Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

An assessment of the vulnerability of Scotland's river catchments and coasts to the impacts of climate change

Work Package 1 Report

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Executive summary

This report, for Work Package 1 of the project "*An assessment of the vulnerability of Scotland's river catchments and coasts to the impacts of climate change"*, presents the potential impacts of climate change on flood flows across Scotland.

A previous Defra/EA Flood and Coastal Erosion Risk Management (FCERM) project — FD2020 *"Regionalised impacts of climate change on flood flows"* — developed a methodology which enabled the quick estimation of the impact of climatic changes on flood peaks, for catchments across Britain. Its successor project — FD2648 *"Practicalities for implementing regionalised allowances for climate change on flood flows"* — applied the FD2020 methodology, along with probabilistic projections of climate change from UK Climate Projections 09 (UKCP09), to estimate the probabilistic impacts on peak river flows for regions across England and Wales. These previous projects provide the basis for Work Package 1 of this project, which aims to develop FD2020/FD2648 for catchments in Scotland.

This report briefly summarises the FD2020 methodology (Section 1). The method estimates a catchment's **sensitivity** to climatic change, then combines this with information on a specific climatic **hazard** (set of climate change projections) in order to estimate the **risk** in terms of the impacts on peak river flows at four return periods (2, 10, 20 and 50 years).

The re-formulation of one aspect of the FD2020 method is presented (Section 2). This affects the way in which a catchment's sensitivity ('response type') is estimated from its properties, which is re-formulated in order to make it more applicable to Scotland given the greater homogeneity of catchments in Scotland compared to England and Wales.

The application of the method to estimate the response type of each National River Flow Archive (NRFA) catchment in Scotland, at each return period, is described, along with use of UKCP09 data to define the climate change hazard, and the combination of sensitivity and hazard to estimate risk (Section 3). The hazard is derived from the UKCP09 projections for the 2020s, 2050s and 2080s time-horizons under the Medium emissions scenario, and under the Low and High emissions scenarios for the 2080s time-horizon, for 10 river-basin regions covering Scotland: North Highland, North-East Scotland, Forth, Tay, Tweed, Solway, Clyde, Argyll, West Highland, and Orkney and Shetland.

Results are presented for each river-basin region (Section 4). Maps show the estimated response type of each NRFA catchment in each region, while plots summarise the hazard and the risk in each region. As well as presenting the risk for each response type ('response-type risk'), a 'regional risk' is calculated for each region, based on the number of NRFA catchments of each response type in the region. Each type of risk is presented with uncertainty bands.

The results are summarised (Section 5), including a comparison of risk between the 10 river-basin regions. This shows that regions to the west of Scotland have a greater risk that those to the east. The river-basin regions with the highest risk, at all return periods, are Argyll and West Highland, followed by Orkney and Shetland, followed by Clyde. The river-basin region with the lowest risk, at all return periods, is North-East Scotland, followed by Tweed and Tay. Possible uses of the results are discussed, including consideration of uncertainty and applicability (Section 6).

FAST TRACK BOXES

Blue text boxes at the beginning of each section offer an overview of the section and a fast track through the Report. An outline of the whole Report is provided in the First Track Box on page 1.

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1. Introduction

FIRST FAST TRACK BOX

Section 1: Introduction

This section briefly describes the work behind Defra/EA FCERM project FD2020 ("*Regionalised impacts of climate change on flood flows*") and its successor project FD2648 ("*Practicalities for implementing regionalised allowances for climate change on flood flows*"). These provide the basis for Work Package 1 of this project, which aims to develop FD2020/FD2648 in the context of catchments in Scotland.

In contrast to a standard climate change impact assessment, FD2020 took a scenario-neutral approach. That is, a 'sensitivity framework' was designed, which consisted of a fixed, regular set of changes to rainfall and temperature. The response of each catchment was then modelled under the fixed framework, resulting in plots ('response patterns') summarising each catchment's sensitivity to the same changes in their climatic inputs. FD2020 modelled 154 catchments in total (45 in Scotland).

FD2020 then grouped the catchment response patterns, according to similarity, resulting in nine 'response types' each with 'key' (average) response patterns. Furthermore, using information on physical and climatic catchment properties, sets of rules ('decision trees') were developed to allow the estimation of the response type of un-modelled catchments. In addition, extra uncertainty allowances were developed, based on an uncertainty analysis.

Given the response patterns, the impact (risk) of a given set of climate change projections (hazard) can be estimated by overlaying the projections on the response patterns. FD2020 thus developed a methodology for the rapid estimation of the change in four flood indicators (daily peak flows at the 2-, 10-, 20- or 50-year return periods) under any climate change projection (or set of projections), for any catchment in Britain where the required catchment properties are available.

Section 2 describes the development of the decision trees for use in estimating the response type of catchments in Scotland. Section 3 describes the application of these decision trees to NRFA catchments in Scotland, along with use of UKCP09 data, and the combination of these to estimate risk. The results for each river-basin region in Scotland are presented in Section 4, and summarised in Section 5. Section 6 discusses how the results might subsequently be applied.

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This project, "*An assessment of the vulnerability of Scotland's river catchments and coasts to the impacts of climate change"*, comprises three Work Packages. This report covers Work Package 1 only.

Work Package 1 develops the research from Defra/EA FCERM (Flood and Coastal Erosion Risk Management) project FD2020, and its successor project FD2648, in the context of catchments in Scotland. Both FD2020 and FD2648 were focussed on England and Wales, although the hydrological modelling of FD2020 included 45 catchments in Scotland (out of a total of 154 catchments modelled). In this project, the team behind projects FD2020 and FD2648 have made further developments to the methodology appropriate to the range and combination of catchment types and climatic conditions prevalent in Scotland. Together with probabilistic information on climate change taken from UKCP09, the project has produced probabilistic estimates of the impact of climate change on flood flows in different regions of Scotland. These results will enable SEPA to assess how best to develop policy on flood risk under climate change, as required by the FRM Act.

1.1 FD2020

Defra/EA FCERM project FD2020 ("*Regionalised impacts of climate change on flood flows"*) used a scenario-neutral approach, based on a broad sensitivity analysis, to determine catchment response to changes in climate (Prudhomme and Reynard 2009). This approach separates the climate change that a catchment may be exposed to (the hazard) from the catchment response to changes in the climate (the sensitivity, in terms of change in peak flows). In a more standard, scenario-led, approach, differences in impacts between catchments can be due to differences in the catchments themselves (catchment properties) but also due to spatial variations in the scenarios applied, making reliable generalisation of the results to un-modelled catchments very difficult. Using a scenario-neutral approach, spatial variation due to scenarios is removed as the same set of climatic changes is applied to every catchment. This approach enables a better understanding of the influence of catchment properties on the impacts of climate change on flood flows.

The sensitivity of each of the project's 154 catchments (Crooks *et al.* 2009) was modelled using a fixed sensitivity framework. The framework covered a large set of changes to the mean and seasonality of precipitation and temperature (chosen to more-than encompass the range of possible changes suggested by climate models available at the time), with potential evaporation (PE) changes corresponding to each set of temperature changes (Table 1.1). These sets of changes were applied for each catchment using the change factor method. That is, monthly change factors were applied to the catchment's baseline climate time-series (precipitation, temperature and PE), to produce possible future climate time-series. The hydrological model was then run with these possible future time-series as inputs, and the results compared to those from a run using the baseline time-series as inputs. The modelled response, in terms of the difference in a flood indicator between the baseline and each future climate, was then presented graphically in a 'response pattern'. The flood indicators used by FD2020 were the flood peaks at four return periods: 2-, 10-, 20- or 50-years (RP2, RP10, RP20, RP50). An example response pattern, showing changes in flood peaks at the 20-

year return period, is shown in Figure 1.1. By combining current understanding of climate change likelihood (hazard, e.g. from UKCP09) with the sensitivity of a given catchment (response pattern), it is possible to evaluate the risk of flood flow changes.

Table 1.1 The FD2020 sensitivity framework for changes in precipitation, temperature and PE. Total of 4,200 scenarios: 525 precipitation x 8 temperature.

	Phase	Mean annual change	Seasonality	Scenarios
Precipitation	January	-40% to 60%	0 to +120%	All combinations by increments of 5% <u>Total</u>: 525 scenarios
Temperature	January and August	1.5° 2.5° 4.5°	1.2° 0.8° 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) <u>Total</u>: 8 scenarios
Potential Evaporation (PE)	One scenario corresponding to each of the temperature scenarios (based on the Central England temperature series and temperature-based PE formula of Oudin *et al.* 2005).			<u>Total</u>: 8 scenarios

FD2020 then analysed the similarity of the responses of the 154 modelled catchments, and grouped them into nine response types (Prudhomme *et al.* 2009a). The response types were approximately ordered, according to their sensitivity to climatic changes, and named: Damped-Extreme, Damped-High, Damped-Low, Neutral, Mixed, Enhanced-Low, Enhanced-Medium, Enhanced-High and Sensitive (Figure 1.2). For each of the four indicators, each response type has a representative (key) response pattern (the average of the modelled response patterns of that type; Figure 1.3) and a standard deviation (sd) pattern (representing the range of responses within each type; Figure 1.4). The key response patterns clearly illustrate the differing sensitivity to climate change for each response type. Damped types have lower sensitivity, as there is a relatively gradual increase in the impact on flood peaks as both the mean and seasonal amplitude of the rainfall change are increased (i.e. moving from the bottom-left to the top-right of the response pattern). In contrast, Enhanced types have higher sensitivity, as there is a much faster increase in the impact as both the mean and seasonal amplitude of the rainfall change are increased (particularly for Enhanced-

Medium, Enhanced-High and Sensitive types). Note that the key response patterns presented in Figure 1.3 (and sd patterns presented in Figure 1.4) differ slightly from those presented in FD2020, following improvements to the modelling of a small number of catchments since the completion of FD2020.

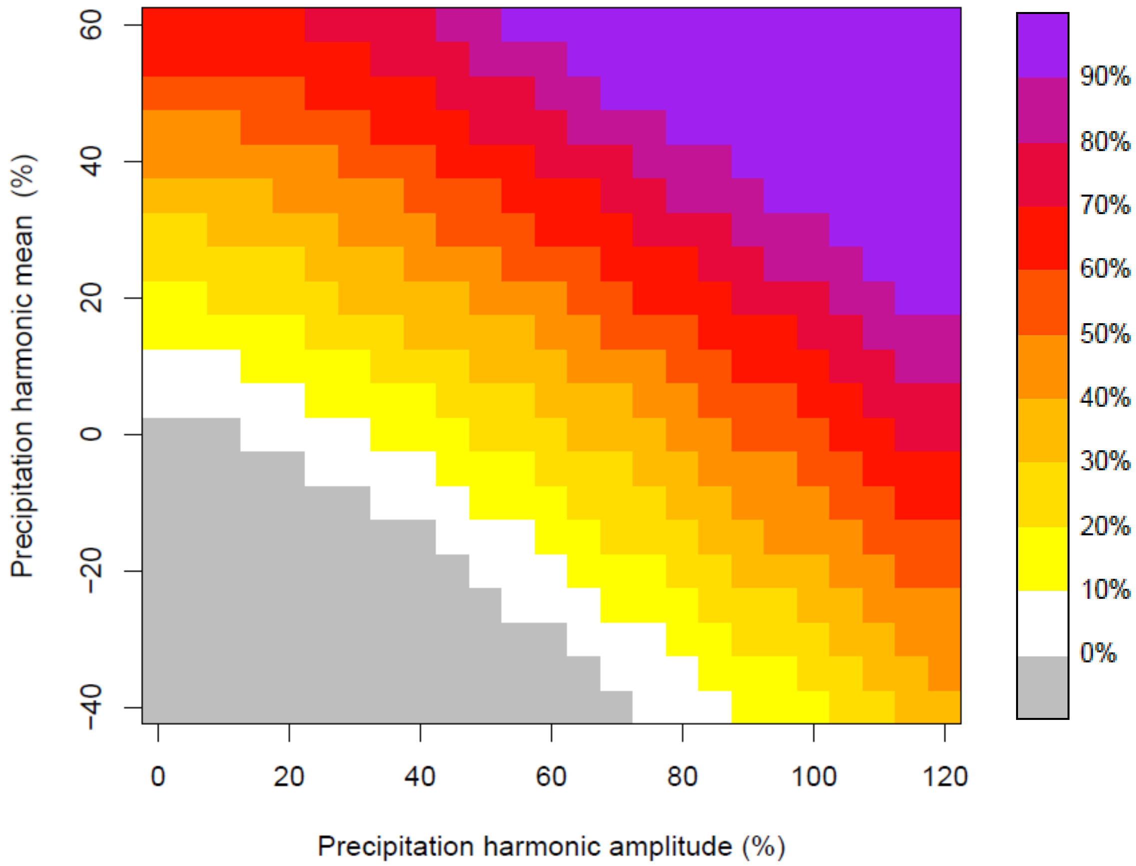

Figure 1.1 Example flood response pattern for percentage changes in the 20-year return period flood peak for the Helmsdale @ Kilphedir (02001), with the Medium-Aug temperature/PE scenario (maximum rainfall change in January).

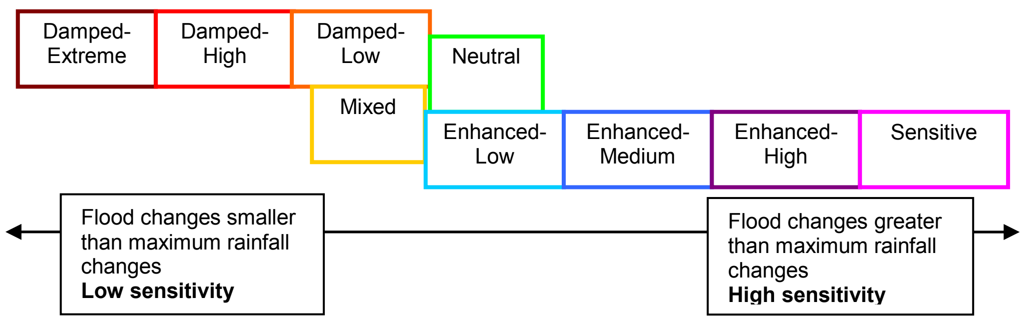

Figure 1.2 Schematic of the nine flood response types from FD2020.

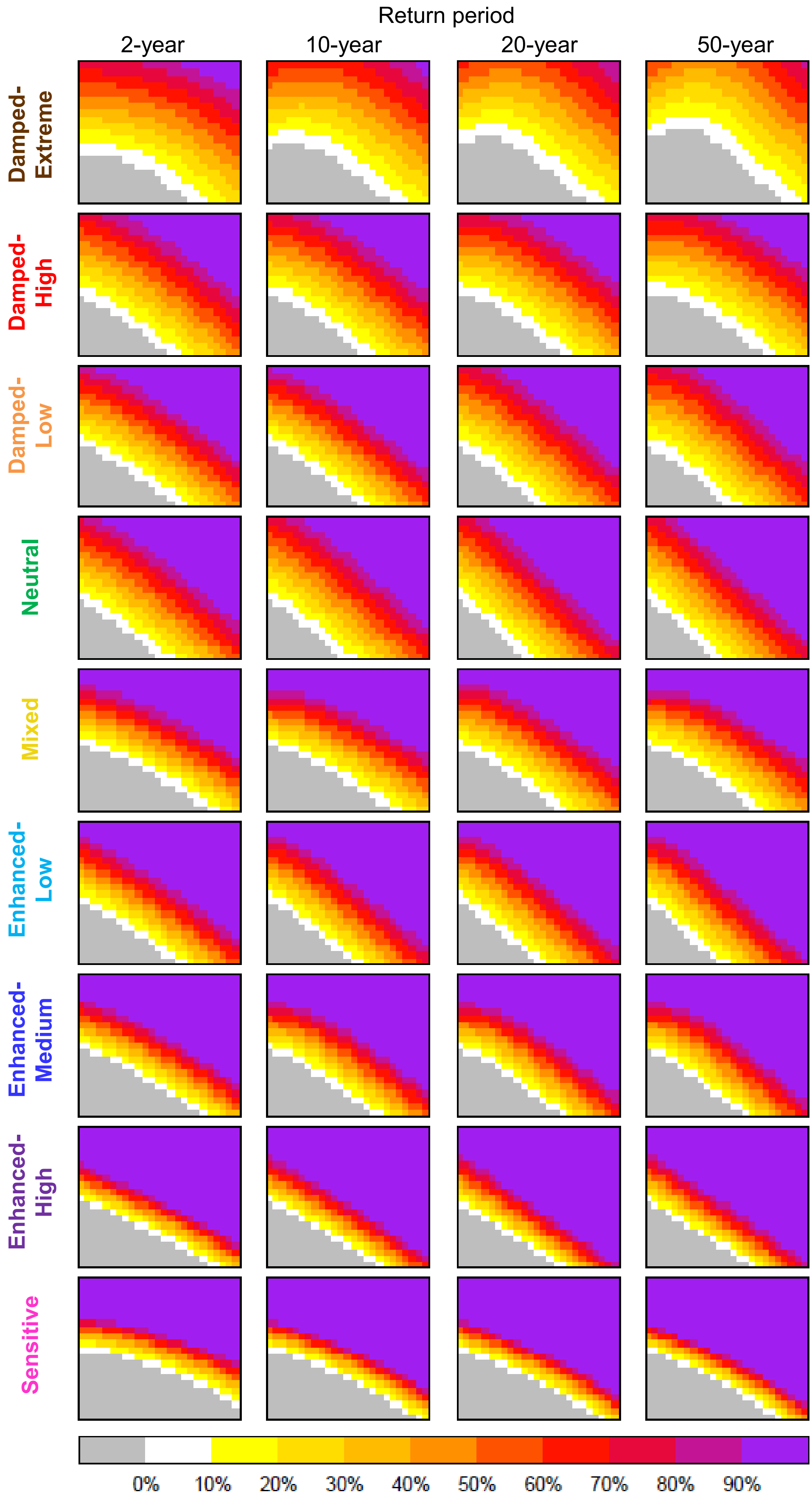

Figure 1.3 Key flood response patterns (averaged over the eight T/PE scenarios), for the nine flood response types and the four flood indicators of FD2020. See Figure 1.1 for axis labels.

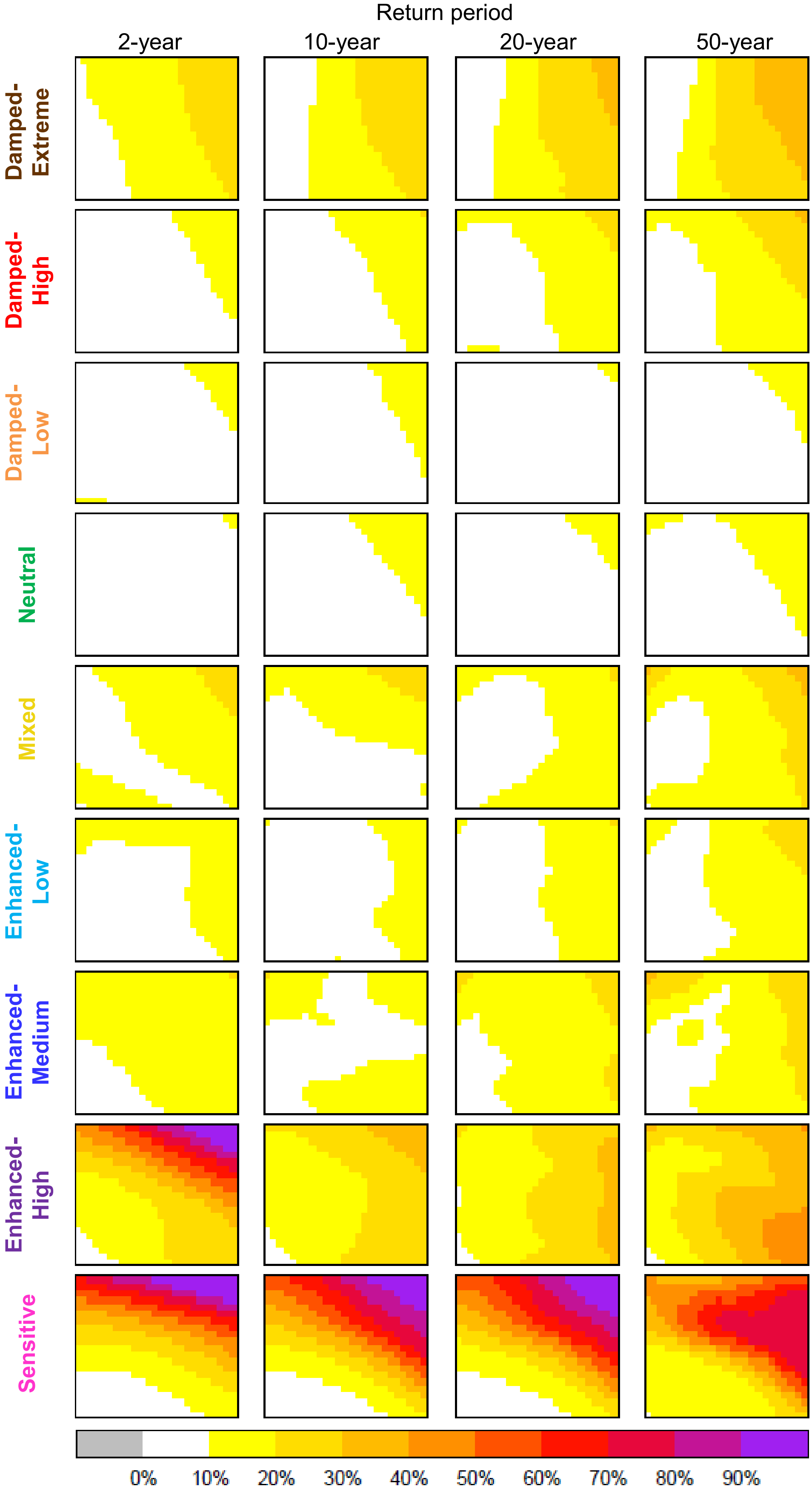

Figure 1.4 Standard deviation of the key flood response patterns (over the eight T/PE scenarios), for the nine flood response types and four flood indicators of FD2020. See Figure 1.1 for axis labels.

Sets of these response types were then characterised by catchment properties, producing decision trees (Prudhomme *et al.* 2009b). The decision trees provide sets of rules, based on catchment properties, which enable the estimation of a catchment's response (sensitivity), and so its risk (when combined with a particular hazard), from those properties. The small number of catchments with a Damped-Extreme type meant that it could not be characterised, and some of the other types were merged at higher return periods (Table 1.2), for reasons discussed in Prudhomme *et al.* (2009b). As a result, 8, 7, 4 and 4 types were characterised at the 2-, 10-, 20- and 50-year return period respectively. In addition, an uncertainty analysis (Kay *et al.* 2009a) suggested extra uncertainty allowances, according to response type and return period (Table 1.3).

Table 1.2 Merging of flood response types for higher return periods, along with the key flood response pattern to be applied in each case.

<table>
<tr><th rowspan="2">Response type</th><th colspan="4">Return period</th></tr>
<tr><th>2-year</th><th>10-year</th><th>20-year</th><th>50-year</th></tr>
<tr><td>Damped-Extreme</td><td>Damped-Extreme</td><td>Damped-Extreme</td><td>Damped-Extreme</td><td>Damped-Extreme</td></tr>
<tr><td>Damped-High</td><td>Damped-High</td><td rowspan="2">Damped-Low</td><td rowspan="3">Neutral</td><td rowspan="3">Neutral</td></tr>
<tr><td>Damped-Low</td><td>Damped-Low</td></tr>
<tr><td>Neutral</td><td>Neutral</td><td>Neutral</td></tr>
<tr><td>Mixed</td><td>Mixed</td><td>Mixed</td><td>Mixed</td><td>Mixed</td></tr>
<tr><td>Enhanced-Low</td><td>Enhanced-Low</td><td>Enhanced-Low</td><td rowspan="3">Enhanced-High</td><td rowspan="3">Enhanced-High</td></tr>
<tr><td>Enhanced-Medium</td><td>Enhanced-Medium</td><td>Enhanced-Medium</td></tr>
<tr><td>Enhanced-High</td><td>Enhanced-High</td><td>Enhanced-High</td></tr>
<tr><td>Sensitive</td><td>Sensitive</td><td>Sensitive</td><td>Sensitive</td><td>Sensitive</td></tr>
</table>

Table 1.3 Suggested FD2020 extra uncertainty allowances by response type and return period (and multiplication factors for larger catchments).

Response type	Return period			
	2-year	10-year	20-year	50-year
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 key response patterns, when response type is estimated from catchment descriptors.
Note that, where flood response types are merged (outlined squares, see Table 1.2), the middle uncertainty allowance is applied. Numbers not in bold are only required for use with modelled catchment response patterns.

FD2020 thus developed a methodology for the rapid estimation of the change in four flood indicators (daily peak flows at the 2-, 10-, 20- or 50-year return periods) under any climate change projection (or set of projections), for any catchment in Britain where the set of catchment properties are available.

Application of the full method involves a three-stage process:

Stage 1 - Sensitivity: Determine the sensitivity of a catchment's 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 sensitivity and hazard.

The **sensitivity** is defined by a set of 4,200 changes for four flood indicators, organised in a flood response pattern.

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

The **risk** is defined by over-laying the hazard on the flood response pattern (sensitivity), for each flood indicator. Extra change can be added to incorporate uncertainty (Table 1.3).

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 properties must be determined and used to assign a flood response type to the un-modelled catchment, and the corresponding key flood response patterns used as proxy for the actual catchment flood response pattern. The flow chart in Figure 1.5 presents the application of the methodology for a specific flood return period, for modelled and un-modelled catchments.

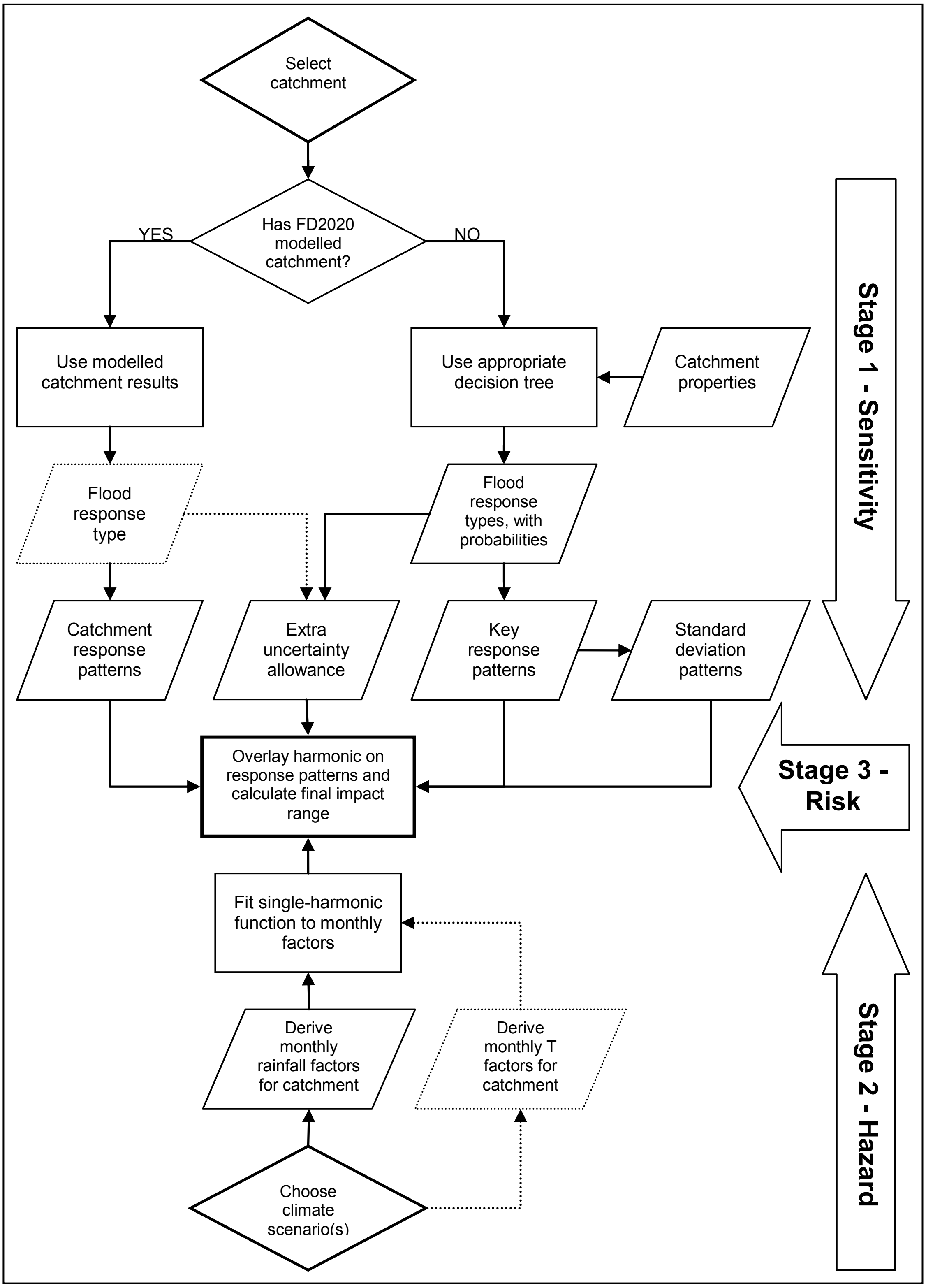

Figure 1.5 Flow chart describing the steps required for the application of the FD2020 methodology for a given flood return period.

1.2 FD2648

Project FD2648 ("*Practicalities for implementing regionalised allowances for climate change on flood flows"*) was then commissioned by Defra (Kay *et al.* 2011). That project

- estimated the response type of all National River Flow Archive (NRFA) catchments in England and Wales, at four return periods;
- used the UKCP09 river-basin region projections (Murphy *et al.* 2009) along with the sensitivity patterns for the response types identified in FD2020, to estimate the probabilistic impact of climate change on flood flows in catchments across England and Wales.

This information was used by Defra and the EA to directly support the revision of their appraisal guidance and is being used to do the same for the Welsh Government.

1.3 Aims of this project

This project aimed to develop the research from Defra/EA FCERM project FD2020, and its successor project FD2648, in the context of catchments in Scotland. In the project, further developments have been to the methodology as appropriate to the range and combination of catchment types and climatic conditions prevalent in Scotland. Together with probabilistic information on climate change taken from UKCP09, the project has produced probabilistic estimates of the impact of climate change on flood flows in different regions of Scotland. These results will enable SEPA to assess how best to develop policy on flood risk allowances for climate change, as required under the FRM Act.

In this report, Section 2 describes the development of the decision trees for use in estimating the response type of catchments in Scotland. Section 3 describes the application of these decision trees to NRFA catchments in Scotland, along with use of UKCP09 data to define the climate change hazard, and the combination of sensitivity and hazard to estimate risk. The results for each river-basin region in Scotland are presented in Section 4, and summarised in Section 5. Section 6 discusses how the results might subsequently be applied.

2. Developing decision trees for Scotland

PREVIOUS FAST TRACK BOX ON PAGE 1

Section 2: Developing decision trees for Scotland

FD2020 developed decision trees to enable the estimation of the response type of a catchment from its properties, based on the modelling of 154 catchments across England, Wales and Scotland (45 in Scotland). However, given the nature of catchments in Scotland, with greater homogeneity compared to England and Wales, it was decided that developing trees specifically for Scotland, based on a subset of catchments, could be advantageous for response-type estimation in Scotland.

Using the same decision tree methodology as in FD2020, new trees were developed for Scotland based on 57 catchments (45 in Scotland plus 12 in northern England). The catchment descriptors included are from the Flood Estimation Handbook (FEH) and the Hydrometric Register. A number of new catchment descriptors, including some based on seasonality of rainfall, were used.

Three decision trees were derived, one for 2-year return period flood peaks, one for the 10-year return period, and one for the 20- and 50-year return periods. The new decision trees perform well, with between 77% and 81% of catchments correctly classified. The selected descriptors relate to aspects of rainfall, catchment wetness and the water balance, with minimum catchment altitude also used. The first descriptor for the three decision trees reflects the shift in emphasis, from importance of catchment wetness for generation of comparatively common flood events (2-year return period), through overall availability of rainfall for medium frequency floods (10-year return period), to likelihood of intense rainfall occurring in the winter for more extreme floods (20- and 50-year return period). Unlike the FD2020 decision trees, those developed for Scotland do not include properties describing catchment permeability.

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FD2020 developed a method to estimate catchment flood response types using readily-available catchment properties, within decision trees. FD2648 made minor modifications to those decision trees, to make them more robust for use on the much larger set of NRFA catchments in England and Wales. These trees were re-considered in the context of the range and combination of catchment types and climatic conditions present in Scotland.

Properties based on geology and soils played a major role in the FD2020/FD2648 decision trees, but Scotland has much more homogeneous soils and geology than the rest of Britain. Thus it was decided to develop new trees, based on a more limited set of catchments, to assess whether alternative trees could be advantageous for response-type estimation in Scotland.

2.1 Background to decision trees

The same decision tree methodology has been used in this project as was used in FD2020. A brief outline of the methodology is given below (see Prudhomme *et al.* 2009b for more details).

In a decision tree;

- 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 (*partitioning rules*), leading to the formation of two child nodes.
- A node becomes a *leaf* when no further split is possible or relevant.
- A leaf is reached by following a set of partitioning rules; a *path*.

An example decision tree, presented graphically, is shown in Figure 2.4.

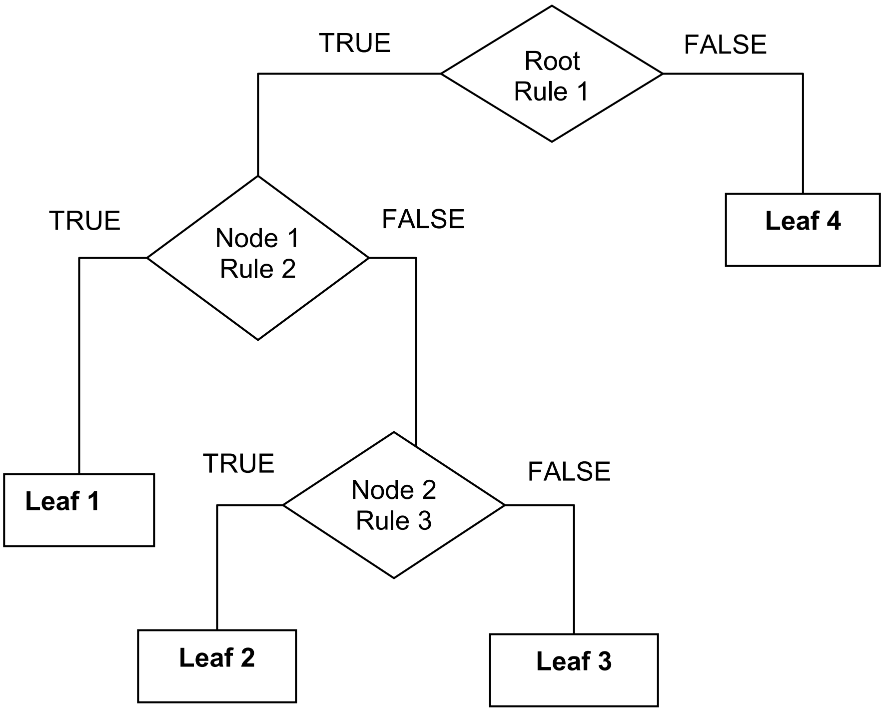

Figure 2.1 An example decision tree, with the root, nodes, partitioning rules and leaves.

Thus the aim of a decision tree is to divide the elements of the original sample (catchments) into sub-samples of the same category (flood response type), using the properties of each element (catchment descriptors). That is:

- The original sample contains all the catchments, each defined by a set of catchment descriptors and a flood response type.
- Catchments in a node are divided according to a binary test, or rule, on the catchment descriptors which aims to maximise the ‘purity’ of the two child nodes.
- A node is pure if it contains only catchments with the same flood response type. It then becomes a leaf.

- An impure node can either be further divided, or become a leaf if it contains too few catchments. In the latter case, catchments in the leaf will be of two, or more, flood response types.
- 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 probabilities are calculated as the proportion of catchments of each flood response type in the leaf.
- The flood response type associated with a leaf is that with the highest probability. When two, or more, flood response types have the same probability, the leaf flood response type is either allocated at random, or can be selected according to preference given the context (e.g. the most severe flood response type could be chosen).

The R freeware package `tree` was used for the tree modelling. As the flood response type of a catchment is not necessarily the same for all flood indicators, separate trees were derived for each indicator (flood return period).

2.2 Catchments

The 45 FD2020 catchments located in Scotland are listed in Table 2.1. Additional catchments from northern England were included for the development of the decision trees, to increase the sample size with similar catchments. These 12 catchments are listed in Table 2.2. Thus a total of 57 catchments were used in the development of the decision trees for Scotland. The boundaries and outlet locations for these 57 catchments are shown on the map in Figure 2.2.

Also included in Table 2.1 and Table 2.2 is information on the hydrological model used in FD2020 for each catchment. That is, whether it was modelled with the semi-distributed grid-based model CLASSIC (Climate and Land-use Scenario Simulation In Catchments; Crooks and Naden 2007), generally used for larger catchments, or the lumped conceptual PDM (Probability Distributed Model; Moore 1985, 2007), generally used for smaller catchments, and whether the latter was run at an hourly or daily time-step (a daily time-step would generally not be appropriate for very small catchments). Note that both hydrological models included a snowmelt module. See Crooks *et al.* (2009) for more details on the FD2020 hydrological modelling.

Table 2.1 FD2020 catchments located in Scotland.

Catchment Number	SEPA region	River	Location	Catchment Area (km^2)	$SAAR_{61\text{-}90}$ (mm)	BFI	Hydrological model
02001	North	Helmsdale	Kilphedir	551.4	1117	0.48	PDM daily
03003	North	Oykel	Easter Turnaig	330.7	1895	0.23	PDM hourly
04005	North	Meig	Glenmeannie	120.5	2145	0.26	PDM daily
06008	North	Enrick	Mill of Tore	105.9	1294	0.32	PDM daily
07001	North	Findhorn	Shenachie	415.6	1219	0.36	PDM hourly
07002	North	Findhorn	Forres	781.9	1064	0.41	PDM daily
07004	North	Nairn	Firhall	313.0	940	0.45	PDM hourly
08004	North	Avon	Delnashaugh	542.8	1111	0.56	PDM daily
08006	North	Spey	Boat O Brig	2861.2	1122	0.60	CLASSIC
10002	North	Ugie	Inverugie	325.0	812	0.64	PDM daily
10003	North	Ythan	Ellon	523.0	826	0.73	PDM hourly
11001	North	Don	Parkhill	1273.0	891	0.69	CLASSIC
12002	North	Dee	Park	1844.0	1113	0.53	CLASSIC
12003	North	Dee	Polhollick	697.0	1231	0.46	CLASSIC
12007	North	Dee	Mar Lodge	289.0	1335	0.45	PDM hourly
13001	North	Bervie	Inverbervie	123.0	890	0.56	PDM daily
13005	East	Lunan Water	Kirkton Mill	124.0	771	0.52	PDM daily
14001	East	Eden	Kemback	307.4	799	0.62	PDM daily
15006	East	Tay	Ballathie	4587.1	1463	0.64	CLASSIC
16003	East	Ruchill Water	Cultybraggan	99.5	1889	0.30	PDM daily
17005	East	Avon	Polmonthill	195.3	989	0.41	PDM daily
19011	East	North Esk	Dalkeith Palace	137.0	907	0.52	PDM daily
20001	East	Tyne	East Linton	307.0	713	0.52	PDM daily
21009	East	Tweed	Norham	4390.0	996	0.53	CLASSIC
21013	East	Gala Water	Galashiels	207.0	930	0.52	PDM hourly
21017	East	Ettrick Water	Brockhoperig	37.5	1733	0.34	PDM hourly
21023	East	Leet Water	Coldstream	113.0	671	0.35	PDM daily
78003	West	Annan	Brydekirk	925.0	1351	0.44	PDM daily
79002	West	Nith	Friars Carse	799.0	1460	0.39	PDM daily
79003	West	Nith	Hall Bridge	155.0	1505	0.27	PDM daily
79005	West	Cluden Water	Fiddlers Ford	238.0	1423	0.38	PDM hourly
81002	West	Cree	Newton Stewart	368.0	1760	0.27	PDM daily
81006	West	Minnoch Water	Minnoch Bridge	141.0	1993	0.28	PDM hourly
83005	West	Irvine	Shewalton	380.7	1228	0.26	PDM daily
84012	West	White Cart Water	Hawkhead	234.9	1314	0.35	PDM daily
84013	West	Clyde	Daldowie	1903.1	1170	0.46	CLASSIC
84030	West	White Cart Water	Overlee	111.8	1367	0.32	PDM hourly
85003	West	Falloch	Glen Falloch	80.3	2842	0.17	PDM daily
86001	West	Little Eachaig	Dalinlongart	30.8	2341	0.23	PDM hourly
90003	North	Nevis	Claggan	76.8	2913	0.26	PDM hourly
93001	North	Carron	New Kelso	137.8	2615	0.26	PDM hourly
94001	North	Ewe	Poolewe	441.1	2273	0.65	PDM daily
95001	North	Inver	Little Assynt	137.5	2211	0.64	PDM daily
96001	North	Halladale	Halladale	204.6	1102	0.26	PDM hourly
97002	North	Thurso	Halkirk	412.8	1057	0.46	PDM daily

Table 2.2 Additional FD2020 catchments, located in northern England, used for development of the decision trees for Scotland.

Catchment Number	River	Location	Catchment Area (km^2)	$SAAR_{61-90}$ (mm)	BFI	Hydrological model
22001	Coquet	Morwick	569.8	850	0.45	PDM daily
22006	Blyth	Hartford Bridge	269.4	696	0.35	PDM hourly
23001	Tyne	Bywell	2175.6	1044	0.38	CLASSIC
23011	Kielder Burn	Kielder	58.8	1199	0.34	PDM hourly
24005	Browney	Burn Hall	178.5	743	0.51	PDM hourly
24009	Wear	Chester le Street	1008.3	885	0.47	CLASSIC
25006	Greta	Rutherford Bridge	86.1	1128	0.22	PDM hourly
73005	Kent	Sedgwick	209	1732	0.46	PDM daily
74001	Duddon	Duddon Hall	85.7	2265	0.29	PDM hourly
75017	Ellen	Bullgill	96	1110	0.49	PDM daily
76007	Eden	Sheepmount	2286.5	1214	0.49	CLASSIC
76014	Eden	Kirkby Stephen	69.4	1483	0.24	PDM daily

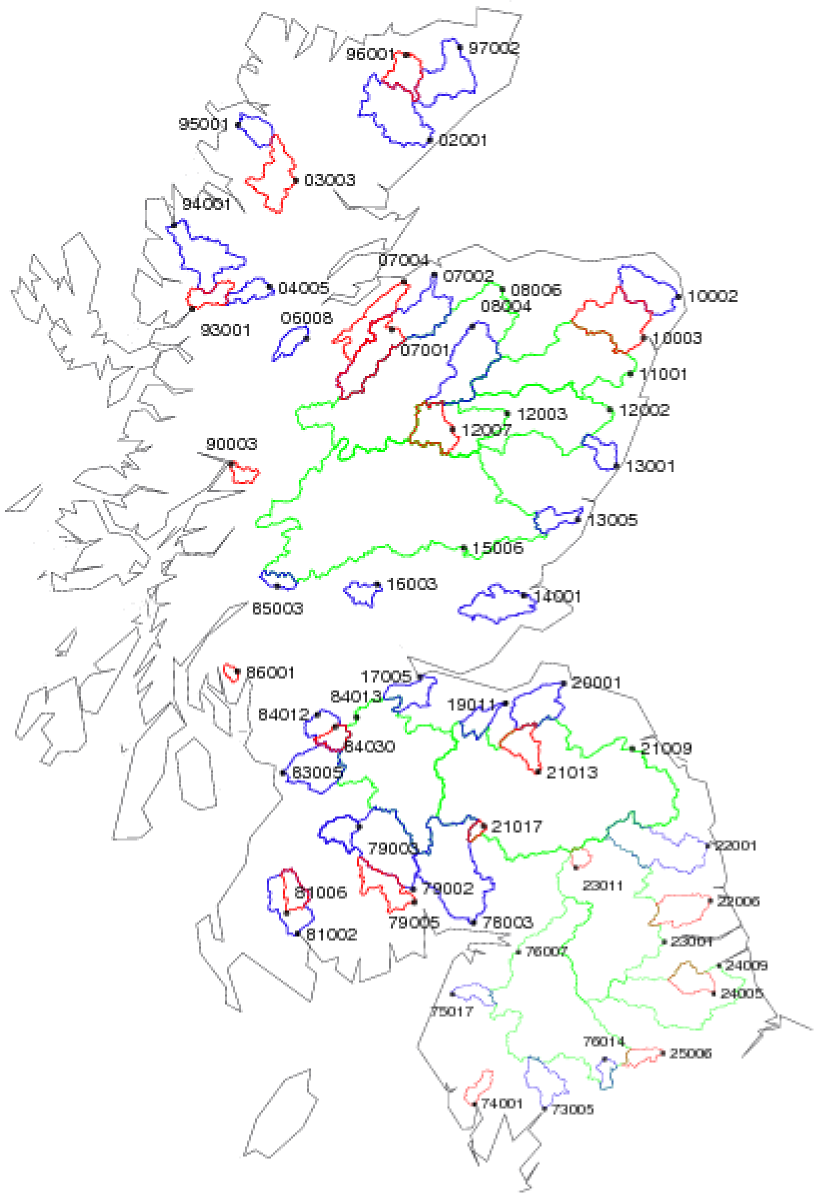

Figure 2.2 Outlets and boundaries of 45 FD2020 catchments in Scotland, and additional 12 in northern England, used in the development of the decision trees for Scotland (PDM hourly – red, PDM daily – blue, CLASSIC – green).

The observed response types for the 57 catchments listed in Table 2.1 and Table 2.2 are summarised in Table 2.3. Note that none of the modelled catchments in Scotland or northern England has Enhanced-High or Sensitive response types, at any of the four return periods, and very few catchments have Enhanced-Medium or Enhanced-Low response types.

Table 2.3 Summary of the observed response types from FD2020.

Response type	3-letter shorthand	Return period			
		2-year	10-year	20-year	50-year
Damped-Extreme	DpE	3	3	3	3
Damped-High	DpH	30	21	16	14
Damped-Low	DpL	8	5	16	16
Neutral	Neu	9	22	12	16
Mixed	Mix	2	4	8	5
Enhanced-Low	EnL	3	0	0	1
Enhanced-Medium	EnM	2	2	2	2
Enhanced-High	EnH	0	0	0	0
Sensitive	Sen	0	0	0	0

2.3 Catchment descriptors

Catchment descriptors from the Flood Estimation Handbook (FEH) and the UK Hydrometric Register used to develop the decision trees in FD2020 (Prudhomme *et al.* 2009b) were considered for the analysis for Scottish catchments, along with additional descriptors brought in for this analysis. The 20 FEH descriptors (Bayliss 1999) are described in Table 2.4. The most recent versions of the FEH descriptors were used, but $URBEXT_{1990}$ rather than $URBEXT_{2000}$ was retained as it is more relevant to the overall time period of the flow data used for the modelling in FD2020. Three new FEH descriptors (Kjeldsen *et al.* 2008) were included for this analysis; these are flood plain descriptors FPEXT, FPLOC and FPDBAR in Table 2.4. The 10 UK Hydrometric Register (Marsh and Hannaford 2008) descriptors are described in Table 2.5, including some additional descriptors based on catchment altitude.

Table 2.4 FEH catchment descriptors.

Descriptor name	Units	Description
EAST	m	Easting of catchment outlet (GB national grid reference)
NORTH	m	Northing of catchment outlet (GB national grid reference)
AREA	km^2	Catchment drainage area
ALTBAR	m	Mean catchment altitude
ASPBAR	°	Mean aspect of catchment slopes
ASPVAR	-	Index describing the degree of alignment of drainage paths
BFIHOST	-	Base flow index derived using HOST*
DPLBAR		Mean drainage path length
DPSBAR	m/km	Mean drainage path slope
FARL	-	Index of flood attenuation due to reservoirs and lakes
LDP	km	Longest drainage path length
PROPWET	-	Proportion of time soils are wet
RMED1D	mm	Median annual maximum daily rainfall
SAAR	mm	Standard average annual rainfall, 1961-90
SMDBAR	mm	Mean soil moisture deficit defined by MORECS**, 1961-90
SPRHOST	%	Standard percentage runoff derived using HOST*
$URBEXT_{1990}$	-	Index of urban/suburban extent
FPEXT	-	Proportion of the catchment estimated to be inundated by a 100-year flood
FPLOC	-	Index of location of floodplains relative to the catchment outlet, for a 100-year flood
FPDBAR	cm	Index of volume of water stored on floodplains for a 100-year flood (standardised by catchment area)

*HOST – Hydrology Of Soil Types classification (Boorman *et al.* 1995)
**MORECS – Met Office Rainfall and Evaporation Calculation Scheme (Thompson *et al.* 1982)

Table 2.5 UK Hydrometric Register catchment descriptors (and additional descriptors derived from them).

Descriptor name (acronym)	Units	Description
MEAN ANNUAL RUNOFF (MARU)	mm	Depth of water over the catchment equivalent to the mean annual flow
MEAN ANNUAL LOSS (MAL)	mm	Difference between mean annual rainfall and mean annual runoff for a catchment
BEDROCK HIGH PERMEABILITY (BHP)	%	Percentage of the catchment underlain by rock formations of high permeability
BEDROCK MODERATE PERMEABILITY (BMP)	%	Percentage of the catchment underlain by rock formations of moderate permeability
BEDROCK VERY LOW PERMEABILITY (BVLP)	%	Percentage of the catchment underlain by rock formations of low permeability
ALTMIN	m	Minimum catchment altitude (i.e. the gauging station altitude)
ALTMED	m	Median catchment altitude
ALTMAX	m	Maximum catchment altitude
ALTDIFF	m	ALTMAX – ALTMIN
RUNOFF-RAINFALL Ratio	-	MEAN ANNUAL RUNOFF / MEAN ANNUAL RAINFALL

In FD2020 some additional statistics were considered to investigate whether the response type was influenced by the seasonality of the hydro-climatology of the catchments. Initial testing of these properties showed some potential but results were only marginally improved when using them compared with only using FEH and Hydrometric Register descriptors. Additionally, the trial statistics used would not have been readily available for catchments not included in the project. For the application to Scottish catchments, seasonal statistics based on rainfall have been investigated instead (Table 2.6). Two variants were tried – using daily rainfall over 0mm (i.e. all daily rainfall) and daily rainfall over 20mm.

Table 2.6 Seasonal rainfall descriptors.

Descriptor name	Units	Description
sprR	-	Proportion of rainfall (1961-90) where the daily rainfall total is above a given threshold (see text), for months March, April, May
sumR	-	As sprR for months June, July, August
autR	-	As sprR for months September, October, November
winR	-	As sprR for months December, January, February
autR/winR	-	Ratio of the proportions of autumn and winter rainfall above

Figure 2.3 compares the distributions of a number of the catchment descriptors from Table 2.4 and Table 2.5, for the set of 45 FD2020 catchments located in Scotland (Table 2.1) versus the full set of 154 FD2020 catchments. This shows that the catchments located in Scotland are generally higher altitude (ALTBAR and ALTMAX), of lower permeability (lower BFIHOST and BHP, and higher BVLP) and steeper (DPSBAR), with slightly reduced losses (MAL). They are also wetter — in terms of soils (PROPWET), annual rainfall (SAAR) and intensity of rainfall (RMED1D). In addition, they are generally less affected by urban development (lower $URBEXT_{1990}$), but perhaps more affected by reservoirs and lakes (lower FARL). These factors illustrate why developing decisions trees specifically for Scotland, based on the reduced set of catchments, may be better than applying trees developed for the set of catchments covering the England and Wales as well as Scotland. They also suggest factors that may need more consideration for Scotland than they did for England and Wales.

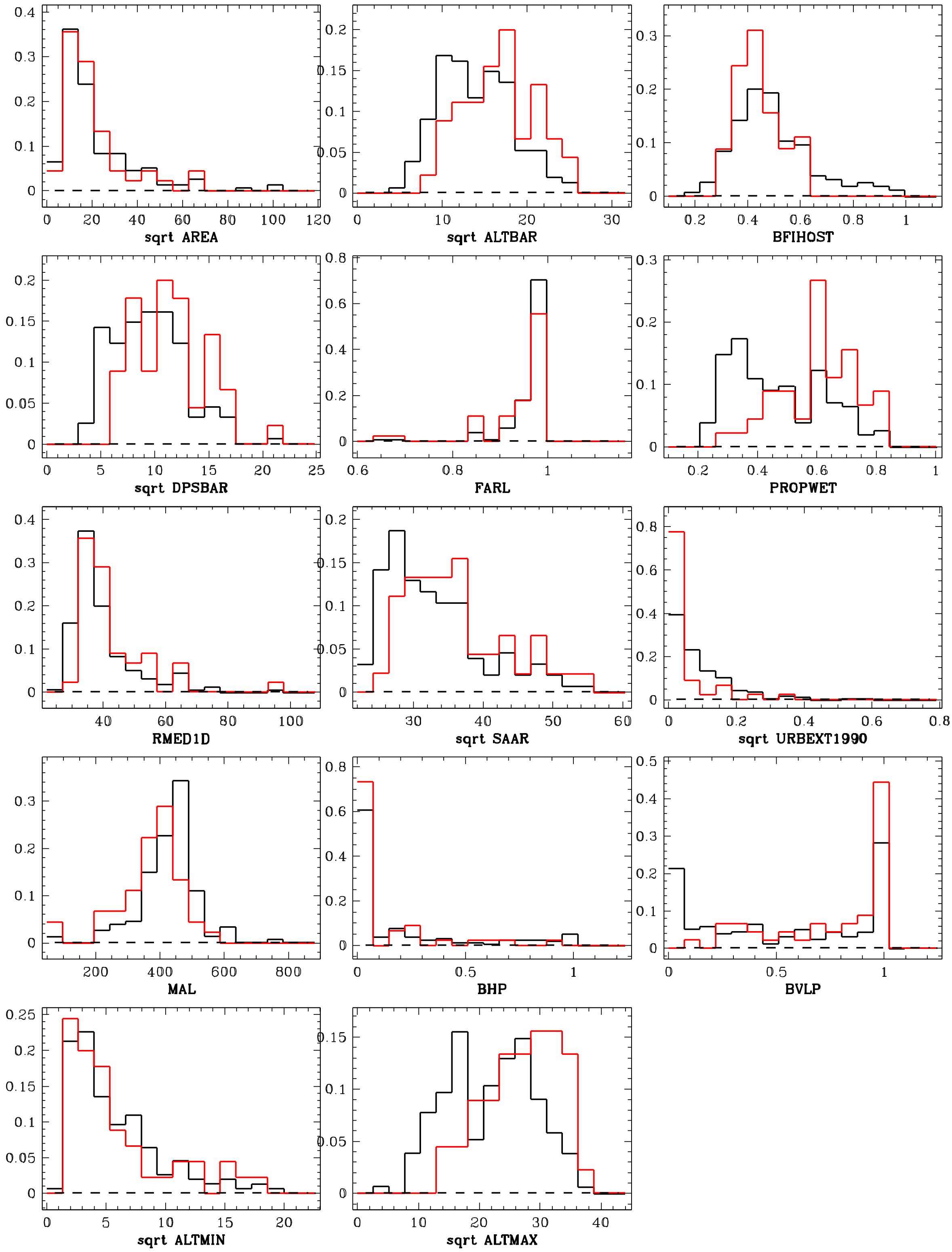

Figure 2.3 Distributions of a number of catchment descriptors, for the set of 45 FD2020 catchments located in Scotland (red) compared to the total of 154 FD2020 catchments (in England, Wales and Scotland; black). For explanations of catchment descriptors see Table 2.4 and Table 2.5. Some catchment descriptor values have been transformed (square-rooted) before plotting – indicated by 'sqrt' before the descriptor name in the x-axis label.

2.4 Tree development

The decision tree methodology used in FD2020 was applied to the 57 catchments listed in Table 2.1 and Table 2.2. The method takes the observed response types of the set of modelled catchments (Table 2.3) along with descriptors for those catchments (Table 2.4, Table 2.5 and Table 2.6), and aims to develop trees which will predict the response types as correctly as possible from the descriptors.

Initial runs to develop decision trees included just the first five UK Hydrometric Register descriptors (Table 2.4) and the first 17 FEH descriptors (Table 2.5). Subsequent runs included the additional Hydrometric Register descriptors (Table 2.4), the FEH Floodplain descriptors (Table 2.5) and the seasonal rainfall descriptors (Table 2.6).

Following FD2020/FD2648, three factors were noted as requiring particular attention with regard to application to Scottish catchments:

- Merging of some response types at higher return periods (Table 1.2);
- Characterisation of the Damped-Extreme response type;
- The threshold values in decision trees for a combination of high standard average annual rainfall (SAAR) and a large percentage of high permeability bedrock (BHP).

The above three factors were considered in combination with the following points when analysing the results from the calculated trees.

- A comparatively small sample size for the range and combination of catchment properties over Scotland.
- Not all of the response types differentiated in FD2020 occur in Scotland (and extension to Northern England) i.e. no catchments with Sensitive or Enhanced-High types.
- There may be several underlying causes resulting in designation of the same response type.
- There is only one catchment with Bedrock High Permeability (BHP)>73.5% (the threshold value used in FD2020).
- The impact of snowmelt on the runoff regime, and floods, is much greater in Scotland than when considering Britain as a whole.
- The tree methodology will not split sets of less than five; therefore not all response types at each return period can be differentiated, even if there is a good discriminator, without manual input. (e.g. Enhanced-Medium at all return periods; Table 2.3).

Results, without any merging or reclassification, showed:

- Tree performance improves when seasonal rainfall fractions for daily rainfall above 20mm are included.
- Reasonable performance for the 2- and 10-year return periods but less good for the 20- and 50-year return periods.
- Apart from the 20-year return period, all trees use Mean Annual Loss (MAL).

The structure of the trees and the descriptors used for the 20- and 50-year return periods indicated particular paths for which it might be appropriate to merge the response types. Therefore, before considering fully the effect of the factors described above, the option to merge or reclassify some of the response types was investigated. The catchments with a Damped-Extreme response type were also investigated to determine whether this response type should be retained as a separate type.

2.5 Reclassification of some catchments

The merging of response types used in FD2020, at 10-, 20- and 50-year return periods, is shown in Table 1.2. All catchments with a Damped response type (apart from Damped-Extreme) were merged to Damped-Low at the 10-year return period and Neutral at the 20- and 50-year return periods. This merging was undertaken partly to allow for the effect of the seasonality of events in the baseline combined with the fixed month of maximum precipitation change (January) used in the FD2020 sensitivity framework (Table 1.1 and Prudhomme and Reynard 2009).

The majority of the FD2020 catchments with a Damped response type at higher return periods are located in Scotland. Consideration must be given to whether it is appropriate that there is no Damped response type at the 20- and 50-year return period for Scottish catchments, if types are merged as in FD2020. A Damped response type at higher return periods may be caused by the delaying impact of snowmelt, as well as the main flood events in the baseline not occurring during the winter. With the latter situation a decision is required as to whether this is likely to be by chance or because flood-producing rainfall mainly occurring in seasons other than winter is a feature of the local climate. For the first case, where the Damped response could have occurred by chance, it was decided to reclassify those catchments (see Section 2.5.2). For the second case, where the Damped response is likely to be a real feature of the local climate, the classification was retained. It is important to be aware that a Damped response type does not mean there is no increase in flood peaks for a particular return period, but that the increase is less than might be expected given the increase in winter precipitation.

2.5.1 Consideration of Damped-Extreme catchments

The three Damped-Extreme catchments of FD2020 could not be characterised via the decision trees when considered alongside the full range of response types in England, Wales and Scotland (Prudhomme *et al.* 2009b). However, given that all three of these catchments are located in Scotland, it was decided that an investigation of the validity of their extremely damped response to changed rainfall and temperature inputs was appropriate.

Response patterns for the eight different temperature scenarios, with and without snowmelt modelling, for the three Damped-Extreme catchments (07002, 08004 and 12007) showed that 12007 was different to the other two catchments. Catchment 12007 has different response patterns according to whether or not snowmelt is modelled, and under different temperature scenarios, whereas the response patterns of 07002 and 08004 are always Damped-Extreme. The difference between 12007 and the other two catchments is partly due to altitude and partly due to seasonality of rainfall (see Table 2.7). Catchment 12007 has the highest mean altitude of all 57 modelled catchments, and runoff from the whole catchment is affected by accumulation of snow during the winter. Although the maximum altitude of 08004 is similar to 12007, the lower mean and minimum altitude mean that the impact of snowmelt, particularly across the whole catchment, is less. While for 07002 the low minimum altitude means that snowmelt is not a dominating factor on the seasonal flow regime.

As well as the impact of snowmelt, the seasonal rainfall descriptors show a difference between 12007 and the other two catchments, with higher values for the proportion of summer extreme rainfall (sumR) and for the ratio between the proportions of autumn and winter extreme rainfall (autR/winR) (see Table 2.7). The higher incidence of extreme rainfall during the summer and autumn, compared with the winter, for catchments 07002 and 08004 leads to their Damped-Extreme response pattern.

Table 2.7 Altitude and seasonal rainfall descriptors for the three Damped-Extreme catchments.

Catchment Number	ALTMIN (m)	ALTBAR (m)	ALTMAX (m)	sumR	autR	winR	autR/winR
07002	10	442	935	0.325	0.348	0.203	1.71
08004	150	525	1303	0.287	0.361	0.209	1.72
12007	218	682	1309	0.213	0.370	0.303	1.22

Given the different causes behind the Damped-Extreme pattern for the three catchments, and that catchment 12007 has a variable response pattern depending on the temperature change, it was decided to reclassify 12007 to Damped-High at all four return periods. The Damped-Extreme response type was retained for 07002 and 08004, and these were included in the development of the decision trees. For catchment 08004 the seasonality of the rainfall provides a stronger signal on impacts of a changing climate than that from snowmelt. The impact of snow on flood frequency is discussed further in Section 3.1.3.

2.5.2 Consideration of other Damped catchments

As noted above, the structure of the initial trees, and the descriptors used for the 20- and 50-year return periods, provided an initial indication of particular paths for which it might be appropriate to reclassify the response types of some catchments, in this case Damped-Low, associated with particular catchment descriptors, to Neutral. Consideration of the catchments affected showed that all of these had an autumn/winter rainfall ratio (for daily rainfall ≥ 20 mm) of less than 1.32. Looking at the overall distribution of this descriptor for all 57 catchments showed a bi-modal distribution with the trough between the peaks with a ratio of 1.3 to 1.4. The shape of the distribution may be indicative of non-random differences in the seasonal pattern of intense rainfall. An autumn/winter rainfall ratio of 1.35 was therefore used as the criterion for reclassifying the response types, and catchments with a ratio less than 1.35 were reassigned as in Table 2.8 (except those showing a variable response pattern with temperature scenario; see Section 2.8). The objective of reassignment is to avoid underestimating the change in flood frequency due to what may be the chance seasonal occurrence of events in the baseline.

Table 2.8 Reassignment of response types (where autR/winR<1.35) for higher return periods.

Return period	Original response type	New response type	No. of catchments
10-year	Damped High	Damped Low	8
20- and 50-year	Damped High	Neutral	6
20- and 50-year	Damped Low	Neutral	10

2.6 Final decision trees for Scotland

Following the reclassification of some of the catchments with Damped response types, the decision tree methodology was re-run. This gave improved performance, with very similar tree structure, at the 20- and 50-year return periods. Some manual adjustment was made to the trees for all return periods:

- To enable characterisation of response types represented by only a few catchments (e.g. Damped-Extreme);
- To use the same tree structure for the 20- and 50-year return periods;
- To use descriptors and threshold values likely to provide meaningful characterisation for a catchment across all four return periods and for the larger sample of NRFA catchments.

The selected descriptors used for the four return periods are listed in Table 2.9 with details of the decision trees in Figure 2.4 to Figure 2.6. All the selected descriptors apart from one (ALTMIN), relate to aspects of rainfall, catchment wetness and the water balance. Due to the small number of catchments with Enhanced response types (Table 2.3), which may have different causative factors, it was considered inadvisable to provide separate paths for these types. For all return periods these are generally defined by the same descriptors as the Mixed response type, and therefore have an estimated response type of Mixed. A path to Damped-Extreme is given in the decision tree for each return period.

Table 2.9 Catchment descriptors used in each decision tree.

Catchment descriptor	Source	Return period		
		2-year	10-year	20- and 50-year
PROPWET	FEH/Hydrometric Register	✓	✓	✓
RMED1D	FEH			✓
SAAR	FEH		✓	
MAL	Hydrometric Register	✓	✓	✓
ALTMIN	Hydrometric Register	✓		
sumR	Rainfall data	✓	✓	✓
autR	Rainfall data		✓	
winR	Rainfall data	✓	✓	✓
autR/winR	Rainfall data	✓	✓	✓

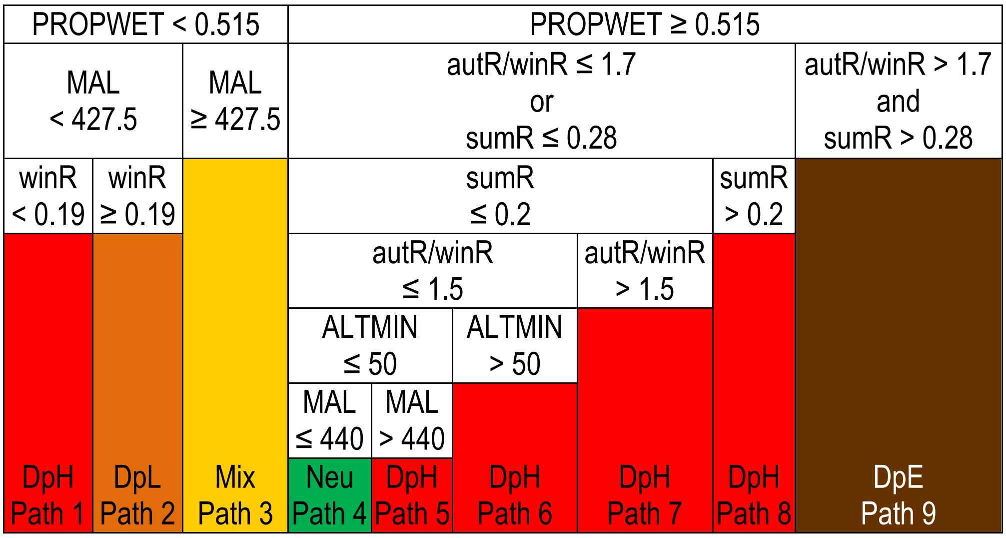

Figure 2.4 Decision tree for the 2-year return period (see Table 2.4, Table 2.5 and Table 2.6 for definitions of the descriptors).

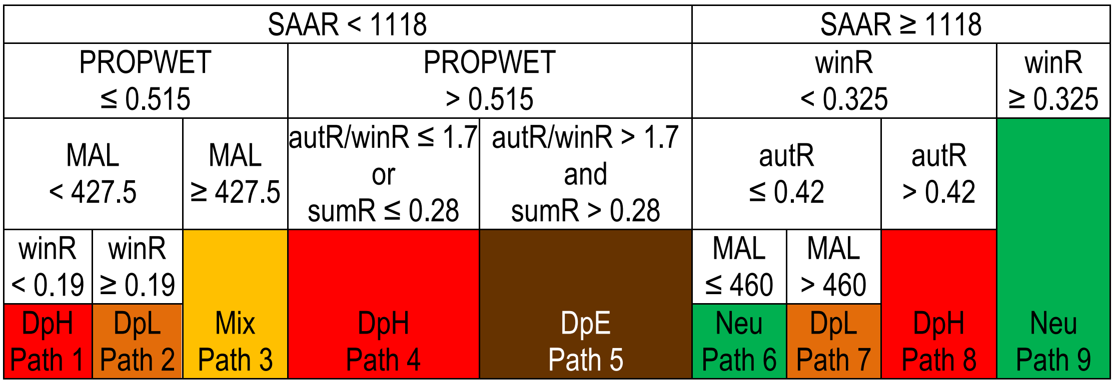

Figure 2.5 Decision tree for the 10-year return period.

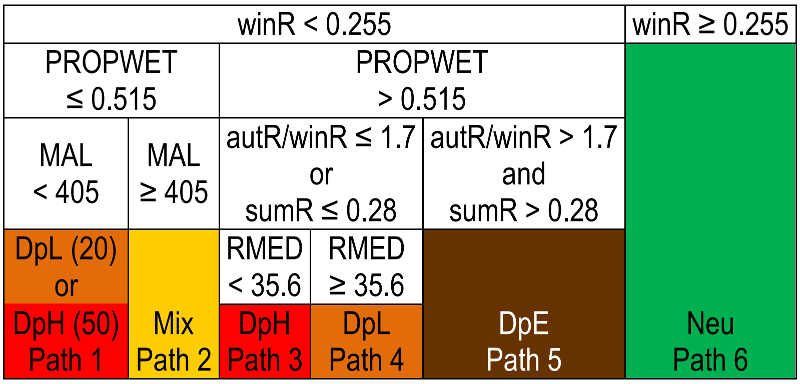

Figure 2.6 Decision tree for the 20- and 50-year return periods. Note the differing response type for path 1 for the two return periods; Damped-Low for the 20-year return period and Damped-High for the 50-year return period.

The decision trees show:

- At the 2-year return period most paths lead to a Damped-High response type (to be expected as flood events of 2-year frequency can occur at any time of year, have many different causes, and are therefore unlikely to increase as much as the maximum increase in precipitation);
- Paths to the Neutral response type are always on the right-hand side of the first split (wetter catchments);
- Paths to the Mixed response type are always on the left-hand side of the first split (drier catchments);
- At the 20- and 50-year return period there is only one path on the right-hand side of the first split (Neutral).

The catchment descriptor used most prominently in the decision trees is PROPWET, the proportion of the time that catchment soils are wet (defined as a soil moisture deficit less than 6mm). Dry soils are likely to inhibit flood formation, while saturated soil conditions precede, and contribute to, many large flood events (Marsh & Hannaford, 2008). Therefore a flood event is more likely to be generated in a catchment with a high value of PROPWET, for the same input of rainfall, than one with a lower value. The first descriptor for the three decision trees reflects a shift in emphasis according to flood severity; from importance of catchment wetness (PROPWET) for generation of comparatively common flood events (2-year return period), through overall availability of rainfall (SAAR) for medium frequency floods (10-year return period), to likelihood of intense rainfall occurring in the winter (winR) for more extreme floods (20- and 50-year return period).

The path to the Mixed response type (including Enhanced) shows catchments with this type are drier (PROPWET<0.515, SAAR<1118mm) but with high MAL (MAL>427.5mm at the 2- and 10-year return periods; MAL>405mm at the 20- and 50-year return periods). This combination of properties, with a balance between input of rainfall and output through losses which is easily changed from a net loss to a net surplus (or vice versa), is what contributes to the increased chance of the percentage change in flood peak being greater than that of the change in rainfall.

There are two other main differences between the set of descriptors used in the trees for FD2020 and those developed for Scotland (apart from the use of PROPWET). One is the absence of properties describing catchment permeability. This predominantly reflects the differing underlying geology between England and Scotland (Figure 2.3); further implications for catchments with permeable bedrock are discussed in Section 3.1.3. The second is the use of the seasonal rainfall descriptors (for daily rainfall above 20mm), which are used in all of the trees for Scotland but were not tried in FD2020. Maps of these descriptors show that the spatial variability has a coherent pattern across Britain, and is not randomly distributed.

The trees given in Figure 2.4, Figure 2.5 and Figure 2.6 are those following minor adjustment made after testing them with all NRFA catchments (see Section 3.1.1). The adjustment to the tree for the 20- and 50-year return periods has meant that the response type for Path 1 is different at the two return periods.

The paths in each decision tree are associated with a probability of a catchment, with the set of descriptors given for the path, having the response type defined for that path. These probabilities are determined from the performance of the decision trees with the 57 modelled catchments and are given for the four return periods in Table 2.10 to Table 2.13. Most paths are not associated with a probability of one as catchments with other response types are also defined by the path descriptors. However, most paths define a response type with a probability greater than 0.5; exceptions are path 3 at the 2-year return period (Mixed; Table 2.10) and path 1 at the 20-year return period (Damped-Low; Table 2.12).

Table 2.10 Probability of each response type for each path of the decision tree for the 2-year return period, with the best-estimate of the response type of each path (highest probability) and its associated confidence level (H – High, M – Medium, L – Low). Note the three equal probabilities (Mix, EnL, EnM) for path number 3; Mix has been chosen to represent the best-estimate for this path.

Path #	Flood response type of path	Confidene level	Probability of flood response type DpE	DpH	DpL	Neu	Mix	EnL	EnM	Size of leaf (number of elements from sample)
1	DpH	L	0	**0.67**	0	0	0	0.33	0	3
2	DpL	H	0	0.14	**0.86**	0	0	0	0	7
3	Mix	L	0	0	0	0	**0.33**	**0.33**	**0.33**	6
4	Neu	H	0	0.17	0	**0.83**	0	0	0	6
5	DpH	H	0	**0.67**	0.17	0.17	0	0	0	6
6	DpH	H	0	**0.71**	0	0.29	0	0	0	7
7	DpH	M	0	**1**	0	0	0	0	0	2
8	DpH	H	0	**0.89**	0.06	0.06	0	0	0	18
9	DpE	M	**1**	0	0	0	0	0	0	2
Original category size			2	31	8	9	2	3	2	57

Table 2.11 As Table 2.10 but for the 10-year return period.

Path #	Flood response type of path	Confidene level	Probability of flood response type DpE	DpH	DpL	Neu	Mix	EnL	EnM	Size of leaf (number of elements from sample)
1	DpH	L	0	**0.67**	0.33	0	0	0	0	3
2	DpL	H	0	0.14	**0.71**	0.14	0	0	0	7
3	Mix	M	0	0	0	0	**0.67**	0	0.33	6
4	DpH	H	0	**1**	0	0	0	0	0	7
5	DpE	M	**1**	0	0	0	0	0	0	2
6	Neu	H	0	0.13	0.13	**0.73**	0	0	0	15
7	DpL	H	0	0	**0.8**	0.2	0	0	0	5
8	DpH	M	0	**1**	0	0	0	0	0	2
9	Neu	H	0	0	0.1	**0.9**	0	0	0	10
Original category size			2	14	13	22	4	0	2	57

Table 2.12 As Table 2.10 but for the 20-year return period. Note the three equal probabilities (DpH, DpL and Mix) for Path number 1; DpL has been chosen to represent the best-estimate for this path.

Path #	Flood response type of path	Confidene level	Probability of flood response type							Size of leaf (number of elements from sample)
			DpE	DpH	DpL	Neu	Mix	EnL	EnM	
1	DpL	L	0	**0.33**	**0.33**	0	**0.33**	0	0	6
2	Mix	H	0	0.11	0	0	**0.67**	0	0.22	9
3	DpH	H	0	**1**	0	0	0	0	0	5
4	DpL	H	0	0	**1**	0	0	0	0	4
5	DpE	M	**1**	0	0	0	0	0	0	2
6	Neu	H	0	0.1	0.03	**0.87**	0	0	0	31
Original category size			2	11	7	27	8	0	2	57

Table 2.13 As Table 2.10 but for the 50-year return period.

Path #	Flood response type of path	Confidene level	Probability of flood response type							Size of leaf (number of elements from sample)
			DpE	DpH	DpL	Neu	Mix	EnL	EnM	
1	DpH	L	0	**0.5**	0.33	0.17	0	0	0	6
2	Mix	H	0	0.11	0.11	0	**0.56**	0	0.22	9
3	DpH	H	0	**0.8**	0.2	0	0	0	0	5
4	DpL	H	0	0	**1**	0	0	0	0	4
5	DpE	M	**1**	0	0	0	0	0	0	2
6	Neu	H	0	0.1	0.03	**0.84**	0	0.03	0	31
Original category size			2	11	9	27	5	1	2	57

In addition to the probability of each response type associated with each path, a measure of confidence has been evaluated, which is also given in Table 2.10 to Table 2.13. The confidence level — High (H), Medium (M) or Low (L) — is determined as a product of certainty and robustness, where certainty is measured by the difference between the top two probabilities for each path and robustness by the proportion of the sample catchments following that path (see Section 4.1 of Prudhomme *et al.* 2009b). High confidence is given where a path has high certainty and high robustness (e.g. path 2 at the 2-year return period). Low confidence is given where a path has low certainty or medium certainty and low robustness (e.g. path 1 at the 20-year return period). A path with high certainty but low robustness has medium confidence (e.g. path 5 at the 50-year return period).

2.7 Performance of the decision trees for Scotland

The performance of the decision trees for the 57 catchments is presented in contingency tables which compare the observed response type with the response type with the highest probability following the paths in the decision trees. A description of contingency tables and their use can be found in Jolliffe and

Stephenson (2003). The contingency tables for the four return periods are given in Table 2.14 to Table 2.17. Each table has three parts:

- The cells on the diagonal of the table (shaded in green) show the number of catchments correctly classified;
- The cells below and left of the diagonal (shaded in blue) show the number of catchments with an estimated response type with a higher sensitivity than the observed response type (i.e. a response type further to the right in Figure 1.2 and likely to over-estimate changes to floods);
- The cells above and right of the diagonal (shaded in red) show the number of catchments with an estimated response type with a lower sensitivity than the observed response type (i.e. a response type further to the left in Figure 1.2 and likely to under-estimate changes to floods).

The overall numbers in each part of the table are given at the bottom right in each case. The aim during development of the trees is to maximise the number of catchments within the diagonal (green). With misclassification, preference may be given to over-estimating rather than under-estimating the response type (i.e. it may be preferable to have more catchments in the blue shaded part of the table than the red).

Table 2.14 Contingency table summarising the performance of the decision tree for the 2-year return period. Cells shaded in green show the number of catchments correctly classified, for each response type and overall (the green cell to the bottom right); those in blue highlight ‘over-estimation’ of the response type (with the overall number in the blue cell to the bottom-right); those in red highlight ‘under-estimation’ of the response type (with the overall number in the red cell to the bottom-right).

		Observed response type							
		DpE	DpH	DpL	Neu	Mix	EnL	EnM	
Estimated response type	DpE	2	0	0	0	0	0	0	
	DpH	0	29	2	4	0	1	0	
	DpL	0	1	6	0	0	0	0	
	Neu	0	1	0	5	0	0	0	
	Mix	0	0	0	0	2	2	2	
	EnL	0	0	0	0	0	0	0	
	EnM	0	0	0	0	0	0	0	11
								2	44

Table 2.15 As Table 2.14 but for the 10-year return period.

		Observed response type							
		DpE	DpH	DpL	Neu	Mix	EnL	EnM	
Estimated response type	DpE	2	0	0	0	0	0	0	
	DpH	0	11	1	0	0	0	0	
	DpL	0	1	9	2	0	0	0	
	Neu	0	2	3	20	0	0	0	
	Mix	0	0	0	0	4	0	2	
	EnL	0	0	0	0	0	0	0	
	EnM	0	0	0	0	0	0	0	5
								6	46

Table 2.16 As Table 2.14 but for the 20-year return period.

Estimated response type	Observed response type: DpE	DpH	DpL	Neu	Mix	EnL	EnM	
DpE	2	0	0	0	0	0	0	
DpH	0	5	0	0	0	0	0	
DpL	0	2	6	0	2	0	0	
Neu	0	3	1	27	0	0	0	
Mix	0	1	0	0	6	0	2	
EnL	0	0	0	0	0	0	0	
EnM	0	0	0	0	0	0	0	4
							7	46

Table 2.17 As Table 2.14 but for the 50-year return period.

Estimated response type	Observed response type: DpE	DpH	DpL	Neu	Mix	EnL	EnM	
DpE	2	0	0	0	0	0	0	
DpH	0	7	3	1	0	0	0	
DpL	0	0	4	0	0	0	0	
Neu	0	3	1	26	0	1	0	
Mix	0	1	1	0	5	0	2	
EnL	0	0	0	0	0	0	0	
EnM	0	0	0	0	0	0	0	7
							6	44

A summary of the overall classification of the performance trees is given in Table 2.18, where the number correctly classified is greater than 75% for all return periods. A total of 13 catchments are misclassified at the 2- and 50-year return periods, with 11 catchments misclassified for the 10- and 20-year return periods. The 10- and 20-year return periods also have more catchments with over-estimated response types than under-estimated, while the opposite is found for the 2- and 50-year return periods. For the 2-year return period it is perhaps not surprising that most misclassified catchments are under-estimated, as five paths of the decision tree lead to Damped-High, with only one path to each of the other response types.

Table 2.18 Summary of performance.

Return period	Number (percentage) correct (green)	Number of over-estimates (blue)				Number of under-estimates (red)			
		Total	1	2	>2	Total	1	2	>2
2-year	44 (77%)	2	1	1	0	11	4	6	1
10-year	46 (81%)	6	4	2	0	5	3	2	0
20-year	46 (81%)	7	3	3	1	4	0	4	0
50-year	44 (77%)	6	1	4	1	7	3	4	0

The number of over- and under-estimates shown in Table 2.18 is also divided into the numbers with estimated response types which are 1, 2 or >2 types different from the observed type. One type different means response types are adjacent in

Figure 1.2, while 2 and >2 means types are separated by one, or more, response types in Figure 1.2. This shows how few catchments have a greatly over- or under-estimated response type. As it has not been advisable to determine separate paths for catchments with Enhanced-Low and Enhanced-Medium response types, these are generally estimated as Mixed and thus contribute to the number of under-estimates. A discussion on Enhanced response types and catchment descriptors is included in Section 3.1.3.

Performance of the decision trees for Scotland, compared with that in FD2020 for 152 catchments, shows a higher correct classification for the 2- and 10-year return periods and slightly lower at the 20- and 50-year return periods. Thus the performance for Scotland seems very reasonable given that the number of catchments available for deriving the trees for Scotland is quite small relative to the range of causes of floods and combinations of catchment descriptors and climatological factors. However, the small sample size does result in some uncertainty in designation of response type when there are equal numbers of catchments with two or more different observed response types for a particular path (e.g. Path 3 at the 2-year return period and Path 1 at 20-year return period). Also, with a small sample, changing a threshold value in a way which causes one catchment to follow a different path is more likely to change the response type of either the original path, the new path or both and make large differences to the associated probabilities. These factors result in an allocated confidence level of Low (L) for some paths of the decision trees (see Table 2.10-Table 2.13). It is recommended that this confidence level is taken into account when estimating the sensitivity and risk for individual catchments, by considering the results for the other possible response types.

2.8 Performance for snow-affected catchments

A major difference between the impacts of climate change on floods between Scotland and England is the contribution from snowmelt. Most catchments in Britain include in the baseline period (1961-2001) at least one flood peak which has been altered, either increased or diminished, by precipitation falling as snow rather than rain. In many cases the peak is diminished, as the snow melts gradually, but where a rapid thaw is combined with substantial rainfall then the peak is increased. Scotland, due to its higher latitude and higher altitudes, is more likely to see an impact of temperature on changes in floods. In FD2020 all catchments were modelled with eight different temperature scenarios for each of the 525 precipitation scenarios (Table 1.1) and for the majority of catchments the response patterns are much more determined by the changes in overall precipitation and evaporation than by changes in temperature on snowmelt (i.e. there are not enough snowmelt influenced flood events in the flood history of most catchments for them to affect the shape of the flood frequency curve). Hence, the FD2020 key response patterns were determined by combining all eight temperature scenarios. However, for some Scottish catchments the modelled catchment response patterns show a difference in type depending on the temperature scenario, and also a difference depending on whether the catchment is modelled with or without the snowmelt module. These differences are illustrated in Figure 2.7 for catchments 12007 and 08004.

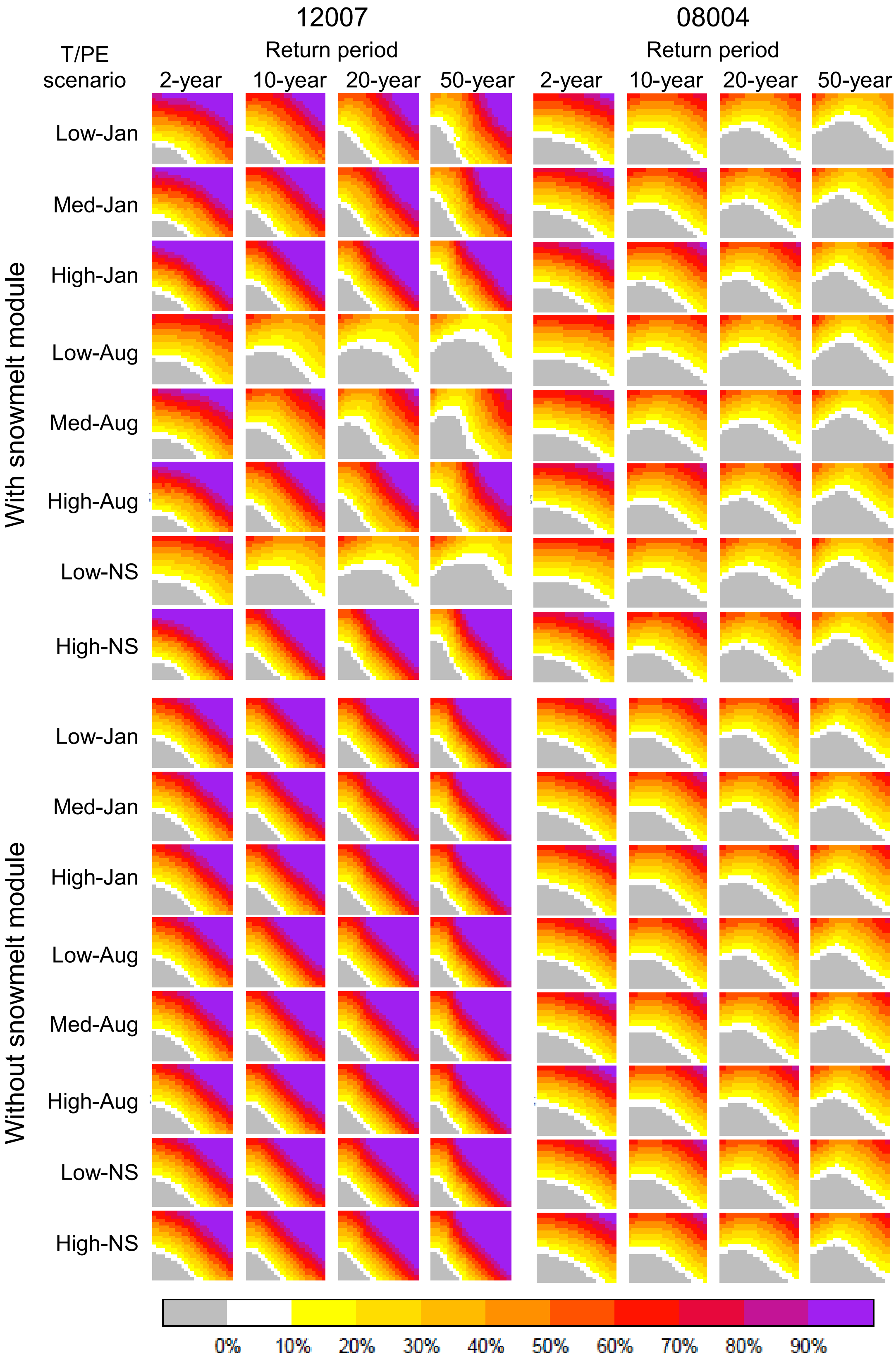

Figure 2.7 Response patterns of catchments 12007 (left) and 08004 (right), for each T/PE scenario (Table 1.1) and each return period, modelled with (top) and without (bottom) the snowmelt module.

Inspection of modelled response patterns for higher altitude catchments shows that the higher the mean altitude (ALTBAR) and minimum altitude (ALTMIN) of a catchment, the more likely that a difference in response patterns with temperature scenario is evident. However, as with catchment 08004, other factors, such as seasonality of intense rainfall, may mask changes due to snow/rain occurrence. The range in altitude is also likely to affect the synchronicity of melting snow across a catchment, so that those with high mean and high minimum altitude see the most affect on the response patterns by temperature scenario (e.g. 12007: maximum altitude 1309m, mean altitude 682m, minimum altitude 332m). This contrasts with catchments such as 90003 (maximum altitude 1341m, mean altitude 511m, minimum altitude 4m) where, although the upper parts of the catchment have significant snowfall, the low altitude of the catchment outlet results in a more limited contribution of snowmelt to the flood regime with only a very small effect of temperature on the response pattern. A further contributory factor in the role of snowmelt in floods is likely to be the difference in climatology between catchments draining westerly (e.g. 90003) and easterly (e.g. 12007) areas, with the former under the influence of a warmer, wetter climate in which the more extreme floods are caused by sustained rainfall events not associated with snow.

Neither the decision trees nor the FD2020 key response patterns specifically allow for differences in response type with temperature scenario. For catchment 12007 (Figure 2.7), the overall modelled response type is Damped-Extreme, but for ‘High’ temperature scenarios (Table 1.1) the modelled response type is nearer to Neutral or Mixed. The modelled response type was reclassified as Damped-High in the development of the decision trees (see Section 2.5.1). Using the final decision trees the estimated response type is Damped-High at the 2-year return period but Neutral for higher return periods. Thus the estimated response type is precautionary and allows for a medium to high temperature change.

The three modelled catchments with an observed response type of Damped-High and estimated response type of Neutral are all high altitude catchments. These catchments (12002, 12003 and 12007) could have been reassigned to Damped-Low at the 10-year return period and Neutral at 20 and 50-year return periods as their autR/winR ratio is less than 1.35 (see Section 2.5.2 and Table 2.8). However, because their response pattern varies with temperature scenario it was decided to develop the trees using their modelled response types in case their combination of descriptors was relevant in the trees. These catchments thus contribute to the number of catchments with apparently over-estimated response types (Neutral rather than Damped-High), but use of this ‘precautionary’ response type might in fact be advisable due to the critical dependence on the temperature scenario for these catchments.

2.9 Uncertainty allowances for Scotland

An uncertainty analysis undertaken as part of FD2020 (Kay *et al.* 2009a) suggested extra uncertainty allowances for use alongside the response patterns, which varied according to response type and return period (Table 1.3; see Section 7.2 of Reynard *et al.* 2009). The analysis assessed the potential level of uncertainty due to various assumptions and simplifications necessary to develop FD2020's sensitivity framework approach. The main aim of the uncertainty analysis was to assess whether values extracted from the flood response patterns would consistently over- or under-estimate the impact of climate change scenarios. The following factors were addressed:

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 was performed on a small subset of catchments, chosen to be as representative as possible of the nine flood response types found in Great Britain. Nine catchments modelled with the PDM were selected, one for each response type, and four catchments modelled with CLASSIC were selected, representing four of the response types. The PDM catchments were used for the full uncertainty analysis, while the CLASSIC catchments were used for a subset of the analysis.

The results showed that the level of uncertainty from different factors varied significantly between catchments. For some catchments the overall level of uncertainty varied little with return period, whilst for others it increased / decreased with return period. The four CLASSIC catchments showed a similar pattern of uncertainty to that for the corresponding PDM catchments, but each CLASSIC catchment had a higher level of uncertainty than its corresponding PDM catchment. It was considered that this reflected the larger area of the CLASSIC catchments.

Generalising the catchment results to their response types suggested that 'Neutral' catchments have the lowest level of uncertainty and 'Sensitive' catchments have the highest level of uncertainty. The different levels of uncertainty for the different catchments were considered compatible with the underlying climatological and hydrological differences between their flood response types. Despite the small number of catchments investigated, the fact that the results were physically reasonable, and the similarity of the results for comparable PDM and CLASSIC catchments, gave confidence in the extension of the results to response type.

The uncertainty allowances for use with the decision trees for Scotland are essentially the same as those of FD2020, but simpler because there is no merging of response types at higher return periods like there was in FD2020. The uncertainty allowances for use in Scotland are thus given in Table 2.19 (cf. Table 1.3).

Table 2.19 Suggested extra uncertainty allowances, by response type and return period, for use in Scotland (and multiplication factors for larger catchments).

Response type	Return period			
	2-year	10-year	20-year	50-year
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
If Area>2000km^2	x1.0	x1.3	x1.7	x2.1

3. Sensitivity – Hazard – Risk methodology

PREVIOUS FAST TRACK BOX ON PAGE 11

Section 3: Sensitivity – Hazard – Risk methodology

This section describes the application of the Scottish decision trees to estimate the response type of each NRFA catchment in Scotland (sensitivity), along with use of UKCP09 data (hazard), and how these are combined to estimate the impact on flood peaks (risk).

The decision trees, developed on the basis of 57 catchments, were applied to the 349 NRFA catchments in Scotland (including any catchments in Solway and Tweed; see below). This application requires consideration of any differences in catchment descriptor ranges between the two catchment sets. A comparison showed that differences are minimal.

The UKCP09 projections were then obtained for 10 river-basin regions covering Scotland: North Highland, North-East Scotland, Forth, Tay, Tweed, Solway, Clyde, Argyll, West Highland, and Orkney and Shetland. These provide sets of 10,000 (annual, seasonal or monthly) changes in a number of climate variables. The monthly changes in precipitation were used, for five time-horizon and emissions scenario combinations: 2020s, 2050s and 2080s Medium, to illustrate the dependence on time-horizon, and 2080s Low, Medium and High, to illustrate the dependence on emissions. Harmonic functions were fitted to the monthly changes in precipitation from each set of scenarios in each region; the mean and amplitude of the precipitation harmonic functions represent the hazard.

The impact (risk) of each set of UKCP09 projections (hazard) can then be estimated for each response type in each region, by using the mean and amplitude to overlay the projections onto the key response pattern for each response type (sensitivity). This gives estimates of response-type risk in each river-basin region in Scotland. These are then combined with the estimated response types of the NRFA catchments in each region, to estimate regional risk. Uncertainty information is also incorporated.

NEXT FAST TRACK BOX ON PAGE 51

3.1 Sensitivity – NRFA catchments

In order to assess any regional differences in sensitivity, the response type of each of the NRFA catchments in Scotland is estimated from its catchment properties using the decision trees developed in Section 2. The application of the decision trees, developed on the set of 57 FD2020 modelled catchments in Scotland and northern England, first requires consideration of the applicability of those trees to the much larger set of NRFA catchments in Scotland. In particular, consideration of any differences in the ranges of catchment descriptors between the two sets of catchments, and examination of any seemingly unrealistic patterns in estimated response types across the four return periods.

3.1.1 Initial considerations for wider application of the decision trees

The range of values for the 10 catchment descriptors used in the decision trees are given in Table 3.1 (and distributions plotted in Figure 3.1) for the 57 FD2020 modelled catchments (Table 2.1 and Table 2.2) and 349 NRFA catchments in Scotland (see Table 2.4 and Table 2.5 for definitions of the descriptors).

For most descriptors the full set of NRFA catchments is represented well by the sample set; the main exception is MAL (Mean Annual Loss). MAL shows a much wider range in the full set of NRFA catchments than the modelled ones, which is to be expected given that the modelled catchments were predominantly selected, for calibration reasons, to have a reasonably natural flow regime; for these catchments MAL is largely a measure of evaporative losses. The threshold values used in the decision trees are appropriate for natural losses. However, for many catchments MAL is also inclusive of water usage including import/export of water from/to other catchments. Hence MAL for the NRFA catchments (Table 3.1) includes those with both unnaturally high losses (MAL>1000mm) and gains (MAL<0mm). All these catchments have high values of PROPWET and SAAR, and using the appropriate descriptors in the decision trees (Figure 2.4-Figure 2.6) gives an estimated response type of Neutral for all return periods where there are high gains, or Damped-High (2-year return period), Damped-Low (10-year return period) and Neutral (20- and 50-year return period) where there are high losses. These sets of response types seem appropriate for the impact of alteration on the flow. However it is recommended that future work investigates how the range of MAL, in combination with a wide range of the other catchment descriptors used in the trees, affects the hydrological and flood regimes.

Table 3.1 Minimum, mean and maximum values of the catchment descriptors used in the decision trees, for the 57 FD2020 modelled catchments in Scotland and northern England and the 349 NRFA catchments in Scotland (including all in Solway and Tweed).

Catchment descriptor	Minimum		Mean		Maximum	
	57 FD2020	349 NRFA	57 FD2020	349 NRFA	57 FD2020	349 NRFA
ALTBAR (m)	87	32	296	301	682	686
ALTMIN (m)	4	3	56	87	332	434
PROPWET	0.30	0.29	0.60	0.61	0.83	0.85
RMED1D (mm)	31.5	30.2	42.8	42.6	94.1	94.1
SAAR (mm)	671	616	1349	1384	2913	3131
MAL (mm)	82	-4539	376	421	570	2463
sumR	0.095	0.090	0.231	0.218	0.368	0.436
autR	0.301	0.291	0.368	0.374	0.446	0.460
winR	0.090	0.083	0.260	0.269	0.366	0.387
autR/winR	0.982	0.923	1.521	1.525	4.045	4.352

The fact that performance of the decision trees improves when MAL is included, and that it is difficult to develop meaningful trees without it, suggests that MAL plays an important role in how climatic changes impact on flood flows in a catchment. It should be noted that a problem with using the MAL available from the Hydrometric Register is that it is not standardised, but is the average annual value for the period of flow record, which is different for every catchment and varies between over 40 years to less than 10 years. It is, therefore, not generally consistent with SAAR (which is standardised to 1961-1990) and is likely to be non-stationary – trends in water usage are incorporated into MAL.

As the decision trees for the different return periods are developed separately, it is possible that applying the trees to the larger set of catchments can generate some seemingly unrealistic differences in the estimated response types for a catchment across the four return periods. Although many of the modelled catchments do not have the same response type for all four return periods, the response types across the return periods are normally related. For example, Damped at the lower return period and Neutral at higher return periods, or a combination of Mixed and Enhanced. Unusual sets of estimated response types may be indicative of different combinations of catchment descriptors in the full catchment set, compared to the modelled set, resulting in inconsistencies in estimated response types. The inconsistencies are often caused by the order in which the descriptors are applied in the trees, or by the fact that descriptors used implicitly in the original trees need to be made explicit.

As stated at the end of Section 2.6, some minor manual adjustments were made to the decision trees after applying them to the 349 NRFA catchments in Scotland, in order to correct some common inconsistencies. Two small changes were made, one to the tree for the 10-year return period and one to the tree for the 20- and 50-year return period.

3.1.2 Final application of the decision trees

The final decision trees for Scotland, summarised in Section 2.6 (Figure 2.4-Figure 2.6), are thus applied to the NRFA catchment set (349 catchments in Scotland plus Solway and Tweed, for which all required properties are available). For each catchment, at each return period, the decision trees determine the best-estimate of the response type. They also give a confidence level (Low, Medium or High) associated with that best-estimate. The number of catchments of each response type at each return period is summarised in Table 3.2. Maps showing the estimated response type (and its confidence level) for each of the NRFA catchments are given in Section 4 (see for example Figure 4.1 and Figure 4.2). Note that, as recommended in FD2020 (Table 7.2 of Reynard *et al.* 2009), the confidence level for larger catchments (AREA>1000 km^2) has been reduced by one (i.e. High reduced to Medium, or Medium reduced to Low), to reflect the fact that larger catchments are slightly less well represented by whole-catchment descriptors. This affects just 26 of the 349 NRFA catchments.

Table 3.2 Summary of the estimated response types for the NRFA catchments in Scotland (including all of Solway and Tweed). The predominant response type is highlighted in bold at each return period.

	Return period			
	2-year	10-year	20-year	50-year
Damped-Extreme	9	9	9	9
Damped-High	**252**	91	25	51
Damped-Low	22	51	60	34
Neutral	30	**163**	**210**	**210**
Mixed	36	35	45	45
Total	349	349	349	349

The slight inconsistency in the numbers of catchments with Damped-High and Damped-Low response types at the 20-year return period, when compared to the 10- and 50-year return periods, is due to the different classification for path 1 for the decision tree valid at the 20- and 50-year return periods. This path is defined as Damped-Low at the 20-year return but Damped-High at the 50-year return period (Figure 2.6). This differing definition is due to one of the 6 FD2020 catchments that follow this path (catchment 21013) having a Damped-High modelled response type at the 50-year return period, leading to Damped-High being the dominant response type for the path (Table 2.17), but having a Mixed modelled response type at the 20-year return period, leading to equal numbers of Damped-High, Damped-Low and Mixed for the path (Table 2.16). Damped-Low was then chosen to represent the path in the latter case, in order not to under-estimate the response type too much.

3.1.3 Further considerations

The range of values for six descriptors not included in the decision trees but which may be of relevance to the response type are given in Table 3.3 (see Table 2.4 and Table 2.5 for explanations of the descriptors), for the 57 FD2020 modelled catchments in Scotland and northern England (Table 2.1 and Table 2.2) and 349 NRFA catchments in Scotland. The distributions of these descriptors for the two catchment sets are also shown in Figure 3.1. For most descriptors the full set of NRFA catchments is represented well by the sample set.

The difference between the mean AREA for the two sets of catchments indicates that small catchments may be slightly under-represented in the modelled set. However, as it is only for large catchments that any distinction is made on catchment area (see Section 2.9 and Section 3.1.2), this difference is not thought to be important.

Table 3.3 Minimum, mean and maximum values of selected catchment descriptors for the 57 FD2020 modelled catchments in Scotland and northern England and the 349 NRFA catchments in Scotland (including all in Solway and Tweed).

Catchment descriptor	Minimum		Mean		Maximum	
	57 FD2020	349 NRFA	57 FD2020	349 NRFA	57 FD2020	349 NRFA
FARL	0.664	0.614	0.955	0.934	1.000	1.000
$URBEXT_{1990}$	0.000	0.000	0.007	0.009	0.128	0.370
AREA (km^2)	31.8	0.86	622	331	4587	4587
ALTMAX (m)	221	121	765	691	1341	1341
BFI	0.16	0.11	0.42	0.44	0.74	0.99
BFIHOST	0.24	0.20	0.43	0.44	0.62	0.70
BHP (%)	0	0	9	14	91	100

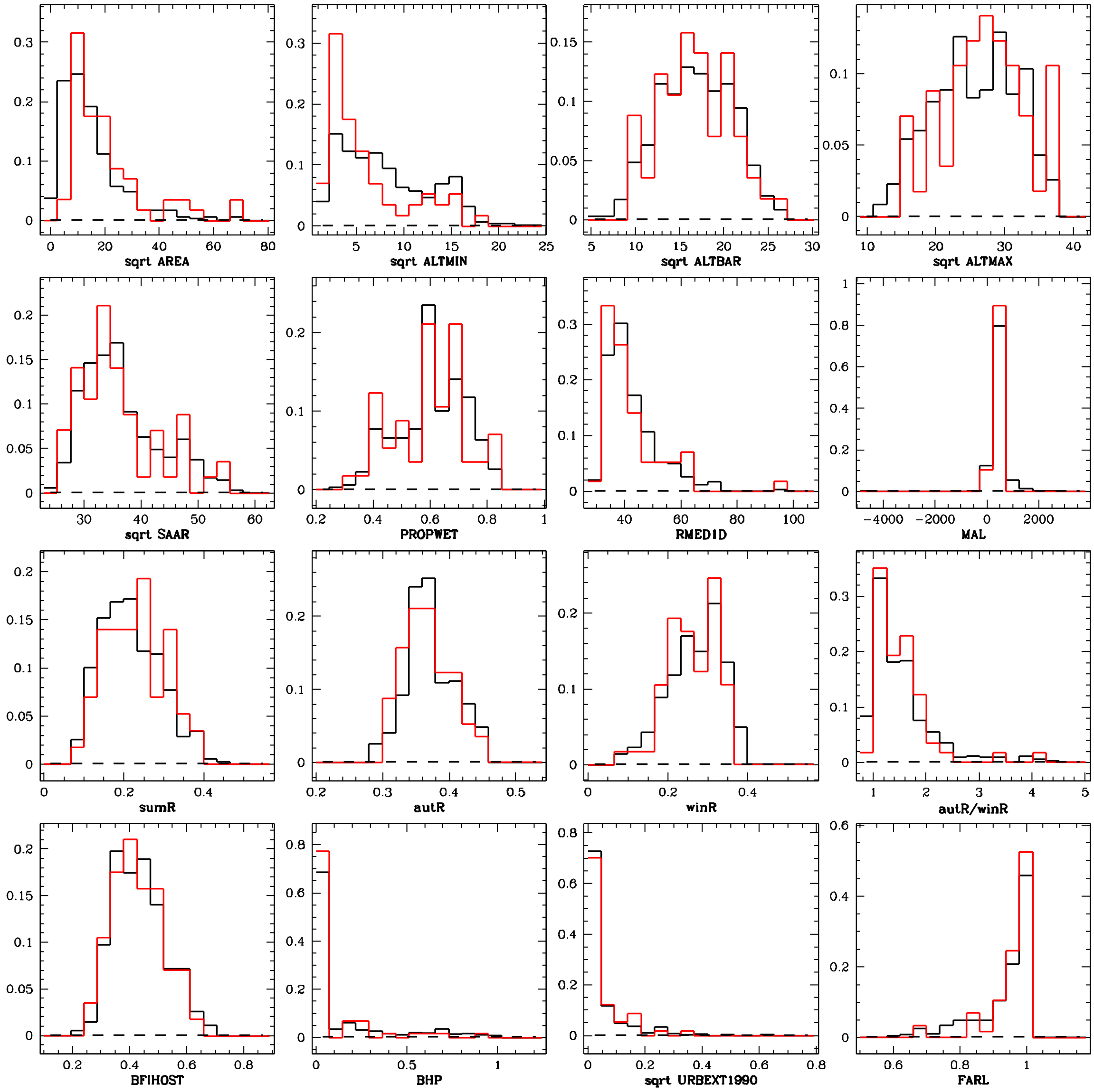

Figure 3.1 Distributions of a number of catchment descriptors, for the set of 57 FD2020 catchments in Scotland and northern England (red) compared to the total of 349 NRFA catchments in Scotland (black). For explanations of catchment descriptors see Table 2.4 and Table 2.5. Some catchment descriptor values have been transformed (square-rooted) before plotting – indicated by 'sqrt' before the descriptor name in the x-axis label.

Despite the general similarity of the descriptor ranges for FARL and URBEXT, the decision trees are not necessarily suitable for catchments with either a low value of FARL (indicating a larger effect of flood attenuation from reservoirs and lakes) or a high value of URBEXT (indicating a larger urban extent). The impact of these properties, particularly URBEXT, on changes in flood frequency may not be appropriate to generalise as they may be non-stationary and depend on the location and specific characteristics of the urban area or water body within the catchment. In addition, for urban catchments, changes in sub-daily rainfall intensity are of prime importance but are not necessarily well-represented by the use of the simple delta change method of downscaling (used to produce the response patterns) as this method applies the same monthly changes to all events in the month. Further modelling focussing on such catchments would enable these factors to be investigated and possible boundary limits for these properties to be determined for use with the decision trees.

Two catchments with comparatively low values of FARL are included in the modelled catchments (94001 and 95001, with FARL values of 0.664 and 0.670 respectively). Both of these catchments include large lochs, but the flow regime in both is predominantly natural. However, many catchments in the NRFA set with similar or lower values of FARL do not have natural flow regimes and the flow at the gauging stations may be heavily regulated by upstream dams. Impacts of climate change on floods below impounding structures are unlikely to be represented by the modelled catchments. All NRFA catchments have been included in the regional analysis but the response type for such a catchment will be that for a natural catchment.

A catchment descriptor absent from the Scottish decision trees, and therefore different from the trees in FD2020, is any representation of catchment permeability. The range of descriptor values for BFI (baseflow index), BFIHOST (baseflow index derived from soil data) and BHP (percentage of high permeability bedrock) for the modelled and NRFA catchments are given in Table 3.3. The absence of any of these descriptors is probably because there is only one modelled catchment in Scotland (21023) with a BHP exceeding the threshold value of 73.5% used in the FD2020 decision trees. This catchment has a response type of Enhanced-Medium at all four return periods, but its baseflow indices (BFI=0.33 and BFIHOST=0.39) are not consistent with significant contribution of groundwater to the runoff regime (one of the factors associated with an Enhanced response type). One reason for the disparity between bedrock permeability and BFI is the presence of an almost complete cover of drift deposits with low permeability (97% Superficial Generally Low Permeability; Marsh and Hannaford 2008).

The other modelled catchment in Scotland with an Enhanced response type at all four return periods is 07004, but in this case the Enhanced type is not related to bedrock permeability (BHP=0%) but to MAL (463mm) and impacts of change on the seasonal water balance. It is possible that it is this combination of factors which is also dominant in catchment 21023 (MAL=436mm), and that the presence of the high permeability bedrock does not in fact impact on the runoff regime. For these reasons, it was considered unwise to define a path to an Enhanced response type, using Bedrock High Permeability, based on only one catchment. There are a number of NRFA catchments in Scotland with a high value of Bedrock High Permeability, combined with a variable amount of drift cover and range of BFI. Some catchments have quite a large difference between BFI and BFIHOST (e.g. 17017: BFI=0.25, BFIHOST=0.66, BHP=82%; 84013: BFI=0.50, BFIHOST=0.31, BHP=81%) which can be indicative of impacts of drift deposits on the flow regime. Further hydrological modelling is therefore advisable, for appropriate catchments, to clarify the relationships between response types and catchment descriptors such as bedrock permeability, BFIHOST, SAAR, PROPWET and MAL in Scotland.

Looking at the NRFA catchments which may be more affected by snowmelt (see discussion in Section 2.8), all except two of the 10 catchments with ALTBAR>575m also have winR>0.255, so have an estimated response type of Neutral at the 20- and 50-year return periods (Figure 2.6); the estimated response type for the other two catchments is Damped-Low. Therefore the decision trees provide an estimated response type for high altitude catchments that is generally precautionary, so are considered to be appropriate for general use. However, it is recommended that catchment altitude be borne in mind if applying the decision trees to any further catchments, and that response types may differ with temperature for catchments with a high mean and high minimum altitude.

The decision trees developed for Scotland, unlike those developed in FD2020, allow the identification of Damped-Extreme catchments (see Sections 2.5 and 2.6). The key response pattern for the Damped-Extreme response type has a much lower impact of change than even that for Damped-High, particularly at the 20- and 50-year return periods, which can be seen by comparing the top two rows of Figure 1.3. This difference is characterised predominantly by the lack of extreme rainfall events in the baseline in winter, and the occurrence of such events in both summer and autumn, in catchments with a Damped-Extreme response type (Section 2.5.1). However, the response patterns are based on the use of the simple delta change method of downscaling, and a premise of this method is that seasonal extremes change in a similar way to seasonal means. The extent to which this premise may or may not be appropriate for Damped-Extreme catchments is not known (and the reliability of changes in extremes projected by climate models is much lower than that for changes in means). Therefore, it may be advisable to consider a more precautionary response type (e.g. Damped-High) for catchments where the best-estimate of the response type is Damped-Extreme; there are only 9 such catchments out of the 349 NRFA catchments in Scotland (Table 3.2).

3.2 Hazard – UKCP09 projections

UKCP09 provides probabilistic climate projections (Murphy *et al.* 2009; ukclimateprojections.defra.gov.uk), consisting of 10,000 sets of monthly, seasonal or annual changes in a number of climate variables (termed Sampled Data). These are available as changes from the baseline time-slice (1961-1990) to a number of future 30-year time-slices including the 2020s (2010-2039), 2050s (2040-2069) and 2080s (2070-2099), for three emissions scenarios (Low, Medium and High). The resolution of the projections is 25km over the land area of the UK, and the Sampled Data are provided on this 25km grid (Figure 3.2a). However, the methodology used to produce the Sampled Data means that they are not spatially coherent between different grid squares, so data cannot simply be averaged over several grid squares to produce Sampled Data for a region, like a river catchment. Instead, UKCP09 also provides Sampled Data processed for two different sets of aggregated areas: administrative regions and river-basin regions (Figure 3.2b). It is the data from the river-basin regions which are used here, as they will be consistent across the whole of any river catchment (that is, the river-basin regions were designed in such a way that no catchment will be contained partly in one river-basin region and partly in another river-basin region). Only the 10 river-basin regions covering Scotland are used: North Highland, North-East Scotland, Tay, Forth, Tweed, Solway, Clyde, Argyll, West Highland, and Orkney and Shetland. Examples of UKCP09 grid-box and river-basin region Sampled Data, for changes in winter mean precipitation, are shown in Figure 3.3.

a) UKCP09 25km grid

b) UKCP09 river-basin regions

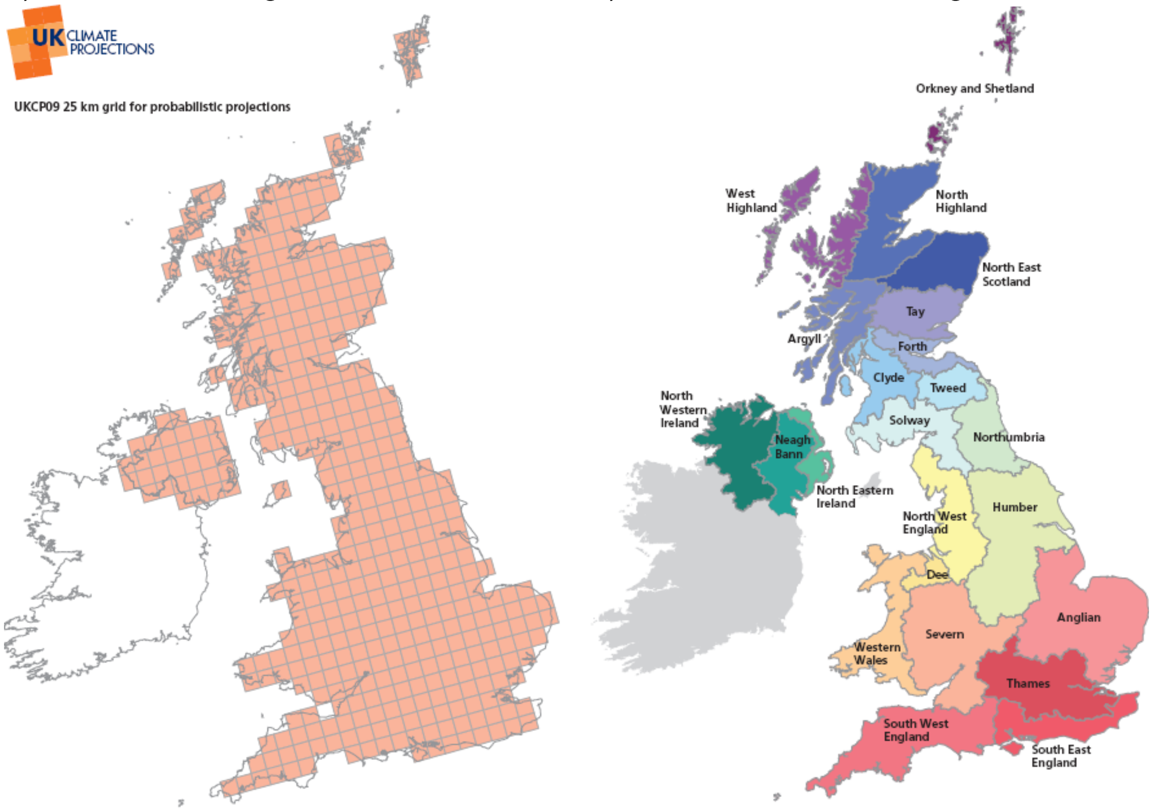

Figure 3.2 Areas over which the UKCP09 probabilistic projections are available.

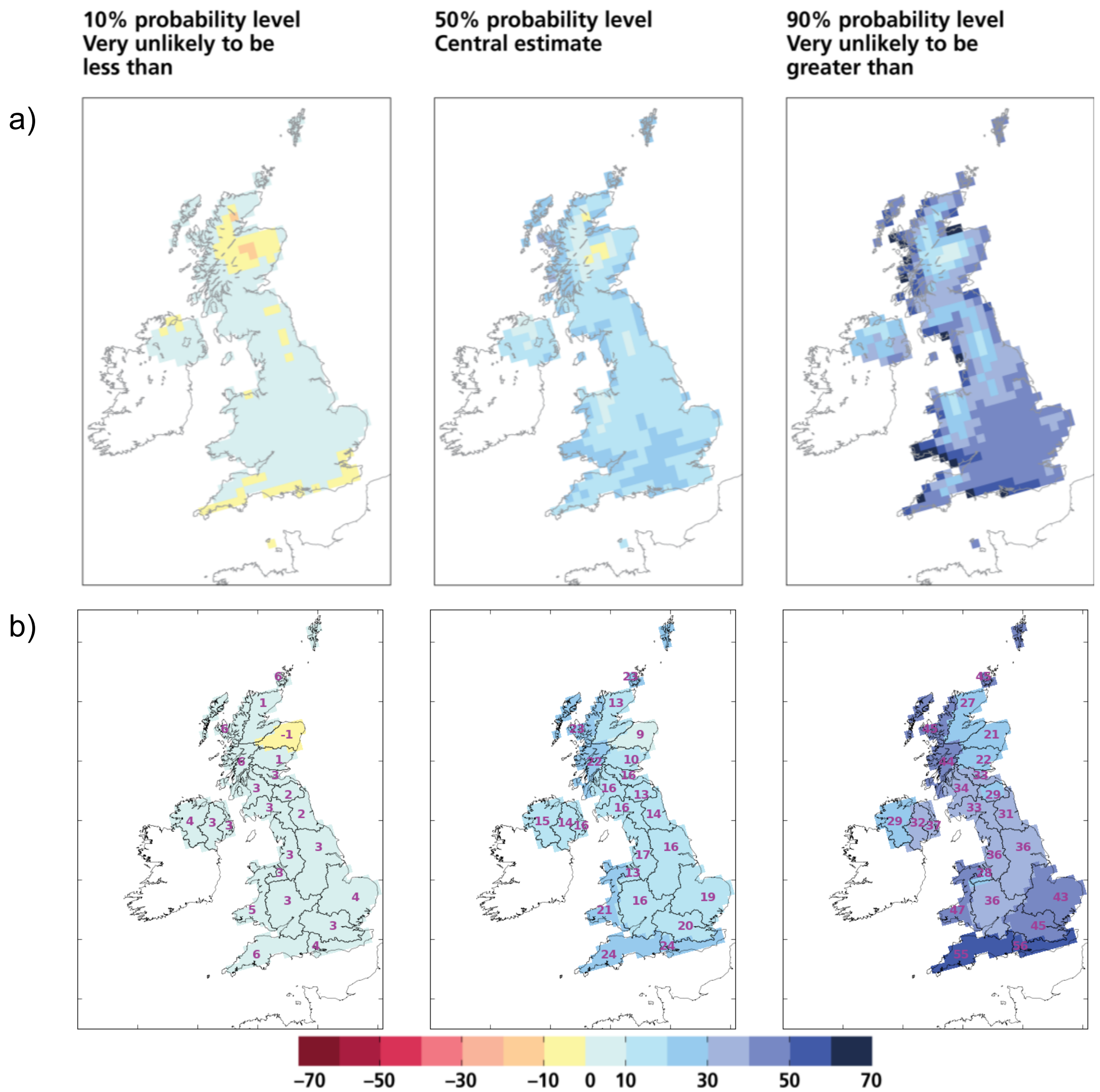

Figure 3.3 UKCP09 estimates of the percentage change in winter mean precipitation, for the 2080s under the Medium emissions scenario, for a) the 25km grid and b) the river-basin regions (© UK Climate Projections 2009).

For each river-basin region, the Sampled Data for the required time-horizons and emissions scenarios (here the 2020s, 2050s and 2080s time-horizon under the Medium (A1B) emissions scenario and under the Low (B1) and High (A1F1) emissions scenarios for the 2080s time-horizon) are downloaded from the UKCP09 user interface (ukclimateprojections-ui.defra.gov.uk/ui/admin/login.php). Only the data on monthly changes in mean daily precipitation are required for the methodology as applied here (see Section 3.3), but data on monthly changes in mean daily mean temperature are obtained at the same time, for information. For both the precipitation and temperature monthly change data, a single-harmonic function is fitted to each of the 10,000 sets of monthly changes. This is given by

$$X(t) = X_0 + A \cos [2\pi (t - \Phi) / 12]$$

with $X(t)$ the change for month t (t is 1 for January, 12 for December), X_0 the mean annual change (harmonic mean), and A and Φ the harmonic amplitude and phase respectively. The phase is the month of the peak change. The distributions of the three parameters (mean, amplitude and phase) of the 10,000 fitted single-harmonic functions are given in Section 4 and Appendix A (see for example Figure 4.3), in order to assess how the range of precipitation (and temperature) changes predicted by UKCP09 compares to the set of precipitation (and temperature) changes applied in the FD2020 sensitivity framework (Table 1.1). It is two of the parameters of the fitted precipitation harmonics, the mean and amplitude, which determine the hazard that is applied here for each UKCP09 river-basin region.

The use of the UKCP09 Sampled Data for river-basin regions greatly simplifies the results, as there is one set of results for each response type, return period and river-basin region. The precise location of a catchment, other than the river-basin region which contains it, becomes unimportant. In general it is not thought that the use of river-basin region Sampled Data as against 25km grid-box Sampled Data will make a big difference to the results for a catchment. However, there is obviously more chance of differences for a small catchment within a large river-basin region, especially in regions of highly variable topography (see the example in Figure 3.3). In any case it should be recalled that, as discussed above, the 25km grid-box Sampled Data are not spatially coherent so cannot be averaged over several grid squares to produce Sampled Data for a river catchment, nor can they be used to provide different inputs to different parts of a river catchment.

3.3 Risk – combining sensitivity and hazard

As described in Section 3.2, the hazard is assessed from the UKCP09 Sampled Data for each river-basin region, time-horizon and emissions scenario, by fitting a single-harmonic function to each of the 10,000 sets of monthly changes in precipitation. The hazard is then combined with the sensitivity, by using the mean and amplitude of each fitted precipitation harmonic to extract the estimated impact from the corresponding position on the key response pattern (sensitivity; Figure 1.3) for each response type and return period. Example plots showing the combination of sensitivity and hazard are given in Figure 3.4 for two response types (Damped-High and Neutral) and two river-basin regions (West Highland and Tweed). These plots show how the extracted impacts will vary according to both sensitivity and hazard.

The set of 10,000 extracted impacts then represents an initial estimate of the range of risk (due to climate modelling uncertainty and natural variability) in each case. This range is shown as cumulative distribution functions (cdfs) on the plots in Figure 3.5a, for the same two response types and two river-basin regions shown in Figure 3.4. A cdf presents the probability of the climate change impact being less than a certain threshold value, and is a very useful way of presenting a distribution of impacts since it allows the user to easily read off the impact threshold at any probability level (or percentile). For instance, the impact threshold at the 50% probability level (or 50th percentile) is called the median, and is the impact that is as likely as not to be exceeded (the 'central estimate' in UKCP09 terminology). The impact threshold at the 90% probability level (or 90th percentile) is that which is 'very unlikely to be exceeded' (in UKCP09 terminology), whilst the impact threshold at the 10% probability level (or 10th percentile) is very likely to be exceeded.

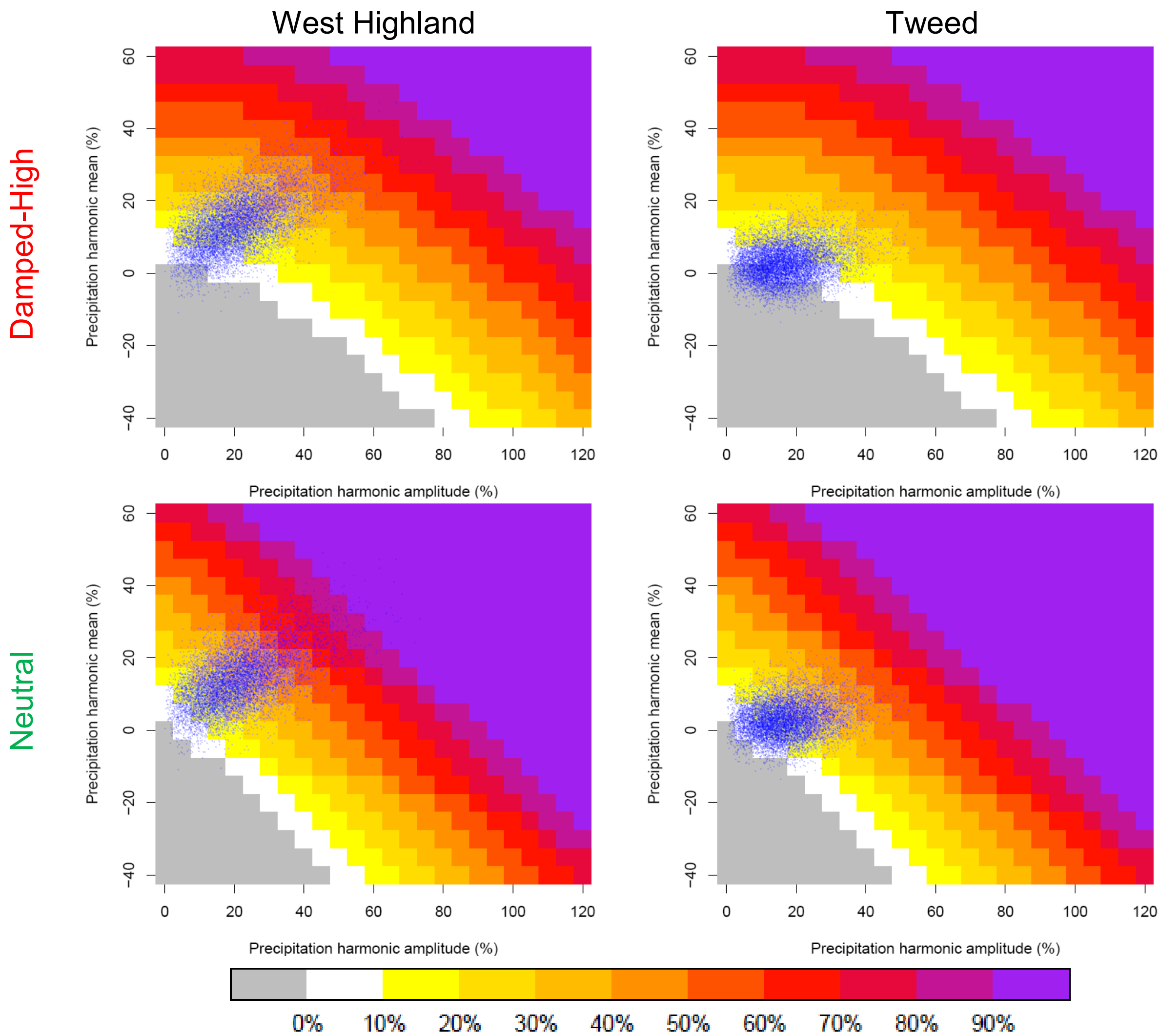

Figure 3.4 Example plots combining sensitivity (key response patterns) and hazard (UKCP09 river-basin region Sampled Data; blue dots). The examples combine the key response patterns (at the 20-year return period) for two response types (Damped-High and Neutral) with the hazard sets for two river-basin regions (West Highland and Tweed) under the Medium emissions scenario for the 2080s time-horizon.

The appropriate extra uncertainty allowance (Table 2.19) is then added to the cdfs, depending on the response type and return period, to get a more robust estimate of the range of risk (allowing for bias due to the assumptions and simplifications necessary to implement the sensitivity framework approach). The plots in Figure 3.5b show the new cdfs corresponding to the initial cdfs plotted in Figure 3.5a, for the two response types and two river-basin regions. These cdfs, based on the use of key response patterns (sensitivity) and UKCP09 river-basin region data (hazard), will hereafter be called ‘response-type risk cdfs’.

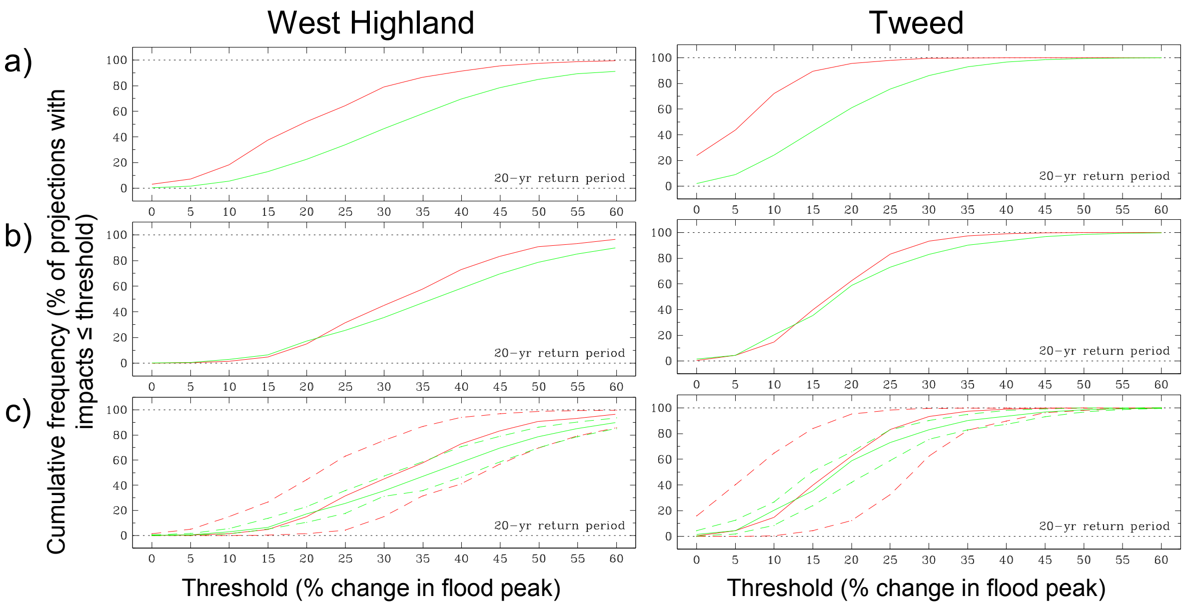

Figure 3.5 Example plots showing two response-type risk cdfs (Damped-High – red; Neutral – green) for two river-basin regions (West Highland and Tweed) under the Medium emissions scenario for the 2080s time-horizon. a) response-type risk with no added uncertainty; b) response-type risk with extra uncertainty allowances (Table 2.19); c) response-type risk cdfs as in b with corresponding cdfs for +-2sds.

To allow for the uncertainty due to the use of key response patterns to represent what is actually a range of possible catchment responses classified as the same response type, the standard deviation (sd) patterns (Figure 1.4) can be used. That is, the mean and amplitude of the fitted precipitation harmonics are also used to extract, from the sd patterns for each response type and return period, an estimate of the sd corresponding to each estimate of the impact. Assuming an approximately normal distribution, the impact ±1sd covers about 68% of the range, whilst the impact ±2sd covers about 95% of the range. The plots in Figure 3.5c show additional (dashed) cdfs corresponding to ±2sd for each of the cdfs in Figure 3.5b. These show narrower bands for Neutral than for Damped-High, reflecting the fact that the Neutral response type generally has lower values derived from its sd patterns than do the other response types (Figure 1.4).

Thus each region has a set of response-type risk cdfs, each with uncertainty bands. Figure 3.6a shows the set of response-type risk cdfs (at the 20-year return period) for the two river-basin regions used in Figure 3.4 and Figure 3.5 (without their corresponding uncertainty bands). From these sets of response-type risk cdfs, a 'regional average' risk is calculated for each river-basin region. This is based on using the number of NRFA catchments of each response type in the region as weights for the corresponding response-type risk cdfs. The weighted risk for a given region could be considered to represent a reasonable estimate of the regional risk, applicable to any catchment in that river-basin region regardless of type. Thus these weighted cdfs, based on the use of response-type risk cdfs and the estimated response types of NRFA catchments, will hereafter be called 'regional risk cdfs'. Figure 3.6b shows the regional risk cdfs corresponding to the sets of response-type risk cdfs in Figure 3.6a. The uncertainty bands on the response-type risk cdfs can also be weighted, to make uncertainty bands on the regional risk cdfs.

The risk can be presented as continuous curves, or only at discrete values of the threshold. In Figure 3.6b, continuous curves have been used for plotting the regional risk cdfs but discrete values (5% intervals between 0% and 60%) have been used for plotting the response-type risk cdf, in order to clearly distinguish the two levels of information. Note that, although the regional risk is presented as a continuous curve, it is in fact only calculated at the same discrete values as the response-type risk. Plotting the regional risk as continuous curves but the response-type risk at discrete values of the threshold also allows the presentation of the uncertainty bands for the two types of risk, without having too many intersecting curves. That is, the regional risk uncertainty bands can also be plotted as continuous curves, whilst the response-type risk uncertainty bands can be presented only for discrete values of the threshold.

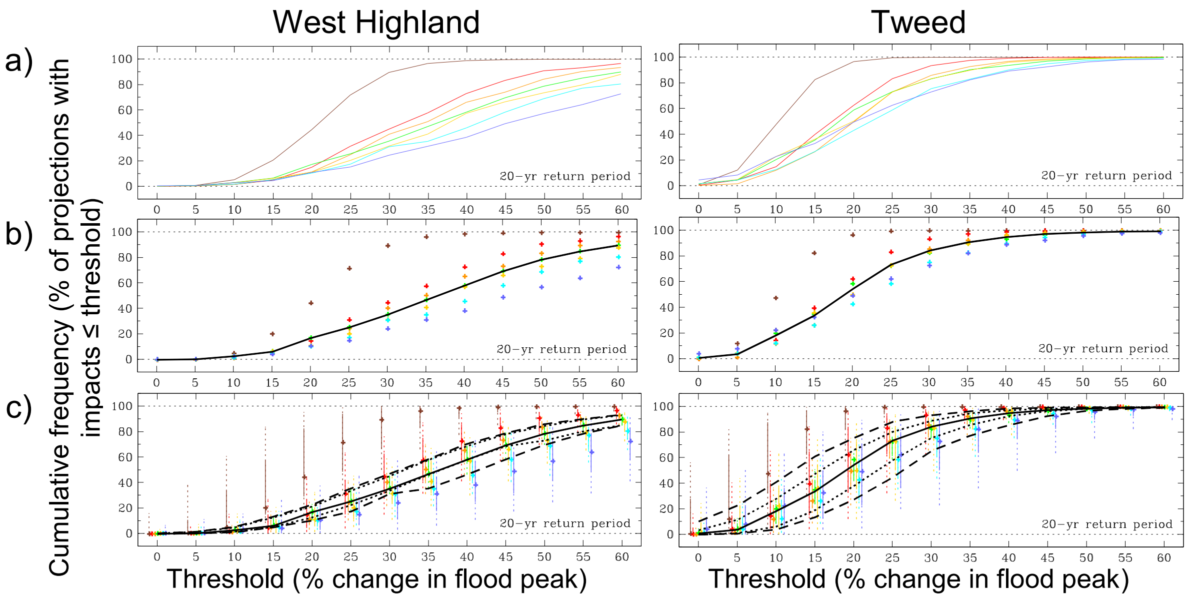

Figure 3.6 Example plots showing a) response-type risk cdfs (coloured solid curves), b) regional risk cdf (black solid curves) produced by weighting the response-type risk cdfs (coloured plus signs), and c) response-type and regional risk with uncertainty bands, for two river-basin regions (West Highland and Tweed) under the Medium emissions scenario for the 2080s time-horizon. The response-type risk from a) is also shown in b) and c), but plotted at discrete threshold positions (plus signs; every 5% between 0% and 60%) rather than as continuous curves. In c) the uncertainty bands are shown for the response-type risk (coloured vertical lines; ±1sd – solid, ±2sd – dotted) and regional risk (±1sd – black dotted curve , ±2sd – black dashed curve), with small horizontal offsets used for each response-type risk (see text). Response-type key: Damped-Extreme – brown; Damped-High – red; Damped-Low – orange; Neutral – green; Mixed – gold; Enhanced-Low – cyan; Enhanced-Medium – blue.

Figure 3.6c shows examples of final risk plots for two river-basin regions. Here, the regional risk cdf is plotted as a solid black curve, with its corresponding uncertainty bands plotted as dotted (±1sd) and dashed (±2sd) black curves. Each response-type risk cdf is plotted at discrete values of the threshold (5% intervals between 0% and 60%), using plus signs coloured according to the response type. The uncertainty bands for each response-type risk cdf are plotted as vertical lines around the central estimate (plus sign), using the appropriate colour. Note that, in order to better distinguish the differing response-type risk and its corresponding uncertainty bands when plotted at discrete values, small horizontal offsets have been used. That is, while the vertical lines showing the uncertainty bands for the Neutral response type are plotted at the threshold to which they apply, the vertical lines showing the uncertainty bands for the Damped-Extreme, Damped-High and Damped-Low response types are offset to the left of the threshold to which they apply. Similarly, the vertical lines showing the uncertainty bands for the Mixed, Enhanced-Low and Enhanced-Medium response types are offset to the right of the threshold to which they apply. Greater negative offsets apply for Damped-Extreme than for Damped-High, and for Damped-High than Damped-Low. Similarly, greater positive offsets apply for Enhanced-Medium than for Enhanced-Low and for Enhanced-Low than Mixed.

The response-type risk and regional risk are thus presented in the risk plots in Section 4 (and Appendix B.1), for each river-basin region and return period, in the manner illustrated in Figure 3.6c. Presentation of both response-type and regional risk for a region on one plot allows direct comparison of the two levels of risk information. However, it should be noted that it may not be possible to produce a sensible regional risk curve for some river-basin regions due to the very small number of NRFA catchments in the region (e.g. West Highland and Orkney and Shetland; Table 3.4). It should also be noted that, although the response-type risk for the Enhanced-Low and Enhanced-Medium response types is presented in the risk plots, this information is not used in the production of the regional risk curves (i.e. they have zero weight) since the decision trees could not distinguish these types; there are too few catchments of these types in the modelled catchment set applied (see Section 2). They are nevertheless shown on the risk plots, to illustrate how the risk for these types differs from that for Damped, Neutral and Mixed types. In future, further modelling may enable the better characterisation of Enhanced response types in Scotland, by increasing the sample of these types of catchment on which to base the decision trees.

Table 3.4 Summary of the number of NRFA catchments in each UKCP09 river-basin region in Scotland.

UKCP09 river-basin region	Number of NRFA catchments	UKCP09 river-basin region	Number of NRFA catchments
Orkney and Shetland	1	North Highland	42
West Highland	6	North-East Scotland	46
Argyll	14	Tay	54
Clyde	59	Forth	53
Solway	43	Tweed	31

It should be noted that, although harmonic functions have also been fitted to the UKCP09 river-basin Sampled Data for temperature (Section 3.2), this was done purely to enable a comparison of the range of temperature changes predicted by UKCP09 with the set of eight temperature scenarios used in the FD2020 sensitivity framework (Table 1.1). That is, there has been no attempt to select which of the eight FD2020 temperature scenarios is 'closest' to each of the 10,000 UKCP09 projections, in order to use its specific response pattern. Instead the response patterns averaged over all eight temperature scenarios (Figure 1.3) have been used for each of the 10,000 UKCP09 projections in each river-basin region. This is a reasonable simplification, as there are generally much smaller differences between the response patterns across the eight temperature scenarios for a given response type than there are across different response types (Figure 4.7 of Reynard *et al.* 2009; although see the discussion in Section 2.8 for snow-affected catchments). The use of the standard deviation patterns derived over all eight temperature scenarios (Figure 1.4) then includes the (small) additional uncertainty introduced by the use of the key response patterns averaged over the eight temperature scenarios, as well as covering the uncertainty due to the range of possible catchment responses of a given response type.

4. Results by region

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Section 4: Results by region

This section presents the sensitivity, hazard and risk results on a regional basis. For each of the 10 river-basin regions in Scotland:

- A table summarises the number of NRFA catchments estimated to have each response type, at each of the four return periods.
- Maps show the best-estimate of the response type, and its confidence level, for each NRFA catchment at each return period.
- Plots summarise the hazard, in terms of the parameters of harmonic functions fitted to the monthly changes in precipitation and temperature.
- Plots summarise the response-type and regional risk, for flood peaks at each return period, including the uncertainty in each.

The hazard and risk plots presented in this section are for the 2080s time-horizon under the Medium emission scenario. Equivalent plots for the four alternative time-horizon and emissions scenario combinations are given in Appendices.

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4.1 North Highland

4.1.1 Sensitivity

A total of 42 NRFA catchments are located within the North Highland river-basin region. The best-estimate of the response type for these catchments is generally Damped-High at the 2-year return period and Neutral at higher return periods (Table 4.1). The maps in Figure 4.1 show the best-estimate of the response type for each catchment at each return period, while those in Figure 4.2 show the corresponding confidence levels (High – H, Medium – M, Low – L). (Note that the maps in these two figures also include the response type and confidence level, respectively, for the one NRFA catchment in the Orkney and Shetland river-basin region – see Section 4.10.1).

Table 4.1 The number of NRFA catchments of each response type at each return period, for the North Highland river-basin region. The predominant response type is highlighted in bold at each return period.

	Return period			
Response type	2-year	10-year	20-year	50-year
Damped-Extreme	1	1	1	1
Damped-High	**33**	10	5	8
Damped-Low	0	0	5	2
Neutral	4	**27**	**27**	**27**
Mixed	4	4	4	4
Enhanced-Low	NA	NA	NA	NA
Enhanced-Medium	NA	NA	NA	NA
Total	42	42	42	42

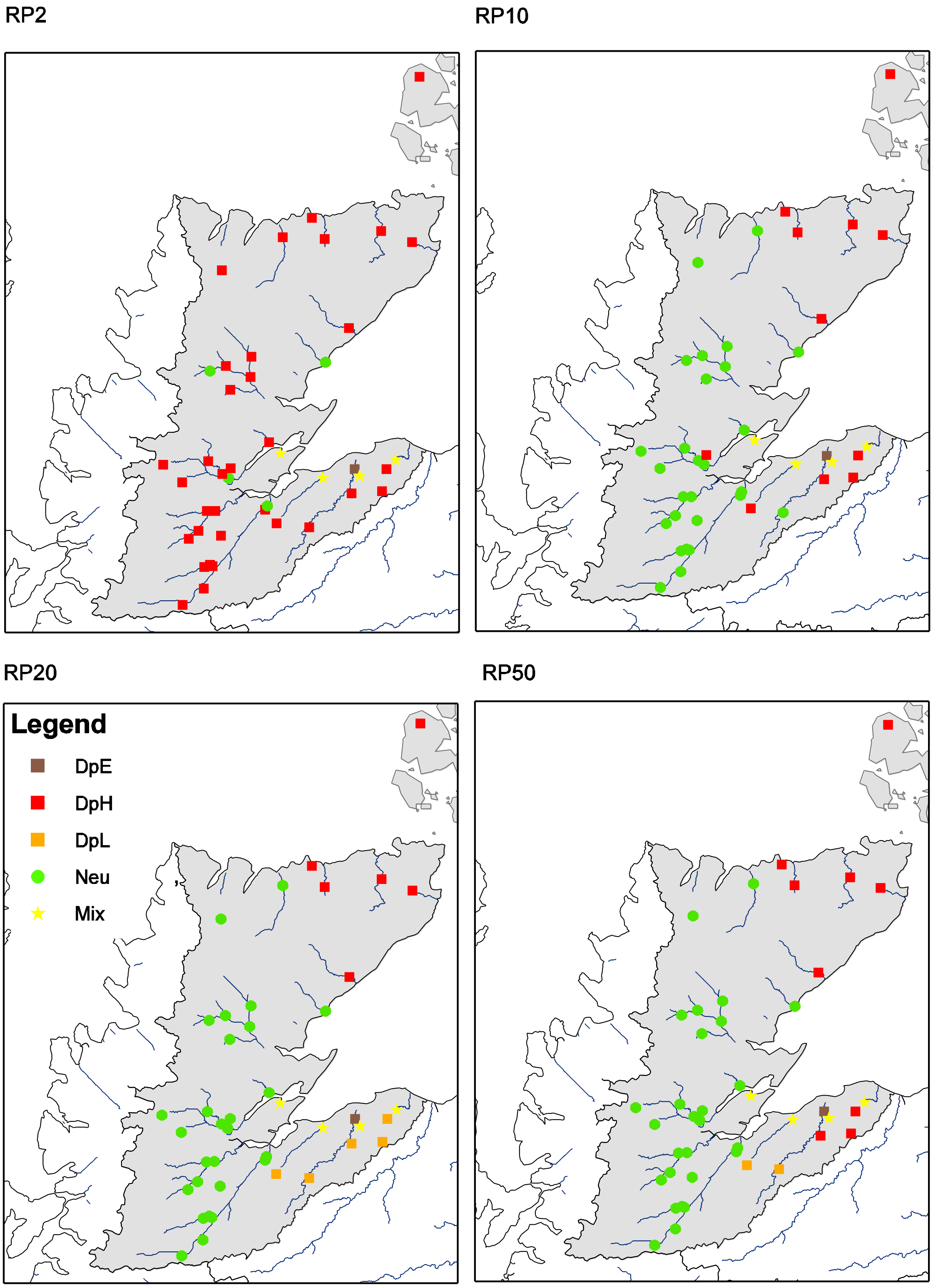

Figure 4.1 The best-estimate of the response type for each NRFA catchment in the North Highland river-basin region.

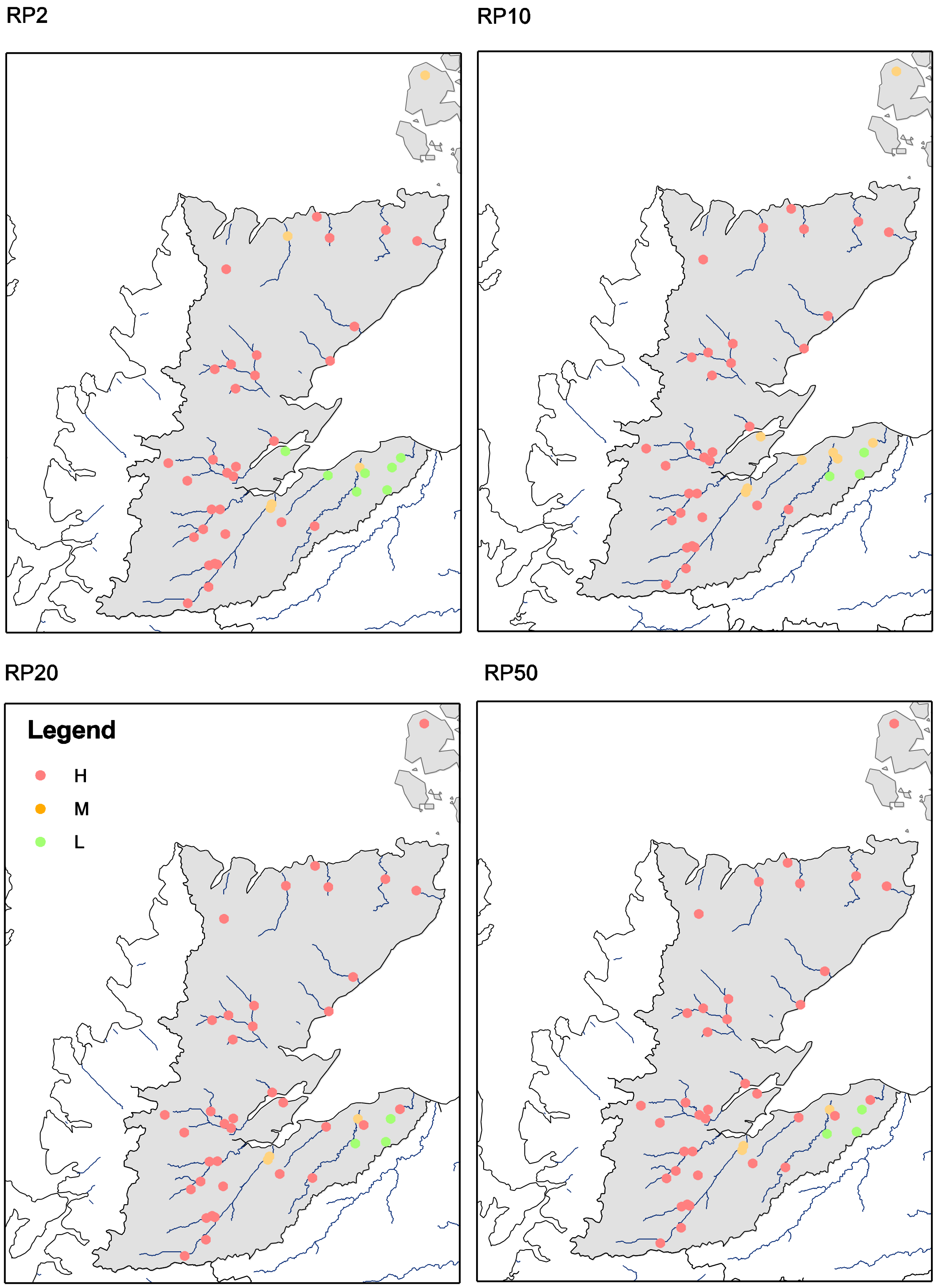

Figure 4.2 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the North Highland river-basin region.

4.1.2 Hazard

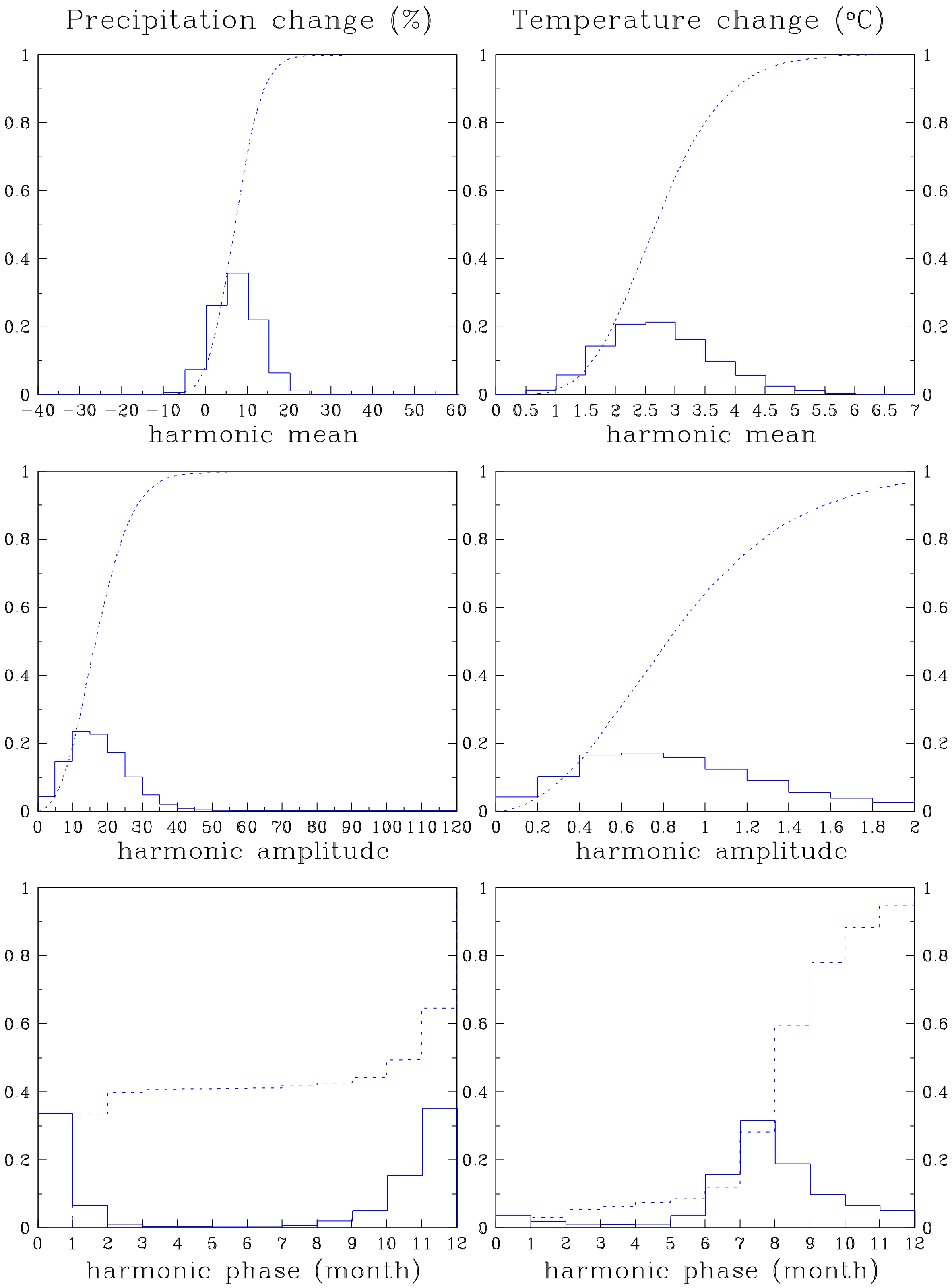

Figure 4.3 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s Medium) for the North Highland river-basin region.

4.1.3 Risk

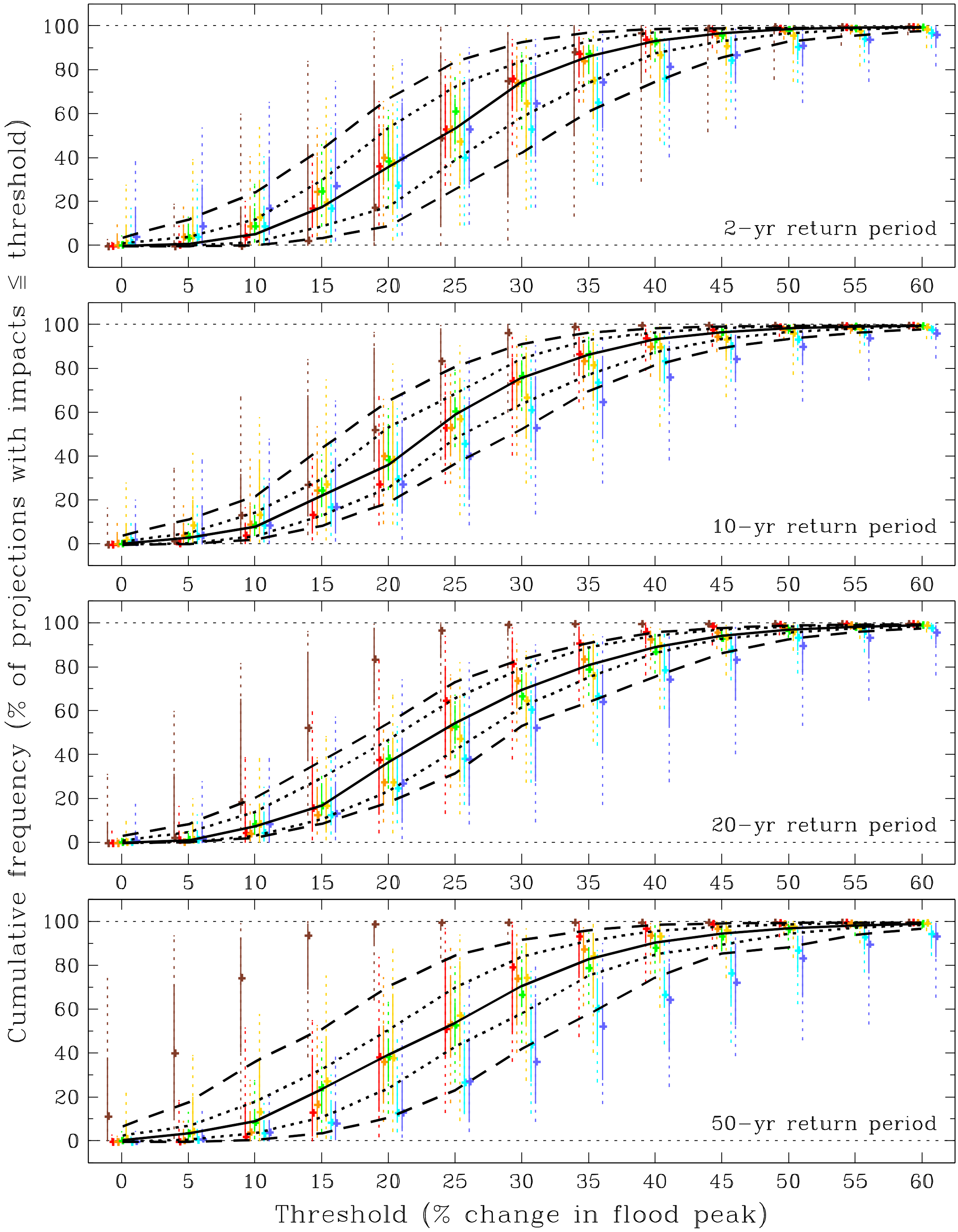

Figure 4.4 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s Medium) for the North Highland river-basin region. Response-type risk (colours): Damped-Extreme (brown), Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue); central-estimate (plus sign), ±1sd (solid vertical line), ±2sd (dotted vertical line). Regional risk (black): central-estimate (solid curve), ±1sd (dotted curves), ±2sd (dashed curves).

4.2 North-East Scotland

4.2.1 Sensitivity

A total of 46 NRFA catchments are located within the North-East Scotland river-basin region. The best-estimate of the response type for these catchments is generally Damped-High at the 2-year return period, with a combination of Damped-High, Damped-Low and Neutral at higher return periods (Table 4.2). The maps in Figure 4.5 show the best-estimate of the response type for each catchment at each return period, while those in Figure 4.6 show the corresponding confidence levels (High – H, Medium – M, Low – L).

Table 4.2 The number of NRFA catchments of each response type at each return period, for the North-East Scotland river-basin region. The predominant response type is highlighted in bold at each return period.

	Return period			
Response type	2-year	10-year	20-year	50-year
Damped-Extreme	4	4	4	4
Damped-High	**36**	**20**	4	12
Damped-Low	3	5	**18**	10
Neutral	0	14	17	**17**
Mixed	3	3	3	3
Enhanced-Low	NA	NA	NA	NA
Enhanced-Medium	NA	NA	NA	NA
Total	46	46	46	46

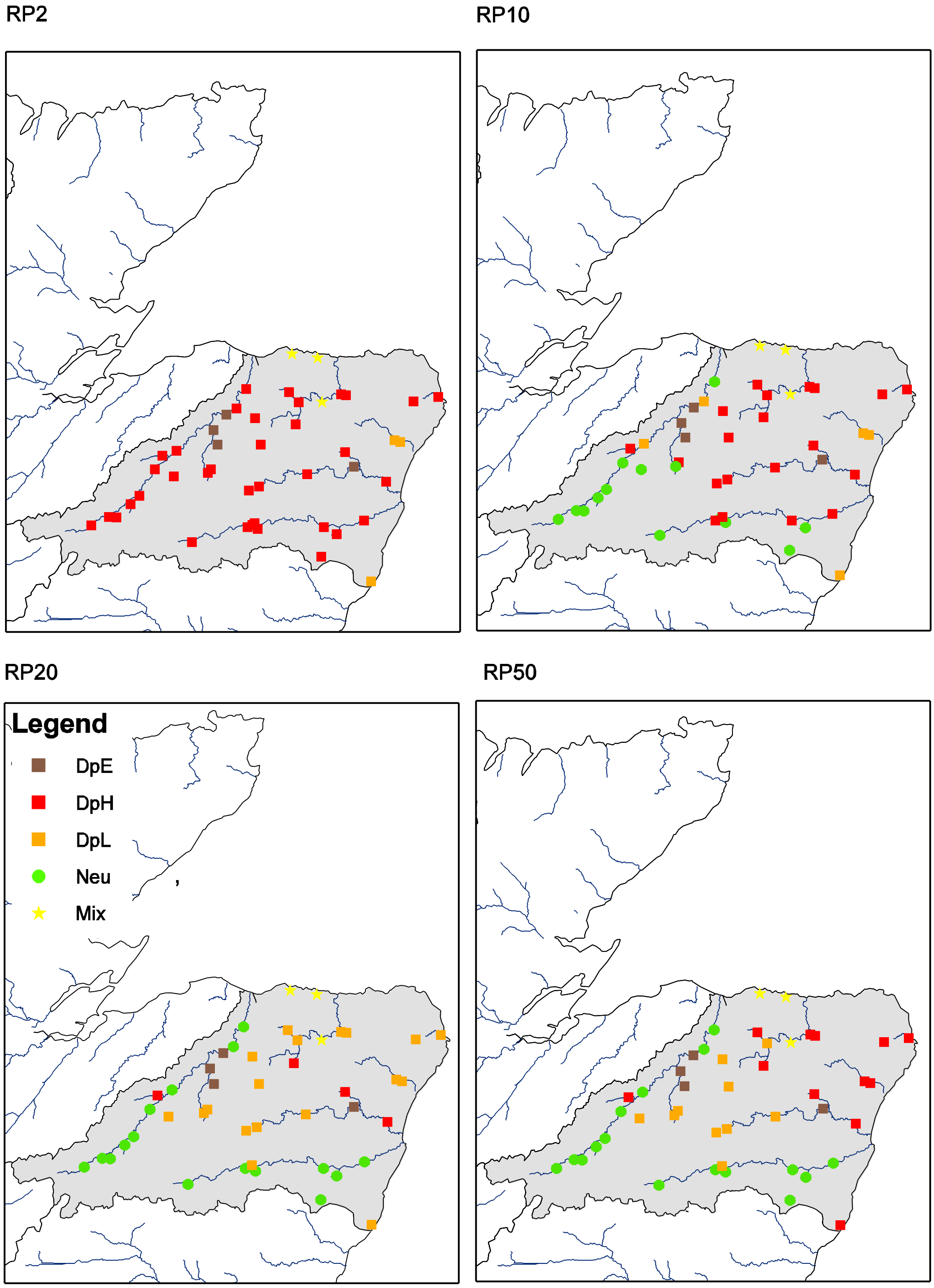

Figure 4.5 The best-estimate of the response type for each NRFA catchment in the North-East Scotland river-basin region.

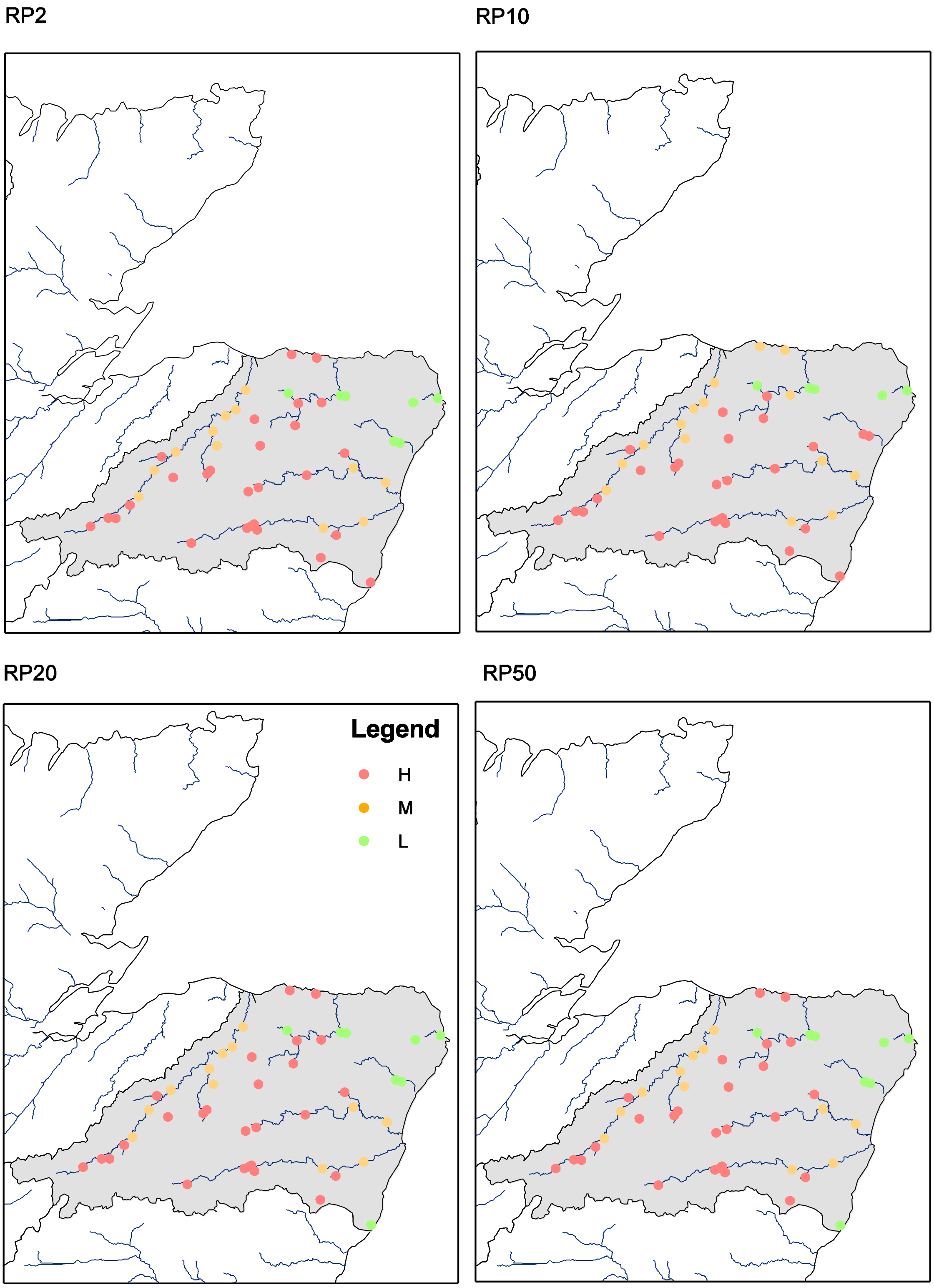

Figure 4.6 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the North-East Scotland river-basin region.

4.2.2 Hazard

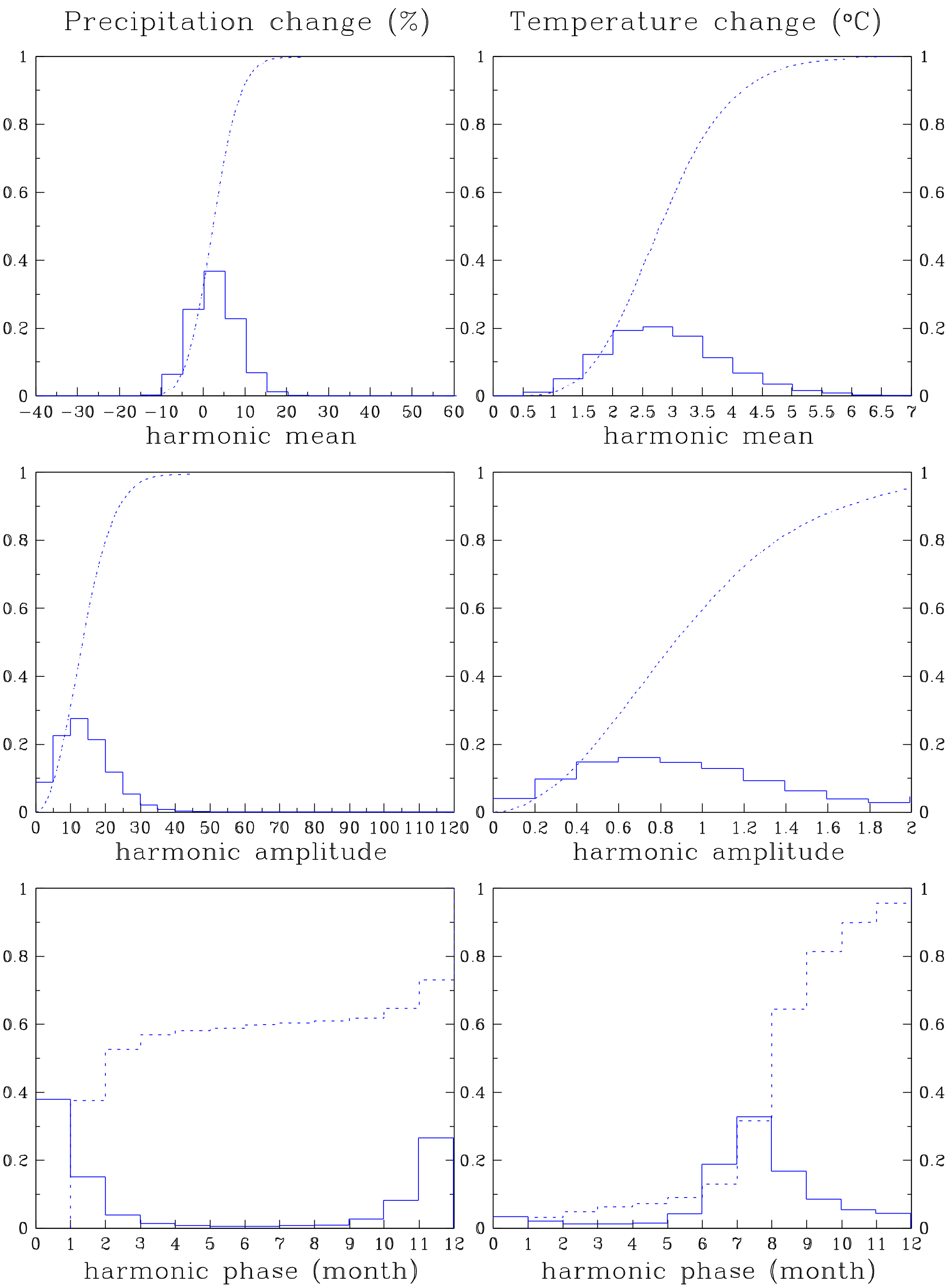

Figure 4.7 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s Medium) for the North-East Scotland river-basin region.

4.2.3 Risk

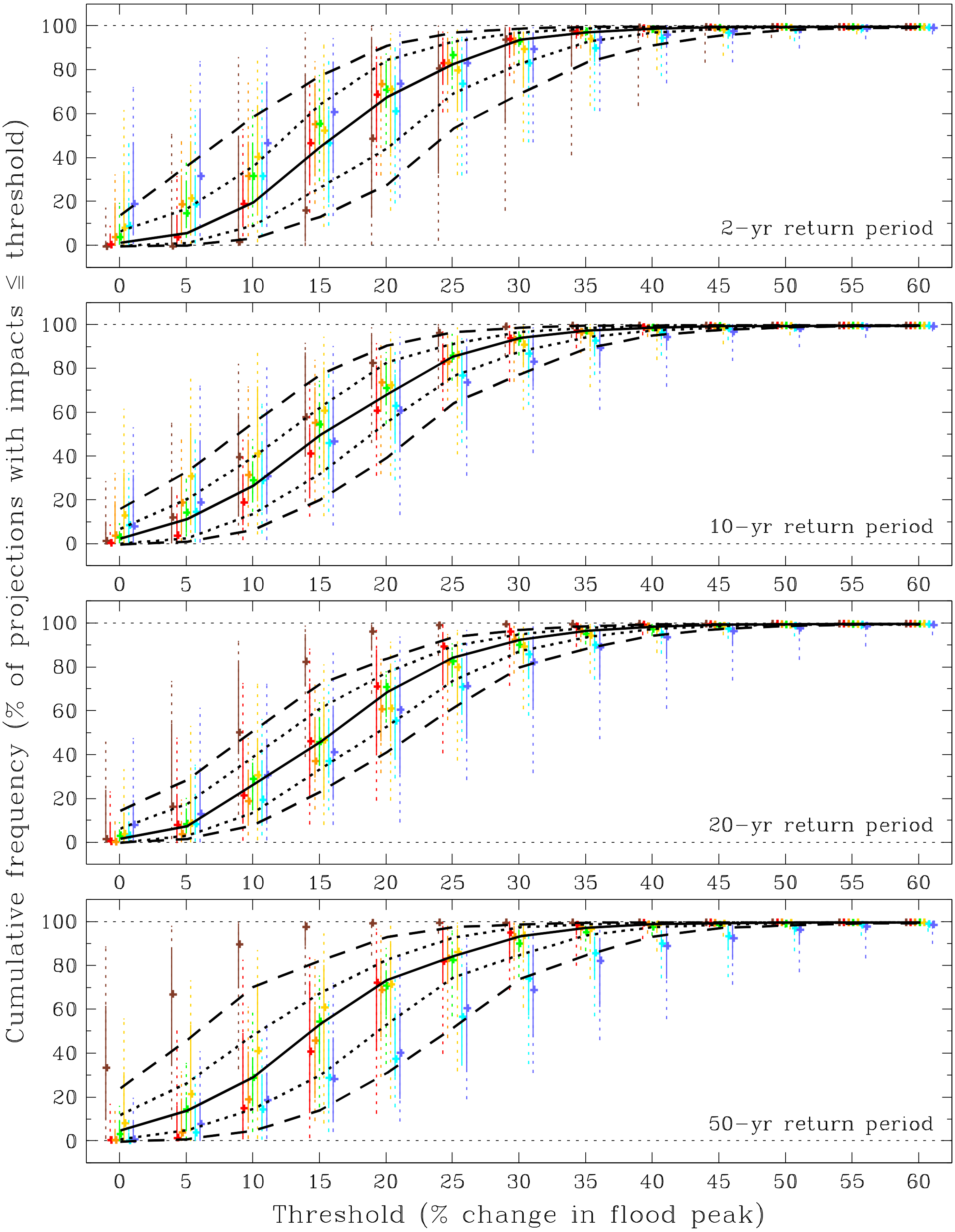

Figure 4.8 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s Medium) for the North-East Scotland river-basin region. Response-type risk (colours): Damped-Extreme (brown), Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue); central-estimate (plus sign), ±1sd (solid vertical line), ±2sd (dotted vertical line). Regional risk (black): central-estimate (solid curve), ±1sd (dotted curves), ±2sd (dashed curves).

4.3 Tay

4.3.1 Sensitivity

A total of 54 NRFA catchments are located within the Tay river-basin region. The best-estimate of the response type for these catchments is generally Damped-High at the 2-year return period and Neutral at the higher return periods (Table 4.3). The maps in Figure 4.9 show the best-estimate of the response type for each catchment at each return period, while those in Figure 4.10 show the corresponding confidence levels (High – H, Medium – M, Low – L).

Table 4.3 The number of NRFA catchments of each response type at each return period, for the Tay river-basin region. The predominant response type is highlighted in bold at each return period.

	Return period			
Response type	2-year	10-year	20-year	50-year
Damped-Extreme	0	0	0	0
Damped-High	**27**	4	0	6
Damped-Low	13	14	6	0
Neutral	7	**29**	**41**	**41**
Mixed	7	7	7	7
Enhanced-Low	NA	NA	NA	NA
Enhanced-Medium	NA	NA	NA	NA
Total	54	54	54	54

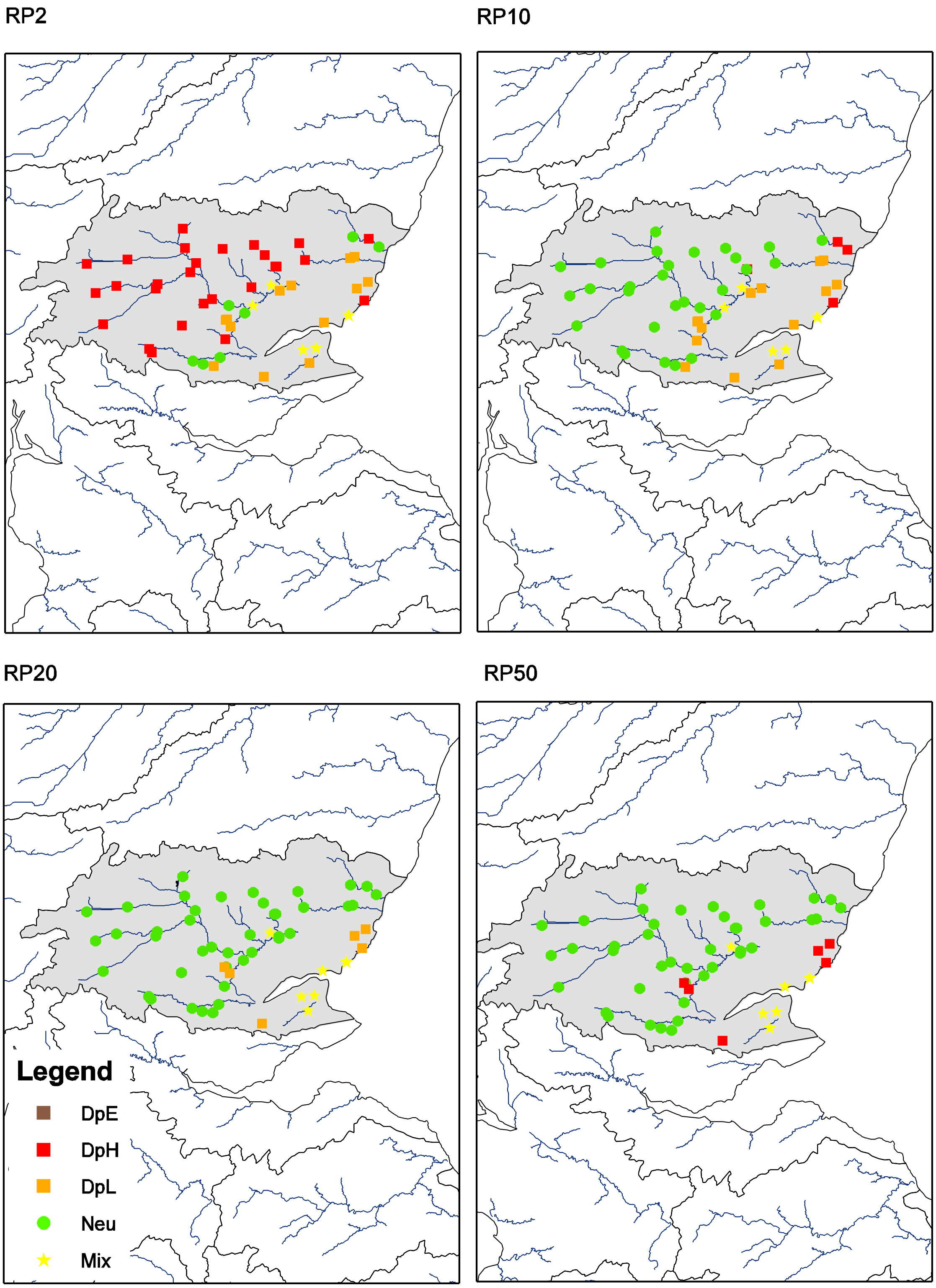

Figure 4.9 The best-estimate of the response type for each NRFA catchment in the Tay river-basin region.

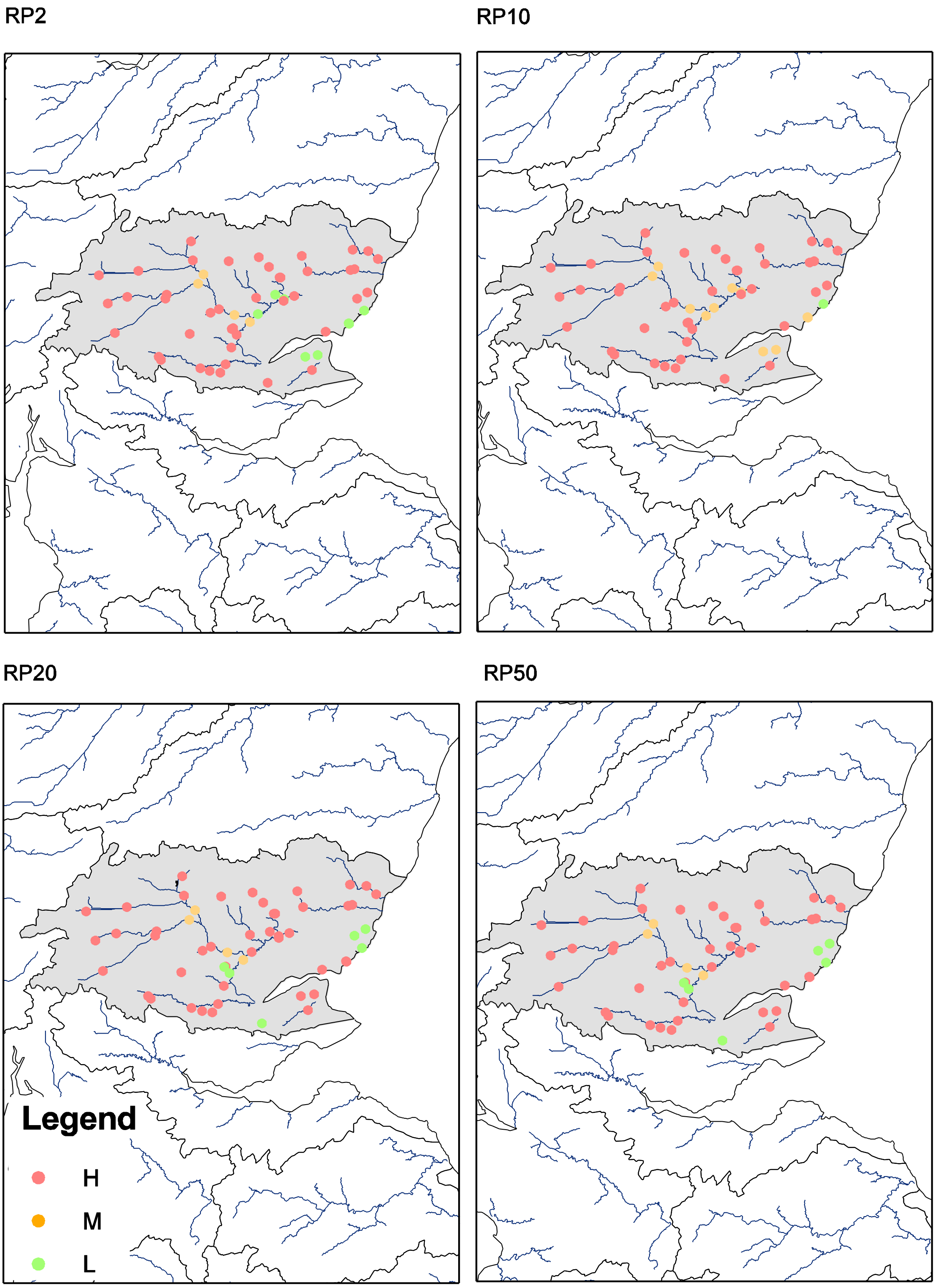

Figure 4.10 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the Tay river-basin region.

4.3.2 Hazard

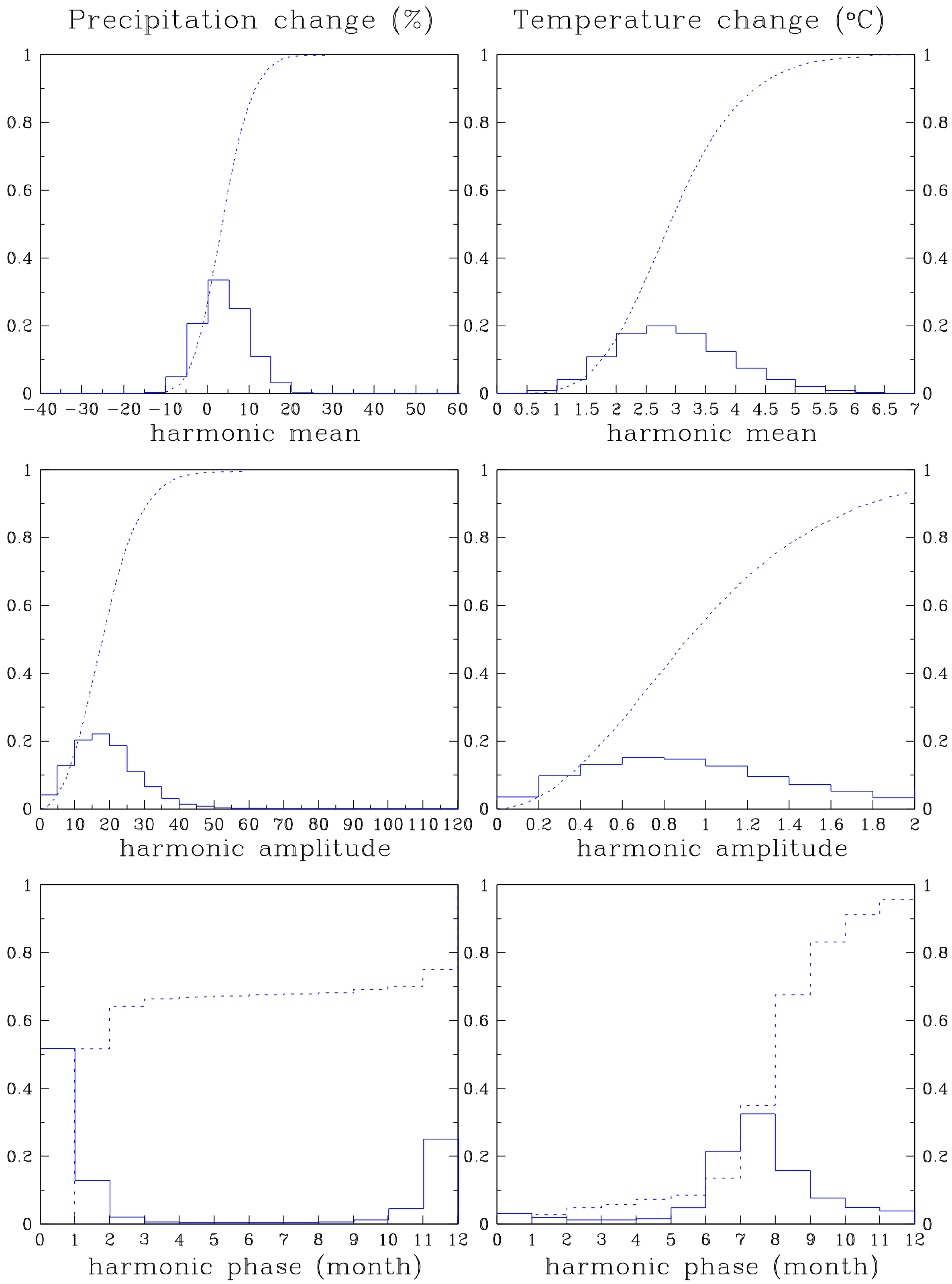

Figure 4.11 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s Medium) for the Tay river-basin region.

4.3.3 Risk

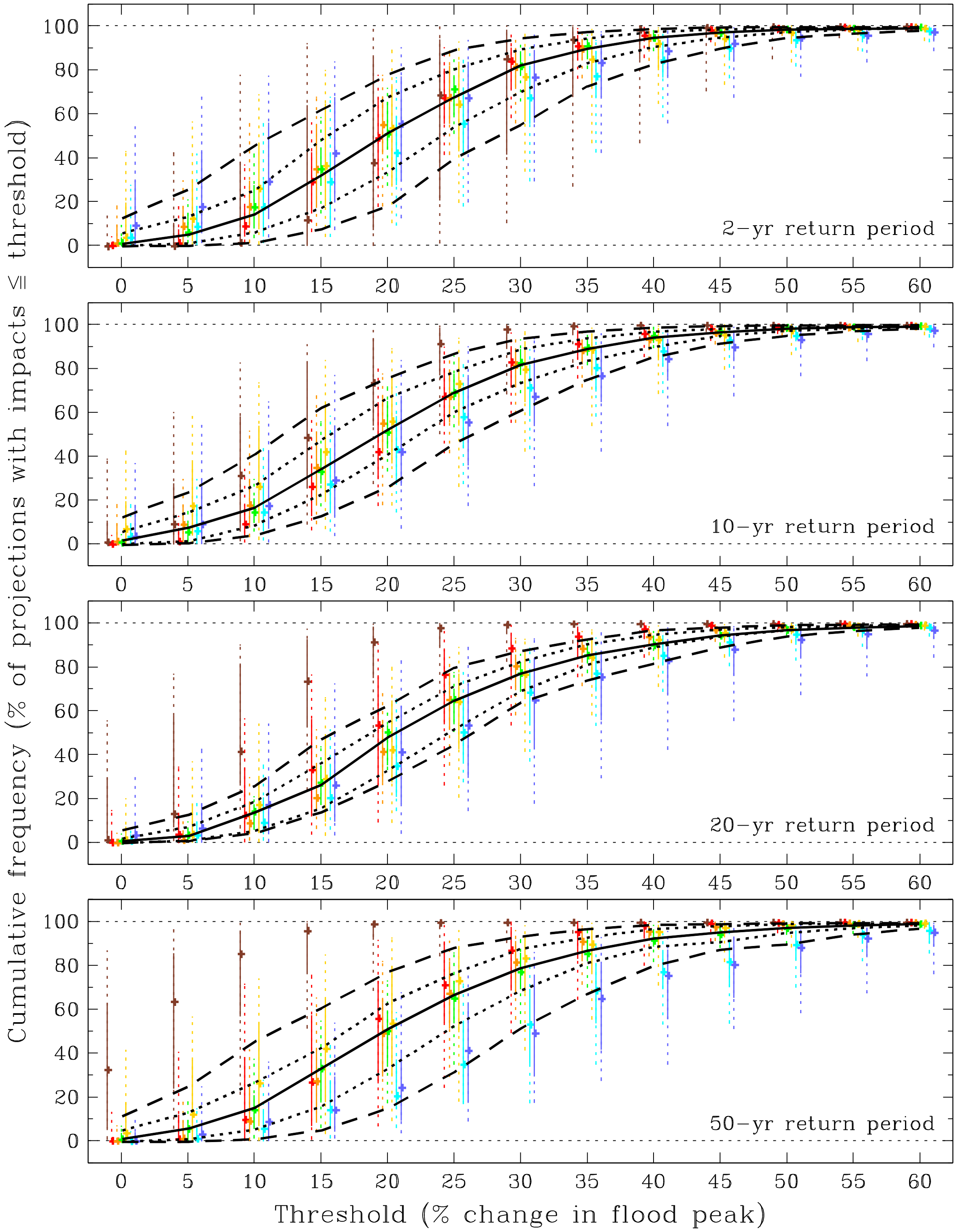

Figure 4.12 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s Medium) for the Tay river-basin region. Response-type risk (colours): Damped-Extreme (brown), Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue); central-estimate (plus sign), ±1sd (solid vertical line), ±2sd (dotted vertical line). Regional risk (black): central-estimate (solid curve), ±1sd (dotted curves), ±2sd (dashed curves).

4.4 Forth

4.4.1 Sensitivity

A total of 53 NRFA catchments are located within the Forth river-basin region. The best-estimate of the response type for these catchments is a combination of Damped-High and Mixed at the 2-year return period, with Neutral and Mixed at higher return periods (Table 4.4). The maps in Figure 4.13 show the best-estimate of the response type for each catchment at each return period, while those in Figure 4.14 show the corresponding confidence levels (High – H, Medium – M, Low – L).

Table 4.4 The number of NRFA catchments of each response type at each return period, for the Forth river-basin region. The predominant response type is highlighted in bold at each return period.

	Return period			
Response type	2-year	10-year	20-year	50-year
Damped-Extreme	0	0	0	0
Damped-High	**29**	14	4	9
Damped-Low	5	8	7	2
Neutral	2	14	20	20
Mixed	17	**17**	**22**	**22**
Enhanced-Low	NA	NA	NA	NA
Enhanced-Medium	NA	NA	NA	NA
Total	53	53	53	53

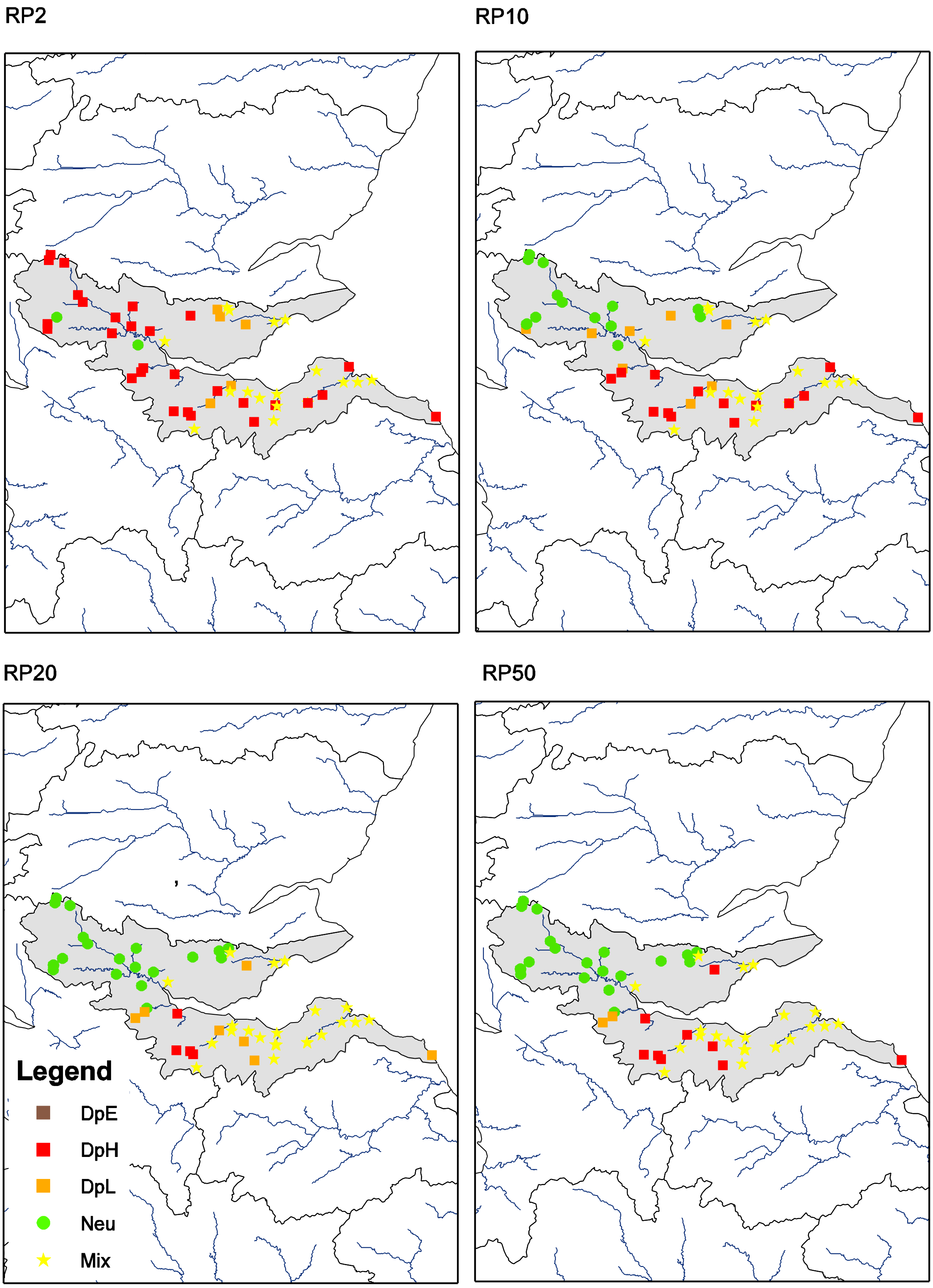

Figure 4.13 The best-estimate of the response type for each NRFA catchment in the Forth river-basin region.

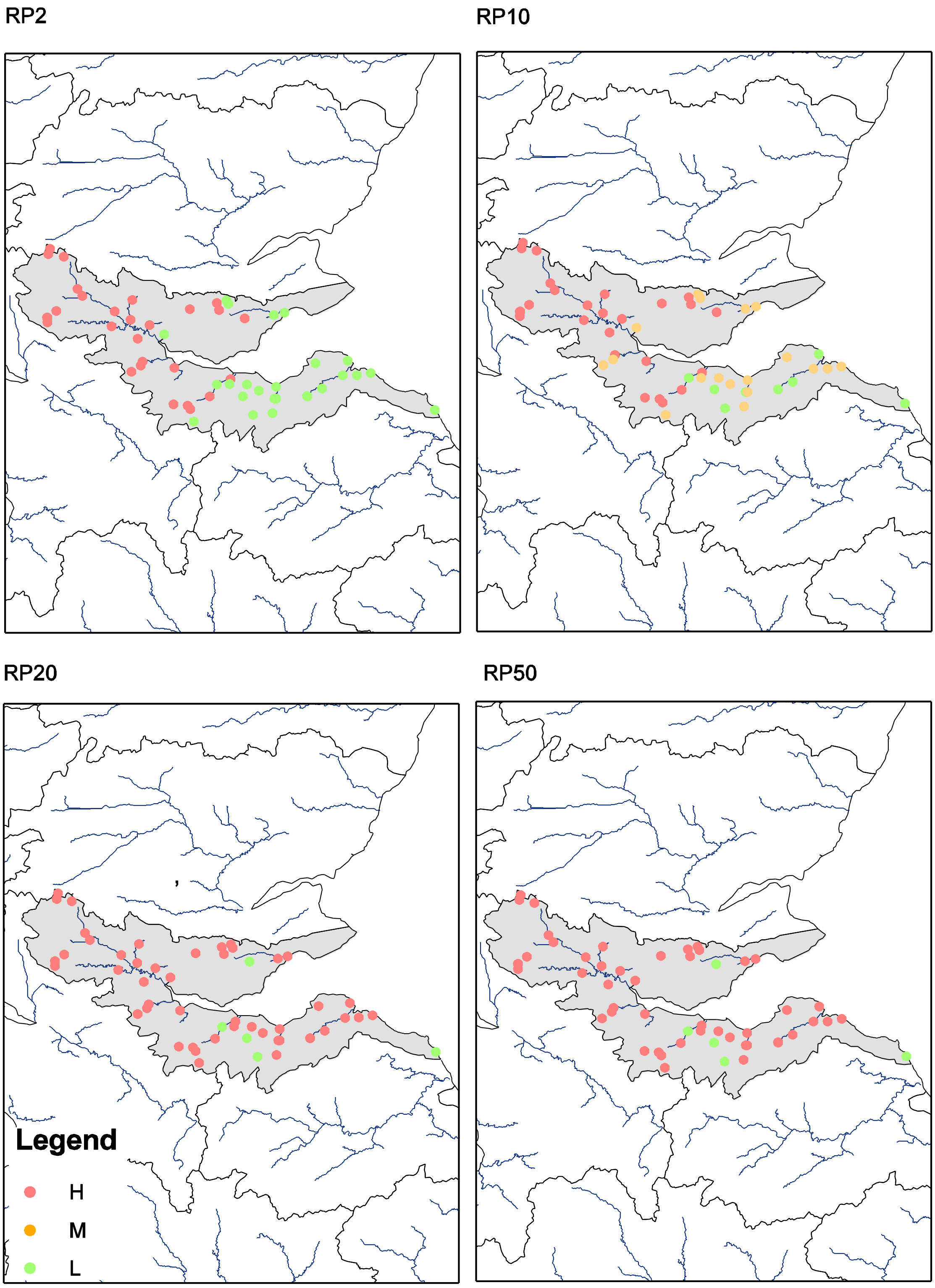

Figure 4.14 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the Forth river-basin region.

4.4.2 Hazard

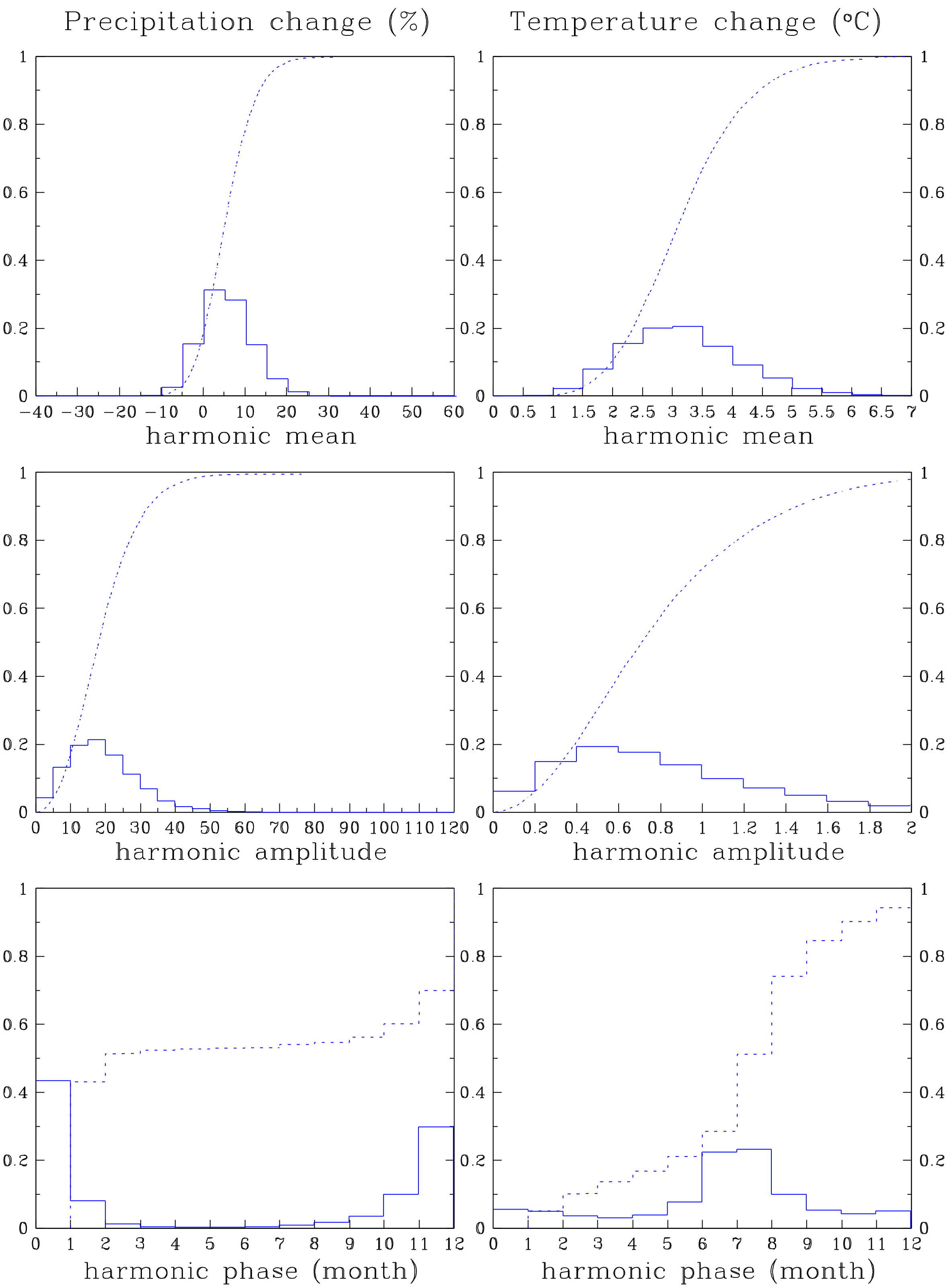

Figure 4.15 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s Medium) for the Forth river-basin region.

4.4.3 Risk

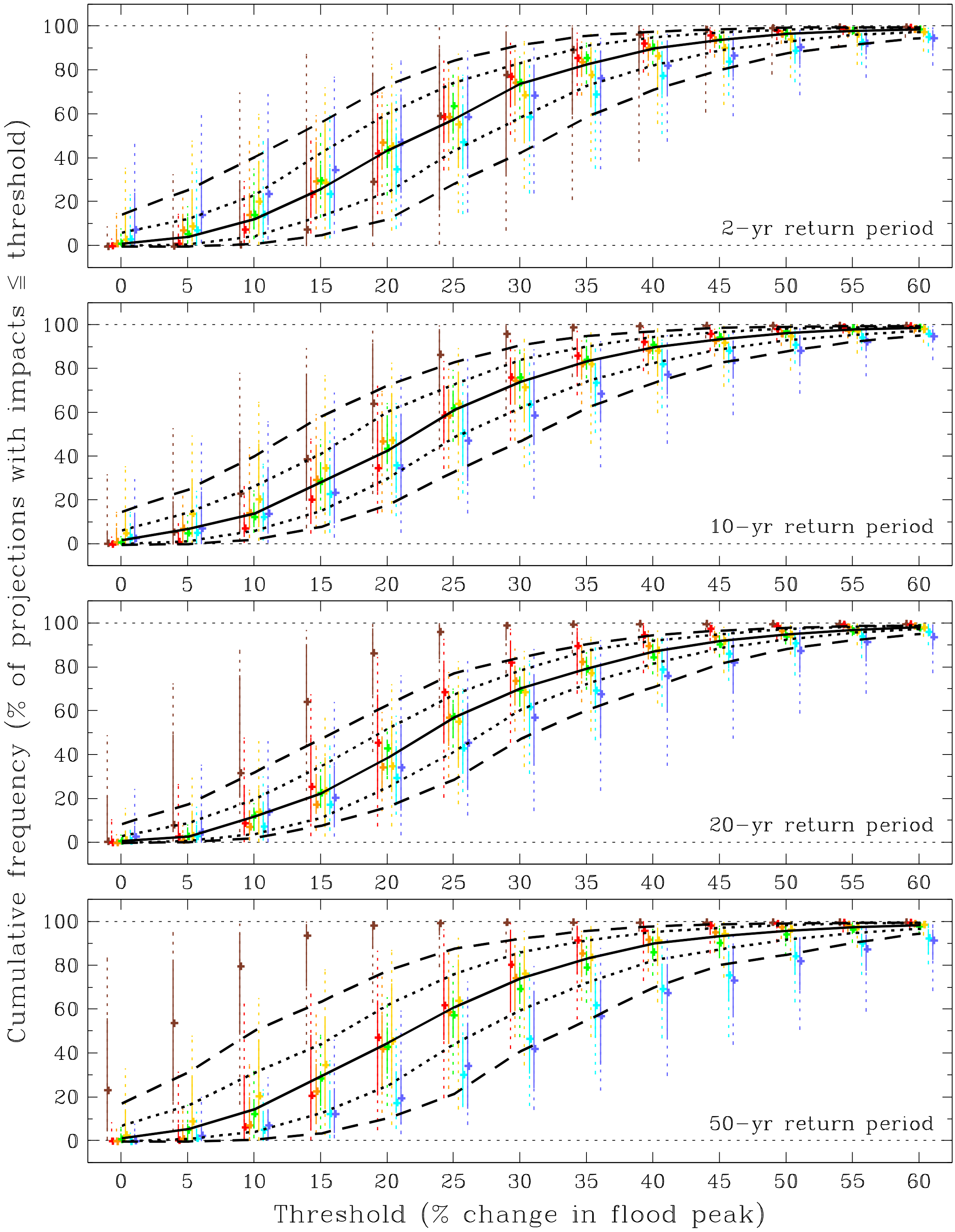

Figure 4.16 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s Medium) for the Forth river-basin region. Response-type risk (colours): Damped-Extreme (brown), Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue); central-estimate (plus sign), ±1sd (solid vertical line), ±2sd (dotted vertical line). Regional risk (black): central-estimate (solid curve), ±1sd (dotted curves), ±2sd (dashed curves).

4.5 Tweed

4.5.1 Sensitivity

A total of 31 NRFA catchments are located within the Tweed river-basin region (although 2 of these are in England rather than Scotland). The best-estimate of the response type for these catchments is generally Damped-High at the 2-year return period and Neutral at the 20- and 50-year return periods, with a combination of these at the 10-year return period (Table 4.5). The maps in Figure 4.17 show the best-estimate of the response type for each catchment at each return period, while those in Figure 4.18 show the corresponding confidence levels (High – H, Medium – M, Low – L).

Table 4.5 The number of NRFA catchments of each response type at each return period, for the Tweed river-basin region. The predominant response type is highlighted in bold at each return period.

	Return period			
Response type	2-year	10-year	20-year	50-year
Damped-Extreme	0	0	0	0
Damped-High	**26**	11	3	7
Damped-Low	1	2	6	2
Neutral	0	**14**	**14**	**14**
Mixed	4	4	8	8
Enhanced-Low	NA	NA	NA	NA
Enhanced-Medium	NA	NA	NA	NA
Total	31	31	31	31

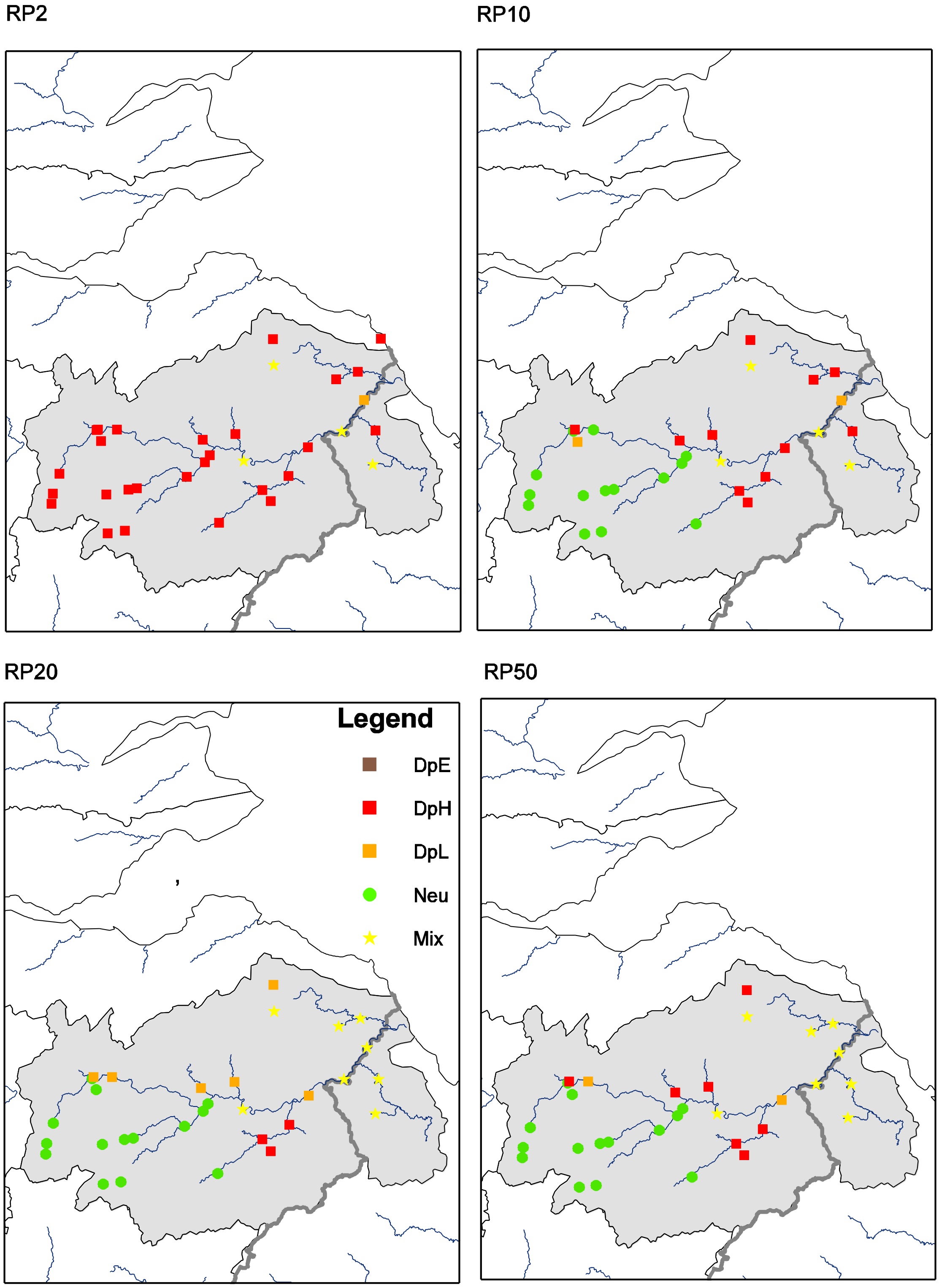

Figure 4.17 The best-estimate of the response type for each NRFA catchment in the Tweed river-basin region. The thick grey line shows the Scotland / England border.

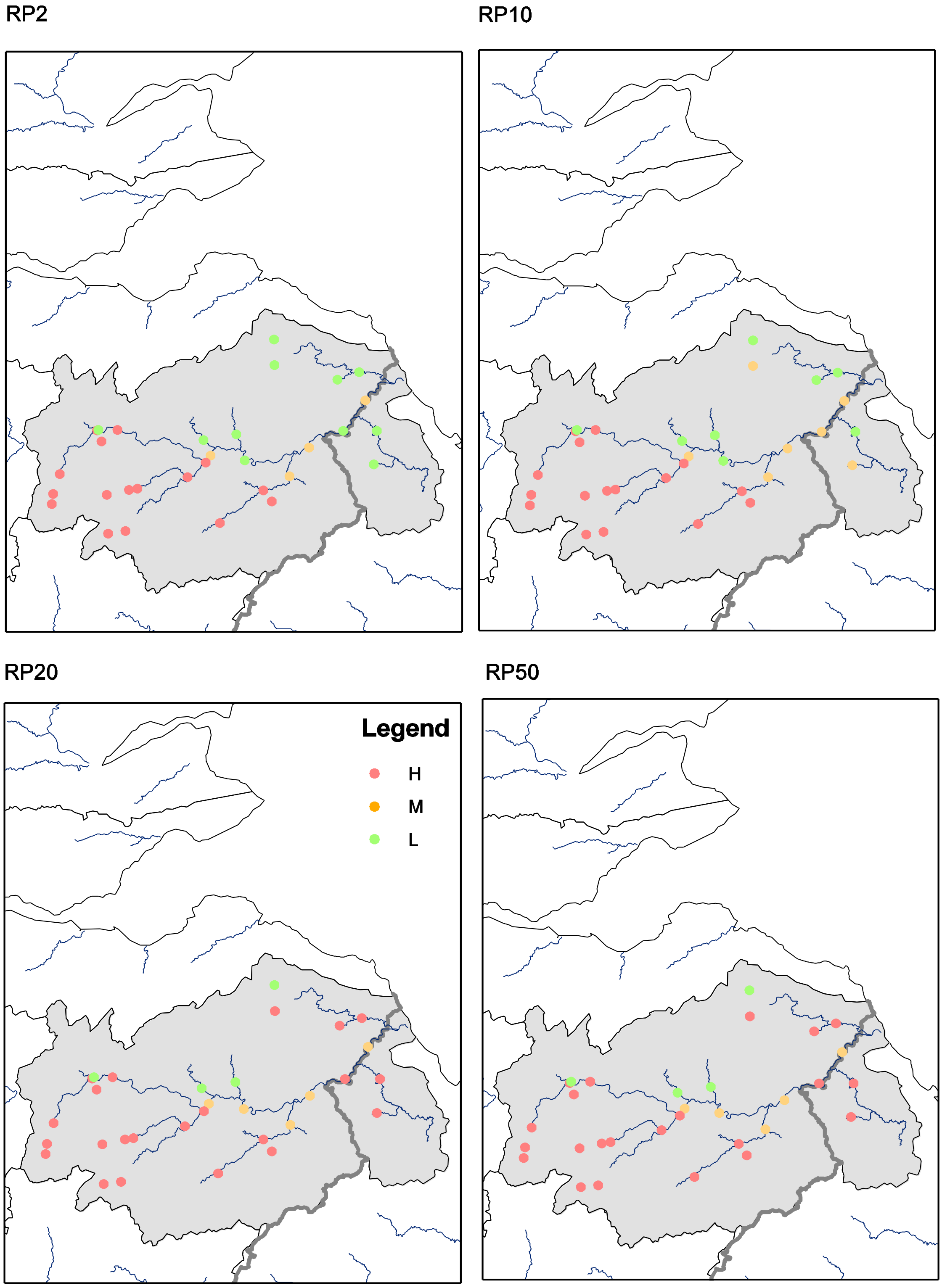

Figure 4.18 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the Tweed river-basin region.

4.5.2 Hazard

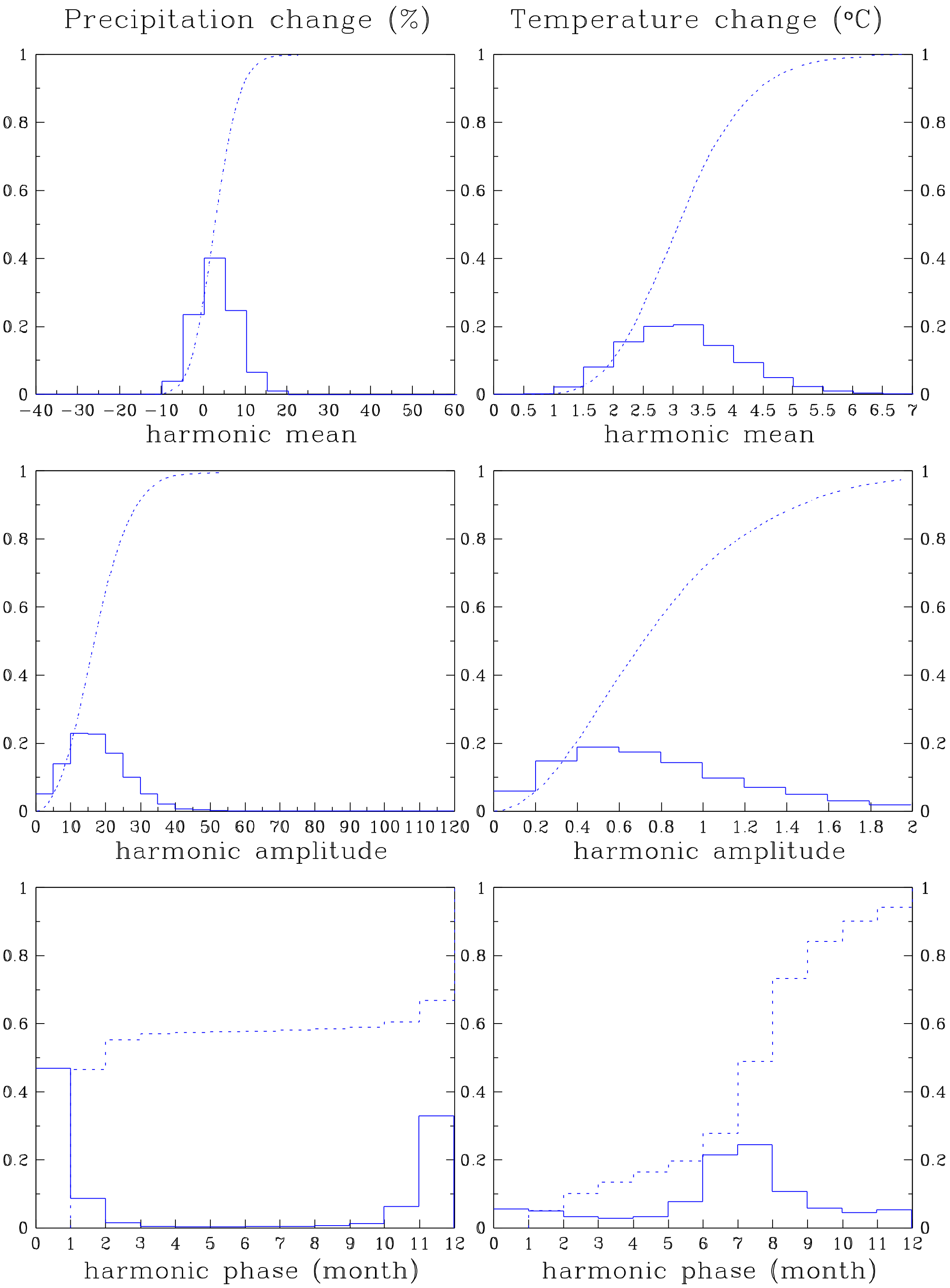

Figure 4.19 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s Medium) for the Tweed river-basin region.

4.5.3 Risk

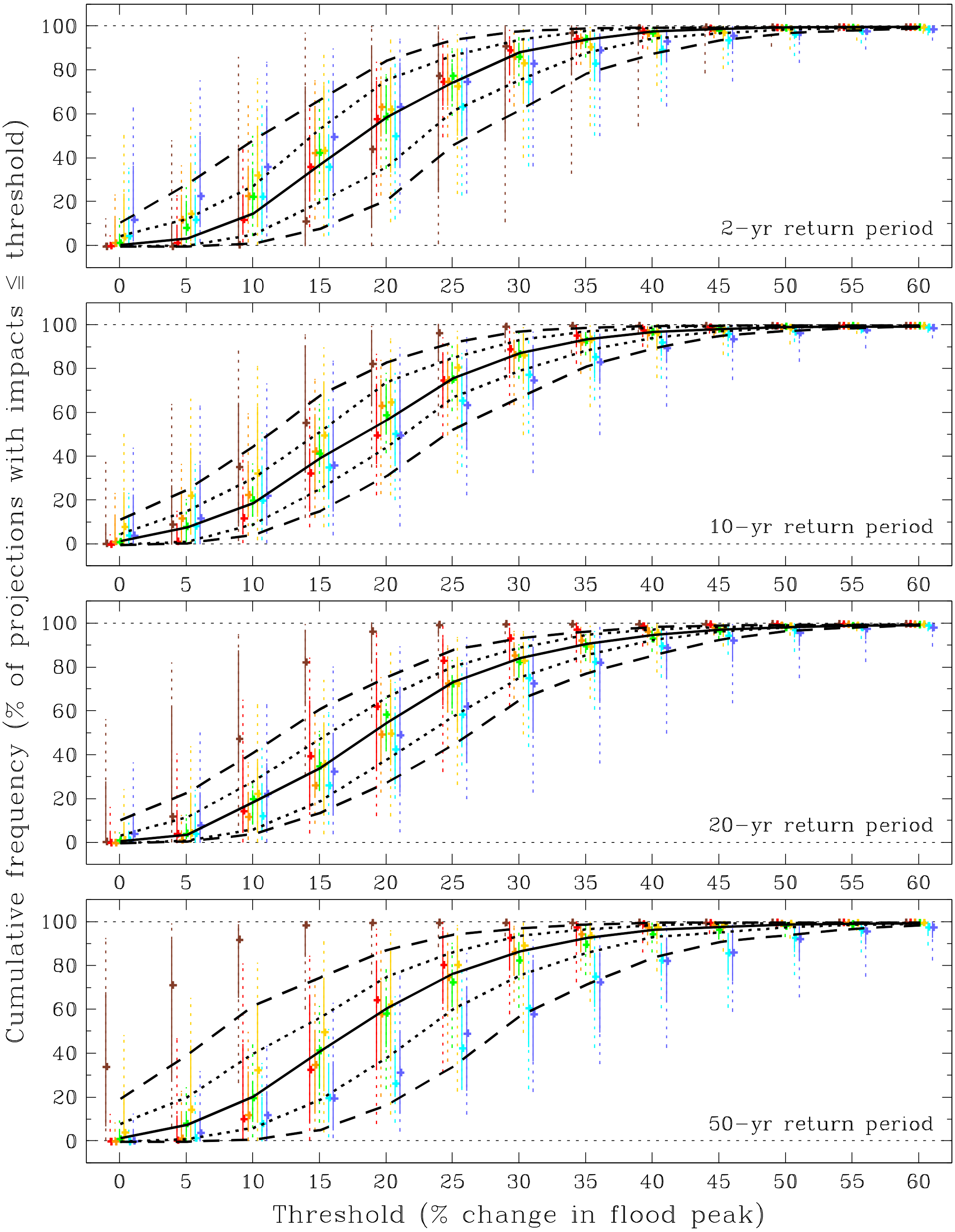

Figure 4.20 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s Medium) for the Tweed river-basin region. Response-type risk (colours): Damped-Extreme (brown), Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue); central-estimate (plus sign), ±1sd (solid vertical line), ±2sd (dotted vertical line). Regional risk (black): central-estimate (solid curve), ±1sd (dotted curves), ±2sd (dashed curves).

4.6 Solway

4.6.1 Sensitivity

A total of 43 NRFA catchments are located within the Solway river-basin region (although 15 of these are in England rather than Scotland). The best-estimate of the response type for these catchments is generally Damped-High at the 2-year return period and Neutral at higher return periods (Table 4.6). The maps in Figure 4.21 show the best-estimate of the response type for each catchment at each return period, while those in Figure 4.22 show the corresponding confidence levels (High – H, Medium – M, Low – L).

Table 4.6 The number of NRFA catchments of each response type at each return period, for the Solway river-basin region. The predominant response type is highlighted in bold at each return period.

	Return period			
Response type	2-year	10-year	20-year	50-year
Damped-Extreme	0	0	0	0
Damped-High	**40**	5	3	3
Damped-Low	0	10	2	2
Neutral	2	**28**	**37**	**37**
Mixed	1	0	1	1
Enhanced-Low	NA	NA	NA	NA
Enhanced-Medium	NA	NA	NA	NA
Total	43	43	43	43

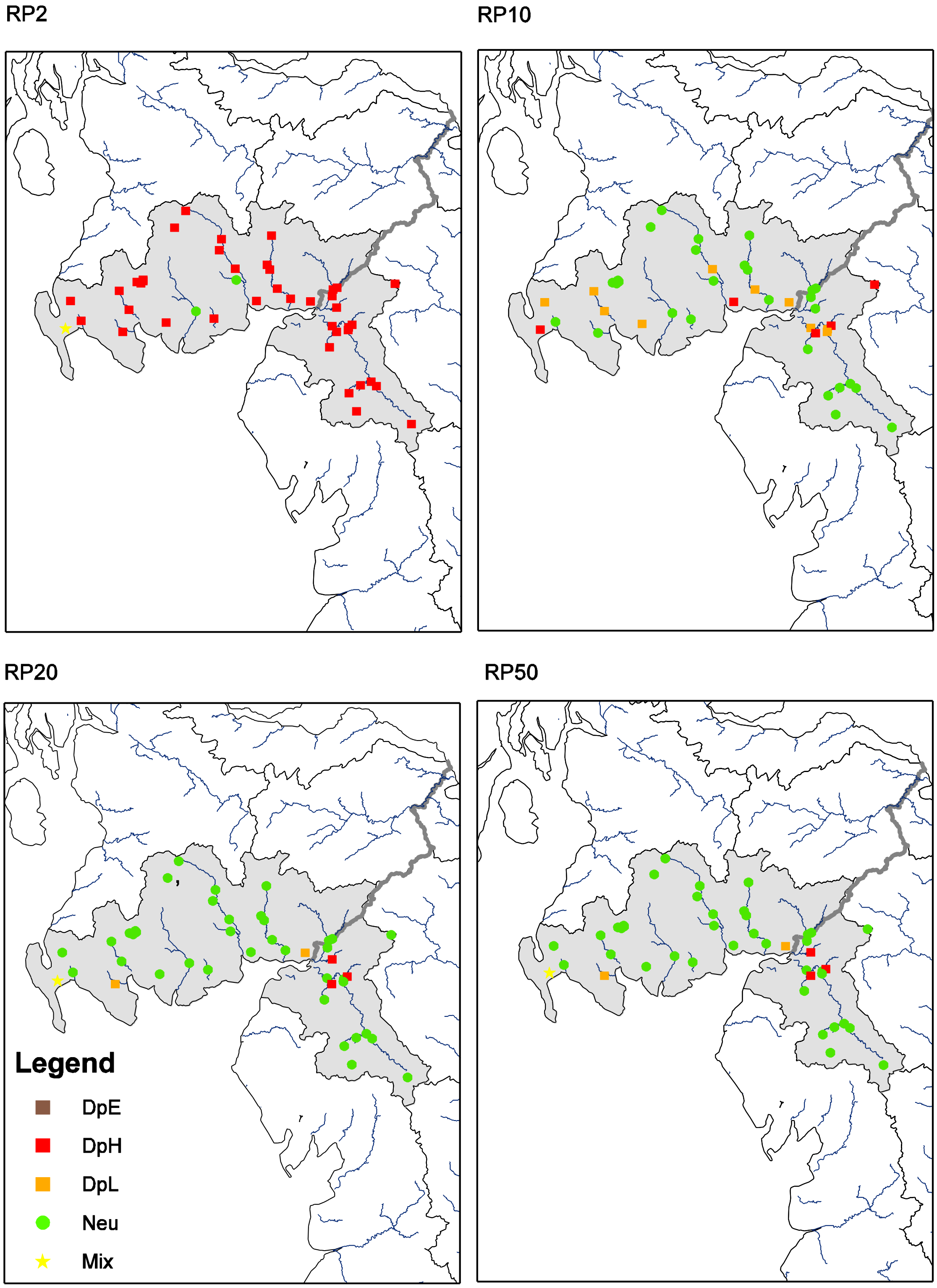

Figure 4.21 The best-estimate of the response type for each NRFA catchment in the Solway river-basin region. The thick grey line shows the Scotland / England border.

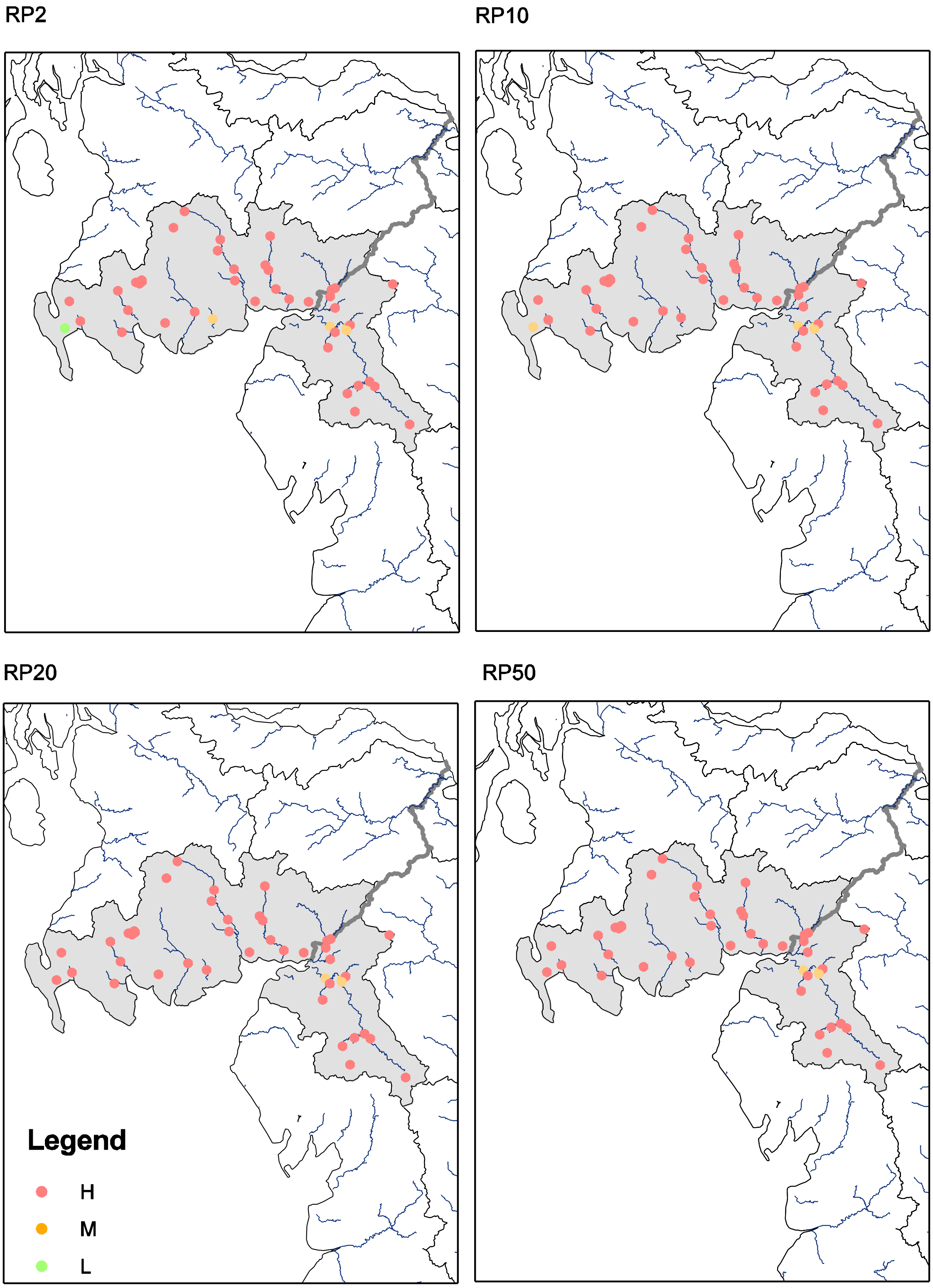

Figure 4.22 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the Solway river-basin region.

4.6.2 Hazard

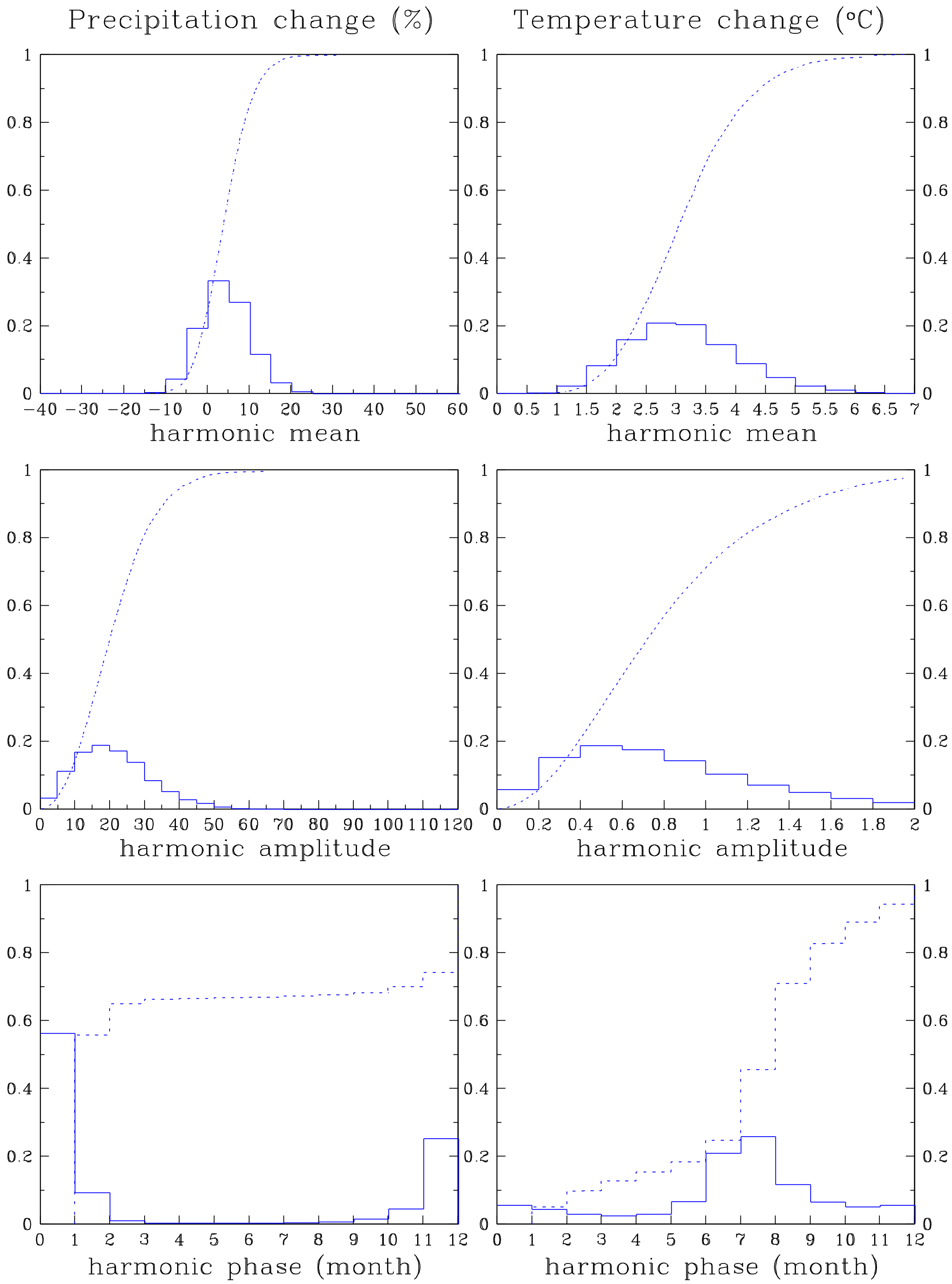

Figure 4.23 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s Medium) for the Solway river-basin region.

4.6.3 Risk

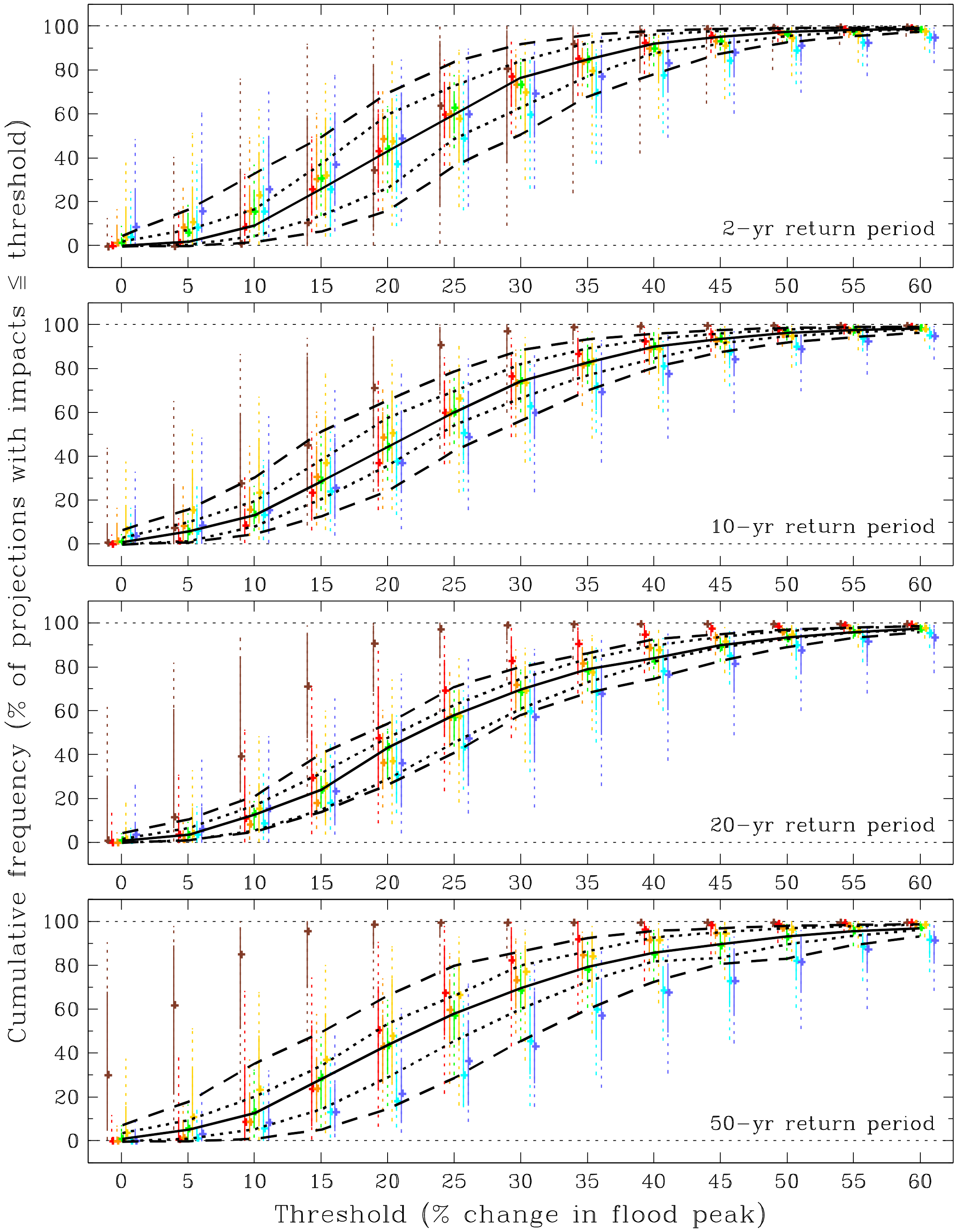

Figure 4.24 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s Medium) for the Solway river-basin region. Response-type risk (colours): Damped-Extreme (brown), Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue); central-estimate (plus sign), ±1sd (solid vertical line), ±2sd (dotted vertical line). Regional risk (black): central-estimate (solid curve), ±1sd (dotted curves), ±2sd (dashed curves).

4.7 Clyde

4.7.1 Sensitivity

A total of 59 NRFA catchments are located within the Clyde river-basin region. The best-estimate of the response type for these catchments is generally Damped-High at the 2-year return period and Neutral at the 20- and 50-year return periods, with a combination of these at the 10-year return period (Table 4.7). The maps in Figure 4.25 show the best-estimate of the response type for each catchment at each return period, while those in Figure 4.26 show the corresponding confidence levels (High – H, Medium – M, Low – L).

Table 4.7 The number of NRFA catchments of each response type at each return period, for the Clyde river-basin region. The predominant response type is highlighted in bold at each return period.

	Return period			
Response type	2-year	10-year	20-year	50-year
Damped-Extreme	4	4	4	4
Damped-High	**49**	**25**	5	5
Damped-Low	0	8	16	16
Neutral	6	22	**34**	**34**
Mixed	0	0	0	0
Enhanced-Low	NA	NA	NA	NA
Enhanced-Medium	NA	NA	NA	NA
Total	59	59	59	59

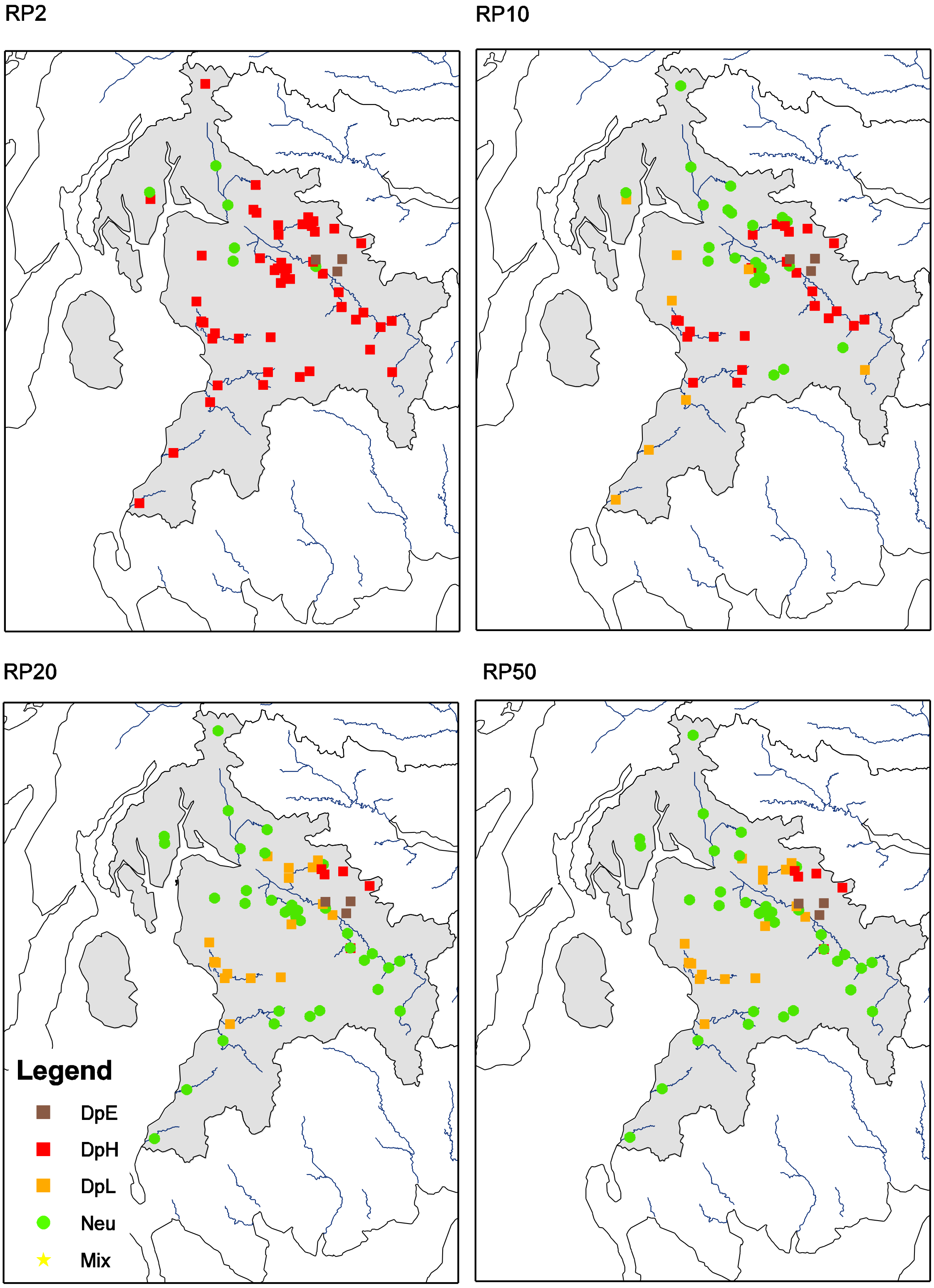

Figure 4.25 The best-estimate of the response type for each NRFA catchment in the Clyde river-basin region.

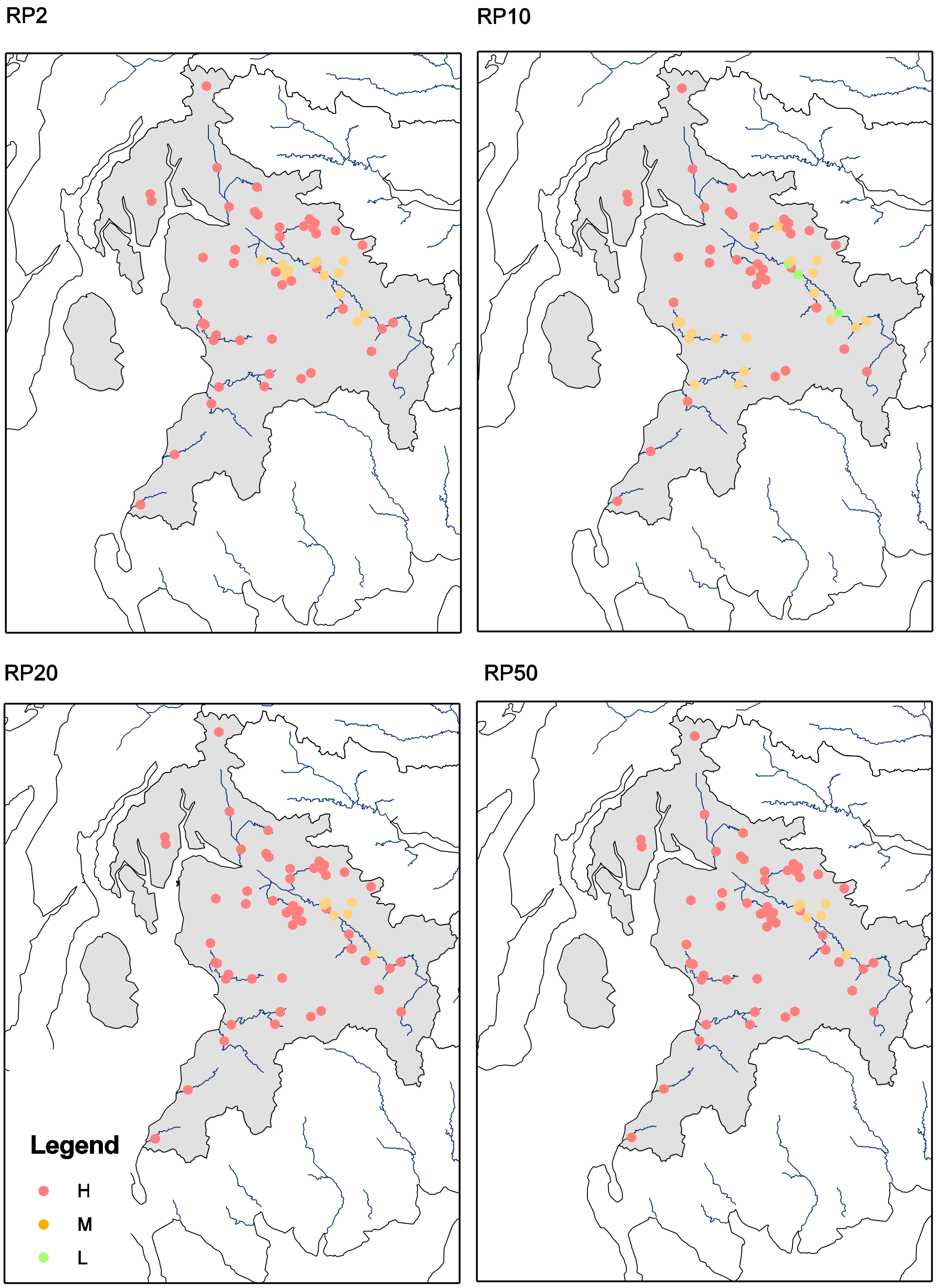

Figure 4.26 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the Clyde river-basin region.

4.7.2 Hazard

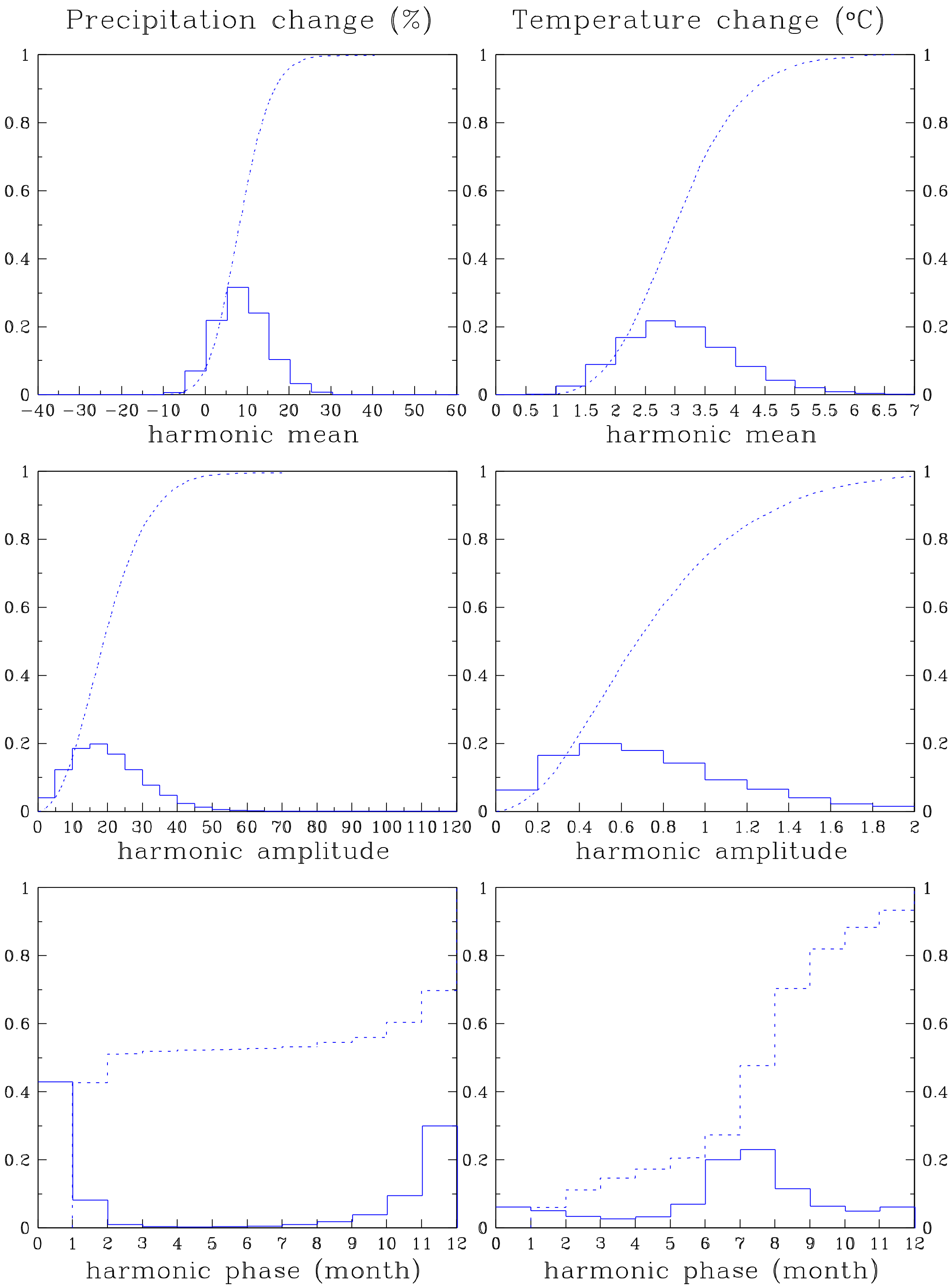

Figure 4.27 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s Medium) for the Clyde river-basin region.

4.7.3 Risk

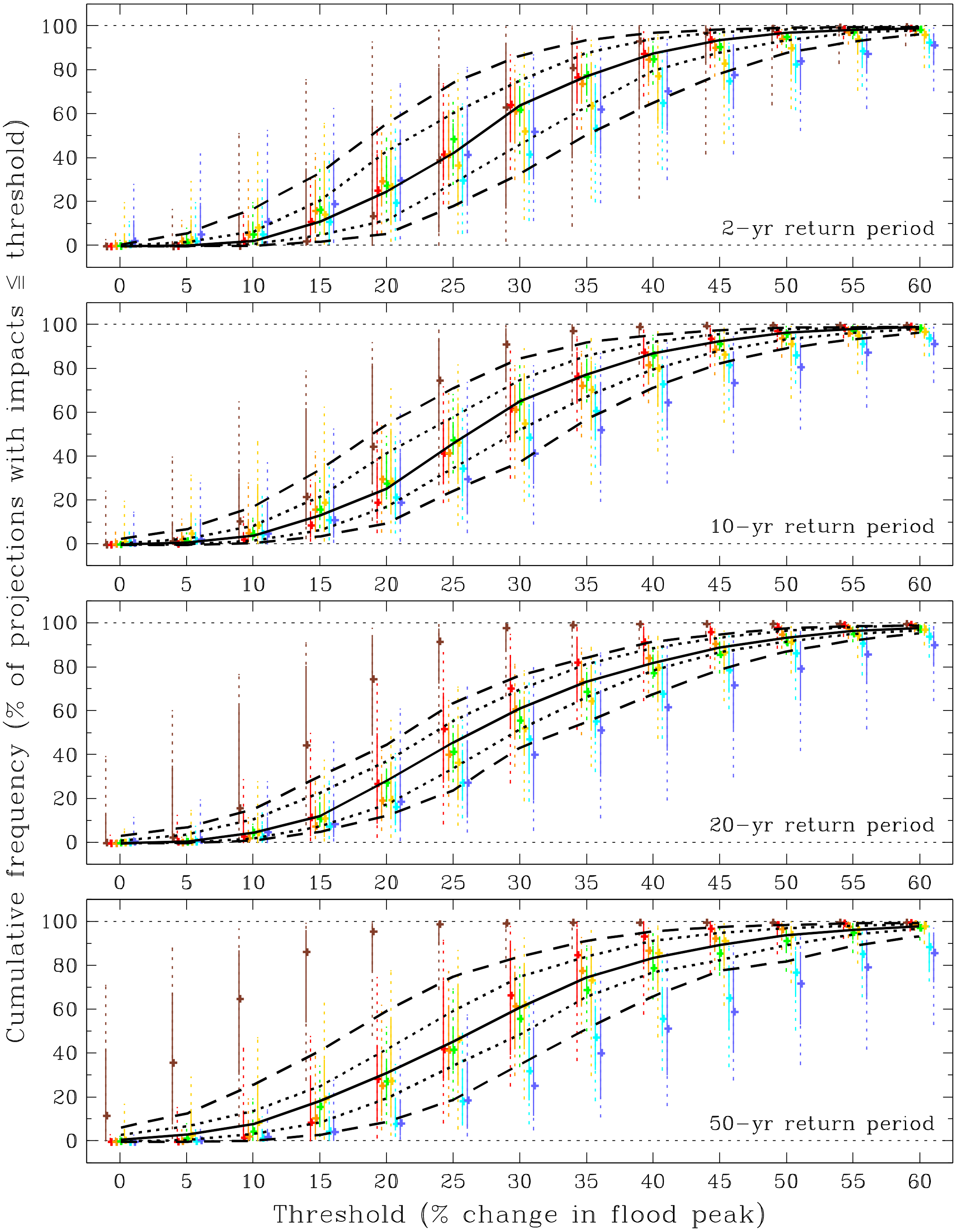

Figure 4.28 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s Medium) for the Clyde river-basin region. Response-type risk (colours): Damped-Extreme (brown), Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue); central-estimate (plus sign), ±1sd (solid vertical line), ±2sd (dotted vertical line). Regional risk (black): central-estimate (solid curve), ±1sd (dotted curves), ±2sd (dashed curves).

4.8 Argyll

4.8.1 Sensitivity

A total of 14 NRFA catchments are located within the Argyll river-basin region. The best-estimate of the response type for these catchments is generally Damped-High at the 2-year return period and Neutral at higher return periods (Table 4.8). The maps in Figure 4.29 show the best-estimate of the response type for each catchment at each return period, while those in Figure 4.30 show the corresponding confidence levels (High – H, Medium – M, Low – L).

Table 4.8 The number of NRFA catchments of each response type at each return period, for the Argyll river-basin region. The predominant response type is highlighted in bold at each return period.

	Return period			
Response type	2-year	10-year	20-year	50-year
Damped-Extreme	0	0	0	0
Damped-High	**10**	0	0	0
Damped-Low	0	4	0	0
Neutral	4	**10**	**14**	**14**
Mixed	0	0	0	0
Enhanced-Low	NA	NA	NA	NA
Enhanced-Medium	NA	NA	NA	NA
Total	14	14	14	14

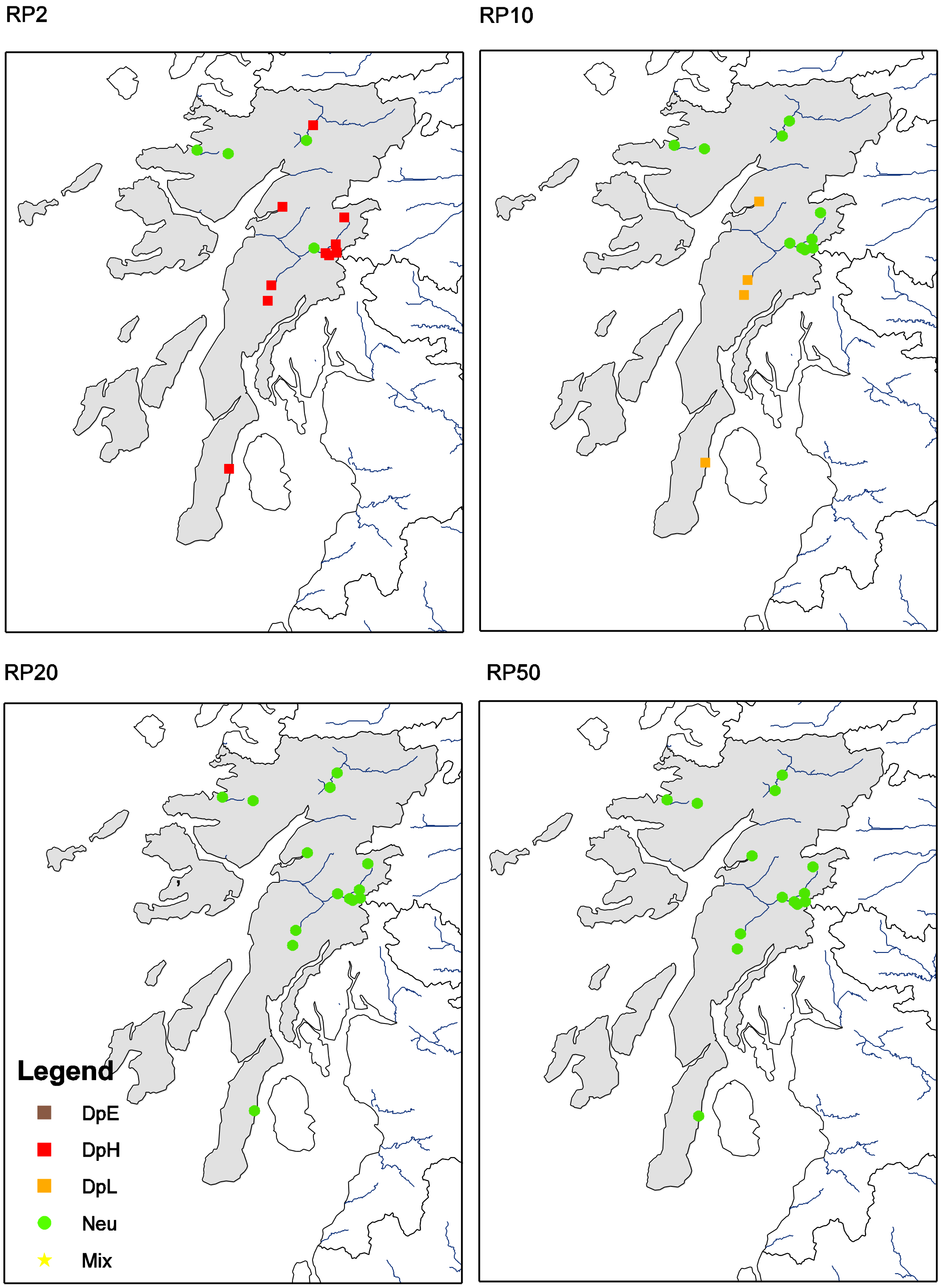

Figure 4.29 The best-estimate of the response type for each NRFA catchment in the Argyll river-basin region.

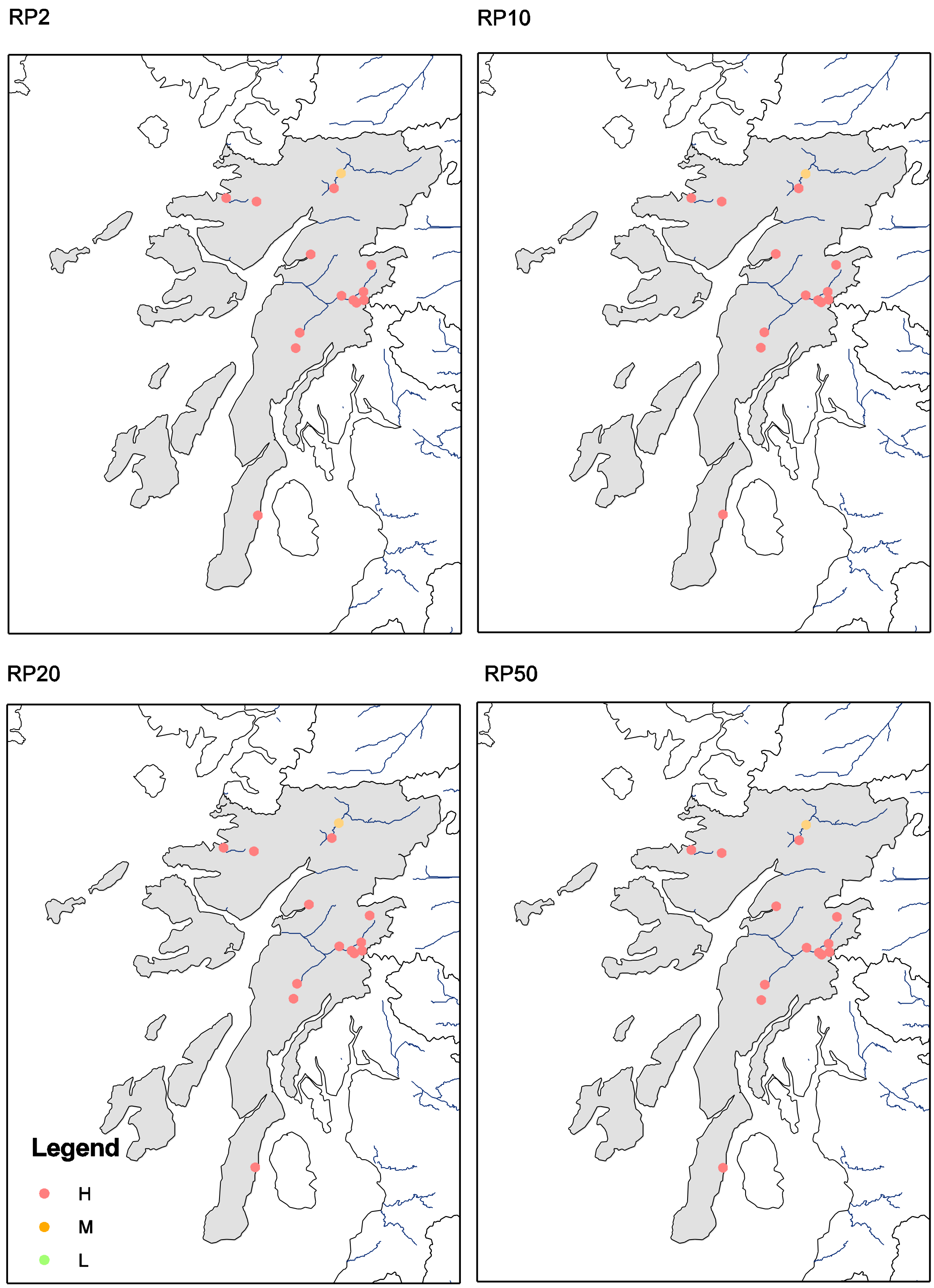

Figure 4.30 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the Argyll river-basin region.

4.8.2 Hazard

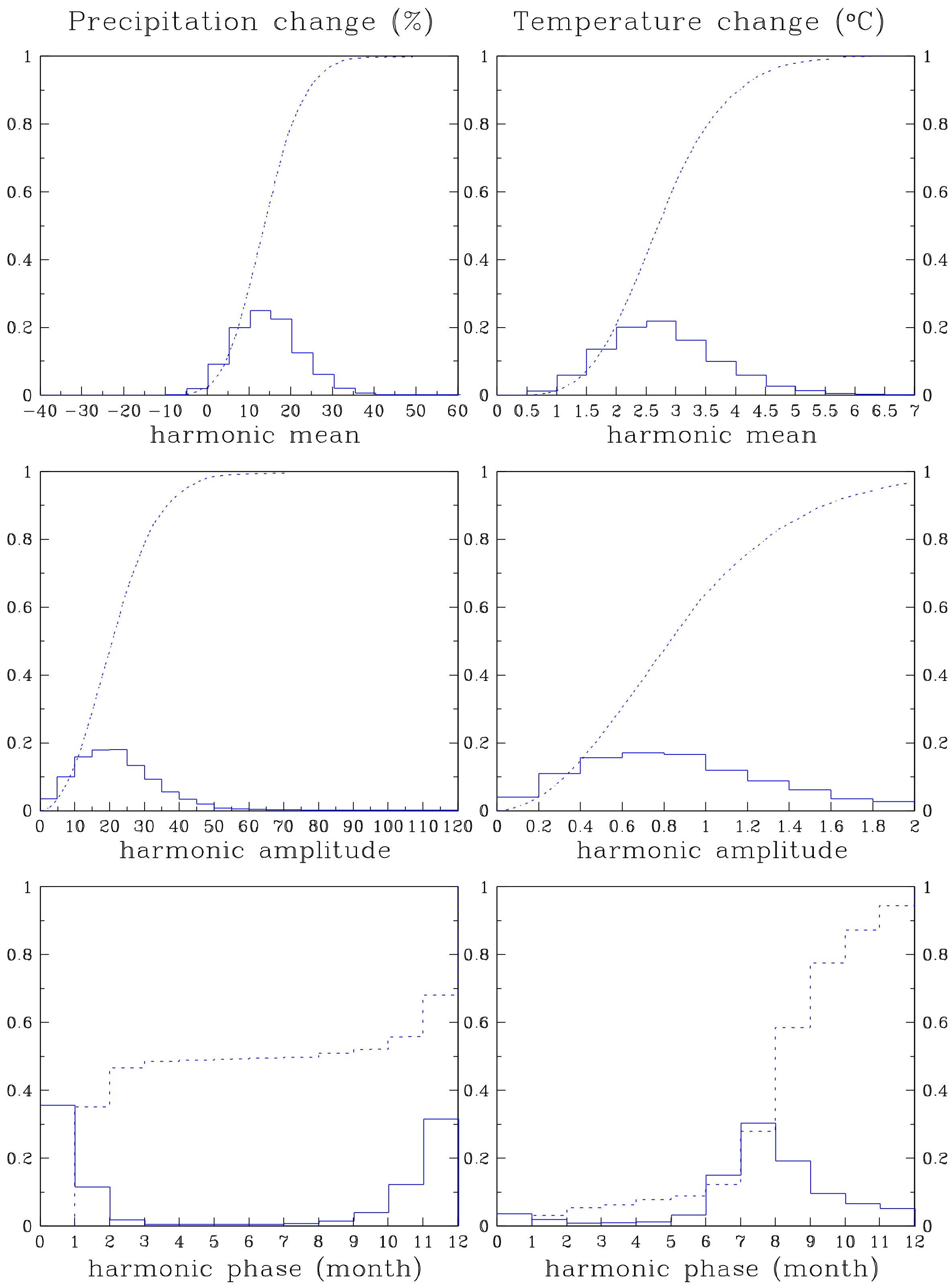

Figure 4.31 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s Medium) for the Argyll river-basin region.

4.8.3 Risk

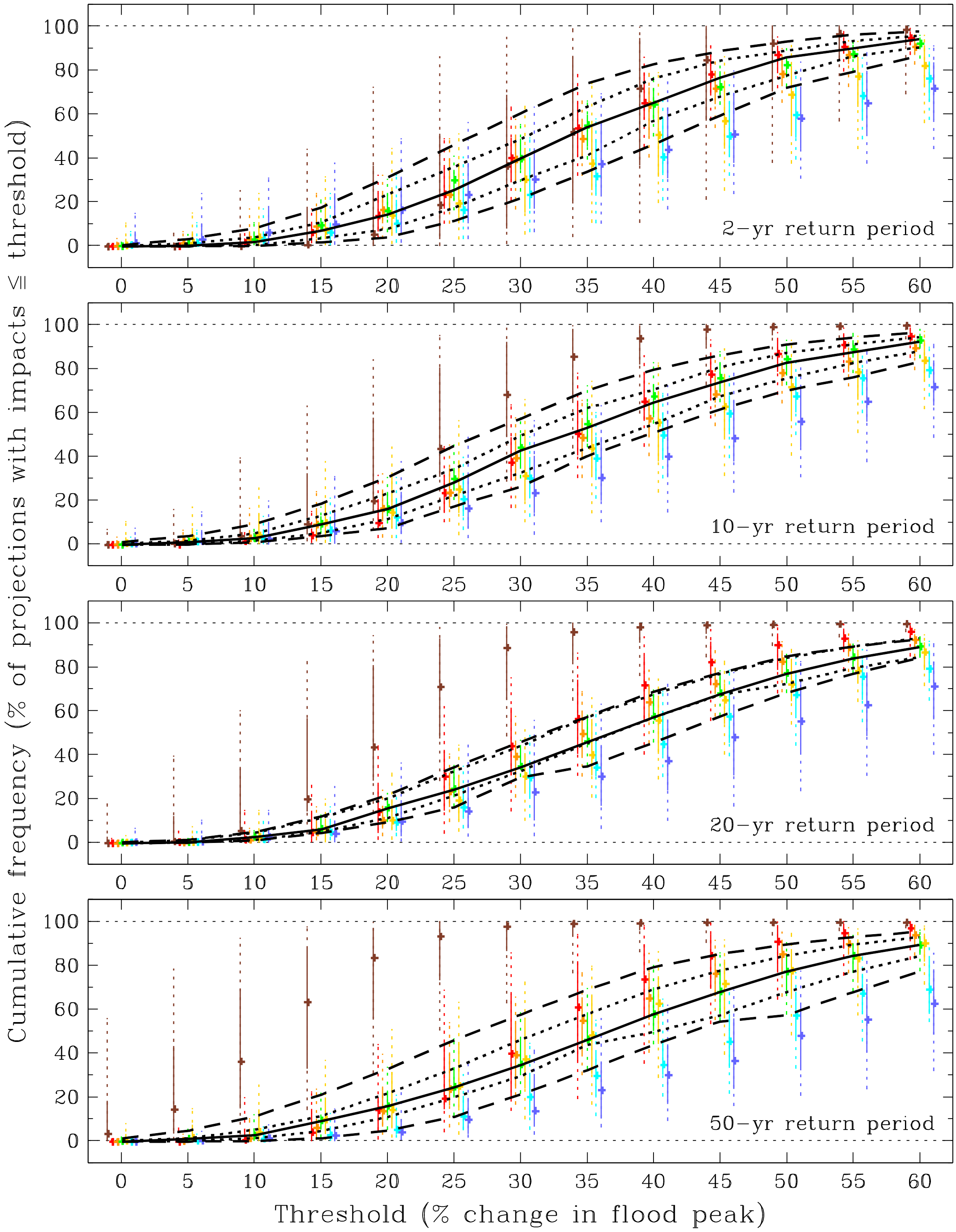

Figure 4.32 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s Medium) for the Argyll river-basin region. Response-type risk (colours): Damped-Extreme (brown), Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue); central-estimate (plus sign), ±1sd (solid vertical line), ±2sd (dotted vertical line). Regional risk (black): central-estimate (solid curve), ±1sd (dotted curves), ±2sd (dashed curves).

4.9 West Highland

4.9.1 Sensitivity

There are only 6 NRFA catchment located within the West Highland river-basin region. The best-estimate of the response type for these catchments is generally Neutral (Table 4.9). The maps in Figure 4.33 show the best-estimate of the response type for each catchment at each return period, while those in Figure 4.34 show the corresponding confidence levels (High – H, Medium – M, Low – L).

Table 4.9 The number of NRFA catchments of each response type at each return period, for the West Highland river-basin region. The predominant response type is highlighted in bold at each return period.

	Return period			
Response type	2-year	10-year	20-year	50-year
Damped-Extreme	0	0	0	0
Damped-High	1	1	0	0
Damped-Low	0	0	0	0
Neutral	**5**	**5**	**6**	**6**
Mixed	0	0	0	0
Enhanced-Low	NA	NA	NA	NA
Enhanced-Medium	NA	NA	NA	NA
Total	6	6	6	6

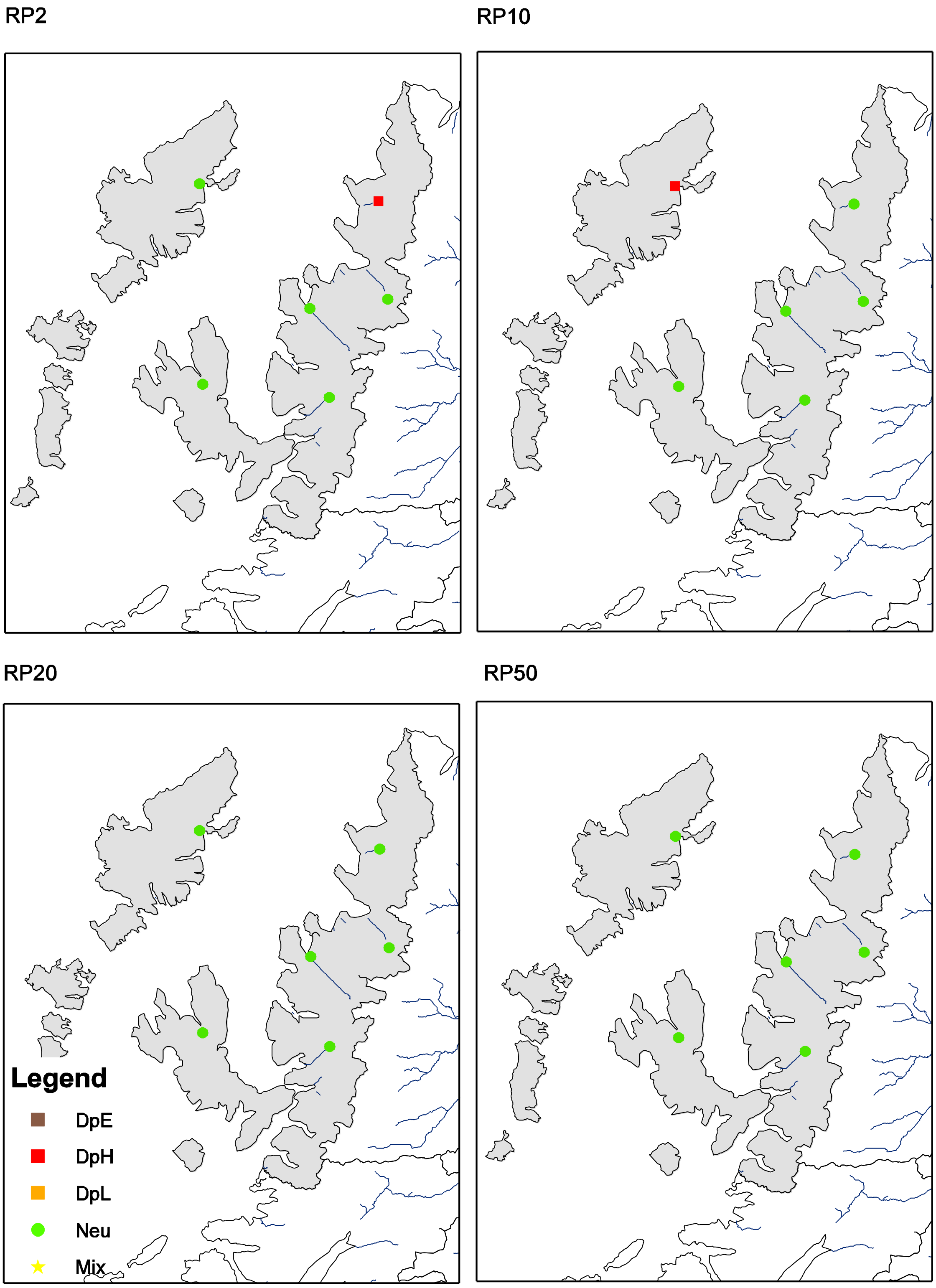

Figure 4.33 The best-estimate of the response type for each NRFA catchment in the West Highland river-basin region.

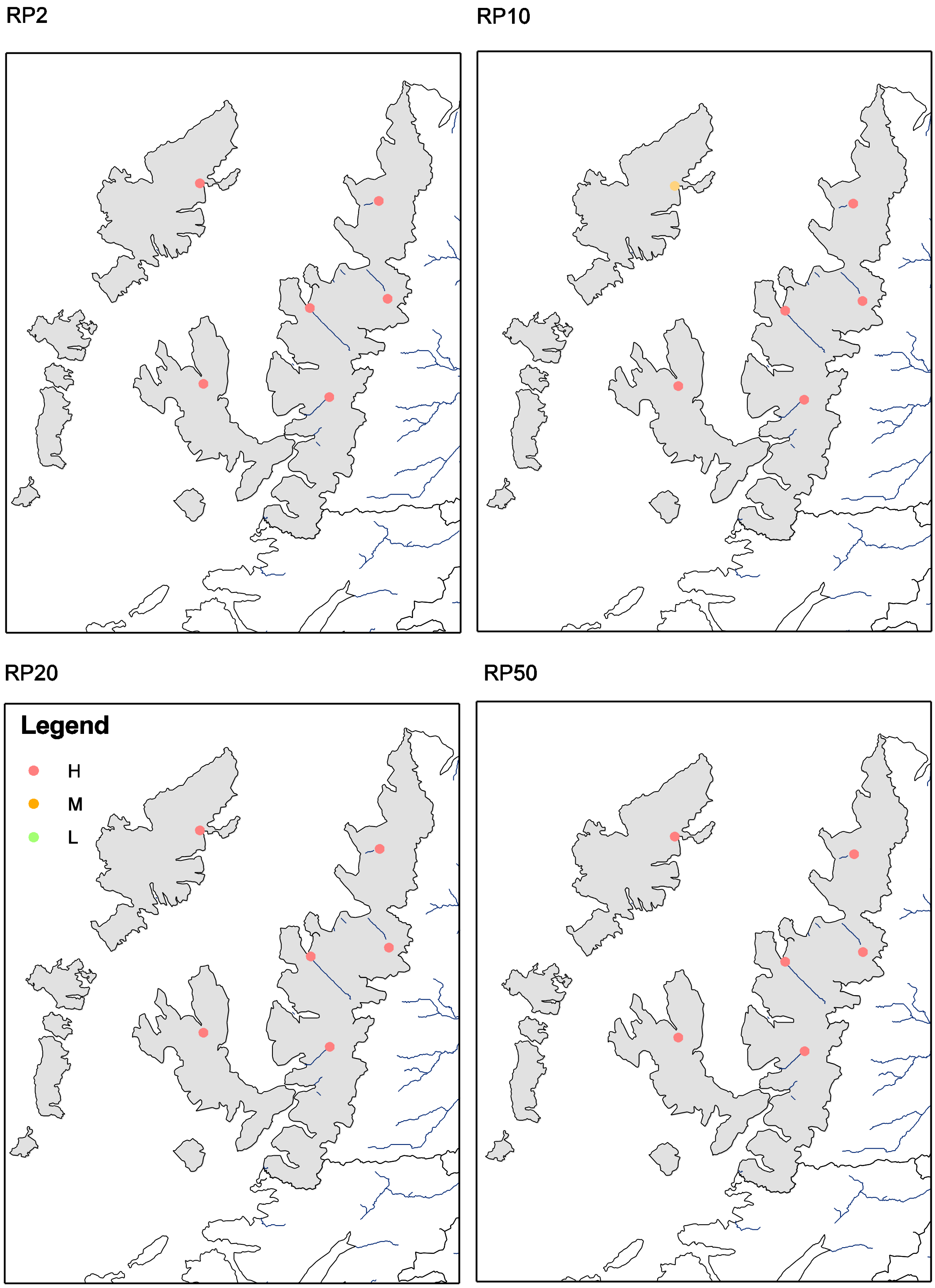

Figure 4.34 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the West Highland river-basin region.

4.9.2 Hazard

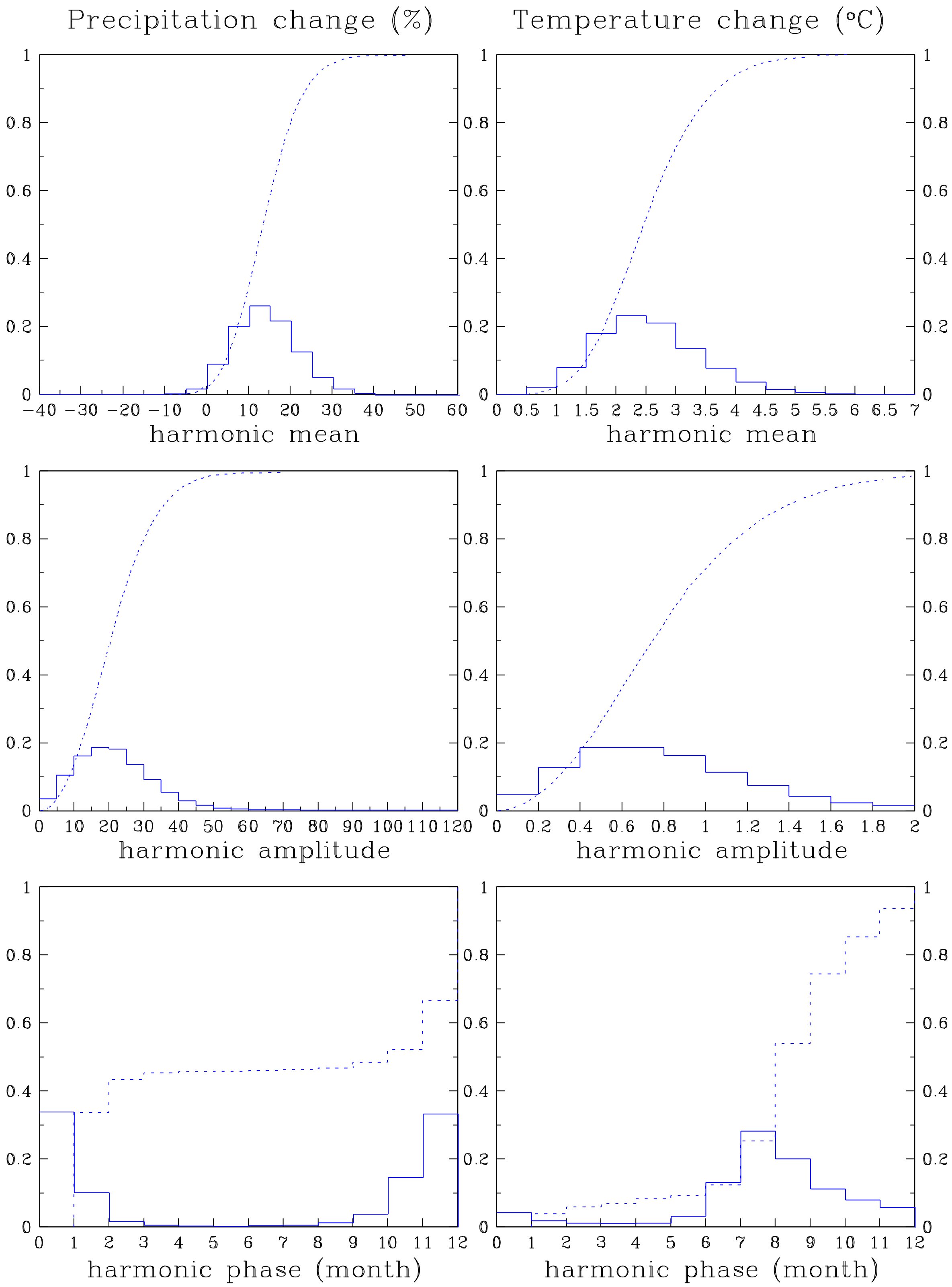

Figure 4.35 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s Medium) for the West Highland river-basin region.

4.9.3 Risk

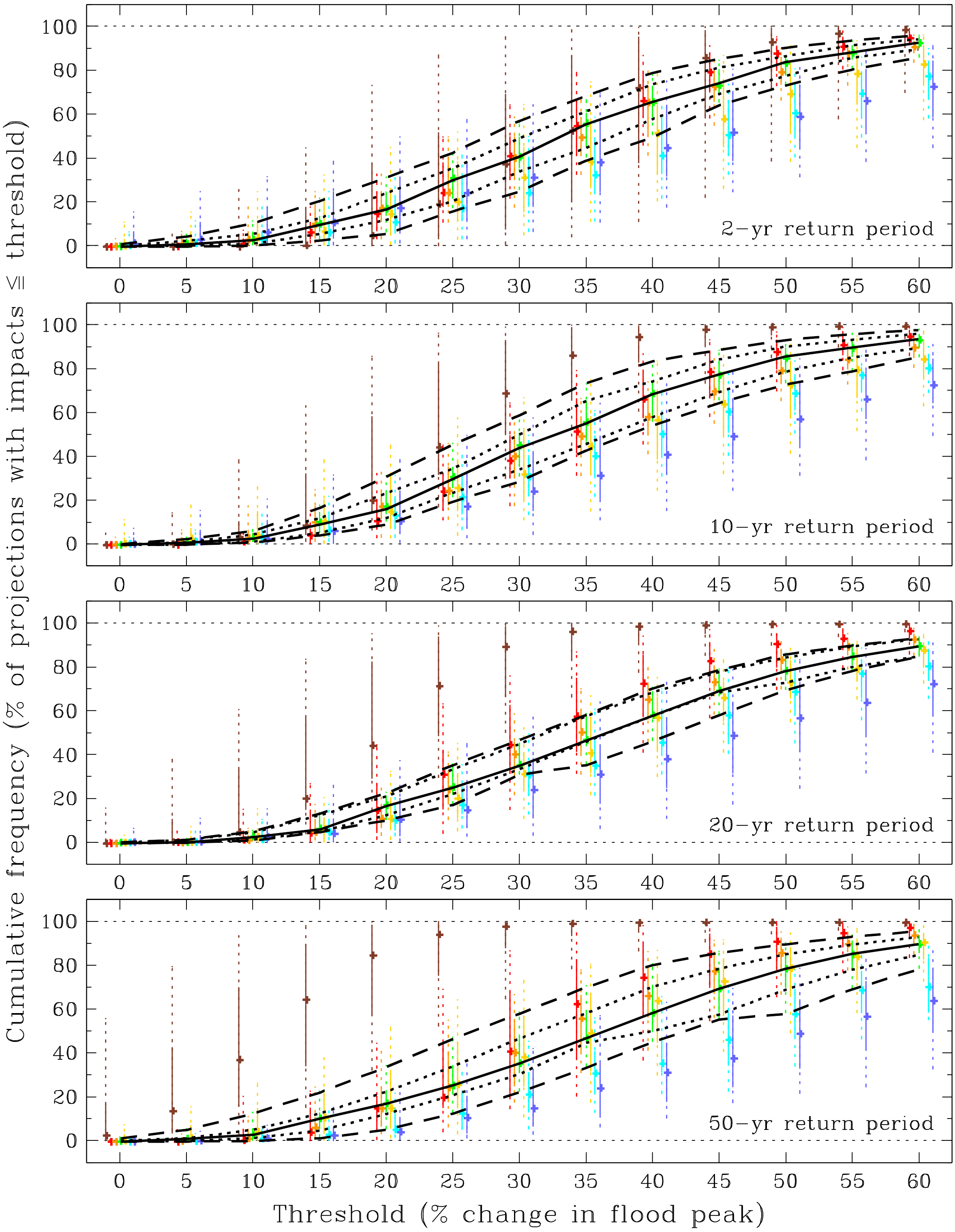

Figure 4.36 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s Medium) for the West Highland river-basin region. Response-type risk (colours): Damped-Extreme (brown), Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue); central-estimate (plus sign), ±1sd (solid vertical line), ±2sd (dotted vertical line). Regional risk (black): central-estimate (solid curve), ±1sd (dotted curves), ±2sd (dashed curves).

4.10 Orkney and Shetland

4.10.1 Sensitivity

There is only 1 NRFA catchment located within the Orkney and Shetland river-basin region. The best-estimate of the response type of this catchment is Damped-High (Table 4.10). The maps for the North Highland river-basin region include the best-estimate of the response type for this catchment at each return period (Figure 4.1), and the corresponding confidence levels (Figure 4.2; High – H, Medium – M, Low – L).

Table 4.10 The number of NRFA catchments of each response type at each return period, for the Orkney and Shetland river-basin region.

	Return period			
Response type	2-year	10-year	20-year	50-year
Damped-Extreme	0	0	0	0
Damped-High	**1**	**1**	**1**	**1**
Damped-Low	0	0	0	0
Neutral	0	0	0	0
Mixed	0	0	0	0
Enhanced-Low	NA	NA	NA	NA
Enhanced-Medium	NA	NA	NA	NA
Total	1	1	1	1

4.10.2 Hazard

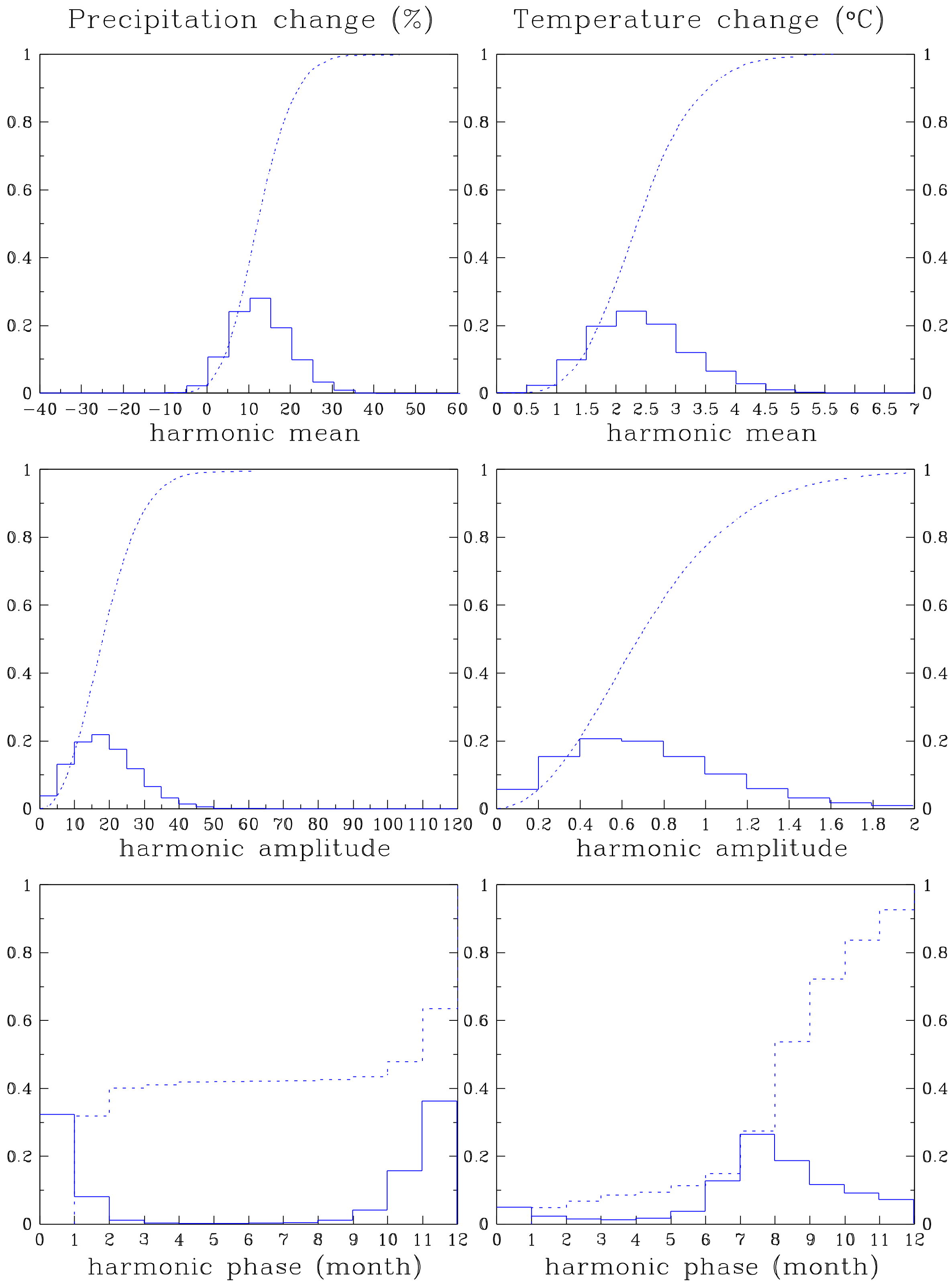

Figure 4.37 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s Medium) for the Orkney and Shetland river-basin region.

4.10.3 Risk

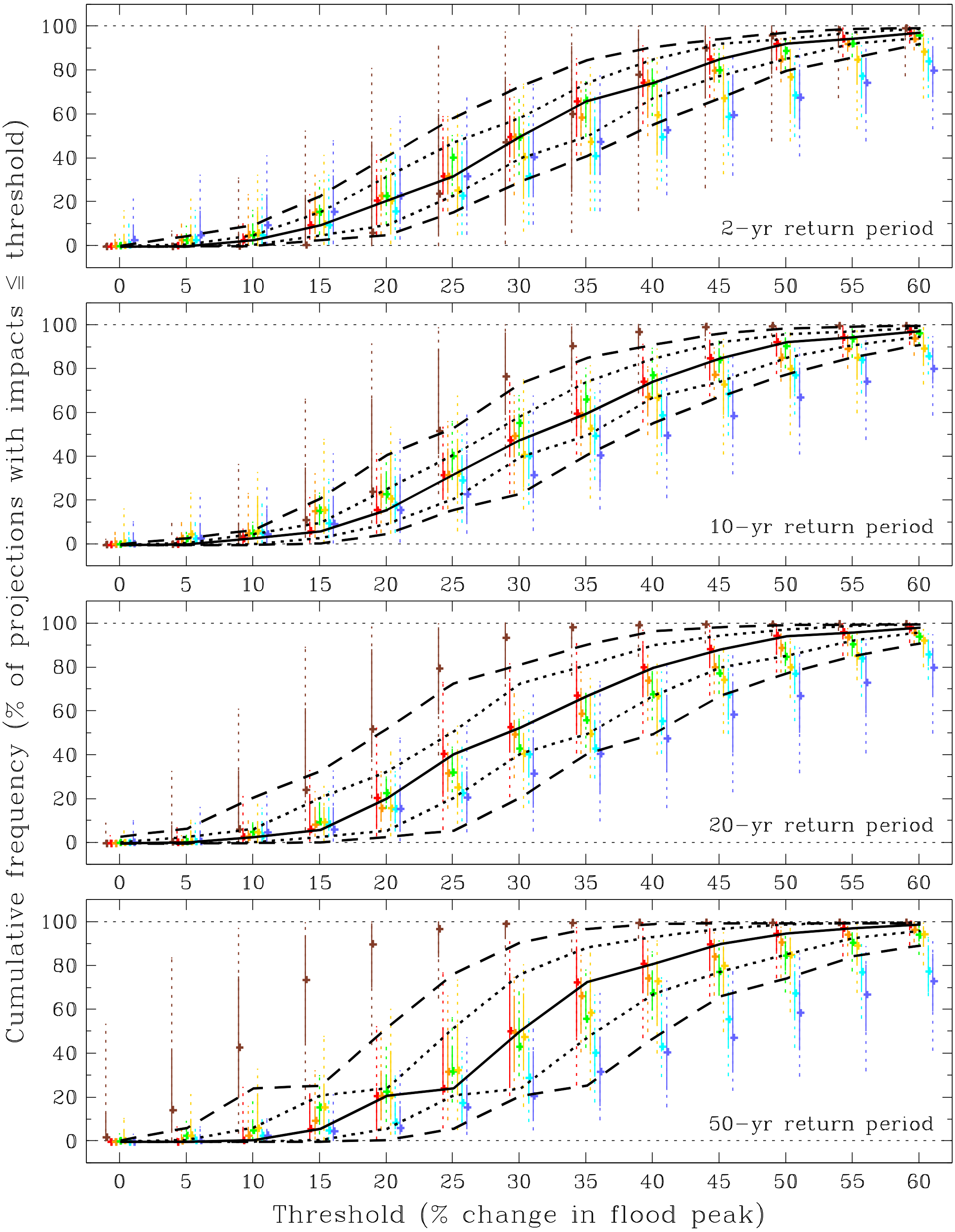

Figure 4.38 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s Medium) for the Orkney and Shetland river-basin region. Response-type risk (colours): Damped-Extreme (brown), Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue); central-estimate (plus sign), ±1sd (solid vertical line), ±2sd (dotted vertical line). Regional risk (black): central-estimate (solid curve), ±1sd (dotted curves), ±2sd (dashed curves).

5. Summary of results

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Section 5: Summary of results

This section summarises the sensitivity, hazard and risk results.

The sensitivity (estimated response type) of the NRFA catchments appears to be more homogeneous in some areas of Scotland than other areas. Similarly, catchments with lower confidence in the response-type estimate are generally located close to the east coast of Scotland.

The hazard clearly differs between river-basin regions. The more northerly/westerly regions tend to have a greater proportion of projections with a positive mean than do more southerly/easterly regions. In addition, the more northerly and westerly river-basin regions show greater dependence between the harmonic mean and amplitude than other regions.

The risk also clearly differs between river-basin regions. In general, regions to the west of Scotland have a greater risk that those to the east. The river-basin regions with the greatest risk, at all return periods, are Argyll and West Highland, followed by Orkney and Shetland, followed by Clyde. The river-basin region with the lowest risk, at all return periods, is North-East Scotland, followed by Tweed and Tay. The Solway, North Highland and Forth river-basin regions have quite similar central estimates of regional risk.

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5.1 Sensitivity

Although Damped-High is the predominant response type overall at the 2-year return period, and Neutral the predominant type overall at higher return periods (Table 3.2), it appears that some areas of Scotland have greater homogeneity of response types than other areas. This is illustrated by the maps in Figure 5.1, which combine those from Section 4 showing the best-estimate of the response type at each return period for each NRFA catchment in each of the 10 river-basin regions over Scotland. Similarly, the maps in Figure 5.2 combine those from Section 4 showing the confidence level associated with the best-estimate of the response type for each NRFA catchment in each of the 10 river-basin regions over Scotland. These show that those catchments with lower confidence in the response-type estimate are generally located close to the east coast of Scotland.

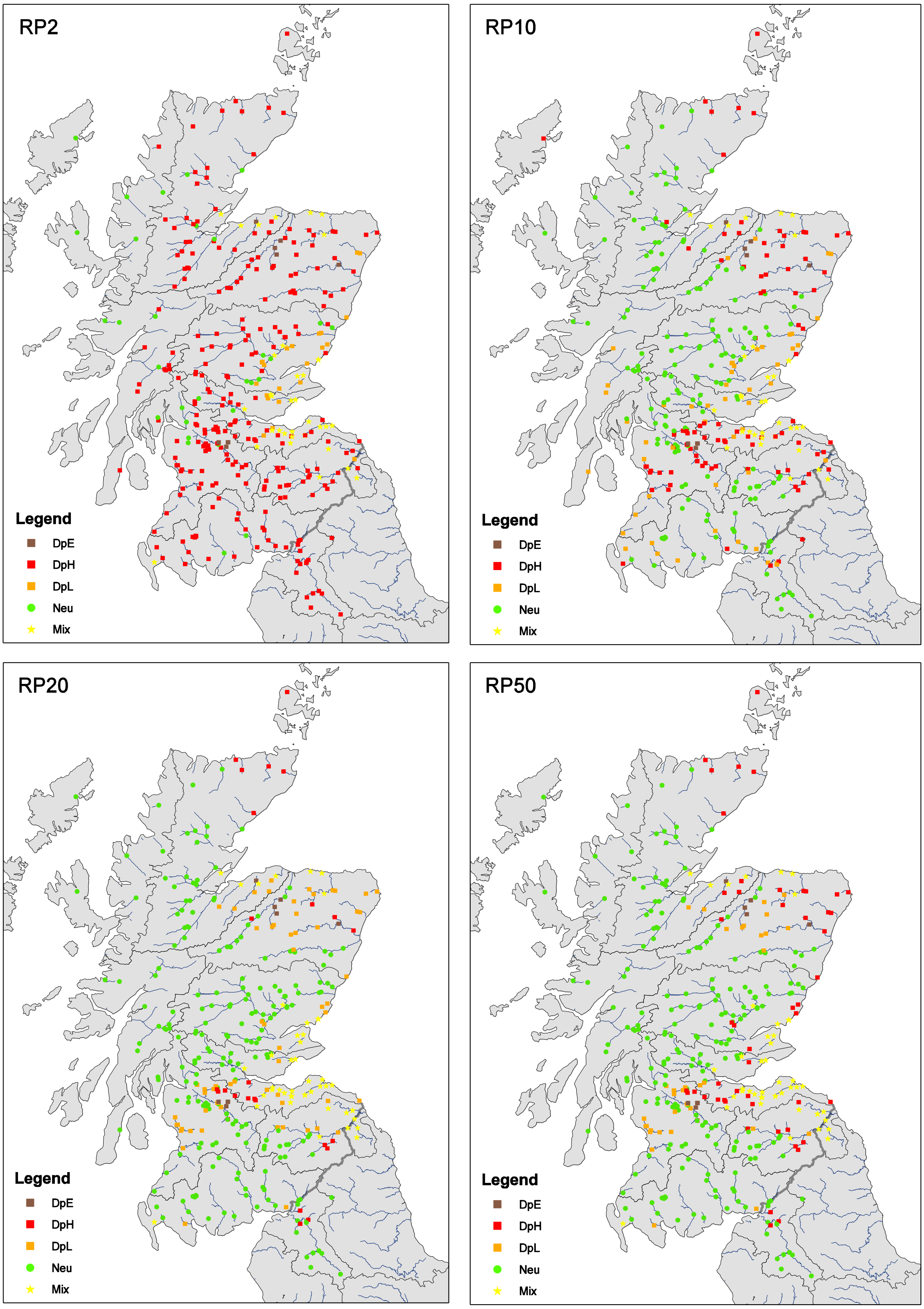

Figure 5.1 The best-estimate of the response type for each NRFA catchment in Scotland, at each of the four return periods. The thick grey line shows the Scotland / England border.

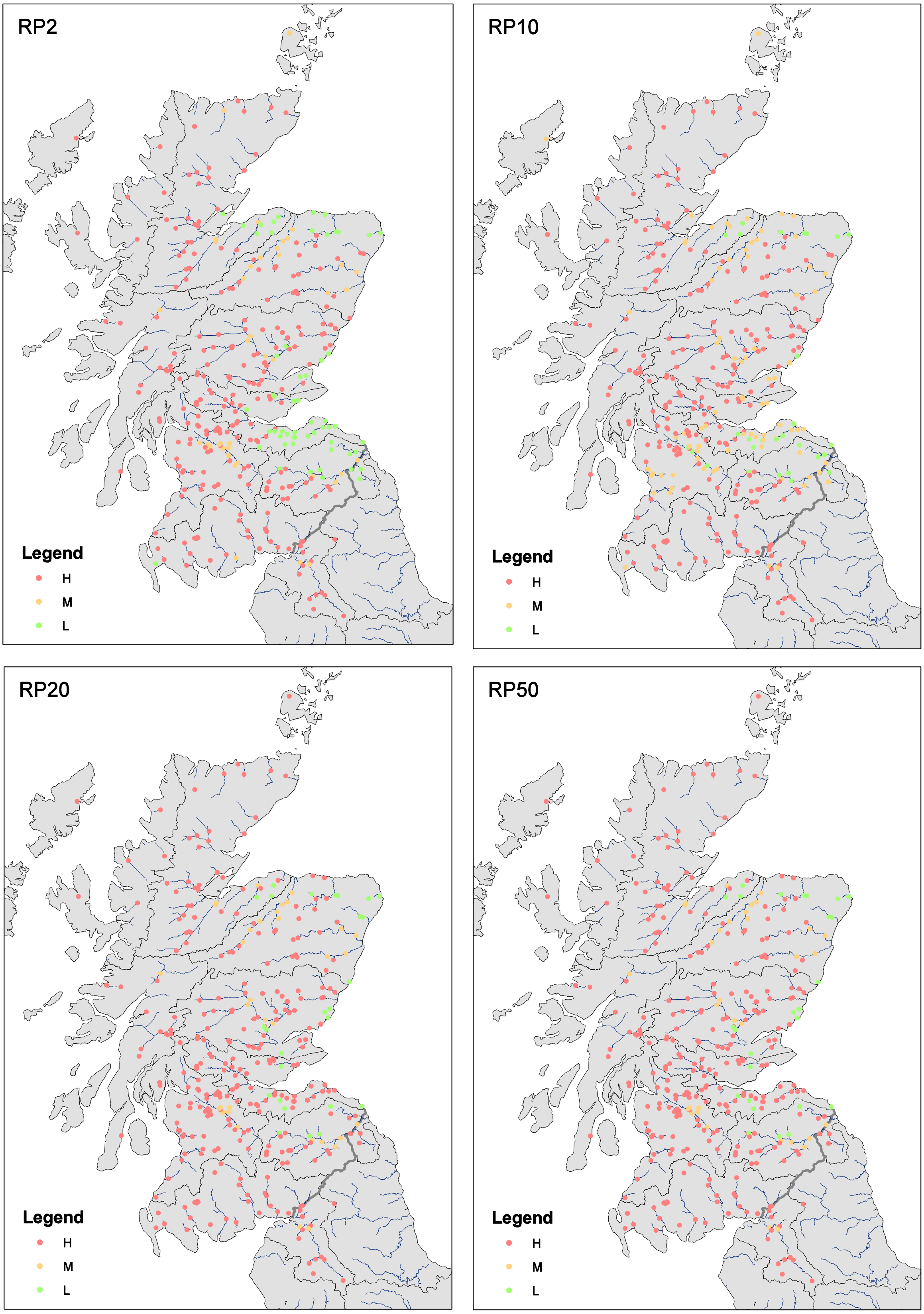

Figure 5.2 The confidence level associated with the best-estimate of the response type for each NRFA catchment in Scotland, at each of the four return periods.

5.2 Hazard

Plots of the mean against the amplitude of the harmonic functions fitted to the UKCP09 Sampled Data for precipitation (Figure 5.3, 2080s Medium) clearly show how the hazard differs between river-basin regions. The more northerly/westerly regions tend to have a greater proportion of projections with a positive mean than do more southerly/easterly regions. In addition, the more northerly and westerly river-basin regions show greater dependence between the harmonic mean and amplitude than others. For instance, the Argyll, West Highland and Orkney and Shetland river-basin regions show a positive correlation between the harmonic mean and amplitude, whilst for the Clyde, Tay and North-East Scotland river-basin regions the harmonic mean and amplitude appear to be more independent. A positive correlation between the harmonic mean and amplitude suggests a greater range of impacts, as the response patterns (sensitivity) change fastest in this direction (when both mean and amplitude are increased; Figure 1.3).

The means and amplitudes of the fitted precipitation harmonics are the two factors which completely define the hazard as applied here, by defining the position on the key response pattern from which the impact is extracted. The phases of the precipitation harmonics are not used, as all of the FD2020 response patterns correspond to a January peak of precipitation change, as this was the dominant month of the precipitation peak change from harmonics fitted to the AR4 climate projections analysed for FD2020 (Figure 3.3 of Prudhomme and Reynard 2009). Histograms of the phases of the harmonics fitted to the UKCP09 precipitation Sampled Data (2080s Medium) in each river-basin region (Section 4; grouped together in Figure 5.4), confirm that the dominant month of the peak precipitation change for these projections is also January, with the next most dominant month being February. The exceptions to this are the Orkney and Shetland and North Highland river basin regions, where there are marginally more projections with a December peak than with a January peak. The uncertainty analysis undertaken as part of FD2020 (Kay *et al.* 2009a) showed that the response patterns would be slightly more extreme if the peak occurred in December rather than January, but this difference is not thought to be significant.

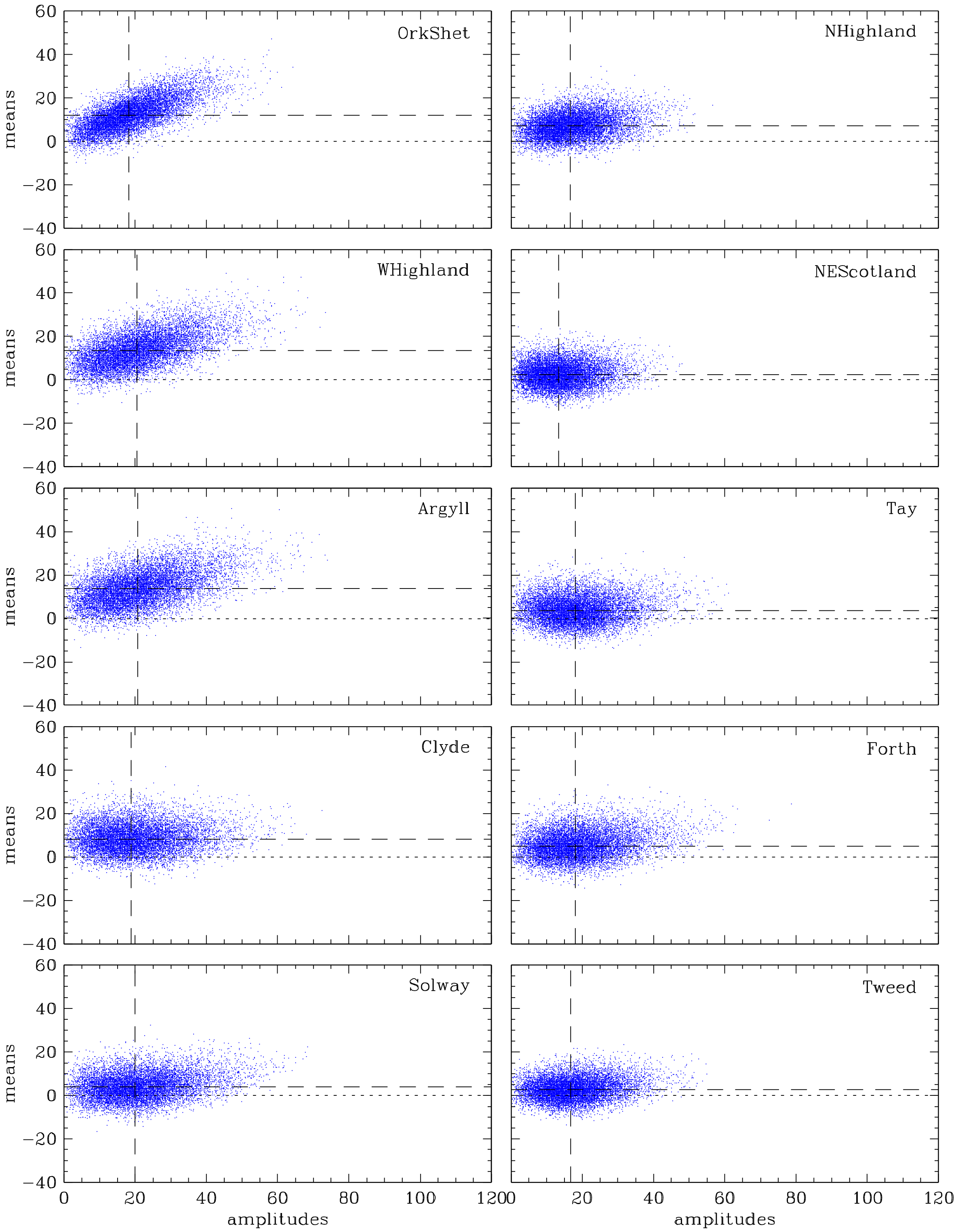

Figure 5.3 Plots of the mean versus the amplitude of the harmonic functions fitted to the UKCP09 precipitation Sampled Data (2080s Medium; blue dots), for each of the 10 river-basin regions in Scotland (arranged roughly geographically). The median of each harmonic parameter is shown by the black dashed lines. Note that the ranges of the *x* (harmonic amplitude) and *y* (harmonic mean) axes on these plots are the same as the corresponding ranges of the FD2020 sensitivity framework (Table 1.1) and thus the response patterns and standard deviation patterns (Figure 1.3 and Figure 1.4).

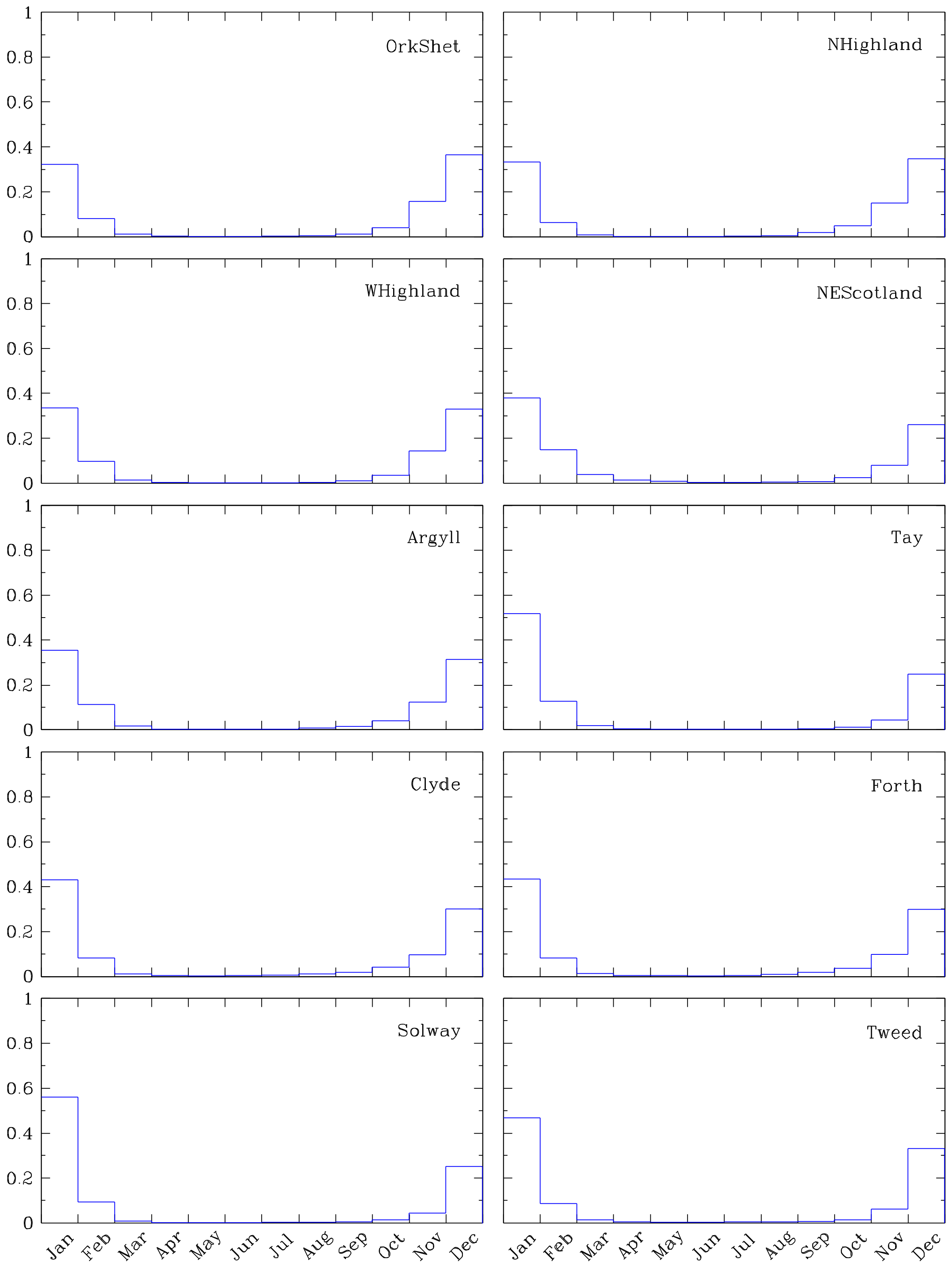

Figure 5.4 Histograms of the phase of the harmonic functions fitted to the UKCP09 precipitation Sampled Data (2080s Medium), for each of the 10 river-basin regions in Scotland.

Histograms of the mean, amplitude and phase of the harmonic functions fitted to the UKCP09 precipitation Sampled Data, for each of the river-basin regions, for the alternative time-horizons and emissions scenarios are given in Appendix A.1 (Figures A.1-3 and A.5-7). Contour plots comparing the hazard for the alternative time-horizons and emissions scenarios are given in Figures A.4 and A.8 of Appendix A.1. The harmonic amplitude differs more between time-horizons and emissions scenarios than does the harmonic mean, particularly for more southerly/easterly regions. The median amplitude increases through the time-horizons, with a larger increase from the 2020s to the 2050s than from the 2050s to the 2080s. For the different emissions scenarios, the harmonic means and amplitudes are lowest under Low emissions and highest under High emissions, with those for Medium emissions lying approximately mid-way between, or slightly closer to those for Low emissions.

The UKCP09 Sampled Data for temperature are not required here, as the key response patterns applied are those averaged over the eight FD2020 temperature scenarios (see discussion in Section 3.3). However, it is informative to compare the distribution of the harmonic functions fitted to the UKCP09 temperature data with the eight temperature scenarios modelled in FD2020 (Table 1.1), as the latter were selected to cover the range given by an analysis of AR4 climate projections (Prudhomme and Reynard 2009). The plots in Figure 5.5 show the mean against the amplitude of the harmonic functions fitted to the UKCP09 Sampled Data for temperature (2080s Medium), along with the harmonic mean and amplitude of the FD2020 temperature scenarios. These plots indicate that both the harmonic mean and amplitude can take higher values under the UKCP09 projections (2080s Medium) than was expected from the AR4 climate projection analysis, as FD2020's 'High' temperature scenarios (mean 4.5^{o}C, Table 1.1), are not as extreme as originally thought. FD2020's 'Medium' temperature scenarios (mean 2.5^{o}C and amplitude 0.8^{o}C, Table 1.1) are also sometimes lower than the median from the UKCP09 Sampled Data (2080s Medium), especially for the harmonic mean and for more southerly regions.

Histograms of the phase of the harmonics fitted to the UKCP09 Sampled Data for temperature (2080s Medium) in each river-basin region (Section 4; grouped together in Figure 5.6), show that the dominant month of the peak temperature change for the UKCP09 Sampled Data is August. This was one of the two months chosen for the seasonal temperature scenarios in FD2020, the other one being January (Table 1.1). From the UKCP09 temperature data (2080s Medium), for each river-basin region, January has a very low likelihood of being the month of peak temperature change, although a slightly higher likelihood than spring months; the months of July and September are the next most likely months, after August.

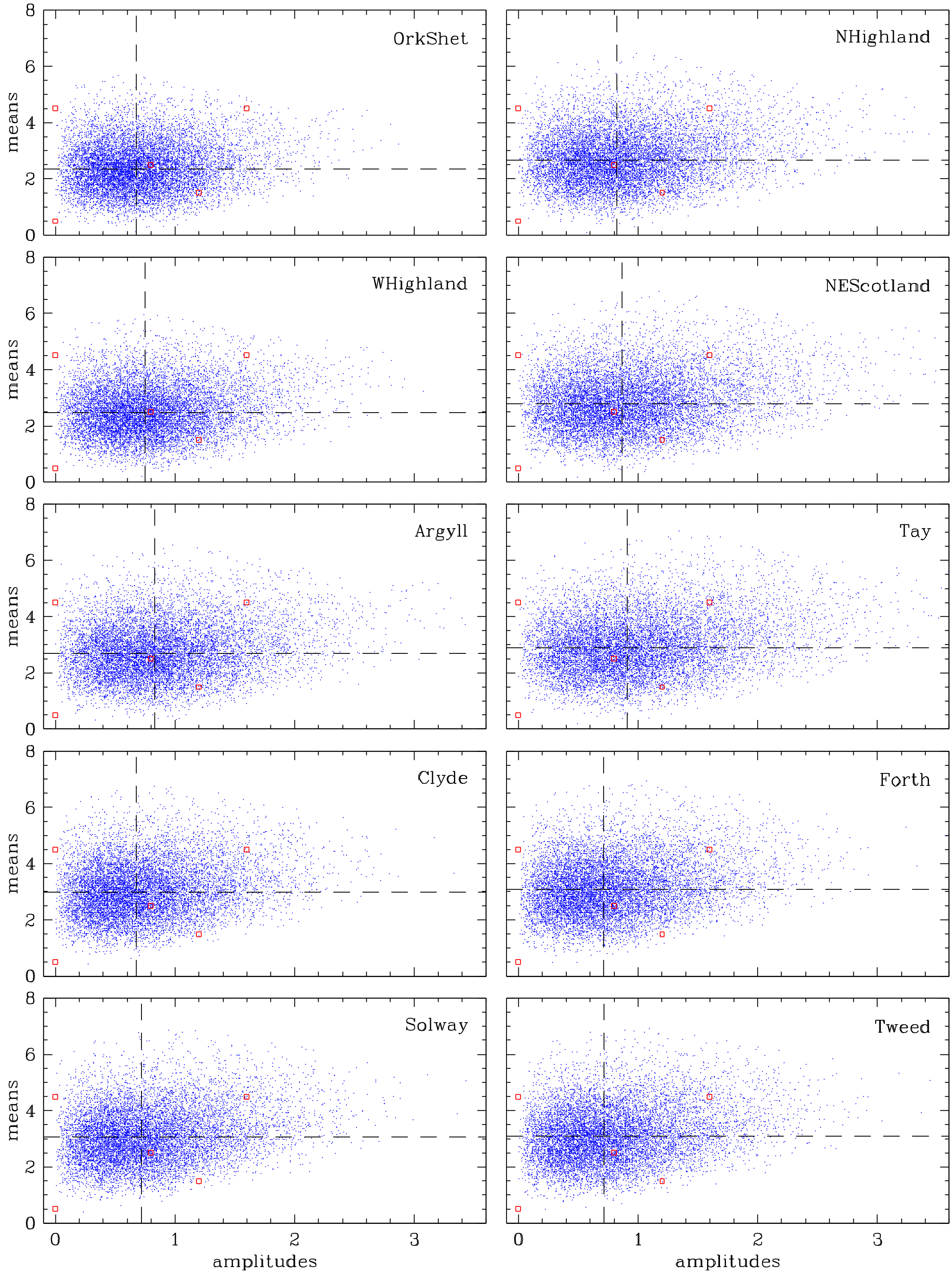

Figure 5.5 Plots of the mean versus the amplitude of the harmonic functions fitted to the UKCP09 temperature Sampled Data (2080s Medium; blue dots), for each of the 10 river-basin regions in Scotland (arranged roughly geographically). The median of each parameter is shown by the black dashed lines. The red squares indicate the positions of the scenarios used for the FD2020 sensitivity framework (Table 1.1).

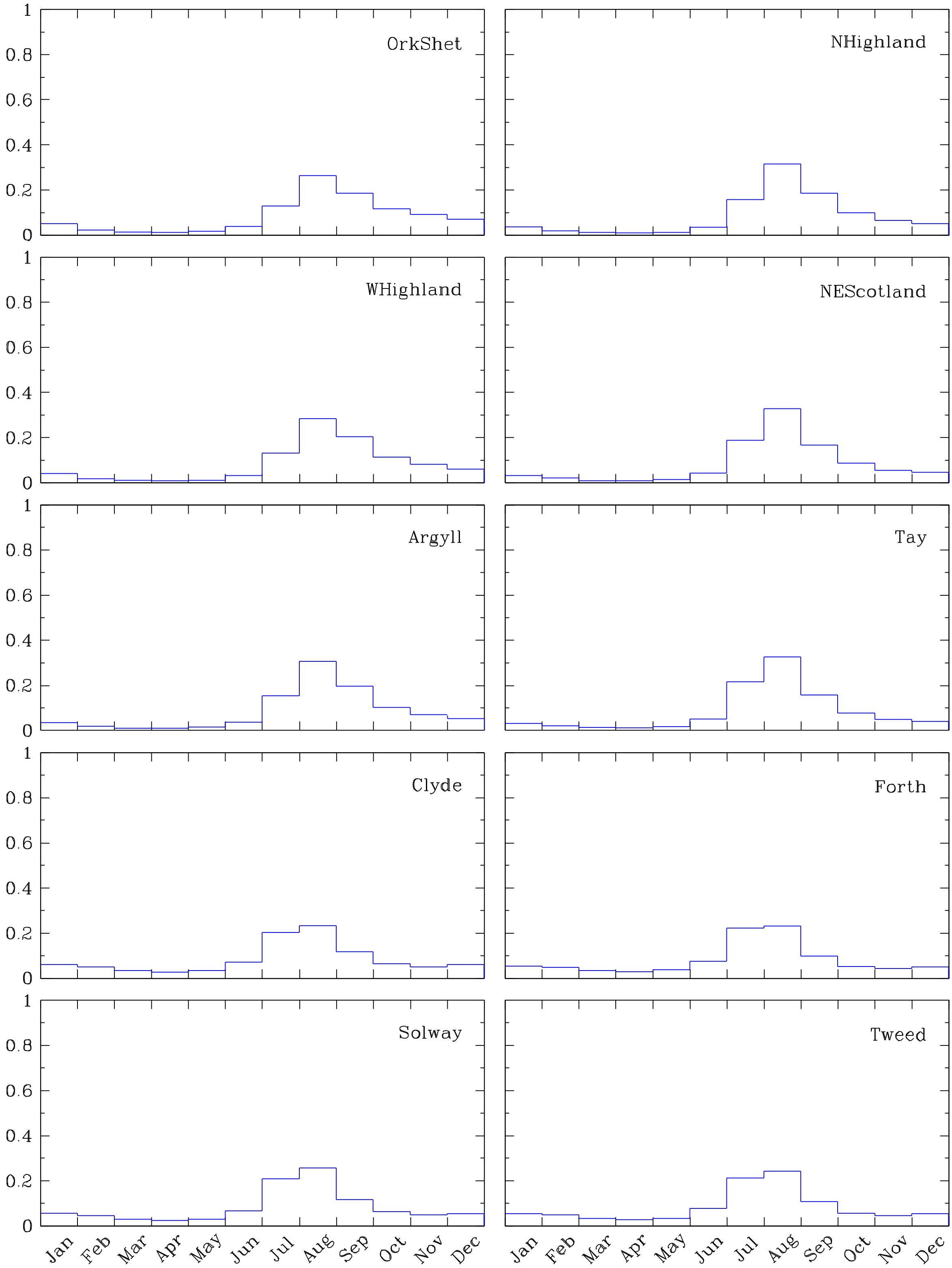

Figure 5.6 Histograms of the phase of the harmonic functions fitted to the UKCP09 temperature Sampled Data (2080s Medium), for each of the 10 river-basin regions in Scotland.

Histograms of the mean, amplitude and phase of the harmonic functions fitted to the UKCP09 temperature Sampled Data, for each of the river-basin regions, for the alternative time-horizons and emissions scenarios are given in Appendix A.2 (Figures A.9-11 and A.13-15). Contour plots comparing the temperature changes for the alternative time-horizons and emissions scenarios are given in Figures A.12 and A.16 of Appendix A.2. There are differences in both the harmonic mean and amplitude with both time-horizon and emissions scenario. The increases in harmonic mean and amplitude, from the 2020s through the 2050s to the 2080s, are similar across the geographic regions. For variation with emissions scenario (Figure A.16) the lowest increase in harmonic mean and amplitude occurs under the Low emissions scenario and the highest under the High emissions scenario, with a similar pattern across the geographical regions.

The differences between the 2080s Medium UKCP09 temperature projections and those used in FD2020 (Figure 5.5) are not thought to be crucial, particularly in terms of the use of the key response patterns averaged over the eight FD2020 temperature scenarios (Figure 1.3). Although the range of the harmonic means and amplitudes from the UKCP09 temperature Sampled Data (2080s Medium) is wider than that covered by the FD2020 temperature scenarios, the main part of the harmonic space not covered is for higher mean temperatures and amplitudes. Use of temperature projections with a higher increase and an August (rather than January) peak (as in UKCP09) would result in generally higher evaporation, contributing to a reduction in flood sensitivity and risk in comparison to that given by the FD2020 scenarios. Thus the results (for the 2080s under Medium emissions) using the FD2020 key response patterns are more likely to over- rather than under-estimate the risk from the UKCP09 projections, and even this effect is likely to be small.

For the alternative time-horizons and emissions scenarios, Figure A.12 suggests that the FD2020 scenarios represent well the change for the 2050s but cover a higher increase than is likely for the 2020s. The 2020s is represented better by the FD2020 scenarios with increase in mean temperature up to 2.5^{o}C. Temperature projections with a lower overall increase than the average of the eight FD2020 scenarios would result in generally lower evaporation leading to slightly higher river flows. Response patterns for the FD2020 T/PE scenarios up to an increase of 2.5^{o}C show that, for most response types, the difference in percentage change in flood discharge compared with the average from all eight scenarios is negligible. Where the balance between summer rainfall and evaporation is important for flood potential in the following months (i.e. the Mixed, Enhanced and Sensitive response types), the percentage change for projections for the 2020s may be slightly underestimated, particularly for lower return periods. Events with high return periods are probably not affected as the magnitude of the flood event is dominated by the depth of precipitation. Also, it is likely that there are very few catchments with Enhanced or Sensitive response types in Scotland.

For high altitude catchments, a higher temperature increase may result in higher flood peaks than predicted but only up to a temperature increase in which all precipitation falls as rain. Winter temperatures would not change as much with an August peak as with a January peak, so snow may still play a contributory role in flood peak generation. A lower temperature increase would result in little change to magnitude of flood peaks. For other catchments the overall impact of higher or lower temperature increases on snowmelt-related flood peaks depends on the precise combination of timing of precipitation and temperature but could result in lower peaks with a higher temperature increase (no change once temperatures are such that snowpack accumulation does not occur) and higher peaks with a lower increase.

5.3 Risk

Figure 5.7 brings together the central-estimate of the regional risk for the 10 river-basin regions (2080s Medium, shown separately in Section 4), to illustrate where there are similarities and differences between regions. Recall that the (weighted) regional risk curve is produced from a combination of two factors: the estimated response types of the NRFA catchments in the region, and the UKCP09 precipitation Sampled Data for the region. Thus the regional risk could be similar because both of these factors are similar, or could be similar even if these two factors are quite different, if their differences happen to balance each other out. Equivalent plots for the alternative time-horizons and emissions scenarios are given in Figures B.41-44 of Appendix B.2.

Figure 5.7 shows that there is quite a range of results across the 10 river-basin regions, but that certain regions stand out as being clearly more/less at risk than other regions (for the 2080s under Medium emissions). In general, regions to the west of Scotland have a greater risk that those to the east. The river-basin regions most at risk (for a greater than 20% change), at all return periods, are Argyll and West Highland, followed by Orkney and Shetland, followed by Clyde. The river-basin region least at risk, at all return periods, is North-East Scotland, followed by Tweed and Tay. The Solway, North Highland and Forth river-basin regions have quite similar central estimates of regional risk.

Similar relative risk between river-basin regions is seen for the alternative time-horizons under the Medium emissions scenario and for the alternative emissions scenarios (Low and High) for the 2080s (Appendix B.2, Figures B.41-44), although, for the High emissions scenario, the risk for the Solway river-basin region is higher than that for North Highland and Forth regions, and closer to the that for the Clyde region (Appendix B.2, Figures B.44).

Figures B.45-54 of Appendix B.2 compare the regional risk curves for the alternative time-horizons and emissions scenarios, for each of the 10 river-basin regions over Scotland. These figures confirm that the risk is higher under the High emissions scenarios and lower under the Low emissions scenarios than it is under the Medium emissions scenario, and that the risk increases with time.

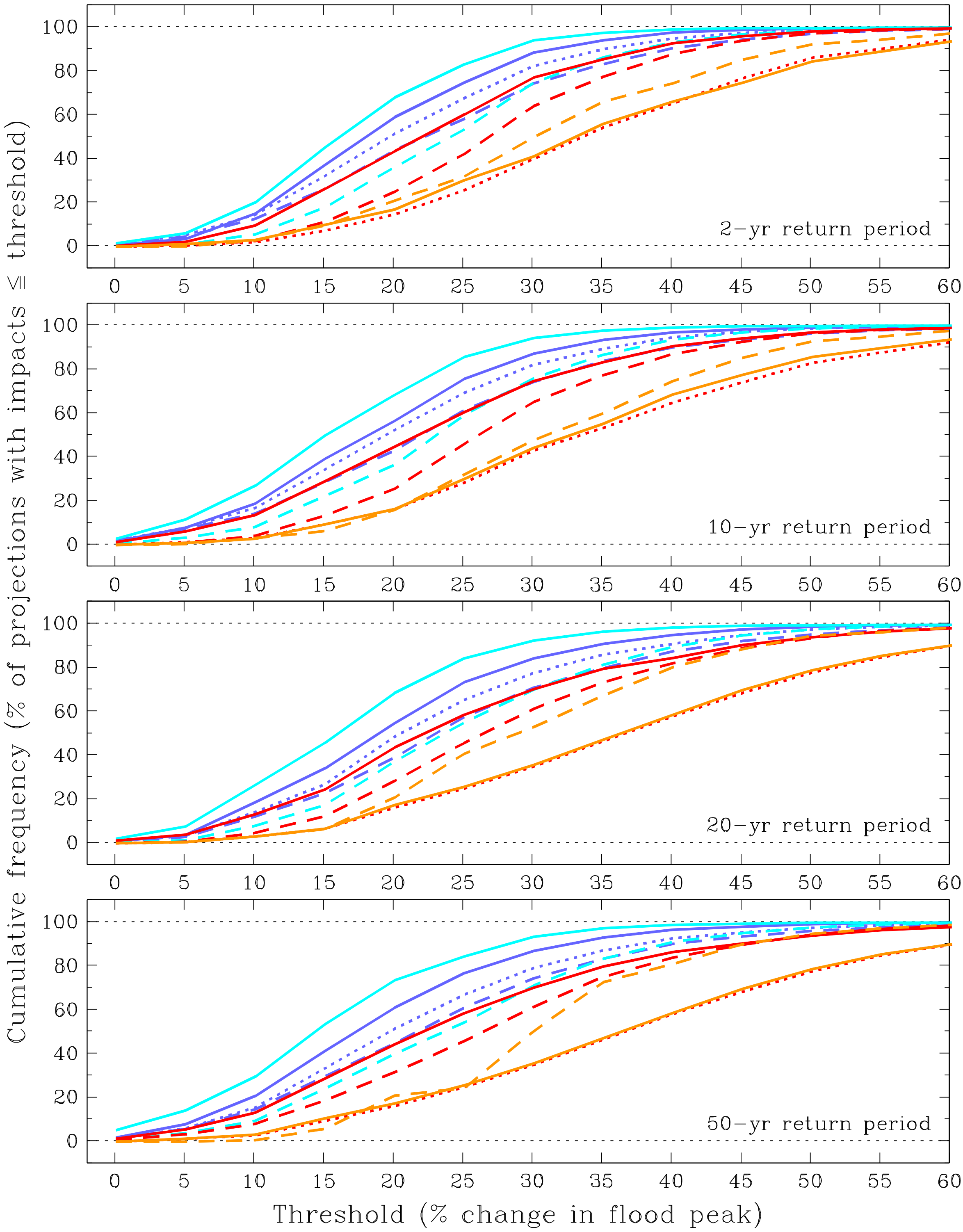

Figure 5.7 Regional risk curves (central-estimates) for each of the 10 UKCP09 river-basin regions in Scotland (2080s Medium). Key: North Highland – cyan dashed; North-East Scotland – cyan solid; Tay – blue dotted; Forth – blue dashed; Tweed – blue solid; Orkney and Shetland – orange dashed; West Highland – orange solid; Argyll – red dotted; Clyde – red dashed; Solway – red solid. Note that cooler colours (cyan and blue) are used for more easterly regions, while hotter colours (orange and red) are used for more westerly (or westerly-exposed) regions.

It should be recalled, when looking at the (weighted) regional risk curves presented in Figure 5.7 and Appendix B.2, that they only represent the central-estimate of the regional risk. That is, they do not cover the uncertainty due to the use of the key response patterns to represent any catchment of a given response type. The potential range of this uncertainty for each river-basin region is shown on the risk plots in Section 4 and Appendix B.1. Also, the weighting is based only on the set of NRFA catchments in each river-basin region. It is possible that this set may not give a true representation of the distribution of the response types within each river-basin region. This is particularly the case for regions with very few NRFA catchments, like West highland and Orkney and Shetland, but could still be the case for regions with a greater number of NRFA catchments. For instance, there may be more gauges in the more-populated parts of the region and less in the less-populated areas, thus potentially skewing the distribution of response types. Ideally, the response type would be calculated for a more even distribution of river reaches across each river-basin region. Also recall that, for a given river-basin region, the risk for a catchment of a particular response type could be quite different to the regional risk (see discussion in Section 3.3 and the risk plots in Section 4 and Appendix B.1).

5.4 Risk for larger catchments

The extra uncertainty allowances given in Table 2.19 have been included in all of the results presented here, but the FD2020 uncertainty analysis (Kay *et al.* 2009a) found that there was greater uncertainty for larger catchments. Thus multiplication factors for the standard extra uncertainty allowances were suggested, for use with larger catchments (Area>~2000km^2; see Table 2.19 and Reynard *et al.* 2009). Using the FD2020 multiplication factors would necessitate, for larger catchments, additions (dependent on response type and return period) to the risk calculated for smaller catchments (Table 5.1). These additions could be weighted according to the number of catchments of each type within each region, to produce additions to be used with the regional risk curves (that is, dependent on location and return period).

Table 5.1 Suggested additions to the risk, for use with larger catchments (Area>~2000km^2; cf. Table 2.19).

Response type	Return period			
	2-year	10-year	20-year	50-year
Damped-Extreme	0	3	8	12
Damped-High	0	3	8	18
Damped-Low	0	2	5	9
Neutral	0	1	2	3
Mixed	0	4	8	11
Enhanced-Low	0	2	5	9
Enhanced-Medium	0	4	11	20

It should be noted that the FD2020 multiplication factors were based on an investigation for relatively few catchments (nine smaller catchments, for which the full uncertainty analysis was performed, and four larger catchments, on which a subset of the analysis was performed). Ideally further analyses would be done, in order to better understand the reasons for the apparently greater uncertainty for larger catchments, and to provide sounder basis for guidance on how uncertainty increases with catchment area. Only about 2.1% of the 332 NRFA catchments in Scotland have an area greater than 2000km^2, and so would be affected by the FD2020 suggestions for allowances for larger catchments, but it could be that allowances should be increased by some amount for mid-sized catchments too.

5.5 Comparison with FD2648 results for Solway and Tweed

The Solway and Tweed regions were also included in the FD2648 work for Defra, since both of these regions cover parts of England as well as parts of Scotland. Here, the sensitivity and risk based on the FD2648 decision trees are compared with those presented in this report, using the trees derived specifically for Scotland.

For the Solway river-basin region (Table 5.2) the predominant response type at each return period is the same regardless of which set of decision trees is applied. That is, Damped-High at the 2-year return period and Neutral at the higher return periods. The same applies for the Tweed river-basin region (Table 5.3) except at the 10-year return period, where the predominant response type is Neutral using the Scottish decision trees but Damped-Low using the FD2648 trees. However, for both sets of trees at the 10-year return period, the second most common response type (Damped-High for the Scottish decision trees and Neutral using the FD2648 trees) has only just fewer catchments than does the predominant type.

Table 5.2 The number of NRFA catchments of each response type at each return period, for the Solway river-basin region, using the Scottish decision trees (left) and the FD2648 decision trees (right). The predominant response type is highlighted in bold at each return period, for each set of trees.

Response type	Scottish trees				FD2648 trees			
	Return period (years)				Return period (years)			
	2	10	20	50	2	10	20	50
Damped-Extreme	0	0	0	0	NA	NA	NA	NA
Damped-High	**40**	5	3	3	**38**	NA	NA	NA
Damped-Low	0	10	2	2	1	9	NA	NA
Neutral	2	**28**	**37**	**37**	3	**34**	**43**	**41**
Mixed	1	0	1	1	0	0	0	1
Enhanced-Low	NA	NA	NA	NA	1	0	NA	NA
Enhanced-Medium	NA	NA	NA	NA	0	0	NA	NA
Enhanced-High	NA	NA	NA	NA	0	0	0	1
Sensitive	NA	NA	NA	NA	0	0	0	0
Total	43	43	43	43	43	43	43	43

Table 5.3 As Table 5.2 but for the Tweed river-basin region.

Response type	Scottish trees				FD2648 trees			
	Return period (years)				Return period (years)			
	2	10	20	50	2	10	20	50
Damped-Extreme	0	0	0	0	NA	NA	NA	NA
Damped-High	**26**	11	3	7	**14**	NA	NA	NA
Damped-Low	1	2	6	2	11	**16**	0	NA
Neutral	0	**14**	**14**	**14**	1	13	**24**	**26**
Mixed	4	4	8	8	0	0	2	0
Enhanced-Low	NA	NA	NA	NA	3	0	NA	NA
Enhanced-Medium	NA	NA	NA	NA	1	0	NA	NA
Enhanced-High	NA	NA	NA	NA	1	0	5	5
Sensitive	NA	NA	NA	NA	0	2	0	0
Total	31	31	31	31	31	31	31	31

If Damped-High is merged with Damped-Low at the 10-year return period (and Damped-High and Damped-Low with Neutral at the higher return periods) for the Scottish trees, as for the FD2648 trees (Table 1.2), then the numbers are in fact very similar. However, the presence of some Damped catchments even at higher return periods using the Scottish trees, where this cannot occur under the FD2648 trees (because of the merging), may have had the effect of decreasing the regional risk, for both the Solway and Tweed regions, when using the Scottish trees. Similarly, for the Tweed river-basin region, the presence of a (small) number of Enhanced/Sensitive catchments under the FD2648 trees, which cannot occur under the Scottish trees, may have had the effect of increasing the estimated regional risk for the Tweed region when using the FD2648 trees. This is particularly the case given the merging of Enhanced-Low and Enhanced-Medium to Enhanced-High at the 20- and 50-year return periods for the FD2648 trees (Table 1.2).

Figure 5.8 compares the regional risk cdfs for the Solway and Tweed regions when derived using the Scottish decision trees and the FD2648 decision trees. This confirms the increased risk under the FD2648 decision trees compared to that under the Scottish decision trees, at the 20- and 50-year return periods, for both regions. The risk is basically the same for each region at the 2- and 10-year return periods, regardless of which set of decision trees is applied.

This difference in risk at the 20- and 50-year return periods is not unexpected, and is a direct consequence of the merging of response types used in FD2020. Thus it is more likely that the use of the FD2020 decision trees leads to an over-estimate of the risk, rather that the use of the Scottish decision trees leading to an under-estimate of the risk.

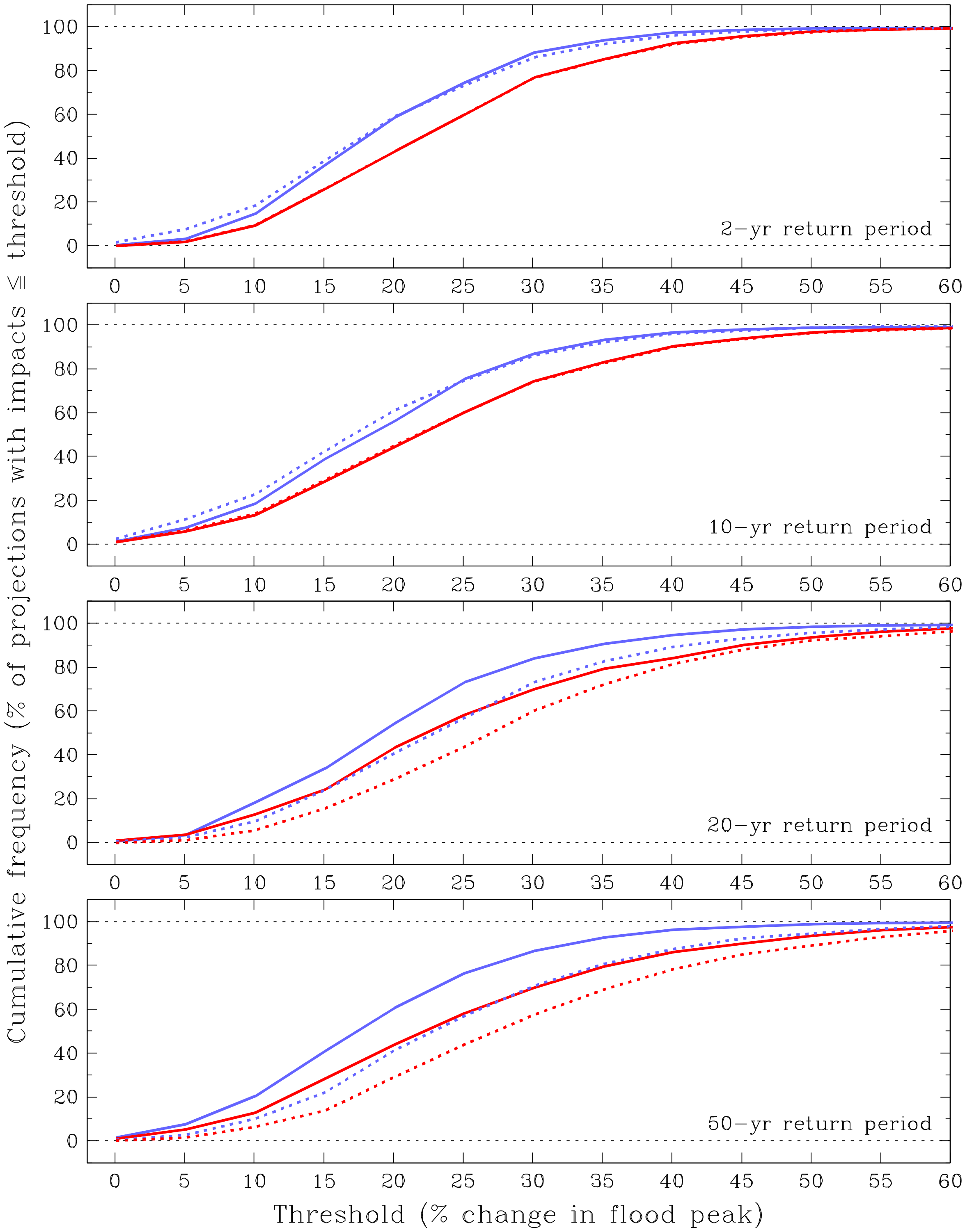

Figure 5.8 Comparison of the regional risk cdfs for the Solway (red) and Tweed (blue) river-basin regions derived using the Scottish decision trees (solid) and the FD2648 decision trees (dotted).

6. Summary and discussion

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Section 6: Summary and discussion

This section provides a brief summary of the work presented in this report, along with a discussion on uses of the risk plots. Uncertainty is also discussed, along with a number of other considerations.

It is recommended that this section is read in full.

END OF FAST TRACK BOXES

6.1 Summary

The methodology produced by Defra/EA FCERM project FD2020 provided a powerful tool enabling the rapid assessment of the impact of climate change on four flood indicators (flood peaks with return periods or 2-, 10-, 20- and 50-years), for catchments in Britain. The methodology involves the use of decision trees, based on catchment descriptors, to estimate the response type of a catchment (i.e. its sensitivity to climatic changes). The key response patterns corresponding to that response type (sensitivity) can then be combined with a climate projection (hazard) to estimate the impact on flood peaks (risk). Indeed, multiple climate projections can be applied relatively quickly and easily, whether for alternative time-horizons and emissions scenarios, for probabilistic ensembles like UKCP09, or for any new sets of climate projections that may be released subsequently. FD2648, the successor project to FD2020, applied the UKCP09 projections for 12 river-basin regions across England and Wales, to estimate the range of risk for each possible response type in each region (response-type risk). Furthermore, FD2648 estimated the response type of all NRFA in each region, and used this information to estimate regional risk (by weighting the response-type risk).

This project has developed the work of FD2020/FD2648 for Scotland. Given the nature of catchments in Scotland, with greater homogeneity compared to England and Wales, new decision trees were developed based on 45 catchments in Scotland (and 12 in northern England), rather than the full FD2020 catchment set (154 catchments covering the whole of England, Wales and Scotland). This enabled better discrimination of Damped response types at all return periods; Scotland has predominantly Damped and Neutral response types, and very few catchments with Enhanced response types. The resulting decision trees were used to estimate the response type of 349 NRFA catchments in Scotland.

The UKCP09 projections were then obtained for 10 river-basin regions covering Scotland: North Highland, North-East Scotland, Forth, Tay, Tweed, Solway, Clyde, Argyll, West Highland, and Orkney and Shetland. These provide sets of 10,000 (annual, seasonal or monthly) changes in a number of climate variables. Monthly changes in precipitation were used here, for five time-horizon and emissions scenario combinations: 2020s, 2050s and 2080s Medium, to illustrate the dependence on time-horizon, and 2080s Low, Medium and High, to illustrate the dependence on emissions. Harmonic functions were fitted to the monthly changes in precipitation from each set of projections in each region.

The mean and amplitude of the harmonic functions was then used to combine the climate projections (hazard) with each possible sensitivity (key response pattern), to estimate response-type risk in each river-basin region in Scotland. The latter were then combined with the estimated response types of the NRFA catchments in each region, to estimate the regional risk. Thus regional risk and response-type risk were presented, as cdfs (including uncertainty), for each of 10 river-basin regions, for four flood indicators, for five time-horizon and emissions scenarios combinations.

6.2 Use of risk plots

The risk plots generated by this work can be used in a number of ways:

- To assess the level of protection provided by a specified climate change allowance (e.g. 20%).
- To assess the climate change allowance necessary to provide a specified level of protection.
- To assess the need for regional allowances compared to a national allowance.
- To assess the need for sub-regional allowances, perhaps based on response-type, compared to regional allowances.

Take, for example, the bottom plot in Figure 5.7 showing the regional risk at the 50-year return period for each river-basin region (for the 2080s under the Medium emissions scenario), and assume an allowance of 20%. In order to derive the percentage of projections protected against by that allowance, a vertical line is drawn up from 20% on the x-axis until it intersects a regional risk cdf, then a horizontal line is drawn from the intersection point to the y-axis. The value this horizontal line hits on the y-axis can be thought of as the level of protection corresponding to the 20% allowance, based on the regional risk for that river-basin region. The level of protection will clearly differ for each region, in this case from about 20% for the Argyll, West Highland and Orkney and Shetland regions to about 75% for the North-East Scotland region. This sort of analysis can be used to assess whether certain regions may be more or less at risk than others if a national allowance is applied.

Reversing this procedure, one can derive the allowance necessary to provide a specified level of protection. For example, using the same plot in Figure 5.7 and assuming a level of protection of 60%, a horizontal line is drawn from 60% on the y-axis until it intersects a regional risk cdf, then a vertical line is drawn down to the x-axis. The value this vertical line hits on the x-axis can be thought of as the allowance necessary to provide a 60% level of protection, based on the regional risk for that river-basin region. The allowance will clearly differ for each region, in this case from about 16% for the North-East Scotland region to about 40% for the Argyll, West Highland and Orkney and Shetland regions. This sort of analysis can be used to assess how regional allowances may work.

A regional allowance derived from a regional risk cdf may not be appropriate for all catchments in the river-basin region. For instance, if a region is dominated by catchments of the Damped-High response type, but contains a small number of catchments with Neutral or Mixed types, then the regional risk will be dominated by the Damped-High response-type risk, and may under-estimate the risk (and therefore allowance necessary) for the Neutral/Mixed catchments. Similarly, if a region has a quite a spread of response types, then the regional risk will represent an average of those response-type risks, but that average may clearly under-estimate the risk for some of types. For the Scottish river-basin regions, this seems to be a problem mainly for the 2-year return period flood peaks, as there are many more Damped-High catchments at this low return period. For example, take the top plot in Figure 4.32 showing the regional and response-type risk at the 2-year return period for the Argyll river-basin region (for the 2080s under the Medium emissions scenario), and assume a 60% level of protection. Using the regional risk cdf (black) suggests an allowance of about 38%, but using the Mixed response-type risk (gold) suggests an allowance of about 45%. There is also some effect on the risk under the 2080s High emissions scenario, even at higher return periods (particularly for Neutral catchments in the Forth and Clyde river-basin regions; Figures B.34 and B.37 in Appendix B).

There are so few catchments with Enhanced types in the subset of catchments used to derive the Scottish decision trees that these types could not be discriminated by the trees – such catchments are likely to end up with an estimated response type of Mixed. However, the response-type risk for Enhanced-Low and Enhanced-Medium types has been presented alongside that for the lower response types in the risk plots in Section 4 and Appendix B.1, to highlight the fact that any catchments with these types are likely to be at much greater risk.

6.3 Uncertainty

It should be recalled, when looking at the regional risk curves as presented in Figure 5.7 and Appendix B.2, that they represent only the central-estimate of the regional risk. That is, they do not cover the uncertainty due to the use of the key response patterns to represent any catchment of a given response type. The potential range of this uncertainty for each river-basin region is shown on the risk plots in Section 4 and Appendix B.1. Also, the fact that the regional risk cdfs presented here are based purely on the NRFA catchments in the river-basin region may have skewed the distribution of response types (see discussion in Section 5.3). Ideally the distribution of response types in a region, on which the derivation of the regional risk curve is based, would be calculated for a more even spread of river reaches across each river-basin region.

Decisions have to be made by the policy-maker on how much uncertainty information is taken into account. That is;

- Should the chosen allowance take account of the range of uncertainty just from climate change (i.e. be based just on the central-estimate of the risk?
- Or should the chosen allowance also take account of the uncertainty from the use of key response patterns to represent each response type (i.e. the range given by the standard deviation patterns)?

- How should the fact that different allowances may be derived at different return periods, and that the allowance derived for the 50-year return period may not necessarily be larger than that derived for lower return periods, be dealt with?
- How should information about the risk under different emissions scenarios be used?
- Should different allowances be derived for different time-horizons?
- Should allowances be higher for catchments with a larger area?

Also, if any catchment-specific allowances are derived, based on the estimated response type of particular catchments, should these take account of the confidence level ascribed to the response type estimate, or of how close the catchment's descriptors are to the threshold values used in the decision trees? For instance, in the case of Medium or Low confidence in the best-estimate response type, the next most likely response type (or types) of that path could be examined. Or, in the case of a catchment descriptor being very close to a threshold value, the alternative path could be followed to derive an alternative estimate of the response type. The allowance for any alternative response type estimate could then be compared to that for the original estimate, and the largest allowance adopted. This would need knowledge of the catchment's properties. Note that the derivation of the regional risk curves does not take into consideration the confidence levels of the best-estimate response types for the NRFA catchments.

Further considerations, regarding the estimation of a catchment's response type(s) from its catchment properties and whether the methodology could be less appropriate for certain types of catchment (e.g. highly urbanised catchments, those whose flow regime is highly affected by large water bodies, those with very high losses or gains of water, those with a high mean and minimum altitude, or those whose response is strongly dictated by seasonality of baseline extremes), were discussed in Section 3.1.3. Note that such factors are likely to affect relatively few catchments.

6.4 Discussion

Natural variability, on a range of time-scales (from hours to decades), is an important but perhaps underestimated feature of our climate and, consequently, of flood risk. This natural variability has a number of effects in terms of estimating both flood risk and the potential change in flood risk under climate change.

On shorter time-scales, natural variability results in uncertainty in the estimation of higher return period events. From 50 years of observed flow data, there will be greater uncertainty in the estimation of the 50-year return period event than for the 10-year return period event, as natural variability means that extreme events do not occur like clockwork. That is, given a relatively short period of record, it is not possible to tell with a high degree of certainty how extreme the most extreme events in that record actually were. The data available to drive the hydrological models in FD2020 thus restricted the choice of flood indicators; relatively short record lengths (longest 41 years) meant that nothing more extreme than the 50-year return period could reasonably be evaluated (and even that has a higher degree of uncertainty). To develop allowances for higher return periods (e.g. 100-

year), those for lower return periods could potentially be extrapolated, but the best way to do this would require investigation.

Another issue at these time-scales is how representative the baseline climate is, in terms of the occurrence and ordering of weather events, given that the change factor method is used to produce the possible future climates from the baseline climate (see Section 1.1). This has been borne in mind during the development of the decision trees (see Section 2.5), and the FD2020 extra uncertainty allowances were designed to account for this to some extent (see Kay *et al.* 2009a), but the possibility of it affecting some of the results cannot be completely ruled out. Peak flows in some catchments may be more affected by this sort of variability than those in other catchments, as demonstrated by Kay *et al.* (2009b) using a technique based on resampling the baseline climate time-series.

In Scotland, a particular issue in this regard could be the effect of increasing temperature on the transition from many snowfall-affected flood events to predominantly rainfall-generated ones. In general, for high altitude catchments the impact of increasing temperature on flow regimes is for flood peaks to increase, as the proportion of the runoff contributed directly from rainfall increases and the timing of peaks shifts more from early spring to winter. However, for all catchments the highest peaks associated with snow are those events with a combination of sustained rainfall and melting snow. This is particularly the case for catchments with lower mean and minimum altitude. Thus the spatial patterns of timing of rainfall combined with rising temperatures are often critical in determining the severity of the flood. How higher temperatures will affect the generation of such events is probably quite variable, again depending on the precise combinations of temperature, rainfall and snowpack depth but, in general, a warmer climate would be less likely to have accumulated snow and thus lead to lower rainfall-only peaks with increased temperature.

At longer time-scales, decadal-scale variations have been shown in extreme rainfall in the UK for 1961-2000 (Fowler and Kilsby 2003), and it is now generally accepted that natural variability results in flood-rich and flood-poor periods (Wilby *et al.* 2008). For example, the multi-decadal variations in the North Atlantic Oscillation (NAO) show a degree of correlation with changes in high flow indicators in some UK rivers (Hannaford and Marsh 2007). Consequently, flood frequency estimated from a relatively short observational record can be biased to that specific period (even at lower return periods) and can potentially change significantly over a relatively short period of time, even without the effects of anthropogenic climate change. When combined with climate change, for a given period the natural oscillations could act to reinforce the effect of climate change in that period, or they could act in the opposite direction, thus reducing the effect of climate change in that period (Wood 2008; Kerr 2007). This is the case for a modelled climate, for the past climate, and for the real future climate.

This aspect of natural variability is discussed in the UKCP09 report (Murphy *et al.* 2009; Section 2.2), as the UKCP09 projections include natural climate variability (to some extent) in their uncertainty range. However, they cannot yet predict the direction of this effect in any given period over the next century, and this should be borne in mind when using results based on the UKCP09 projections. A recent study (Kay *et al.* 2011) used data from a 3-member RCM ensemble for the period

1950-2099 to model the potential changes in flood peaks for two catchments in England. It showed, using a 30-year moving window analysis, that changes over the period are often non-linear, and depend on the catchment, the flow time-step and the RCM ensemble member. Thus understanding historic natural variability, and how natural variability may itself alter under climate change, could be important for understanding (and detecting) the impacts of climate change on river flows.

Finally, although the probabilistic projections from UKCP09 have been a big step forward for impact studies, allowing a more risk-based approach to decision-making, the results are still conditional on available data and resources. That is, the probabilities given by UKCP09 represent "the relative degree to which each possible climate outcome is supported by the evidence available, taking into account our current understanding of climate science and observations, as generated by the UKCP09 methodology" (Murphy *et al.* 2009, Section 1.1.1). Any new projections, developed at some future date, are likely to be based on more data, enhanced modelling and use of greater computing (and other) resources, and so any probabilistic impacts derived from such projections will not be the same, and may not even be similar (New *et al*. 2007). Also, factors such as land-use and land-management changes can potentially affect flood occurrence and magnitude (Wilby *et al.* 2008), both directly (e.g. through hard surfaces boosting quick runoff) and indirectly (e.g. through changes in evaporation and soil moisture). Such factors are not included in either the UKCP09 projections or the FD2020 hydrological modelling.

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Glossary

Baseline	The climate variables and river flow representing the current time period (e.g. 1961 – 2001)
Catchment descriptor or catchment property	Physical or climatic attribute of a catchment (e.g. mean altitude, catchment area)
Cdf	See Cumulative distribution function
Change factor	The (percentage or absolute) amount by which a climate variable is projected to change
Change factor method	The change factor is applied to the baseline climate variables (rainfall, PE, temperature) to give a ‘future’ climate. Here, monthly change factors are applied to daily rainfall and temperature and monthly PE, with percentage changes used for rainfall and PE and absolute changes used for temperature
CLASSIC	Climate and Land-use Scenario Simulation in Catchments rainfall-runoff model
Climate change projection or scenario	Combination of changes for climate variables (e.g. mean monthly precipitation and temperature) projected for some future time period
Cumulative distribution function	Way of plotting a set of values, where the probability of the value being less than a threshold value is plotted on the y-axis, with the threshold value plotted on the x-axis, for a range of threshold values
Decision tree	Set of rules (based on catchment descriptors) for dividing a sample (set of catchments) into a number of sub-samples (flood response types)
FEH	Flood Estimation Handbook
Flood frequency distribution	Statistical relationship used to fit to sampled flood magnitudes
Flood indicator	Percentage change in magnitude of flood peak for a specified return period
Flood magnitude	The maximum river discharge for a flood event (here derived from mean daily flow)
Flood response pattern (cf. Key flood response pattern)	Percentage changes in a flood indicator for a catchment, resulting from applying the Sensitivity framework
Flood response type	Name given to a grouping of similar flood response patterns, for which a key flood response pattern is calculated (i.e. Damped-Extreme, Damped-High, Damped-Low, Neutral, Mixed, Enhanced-Low, Enhanced-Medium, Enhanced-High, Sensitive)
GCM	Global Climate Model

Harmonic amplitude	The difference between the maximum and mean value of a harmonic function
Harmonic function	Mathematical expression of a combination of sine curves over a certain period (here applied to monthly mean climatic changes)
Harmonic mean	The mean value of a harmonic function
Harmonic phase	The timing (month) of the maximum (peak) of a harmonic function
Hazard	The change in climate to which a catchment is exposed
Hydrometric Register	Catalogue of UK hydrometric monitoring networks with reference and statistical information
Key flood response pattern or Key response pattern (cf. Flood response pattern)	Percentage changes in a flood indicator identified as typical for a group of catchments in Britain (i.e. the mean response pattern across a grouping of similar flood response patterns). Represents a Flood response type
NRFA	National River Flow Archive
PDM	Probability Distributed Model; a rainfall-runoff model
PE	Potential Evaporation
RCM	Regional Climate Model
Regional risk	An average risk for a particular river-basin region, based on weighting each response-type risk by the number of NRFA catchments of that type in the region
Response pattern	See Flood response pattern and Key flood response pattern
Response type	See Flood response type
Response-type risk	The risk of flood peak changes in a particular river-basin region, based on a particular response type
Return period (or RP)	Frequency of occurrence — the average time between river discharges exceeding a specified magnitude
Risk	Combination of Sensitivity and Hazard
River-basin regions	Division of England, Wales and Scotland into 20 regions, used by UKCP09. Regions are delineated in such a way that no river catchment is contained in more than one region
SD	Standard Deviation
SD pattern	The pattern of standard deviations corresponding to a particular Key flood response pattern; gives an idea of the range of responses possible within a Flood response type

Sensitivity	For a catchment, how much peak flows change in relation to changes in the climate
Sensitivity framework	The set of regular changes in climate, defined by mean annual change and change in seasonality (harmonic mean and amplitude), applied to the baseline climate using the change factor method
T	Temperature
Time-horizon or time-slice	The range of years over which a climate change projection is applicable. e.g. the 30 years 2070-2099 (2080s)
UKCP09	UK Climate Projections 2009
Uncertainty	Variation in outputs attributable to range of assumptions and simplifications necessary in developing the overall Sensitivity framework methodology