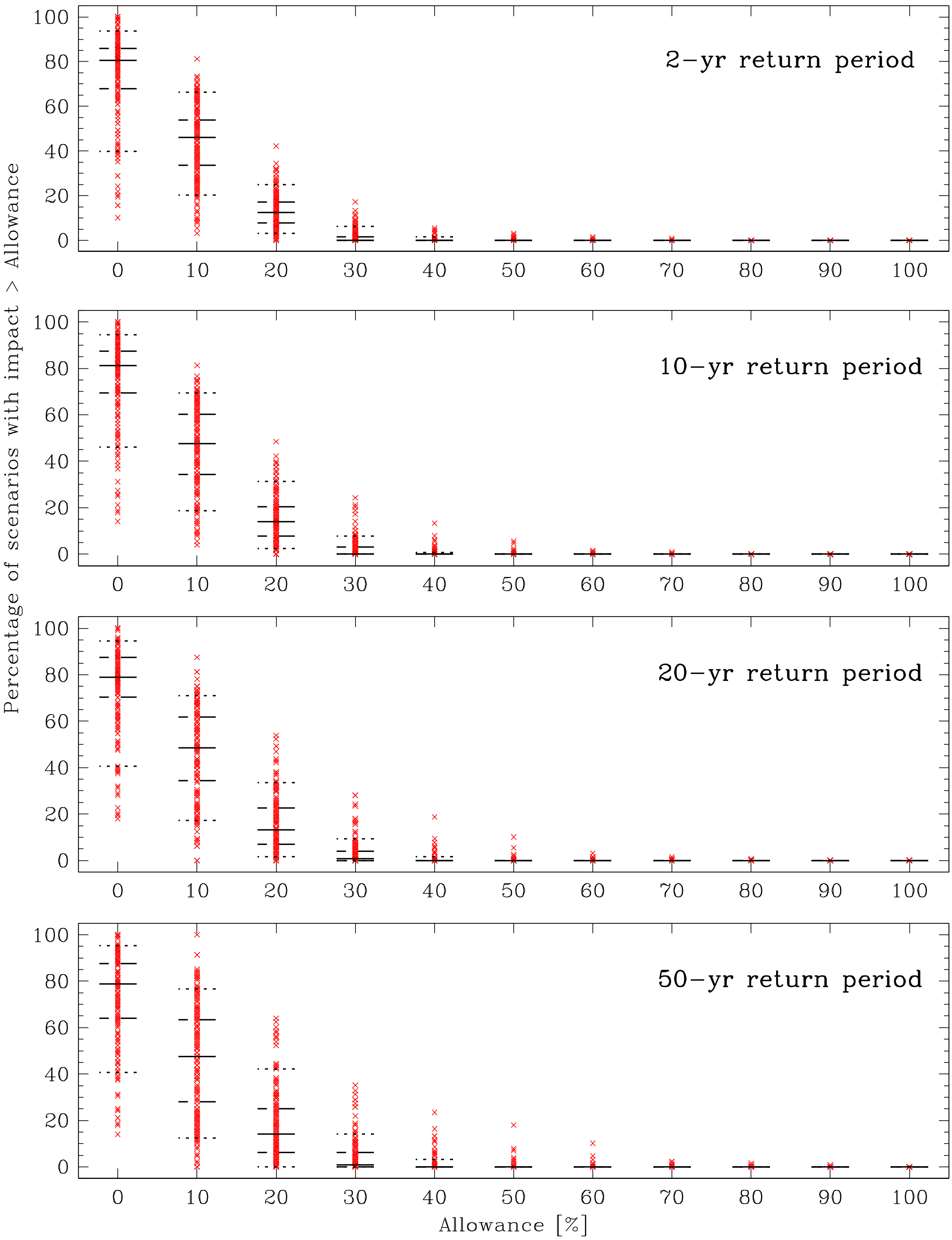


Figure 7.4 Summary of the impacts obtained from the catchment response patterns (for all 8 T/PE scenarios), relative to a given set of allowances, for 16 AR4 GCMs (2080s, A1B emissions scenario). Each cross for a given value of the allowance represents the results for one catchment (not including any extra uncertainty allowances). The 50th, 30th and 70th, and 10th and 90th percentiles (solid, dashed and dotted lines respectively) are shown for each value of the allowance

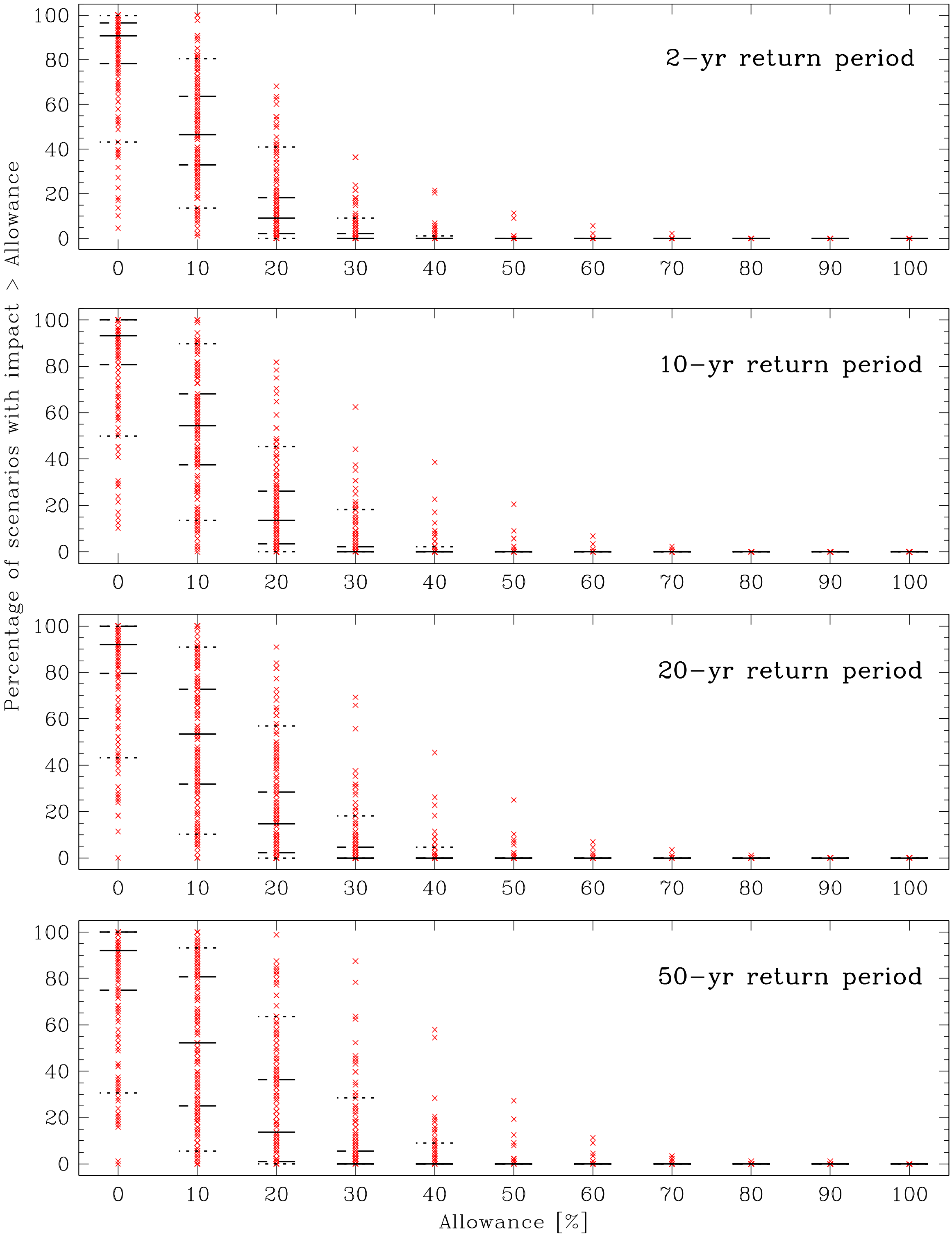


Figure 7.5 As Figure 7.4 but for the 11 UKCP09 RCMs (2080s, A1B emissions scenario)

The results in Figure 7.4 and Figure 7.5 do not include the uncertainty due to the assumptions made in developing the sensitivity framework. The uncertainty analysis (Section 6) showed that some types of catchment have a greater level of uncertainty than others. The flood response type of each modelled catchment can be used to add the appropriate extra uncertainty allowance according to the flood response type and return period (Table 7.1). Figure 7.6 illustrates how the results in Figure 7.4 are altered when this extra uncertainty is included (where in this case the flood response type has been determined by the grouping methodology, Section 4, rather than via regionalisation, Section 5). In this case, there is a much slower decrease in the proportion of catchments and scenarios for which the different allowance thresholds are exceeded, suggesting the need for a higher allowance to achieve the same level of protection. For instance, without the extra uncertainty added, for half of the modelled catchments 15% of (GCM) scenarios produce changes in the 20-year flow above the 20% allowance (Figure 7.4). When the uncertainty is added this value increases to nearly 50% of scenarios exceeding the 20% allowance in half the catchments (Figure 7.6).

One of the objectives of the FD2020 project was to assess whether a national climate change allowance for flood risk was appropriate, or whether this allowance should be different depending on catchment type (i.e. is the vulnerability to climatic change different for catchments with different characteristics?) or catchment location (is the climate change hazard different for different regions of Britain?). Figure 7.7 (for the GCMs) and Figure 7.8 (for the RCMs) are the same as Figure 7.6 but with the probability of exceedance of an allowance threshold coloured according to the catchment’s flood response type (obtained by the grouping methodology, Section 4, rather than regionalisation, Section 5). This probability does appear to vary by catchment type, and in particular, catchments with Enhanced or Sensitive flood response types seem to be much more likely to have an above average level of risk.

As the risk is a combination of vulnerability (flood response pattern, depending on catchment type) and hazard (climate change scenarios, depending on catchment location), the conclusions obtained from Figure 7.7 and Figure 7.8 could depend on the specific set of catchments modelled in the project. In particular, some flood response types might not be present in a region so the risk associated with the corresponding vulnerability-hazard combination will not be covered in such summary plots. A nationwide assessment of the vulnerability of British flood regime to climate change would be necessary to evaluate with more accuracy current climate change flood risk allowance and evaluate the importance of catchment type in their resilience to fixed flood risk allowances.

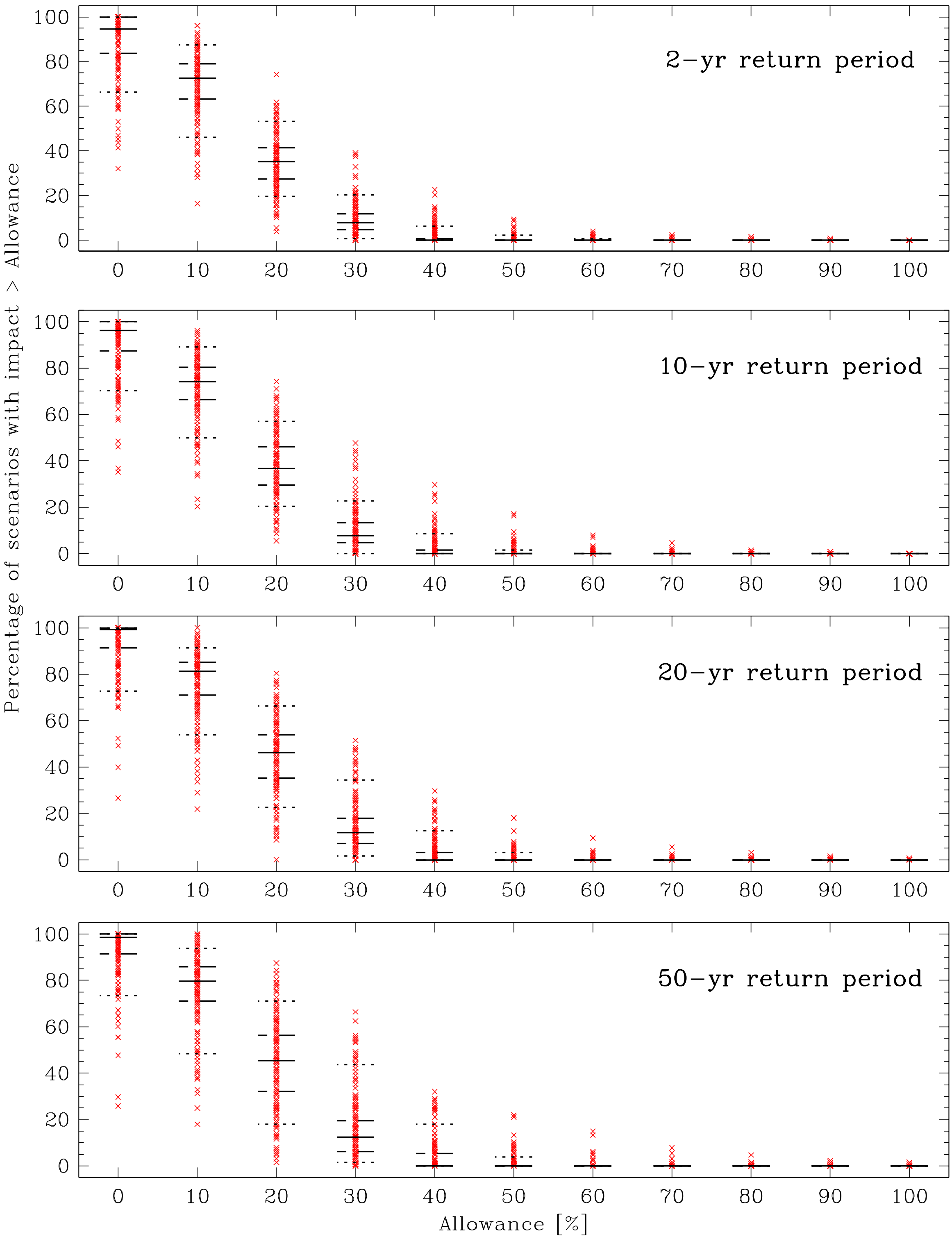


Figure 7.6 As Figure 7.4 but including the appropriate extra uncertainty allowances for each catchment, according to their flood response type (as determined by the grouping methodology, Section 4, rather than regionalisation, Section 5)

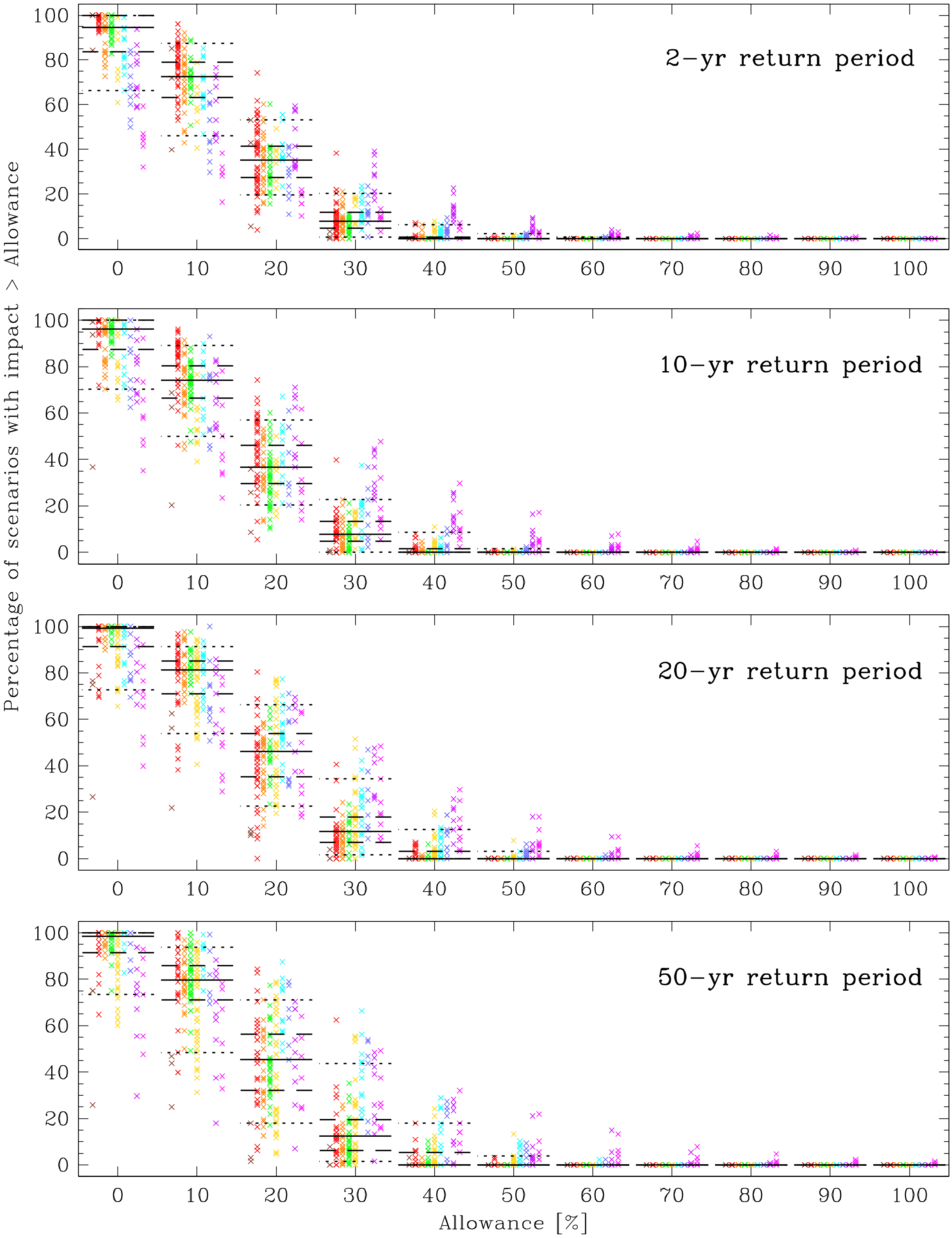


Figure 7.7 As Figure 7.6 (for 16 AR4 GCMs) but with catchments separated/colour-coded by their flood response type (as determined by the grouping methodology). Flood response types, plotted from left to right for each value of the allowance: Damped-Extreme (brown), Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta). As in Figure 7.4, the 50th, 30th and 70th, and 10th and 90th percentiles (solid, dashed and dotted lines respectively) over all catchments are shown for each value of the allowance

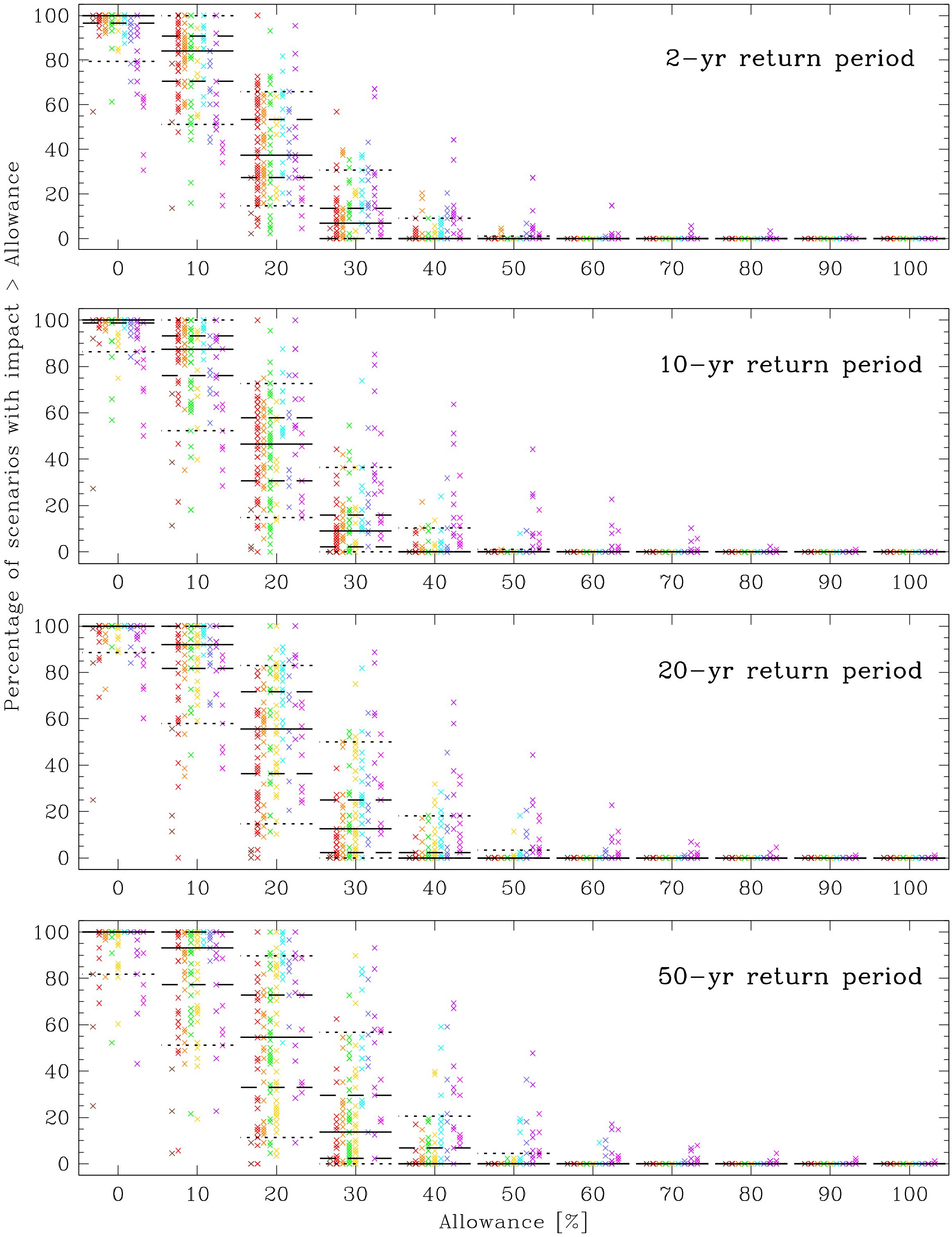


Figure 7.8 As Figure 7.7 but for the 11 UKCP09 RCMs (2080s, A1B emissions scenario)

7.5 Un-modelled catchments

Using the decision trees presented in Section 5 it is possible (although beyond the scope of this project) to derive the most likely flood response type for most of the approximately 1100 British catchments listed in the NRFA Hydrometric Register ('most' rather than 'all' catchments as the Mean Annual Loss may be missing for a small number of catchments, where the periods of available rainfall and runoff are very different). This would deliver a comprehensive assessment of the flood regime vulnerability to climate change in Britain.

Additionally, the climate change hazard (in the form of mean annual change and (semi-)amplitude of a single-harmonic function fitted to monthly climate change factors) can be assessed for Britain using the latest GCM and RCM projections. In this project, we considered 16 GCM projections used for the IPCC-AR4 and 11 RCMs used for the UKCP09 scenarios for the 2080s and for A1B emission scenarios, but other projections will become available and can be incorporated within this framework.

Combining a vulnerability assessment with a multi-climate model hazard for all 1100 catchments would provide a comprehensive assessment of risk, which could be presented as described in Section 7.4. Assuming this large set of catchments does represent accurately the range of catchment types found in all parts of Britain, such risk assessments would provide solid scientific evidence for guiding new climate-change related flood management policy. In addition, regional or catchment-type assessments would also be possible, when the number of catchments from within the NRFA Hydrometric Register set is judged sufficient. Assuming all catchment descriptors required for the decision trees could be derived for any British catchment, it would be possible to make flood risk assessments for all of Britain. When new climate change projections are published, they could easily be incorporated within the framework, and new risk assessments made with minimal effort.

8. Summary and discussion

PREVIOUS FAST TRACK BOX ON PAGE 79

Section 8: Summary and discussion

This section summarises the development of the new scenario-neutral methodology, highlighting the novel and powerful policy-relevant tools that have been derived from the results. The approach investigates the catchment response to changes in climate by imposing the same scenarios of change to all catchments across Britain, hence allowing those catchments that respond in a similar manner to be grouped together and then characterised according to catchment properties ("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.

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.

There is also a discussion of some of the issues that could not be included within such a method, such as the change to short duration intense rainfall and the extension to higher return periods, acknowledging the importance of more extreme events than could be confidently simulated in this project.

END OF FAST TRACK BOXES

Project FD2020 has delivered a robust and flexible methodology, which is a powerful tool for evaluating the potential risk of future climate change for flooding in Britain.

The methodology is a **scenario-neutral** approach based on a broad sensitivity analysis to determine catchment response to changes in climate. The method separates the climate change that a catchment may be exposed to (the **hazard**) from the catchment response (change in peak flows) to changes in the climate (the **vulnerability**). By combining the current understanding of climate change hazard with the vulnerability of a given catchment, it is possible to evaluate the **risk** of flood flow changes.

Because the vulnerability assessment does not rely on any specific climate change projection, the risk assessment can be easily updated when new projections arise, or when the likelihood of climate change projections becomes available. This is not possible with the great majority of climate-change assessment studies, which are directly linked to particular projections, and thus require additional modelling for each new climate projection.

The modelling framework has been designed to evaluate the impact of climate changes on flood indicators for all rainfall change scenarios ranging from a mean annual decrease of 40% to a mean annual increase of 60%, with additional seasonal variability. It is therefore possible to quickly identify which rainfall scenarios generate flood changes greater than a chosen threshold or allowance (for example, the current policy of a 20% national allowance). Combining this information with the current knowledge of the climate change hazard, it is possible to quantify the probability that this allowance would be exceeded, and test the resilience of different allowances. It would be much more difficult to undertake such analyses from the results of a traditional, top-down climate change impact study.

A further objective of this project was to assess the need for regionalised guidance on climate change, rather than national. The methodology developed is based on the modelling of 154 catchments representing a range of catchment characteristics and locations across Britain, and has provided sound evidence that different catchments react differently to climate change, and thus that a national flood risk policy is likely to mask the variability in the catchment vulnerability and in the climate change hazard.

Nine different vulnerability types (called flood response types) have been identified, which represent different flood responses to the same climate changes for four flood indicators. These flood response types can be determined using just nine different catchment properties using a method of decision trees. This regionalised methodology is a powerful tool which enables:

- the assessment of flood changes for four flood indicators from any rainfall change scenario for any catchment with appropriate catchment descriptors, equivalent to a climate change impact study on the peak flows;
- rapid updating when new climate change scenarios become available;

- the evaluation of the resilience of flood risk allowances for any catchment with appropriate catchments descriptors;
- national or regional evaluation of the resilience to flood risk allowances, and the updating of this evaluation as new climate change scenarios become available.

The development of the methodology involved a series of assumptions that were tested within an uncertainty assessment. However, the methodology necessarily excluded changes in some key flood-related indicators, such as the change in the inter-annual rainfall variability and changes to the frequency and magnitude of short duration extreme rainfall. Therefore, where this methodology highlights catchment vulnerability it might still be necessary to undertake more detailed and specific climate change impact analyses to determine better the risk of change in peak flows because of future climate change.

The data available to drive the hydrological models restricted the choice of flood indicators. Relatively short record lengths meant that nothing more extreme than the 50-year return period could be confidently evaluated. To develop results for higher return periods (e.g. 100-year), the changes for lower return periods could be extrapolated, with additional uncertainty added to reflect this crude extrapolation. It is recommended that changes for each of the four lower return periods (2-, 10-, 20-, and 50-years) are used for this extrapolation, rather than just the results for the 50-year return period. The main reason behind this recommendation is to reduce the reliance on the results for the 50-year return period, which are themselves more uncertain than the results for the lower return periods. However, more generally it will mean less reliance on the results for any one return period. This is recommended as, for a given catchment, the paths of the decision trees followed for some return periods may be less clear about that catchment's flood response type (and so the impact of a given climate scenario) than the paths followed for other return periods. Additional research is required to develop a methodology to quantify changes at higher return periods and the associated uncertainty.

The ability to estimate impacts for un-modelled, and even ungauged, catchments, via their catchment properties, is a great strength of this approach over a standard climate impacts study. A further strength of the new methodology is that, whenever new sets of climate scenarios are published, they can simply be added to the analysis in the same manner as for the old scenarios, and any changes in impact assessed without necessitating a great amount of additional work. For instance, the UKCP09 interface can produce 10,000 sets of monthly changes in precipitation for a 25x25km grid box over a catchment. These can each have single harmonic functions fitted to the 12 monthly values, and thus their corresponding impacts derived from the response patterns. The range of results from this set of UKCP09 scenarios can then be compared to the range from the AR4 GCM or UKCP09 RCM scenarios.

Being able to incorporate alternative scenarios within this methodology rapidly means that information for different time horizons in the future can be analysed, such as the seven over-lapping time slices from UKCP09. This provides an assessment of the time-dependent evolution of risk of changing flood flows.

Furthermore, many potential climatic change hazards can be considered within the framework. If enough are available, it is possible to evaluate the probability of occurrence of each of the (pre-fixed) 525 rainfall scenarios, by comparing the number of times each scenario is selected as being representative of a known climate change projection. A probability density function for each mean annual change and seasonal change can then be derived and combined to give a 2-dimensional probability density function, as illustrated in the schematic of Figure 8.1.

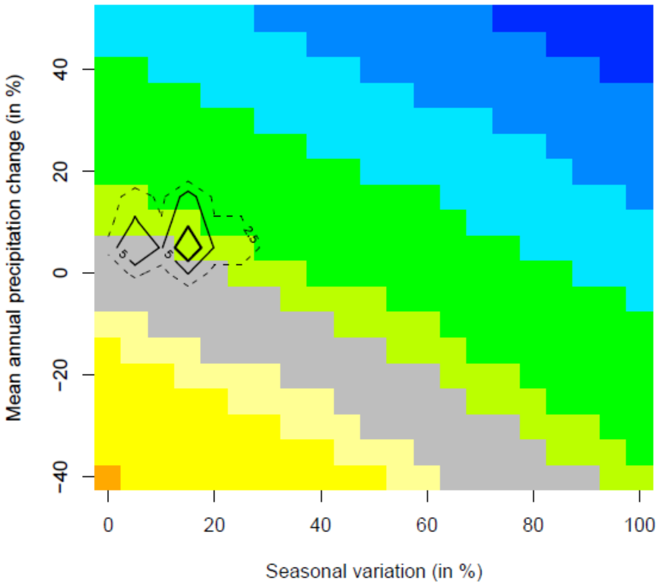


Figure 8.1 Hypothetical sensitivity diagram of hydrological changes (coloured squares) and associated hazard probability (overlying lines)

9. References

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Glossary

Allowance	The maximum change in peak flows to allow for future impacts of climate change
(Semi-)amplitude	The difference between the maximum (peak) and the mean (here annual) of a sinusoid curve
Baseline	The climate variables and river flow representing the current time period (e.g. 1961 – 2001)
Catchment descriptor	Physical attribute of a catchment (e.g. mean altitude, catchment area)
Change factor	The amount by which a climatic variable is projected to change (as percentage or absolute)
Change factor method	The change factor is applied to the baseline climate variables (rainfall, PE or temperature) to give a ‘future’ climate. Here monthly factors of change are applied to daily rainfall and temperature and monthly PE
CLASSIC	Climate and Land-use Scenario Simulation in Catchments rainfall-runoff model
Climate change scenario	Combination of statistics of change for climatic variables (for example mean monthly precipitation, temperature, radiation, wind speed) projected for some future time period
CV	Coefficient of Variation
Delta change method	See change factor method
Damping	When the percentage change in flood peak in response to climate change is less than the maximum monthly percentage increase in rainfall
Decision tree	Set of rules (here based on catchment descriptors) for dividing a sample (here set of catchments) into a number of groups (here flood response types)
Enhancing	When the percentage change in flood peak in response to climate change is more than the maximum monthly percentage increase in rainfall
FEH	Flood Estimation Handbook
Flood frequency distribution	Statistical relationship used to fit to sampled flood discharges
Flood indicator	Percentage change in magnitude of flood peak for a specified frequency of occurrence (RP)
Flood magnitude	The maximum river discharge, in this project from mean daily flow, for a flood event
Flood response pattern	Percentage changes in a flood indicator for a catchment resulting from a sensitivity analysis of changes in rainfall and temperature

Flood response type	Name given to a key flood response pattern
GCM	Global Climate Model
Harmonic function	Mathematical expression of a combination of sinusoidal curves over a certain period (here the year and applied to monthly climatic changes)
Hazard	The change in climate to which a catchment is exposed
Hydrometric Registry	Catalogue of UK hydrometric monitoring networks with reference and statistical information
Indicator	Selected statistic of change between baseline and future river flow regimes
IPCC AR4	The Fourth Assessment report of the Intergovernmental Panel on Climate Change
Key flood response pattern	Percentage changes in a flood indicator identified as typical for a group of catchments in Britain
Likelihood	Measure of the probability of a specified change in climate occurring
NRFA	National River Flow Archive
NS	Nash-Sutcliffe objective function
Objective function	Measure of the difference between observed and modelled river flow, optimised during model calibration
PDM	Probability Distributed Model rainfall-runoff model
PE	Potential Evaporation
Phase	The time (here month) of the maximum (peak) of a sinusoid curve
POT	Peaks-over-threshold – method for sampling flow series to give flood data series
Probabilistic scenario	Climate change scenario with associated probability
Probability	The chance of an event happening 1 = definitely will happen 0 = definitely will not happen
Ratio response pattern	Ratio between percentage change in flood indicator and maximum percentage change in rainfall from sensitivity analysis of changes in rainfall and temperature (catchment or key flood response)
RCM	Regional Climate Model
Resilience	A measure of how a catchment responds to increased rainfall: low resilience = high vulnerability

	high resilience = low vulnerability
Response surface	Similar to flood response pattern
Return period or RP	Frequency of occurrence - the average time period between river discharges exceeding a specified magnitude
Risk	Combination of vulnerability and hazard
SAAR	Standard Average Annual Rainfall – usually calculated for a 30 year period (e.g. 1961-1990)
SD	Standard Deviation
Seasonality	Measure of the monthly difference between change factors (here corresponding to the (semi-) amplitude)
Sensitive	Exaggerated percentage change in flood peak in response to climate change. Small increase/decrease in rainfall may result in much higher increase/decrease in flood peak
Sensitivity framework	The set of regular changes, defined by mean annual change and change in seasonality, applied to the baseline climate
SRES	IPCC Special Report on Emissions Scenarios
T	Temperature
Time horizon	The time when a climate change scenario is projected to be applicable (e.g. 2080)
Time slice	The number, or range, of years over which a climate change scenario is projected to be applicable (e.g. the 30 years from 2041 to 2070)
UKCP09	2009 UK Climate Projections – projections of changes in climate for the UK for the 21st century
Uncertainty	Variation in outputs attributable to range of assumptions and simplifications embraced in developing the overall methodology
Vulnerability	For a catchment, how much peak flows change in relation to changes in the climate
Water balance	Balance for a catchment between inputs (rainfall) and losses (evaporation, abstraction) over a time period such as a month, season or year

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