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

Practicalities for implementing regionalised allowances for climate change on flood flows

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Executive summary

Project FD2020 'Regionalised impacts of climate change on flood flows' provided a methodological framework designed to enable the quick estimation of the impact of a set of climate change scenarios on the flood flows of a catchment. The method separates the climate change that a catchment may be exposed to (the hazard) from the catchment response to changes in the climate (the vulnerability, in terms of change in four flood indicators), through use of a sensitivity framework. Re-combining vulnerability and hazard then leads to an estimate of the risk of change in flood flows. This extension to project FD2020 uses FD2020's representation of vulnerability, along with sets of climate change scenarios from UK Climate Projections 09 (UKCP09), to estimate the probabilistic risk for each of the National River Flow Archive (NRFA) catchments in England and Wales. This report describes the methodology applied to estimate the vulnerability of each of the NRFA catchments for each flood indicator (flood peaks with a return period of 2, 10, 20 and 50 years), summarises the hazard as defined by UKCP09 for river-basin regions over England and Wales, and presents the resulting estimates of risk (with uncertainty ranges).

The vulnerability of each catchment is estimated through the use of the FD2020 response types, and the catchment properties which characterise those response types (via decision trees), rather than through direct hydrological modelling of all NRFA catchments. Minor modifications are made to the FD2020 decision trees before using them to estimate the response type of each NRFA catchment, to make them more robust for use with a wider range of combinations of catchment properties.

The hazard is derived from the UKCP09 climate scenarios, for the 2020s, 2050s and 2080s time-horizon under the A1B (Medium) emissions scenario and under the B1 (Low) and A1F1 (High) emissions scenarios for the 2080s time-horizon, for the 12 river-basin regions covering England and Wales: Northumbria, Humber, Anglian, Thames, South-East England, South-West England, Severn, West Wales, Dee, North-West England, Solway and Tweed. In each case, a single harmonic function is fitted to each of the 10,000 sets of monthly changes in precipitation and temperature. The distributions of the three parameters of these fitted harmonic functions (mean, amplitude and phase) are assessed against the sets of changes applied in the FD2020 sensitivity framework. In general, the two sets compare favourably.

The hazard for a given river-basin region, time-horizon and emissions scenario is combined with the vulnerability for each response type. This is done by using the mean and amplitude of the fitted precipitation harmonics (hazard) to extract the estimated impact from the key response patterns (vulnerability) for each response type and flood indicator. 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. The appropriate uncertainty allowances are added, to get a more robust estimate of the range of risk.

The results are presented by river-basin region, for each time-horizon and emissions scenario. The use of the UKCP09 Sampled Data for river-basin regions simplifies the results, as there is one set of results for each response

type in each river-basin region at each return period, rather than for each catchment at each return period. For each region, time-horizon and emissions scenario, a regional risk is also calculated at each return period, based on the number of NRFA catchments of each response type.

The results present a wealth of information to support the update of guidance on flooding and climate change, and decisions by the policy-maker on what level of detail/complexity is most appropriate:

- Revised nationwide allowances;
- New regional allowances;
- New regional / sub-regional allowances by response type;
- Local decision-making, where the tools are provided to evaluate changes to river flows from user-defined future climate scenarios and catchment characteristics.

The benefits and weaknesses of each level are discussed, including the balance between simplicity of guidance and the possibility of over/under-adaptation. Decisions also have to be made by the policy-maker on the preferred level of protection and how much uncertainty information is taken into account.

Data limitations meant that FD2020 could not reasonably provide response patterns for return periods higher than 50-years. However, for extrapolation of the allowance to higher return periods an investigation suggested that the regional allowances, and those for most of the response types, are likely to remain relatively stable with increasing return period, but that the allowance for Sensitive catchments should probably increase with return period, and increase at a higher rate for more precautionary levels of protection.

Contents

1 Introduction

Project FD2020 'Regionalised impacts of climate change on flood flows' (Reynard *et al.* 2009) provided a methodological framework designed to enable the quick estimation of the impact of a set of climate change scenarios on the flood flows of a catchment. This extension project uses that framework, along with sets of UKCP09 climate change scenarios, to estimate the probabilistic risk for each of the National River Flow Archive (NRFA) catchments in England and Wales, for a number of time-horizons and emissions scenarios.

1.1 Aims

FD2020 provided two key findings.

1. Results for the 2080s showed that, for the catchments modelled (154 in total), the current precautionary nationwide allowance (20%) no longer encompasses the majority of catchment changes in flood flows using global climate model (GCM) projections from IPCC Assessment Report 4 (AR4) or regional climate model (RCM) projections from UK Climate Projections 09 (UKCP09). This calls into question the precautionary nature of the current guidance.

2. There is strong evidence that catchment response to climate change is dependent on catchment properties. This implies that 'regionalised' allowances for climate change, potentially based on catchment properties as well as geographical location, might be more appropriate than a single national allowance.

These findings, if translated into guidance, will require a more complex understanding of the potential changes in high river flows for flood managers and planners. The current 20% allowance has provided a memorable and simple headline figure that has helped others factor in climate change quickly and easily into their work. The science could enable the provision of very detailed guidance on how to account for climate change when considering river flooding in the future, possibly specific for any location in the country. But, questions still remain about what level of detail/complexity is most appropriate for development and planning.

To support the revision of the appraisal and planning guidance, the work in this project will provide information allowing the assessment of four potential ways forward:

- Revised nationwide allowances;
- Regional allowances;
- Regional/sub-regional allowances by FD2020 response type;
- Local decision-making, where the tools are provided to evaluate changes to river flows from user-defined future climate scenarios and catchment characteristics.

This report provides the evidence for the first three of the above ways forward, for the 2020s, 2050s and 2080s time-horizons under the A1B (Medium) emissions scenario and under the B1 (Low) and A1F1 (High) emissions scenarios for the 2080s time-horizon. Each way forward will have benefits and weaknesses, which will be discussed.

1.2 FD2020 – Background

FD2020 used a scenario-neutral approach, based on a broad sensitivity analysis to determine catchment response to changes in climate, rather than being a standard ‘impact study’. 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 vulnerability, in terms of change in peak flows). The vulnerability of each of the project’s 154 catchments was characterised by modelling their response on 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). The modelled response was then presented graphically in a ‘response pattern’, an example of which is shown in Figure 1.1. By combining current understanding of climate change likelihood (hazard, e.g. from UKCP09) with the vulnerability of a given catchment, it is then possible to evaluate the risk of flood flow changes.

Table 1.1 The FD2020 sensitivity framework for changes in precipitation, temperature and PE.

	Phase	Mean annual change	Seasonality	Scenarios
Precipitation	January	-40% to 60%	0 to +120%	All combinations by increments of 5% Total: 525 scenarios
Temperature	January and August	1.5° 2.5° 4.5°	1.2° 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) Total: 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).			Total: 8 scenarios

Furthermore, to enable estimation of the risk for unmodelled, or even ungauged, catchments, FD2020 analysed the similarity of the responses of the 154 modelled catchments, and grouped them into nine response types (Figure 1.2), each with a representative (key) response pattern (Figure 1.3) and standard deviation (sd) pattern (Figure 1.4) at four return periods (2-, 10-, 20- or 50-years; RP2, RP10, RP20, RP50). 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.

A subset of these response types was then characterised according to catchment properties, enabling the estimation of a catchment's response, and so its risk (when combined with a particular hazard), from its 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.* (2009). As a result, 8, 7, 4 and 4 types were characterised at the 2-, 10-, 20- or 50-year return period respectively. In addition, an uncertainty analysis (Kay *et al.* 2009) suggested extra uncertainty allowances, according to response type and return period (Table 1.3).

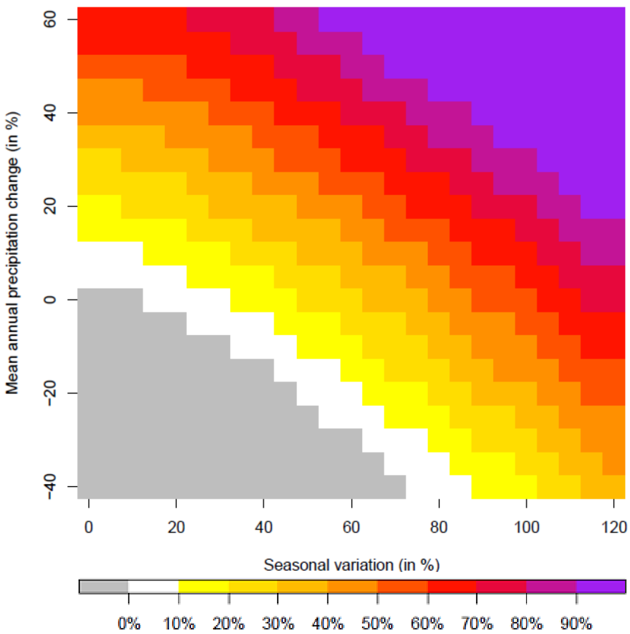

Figure 1.1 Example flood response pattern for changes in 20-year flood peak for the Helmsdale @ Kilphedir with the Medium-Aug temperature/PE scenario (maximum rainfall change in January).

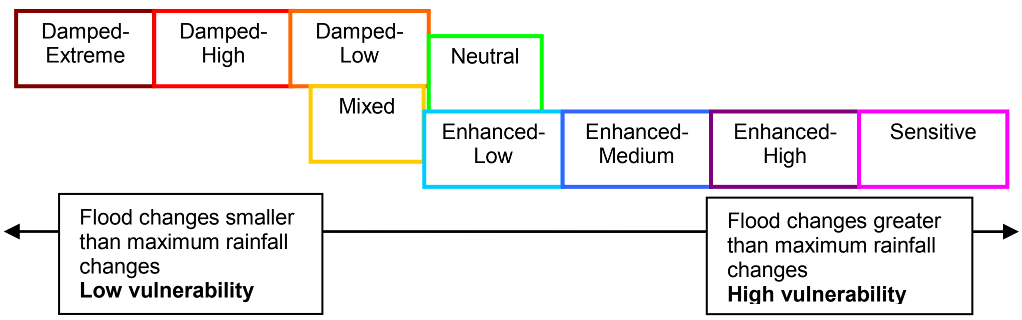

Figure 1.2 Schematic of the nine flood response types from FD2020.

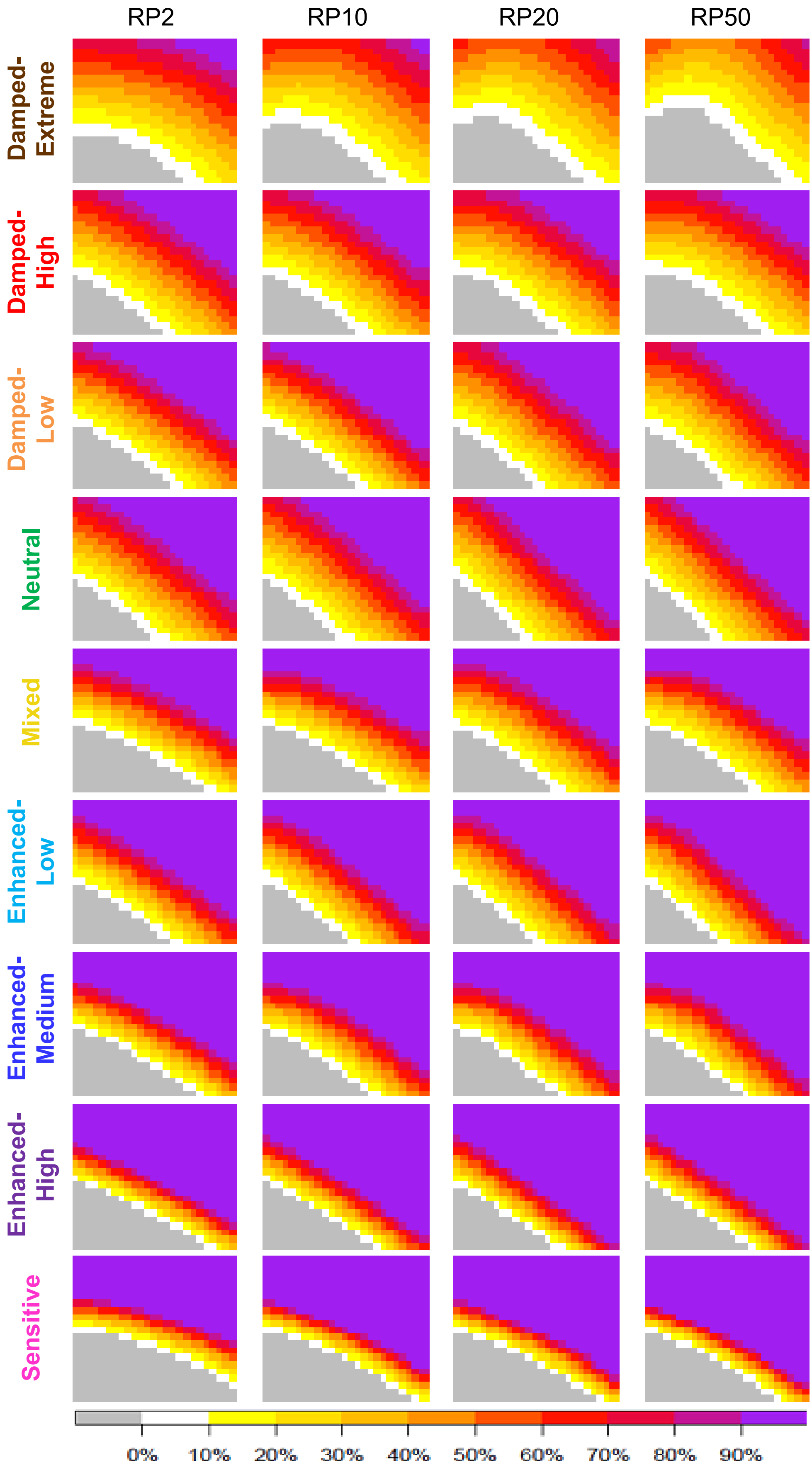

Figure 1.3 Key flood response patterns (averaged over the eight T/PE scenarios), for the nine flood response types and the four flood indicators of FD2020.

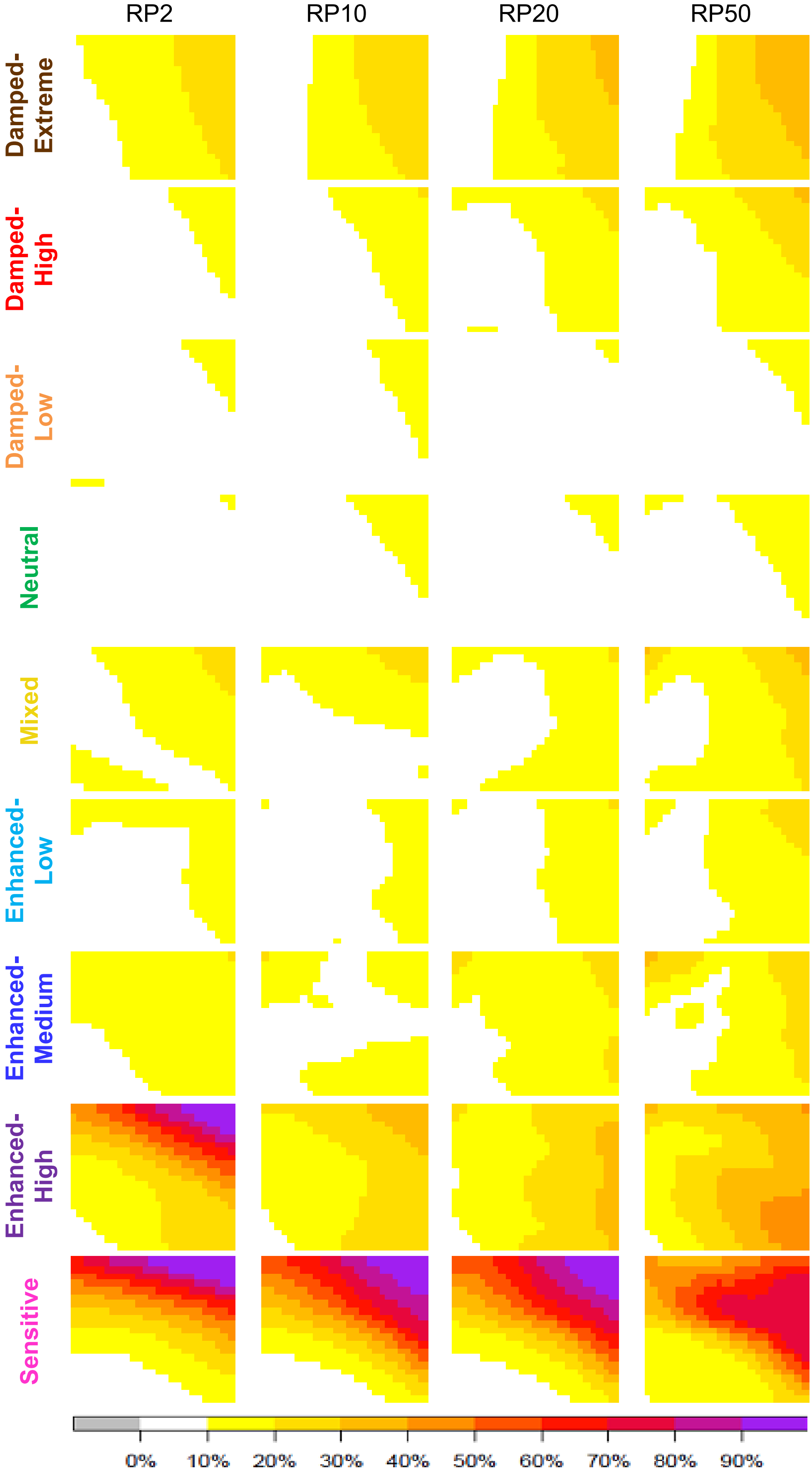

Figure 1.4 Standard deviation of the key flood response patterns (over the eight T/PE scenarios), for the nine flood response types and four flood indicators of FD2020.

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

<table>
<tr><th rowspan="2">Flood response type</th><th colspan="4">Combination of flood response types (with key flood response pattern to be applied) for:</th></tr>
<tr><th>RP2</th><th>RP10</th><th>RP20</th><th>RP50</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).

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

Numbers in bold are those to be used with (merged) key response patterns, when a catchment's response type is estimated from catchment properties. Note that, where flood response types are merged (outlined squares), the middle uncertainty allowance is applied. Numbers not in bold are only required for use with modelled catchment response patterns.

2 Methodology

2.1 Vulnerability – Modification of the FD2020 decision trees

Assessing the vulnerability of each of the NRFA catchments requires estimating its response type from its catchment properties, by applying the decision trees developed from regionalisation of the response patterns for 154 modelled catchments in FD2020. The details of the original decision trees can be found in Figure 5.1 and Table 5.4 of Reynard *et al.* (2009). This section discusses some minor modifications made to the FD2020 decision trees, to make them more robust for use on the larger set of NRFA catchments. The modifications have been designed as a pragmatic solution in applying the trees to a wider range of combinations of catchment properties than covered in the hydrological and response modelling of FD2020. In the longer term further modelling is advisable, to fully investigate critical combinations.

2.1.1 Background

The median value and range (minimum and maximum values) for the nine catchment properties used in the FD2020 decision trees (see Table 5.2 of Reynard et al. 2009) are given in Table 2.1 for the two sets of catchments, FD2020 and NRFA. For the majority of catchment properties, the range of values for the NRFA catchments is slightly wider than that for the FD2020 catchments; exceptions are AREA, BHP and BVLP, where the range is the same, and MAL where the range is considerably wider (but the median values are very similar). Also given in Table 2.1 are the medians and ranges for two further properties, URBEXT and FARL. These two properties may impact on catchment response to climate change but were not selected during development of the decision trees, which may have been because there were insufficient catchments in FD2020 with low FARL or high URBEXT to specifically allow for these factors.

The catchment property which has a much wider range than was included in the FD2020 set is MAL, the mean annual loss. Because the FD2020 catchments were predominantly selected, for calibration reasons, to have a reasonably natural flow regime, MAL for these catchments is largely a measure of evaporative losses. However, for many catchments MAL is also inclusive of water usage including groundwater abstraction and import/export of water from/to other catchments. Hence MAL for the NRFA catchments includes those with both high losses (MAL > 700mm) and gains (MAL < 100mm). Of the FD2020 catchments, 95% have losses between 200 and 600mm, with the comparable figure for the NRFA set being 82%. From the catchment property values in Table 2.1 it can be seen that some catchments have considerable gains (MAL < 0). A regional analysis of catchments with high and low MAL showed a broad distribution across hydrometric regions but with the highest numbers in Scotland and Northern England. Thus the extremes of MAL reflect the pattern of transfers of water between catchments rather than in-catchment water usage.

Table 2.1 Minimum, median and maximum values of selected catchment properties in the FD2020 and NRFA catchment sets.

Catchment property	FD2020			NRFA		
	Min	Median	Max	Min	Median	Max
AREA (km^2)	0.9	238	9948	0.9	106	9948
EASTING (of catchment outlet)	185900	364850	622900	140330	382600	640600
NORTHING (of catchment outlet)	44700	359100	959550	27300	325800	1025300
ALTBAR (mean catchment altitude; masl)	25	181	682	14	158	686
BFIHOST (baseflow index, estimated from HOST soil data; -)	0.22	0.48	0.96	0.17	0.47	0.97
$SAAR_{6190}$ (Standard Average Annual Rainfall; mm)	572	970	2912	543	900	3465
BHP (Bedrock High Permeability; %)	0	0	100	0	0	100
BVLP (Bedrock Very Low Permeability; %)	0	55.2	100	0	40.7	100
MAL (Mean Annual Loss; mm)	82	445	753	-4868	454	2463
FARL (index of Flood Attenuation by Reservoirs and Lakes; -)	0.664	0.984	1.0	0.587	0.979	1.0
$URBEXT_{2000}$ (index of urban/suburban extent; -)	0	0.007	0.454	0	0.009	0.667

An inspection of use of the decision trees for catchments with high and low MAL indicated that such values do not compromise the use of the trees but how such alterations to natural flow impact on the flood regime is not known. Additionally, how the range of MAL (of all values), combined with a wider range of the other catchment properties used in the trees, affects the response type requires investigation. The fact that the decision trees, as developed, perform better with MAL than actual evaporation (AE) suggests that the total loss does play a role in catchment flood hydrology.

The thresholds determined in FD2020 for the decision trees are appropriate for the range and combinations of catchment properties in the set of 154 catchments modelled in FD2020. Although the range of properties in the NRFA set is not much wider (apart from MAL), the combinations of property values are likely to be much greater. Therefore, it is important to identify critical combinations of catchment property values, in relation to decision tree thresholds, where the designated response type for the NRFA catchments, if estimated using the original FD2020 decision trees, might be not as expected from knowledge of the characteristics of the response types. It is likely that there are thresholds in the decision trees which are used implicitly, but which need to be made explicit; for example in the combination of values of SAAR and BHP. This is explained in further detail in the next section.

2.1.2 Modification of the decision trees

As outlined above, the decision trees were assessed to determine whether combinations of threshold values used in the decision tree rules required implicit values to be made explicit. Table 2.2 lists the combinations of catchment properties where modifications were considered to be required for each of the four return periods. The modifications made for each combination of catchment properties are described below and detailed in Table 2.3.

Table 2.2 Combinations of catchment properties for modified decision trees.

Catchment property combination	RP2	RP10	RP20	RP50
SAAR and BHP	✓	✓	✓	✓
MAL and BHP	×	✓	✓	✓

SAAR and BHP

The SAAR value of 969.5 is a dominant threshold in the decision trees for all four return periods, and in the FD2020 catchment set there are no catchments with a SAAR greater than 969.5 combined with a BHP greater than 39. In the decision trees, when the SAAR is in excess of 969.5 the BHP is not used as a further threshold (that is, for the FD2020 catchments BHP is not a factor in determining the response type when SAAR > 969.5). In terms of impact on designated response type, with the original decision trees a catchment with SAAR > 969.5 would have a Damped, Neutral or Mixed response type for all return periods, regardless of permeability. However, this raises the question – if a catchment has SAAR and BHP values which exceed 969.5 and 39 respectively, should its response type be determined more by the rainfall or by the permeability? From knowledge of the structure of the decision trees and characteristics of the response types it was felt that the permeability should be considered in determining the type. Therefore, either the SAAR threshold can be increased or an additional threshold introduced to test for BHP. Changing the SAAR threshold affects the designation of catchments other than just those with a high BHP. Additionally, a new SAAR threshold value would be determined only as appropriate to the set of NRFA catchments and would not necessarily then be 'right' for all points on all rivers in Britain. Therefore, the rules for all return periods were modified to include a BHP threshold with the initial SAAR threshold. The modified rules for each path are given in Table 2.3.

MAL and BHP

Path number 6 for RP20, leading to a response type of Sensitive, is determined only by SAAR (≤ 969.5) and MAL (≥ 500.5). As outlined above, MAL for NRFA catchments covers a much wider range of values than for FD2020 catchments, and thus many NRFA catchments satisfy these two criteria. However, these are unlikely to all have a Sensitive response type. Comparison of the decision tree paths/rules for return periods 10, 20 and 50 shows that although there are differences there is also a similarity between them which can be used to identify implicit threshold values for combinations of BHP and MAL. This situation affects paths 9 and 10 at RP10, path 6 at RP20 and paths 5 and 6 at RP50 for response types Enhanced-High and Sensitive. The modified rules for these paths (and their alternative paths) are given in Table 2.3. They provide greater cohesion between the return periods and introduce MAL into the decision tree for RP10.

Table 2.3 Modified rules for the decision trees.

Catchment property combination	Return period	Path # affected*	Addition to rule on path (in bold)
SAAR and BHP	RP2	1-9	SAAR ≤ 969.5 **or BHP ≥ 73.5**
		10-13	SAAR > 969.5 **and BHP < 73.5**
	RP10	1-10	SAAR ≤ 969.5 **or BHP ≥ 73.5**
		11-12	SAAR > 969.5 **and BHP < 73.5**
	RP20	1-6	SAAR ≤ 969.5 **or BHP ≥ 73.5**
		7-9	SAAR > 969.5 **and BHP < 73.5**
	RP50	1-6	SAAR ≤ 969.5 **or BHP ≥ 73.5**
		7-9	SAAR > 969.5 **and BHP < 73.5**
MAL and BHP	RP10	1-8	BHP < 73.5 **or MAL < 403.5**
		9-10	BHP ≥ 73.5 **and MAL ≥ 403.5**
	RP20	1-5	MAL < 500.5 **or BHP < 73.5**
		6	MAL ≥ 500.5 **and BHP ≥ 73.5**
	RP50	1-4	BHP < 73.5 **or MAL < 403.5**
		5-6	BHP ≥ 73.5 **and MAL ≥ 403.5**

*See Figure 5.1 of Reynard *et al.* (2009)

A further modification has been made to one of the rules on the RP2 decision tree, following improvements to the modelling for a small number of catchments since the completion of FD2020. This modification is simply a change to the threshold used for the MAL split between path number 6 and paths 7 and 8. The threshold has been reduced from 454.5 mm to 435 mm, resulting in a slightly increased chance of a catchment being classified as Enhanced-Low at RP2 (if it has MAL > 435 mm and Area < 1190.97 km^2) rather than Damped-Low (if it has either MAL > 435 mm and Area > 1190.97 km^2, or MAL < 435 mm). See Section 2.1.4 for a full summary of the modified decision trees.

2.1.3 Effect of the modified decision trees

Results using the modified decision trees described in Table 2.3 for the 1469 NRFA catchments were compared with those from using the original trees, to check that there were no unforeseen consequences. Numbers of catchments affected by using the modified rules are given in Table 2.4 for each return period, while the number changed at none, one, and up to all four return periods are given in Table 2.5. Table 2.4 shows that it is the changes for RP20 (path 6) that affect the most catchments, while Table 2.5 confirms that the response types for most catchments (88%) are not affected by the modifications to the rules. The six catchments where the response type is changed at all four return periods are all ones with SAAR > 969.5 and BHP ≥ 73.5 (and MAL > 500.5). For these catchments, the response type changes from Damped-High or Neutral with the original trees to Enhanced-High or Sensitive using the modified trees.

Table 2.4 Number of NRFA catchments at each return period where the response type is changed by the rule modifications.

	RP2	RP10	RP20	RP50
Number of catchments	12	47	133	41

Table 2.5 Number of NRFA catchments affected by the rule modifications at no, one, two, three or all four return periods (RPs).

	No RPs	One RP	Two RPs	Three RPs	Four RPs
Number of catchments	1295	127	41	0	6
Percentage of catchments	88.2	8.6	2.8	0	0.4

The modifications to the decision tree rules described in Table 2.3 alter the estimated response type for three of the FD2020 catchments, all at RP20. For these catchments the modification to rules for path 6 changes the assigned response type from Sensitive to Enhanced-High or Mixed (these types are then the same as those assigned at RP50).

The result of using the adjusted MAL threshold between path 6 and paths 7 and 8 at RP2 for the 1469 NRFA catchments is that the estimated response type of 28 of the catchments changes from Damped-Low to Enhanced-Low. For most of these catchments, this new estimated response type fits better with the estimated response type at the 20- and 50-year return periods, and with the estimated response types for any nested catchments. However, it does highlight a slight inconsistency with estimated response types at the 10-year return period, where there are perhaps too many catchments being assigned the Damped-Low response type rather than more enhanced types. This may be due to MAL not being used at a lower level in the decision tree for RP10. In the original FD2020 decision tree for RP10, MAL was not used at all since a decision tree was not found which used MAL and which distinguished the Enhanced-Low response type.

2.1.4 Summary of the modified decision trees

The full sets of decision tree rules at each return period are detailed in Figure 2.1a-d, along with the best-estimate (highest probability) response type associated with each path, and its confidence level (H – High, M – Medium, L – Low). The probabilities associated with each response type for each path, at each return period, are given in Table 2.6a-d.

Path #					Highest probability response type	Confidence level
11	SAAR > 969.5 and BHP < 73.5	Area ≤ 847.795	North > 171175		Damped-High	H
12	SAAR > 969.5 and BHP < 73.5	Area > 847.795	MAL < 426.5		Damped-High / Damped-Low	L
8	(SAAR ≤ 969.5 or BHP ≥73.5) and SAAR > 726.5	BHP < 73.5	MAL ≥ 435	Area > 1190.97	Damped-Low	H
6	(SAAR ≤ 969.5 or BHP ≥73.5) and SAAR > 726.5	BHP < 73.5	MAL < 435		Damped-Low	L
13	SAAR > 969.5 and BHP < 73.5	Area > 847.795	MAL ≥ 426.5		Neutral	M
10	SAAR > 969.5 and BHP < 73.5	Area ≤ 847.795	North ≤ 171175		Neutral	M
4	SAAR ≤ 726.5	MAL < 500.5	North > 265050	East > 509975	Mixed / Enhanced-High	L
7	(SAAR ≤ 969.5 or BHP ≥73.5) and SAAR > 726.5	BHP < 73.5	MAL ≥ 435	Area ≤ 1190.97	Enhanced-Low	L
2	SAAR ≤ 726.5	MAL < 500.5	North ≤ 265050	ALTBAR > 70	Enhanced-Low	L
3	SAAR ≤ 726.5	MAL < 500.5	North > 265050	East ≤ 509975	Enhanced-Medium	L
1	SAAR ≤ 726.5	MAL < 500.5	North ≤ 265050	ALTBAR ≤ 70	Enhanced-Medium	L
9	(SAAR ≤ 969.5 or BHP ≥73.5) and SAAR > 726.5	BHP ≥ 73.5			Enhanced-High	M
5	SAAR ≤ 726.5	MAL ≥ 500.5			Sensitive	M

Figure 2.1a Schematic of the decision tree for RP2 with associated best estimate of the response type and its confidence level (H – High, M – Medium, L – Low).

Path #						Highest Probability response type	Confidence level
12	SAAR > 969.5 and BHP < 73.5	AREA > 680.86				Damped-Low	H
8	(SAAR ≤ 969.5 or BHP ≥ 73.5) and SAAR > 726.5	BHP < 73.5 or MAL < 403.5	North ≥ 334950	ALTBAR ≥ 191		Damped-Low	M
7	(SAAR ≤ 969.5 or BHP ≥ 73.5) and SAAR > 726.5	BHP < 73.5 or MAL < 403.5	North ≥ 334950	ALTBAR ≤ 191		Damped-Low	H
5	(SAAR ≤ 969.5 or BHP ≥ 73.5) and SAAR > 726.5	BHP < 73.5 or MAL < 403.5	North ≤ 334950	ALTBAR ≤ 159.5		Damped-Low	M
4	SAAR ≤ 726.5	BHP < 73.5 or MAL < 403.5	ALTBAR > 63	BFIHOST > 0.496		Damped-Low	L
11	SAAR > 969.5 and BHP < 73.5	AREA ≤ 680.86				Neutral	H
3	SAAR ≤ 726.5	BHP < 73.5 or MAL < 403.5	ALTBAR > 63	BFIHOST ≤ 0.496	North > 244000	Mixed	L
6	(SAAR ≤ 969.5 or BHP ≥ 73.5) and SAAR > 726.5	BHP < 73.5 or MAL < 403.5	North ≤ 334950	ALTBAR ≥ 159.5		Enhanced-Low	L
2	SAAR ≤ 726.5	BHP < 73.5 or MAL < 403.5	ALTBAR > 63	BFIHOST ≤ 0.496	North ≤ 244000	Enhanced-Low	L
1	SAAR ≤ 726.5	BHP < 73.5 or MAL < 403.5	ALTBAR ≤ 63			Enhanced-Medium	L
10	SAAR ≤ 969.5 or BHP ≥ 73.5	BHP ≥ 73.5 and MAL ≥ 403.5	Area ≥ 146.205			Enhanced-High	L
9	SAAR ≤ 969.5 or BHP ≥ 73.5	BHP ≥ 73.5 and MAL ≥ 403.5	Area < 146.205			Sensitive	L

Figure 2.1b As Figure 2.1a but for RP10 (with merged response types).

Path #				Highest Probability response type	Confidence level
9	SAAR > 969.5 and BHP < 73.5	NORTH ≥ 403275		Neutral	H
7	SAAR > 969.5 and BHP < 73.5	NORTH ≤ 403275	Area < 781.09	Neutral	H
4	(SAAR ≤ 969.5 or BHP ≥ 73.5) and SAAR > 858	(MAL < 500.5 or BHP < 73.5) and MAL ≥ 403.5	4.5 < BHP < 73.5	Neutral	L
1	SAAR ≤ 969.5 or BHP ≥ 73.5	MAL < 403.5		Neutral	M
3	SAAR ≤ 858	(MAL < 500.5 or BHP < 73.5) and MAL ≥ 403.5	4.5 < BHP < 73.5	Mixed	H
8	SAAR > 969.5 and BHP < 73.5	NORTH ≤ 403275	Area ≥ 781.09	Mixed	L
5	SAAR ≤ 969.5 or BHP ≥ 73.5	(MAL < 500.5 or BHP < 73.5) and MAL ≥ 403.5	BHP ≥ 73.5	Enhanced-High	H
2	SAAR ≤ 969.5 or BHP ≥ 73.5	(MAL < 500.5 or BHP < 73.5) and MAL ≥ 403.5	BHP ≤ 4.5	Enhanced-High	H
6	SAAR ≤ 969.5 or BHP ≥ 73.5	MAL ≥ 500.5 and BHP ≥ 73.5		Sensitive	M

Figure 2.1c As Figure 2.1a but for RP20 (with merged response types).

Path #					Highest Probability response type	Confidence level
9	SAAR > 969.5 and BHP < 73.5	ALTBAR > 245.5			Neutral	H
7	SAAR > 969.5 and BHP < 73.5	ALTBAR ≤ 245.5	Area < 781.09		Neutral	H
1	SAAR ≤ 969.5 or BHP ≥ 73.5	BHP < 73.5 or MAL < 403.5	MAL < 427.5		Neutral	H
8	SAAR > 969.5 and BHP < 73.5	ALTBAR ≤ 245.5	Area ≥ 781.09		Mixed	L
2	SAAR < 858	BHP < 73.5 or MAL < 403.5	MAL ≥ 427.5	BVLP ≤ 75	Mixed	H
5	SAAR ≤ 969.5 or BHP ≥ 73.5	BHP ≥ 73.5 and MAL ≥ 403.5	MAL ≤ 493.5		Enhanced-High	H
4	SAAR ≤ 969.5 or BHP ≥ 73.5	BHP < 73.5 or MAL < 403.5	MAL ≥ 427.5	BVLP > 75	Enhanced-High	L
3	(SAAR ≤ 969.5 or BHP ≥73.5) and SAAR ≥ 858	BHP < 73.5 or MAL < 403.5	MAL ≥ 427.5	BVLP ≤ 75	Enhanced-High	L
6	SAAR ≤ 969.5 or BHP ≥ 73.5	BHP ≥ 73.5 and MAL ≥ 403.5	MAL > 493.5		Sensitive	L

Figure 2.1d As Figure 2.1a but for RP50 (with merged response types).

Table 2.6a Probability of each response type for each path at RP2, with the best-estimate of the response type of the path (highest probability) and its confidence level.

Path #	Flood response type of path	Confidence level	Probability of flood response types: Damped-High	Damped-Low	Neutral	Mixed	Enhanced-Low	Enhanced-Medium	Enhanced-High	Sensitive	Number of catchments following path
1	Enhanced-Medium	L	0	0	0	0	0.2	**0.8**	0	0	5
2	Enhanced-Low	L	0	0.33	0	0	**0.44**	0.22	0	0	9
3	Enhanced-Medium	L	0	0	0	0.17	0	**0.67**	0.17	0	6
4	Mixed/Enhanced-High	L	0	0	0	**0.43**	0.14	0	**0.43**	0	7
5	Sensitive	M	0	0	0	0	0	0	0	**1**	6
6	Damped-Low	L	0.35	**0.41**	0.12	0.06	0.06	0	0	0	17
7	Enhanced-Low	L	0	0.36	0	0	**0.64**	0	0	0	11
8	Damped-Low	H	0	**1**	0	0	0	0	0	0	8
9	Enhanced-High	M	0	0	0	0.13	0.13	0	**0.75**	0	8
10	Neutral	M	0.13	0	**0.88**	0	0	0	0	0	8
11	Damped-High	H	**0.77**	0.02	0.21	0	0	0	0	0	48
12	Damped-Low/High	L	**0.45**	**0.45**	0.09	0	0	0	0	0	11
13	Neutral	M	0	0.25	**0.75**	0	0	0	0	0	8
	Original category size		49	30	26	6	15	10	10	6	152

Table 2.6b As Table 2.6a but for RP10 (with merged response types).

Path #	Flood response type of path	Confidence level	Probability of flood response types: Damped-Low	Neutral	Mixed	Enhanced-Low	Enhanced-Medium	Enhanced-High	Sensitive	Number of catchments following path
1	Enhanced-Medium	L	0	0	0.2	0	**0.8**	0	0	5
2	Enhanced-Low	L	0.2	0	0.2	**0.6**	0	0	0	5
3	Mixed	L	0	0	**0.8**	0	0	0	0.2	5
4	Damped-Low	L	**0.57**	0	0	0	0	0.29	0.14	7
5	Damped-Low	M	**0.89**	0	0	0.11	0	0	0	9
6	Enhanced-Low	L	0.17	0.17	0	**0.67**	0	0	0	6
7	Damped-Low	H	**0.91**	0.09	0	0	0	0	0	11
8	Damped-Low	M	**0.6**	0	0.2	0	0.2	0	0	10
9	Sensitive	L	0	0	0	0	0.22	0.22	**0.56**	9
10	Enhanced-High	L	0	0	0.1	0.3	0	**0.5**	0.1	10
11	Neutral	H	0.31	**0.69**	0	0	0	0	0	54
12	Damped-Low	H	**0.76**	0.24	0	0	0	0	0	21
	Original category size		63	44	9	11	8	9	8	152

Table 2.6c As Table 2.6a but for RP20 (with merged response types).

Path #	Flood response type of path	Confidence level	Probability of flood response types: Neutral	Mixed	Enhanced-High	Sensitive	Number of catchments following path
1	Neutral	M	**0.8**	0.2	0	0	10
2	Enhanced-High	H	0.1	0.2	**0.65**	0.05	20
3	Mixed	H	0	**0.86**	0.09	0.05	22
4	Neutral	L	**0.5**	0.17	0.33	0	6
5	Enhanced-High	H	0.09	0	**0.82**	0.09	11
6	Sensitive	M	0	0	0.25	**0.75**	8
7	Neutral	H	**0.91**	0.09	0	0	23
8	Mixed	L	0	**0.57**	0.43	0	7
9	Neutral	H	**1**	0	0	0	45
	Original category size		80	32	31	9	152

Table 2.6d As Table 2.6a but for RP50 (with merged response types).

Path #	Flood response type of path	Confidence level	Probability of flood response types: Neutral	Mixed	Enhanced-High	Sensitive	Number of catchments following path
1	Neutral	H	**0.82**	0.18	0	0	17
2	Mixed	H	0	**0.92**	0.04	0.04	24
3	Enhanced-High	L	0.33	0.17	**0.5**	0	6
4	Enhanced-High	L	0.36	0.09	**0.55**	0	11
5	Enhanced-High	H	0	0	**1**	0	10
6	Sensitive	L	0	0.11	0.33	**0.56**	9
7	Neutral	H	**0.91**	0	0.09	0	22
8	Mixed	L	0.33	**0.44**	0.22	0	9
9	Neutral	H	**1**	0	0	0	44
	Original category size		87	32	27	6	152

2.1.5 Application of the modified decision trees

The modified decision trees, summarised in Figure 2.1, are thus applied to the NRFA catchment set (1469 catchments in England, Wales and Scotland 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 (see Section 4.1 of Prudhomme *et al.* 2009). The number of catchments of each response type at each return period is summarised in Table

2.7. Maps showing the estimated response type (and its confidence level) for each of the NRFA catchments in England and Wales are given in Section 3 (see for example Figure 3.1). The key response patterns (Figure 1.3) corresponding to the best estimate of the response type for each catchment at each return period are then used to represent the catchment's vulnerability. The corresponding standard deviation patterns (Figure 1.4) are used to represent the possible range of responses of each type.

Table 2.7 Number of NRFA catchments (out of 1469 in England, Wales and Scotland) of each response type at each return period.

Flood response type	RP2	RP10	RP20	RP50
Damped-High	506	NA	NA	NA
Damped-Low	155	485	NA	NA
Neutral	104	554	829	865
Mixed	45	67	216	228
Enhanced-Low	265	66	NA	NA
Enhanced-Medium	176	83	NA	NA
Enhanced-High	120	73	304	247
Sensitive	98	141	120	129

It should be noted that, at RP2, two of the paths (4 and 12) lead to two response types with equal likelihood, rather than having one best-estimate of the response type for a catchment with that combination of catchment properties (see Figure 5.1a and Table 5.4a of Reynard *et al.* 2009). Path 4 leads to Mixed and Enhanced-High (probability 0.43 each) whilst path 12 leads to Damped-High and Damped-Low (probability 0.45 each). Here, for the resulting vulnerability and risk assessments, the Mixed type is selected in the former case (45 catchments) whilst the Damped-Low type is selected in the latter case (26 catchments). In each case the choice is based on the range of probabilities and distribution of FD2020 catchments across all response types at RP2. Path 4 is the one with the highest overall probability for the Mixed type while path 12 is the one of the four for SAAR > 969.5 with the highest number of catchments for Damped-Low.

2.1.6 Further considerations

A BHP threshold of 73.5 has been introduced with the SAAR threshold of 969.5 (Table 2.3) which is the same as the main BHP threshold used in other parts of the decision trees. However, the maximum value of BHP for the FD2020 catchments with SAAR > 969.5 is 39. Therefore, further modelling is required to determine a more precise value for this initial BHP threshold and to investigate the balance between dominance of rainfall or permeability on impact of climate change on flood frequency for catchments with higher than average SAAR and moderate to high permeability.

A problem with using MAL, as calculated for the NRFA, 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 100 years to less than 10 years. It is, therefore, not consistent with SAAR and is likely to be non-stationary – trends in water usage are incorporated in MAL. Further work generally is required on the role of superimposed catchment losses or gains, combined with other catchment properties, on flood hydrology.

The decision trees are not necessarily suitable for catchments with a low value of FARL or high value of URBEXT. 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. 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.

2.2 Hazard – UKCP09 Sampled Data

The resolution of the UKCP09 climate projections (Murphy *et al.* 2009) is 25km over the land area of the UK, and the Sampled Data are provided on this 25km grid (Figure 2.2a). 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 2.2b). 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 12 river-basin regions covering England and Wales are used: Northumbria, Humber, Anglian, Thames, South-East England, South-West England, Severn, West Wales, Dee, North-West England, Solway and Tweed. The latter two regions are mainly in Scotland, but do cover parts of England so are included here. No results are presented for the rest of the river-basin regions in Scotland, or for those in Northern Ireland.

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 A1B (Medium) emissions scenario and under the B1 (Low) and A1F1 (High) emissions scenarios for the 2080s time-horizon) are downloaded from the UKCP09 user interface. These data consist of 10,000 sets of changes in a number of variables. Only the data on monthly changes in mean daily precipitation are required for the methodology as applied here (see Section 2.3), 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. The distributions of the three parameters of the 10,000 fitted single harmonic functions are given in Section 3 and Appendix A (see for example Figure 3.3), 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.

a) UKCP09 25km grid b) UKCP09 river-basin regions

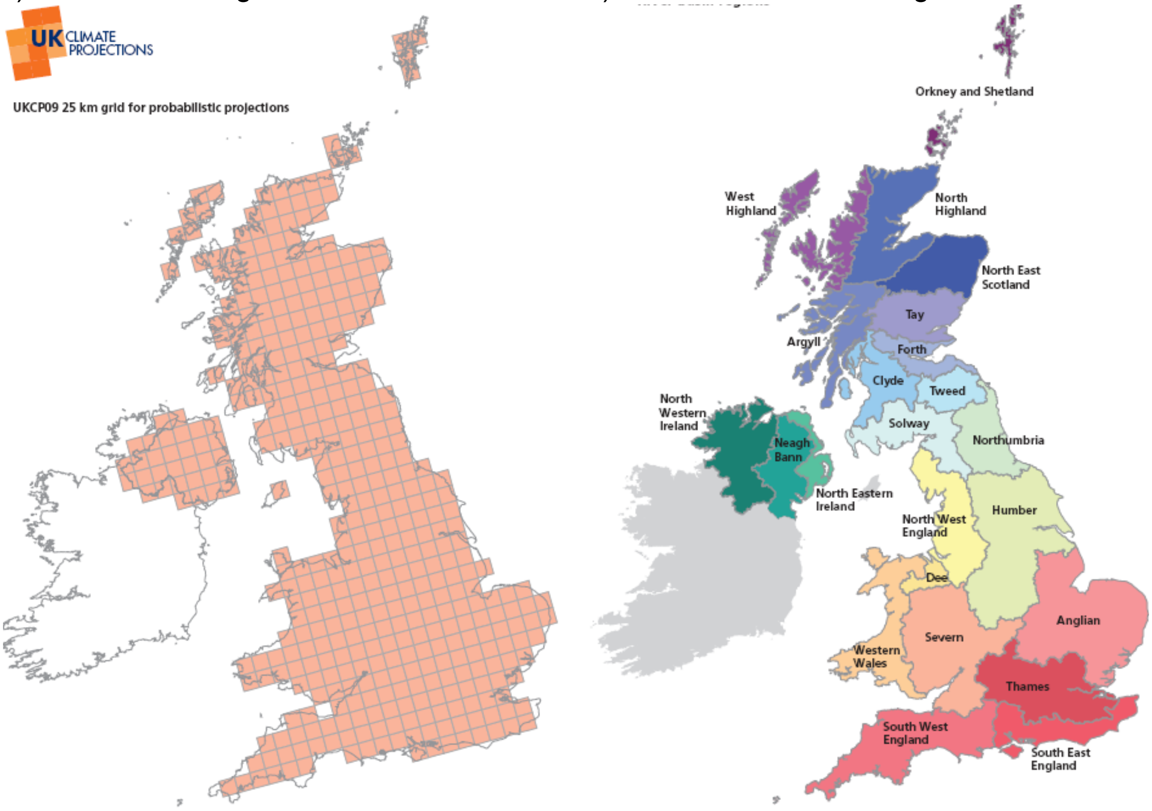

Figure 2.2 Areas over which the UKCP09 probabilistic projections are available.

2.3 Risk – combining vulnerability and hazard

As described in Section 2.2, 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 for a given river-basin region, time-horizon and emissions scenario and is then combined with the vulnerability, by using the mean and amplitude of the fitted precipitation harmonics (hazard) to extract the estimated impact from the key response patterns (vulnerability; Figure 1.3) for each response type and return period. An example plot showing the combining of vulnerability and hazard is given in Figure 2.3. 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. The appropriate extra uncertainty allowance (Table 1.3) is then added, 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).

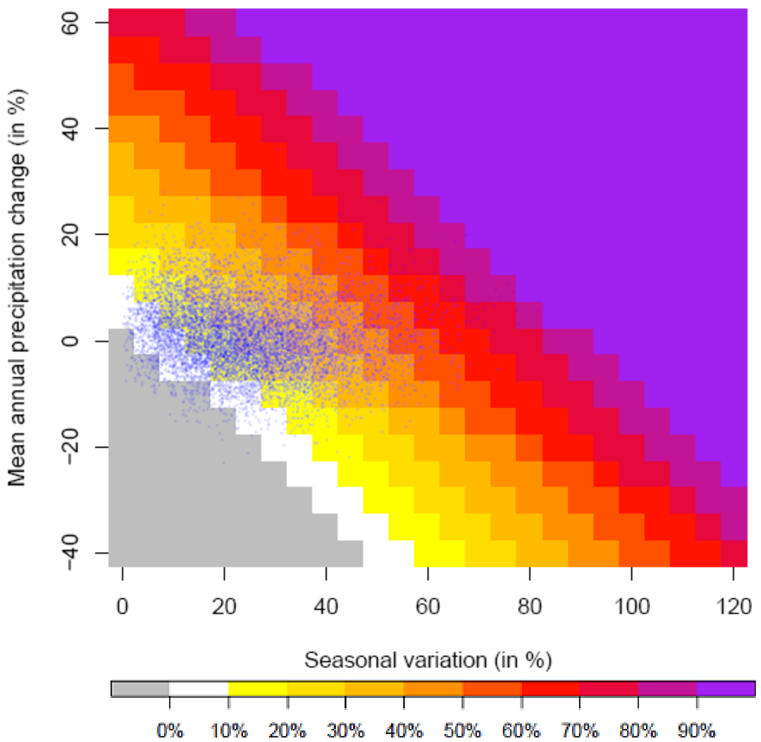

Figure 2.3 Example plot combining vulnerability (here the key flood response pattern for the Neutral response type at the 20-year return period) and hazard (here the set of 10,000 UKCP09 scenarios for the Thames river-basin region under the A1B emissions scenario for the 2080s time-horizon; blue dots).

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 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 standard deviation patterns for each response type and return period, an estimate of the standard deviation (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.

It should be noted that, although harmonic functions have also been fitted to the UKCP09 river-basin Sampled Data for temperature (Section 2.2), 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 scenarios, 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 scenarios in each river-basin region. This is a reasonable simplification, as there are 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). 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.

The use of the UKCP09 Sampled Data for river-basin regions 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 estimate of risk for a catchment. However, there is obviously more chance of differences for a small catchment within a large river-basin region.

The estimated risk, for each response type within each river-basin region at each of the four return periods, is presented as the probability of exceedance of a set of thresholds (or climate change allowances). This is rather like the figures presented in Section 7.4.2 of the FD2020 Technical Report (Reynard *et al.* 2009), except with a different set of results for each response type rather than for each catchment, and using the key response patterns (and their corresponding standard deviation patterns), rather than the modelled catchment response patterns. The risk can be presented as continuous curves, or can be presented at discrete values of the allowance. In this case, discrete values have been used (5% intervals between 0% and 60%) to simplify the plot and to allow the presentation of the central-estimate and the ± 1sd and ± 2sd ranges at each value of the allowance. Graphs showing this response-type risk, with the standard deviation uncertainty ranges, are presented in Section 3 and Appendix B.1 (see for example Figure 3.4).

As well as calculating the risk separately for each response type within each river-basin region at each of the four return periods, a weighted risk is calculated for each river-basin region and return period. This is based on the number of NRFA catchments of each response type. The weighted risk for a given river-basin 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. However it is possible that, for some catchments, the risk will be much higher than that represented by the regional risk for the appropriate river-basin region. For instance, the risk for an Enhanced-High or Sensitive catchment is likely to be underestimated by the (weighted) regional risk if it is located in a river-basin region dominated by Damped or Neutral catchments. The regional risk is thus presented on the same graphs in Section 3 (and Appendix B.1) as the response-type risk (described above), for each river-basin region and return period, to allow direct comparison of the two levels of risk information. The regional risk is presented as a continuous curve, even though it is only calculated at the same discrete values as the response-type risk, to make a clear distinction between the two levels of information.

3 Results – by UKCP09 river-basin region

This section presents the results in terms of vulnerability, hazard (under the A1B emissions scenario for the 2080s time-horizon) and risk (likewise) for each of the 12 river-basin regions over England and Wales. The hazard and risk for alternative time-horizons and emissions scenarios are presented in Appendix A and Appendix B respectively.

3.1 Northumbria

3.1.1 Vulnerability

A total of 55 NRFA catchments are located within the Northumbria river-basin region. The best-estimate of the response type for each of these catchments is mainly Damped at lower return periods and Neutral at higher return periods (Table 3.1). The maps in Figure 3.1 show the best-estimate of the response type for each catchment at each return period, and those in Figure 3.2 show the corresponding confidence levels (High – H; Medium – M; Low – L).

Table 3.1 The number of NRFA catchments of each response type at each return period, for the Northumbria river-basin region.

Response type	RP2	RP10	RP20	RP50
Damped-High	**24**	NA	NA	NA
Damped-Low	14	**24**	NA	NA
Neutral	2	22	**36**	**39**
Mixed	0	5	2	9
Enhanced-Low	5	0	NA	NA
Enhanced-Medium	10	0	NA	NA
Enhanced-High	0	2	17	6
Sensitive	0	2	0	1
Total	55	55	55	55

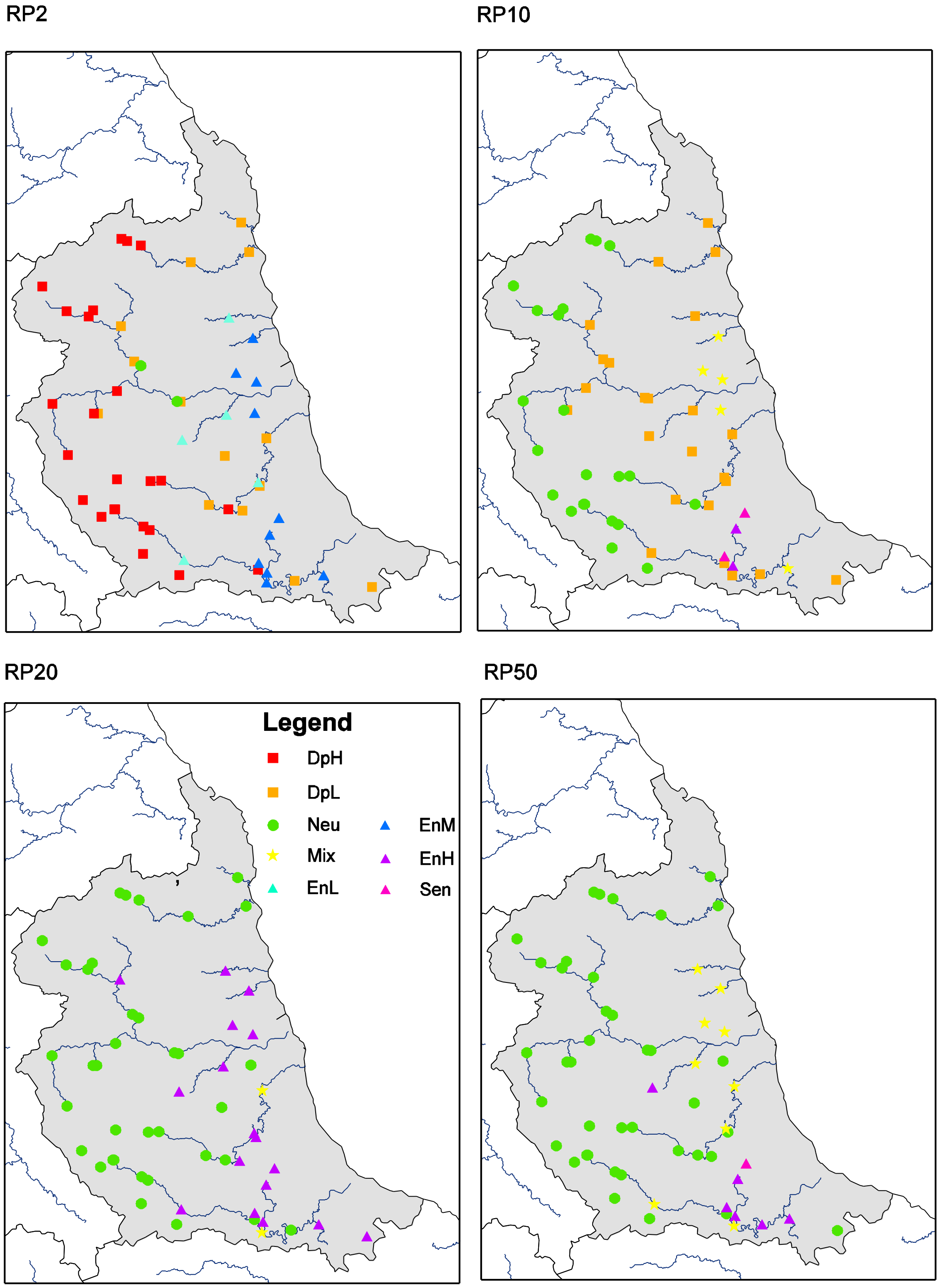

Figure 3.1 The best-estimate of the response type for each NRFA catchment in the Northumbria river-basin region.

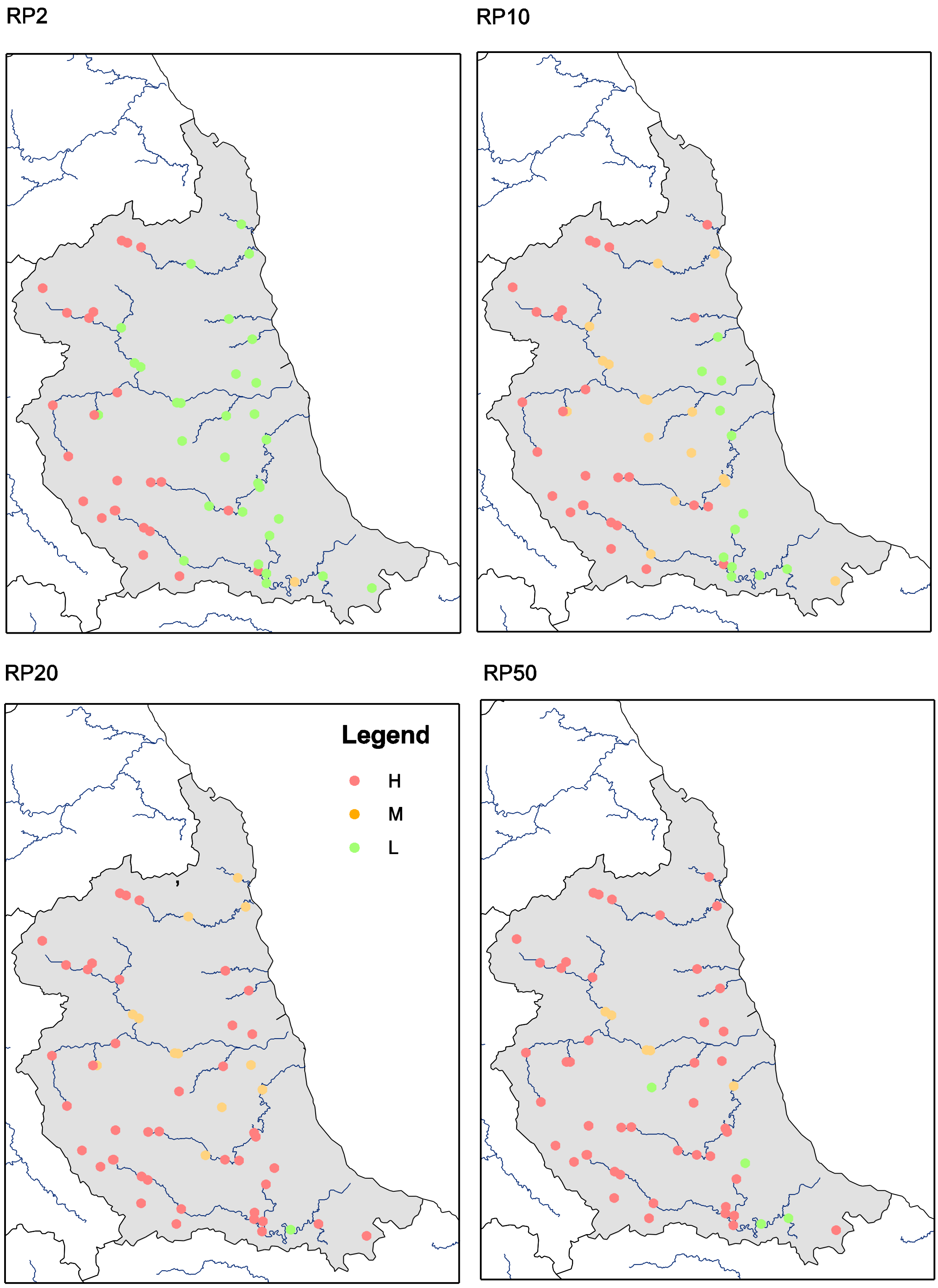

Figure 3.2 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the Northumbria river-basin region.

3.1.2 Hazard

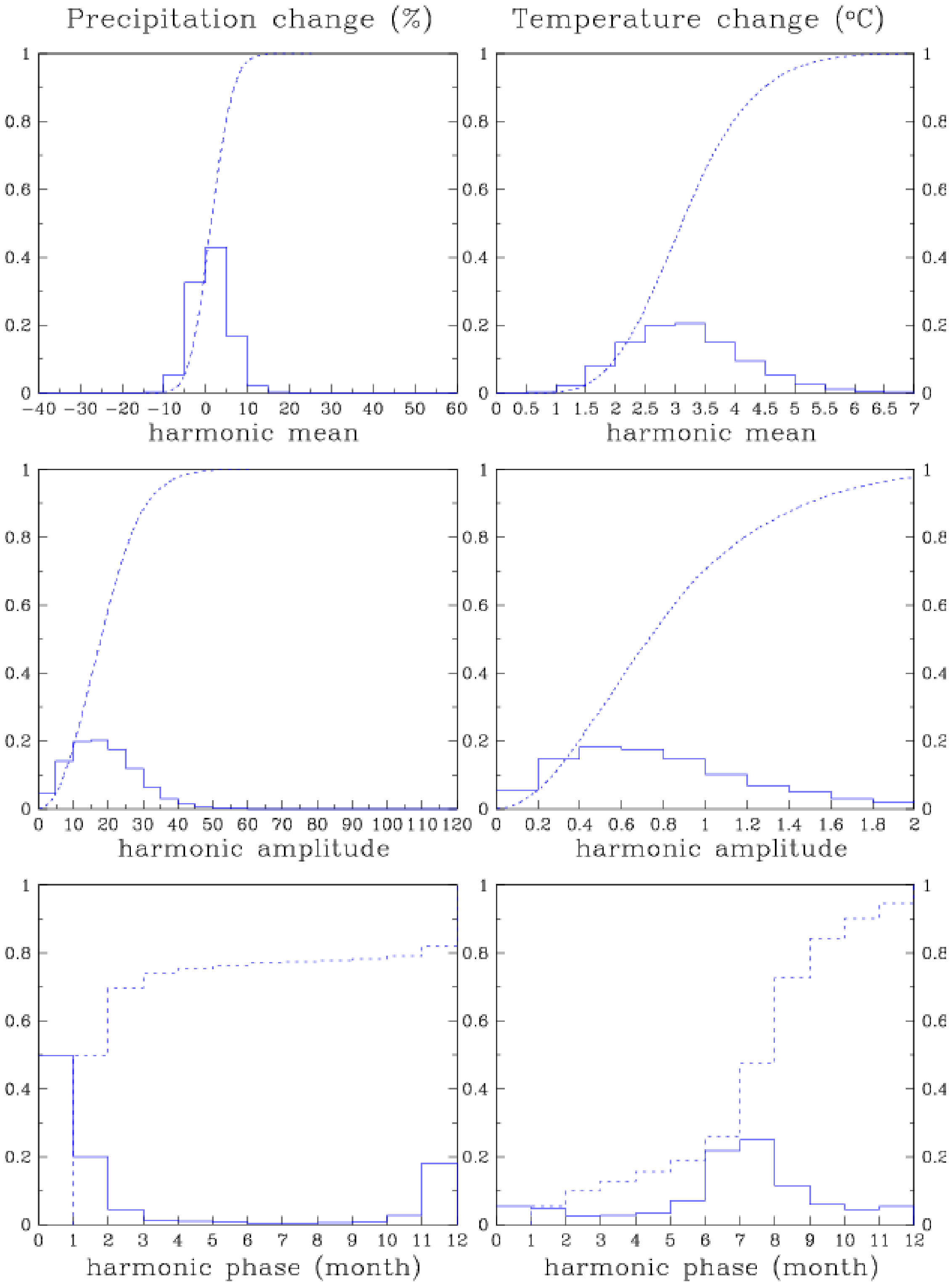

Figure 3.3 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s A1B) for the Northumbria river-basin region.

3.1.3 Risk

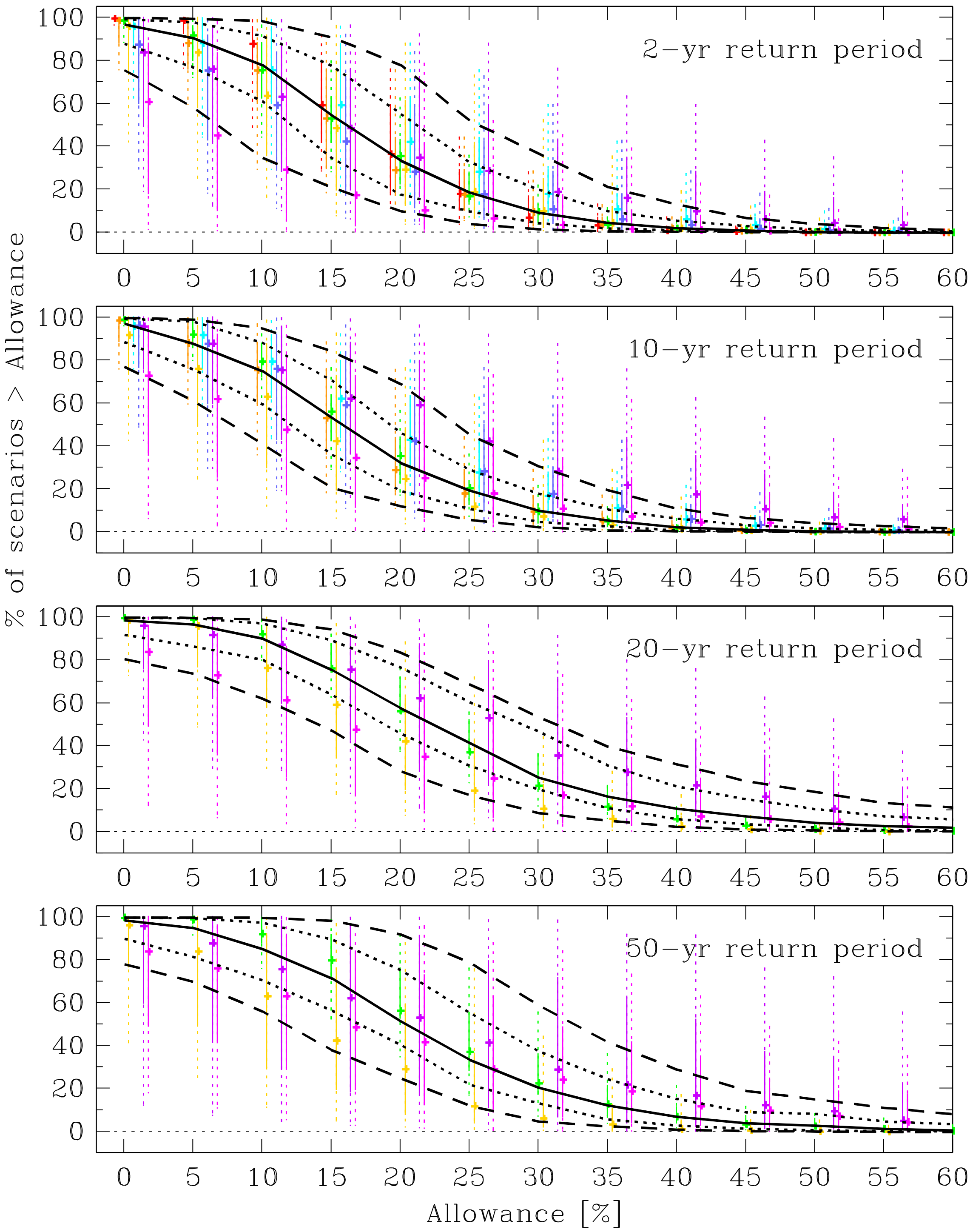

Figure 3.4 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s A1B) for the Northumbria river-basin region. Response-type risk (colours): Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta); 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).

3.2 Humber

3.2.1 Vulnerability

A total of 182 NRFA catchments are located within the Humber river-basin region. The best-estimate of the response type for each of these catchments is a mixture of Damped and Enhanced at lower return periods but mainly Neutral at higher return periods (Table 3.2). The maps in Figure 3.5 show the best-estimate of the response type for each catchment at each return period, and those in Figure 3.6 show the corresponding confidence levels (High – H; Medium – M; Low – L).

Table 3.2 The number of NRFA catchments of each response type at each return period, for the Humber river-basin region.

Response type	RP2	RP10	RP20	RP50
Damped-High	50	NA	NA	NA
Damped-Low	33	**84**	NA	NA
Neutral	4	45	**107**	**115**
Mixed	2	23	31	34
Enhanced-Low	25	3	NA	NA
Enhanced-Medium	**54**	12	NA	NA
Enhanced-High	1	6	35	24
Sensitive	13	9	9	9
Total	182	182	182	182

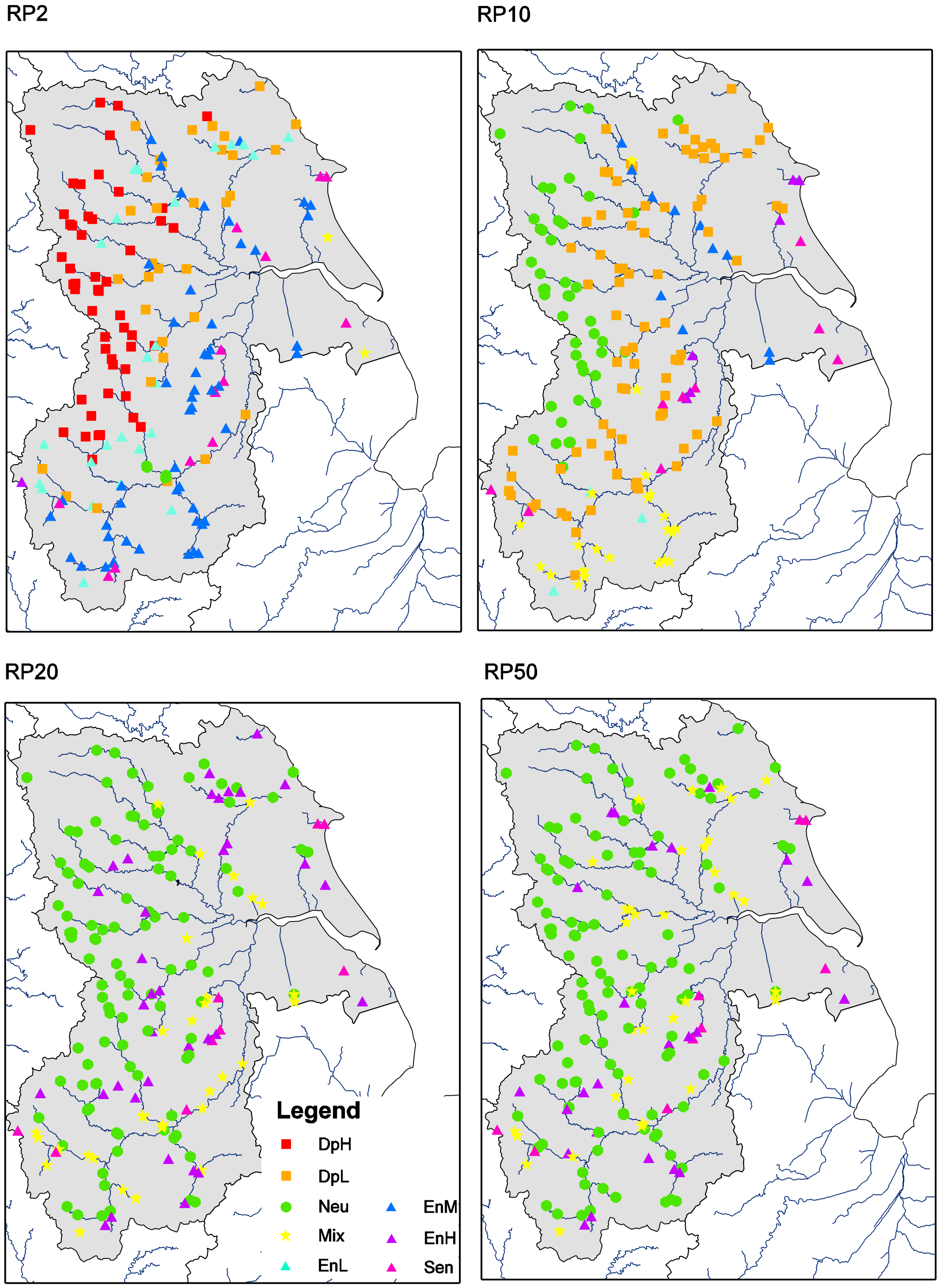

Figure 3.5 The best-estimate of the response type for each NRFA catchment in the Humber river-basin region.

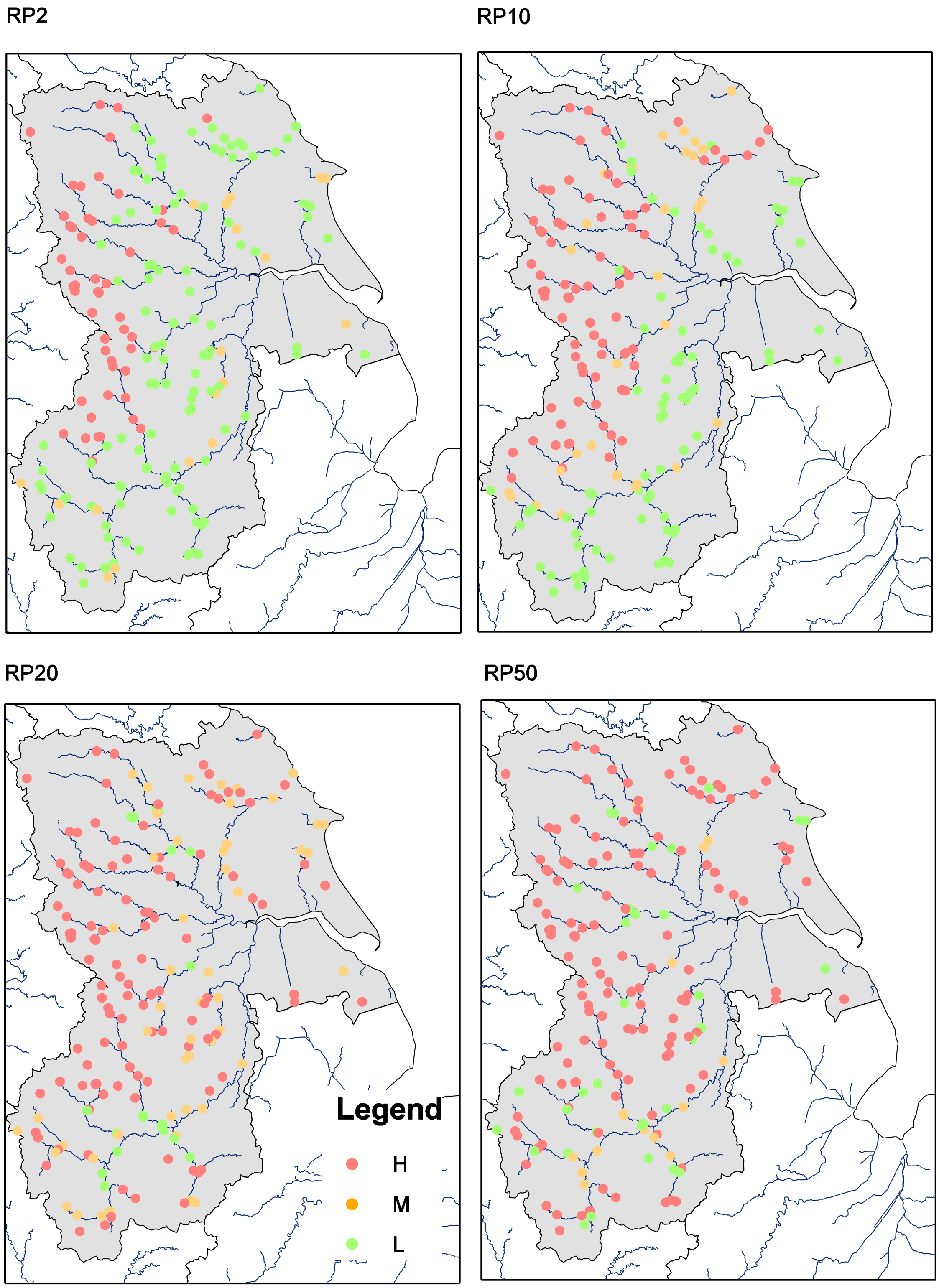

Figure 3.6 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the Humber river-basin region.

3.2.2 Hazard

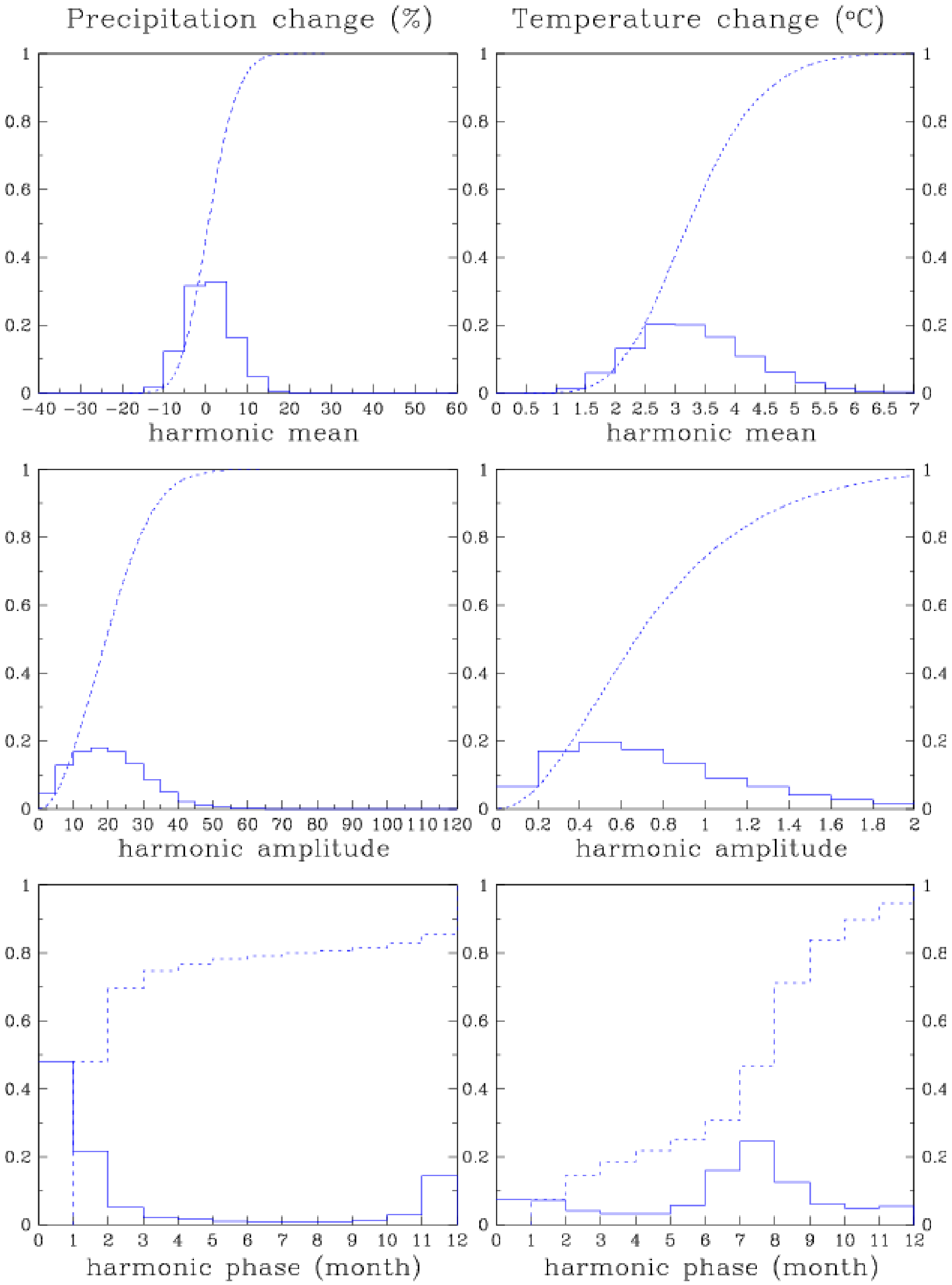

Figure 3.7 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s A1B) for the Humber river-basin region.

3.2.3 Risk

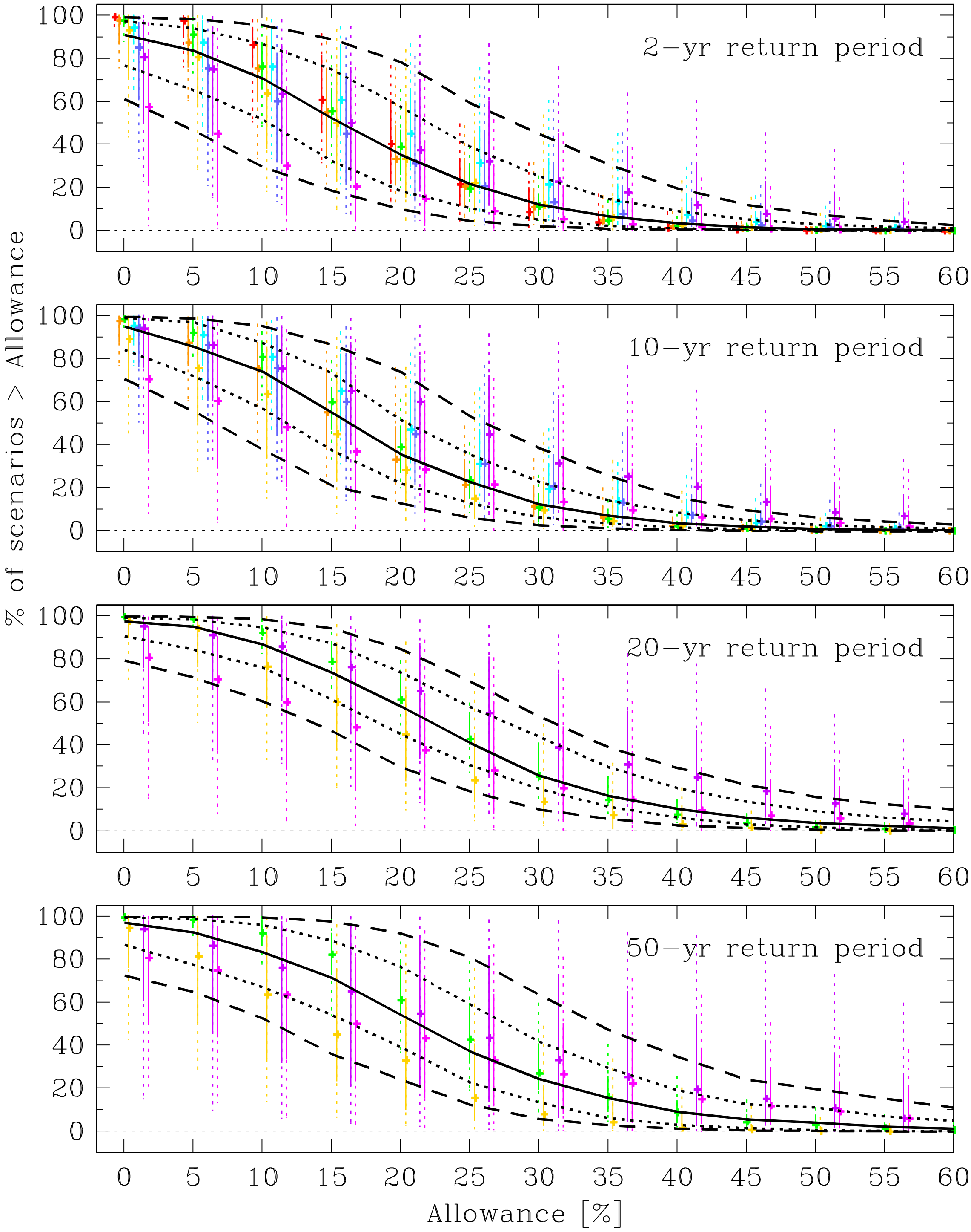

Figure 3.8 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s A1B) for the Humber river-basin region. Response-type risk (colours): Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta); 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).

3.3 Anglian

3.3.1 Vulnerability

A total of 180 NRFA catchments are located within the Anglian river-basin region. The best-estimate of the response type for each of these catchments is mainly Mixed or Enhanced (Table 3.3). The maps in Figure 3.9 show the best-estimate of the response type for each catchment at each return period, and those in Figure 3.10 show the corresponding confidence levels (High – H; Medium – M; Low – L).

Table 3.3 The number of NRFA catchments of each response type at each return period, for the Anglian river-basin region.

Response type	RP2	RP10	RP20	RP50
Damped-High	0	NA	NA	NA
Damped-Low	0	25	NA	NA
Neutral	0	0	26	39
Mixed	43	31	54	54
Enhanced-Low	40	17	NA	NA
Enhanced-Medium	**66**	**46**	NA	NA
Enhanced-High	0	25	**84**	**68**
Sensitive	31	36	16	19
Total	180	180	180	180

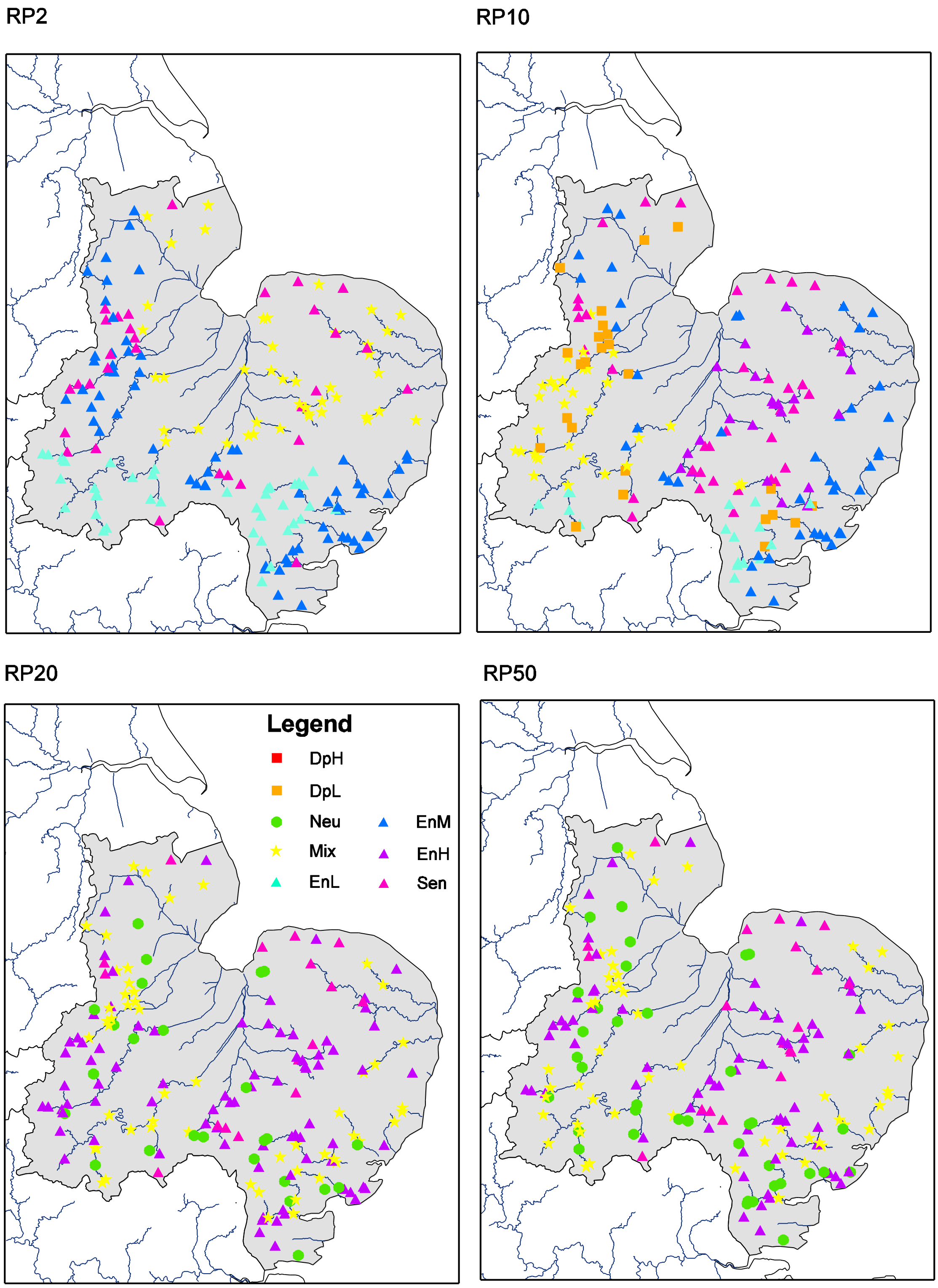

Figure 3.9 The best-estimate of the response type for each NRFA catchment in the Anglian river-basin region.

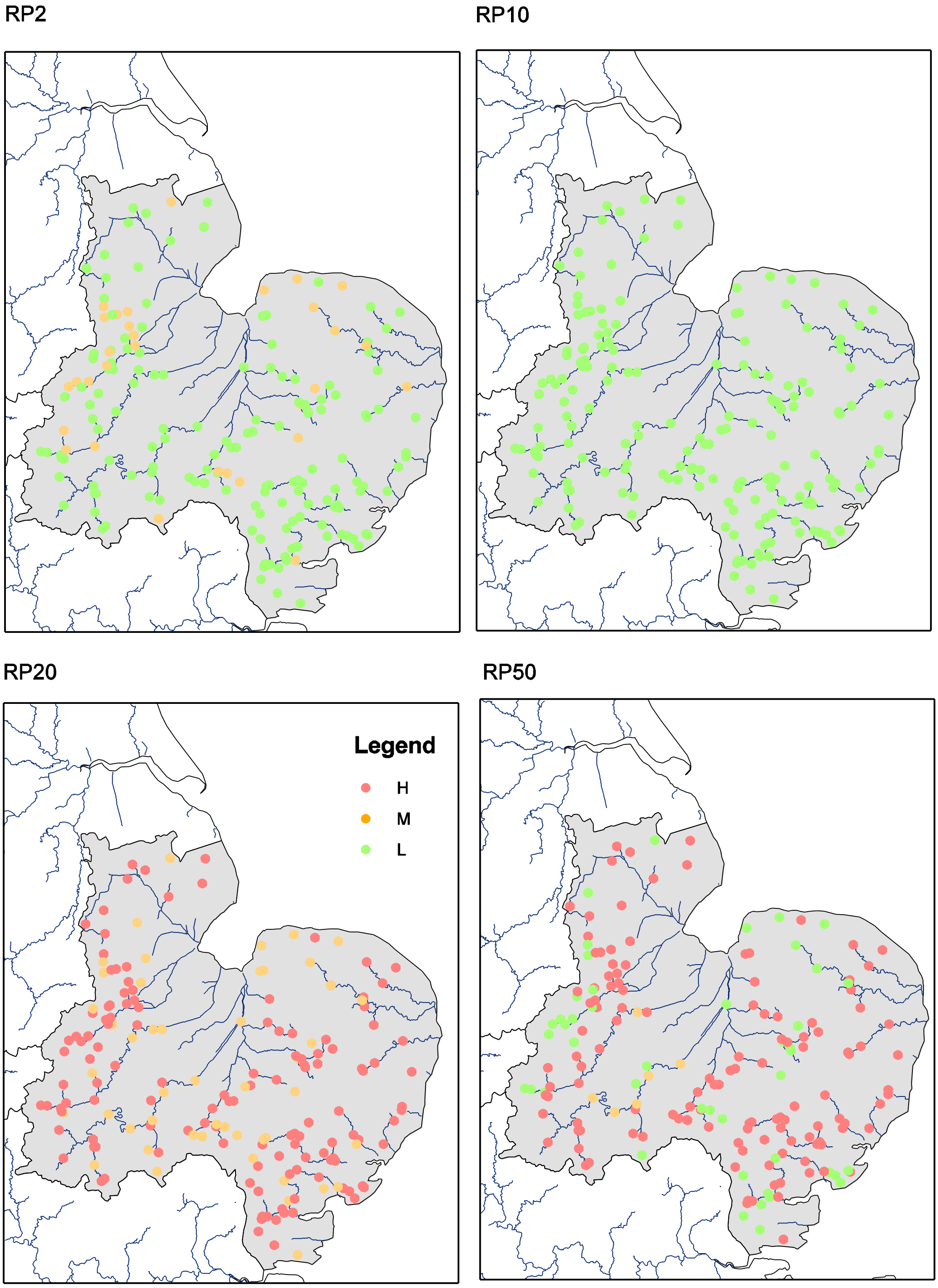

Figure 3.10 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the Anglian river-basin region.

3.3.2 Hazard

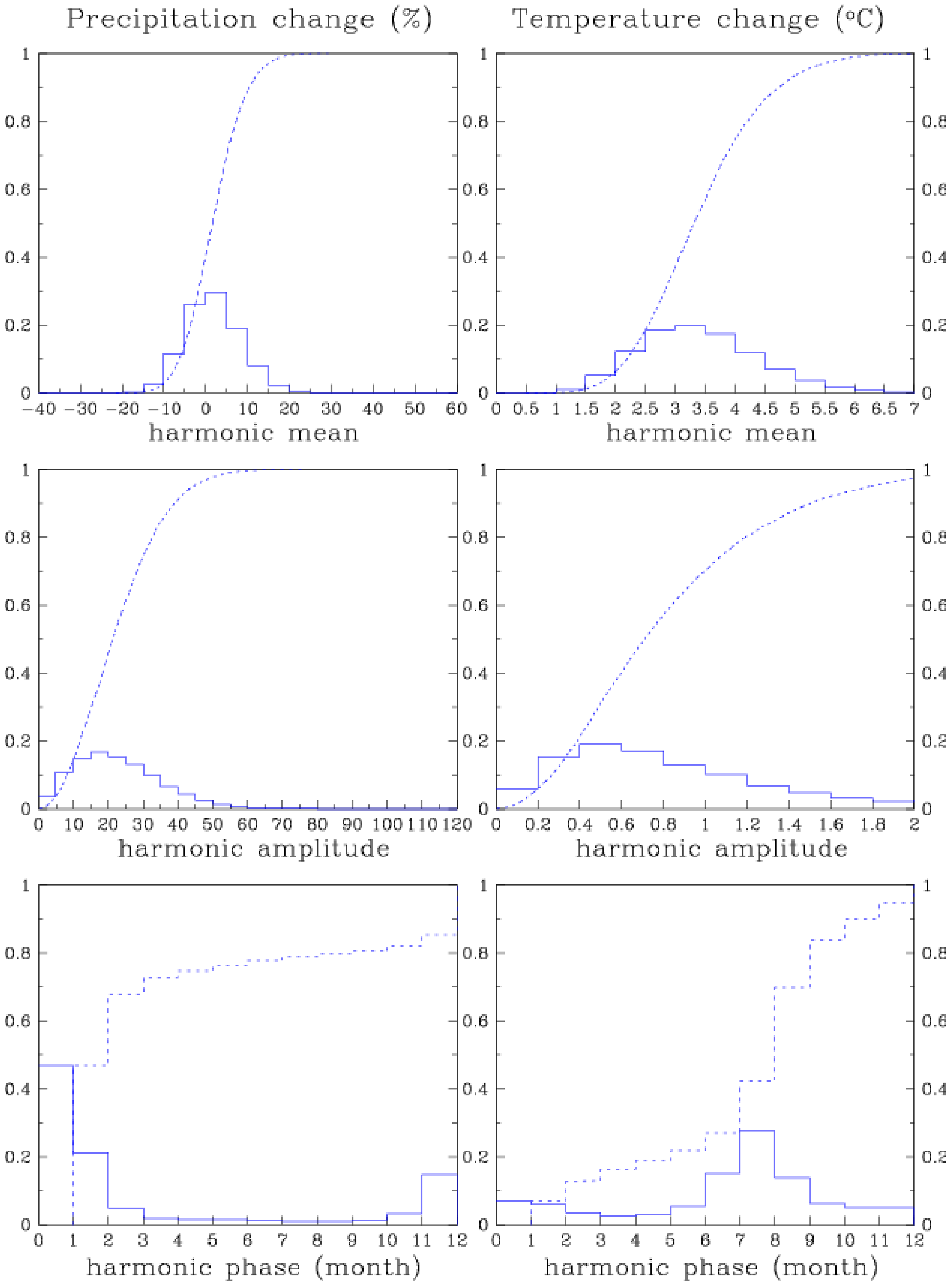

Figure 3.11 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s A1B) for the Anglian river-basin region.

3.3.3 Risk

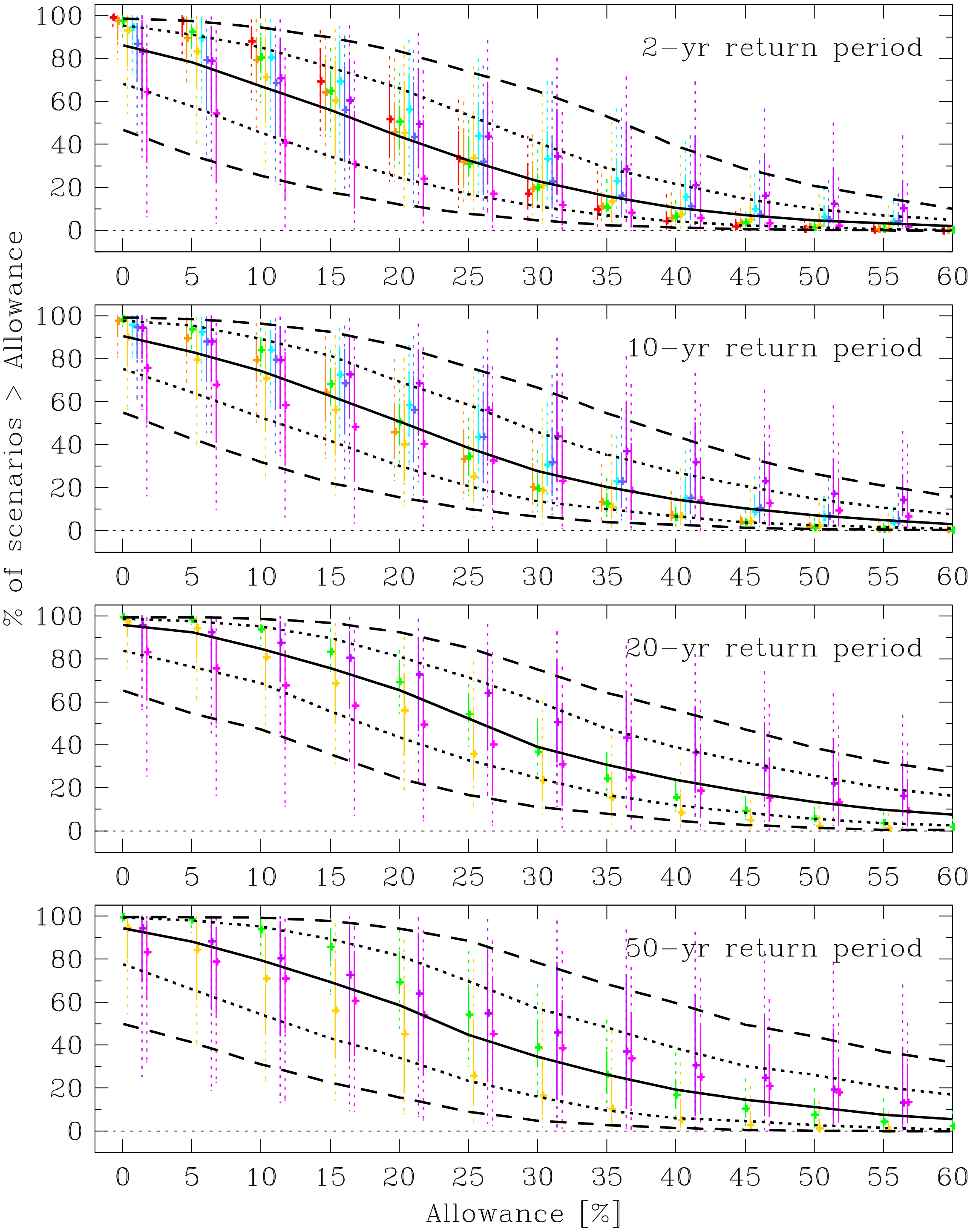

Figure 3.12 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s A1B) for the Anglian river-basin region. Response-type risk (colours): Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta); 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).

3.4 Thames

3.4.1 Vulnerability

A total of 173 NRFA catchments are located within the Thames river-basin region. The best-estimate of the response type for each of these catchments is mainly Enhanced at the lowest return period, but with a more equal spread between the four response types at the two highest return periods (Table 3.4). The maps in Figure 3.13 show the best-estimate of the response type for each catchment at each return period, and those in Figure 3.14 show the corresponding confidence levels (High – H; Medium – M; Low – L).

Table 3.4 The number of NRFA catchments of each response type at each return period, for the Thames river-basin region.

Response type	RP2	RP10	RP20	RP50
Damped-High	0	NA	NA	NA
Damped-Low	11	**63**	NA	NA
Neutral	0	0	25	41
Mixed	0	0	42	47
Enhanced-Low	**57**	23	NA	NA
Enhanced-Medium	21	20	NA	NA
Enhanced-High	48	17	52	28
Sensitive	36	50	**54**	**57**
Total	173	173	173	173

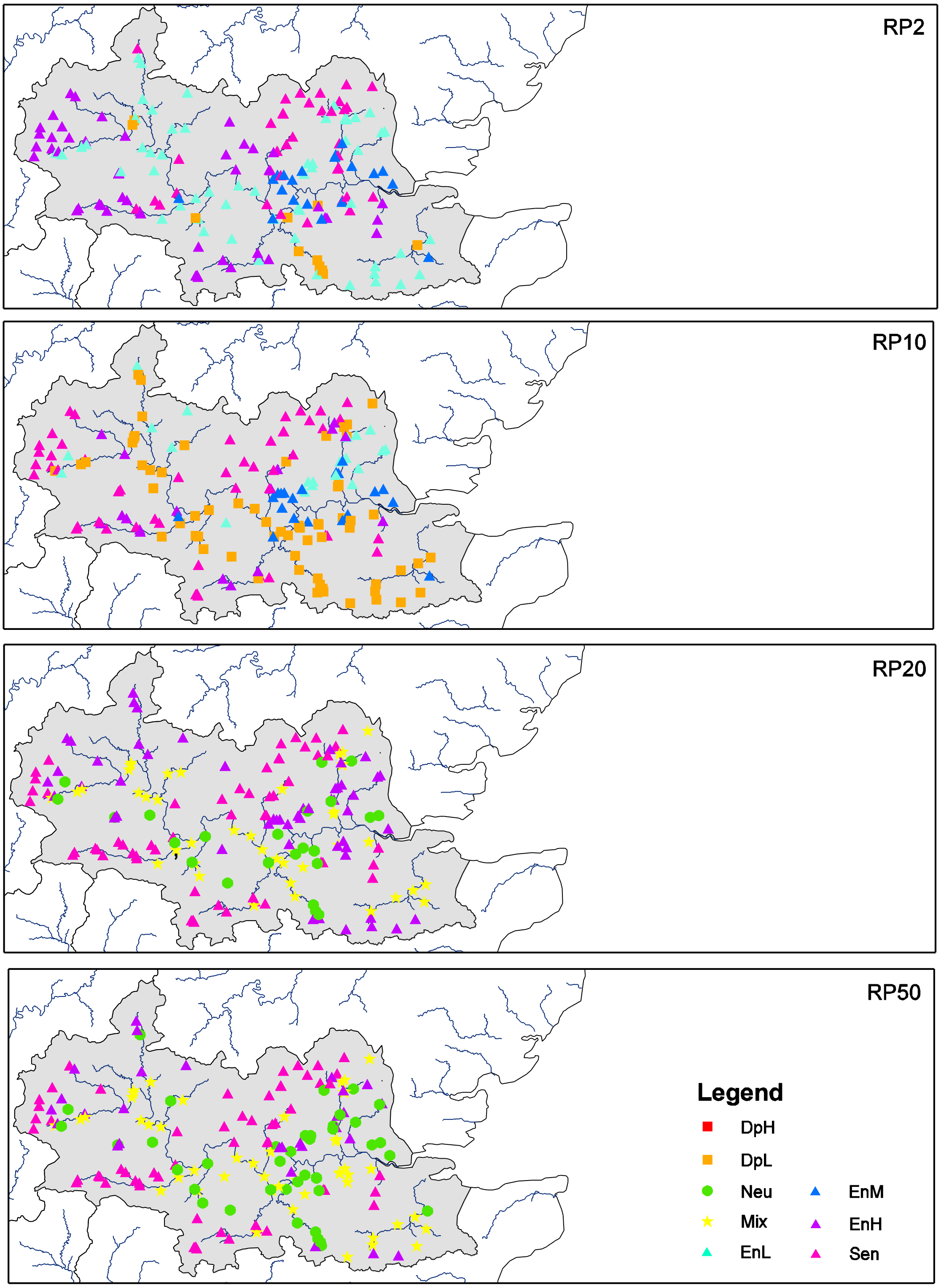

Figure 3.13 The best-estimate of the response type for each NRFA catchment in the Thames river-basin region.

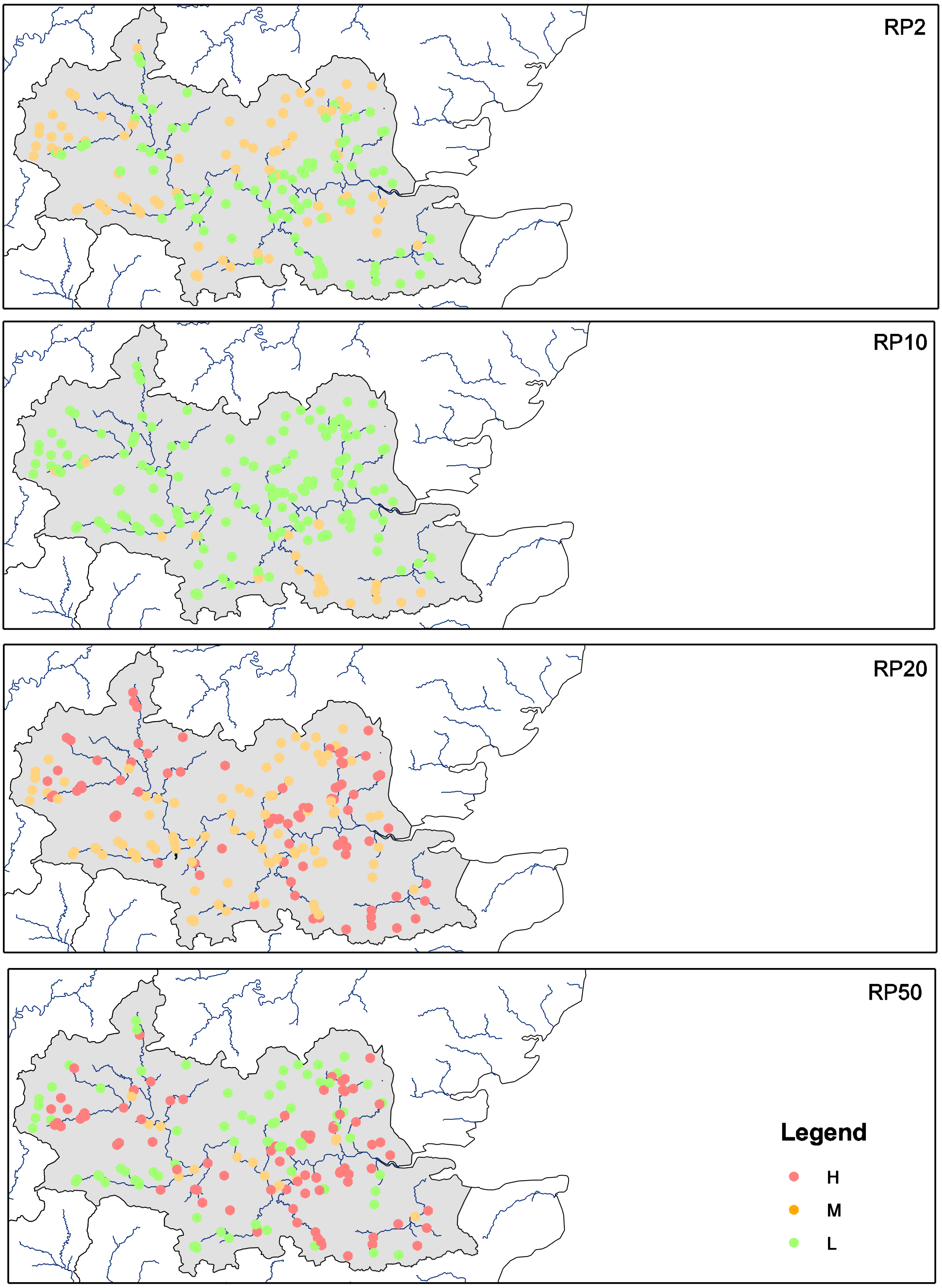

Figure 3.14 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the Thames river-basin region.

3.4.2 Hazard

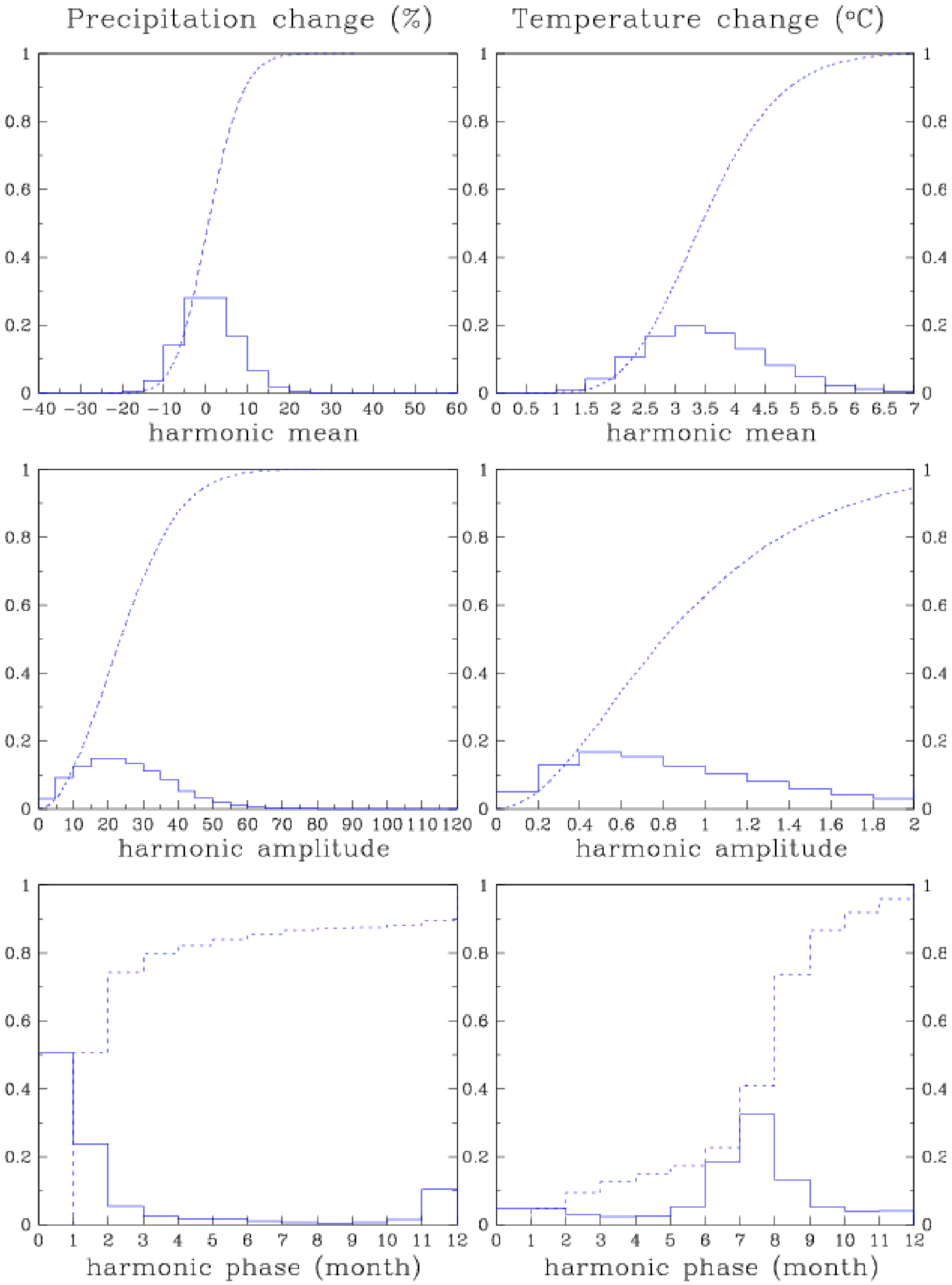

Figure 3.15 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s A1B) for the Thames river-basin region.

3.4.3 Risk

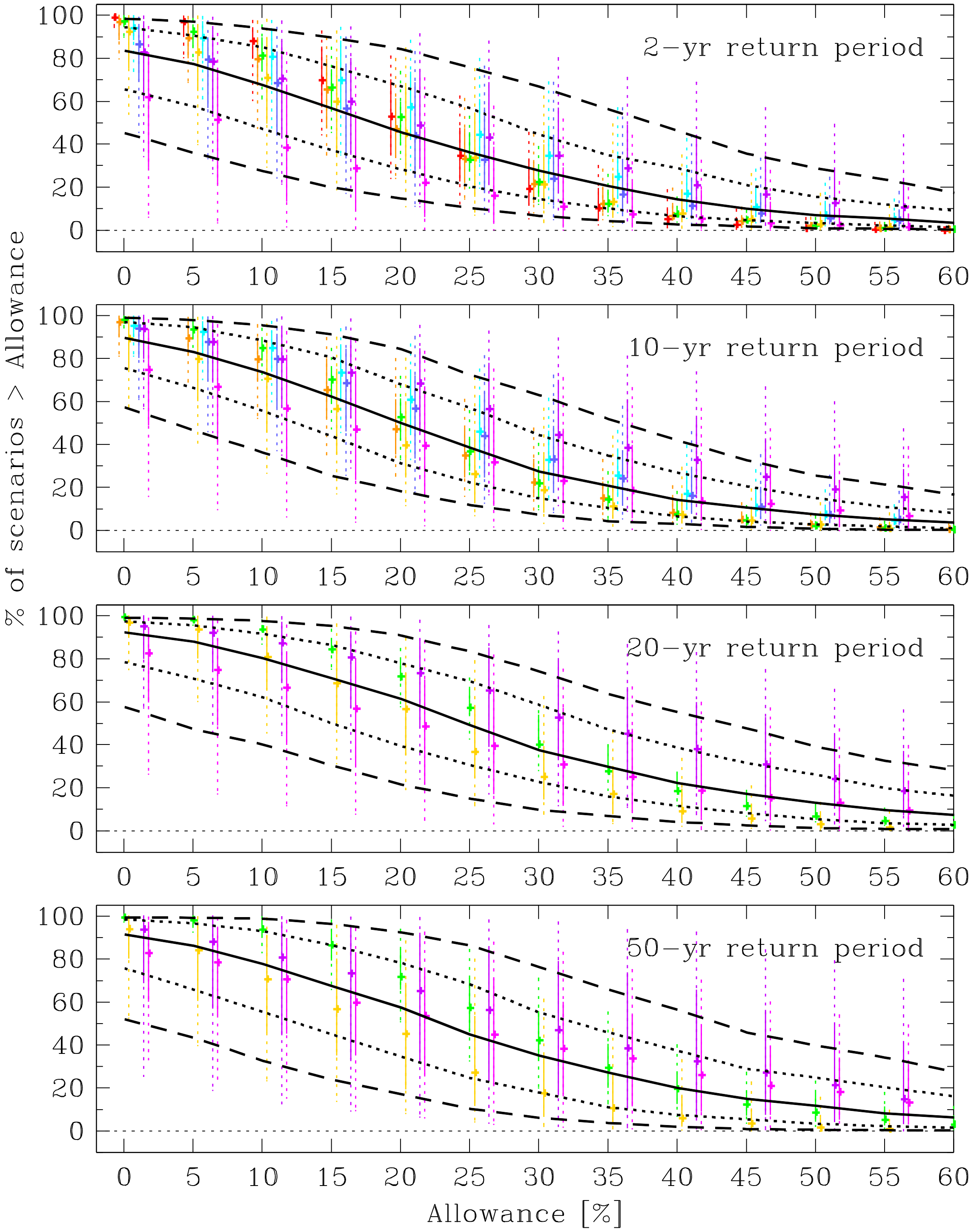

Figure 3.16 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s A1B) for the Thames river-basin region. Response-type risk (colours): Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta); 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).

3.5 South-East England

3.5.1 Vulnerability

A total of 75 NRFA catchments are located within the South-East England river-basin region. The best-estimate of the response type for each of these catchments is mainly Enhanced at the lowest return period, but with a more equal spread between the four response types at the two highest return periods (Table 3.5). The maps in Figure 3.17 show the best-estimate of the response type for each catchment at each return period, and those in Figure 3.18 show the corresponding confidence levels (High – H; Medium – M; Low – L).

Table 3.5 The number of NRFA catchments of each response type at each return period, for the South-East England river-basin region.

Response type	RP2	RP10	RP20	RP50
Damped-High	0	NA	NA	NA
Damped-Low	6	**50**	NA	NA
Neutral	0	0	13	11
Mixed	0	0	15	**25**
Enhanced-Low	**39**	1	NA	NA
Enhanced-Medium	0	0	NA	NA
Enhanced-High	27	6	**30**	22
Sensitive	3	18	17	17
Total	75	75	75	75

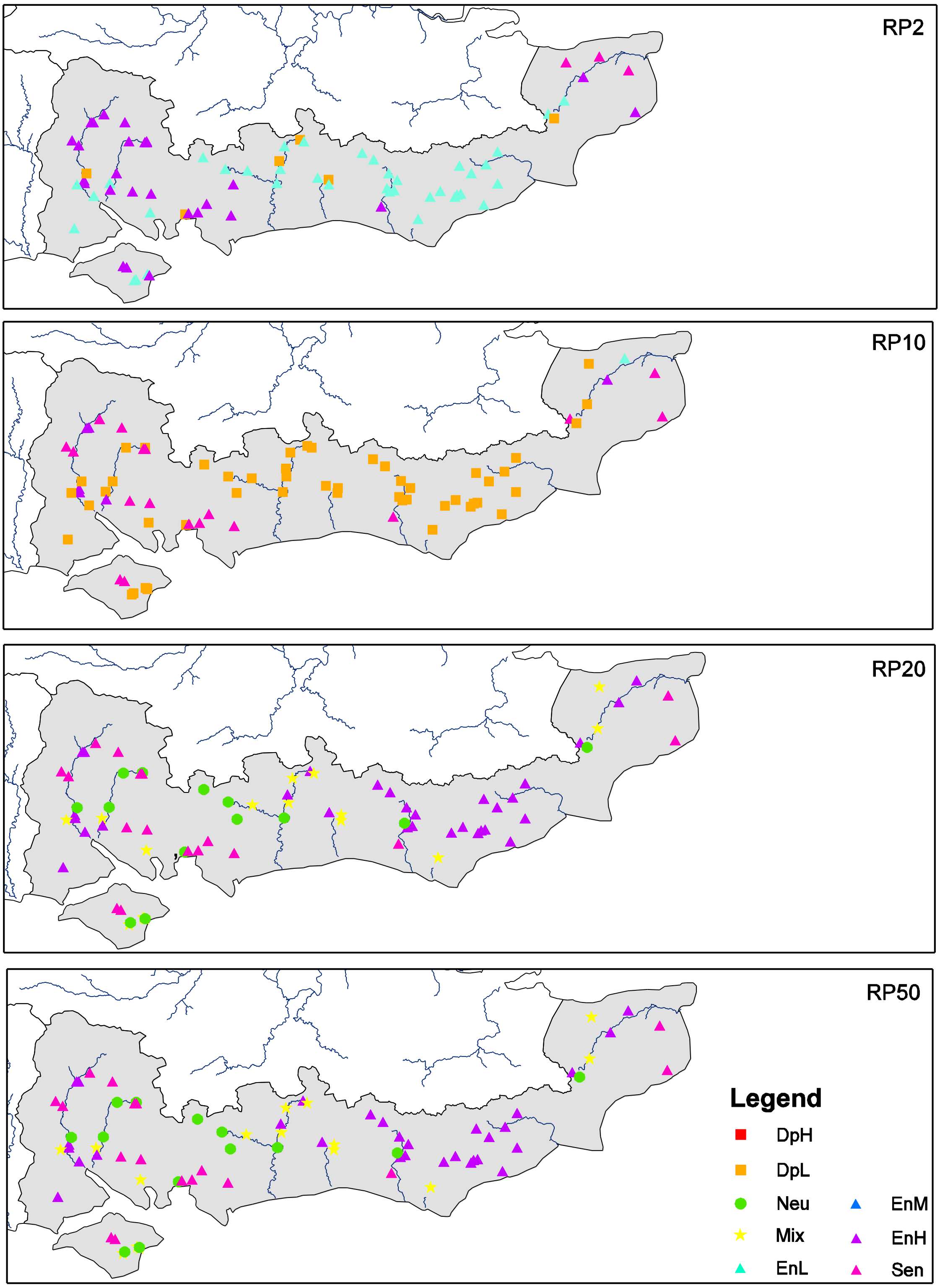

Figure 3.17 The best-estimate of the response type for each NRFA catchment in the South-East England river-basin region.

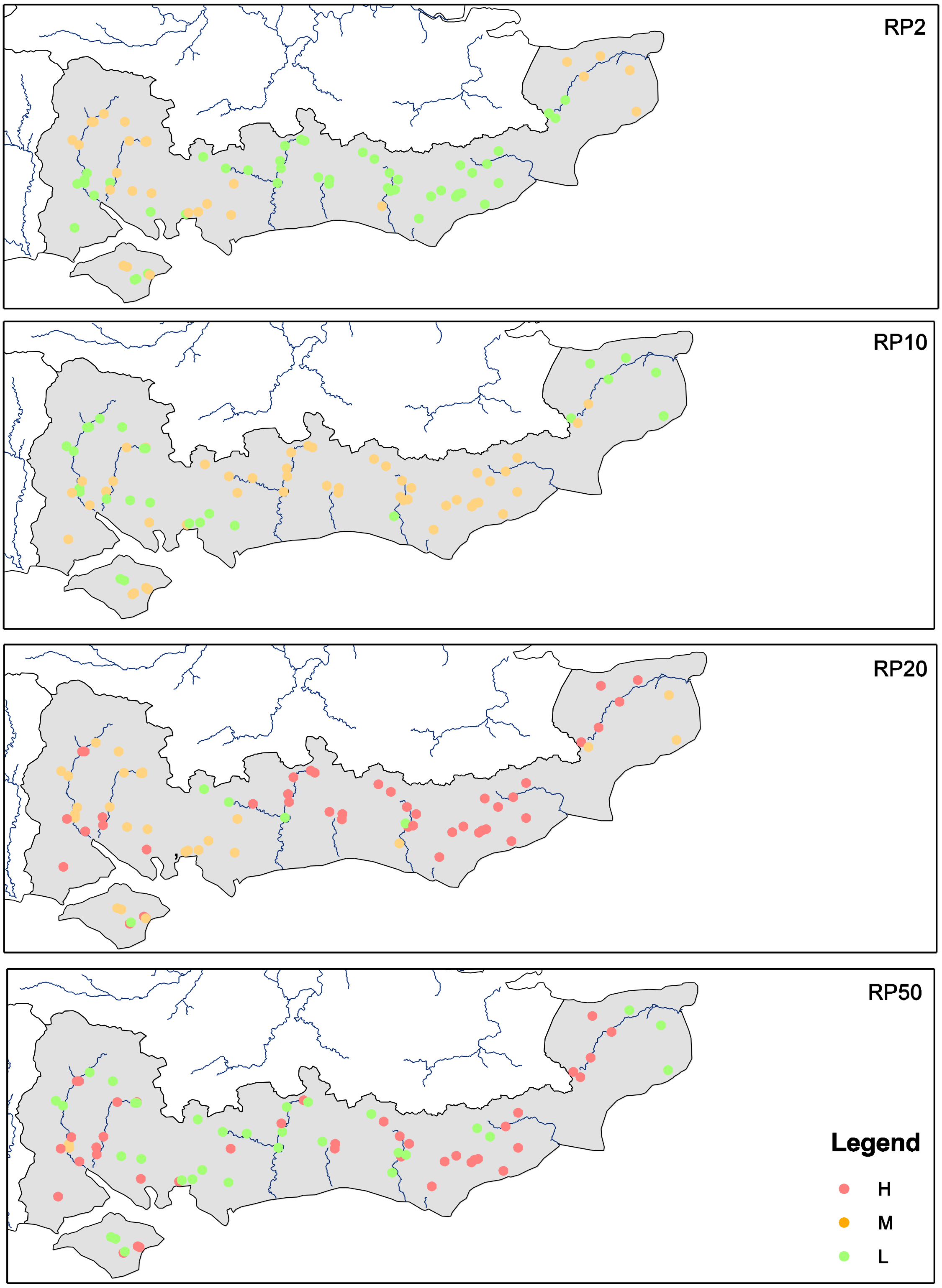

Figure 3.18 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the South-East England river-basin region.

3.5.2 Hazard

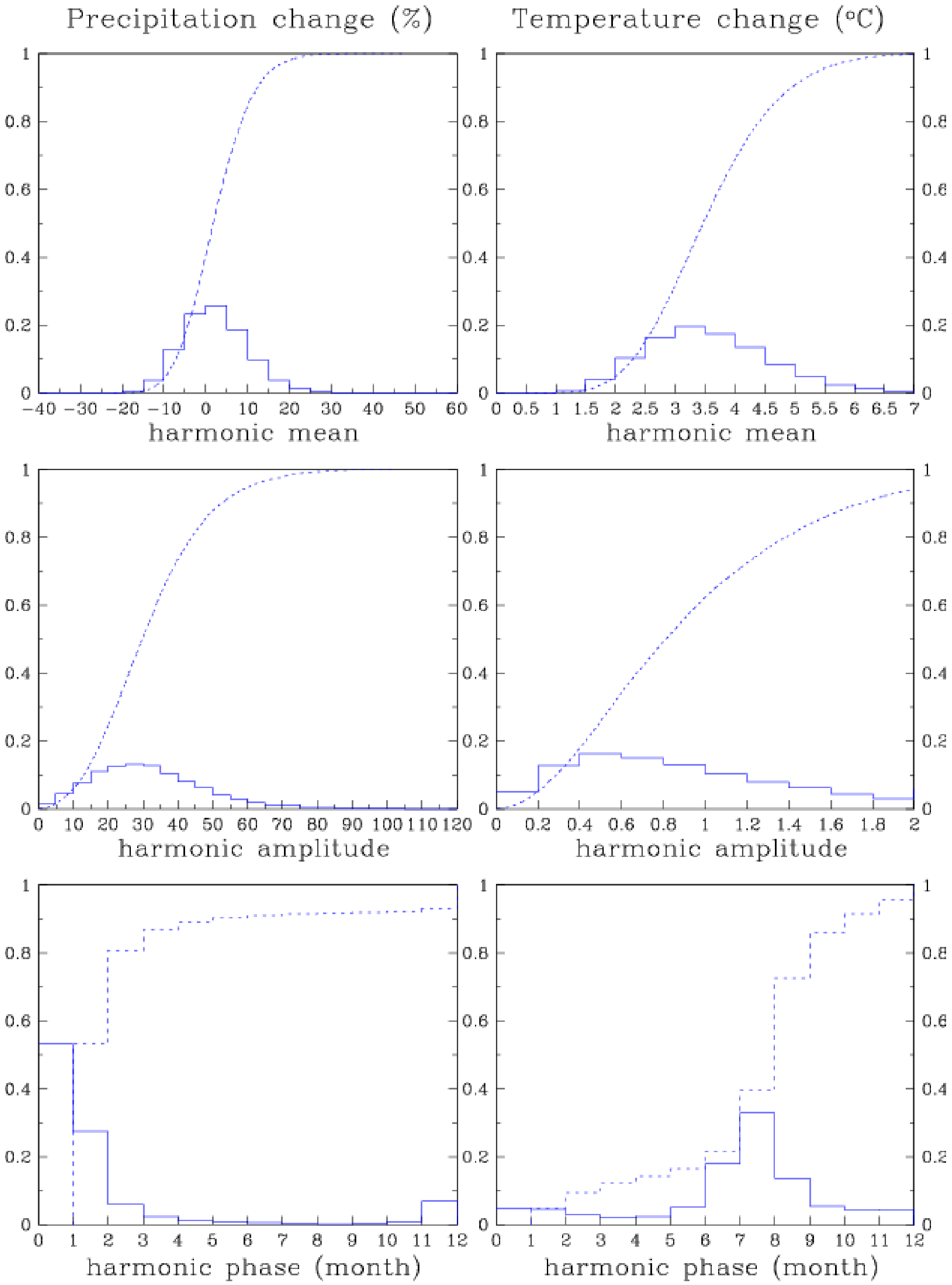

Figure 3.19 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s A1B) for the South-East England river-basin region.

3.5.3 Risk

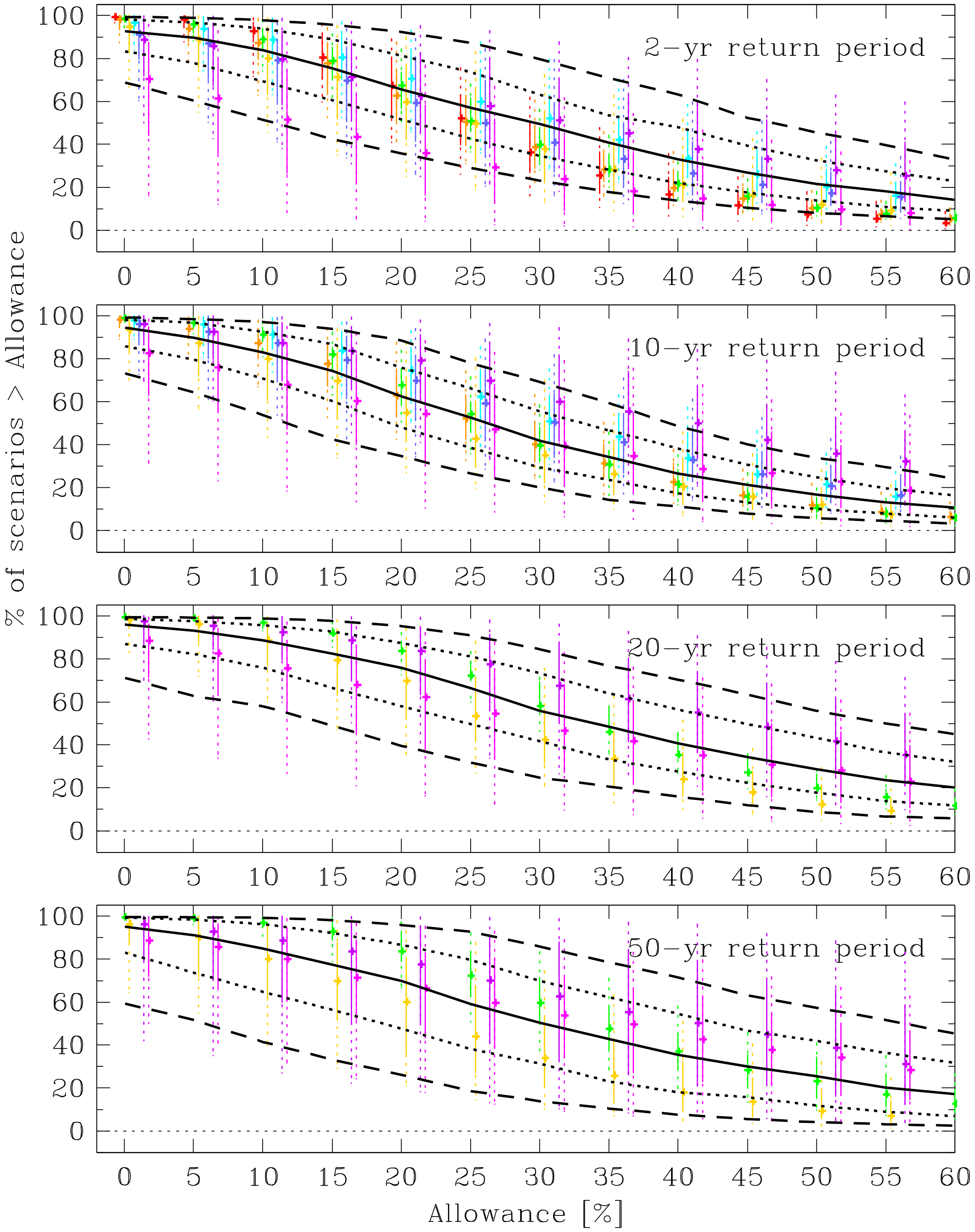

Figure 3.20 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s A1B) for the South-East England river-basin region. Response-type risk (colours): Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta); 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).

3.6 South-West England

3.6.1 Vulnerability

A total of 110 NRFA catchments are located within the South-West England river-basin region. The best-estimate of the response type for each of these catchments is mainly Neutral at all four return periods (Table 3.6). The maps in Figure 3.21 show the best-estimate of the response type for each catchment at each return period, and those in Figure 3.22 show the corresponding confidence levels (High – H; Medium – M; Low – L).

Table 3.6 The number of NRFA catchments of each response type at each return period, for the South-West England river-basin region.

Response type	RP2	RP10	RP20	RP50
Damped-High	0	NA	NA	NA
Damped-Low	6	26	NA	NA
Neutral	**67**	**65**	**81**	**72**
Mixed	0	0	8	8
Enhanced-Low	19	3	NA	NA
Enhanced-Medium	1	1	NA	NA
Enhanced-High	17	9	8	17
Sensitive	0	6	13	13
Total	110	110	110	110

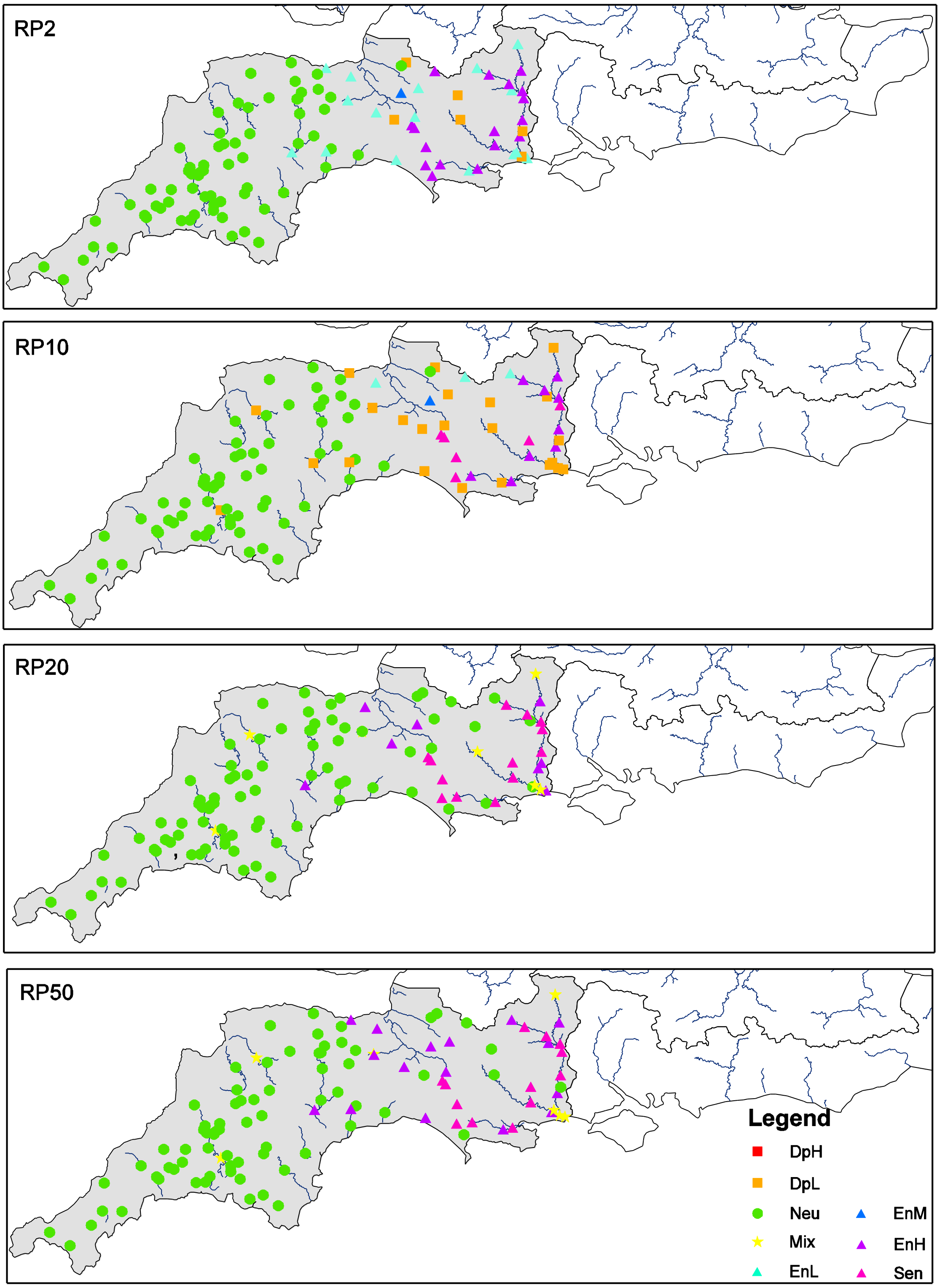

Figure 3.21 The best-estimate of the response type for each NRFA catchment in the South-West England river-basin region.

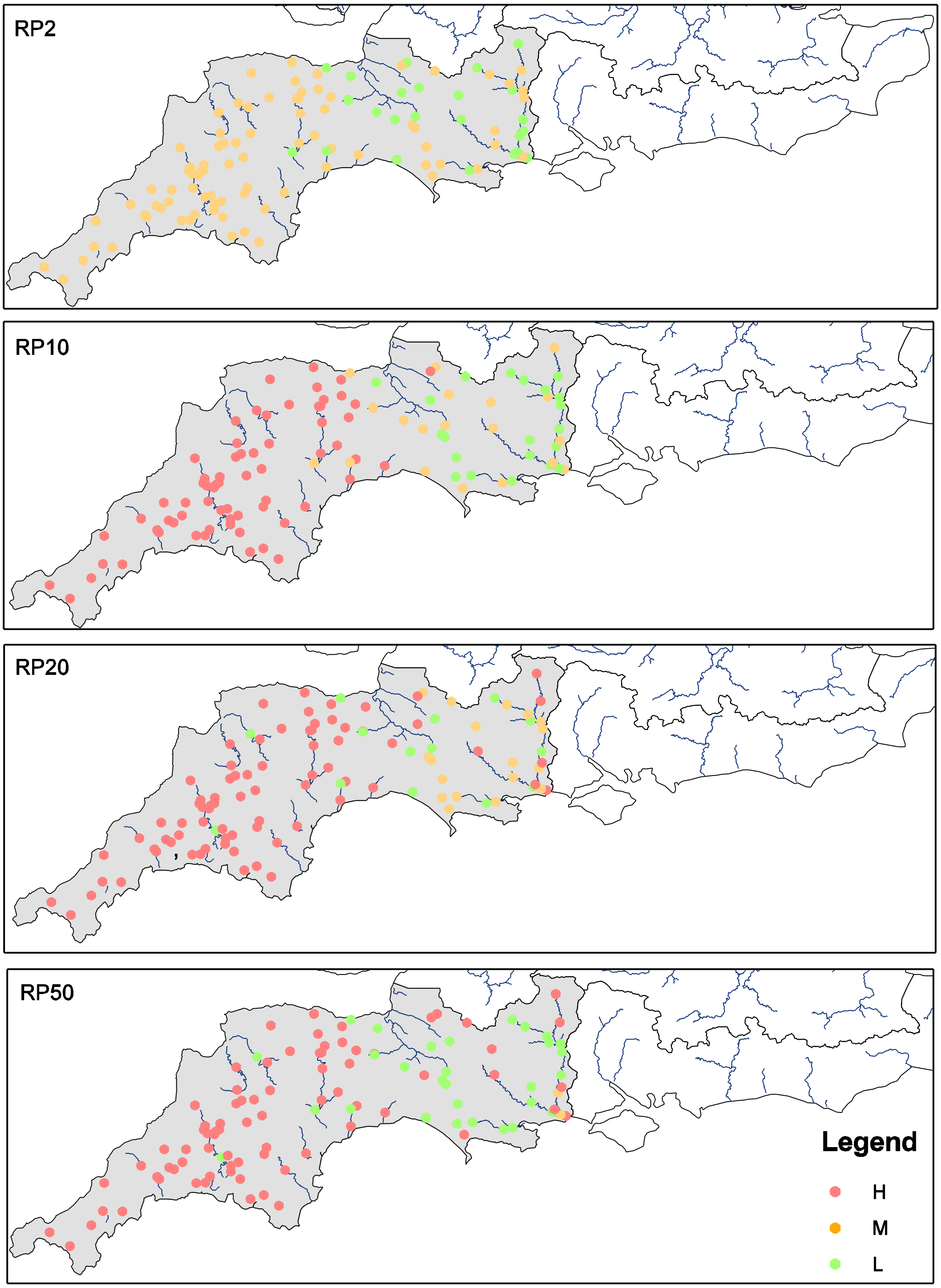

Figure 3.22 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the South-West England river-basin region.

3.6.2 Hazard

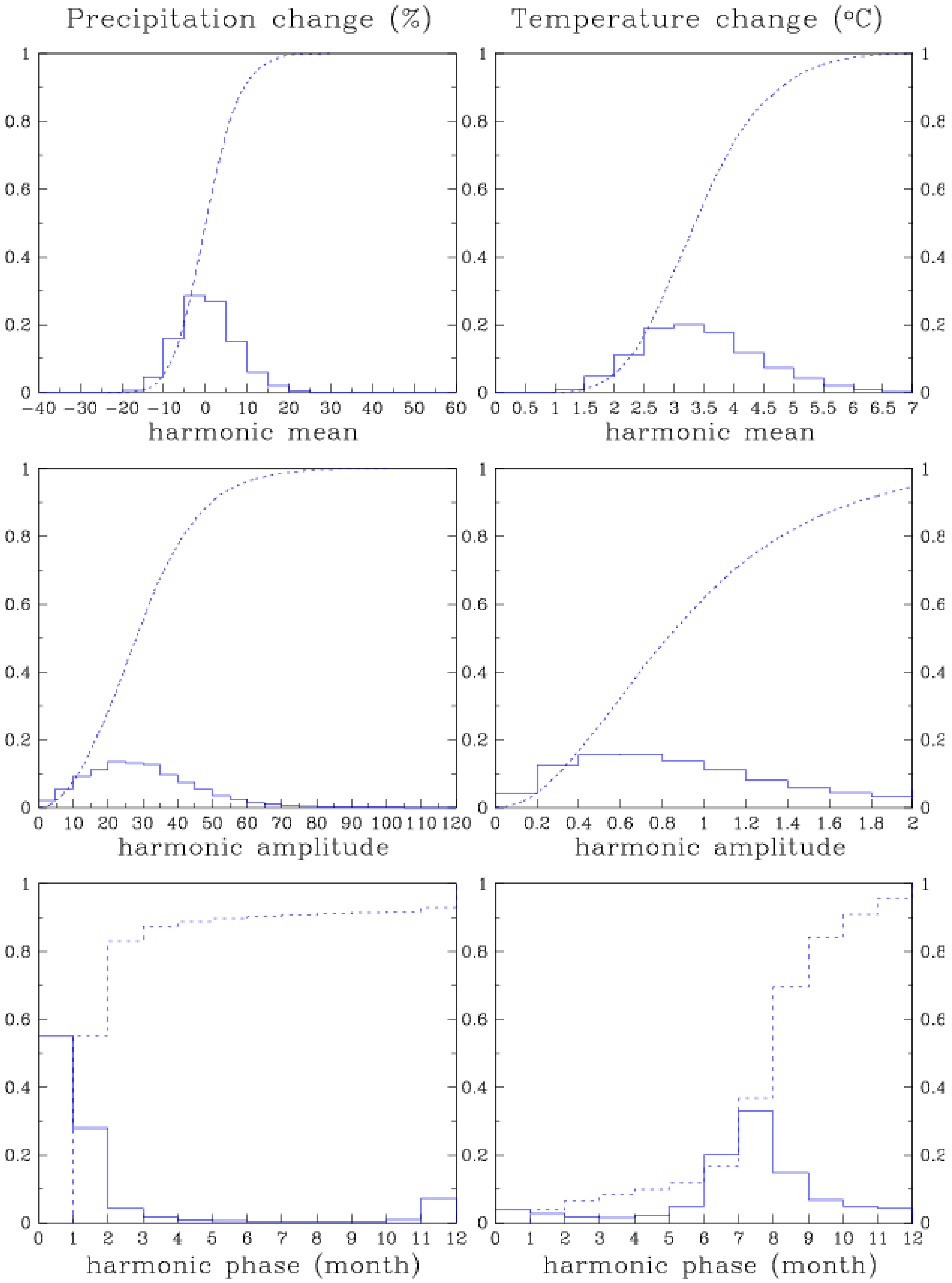

Figure 3.23 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s A1B) for the South-West England river-basin region.

3.6.3 Risk

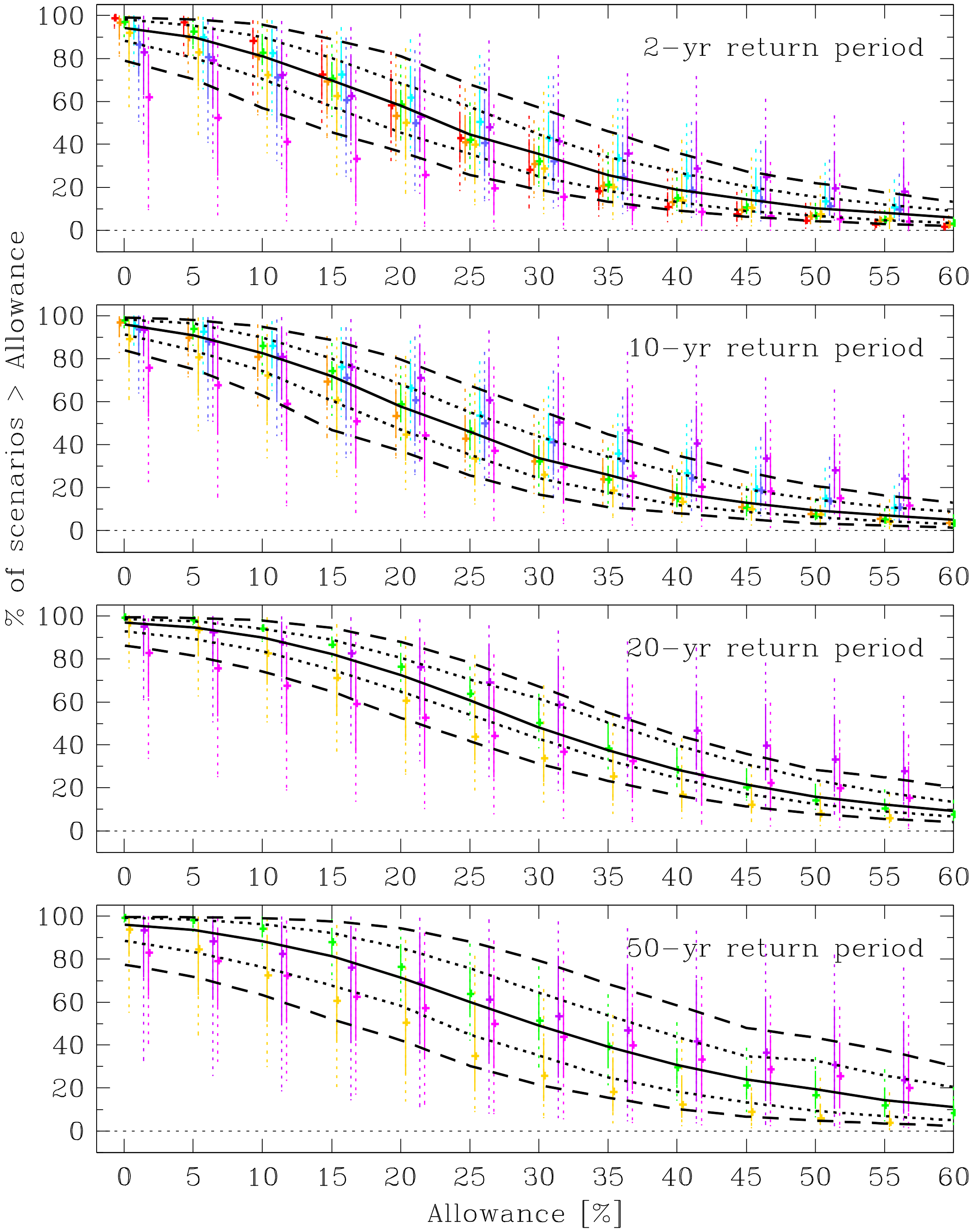

Figure 3.24 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s A1B) for the South-West England river-basin region. Response-type risk (colours): Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta); 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).

3.7 Severn

3.7.1 Vulnerability

A total of 162 NRFA catchments are located within the Severn river-basin region. The best-estimate of the response type for each of these catchments is a mixture of Damped and Enhanced at lower return periods, and Neutral at the higher return periods (Table 3.7). The maps in Figure 3.25 show the best-estimate of the response type for each catchment at each return period, and those in Figure 3.26 show the corresponding confidence levels (High – H; Medium – M; Low – L).

Table 3.7 The number of NRFA catchments of each response type at each return period, for the Severn river-basin region.

Response type	RP2	RP10	RP20	RP50
Damped-High	**61**	NA	NA	NA
Damped-Low	16	57	NA	NA
Neutral	10	**64**	**78**	**84**
Mixed	0	7	36	29
Enhanced-Low	40	19	NA	NA
Enhanced-Medium	16	1	NA	NA
Enhanced-High	6	3	40	40
Sensitive	13	11	8	9
Total	162	162	162	162

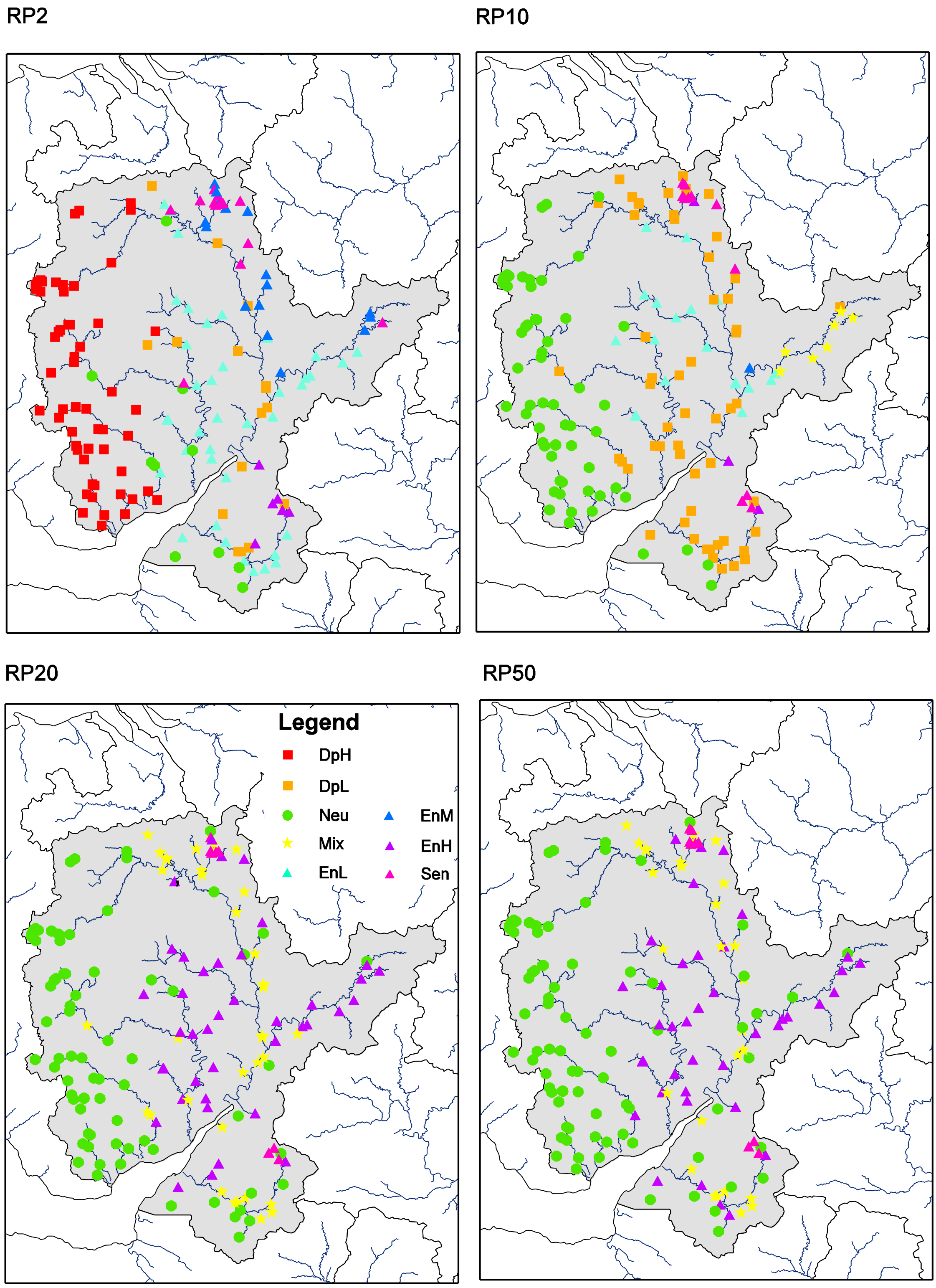

Figure 3.25 The best-estimate of the response type for each NRFA catchment in the Severn river-basin region.

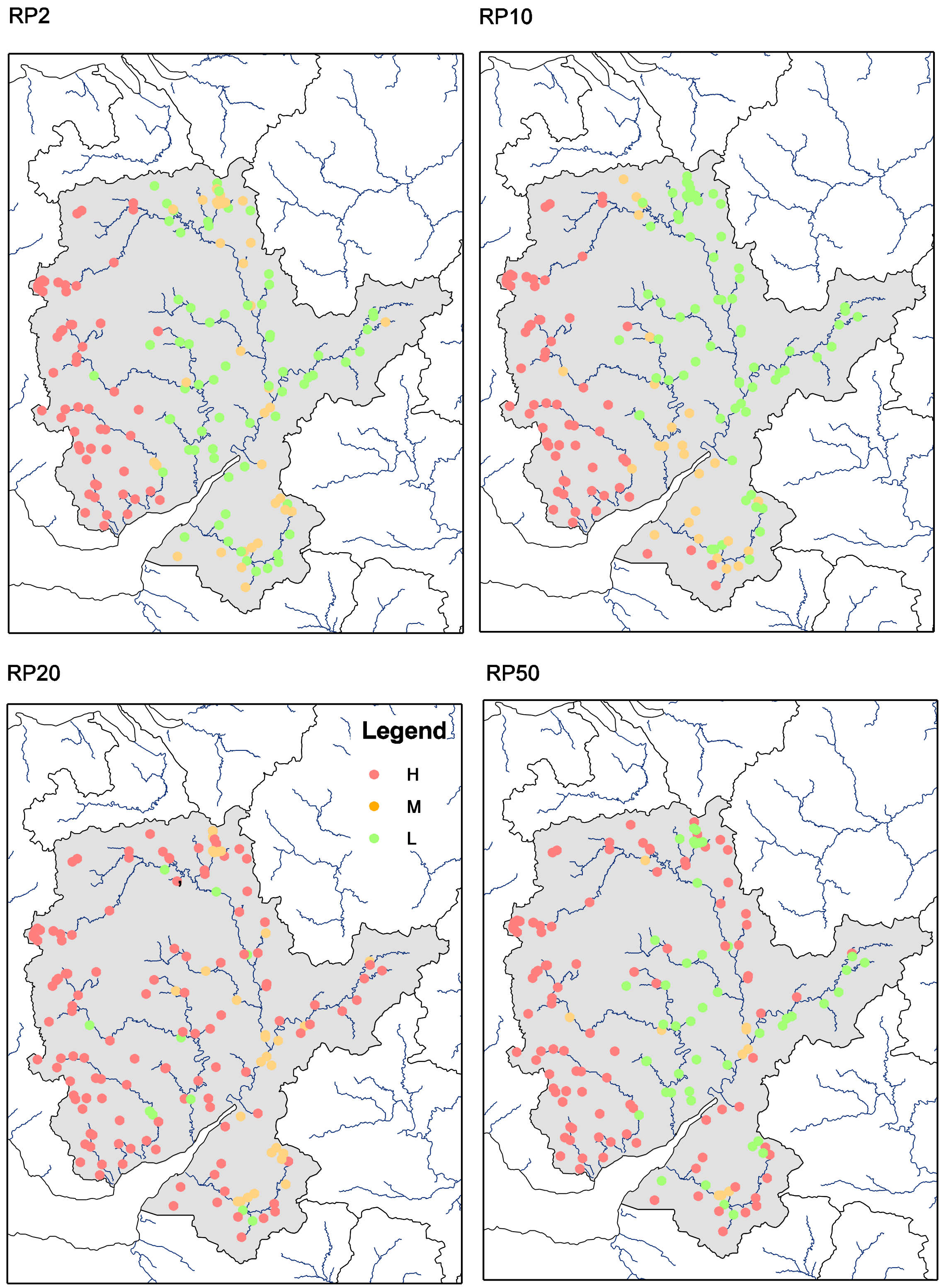

Figure 3.26 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the Severn river-basin region.

3.7.2 Hazard

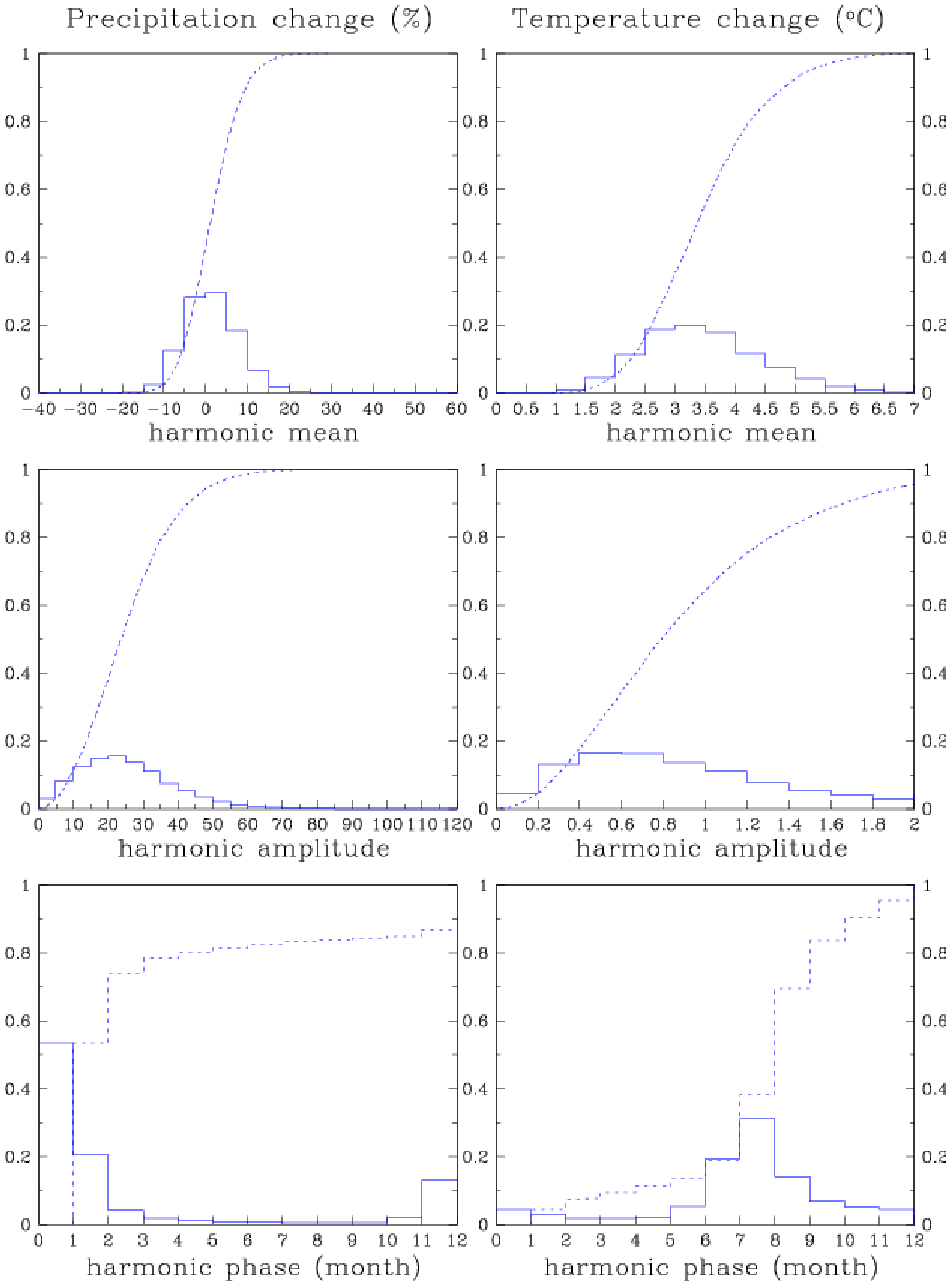

Figure 3.27 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s A1B) for the Severn river-basin region.

3.7.3 Risk

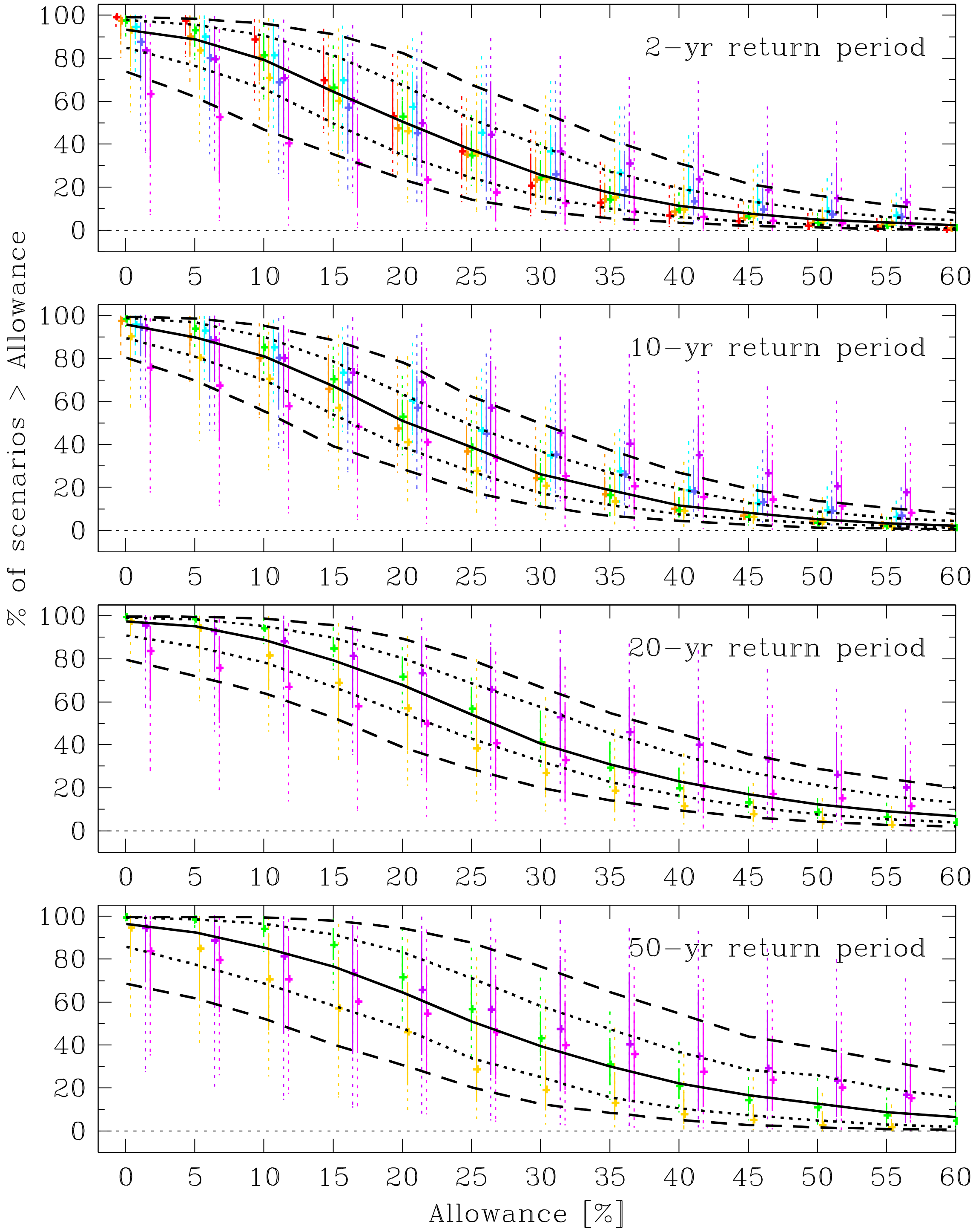

Figure 3.28 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s A1B) for the Severn river-basin region. Response-type risk (colours): Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta); 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).

3.8 West Wales

3.8.1 Vulnerability

A total of 57 NRFA catchments are located within the West Wales river-basin region. The best-estimate of the response type for each of these catchments is Damped at the lowest return period and Neutral at the higher return periods (Table 3.8). The maps in Figure 3.29 show the best-estimate of the response type for each catchment at each return period, and those in Figure 3.30 show the corresponding confidence levels (High – H; Medium – M; Low – L).

Table 3.8 The number of NRFA catchments of each response type at each return period, for the West Wales river-basin region.

Response type	RP2	RP10	RP20	RP50
Damped-High	**51**	NA	NA	NA
Damped-Low	1	6	NA	NA
Neutral	1	**51**	**54**	**51**
Mixed	0	0	2	2
Enhanced-Low	4	0	NA	NA
Enhanced-Medium	0	0	NA	NA
Enhanced-High	0	0	1	4
Sensitive	0	0	0	0
Total	57	57	57	57

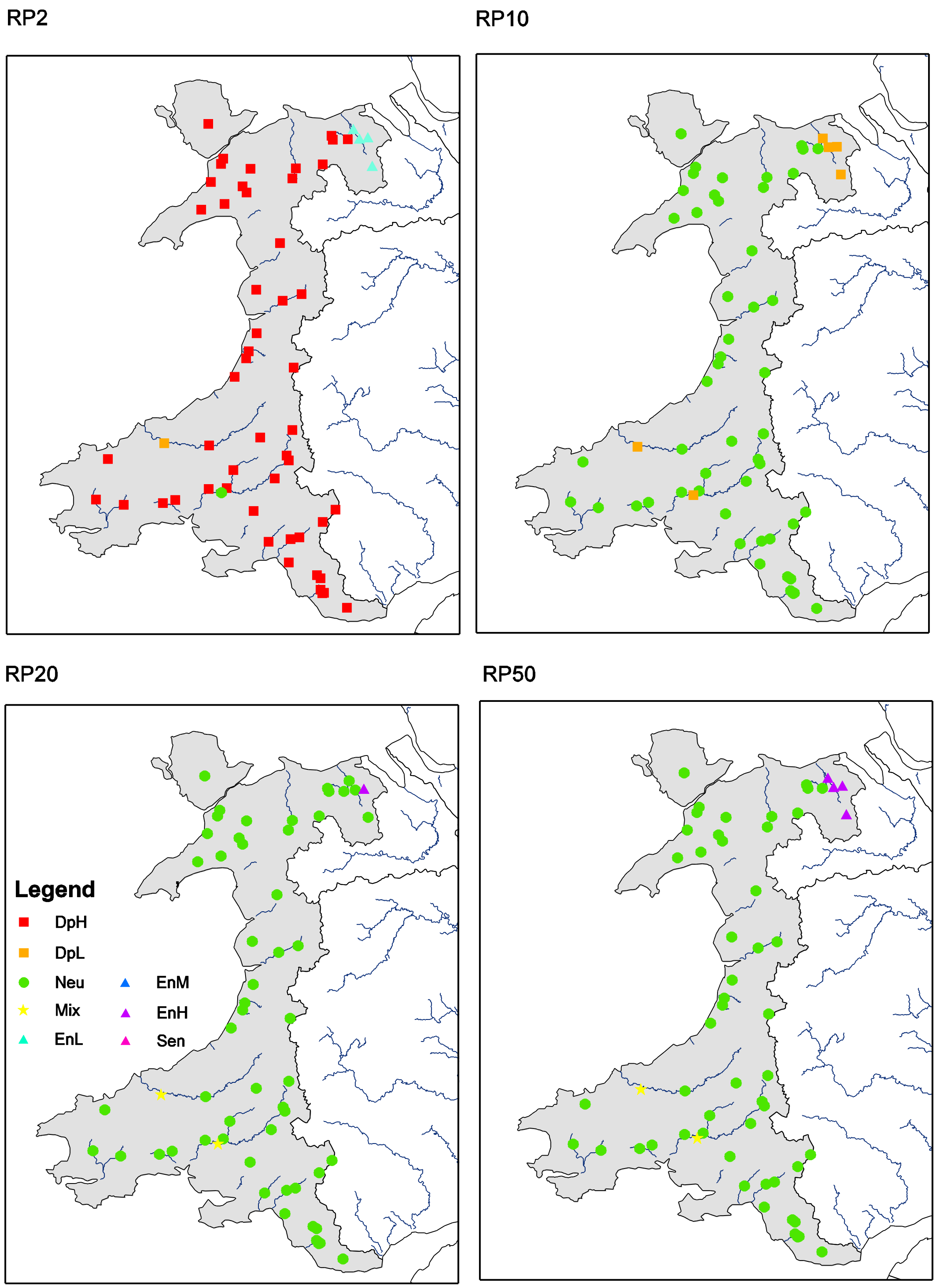

Figure 3.29 The best-estimate of the response type for each NRFA catchment in the West Wales river-basin region.

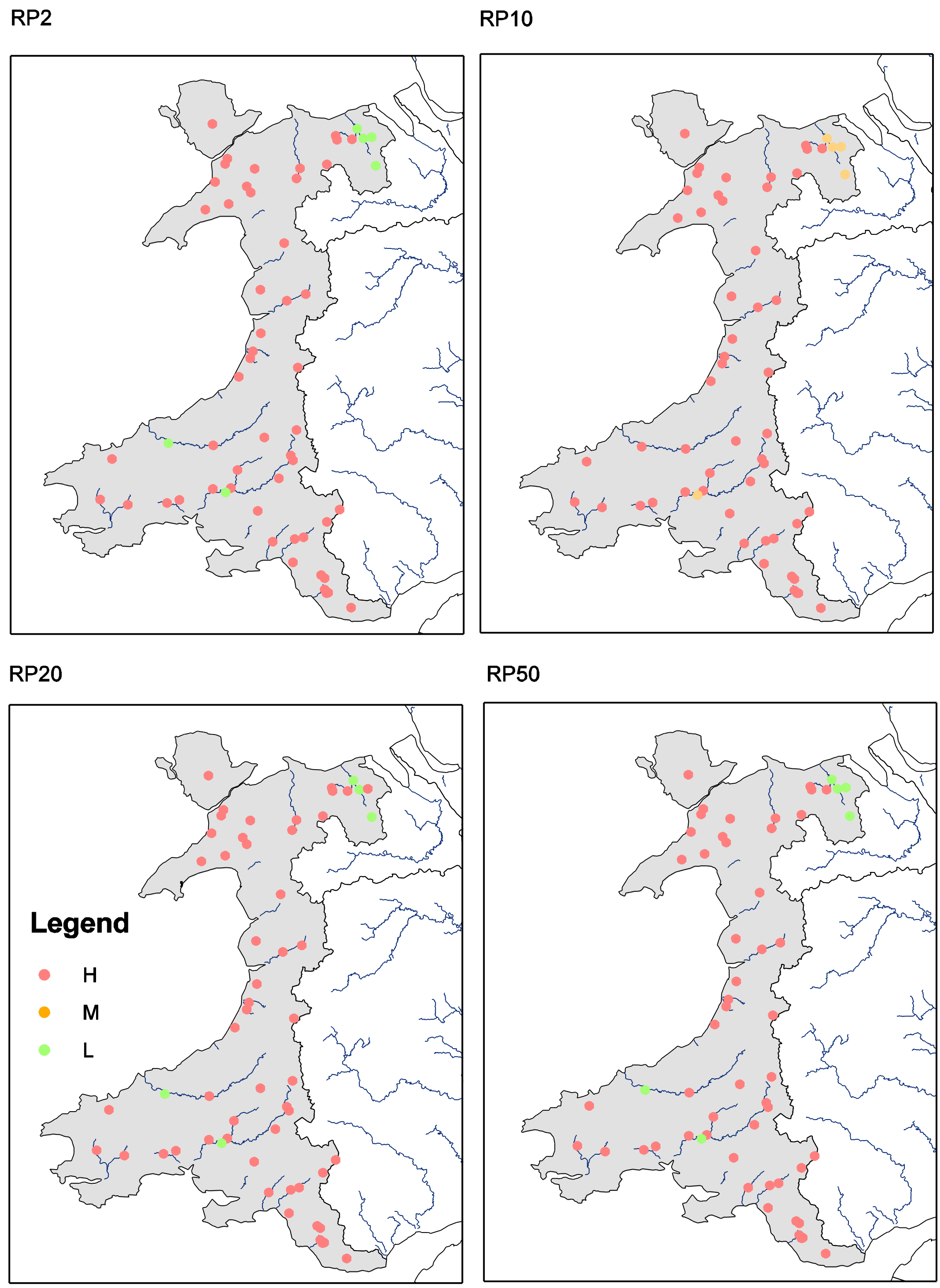

Figure 3.30 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the West Wales river-basin region.

3.8.2 Hazard

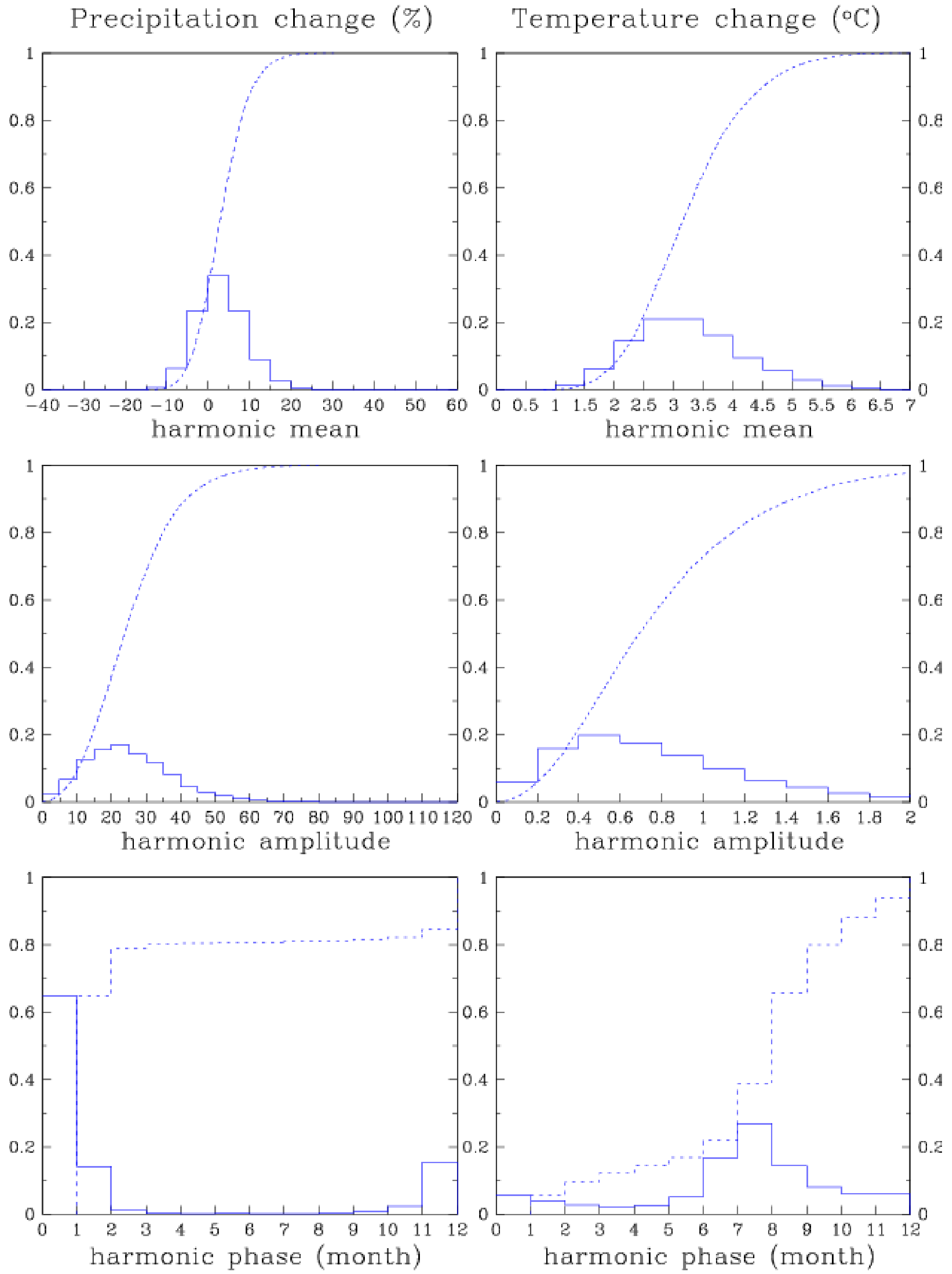

Figure 3.31 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s A1B) for the West Wales river-basin region.

3.8.3 Risk

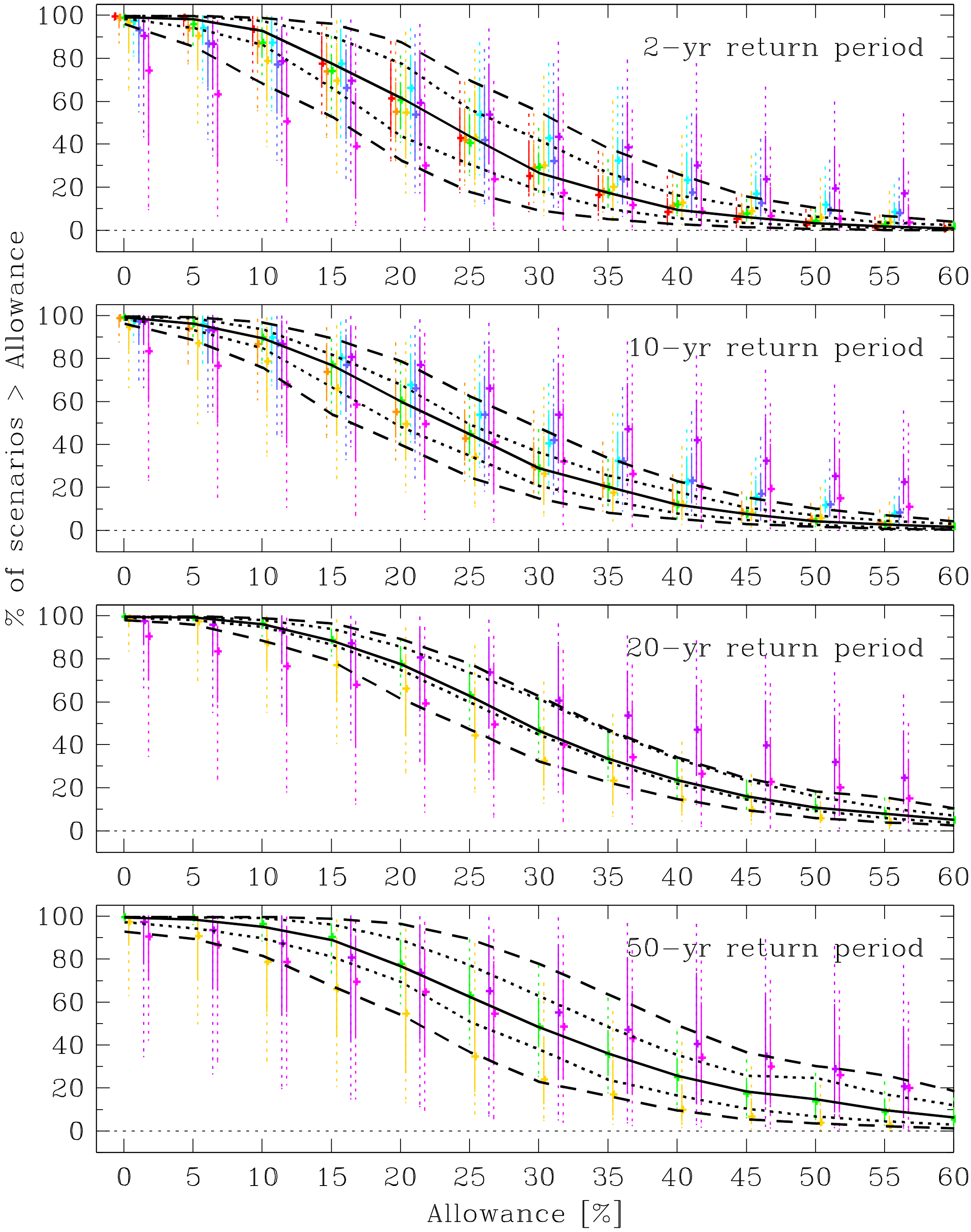

Figure 3.32 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s A1B) for the West Wales river-basin region. Response-type risk (colours): Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta); 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).

3.9 Dee

3.9.1 Vulnerability

A total of 23 NRFA catchments are located within the Dee river-basin region. The best-estimate of the response type for each of these catchments is Damped at the lowest return period and Neutral at the higher return periods (Table 3.9). The maps in Figure 3.33 show the best-estimate of the response type for each catchment at each return period, and those in Figure 3.34 show the corresponding confidence levels (High – H; Medium – M; Low – L).

Table 3.9 The number of NRFA catchments of each response type at each return period, for the Dee river-basin region.

Response type	RP2	RP10	RP20	RP50
Damped-High	**13**	NA	NA	NA
Damped-Low	0	10	NA	NA
Neutral	6	**12**	**13**	**17**
Mixed	0	0	7	3
Enhanced-Low	3	0	NA	NA
Enhanced-Medium	0	0	NA	NA
Enhanced-High	0	0	2	2
Sensitive	1	1	1	1
Total	23	23	23	23

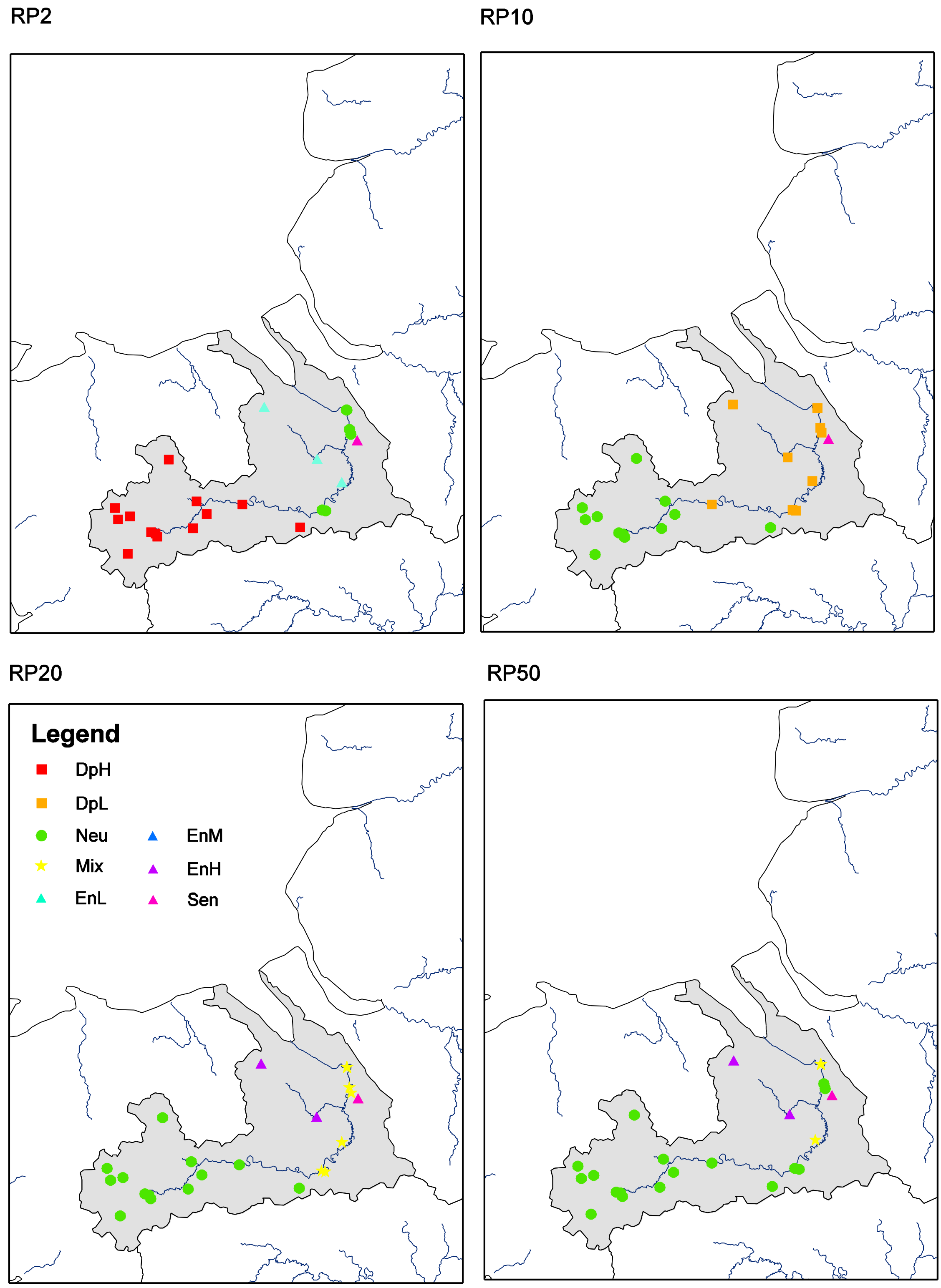

Figure 3.33 The best-estimate of the response type for each NRFA catchment in the Dee river-basin region.

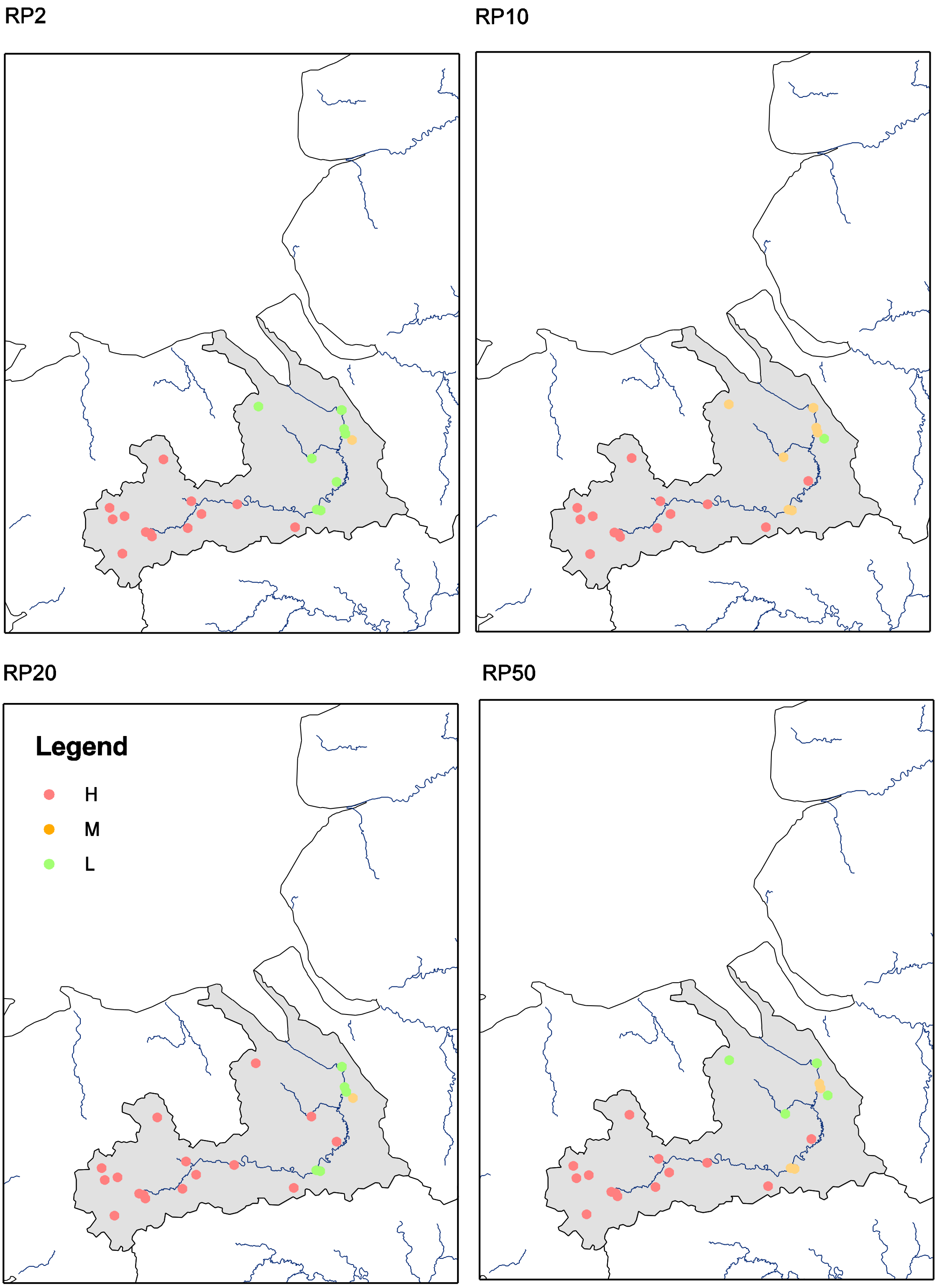

Figure 3.34 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the Dee river-basin region.

3.9.2 Hazard

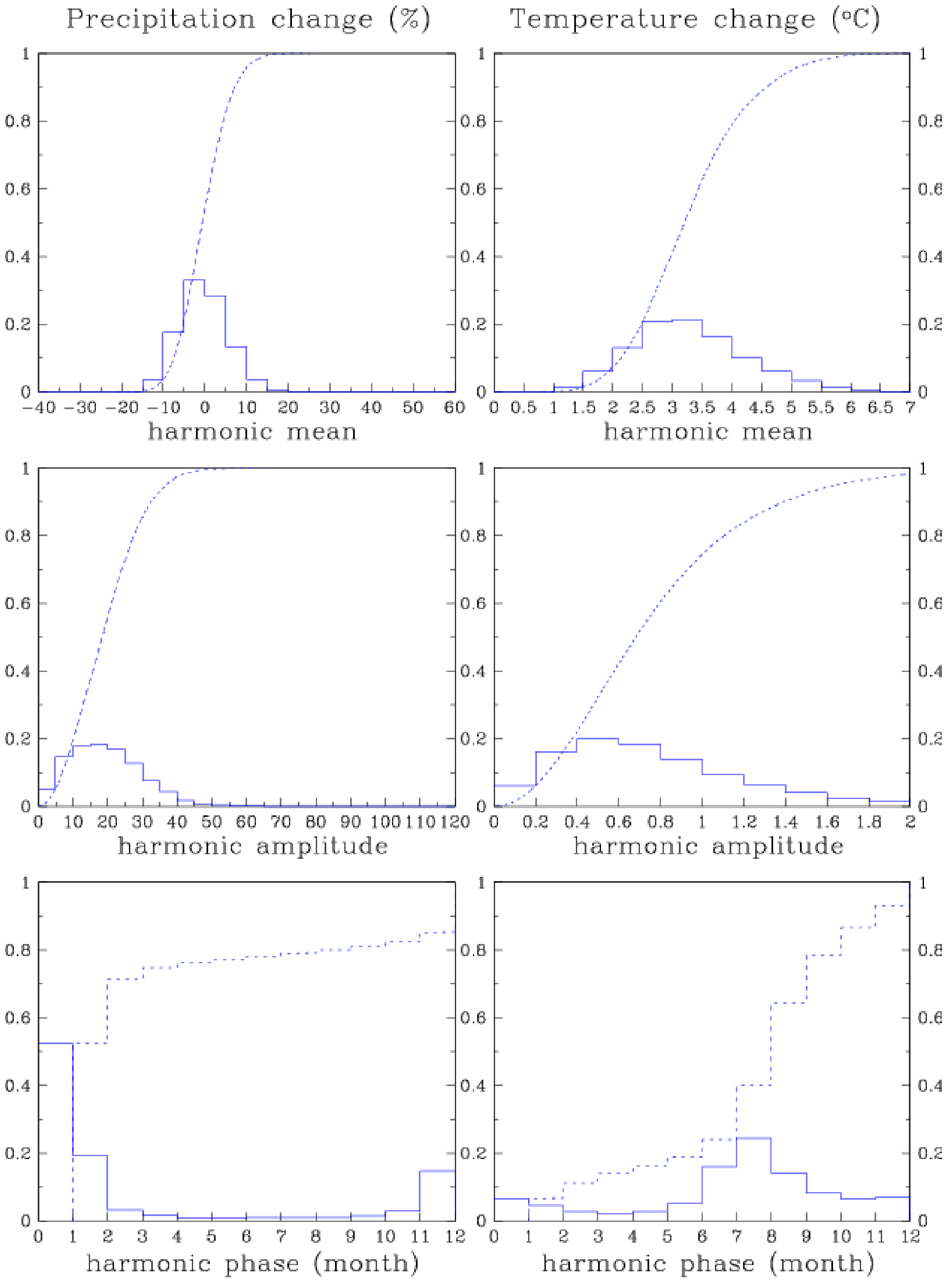

Figure 3.35 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s A1B) for the Dee river-basin region.

3.9.3 Risk

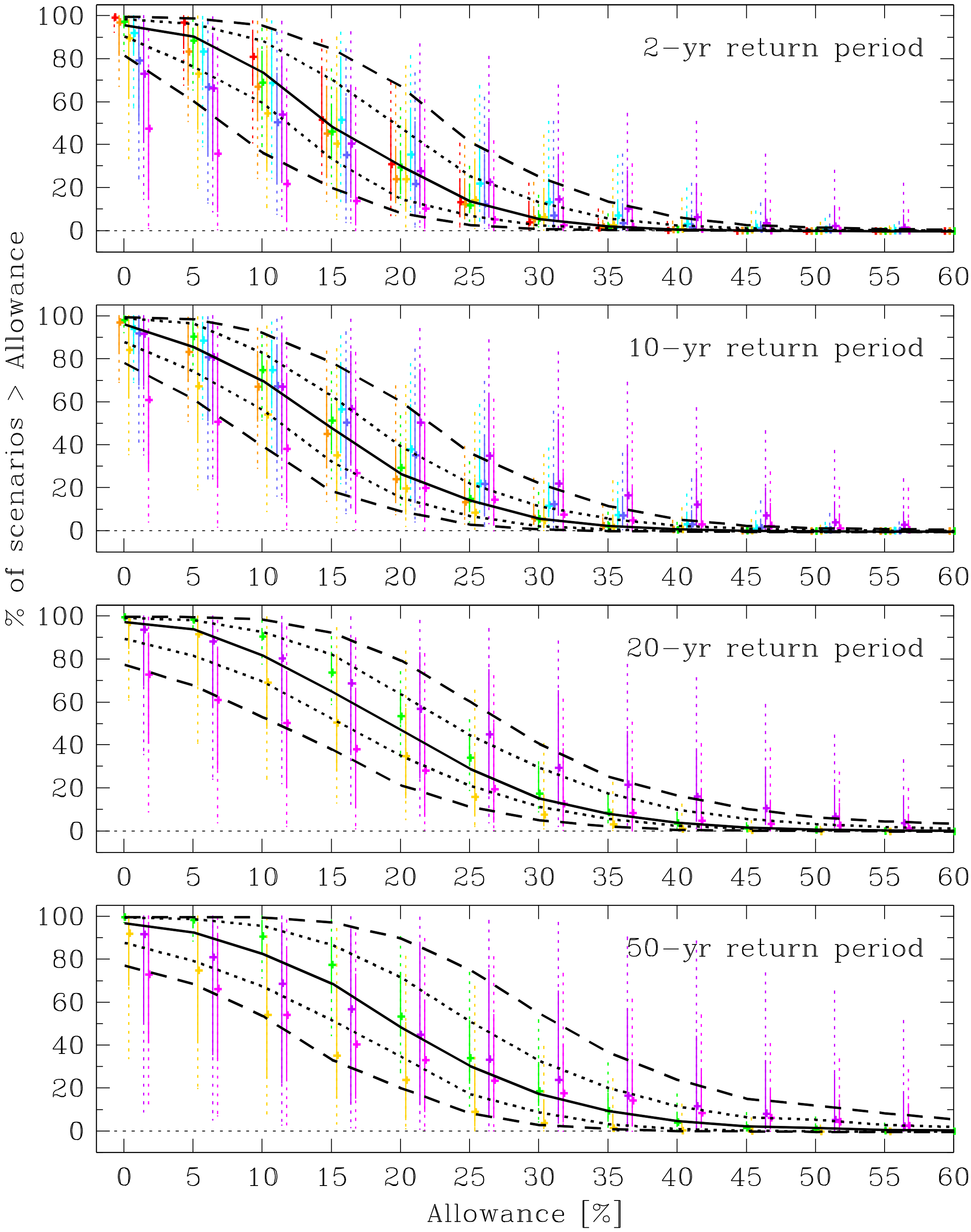

Figure 3.36 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s A1B) for the Dee river-basin region. Response-type risk (colours): Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta); 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).

3.10 North-West England

3.10.1 Vulnerability

A total of 103 NRFA catchments are located within the North-West England river-basin region. The best-estimate of the response type for each of these catchments is Damped at the lowest return period and Neutral at the higher return periods (Table 3.10). The maps in Figure 3.37 show the best-estimate of the response type for each catchment at each return period, and those in Figure 3.38 show the corresponding confidence levels (High – H; Medium – M; Low – L).

Table 3.10 The number of NRFA catchments of each response type at each return period, for the North-West England river-basin region.

Response type	RP2	RP10	RP20	RP50
Damped-High	**78**	NA	NA	NA
Damped-Low	8	23	NA	NA
Neutral	3	**78**	**91**	**89**
Mixed	0	0	5	5
Enhanced-Low	8	0	NA	NA
Enhanced-Medium	1	0	NA	NA
Enhanced-High	5	2	6	7
Sensitive	0	0	1	2
Total	103	103	103	103

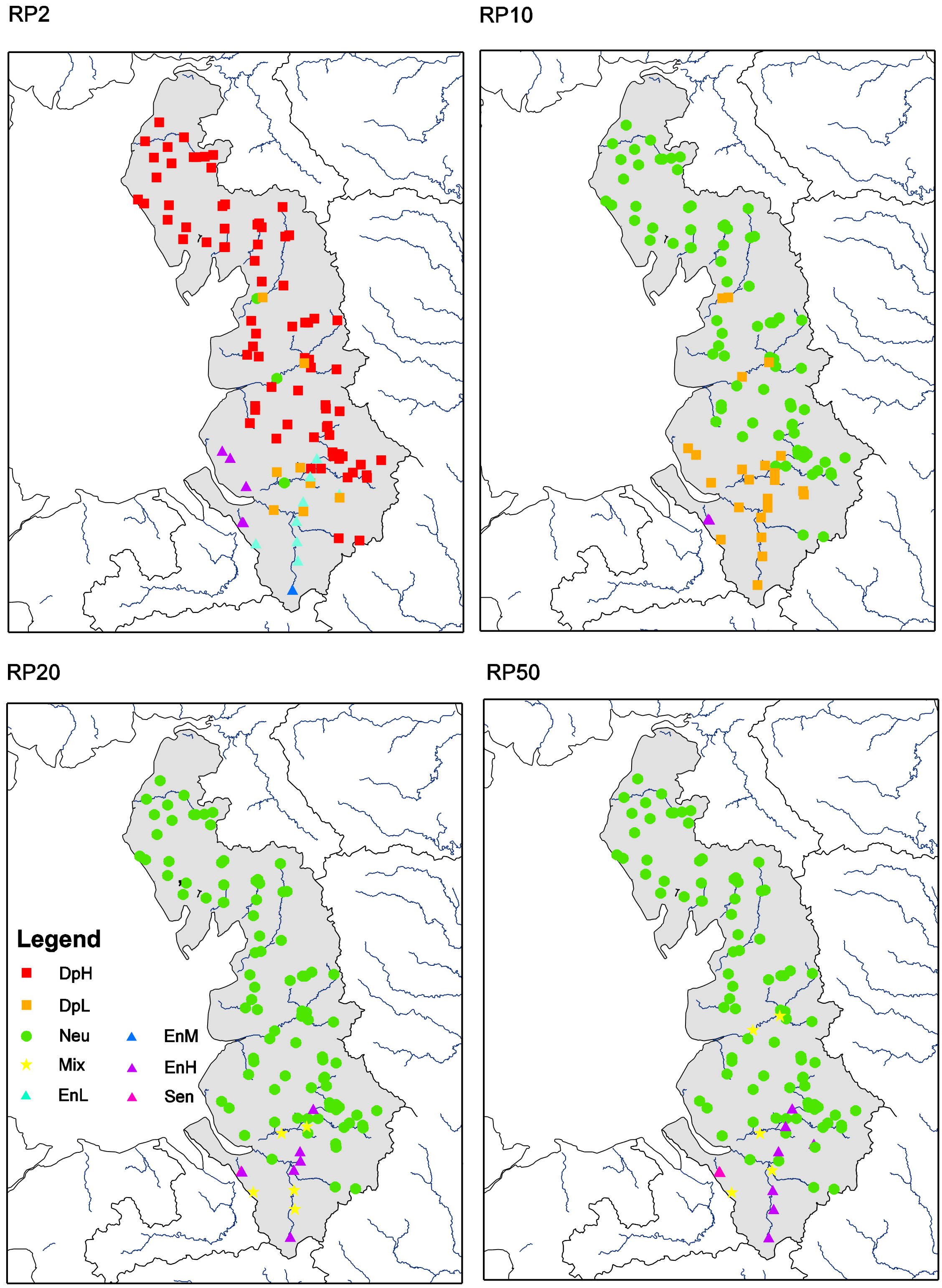

Figure 3.37 The best-estimate of the response type for each NRFA catchment in the North-West England river-basin region.

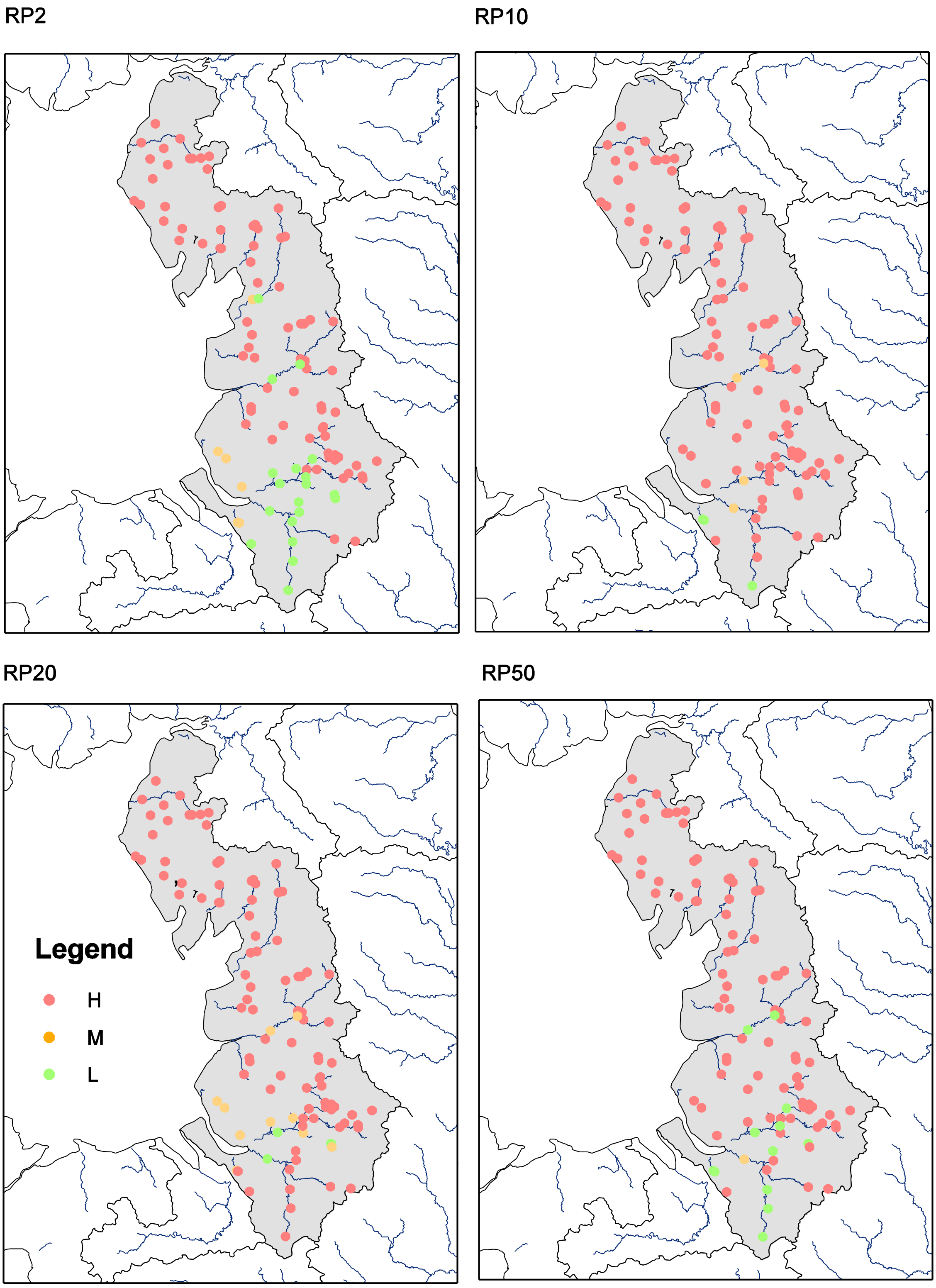

Figure 3.38 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the North-West England river-basin region.

3.10.2 Hazard

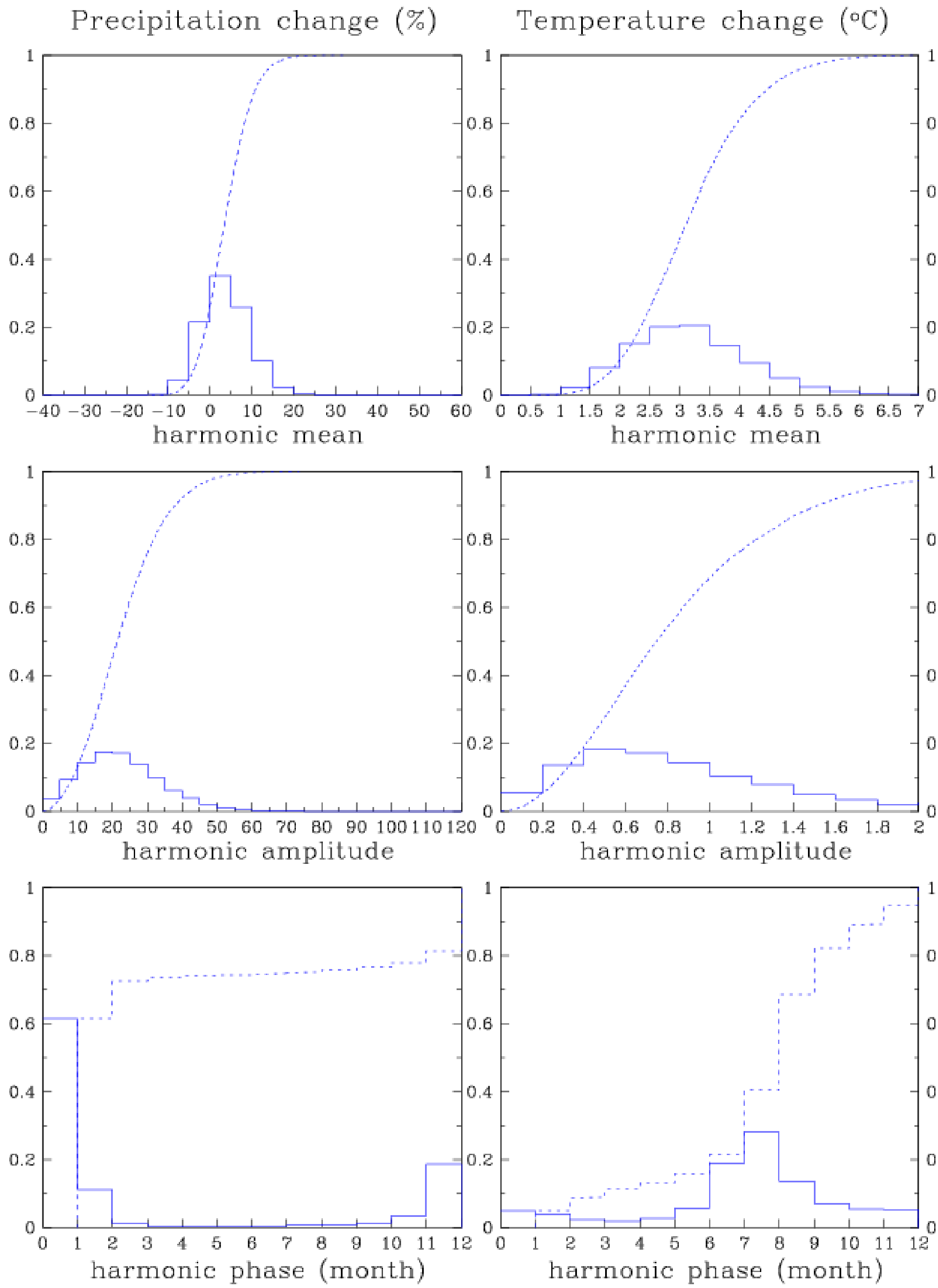

Figure 3.39 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s A1B) for the North-West England river-basin region.

3.10.3 Risk

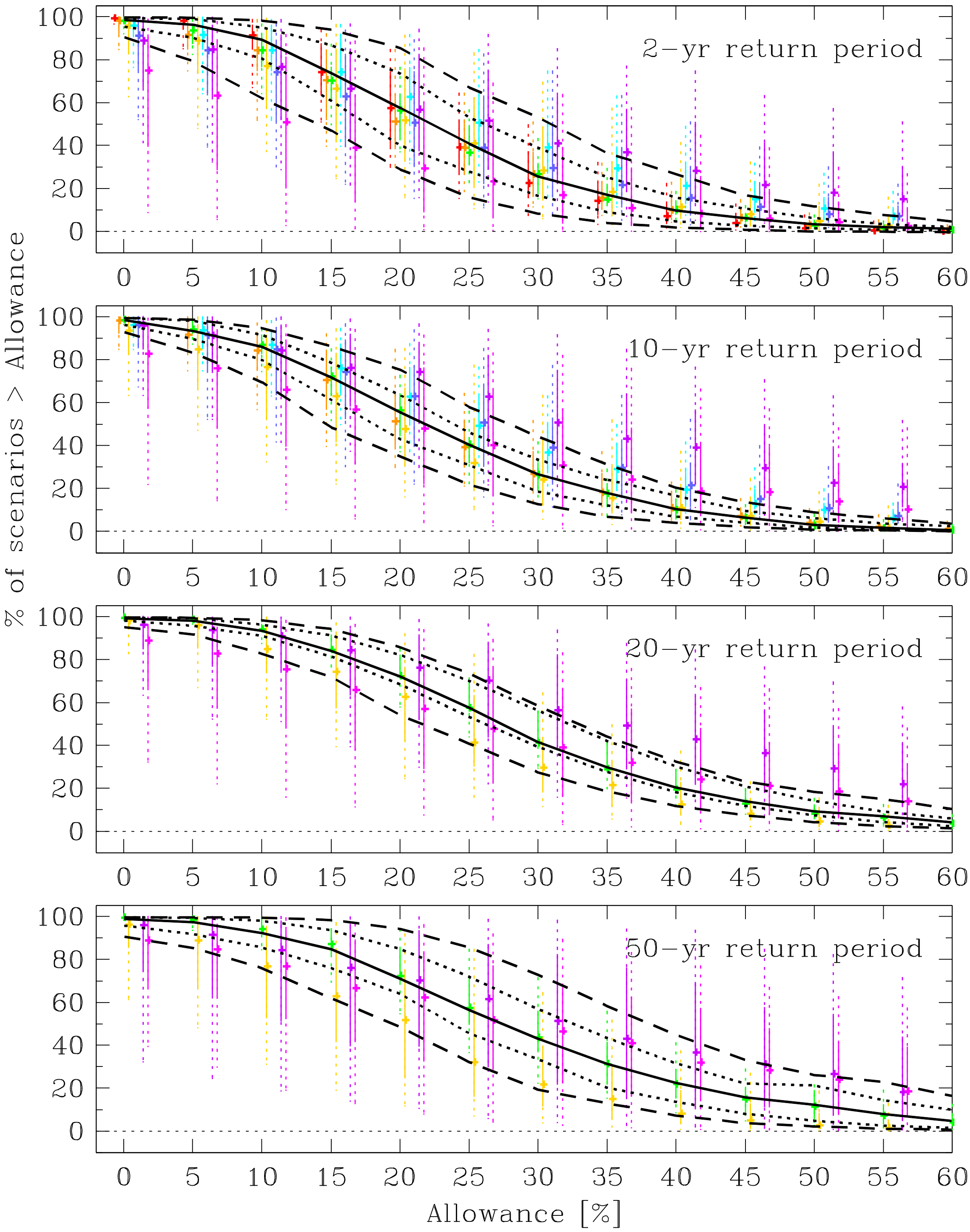

Figure 3.40 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s A1B) for the North-West England river-basin region. Response-type risk (colours): Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta); 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).

3.11 Solway

3.11.1 Vulnerability

A total of 43 NRFA catchments are located within the Solway river-basin region; only 15 of these are in England. The best-estimate of the response type for each of these catchments is Damped at the lowest return period and Neutral at the higher return periods (Table 3.11). The maps in Figure 3.41 show the best-estimate of the response type for each catchment at each return period, and those in Figure 3.42 show the corresponding confidence levels (High – H; Medium – M; Low – L).

Table 3.11 The number of NRFA catchments of each response type at each return period, for the Solway river-basin region.

Response type	RP2	RP10	RP20	RP50
Damped-High	**38**	NA	NA	NA
Damped-Low	1	9	NA	NA
Neutral	3	**34**	**43**	**41**
Mixed	0	0	0	1
Enhanced-Low	1	0	NA	NA
Enhanced-Medium	0	0	NA	NA
Enhanced-High	0	0	0	1
Sensitive	0	0	0	0
Total	43	43	43	43

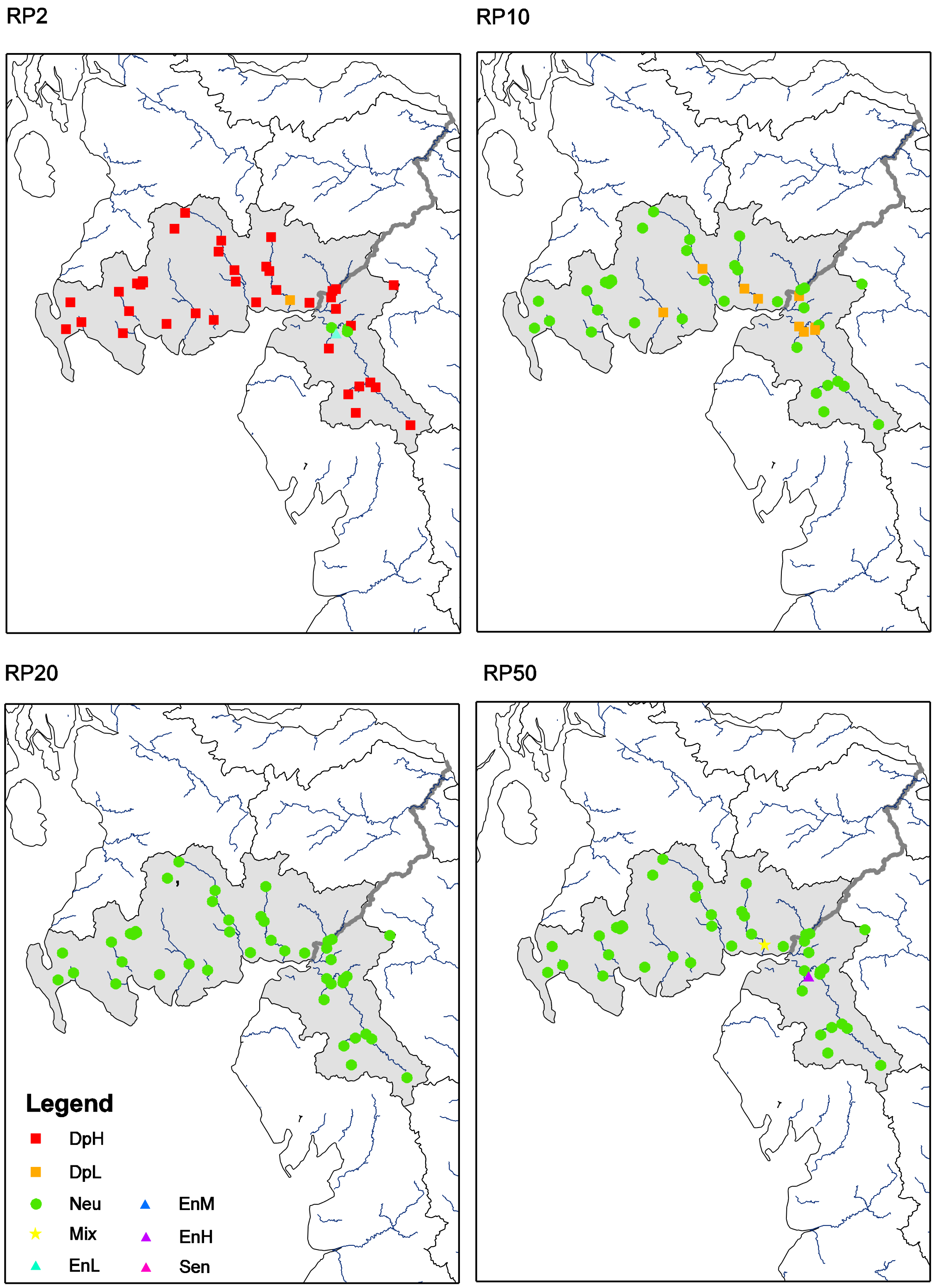

Figure 3.41 The best-estimate of the response type for each NRFA catchment in the Solway river-basin region. The thick grey line shows the Scotland / England border.

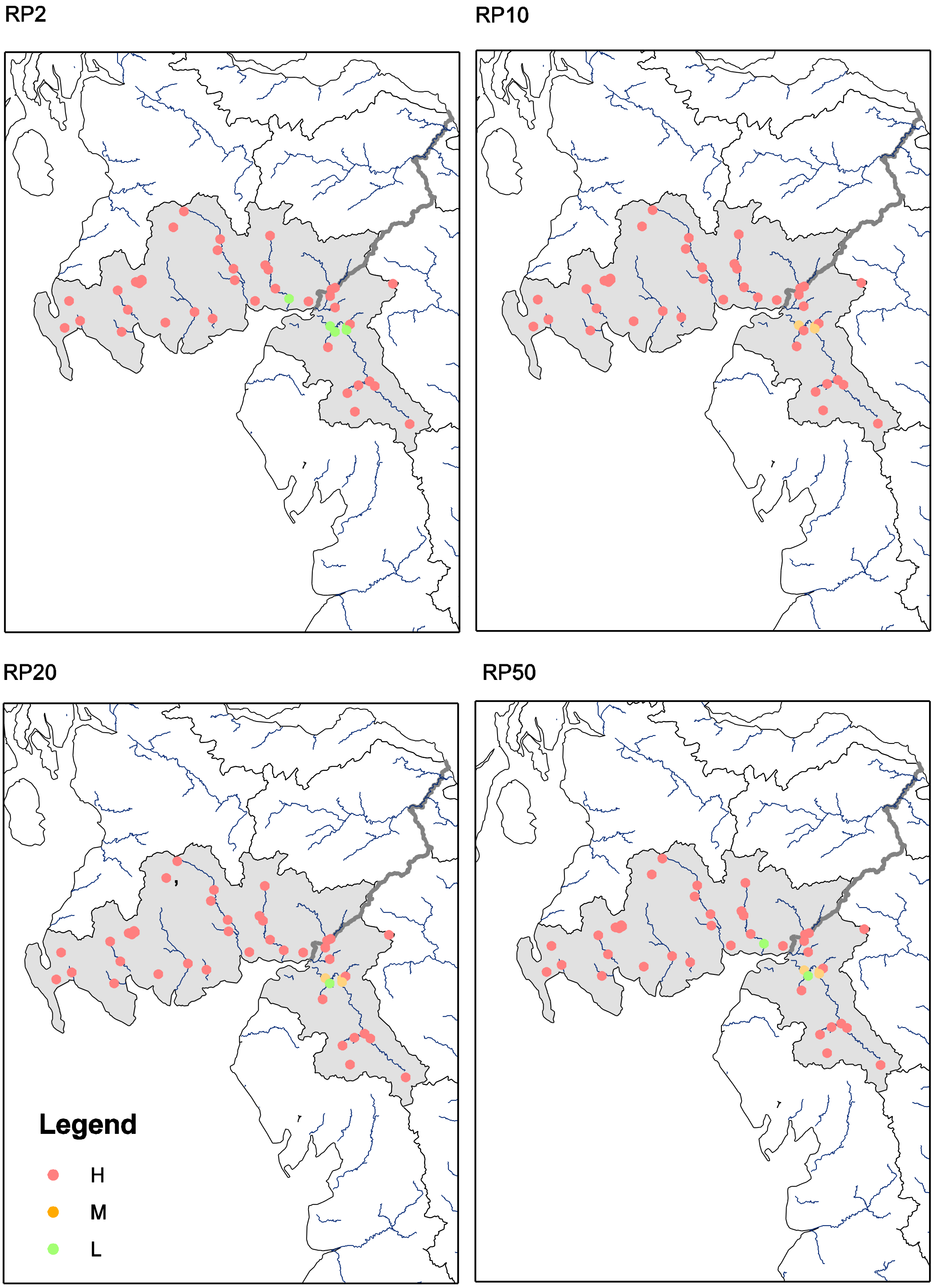

Figure 3.42 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the Solway river-basin region.

3.11.2 Hazard

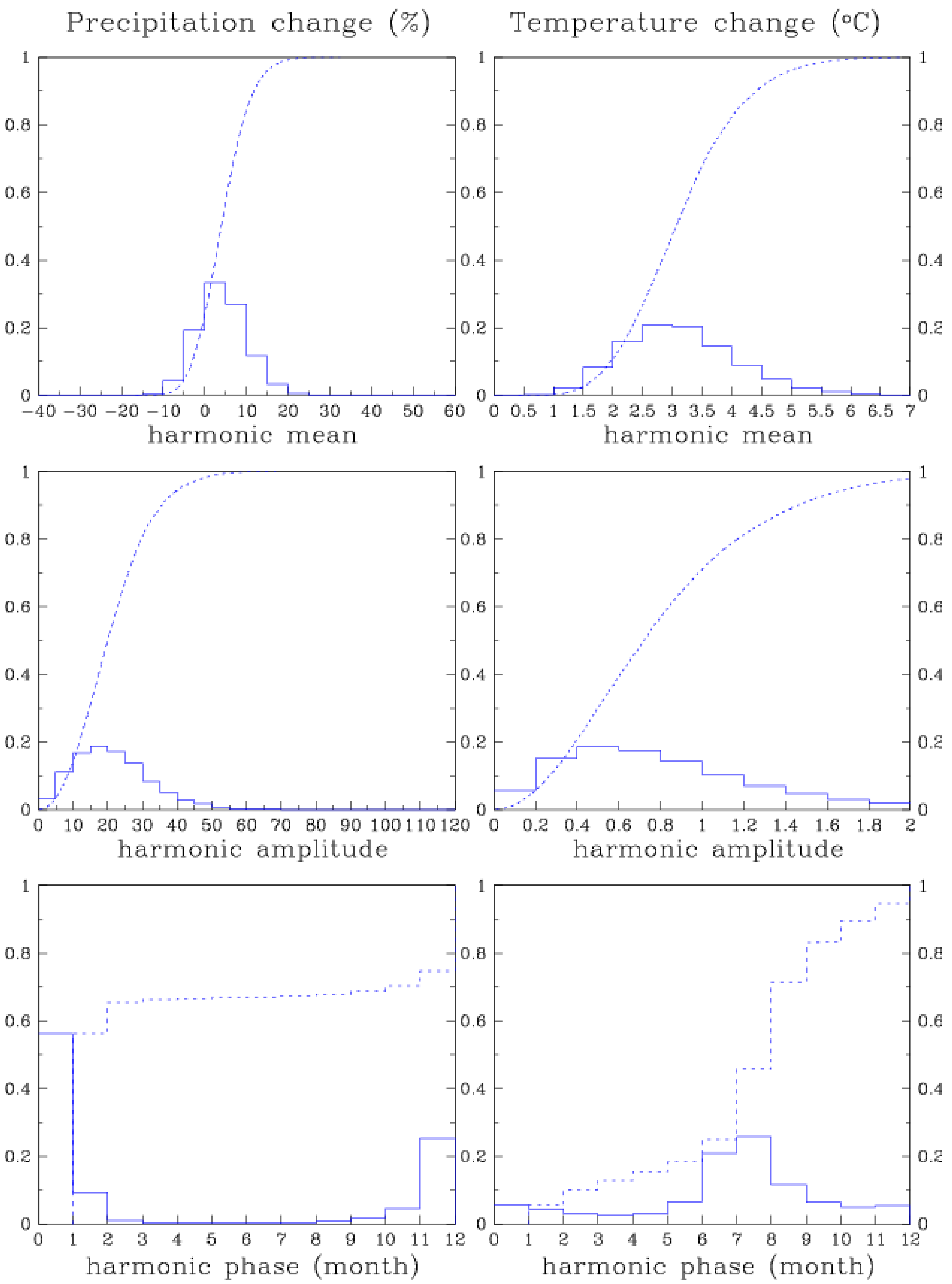

Figure 3.43 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s A1B) for the Solway river-basin region.

3.11.3 Risk

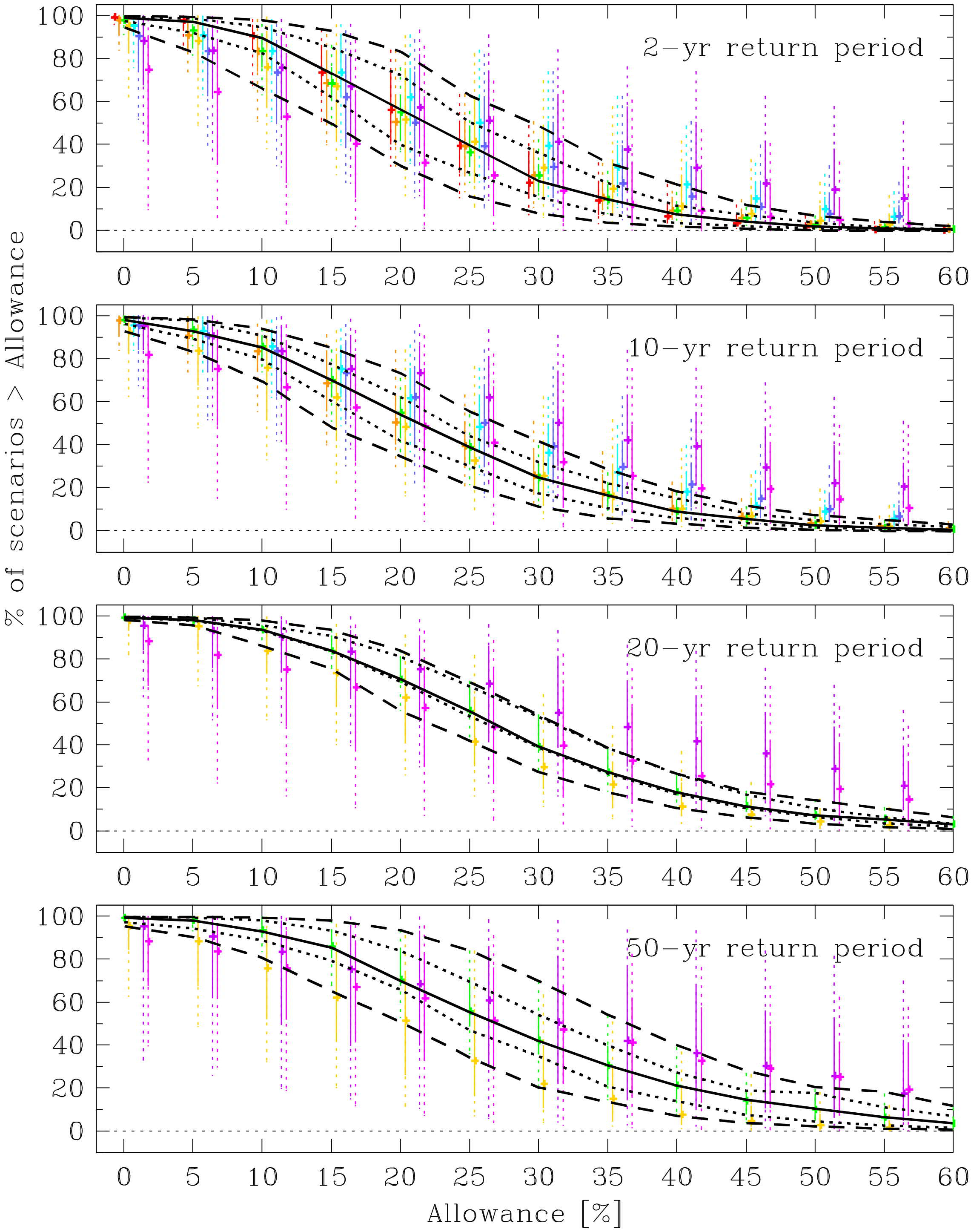

Figure 3.44 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s A1B) for the Solway river-basin region. Response-type risk (colours): Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta); 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).

3.12 Tweed

3.12.1 Vulnerability

A total of 31 NRFA catchments are located within the Tweed river-basin region; only 2 of these are in England. The best-estimate of the response type for each of these catchments is Damped at the lower return periods and Neutral at the higher return periods (Table 3.12). The maps in Figure 3.45 show the best-estimate of the response type for each catchment at each return period, and those in Figure 3.46 show the corresponding confidence levels (High – H; Medium – M; Low – L).

Table 3.12 The number of NRFA catchments of each response type at each return period, for the Tweed river-basin region.

Response type	RP2	RP10	RP20	RP50
Damped-High	**14**	NA	NA	NA
Damped-Low	11	**16**	NA	NA
Neutral	1	13	**24**	**26**
Mixed	0	0	2	0
Enhanced-Low	3	0	NA	NA
Enhanced-Medium	1	0	NA	NA
Enhanced-High	1	0	5	5
Sensitive	0	2	0	0
Total	31	31	31	31

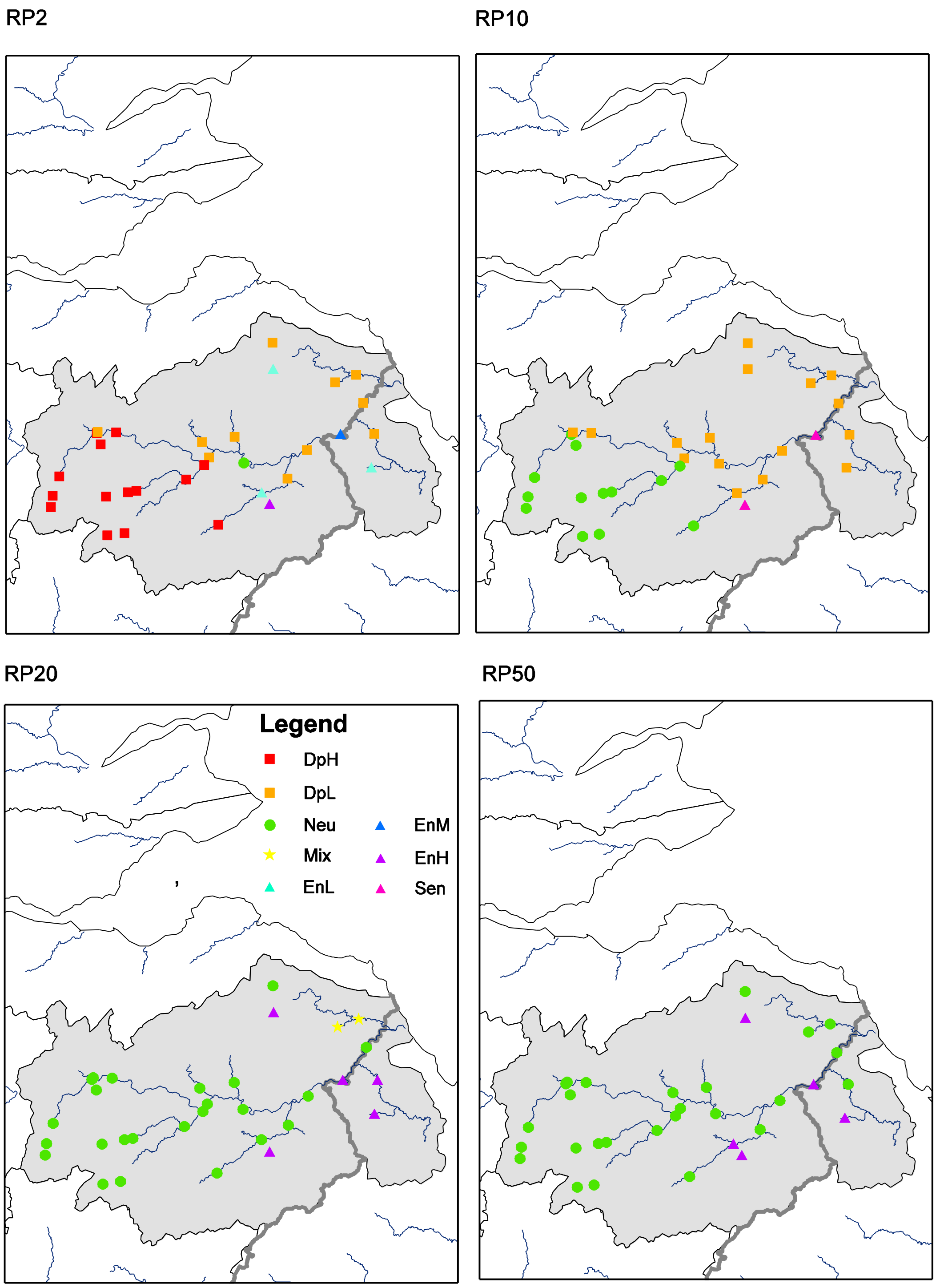

Figure 3.45 The best-estimate of the response type for each NRFA catchment in the Tweed river-basin region. The thick grey line shows the Scotland / England border.

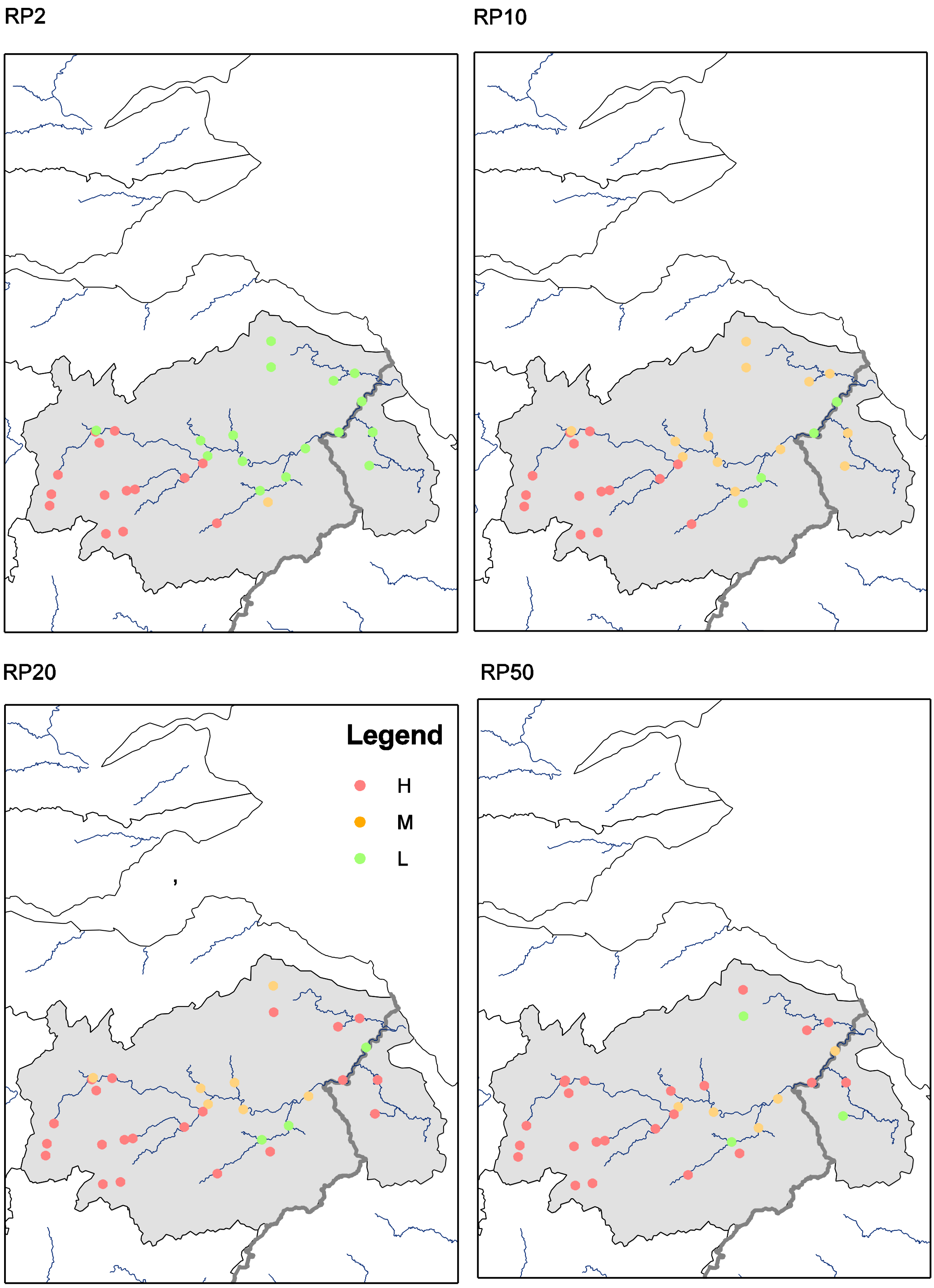

Figure 3.46 The confidence level associated with the best-estimate of the response type for each NRFA catchment in the Tweed river-basin region.

3.12.2 Hazard

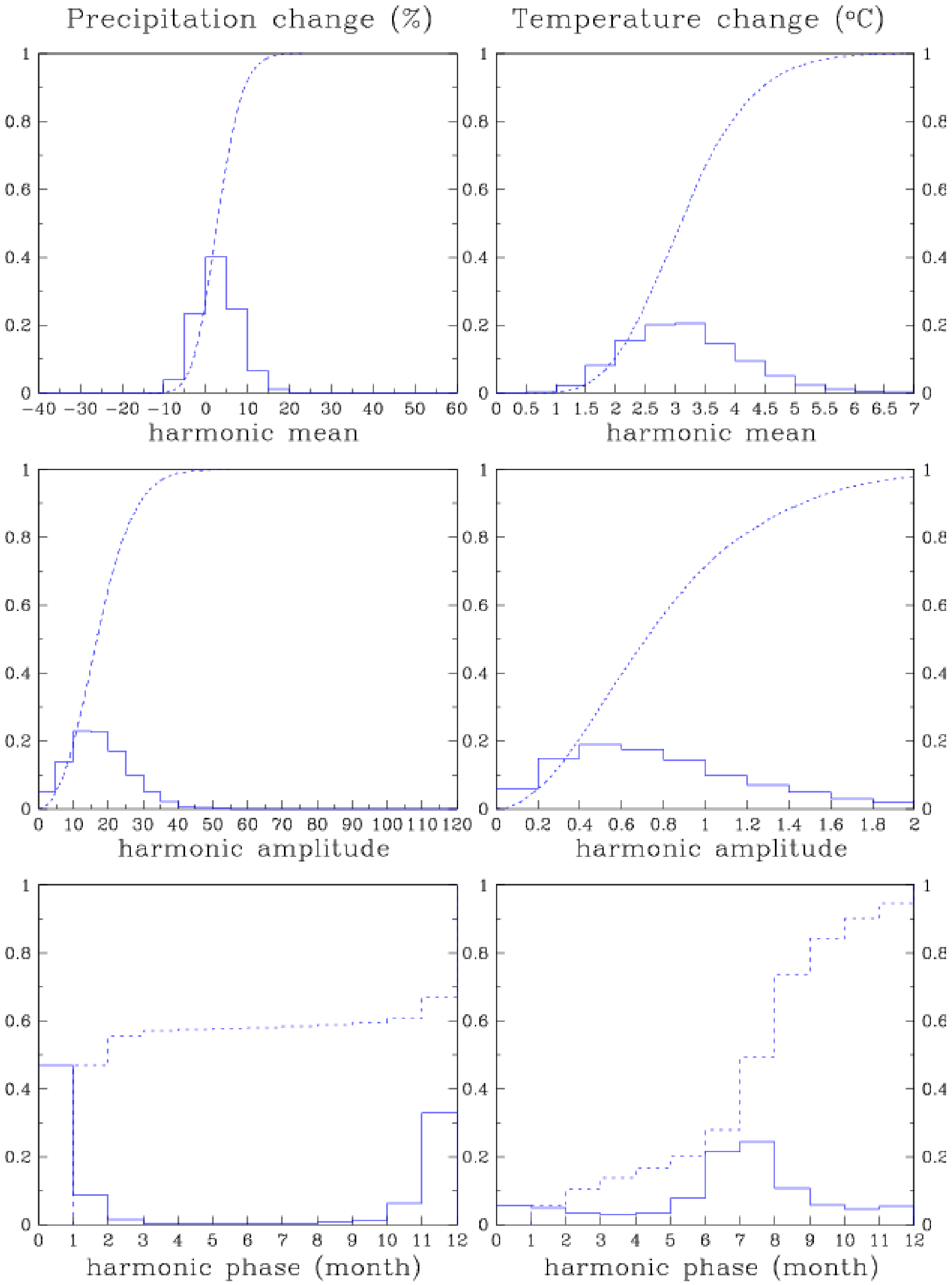

Figure 3.47 Summary of the parameters of the harmonic functions fitted to the UKCP09 Sampled Data (2080s A1B) for the Tweed river-basin region.

3.12.3 Risk

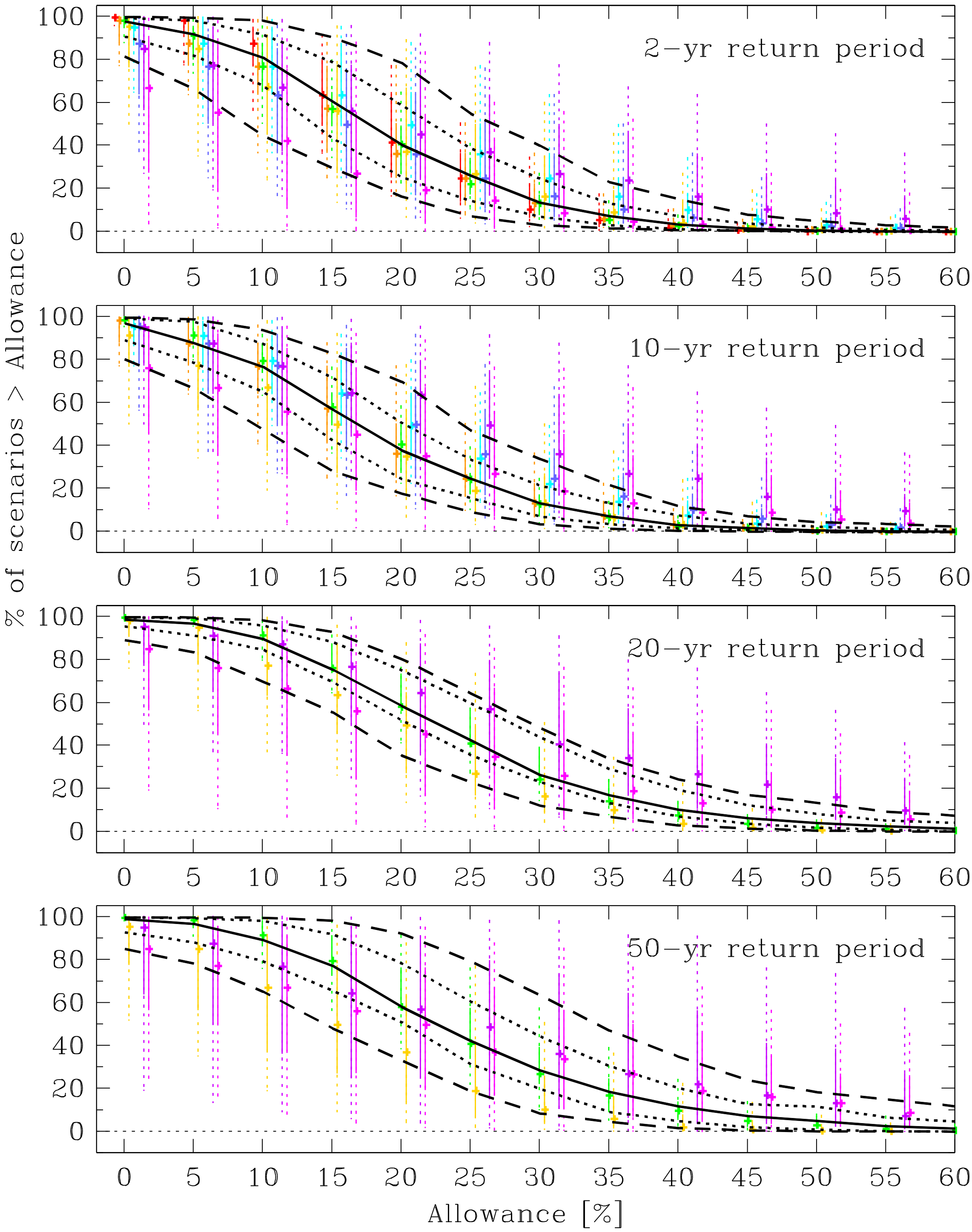

Figure 3.48 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s A1B) for the Tweed river-basin region. Response-type risk (colours): Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta); 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 Summary

4.1 Vulnerability

Areas to the north / west of England and Wales have greater homogeneity of response types (mainly Damped-High at RP2 and Neutral at RP20 and RP50) than areas to the south / east, which are much more heterogeneous (Figure 4.1). This is due to the higher precipitation in the north/west in comparison to the south/east, which is the dominant factor affecting catchment response in the decision trees. In the south and east, the lower rainfall means that the soils and geology have more of an influence, and so the heterogeneity of the soils / geology leads to heterogeneity of response types. Most of the UK's major aquifers are located in the south / east of England, and catchments containing areas of high permeability have Enhanced-High or Sensitive response types. In contrast, nearby catchments which do not contain areas of high permeability can have Damped-Low, Mixed or Enhanced-Low response types at RP2, and Mixed or Neutral response types at higher return periods. The confidence level associated with the best-estimate of the response type is also generally higher in the north / west than the south / east (Figure 4.2).

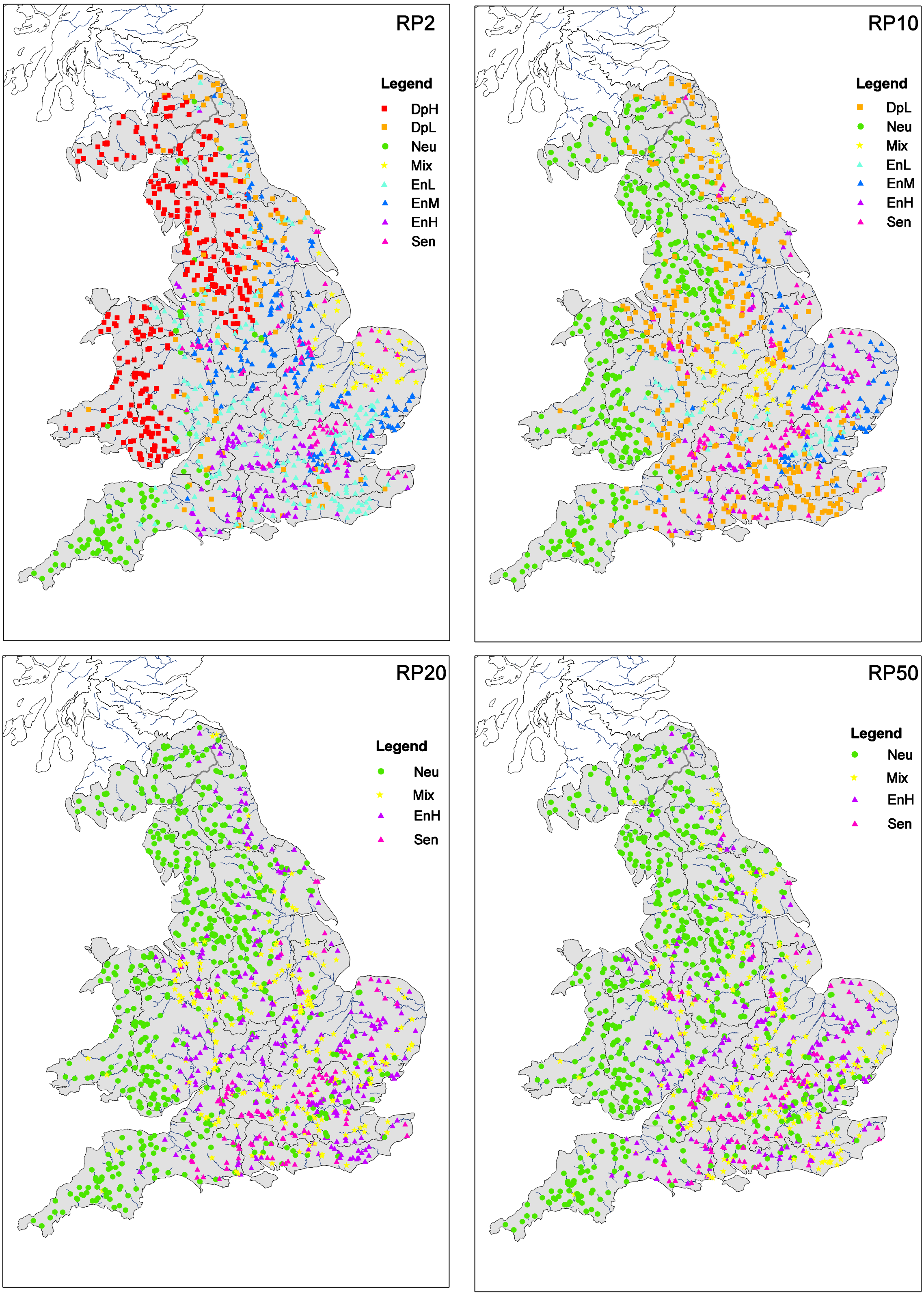

Figure 4.1 The best-estimate of the response type for each NRFA catchment in England and Wales, at each of the four return periods. The thick grey line shows the Scotland / England border.

Figure 4.2 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.

4.2 Hazard

Plots of the mean against the amplitude of the harmonic functions fitted to the UKCP09 Sampled Data for precipitation (Figure 4.3, 2080s A1B) clearly show how the hazard differs between river-basin regions. More southerly regions have a greater range of amplitudes than do more northerly regions, with a slightly more pronounced difference from south to north for the easterly regions than for the westerly regions. The more northerly/westerly regions tend to have a greater proportion of scenarios with a positive mean (that is, increase in annual precipitation) than do more southerly/easterly regions. Some river-basin regions show greater dependence between the harmonic mean and amplitude than others. For instance, the Dee river-basin region shows a negative correlation between the mean and amplitude, whilst for the Northumbria river-basin region the two appear to be more independent.

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 scenarios 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 A1B) in each river-basin region (Section 3; grouped together in Figure 4.4), confirm that the dominant month of the peak precipitation change for these scenarios is also January. The next most dominant month is either February (for more southerly/easterly regions) or December (for more northerly/westerly regions). In the former case, the uncertainty analysis undertaken as part of FD2020 (Kay *et al.* 2009) showed that the response patterns would be slightly less extreme, whereas in the latter case they were shown to be slightly more extreme. FD2020's merging of response types at higher return periods was designed to take this into account.

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. As with the geographic differences in the harmonic mean and amplitude for the 2080s A1B scenario (Figure 4.3), it is the harmonic amplitude which differs more between time-horizons and emissions scenarios than does the harmonic mean. 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. A similar geographic variation in amplitude is evident for the 2020s and 2050s as for the 2080s, with higher median and greater range of amplitudes in the more southerly regions than the more northerly ones. For the different emissions scenarios, the harmonic amplitude is lowest under the B1 scenario and highest under A1F1, with A1B lying approximately mid-way between. Again, amplitudes are higher in the south than the north.

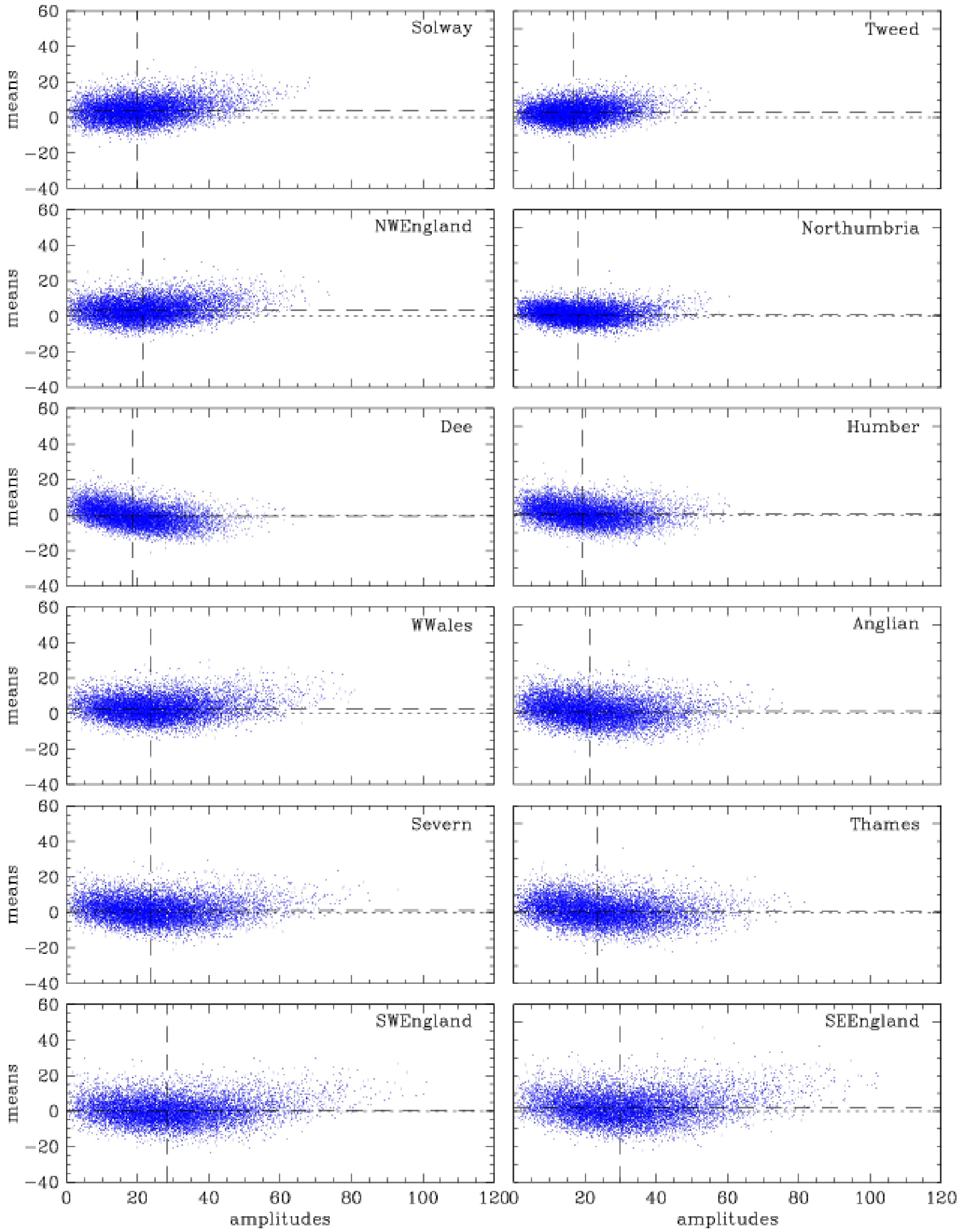

Figure 4.3 Plots of the mean versus the amplitude of the harmonic functions fitted to the UKCP09 precipitation Sampled Data (2080s A1B; blue dots), for each of the 12 river-basin regions in England and Wales (arranged roughly geographically). The median of each harmonic parameter is shown by the black 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).

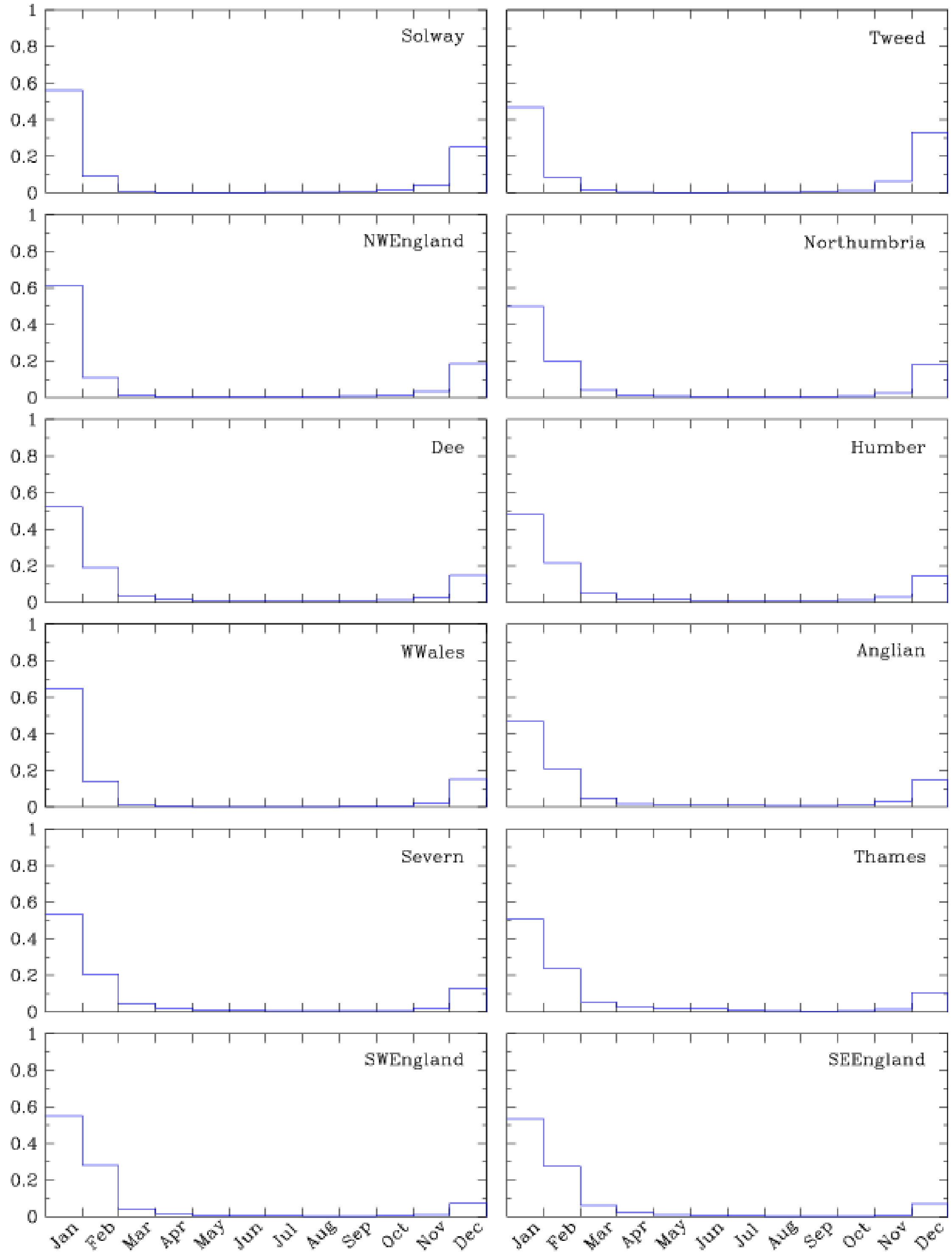

Figure 4.4 Histograms of the phase of the harmonic functions fitted to the UKCP09 precipitation Sampled Data (2080s A1B), for each of the 12 river-basin regions in England and Wales.

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 2.3). 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 scenarios (Prudhomme and Reynard 2009). The plots in Figure 4.5 show the mean against the amplitude of the harmonic functions fitted to the UKCP09 Sampled Data for temperature (2080s A1B), 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 scenarios (2080s A1B) than was expected from the AR4 climate scenario analysis, as FD2020's 'High' scenarios (mean change 4.5^{o}C, Table 1.1), are not as extreme as originally thought. This is particularly the case for the High seasonal scenarios (as against the High non-seasonal scenario). FD2020's 'Medium' scenarios (mean change 2.5^{o}C and amplitude 0.8^{o}C, Table 1.1) are also lower than the median from the UKCP09 Sampled Data (2080s A1B), especially for the harmonic mean.

Histograms of the phase of the harmonics fitted to the UKCP09 Sampled Data for temperature (2080s A1B) in each river-basin region (Section 3; grouped together in Figure 4.6), 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 A1B), 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.

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 B1 scenario and the highest under the A1F1 scenario, with a similar pattern across the geographical regions.

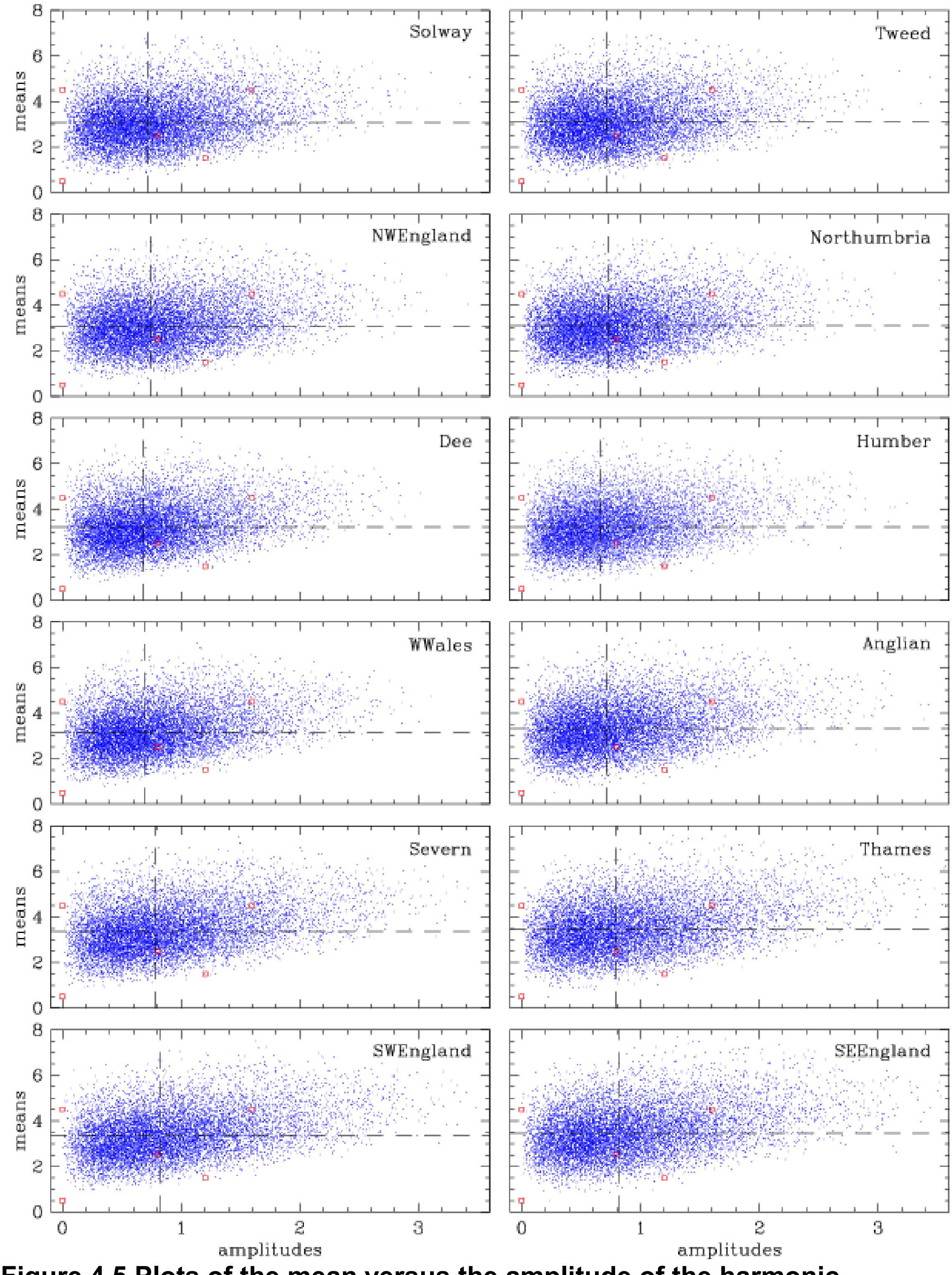

Figure 4.5 Plots of the mean versus the amplitude of the harmonic functions fitted to the UKCP09 temperature Sampled Data (2080s A1B; blue dots), for each of the 12 river-basin regions in England and Wales (arranged roughly geographically). The median of each parameter is shown by the black dashed lines. The red squares indicate the positions of the scenarios used for the FD2020 sensitivity framework (Table 1.1).

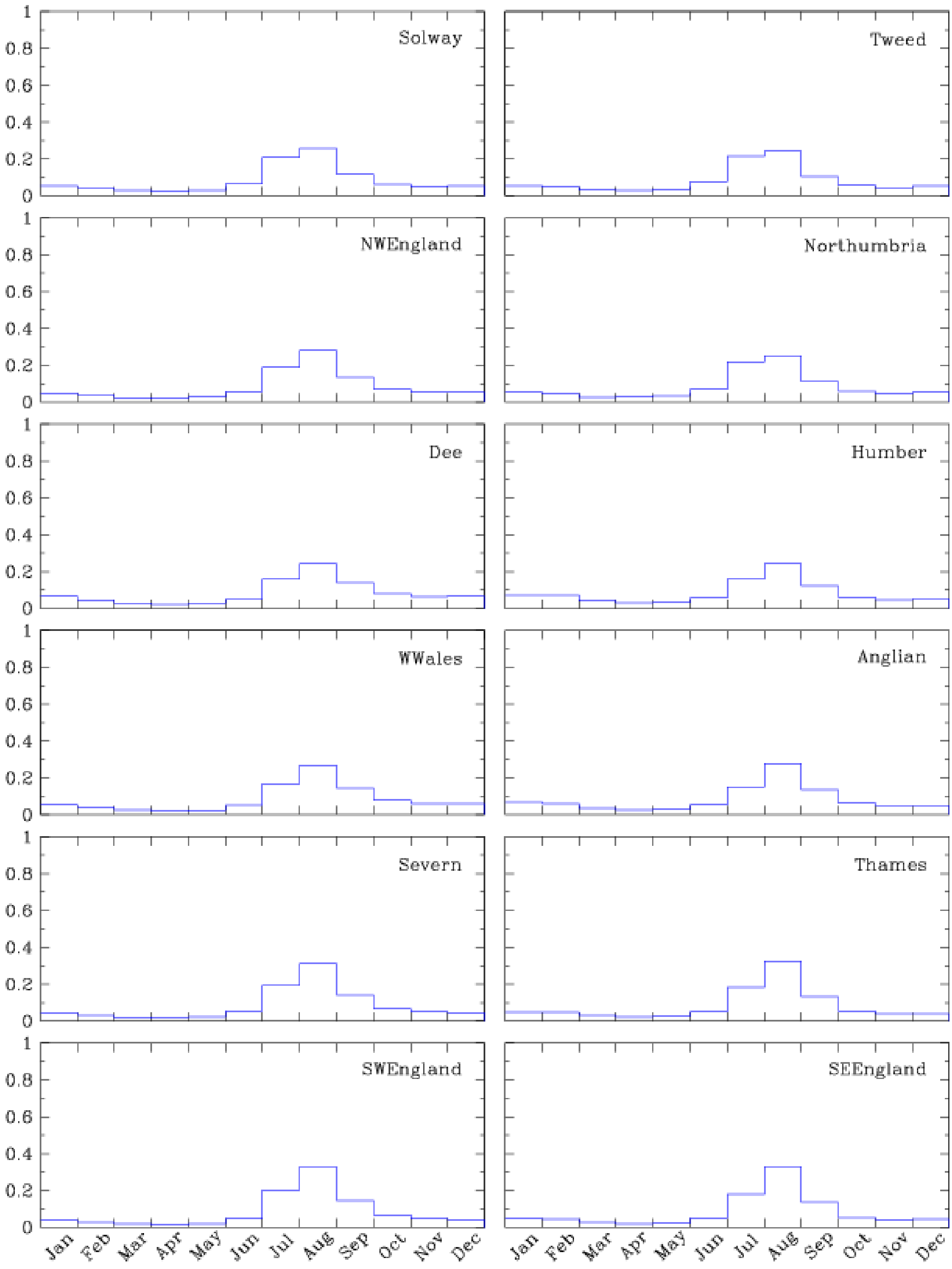

Figure 4.6 Histograms of the phase of the harmonic functions fitted to the UKCP09 temperature Sampled Data (2080s A1B), for each of the 12 river-basin regions in England and Wales.

The differences between the 2080s A1B UKCP09 temperature scenarios and those used in FD2020 (Figure 4.5) 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 A1B) 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 scenarios 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 vulnerability and risk in comparison to that given by the FD2020 scenarios. Thus the results (for the 2080s A1B scenario) using the FD2020 key response patterns are more likely to over- rather than under-estimate the risk from the UKCP09 scenarios, 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 scenarios 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 scenarios 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. For catchments affected by snowmelt-related flood peaks, a lower temperature increase may result in higher flood peaks than predicted but the overall impact depends on the precise combination of timing of precipitation and temperature.

4.3 Risk

Figure 4.7 brings together the central-estimate of the regional risk for the 12 river-basin regions (2080s A1B, shown separately in Section 3), 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.49-52 of Appendix B.2.

Figure 4.7 shows that there is quite a range of results across the 12 river-basin regions, but that certain regions stand out as being clearly more/less at risk than other regions (for the 2080s A1B scenario). The river-basin region most at risk (for an allowance greater than 20%), at all return periods, is South-East England, followed by South-West England. The river-basin region least at risk (for an allowance of 20% or more), at all return periods, is Dee, followed by Northumbria, Humber and Tweed. These four river-basin regions have noticeably lower risk than the other river-basin regions, and the latter three river-basin regions (Northumbria, Humber and Tweed), all in the north-east of England, have quite similar central estimates of regional risk. The Anglian and Thames river-basin regions also have very similar central estimates of regional risk to each other, as do Solway and North-West England. The Severn and West Wales river-basin regions have regional risk curves that are quite similar to those for Solway and North-West England, especially at lower return periods / higher values of the allowance.

Similar relative risk between river-basin regions is seen for the alternative emissions scenarios (B1 and A1F1) for the 2080s, and for the 2050s A1B scenario (Appendix B.2, Figures B.50-52), but much less difference is seen between river-basin regions for the 2020s A1B scenario (Appendix B.2, Figure B.49). In the latter case, Figure B.49 shows that, for all river-basin regions, when the allowance increases from 0 to 20% there is sharp decline in the percentage of scenarios exceeding the allowance, with few scenarios requiring an allowance of more than 20%. However, by the 2050s the rate of decline is much less, with the pattern continuing to the 2080s.

The Dee consistently stands out as the river-basin region with the lowest risk (Figure 4.7, and Figures B.49-52 of Appendix B.2) and as having different alignment of contours in the plots of harmonic mean against amplitude for precipitation change (Figure 4.3, and Figures A.4 and A.8 of Appendix A.1). It is more similar, in terms of hazard and risk, to river-basin regions on the east side of the country (Humber and Northumbria) than those on the west. This may reflect its location in a rain-shadow to the east of the highest mountains in Wales, so that its precipitation characteristics are more akin to the drier east than the wetter west.

Figures B.53-64 of Appendix B.3 compare the regional risk curves for the alternative time-horizons and emissions scenarios, for each of the 12 river-basin regions over England and Wales. These figures confirm that the risk is higher under the high (A1F1) emissions scenarios and lower under the low (B1) emissions scenarios than it is under the medium (A1B) emissions scenario, and that the risk increases with time.

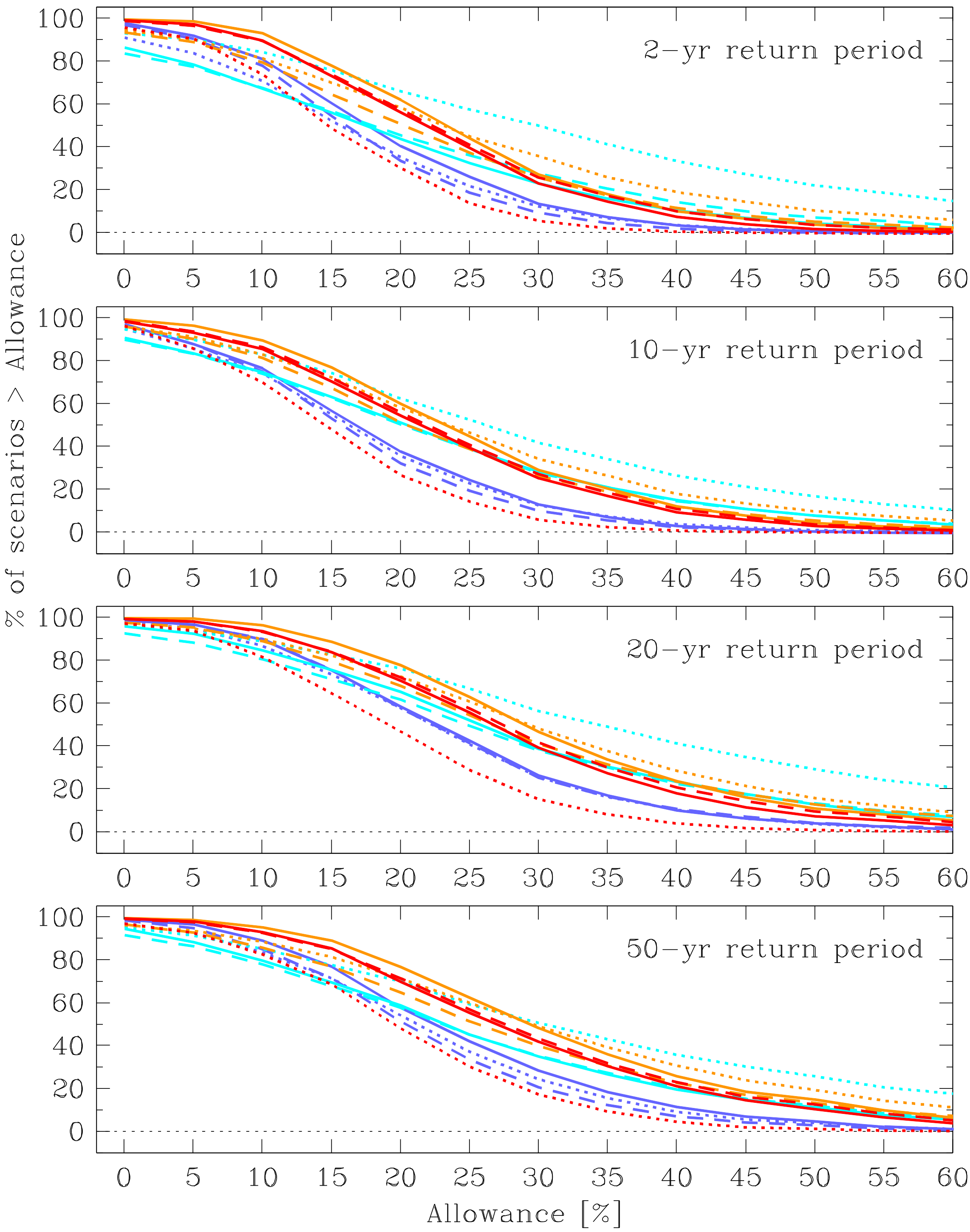

Figure 4.7 Regional risk curves (central-estimates) for each of the 12 UKCP09 river-basin regions in England and Wales (2080s A1B). Key: Tweed – blue solid, Northumbria – blue dashed, Humber – blue dotted, Anglian – cyan solid, Thames – cyan dashed, South-East England – cyan dotted, Solway – red solid, North-West England – red dashed, Dee – red dotted, West Wales – orange solid, Severn – orange dashed, South-West England – orange dotted.

It should be recalled, when looking at the (weighted) regional risk curves presented in Figure 4.7 and Appendix B.2 and B.3, 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 3 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. 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 2.3 and the risk figures in Section 3 and Appendix B.1).

4.4 Risk for larger catchments

The standard FD2020 extra uncertainty allowances have been included in all of the results presented here, but the FD2020 uncertainty analysis (Kay *et al.* 2009) 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 1.3 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 allowance calculated for smaller catchments (Table 4.1). 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).

It should be noted that the 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 2.5% of the 1469 NRFA catchments in England, Wales and 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.

Table 4.1 Suggested additions to allowances calculated for smaller catchments, for use with larger catchments (Area > ~2000km^2; cf. Table 1.3).

Flood response type:	RP2	RP10	RP20	RP50
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
Enhanced-High	**0**	**4**	**6**	7
Sensitive	**0**	**6**	**14**	**22**

Numbers in bold are those to be used with (merged) key response patterns, when a catchment's response type is estimated from catchment properties. Note that, where flood response types are merged (outlined squares), the middle uncertainty allowance is applied. Numbers not in bold are only required for use with modelled catchment response patterns.

4.5 Extension to higher return periods

The data available to drive the hydrological models restricted the choice of flood indicators in FD2020. Relatively short record lengths (longest 41 years) meant that nothing more extreme than the 50-year return period could reasonably be evaluated, and so response patterns were not produced for higher return periods. However, to develop allowances for higher return periods (e.g. 100-year) those for lower return periods could potentially be extrapolated.

Figure 4.8 shows, for each of the river-basin regions for the 2080s A1B scenario, potential allowances versus return period (for the 2-, 10-, 20-, and 50-year return periods). The allowances are derived from the response-type risk for the four types that exist at the higher return periods (Neutral, Mixed, Enhanced-High and Sensitive), and from the regional risk curves. In each case, allowances are derived for two illustrative 'protection levels', where i) 50% and ii) 10% of scenarios exceed the allowance. These plots show that the allowance stays relatively stable / increases slightly with increasing return period for the Neutral response type, and when derived from the regional risk curve (as this is generally weighted towards Neutral catchments; see tables in Section 3). For the Enhanced-High response type, the allowance is relatively stable / increases up to the 20-year return period but then drops slightly for the 50-year return period. The same applies for the Mixed response type. In contrast, for the Sensitive response type the allowance clearly increases with return period, with a more marked increase for the more precautionary level of protection. These differences by response type make sense when considered in terms of the key response patterns (Figure 1.3) and extra uncertainty allowances (Table 1.3) at each return period, and in terms of the hydrological processes controlling the vulnerability for these types of catchment. However, in using extrapolation methods to estimate allowances for higher return periods it is suggested that the allowance should not be decreased below that for the 50-year return period.

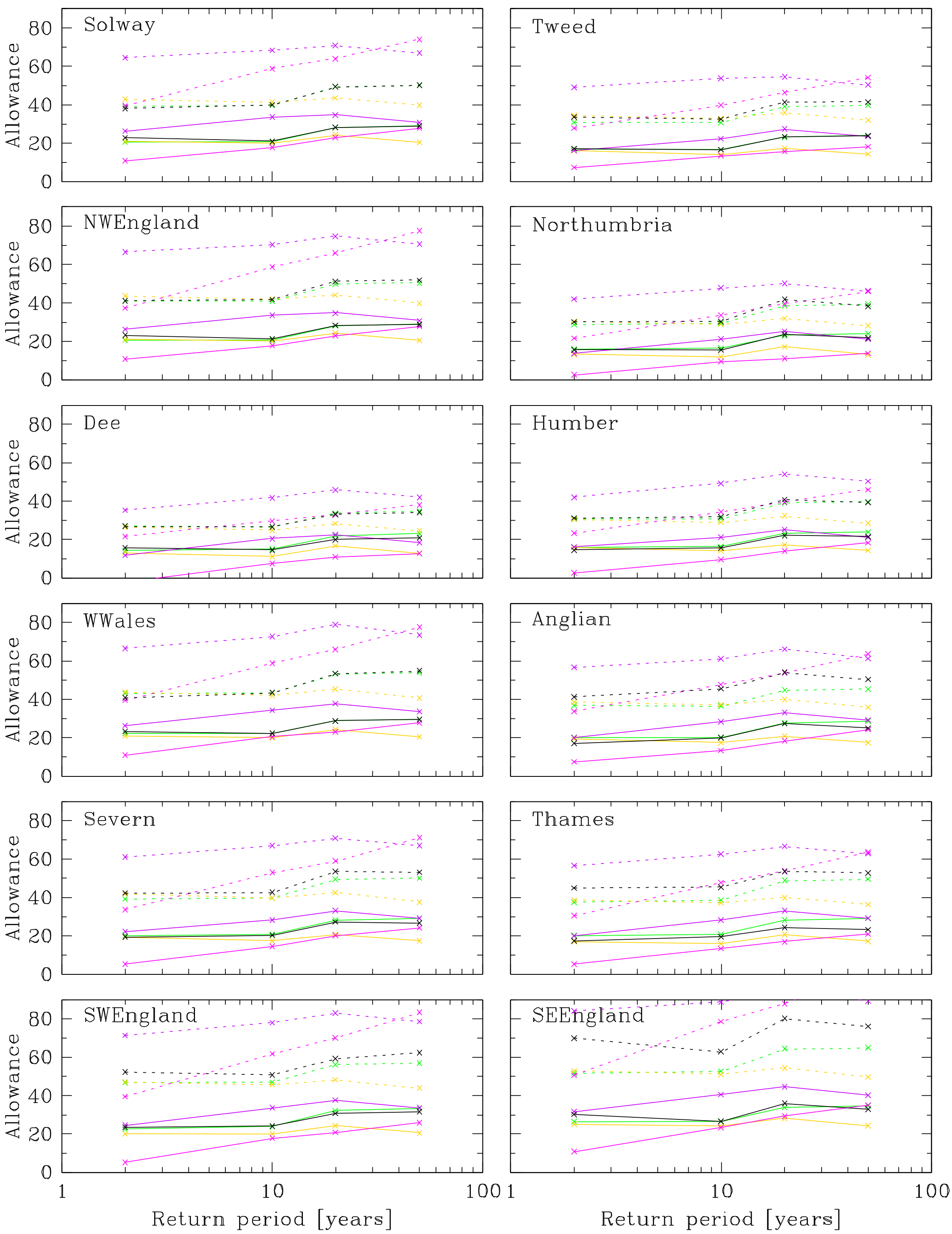

Figure 4.8 Possible allowances versus return period, derived from the (2080s A1B) risk curves for the Neutral (green), Mixed (gold), Enhanced-High (purple) and Sensitive (magenta) response types and from the regional (weighted) risk curves (black). Allowances are shown for two 'protections levels', where i) 50% (solid lines) and ii) 10% (dotted lines) of scenarios exceed the allowance.

Plots of potential allowances against return period for alternative time-horizons and emissions scenarios are given in Figures C.1-4 of Appendix C. These plots show similar relative patterns of change in allowance with return period for the four response types.

Section 4.4 discussed the use of additional uncertainty allowances for larger catchments, based upon multiplication factors for the standard extra uncertainty allowances. These multiplication factors increase with return period (Table 1.3), and so there could be an argument for even larger multiplication factors for use at return periods higher than 50-years.

5 Discussion

5.1 Possible levels of guidance

The results in Sections 3 and 4 and Appendix B, on the impacts of the UKCP09 scenarios for catchments in the 12 river-basin regions over England and Wales, present a wealth of information to support the update of guidance on flooding and climate change. What needs to be decided is what level of detail/complexity is most appropriate for that guidance:

- Revised nationwide allowances;
- New regional allowances;
- New regional / sub-regional allowances by response type;

Or perhaps a fourth level

- Local decision-making, where the tools are provided to evaluate changes to river flows from user-defined future climate scenarios and catchment characteristics.

There are benefits and weaknesses of each level, discussed below. Essentially, the balance between simplicity of guidance and the possibility of over/under-adaptation has to be carefully considered.

The current 20% allowance is simple, memorable, and widely used and understood, so a revised nationwide allowance would be likewise. However, the evidence presented here (for instance Figure 4.7) suggests that the level of risk can vary quite substantially between river-basin regions (at least for later time-horizons), so setting regional allowances may be preferable to a single nationwide allowance. A nationwide allowance is quite likely to over-do the risk in some areas (leading to potentially expensive over-adaptation) and / or under-do the risk in other areas (leading to potentially dangerous under-adaptation). The setting, and application, of regional allowances is obviously more complicated than for a nationwide allowance though.

Although regional allowances may be preferable to use of a single nationwide allowance, the fact that the regional risk curves 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 4.3). 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.

Even if the regional risk curve were based on more catchments, it could be that a regional allowance derived from a regional risk curve is still not appropriate for some catchments in the river-basin region. For instance, the West Wales river-basin region is dominated by catchments of Neutral response type (at least at higher return periods; Table 3.8), and so the (weighted) regional risk curve is basically that of a Neutral catchment (Figure 3.32; compare the black regional risk curves with the green vertical lines, which represent the risk for a Neutral catchment in the region). The use of the regional risk to represent all catchments in the region would mean that the risk for the small number of Enhanced-High catchments in the region (Table 3.8) would be under-estimated (Figure 3.32; compare the black regional risk curves with the purple vertical lines, which represent the risk for an Enhanced-High catchment in the region).

Similarly, it would mean that the risk for the small number of Mixed catchments in the region (Table 3.8) would be over-estimated (Figure 3.32; compare the black regional risk curves with the yellow vertical lines, which represent the risk for a Mixed catchment in the region). Hence the use of regional allowances also carries the chance of over- or under-adaptation, although probably to a lesser extent than the use of a single nationwide allowance. It may be that, at least for some river-basin regions, the use of regional / sub-regional allowances by response type is preferable to the use of regional allowances.

Looking at the risk curves in Section 3, it is mainly the Enhanced-High response type which results in a higher risk than that given by the regional risk curve. Thus it would be useful to know exactly where such catchments are located. Unfortunately this is not straightforward, since the decision trees require knowledge of Mean Annual Loss (MAL; Section 2.1), which is not available for ungauged catchments. Neither can the MAL values available for gauged catchments be easily interpolated, since they incorporate catchment losses from abstractions as well as evaporation, and incorporate gains from effluent returns etc. However, it is possible to define areas of the country where the chance of a catchment being Enhanced-High is nil or very low, and areas where there is a higher probability that a catchment may be Enhanced-High. This can be done by using just the SAAR and BHP/BVLP rules from the Enhanced-High paths of the decision trees. Figure 5.1 shows these areas based on the RP20 decision tree (Figure 2.1c); there are only minor differences when using the RP50 decision tree (Figure 2.1d).

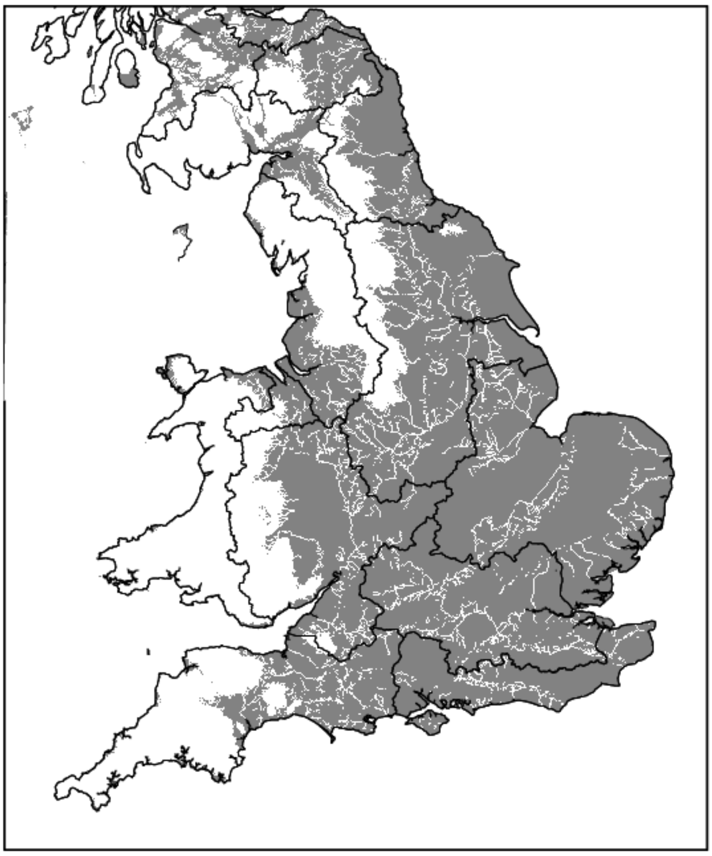

Figure 5.1 Map showing areas (grey) where the Enhanced-High response type is possible (based on the SAAR and BHP rules in the Enhanced-High paths of the RP20 decision tree; Figure 2.1c).

The setting of regional / sub-regional allowances by response type could also allow a user to take into account the confidence level of the best-estimate response type of a catchment, through use of the information in Table 2.6. For instance, the allowance for the best-estimate response type could be compared to that of the next most likely response type (or types), in the case of Medium or Low confidence in the best-estimate, and the largest allowance adopted. This would need knowledge of the catchment properties or decision tree path numbers for a catchment. 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.

The fourth, and highest, level of complexity, local decision-making, would need very clear guidance on usage, as otherwise there is the chance of very different methods and choices being applied in different cases / areas. However, this level gives the most flexibility as, for instance, the UKCP09 grid-box scenarios for a catchment could be used in place of its UKCP09 river-basin region scenarios. The confidence level associated with the best-estimate response type of a catchment can again be taken into consideration, as with the use of regional / sub-regional allowances by response type.

5.2 Other issues to consider

As well as the levels of complexity of guidance, decisions have to be made by the policy-maker on the preferred level of protection and how much uncertainty information is taken into account. That is;

- What percentage of scenarios exceeding the allowance (i.e. protection level) is acceptable?
- 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, whether nationally, regionally, regionally by response type, or locally)?
- 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 information about the impacts under different emissions scenarios be used?
- Should the guidance provide different allowances for different time-horizons?
- Should the guidance provide higher allowances for catchments with a larger area?

Further considerations, regarding the estimation of a catchment's response type(s) from its catchment properties, and whether the methodology could be inappropriate for certain types of catchment (e.g. highly urbanised catchments or those whose flow regime is affected by large water bodies), are discussed in Section 2.1.6.

Data limitations meant that FD2020 could not reasonably provide response patterns for return periods higher than 50 years. However, for extrapolation of the allowance to higher return periods an investigation suggested that the regional allowances, and those for most of the response types, are likely to remain relatively stable with increasing return period, but that the allowance for Sensitive catchments should probably increase with return period, and increase at a higher rate for more precautionary levels of protection.

6 References

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Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Humphrey, K.A., McCarthy, M.P., McDonald, R.E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R.A. 2009. *UK Climate Projections Science Report: Climate change projections.* Met Office Hadley Centre, Exeter.

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Prudhomme, C, Crooks, S.M. and Kay, A.L. 2009. *Regionalised impacts of climate change on flood flows: Regionalising the flood response types in Britain.* Report to Department for Environment, Food and Rural Affairs, FD2020 project milestone, CEH Wallingford, 48pp.

Prudhomme, C. and Reynard, N.S. 2009. *Regionalised impacts of climate change on flood flows: Rationale for definition of climate change scenarios and sensitivity framework*. Report to Department for Environment, Food and Rural Affairs, FD2020 project milestone, CEH Wallingford, 34pp.

Reynard, N.S., Crooks, S., Kay, A.L. and Prudhomme, C. 2009. *Regionalised impacts of climate change on flood flows.* Report to Department for Environment, Food and Rural Affairs, Technical Report FD2020, CEH Wallingford, November 2009, 113pp.

Appendix A: Hazard for alternative time-horizons and emissions scenarios

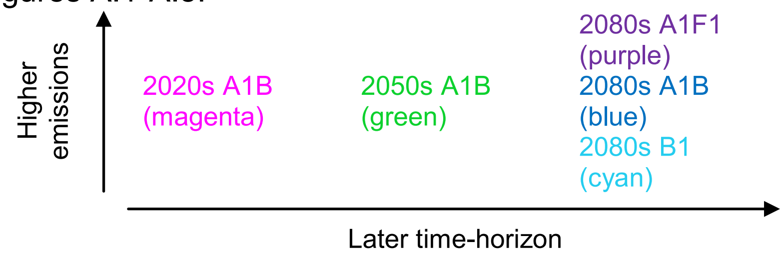
A.1 Precipitation changes

This section presents plots summarising the changes in precipitation derived from the UKCP09 projections for each of the 12 river-basin regions in England and Wales, for five time-horizon and emissions scenario combinations:

- 2020s time-horizon under A1B (Medium) emissions,
- 2050s time-horizon under A1B (Medium) emissions,
- 2080s time-horizon under A1B (Medium) emissions,
- 2080s time-horizon under B1 (Low) emissions,
- 2080s time-horizon under A1F1 (High) emissions.

In each case, the hazard is summarised in terms of the mean, amplitude and phase of the harmonic functions fitted to the sets of 10,000 monthly changes in precipitation provided by the UKCP09 Sampled Data. The table below shows the colours used for each time-horizon / emissions scenario combination. Figures A.1-A.4 show the dependence on time-horizon, while Figures A.5-A.8 show the dependence on emissions.

Key for Figures A.1-A.8:



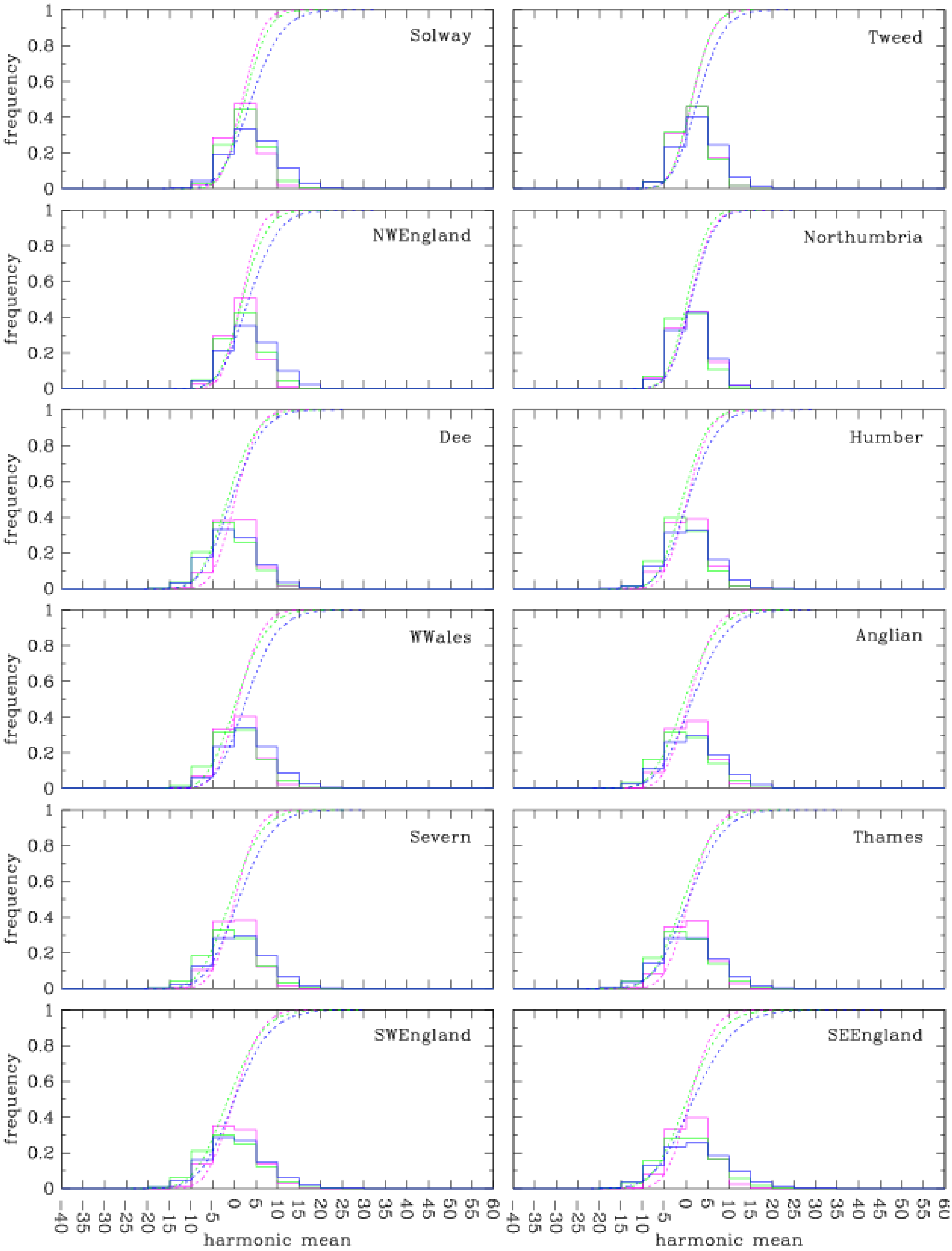


Figure A.1 Histograms and cdfs of the means of the harmonic functions fitted to the UKCP09 precipitation Sampled Data (A1B: 2020s – magenta, 2050s – green, 2080s – blue), for each of the 12 river-basin regions in England and Wales.

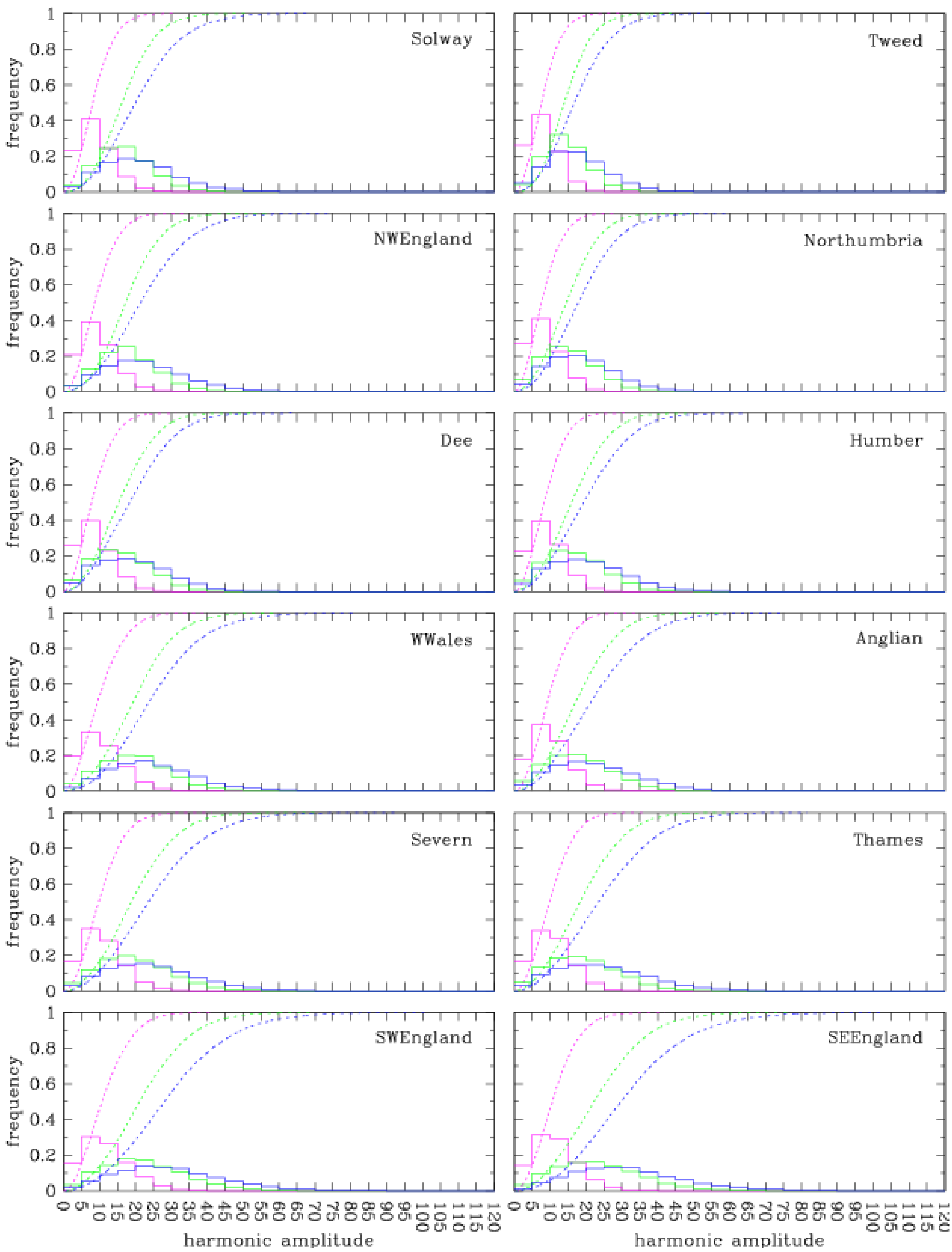


Figure A.2 Histograms and cdfs of the amplitudes of the harmonic functions fitted to the UKCP09 precipitation Sampled Data (A1B: 2020s – magenta, 2050s – green, 2080s – blue), for each of the 12 river-basin regions in England and Wales.

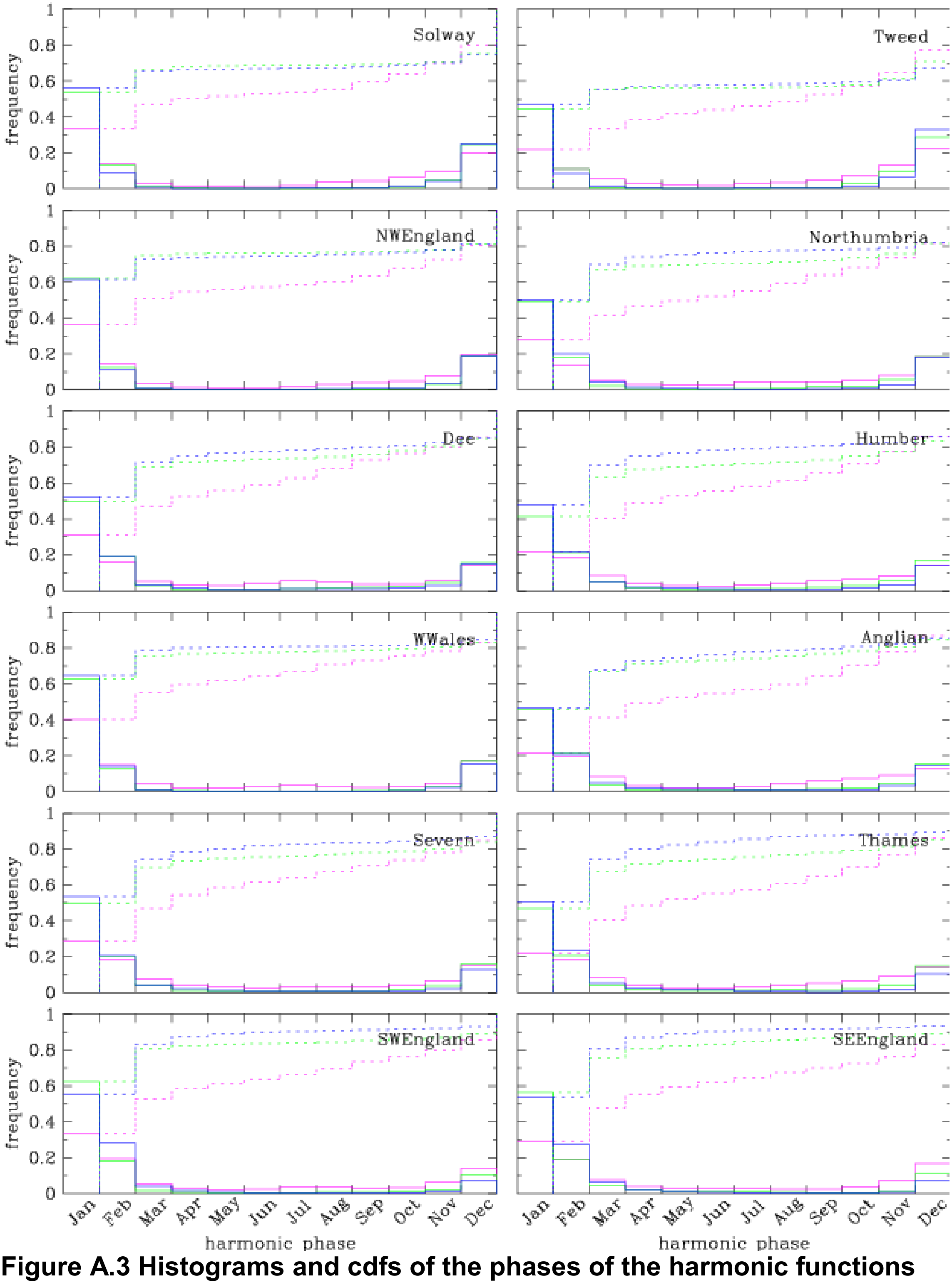


Figure A.3 Histograms and cdfs of the phases of the harmonic functions fitted to the UKCP09 precipitation Sampled Data (A1B: 2020s – magenta, 2050s – green, 2080s – blue), for each of the 12 river-basin regions in England and Wales.

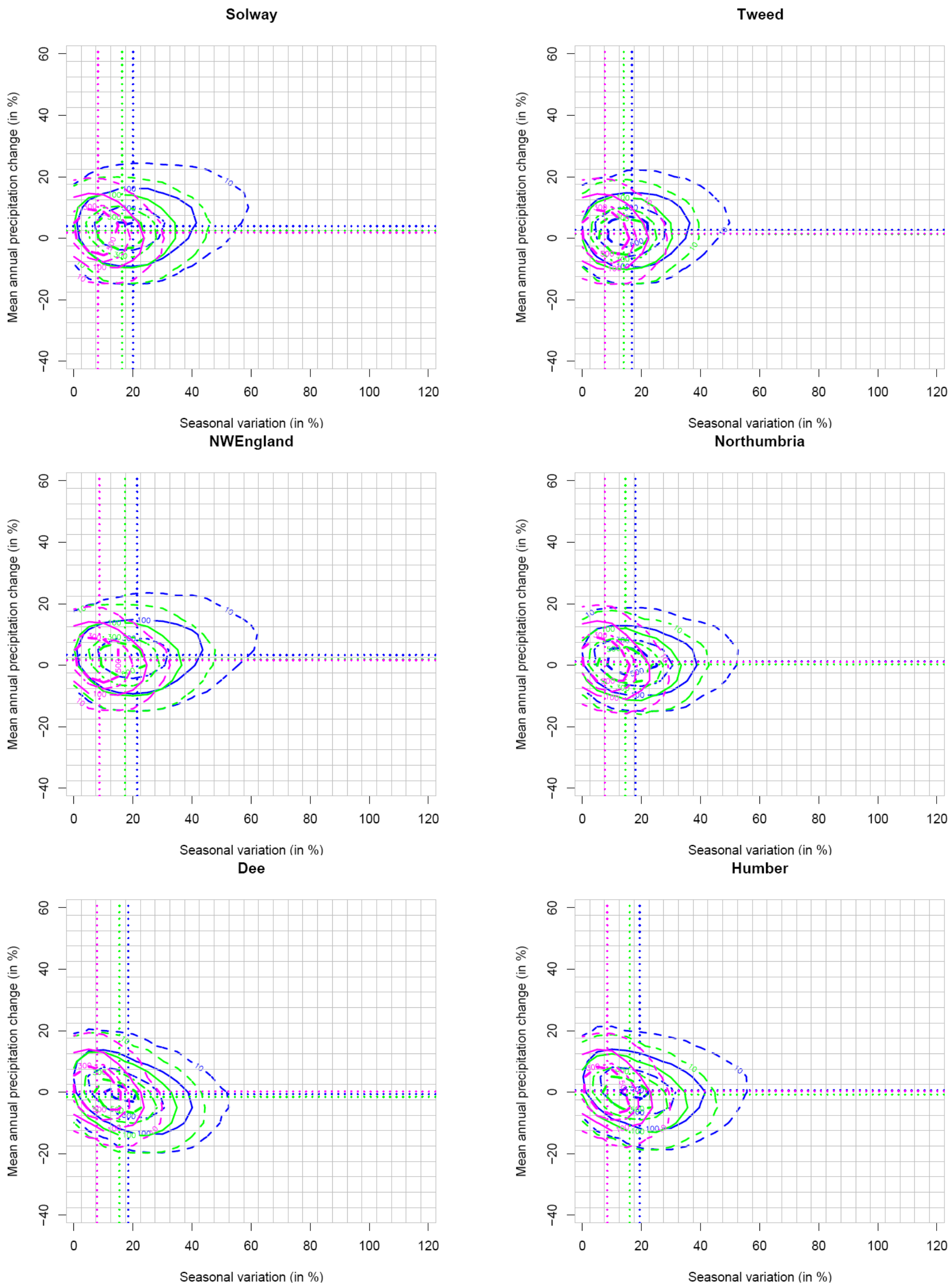


Figure A.4 Contours plots of the mean versus the amplitude of the harmonic functions fitted to the UKCP09 precipitation Sampled Data (A1B: 2020s – magenta, 2050s – green, 2080s – blue), for each of the 12 river-basin regions in England and Wales. The median of each harmonic parameter is shown by the dotted horizontal/vertical lines. Note that the grid on these plots is the same as that of the FD2020 sensitivity framework (Table 1.1) and thus of the response patterns and standard deviation patterns (Figure 1.3 and Figure 1.4). The contours mark densities of 10, 100, 300 and 500 scenarios per grid square, where required. Figure continued on next page.

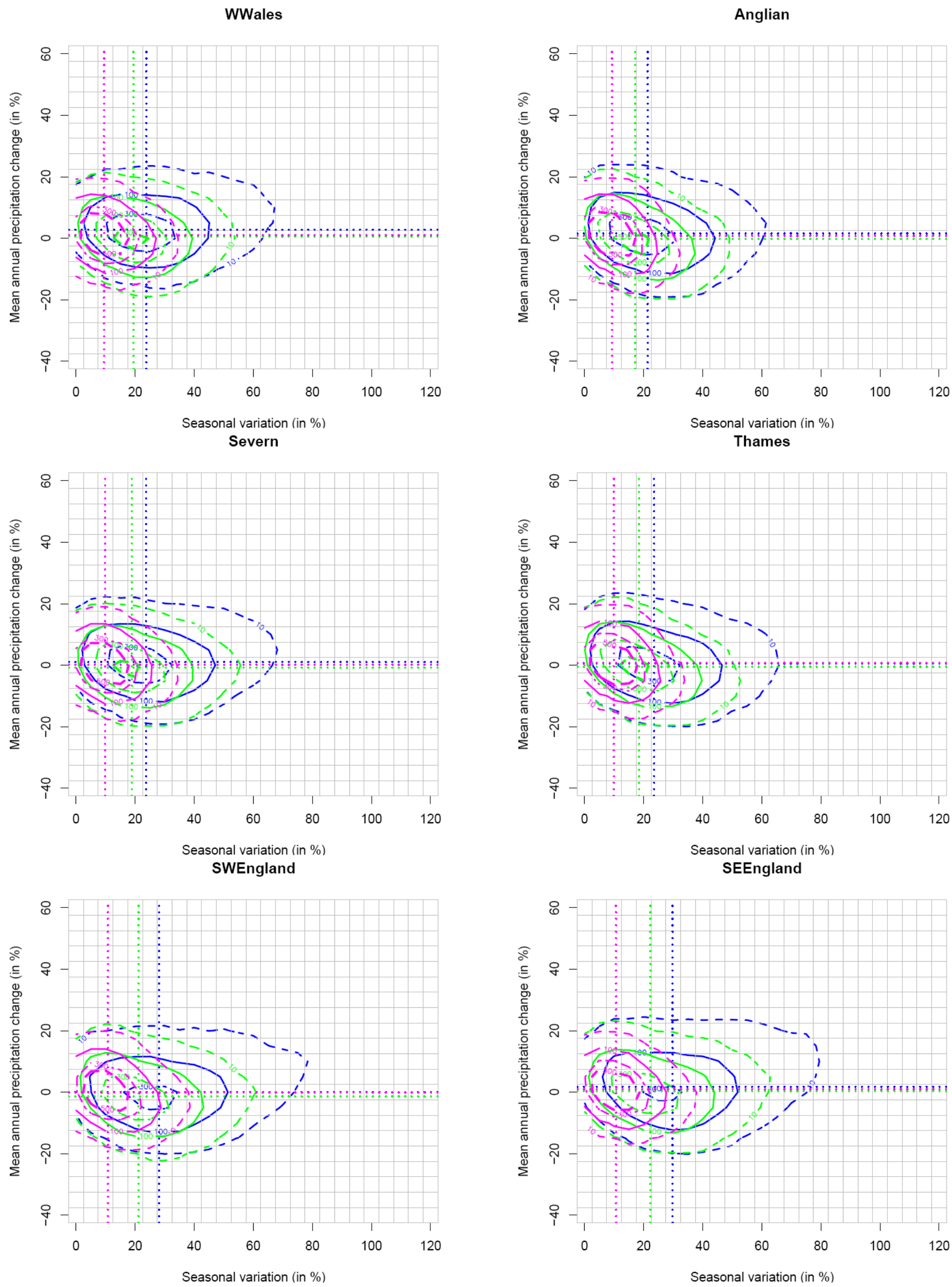


Figure A.4 continued.

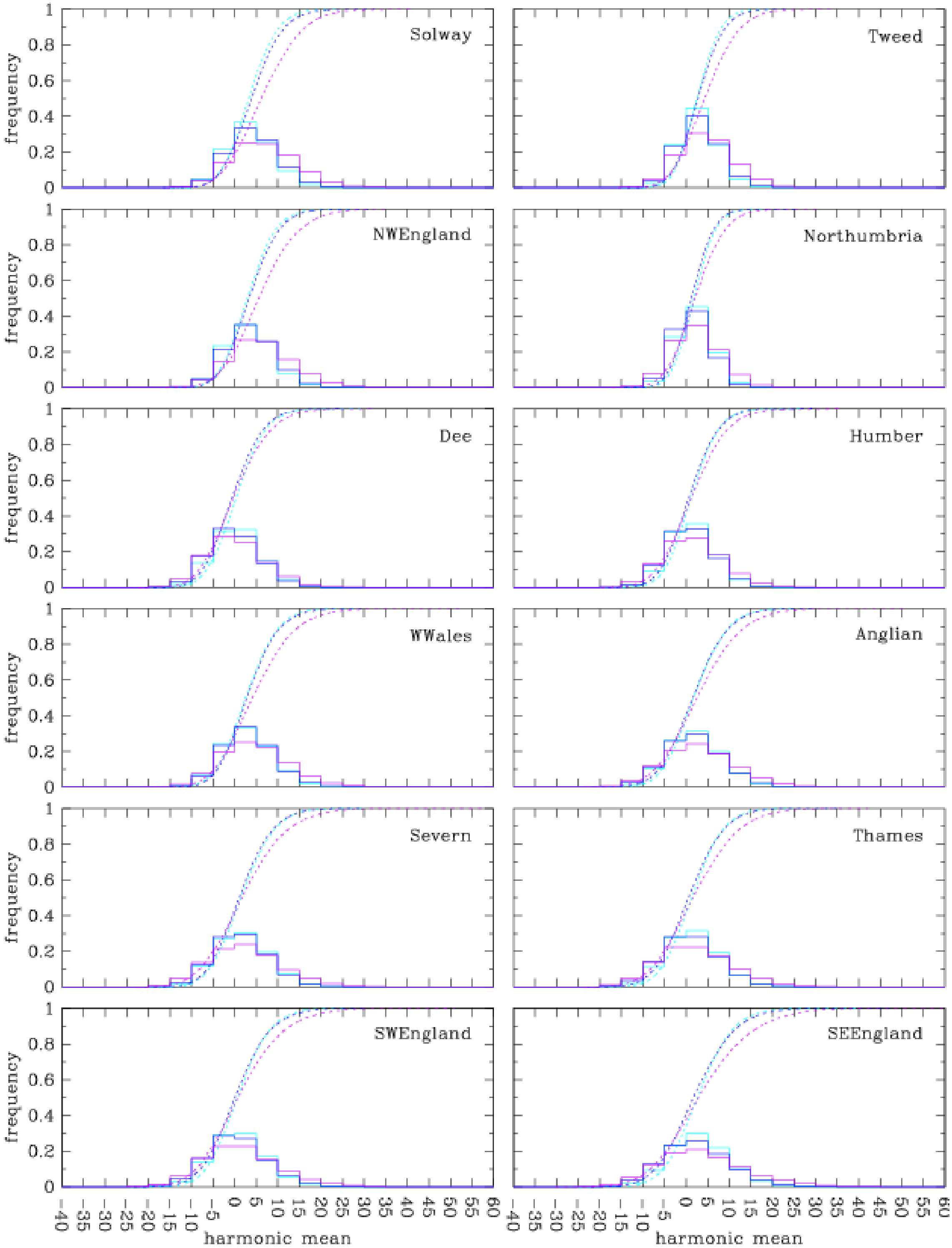


Figure A.5 Histograms and cdfs of the means of the harmonic functions fitted to the UKCP09 precipitation Sampled Data (2080s: B1 – cyan, A1B – blue, A1F1 – purple), for each of the 12 river-basin regions in England and Wales.

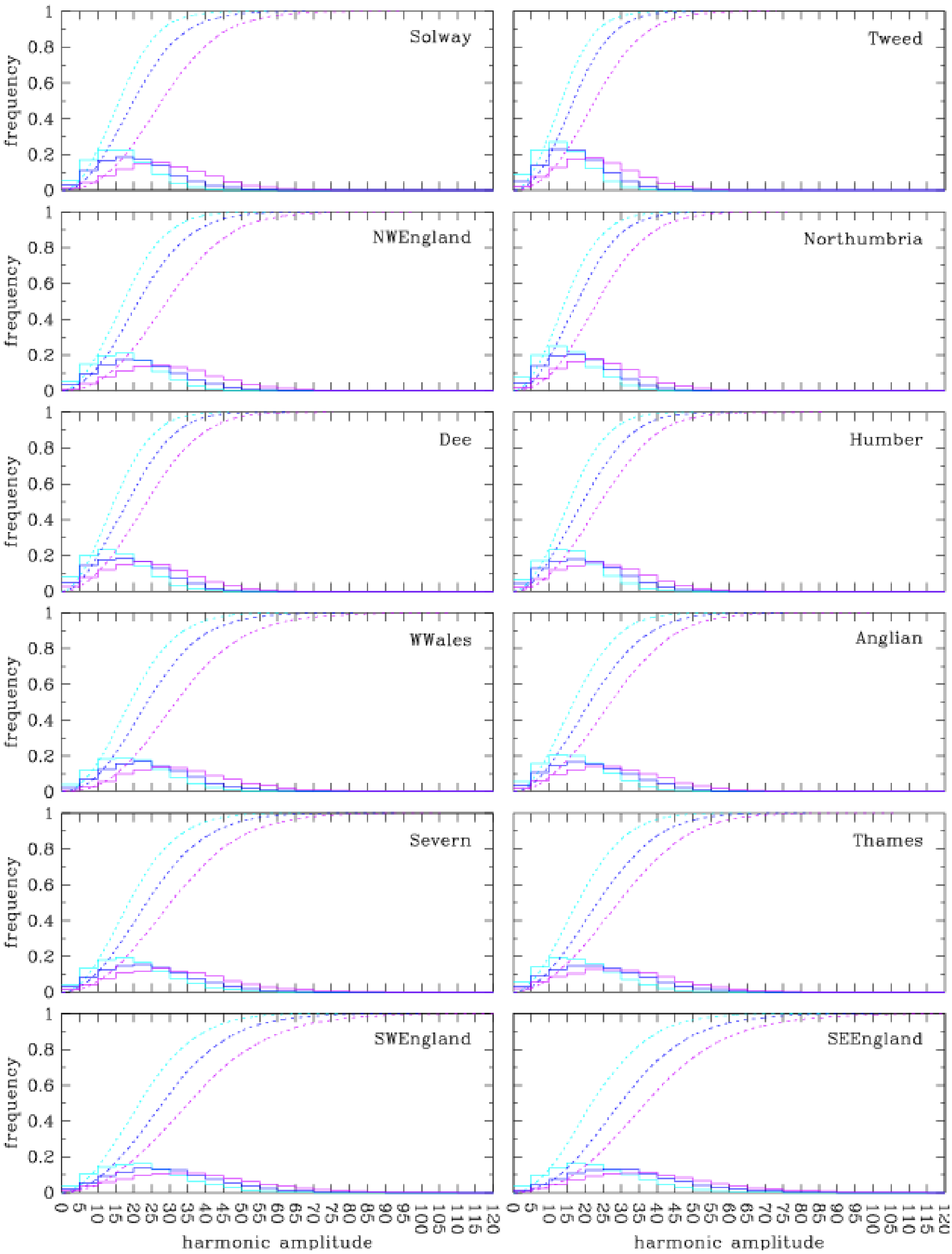


Figure A.6 Histograms and cdfs of the amplitudes of the harmonic functions fitted to the UKCP09 precipitation Sampled Data (2080s: B1 – cyan, A1B – blue, A1F1 – purple), for each of the 12 river-basin regions in England and Wales.

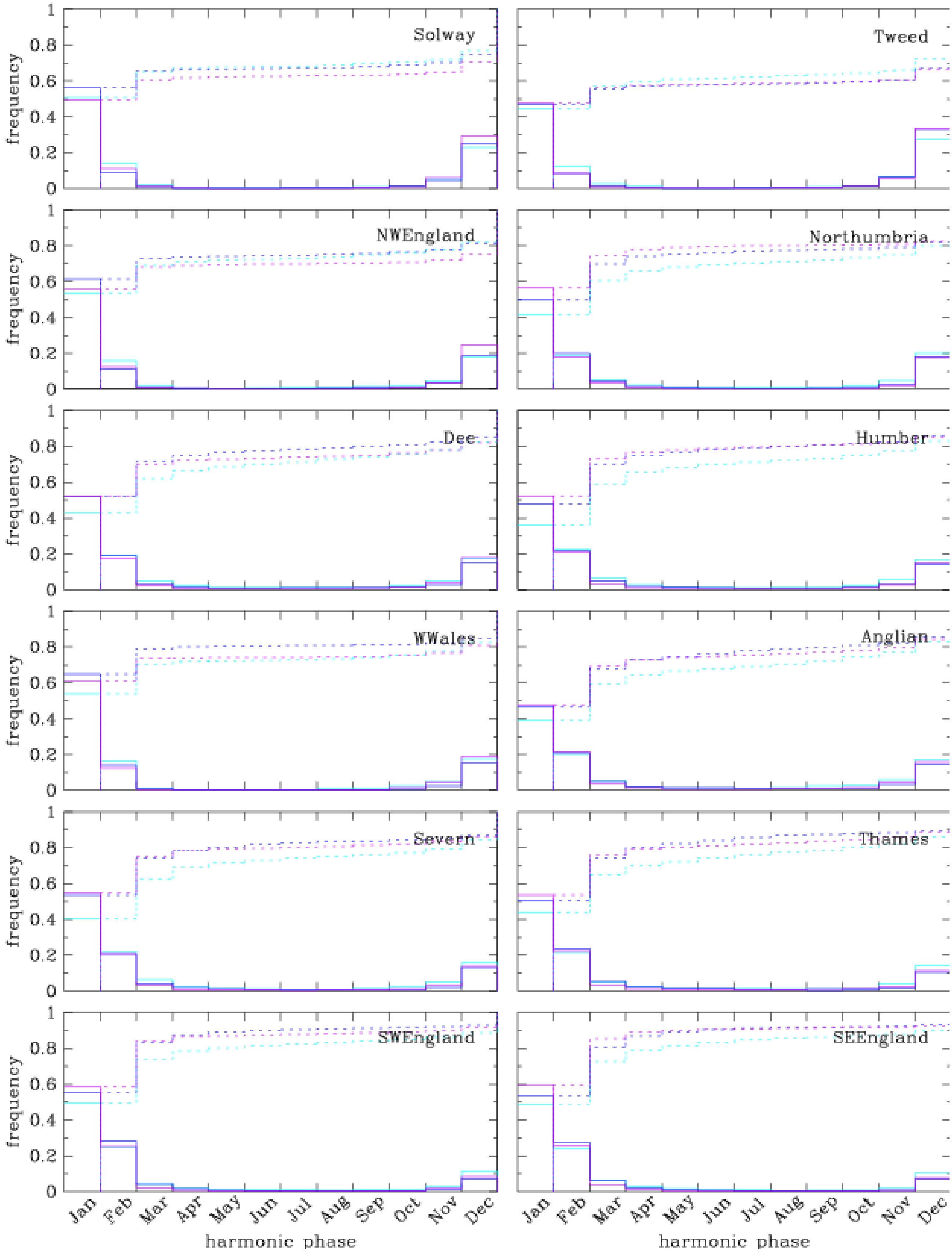


Figure A.7 Histograms and cdfs of the phases of the harmonic functions fitted to the UKCP09 precipitation Sampled Data (2080s: B1 – cyan, A1B – blue, A1F1 – purple), for each of the 12 river-basin regions in England and Wales.

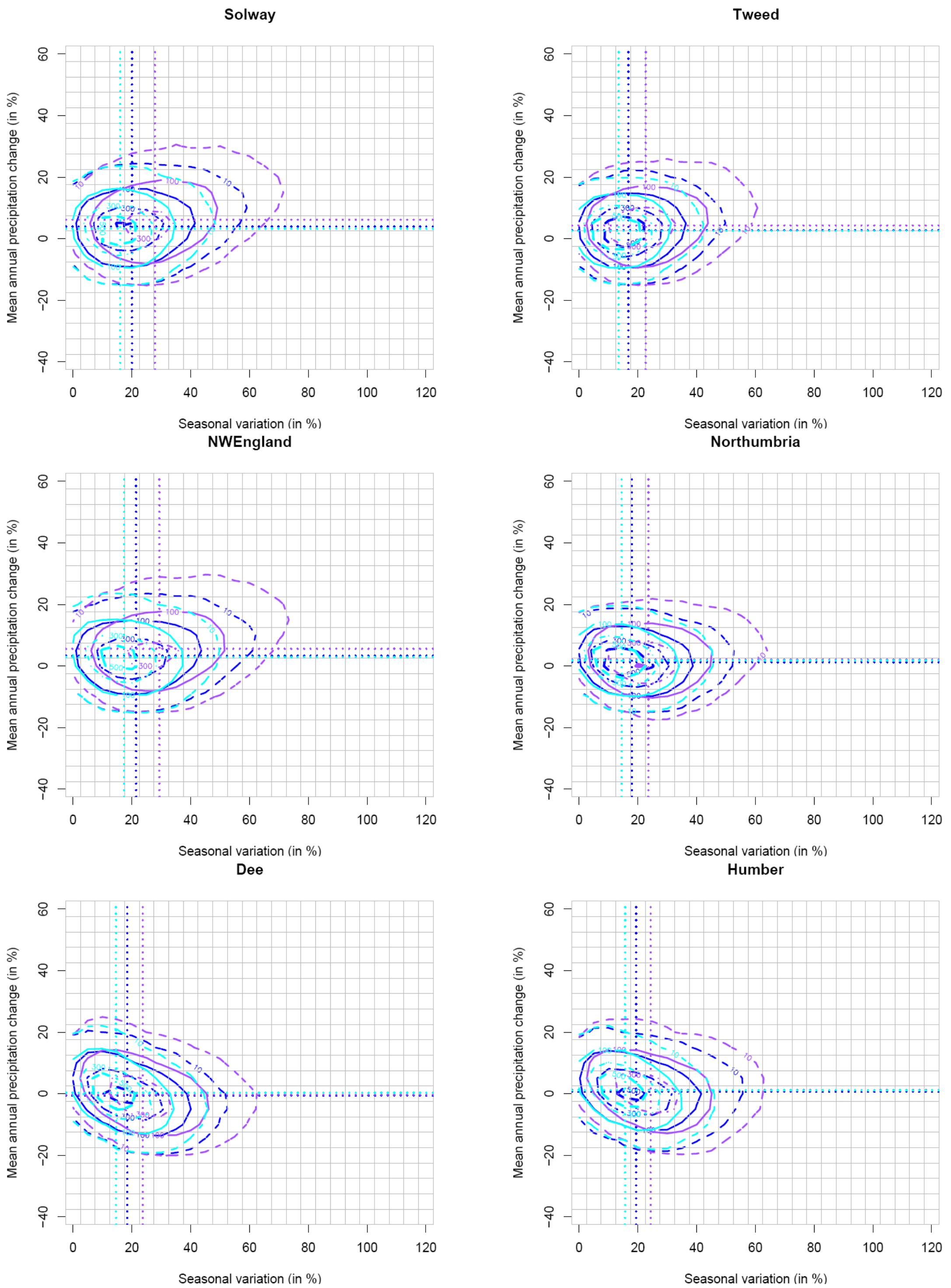


Figure A.8 Contours plots of the mean versus the amplitude of the harmonic functions fitted to the UKCP09 precipitation Sampled Data (2080s: B1 – cyan, A1B – blue, A1F1 – purple), for each of the 12 river-basin regions in England and Wales. The median of each harmonic parameter is shown by the dotted horizontal/vertical lines. Note that the grid on these plots is the same as that of the FD2020 sensitivity framework (Table 1.1) and thus of the response patterns and standard deviation patterns (Figure 1.3 and Figure 1.4). The contours mark densities of 10, 100, 300 and 500 scenarios per grid square, where required. Figure continued on next page.

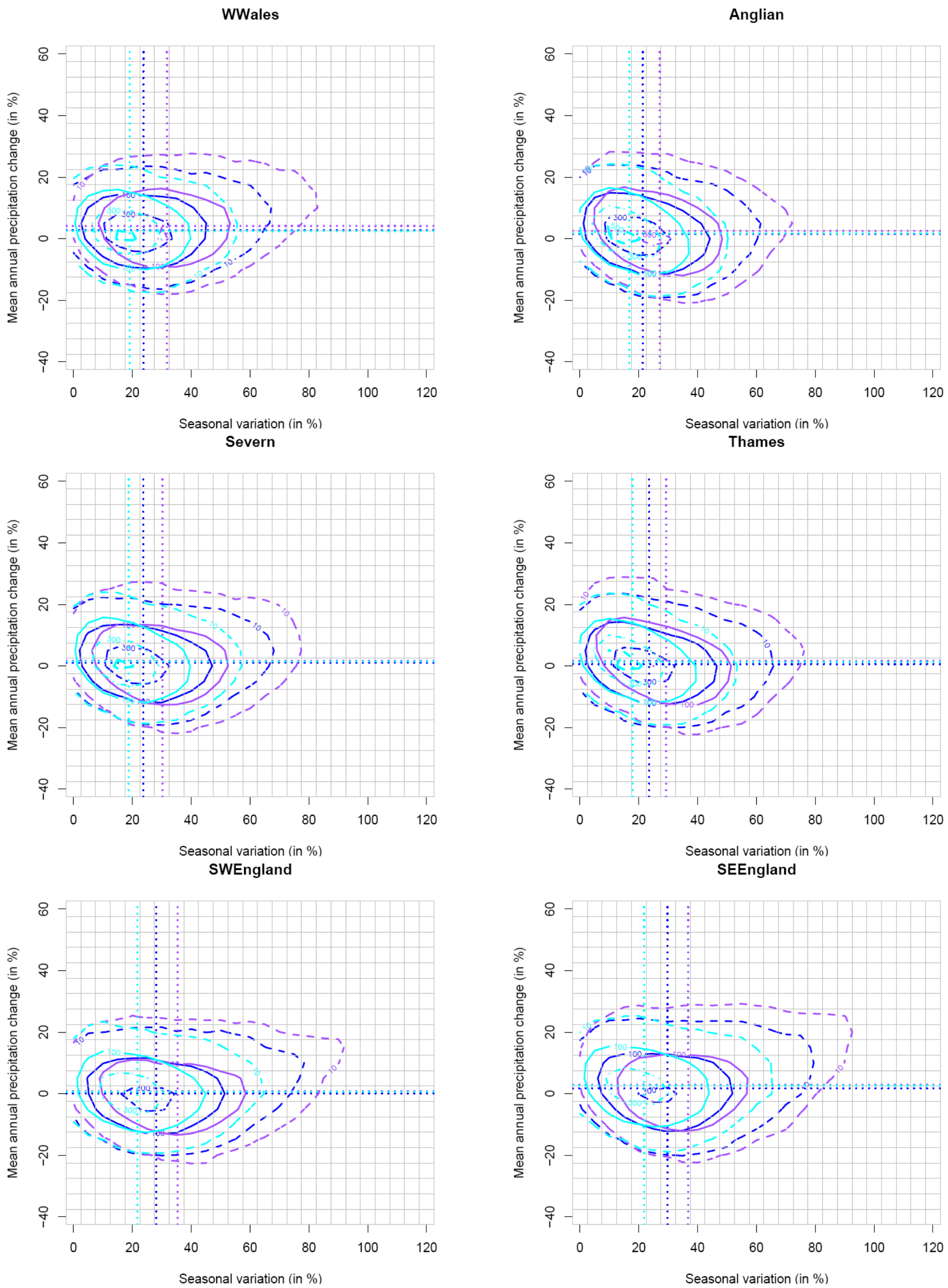
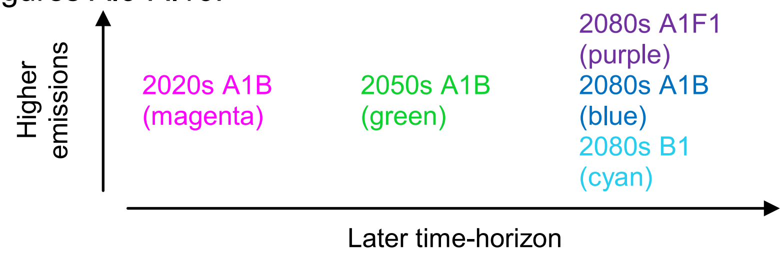


Figure A.8 continued.

A.2 Temperature changes

This section presents plots like in Section A.1, but summarising the changes in temperature derived from the UKCP09 projections for each of the 12 river-basin regions in England and Wales, for five time-horizon and emissions scenario combinations. In each case, the hazard is summarised in terms of the mean, amplitude and phase of the harmonic functions fitted to the sets of 10,000 monthly changes in temperature provided by the UKCP09 Sampled Data. The table below shows the colours used for each time-horizon / emissions scenario combination. Figures A.9-A.12 show the dependence on time-horizon, while Figures A.13-A.16 show the dependence on emissions.

Key for Figures A.9-A.16:



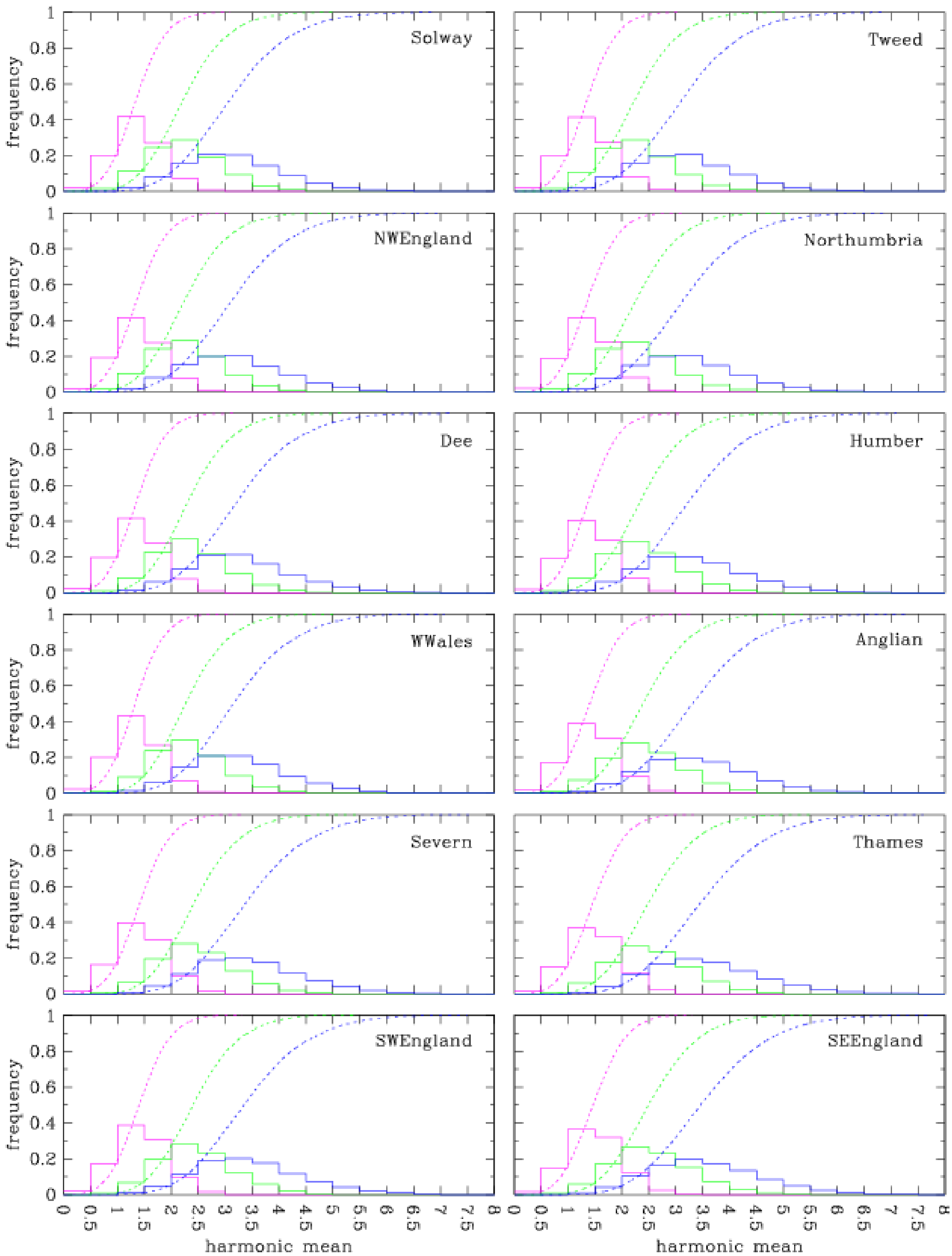


Figure A.9 Histograms and cdfs of the means of the harmonic functions fitted to the UKCP09 temperature Sampled Data (A1B: 2020s – magenta, 2050s – green, 2080s – blue), for each of the 12 river-basin regions in England and Wales.

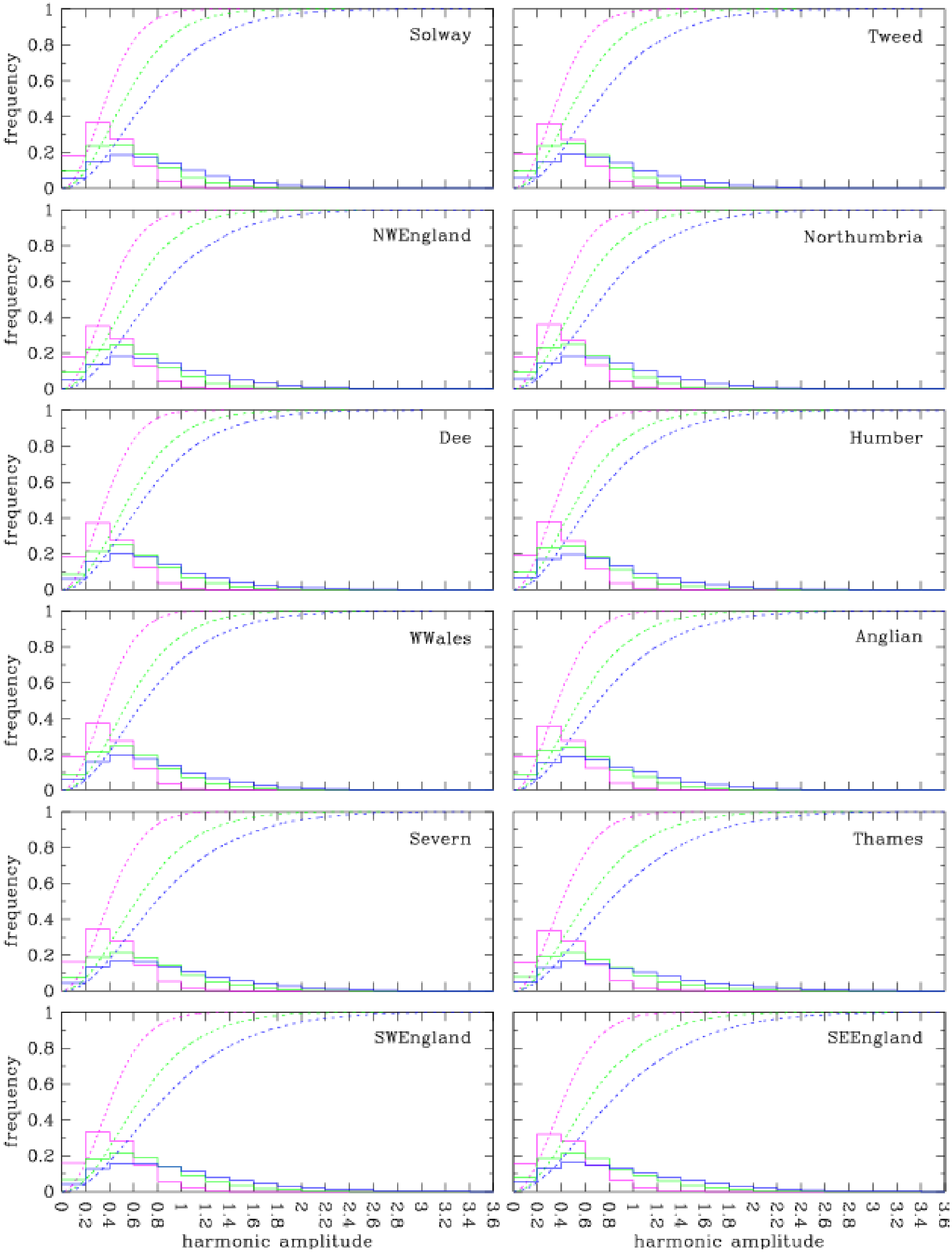


Figure A.10 Histograms and cdfs of the amplitudes of the harmonic functions fitted to the UKCP09 temperature Sampled Data (A1B: 2020s – magenta, 2050s – green, 2080s – blue), for each of the 12 river-basin regions in England and Wales.

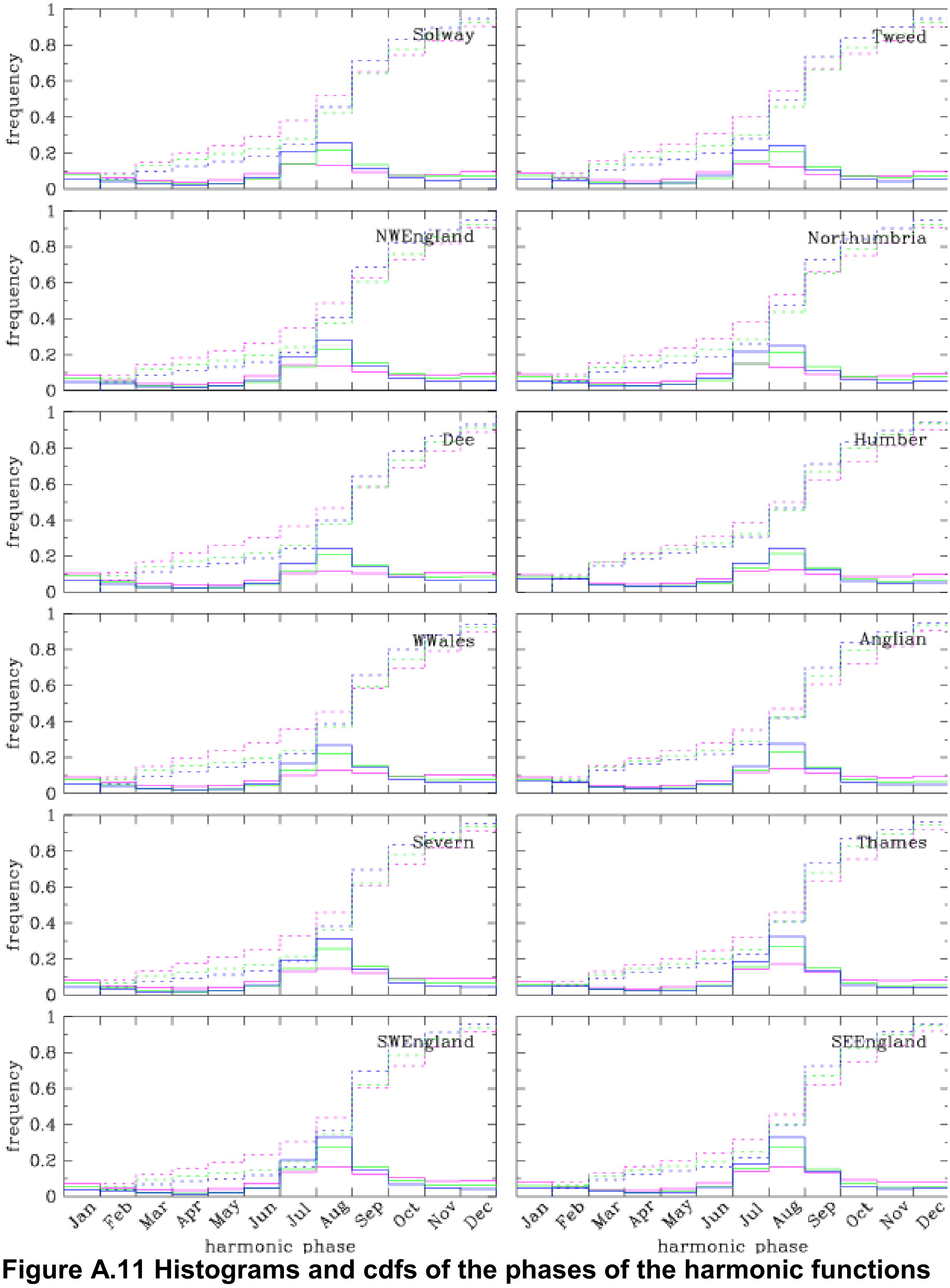


Figure A.11 Histograms and cdfs of the phases of the harmonic functions fitted to the UKCP09 temperature Sampled Data (A1B: 2020s – magenta, 2050s – green, 2080s – blue), for each of the 12 river-basin regions in England and Wales.

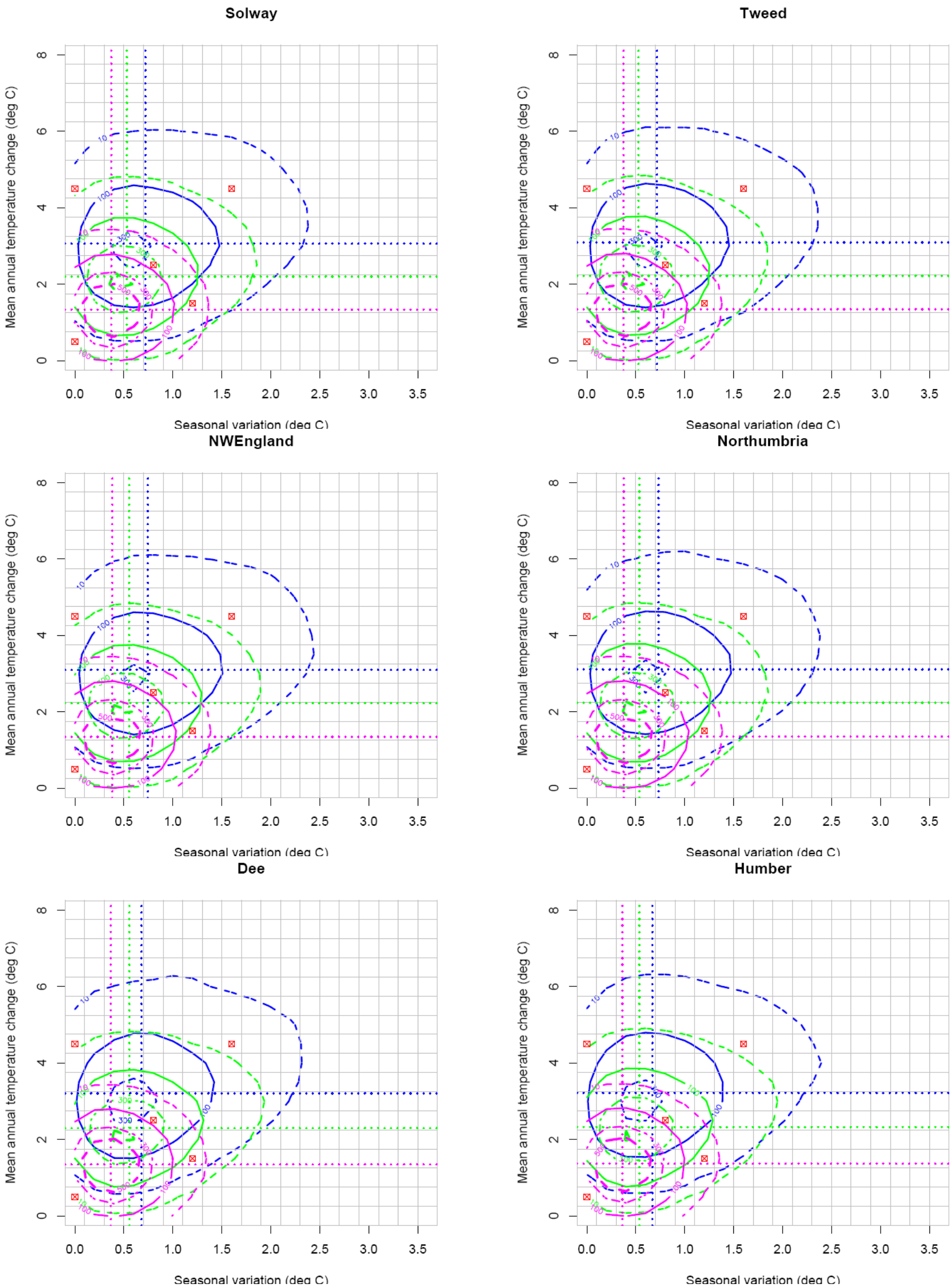


Figure A.12 Contours plots of the mean versus the amplitude of the harmonic functions fitted to the UKCP09 temperature Sampled Data (A1B: 2020s – magenta, 2050s – green, 2080s – blue), for each of the 12 river-basin regions in England and Wales. The median of each harmonic parameter is shown by the dotted horizontal/vertical lines. The temperature scenarios of the FD2020 sensitivity framework (Table 1.1) are shown by the red boxes. The contours mark densities of 10, 100, 300 and 500 scenarios per grid square, where required. Figure continued on next page.

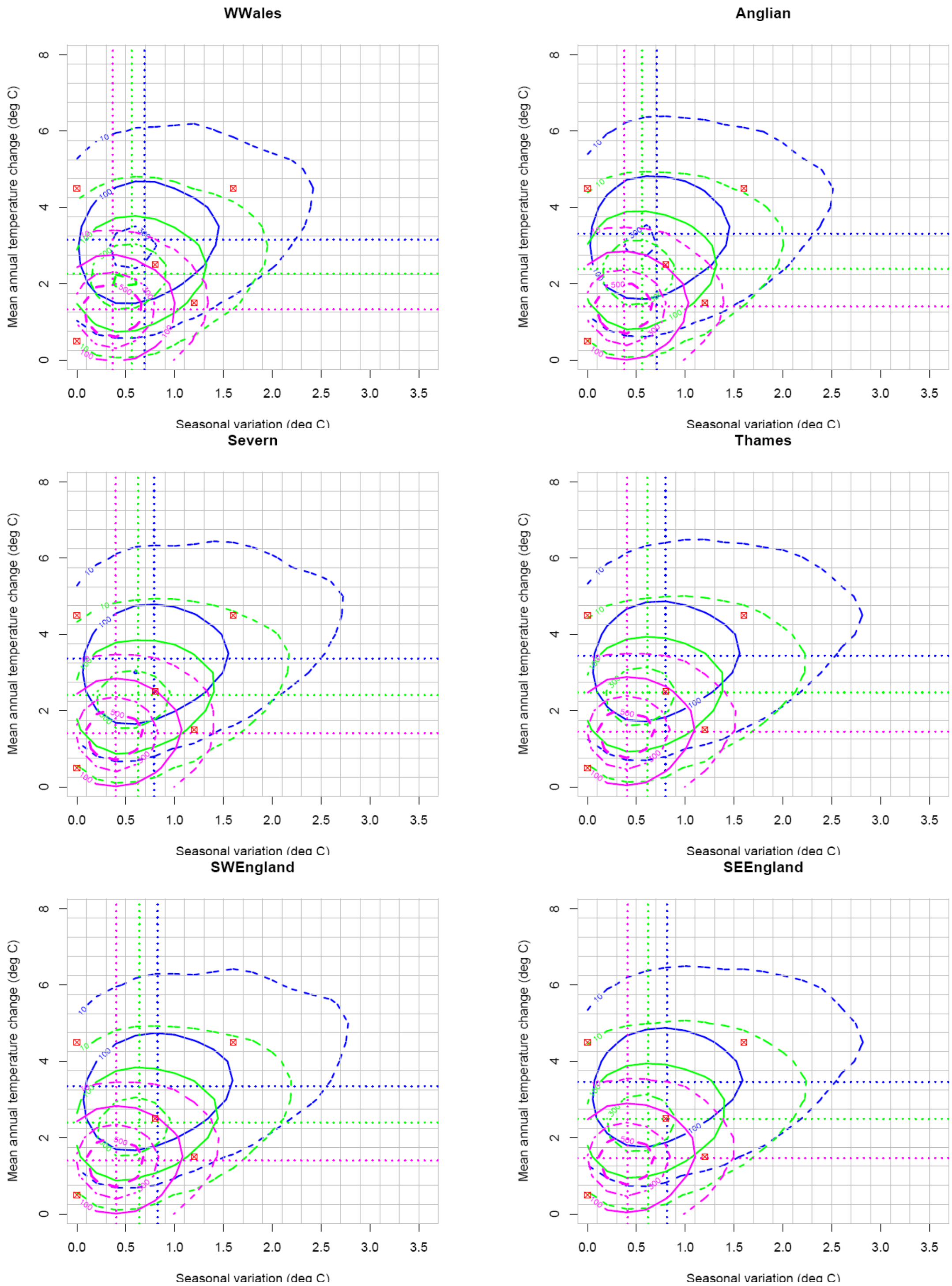


Figure A.13 continued.

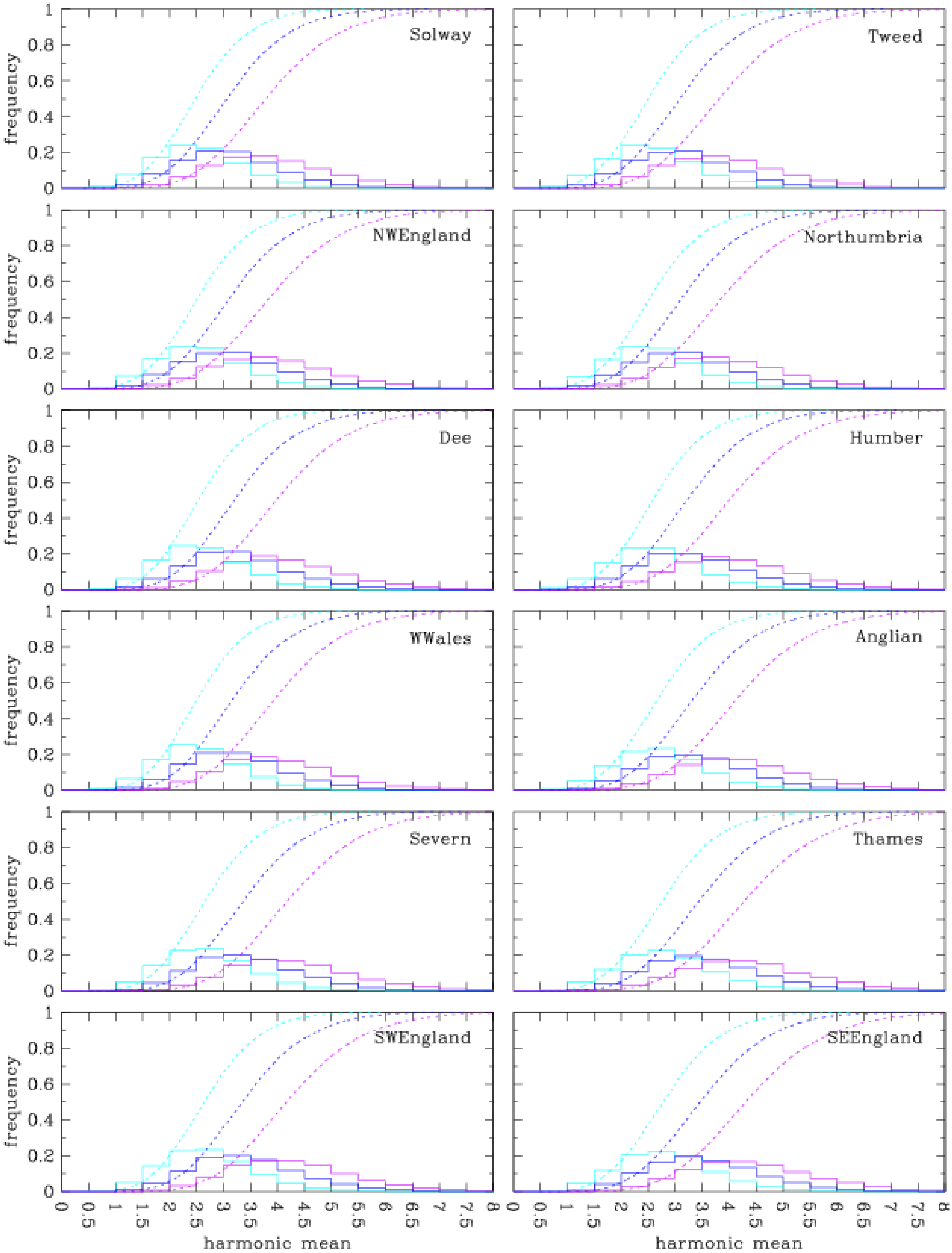


Figure A.13 Histograms and cdfs of the means of the harmonic functions fitted to the UKCP09 temperature Sampled Data (2080s: B1 – cyan, A1B – blue, A1F1 – purple), for each of the 12 river-basin regions in England and Wales.

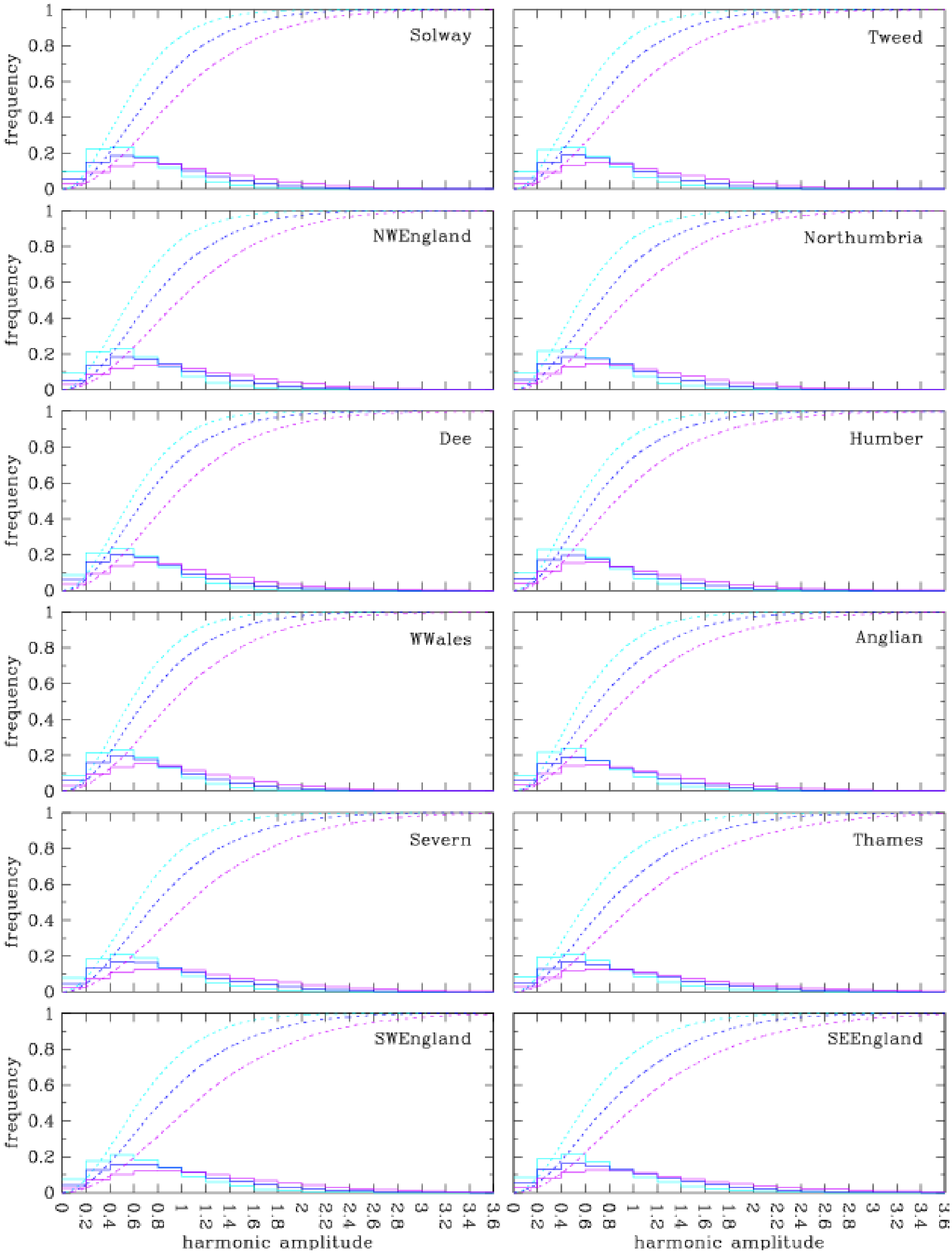


Figure A.14 Histograms and cdfs of the amplitudes of the harmonic functions fitted to the UKCP09 temperature Sampled Data (2080s: B1 – cyan, A1B – blue, A1F1 – purple), for each of the 12 river-basin regions in England and Wales.

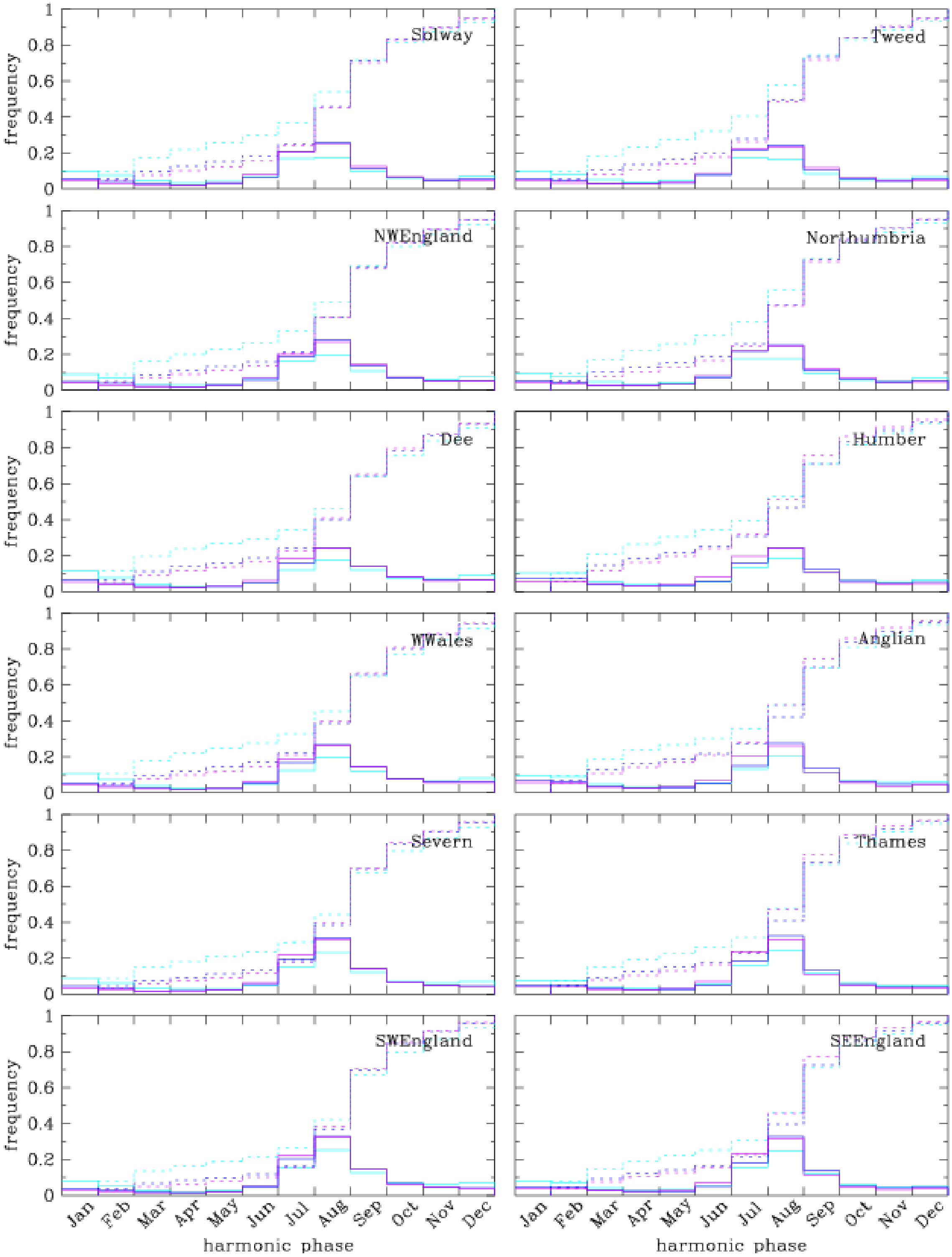


Figure A.15 Histograms and cdfs of the phases of the harmonic functions fitted to the UKCP09 temperature Sampled Data (2080s: B1 – cyan, A1B – blue, A1F1 – purple), for each of the 12 river-basin regions in England and Wales.

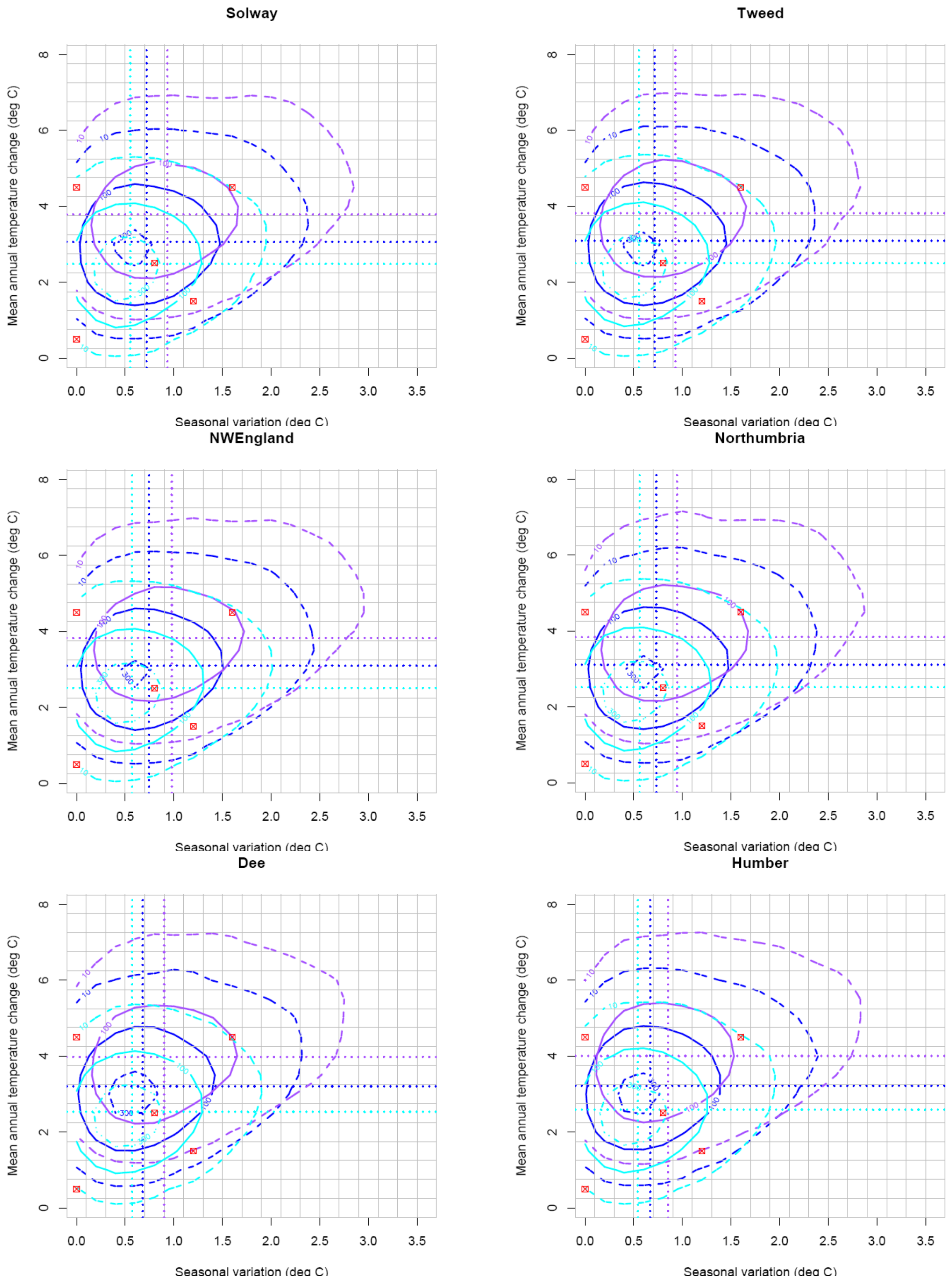


Figure A.16 Contours plots of the mean versus the amplitude of the harmonic functions fitted to the UKCP09 temperature Sampled Data (2080s: B1 – cyan, A1B – blue, A1F1 – purple), for each of the 12 river-basin regions in England and Wales. The median of each harmonic parameter is shown by the dotted horizontal/vertical lines. The temperature scenarios of the FD2020 sensitivity framework (Table 1.1) are shown by the red boxes. The contours mark densities of 10, 100, 300 and 500 scenarios per grid square, where required. Figure continued on next page.

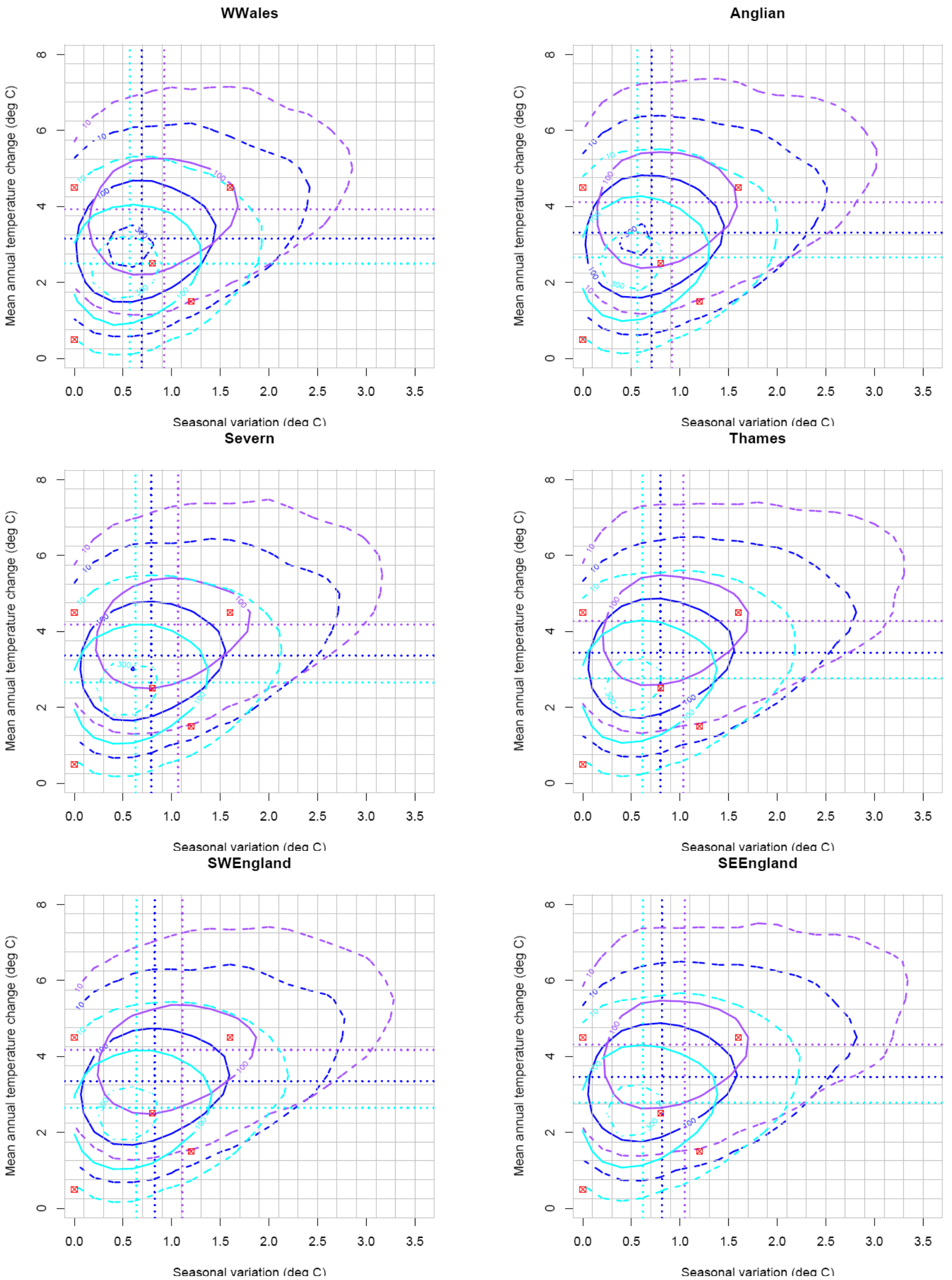


Figure A.16 continued.

Appendix B: Risk for alternative time-horizons and emissions scenarios

B.1 Alternative response-type risk and regional risk curves by region

This section presents plots summarising the response-type and regional risk for each of the 12 river-basin regions in England and Wales, for four time-horizon and emissions scenario combinations:

- 2020s time-horizon under A1B (Medium) emissions (Figures B.1-B.12),
- 2050s time-horizon under A1B (Medium) emissions (Figures B.13-B.24),
- 2080s time-horizon under B1 (Low) emissions (Figures B.25-B.36),
- 2080s time-horizon under A1F1 (High) emissions (Figures B.37-B.48).

Equivalent plots for the 2080s time-horizon under A1B (Medium) emissions are presented in the main body of the report (Section 3).

Response-type risk:
At specific values of the allowance (every 5% between 0% and 60%), the central-estimate of each response-type risk (estimated using the key response patterns) is indicated by plus signs, coloured according to response type as in the table below. The uncertainty bands (estimated using standard deviation, sd, patterns) are given by vertical lines (±1sd – solid, ±2sd – dotted), also coloured by response type.

Key for response-type risk in Figures B.1-B.48:

Response type	Colour
Damped-High	red
Damped-Low	orange
Neutral	green
Mixed	gold
Enhanced-Low	cyan
Enhanced-Medium	blue
Enhanced-High	purple
Sensitive	magenta

Regional risk:
The central-estimate of the regional risk is plotted as a continuous curve, as are uncertainty bands (±1sd and ±2sd). See table below.

Key for regional risk curves in Figures B.1-B.48:

Central-estimate	Black solid
±1sd	Black dotted
±2sd	Black dashed

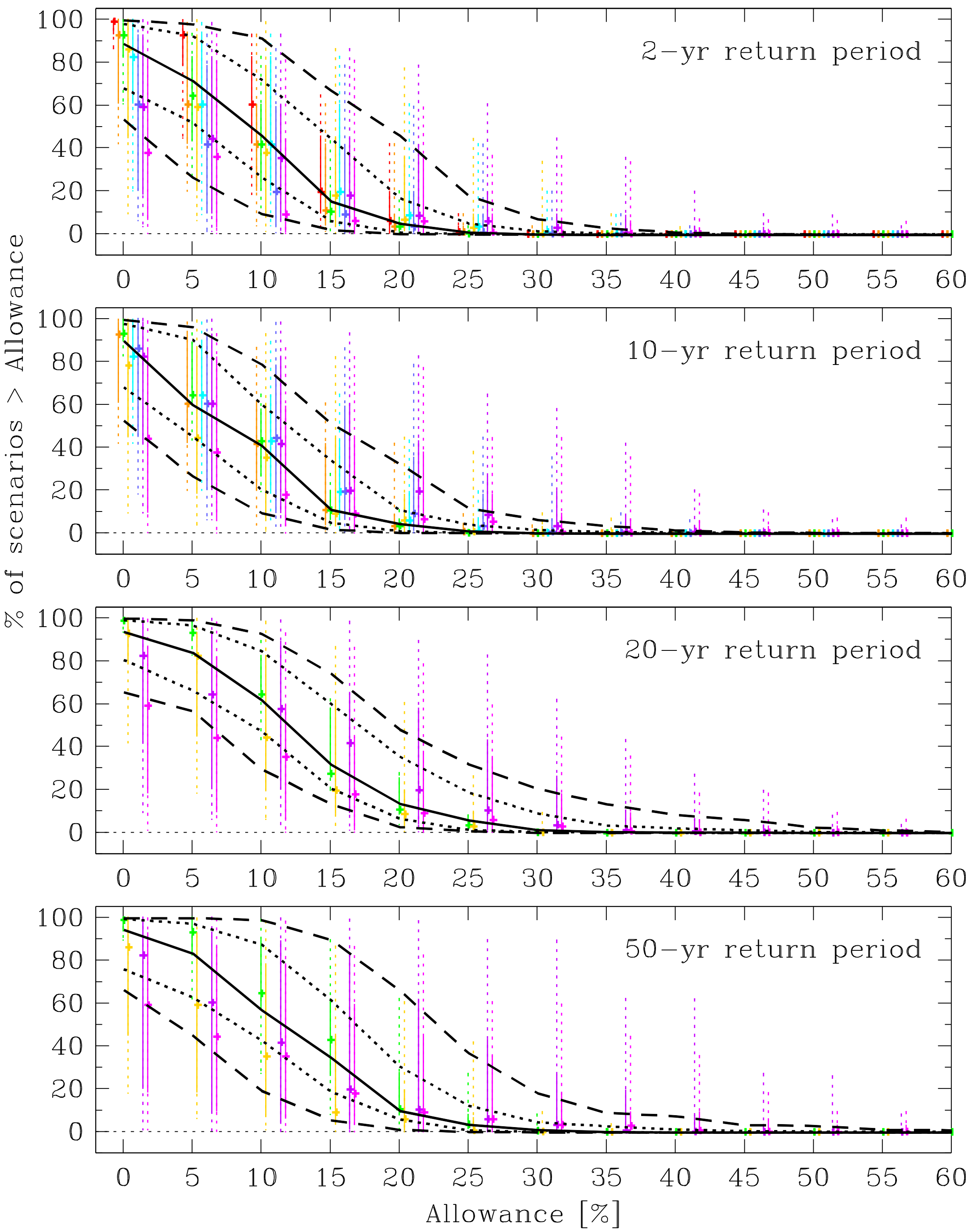


Figure B.6.1 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2020s A1B) for the Northumbria river-basin region. Response-type risk (colours): Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta); 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).

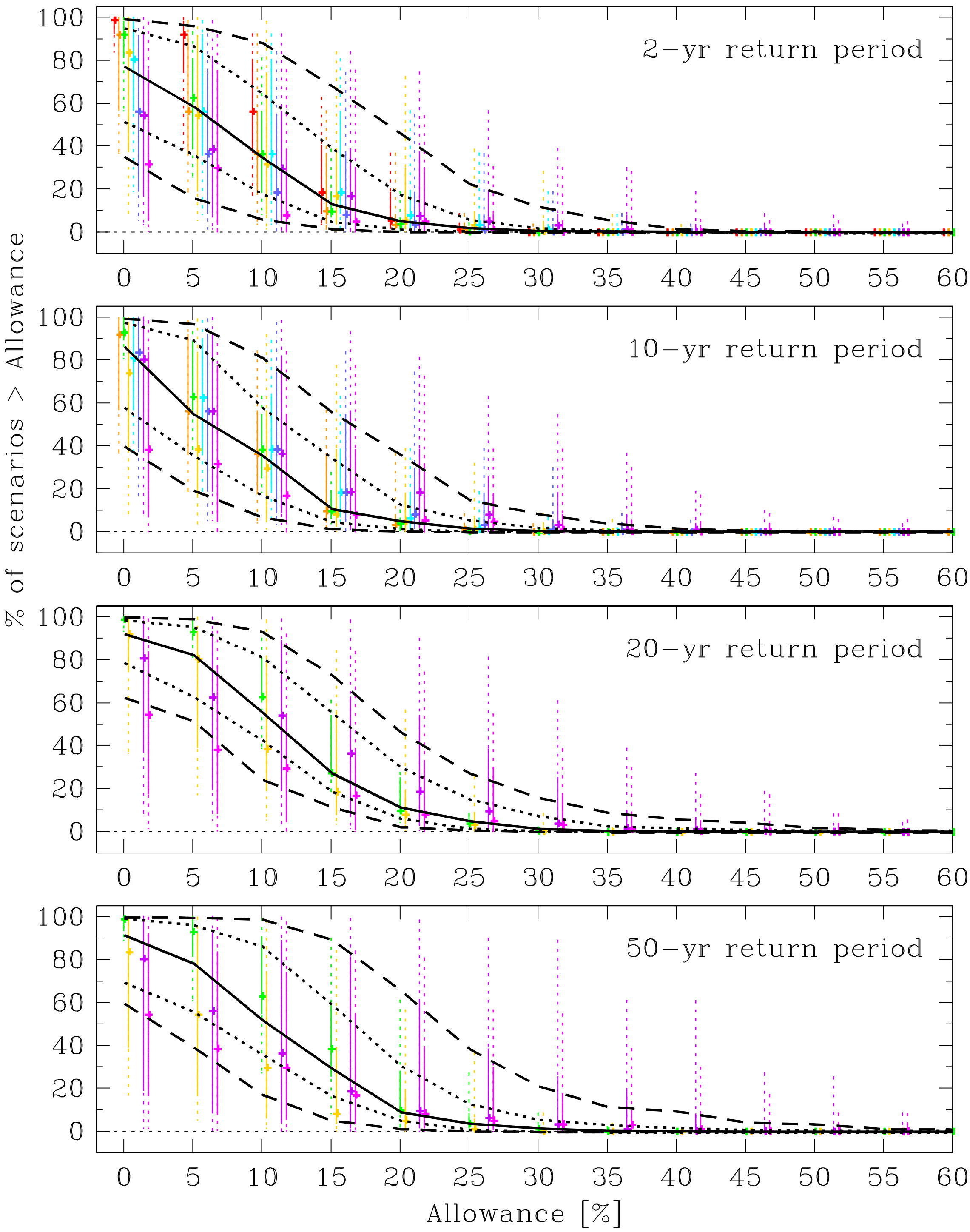


Figure B.6.2 As Figure B.1 but for the Humber river-basin region (2020s A1B).

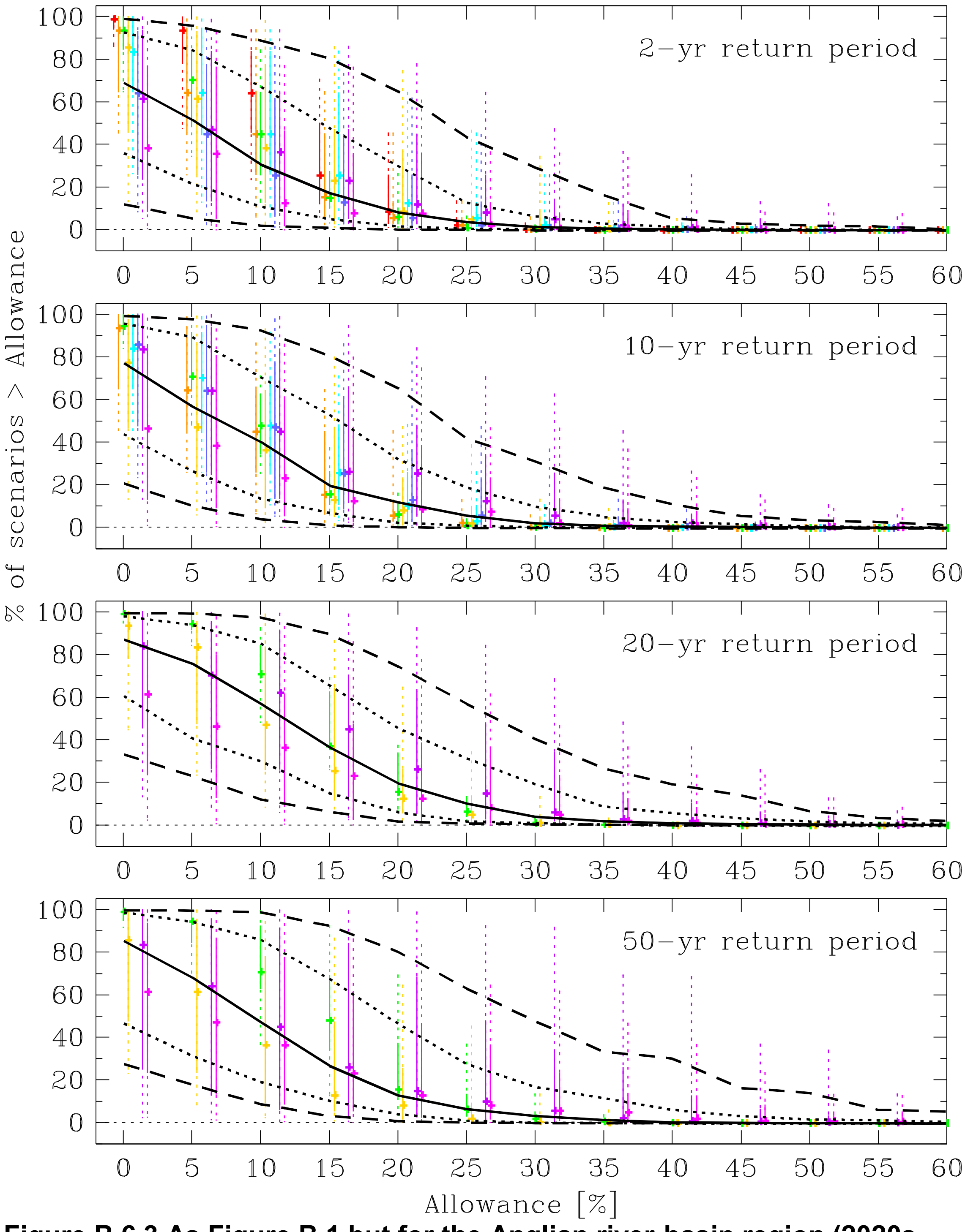


Figure B.6.3 As Figure B.1 but for the Anglian river-basin region (2020s A1B).

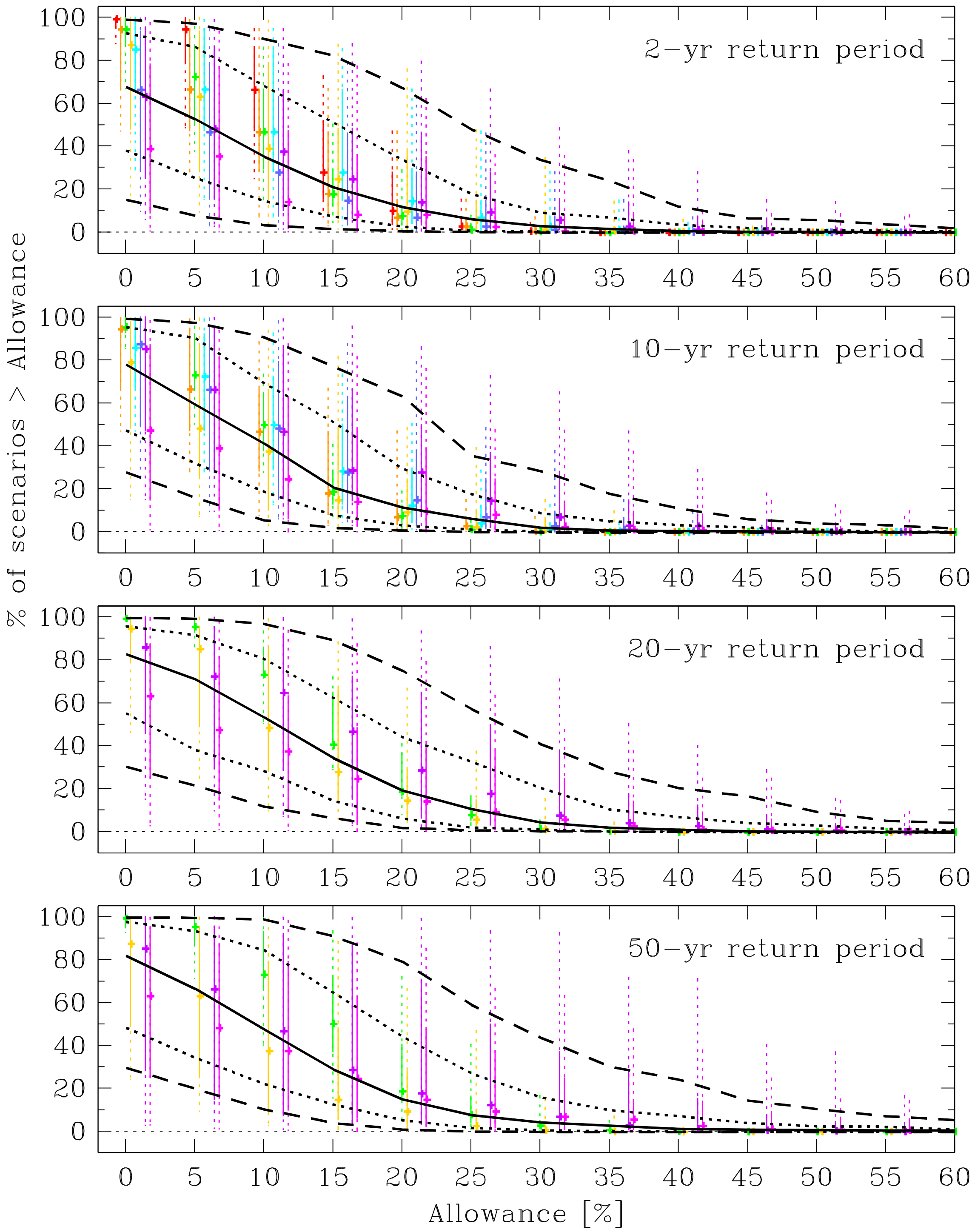


Figure B.6.4 As Figure B.1 but for the Thames river-basin region (2020s A1B).

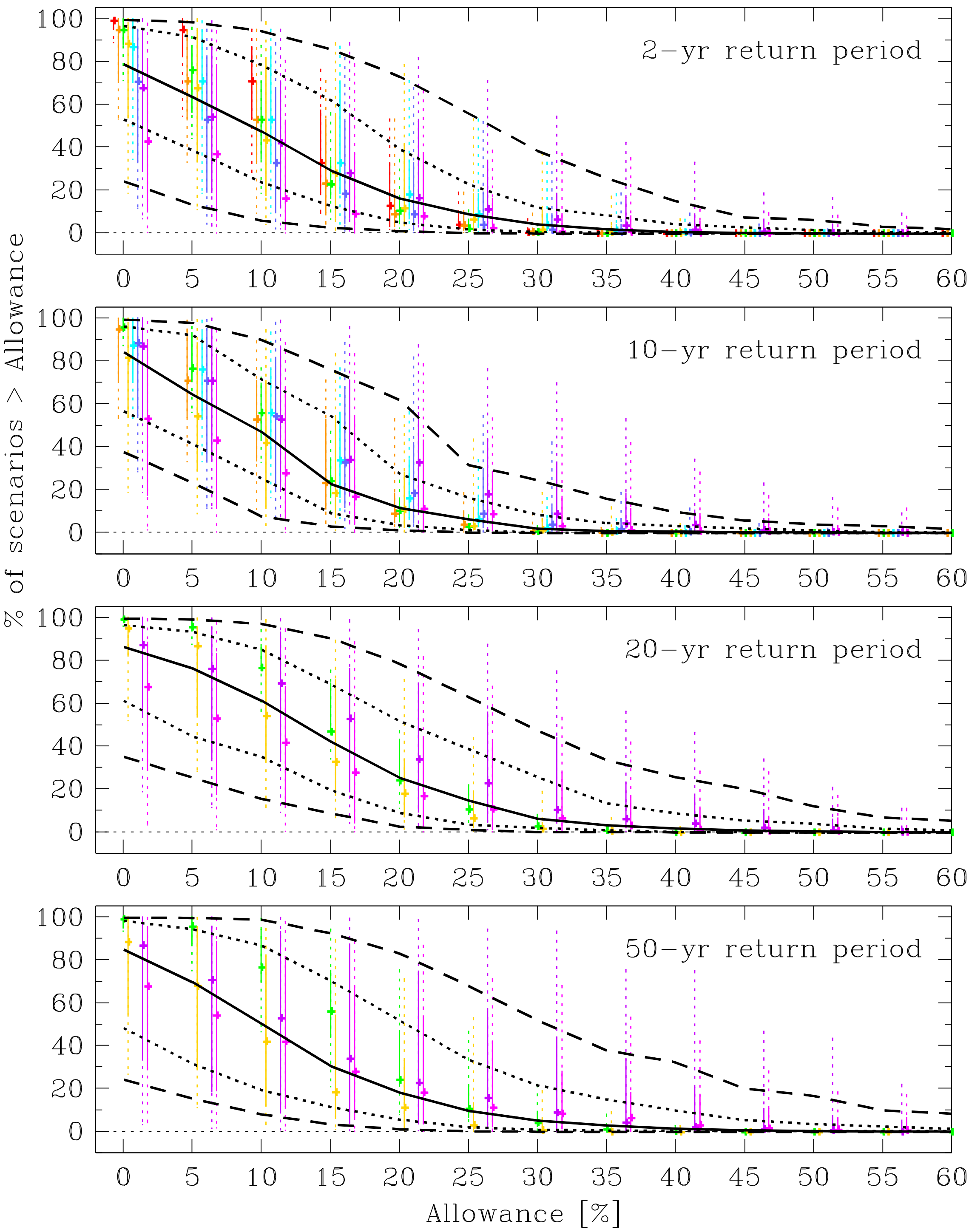


Figure B.6.5 As Figure B.1 but for the South-East England river-basin region (2020s A1B).

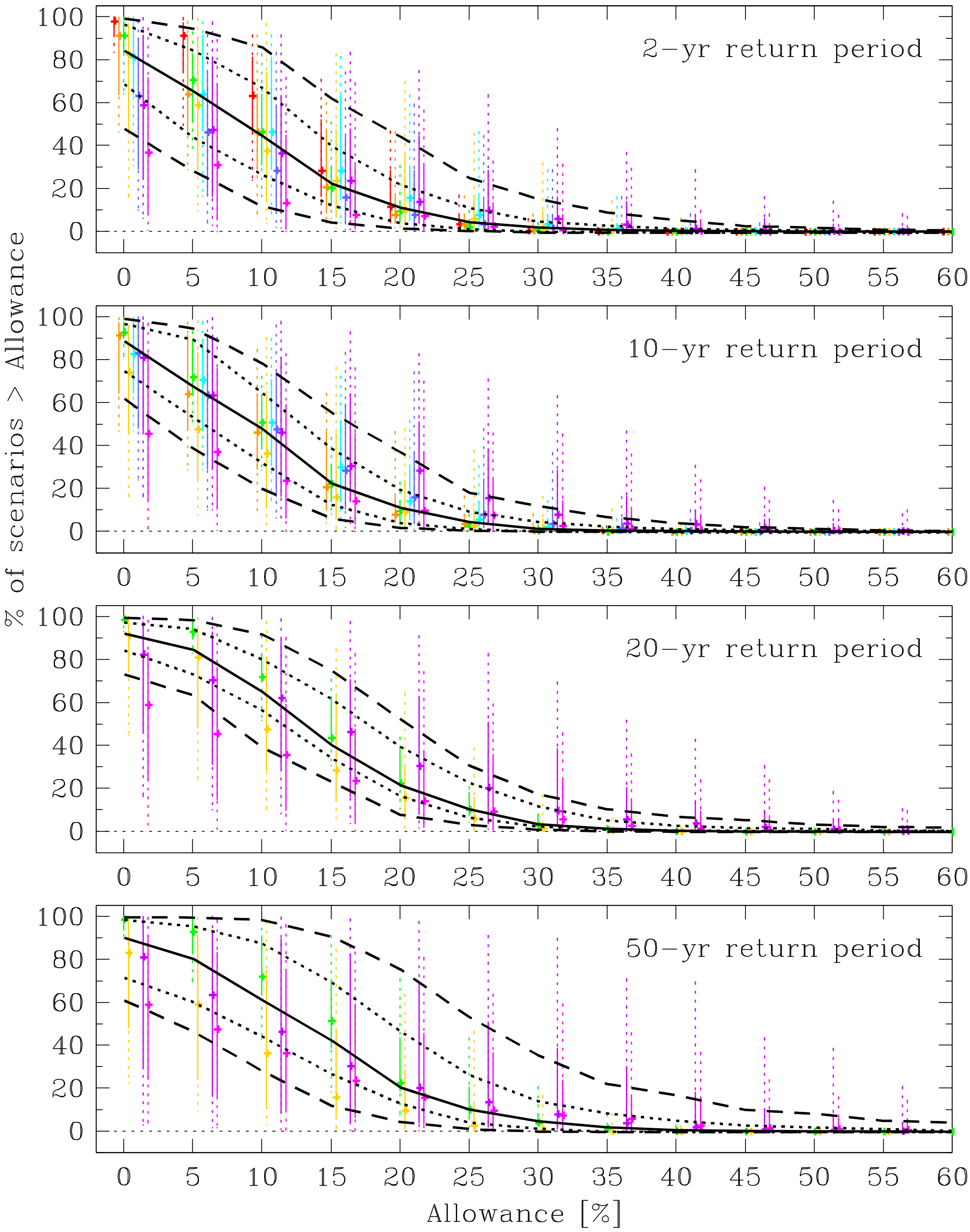


Figure B.6.6 As Figure B.1 but for the South-West England river-basin region (2020s A1B).

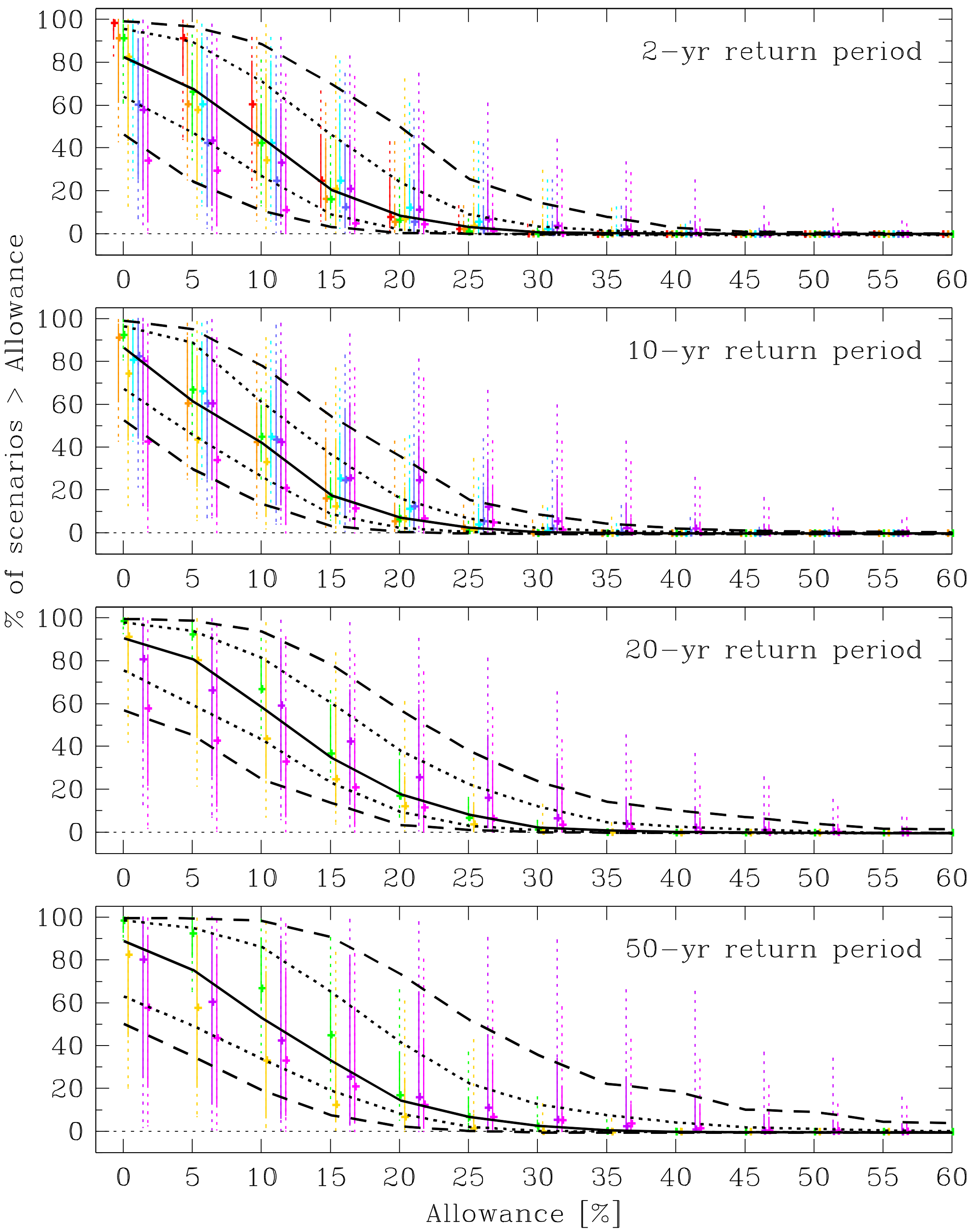


Figure B.6.7 As Figure B.1 but for the Severn England river-basin region (2020s A1B).

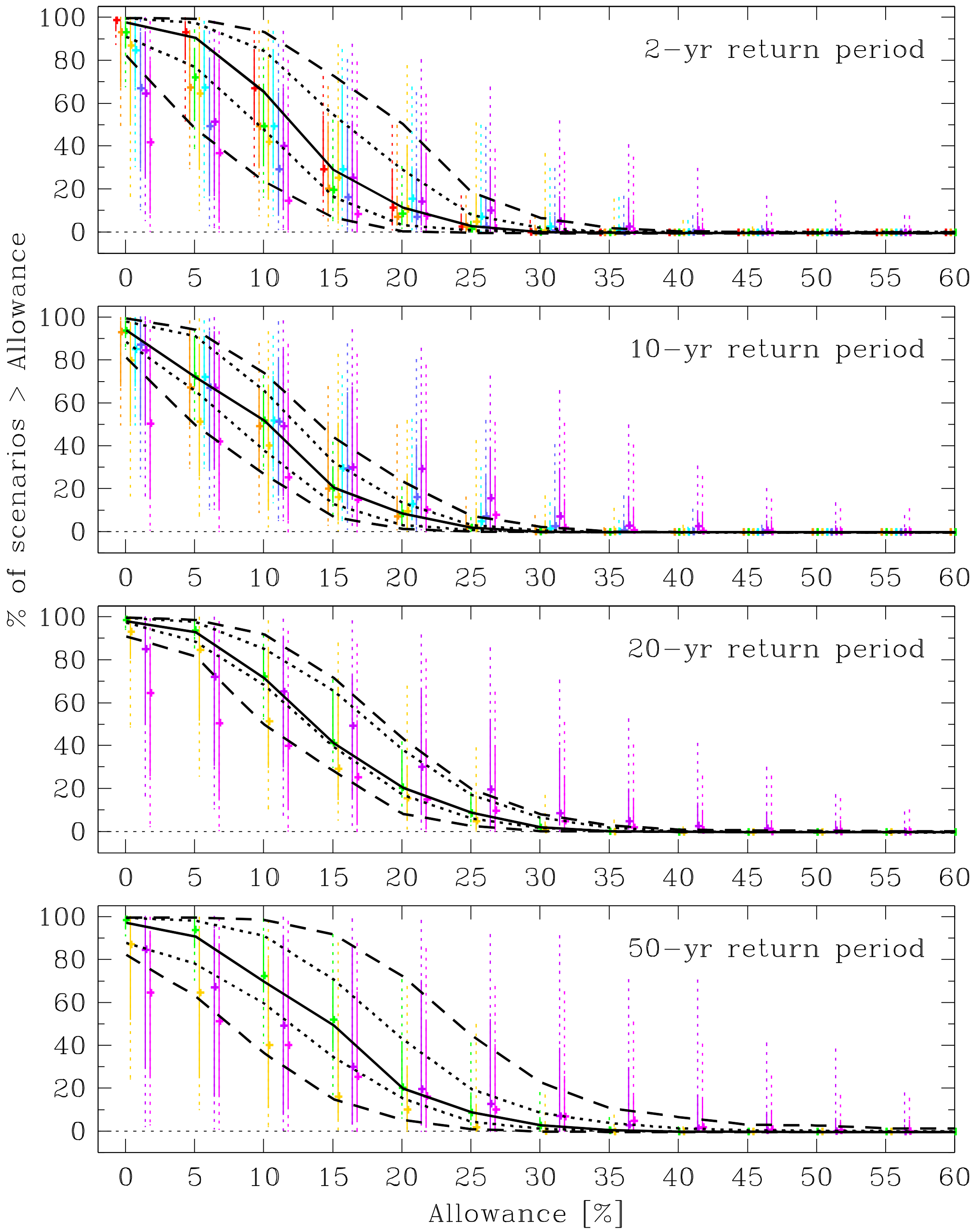


Figure B.6.8 As Figure B.1 but for the West Wales river-basin region (2020s A1B).

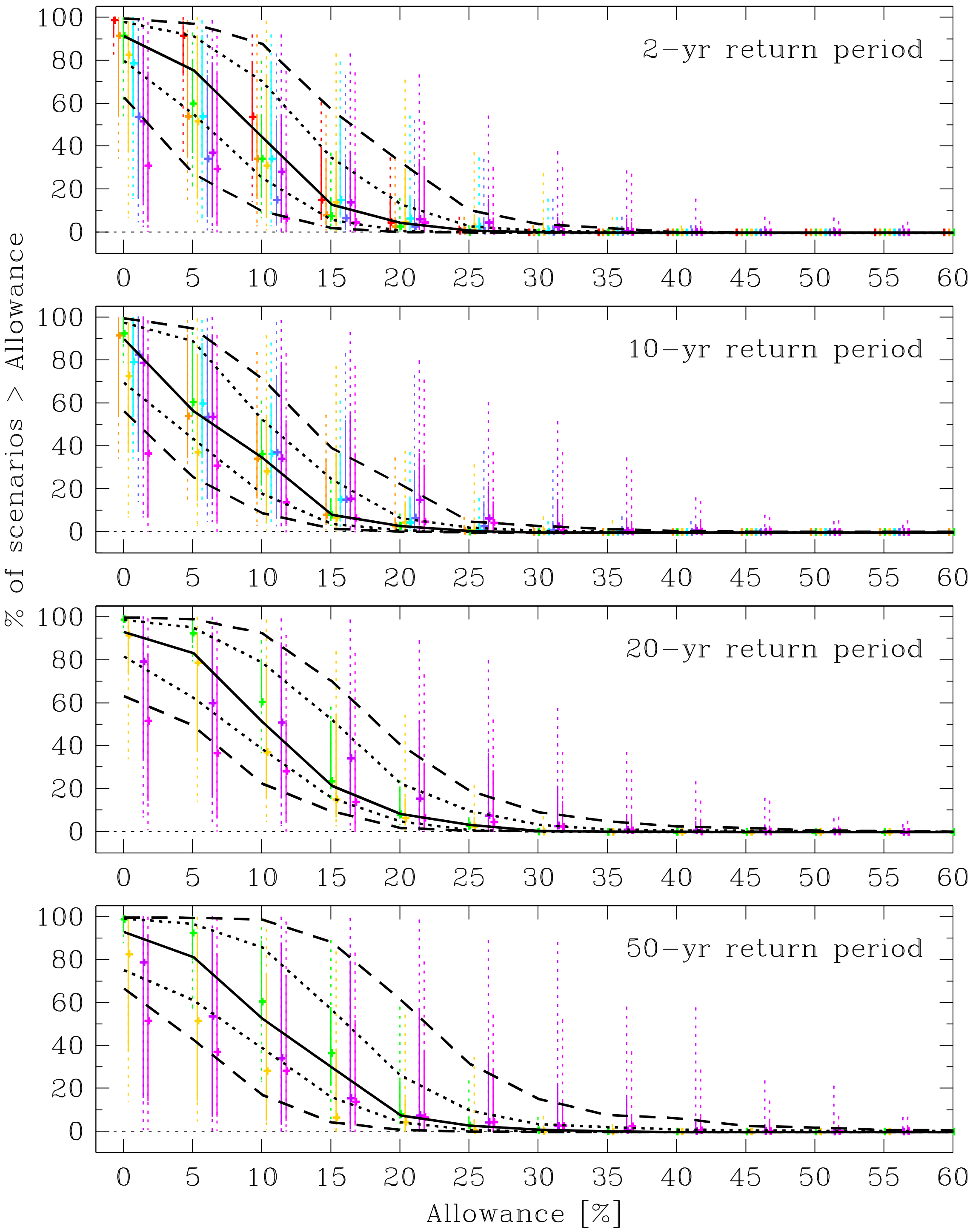


Figure B.6.9 As Figure B.1 but for the Dee river-basin region (2020s A1B).

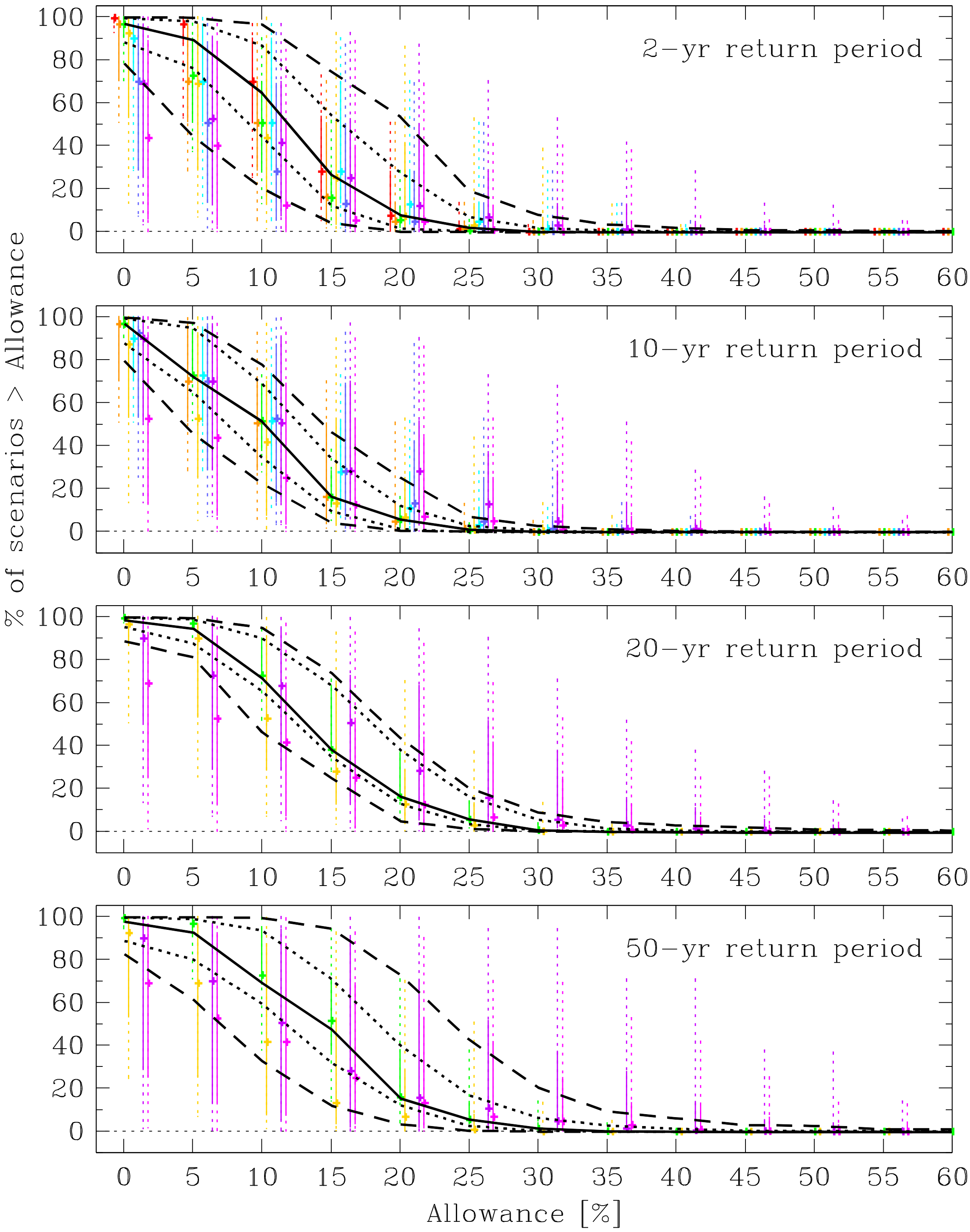


Figure B.6.10 As Figure B.1 but for the North-West England river-basin region (2020s A1B).

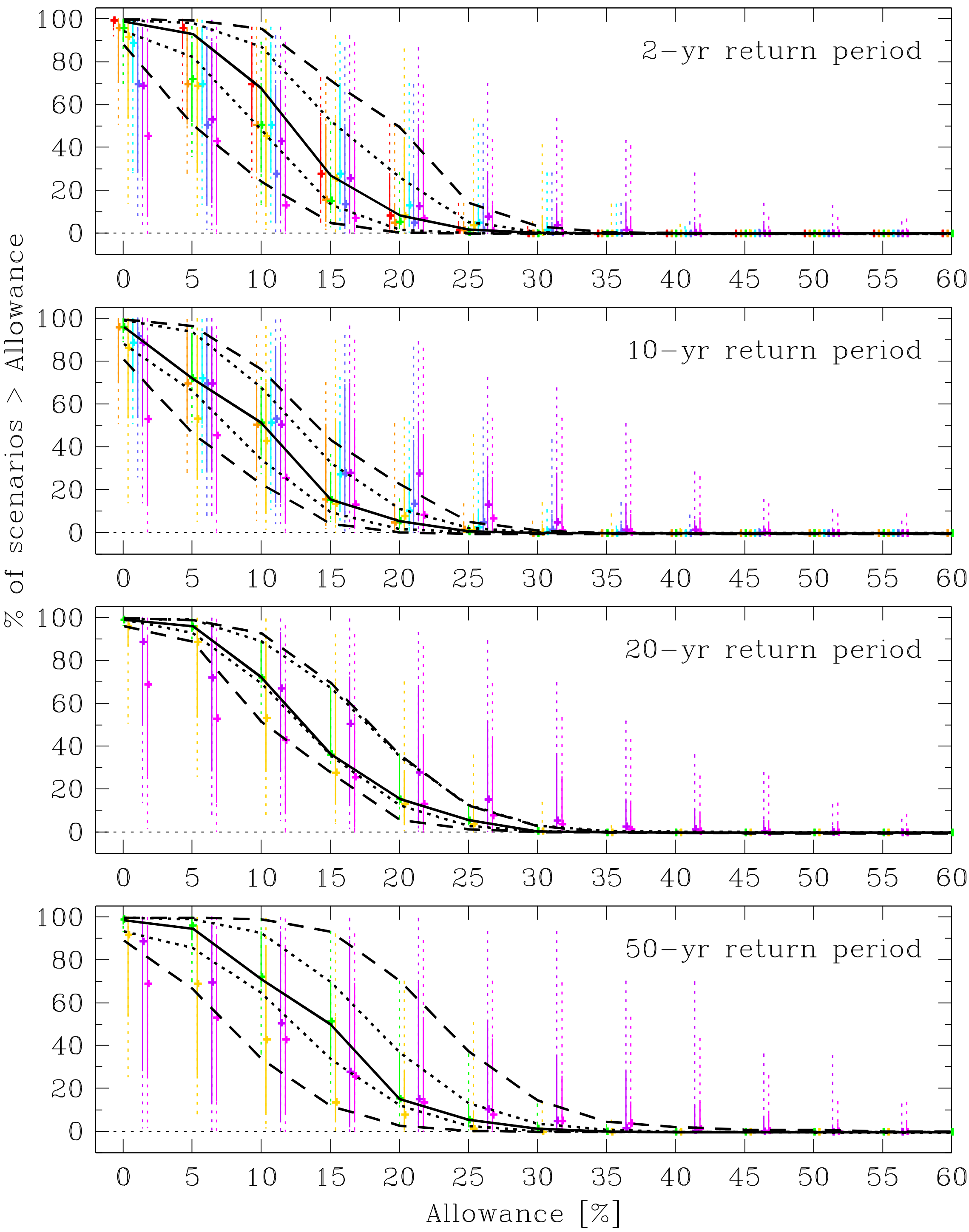


Figure B.6.11 As Figure B.1 but for the Solway river-basin region (2020s A1B).

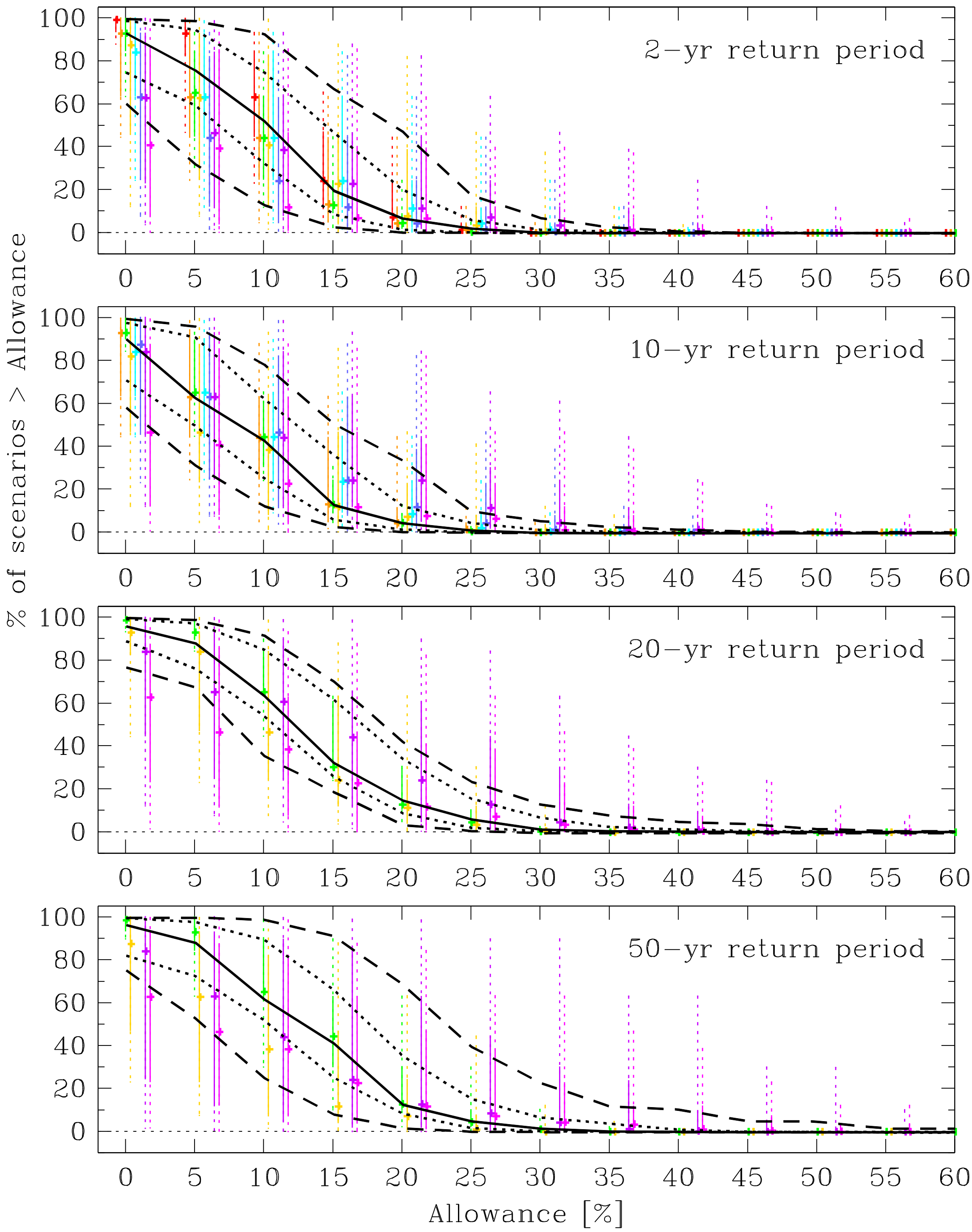


Figure B.6.12 As Figure B.1 but for the Tweed river-basin region (2020s A1B).

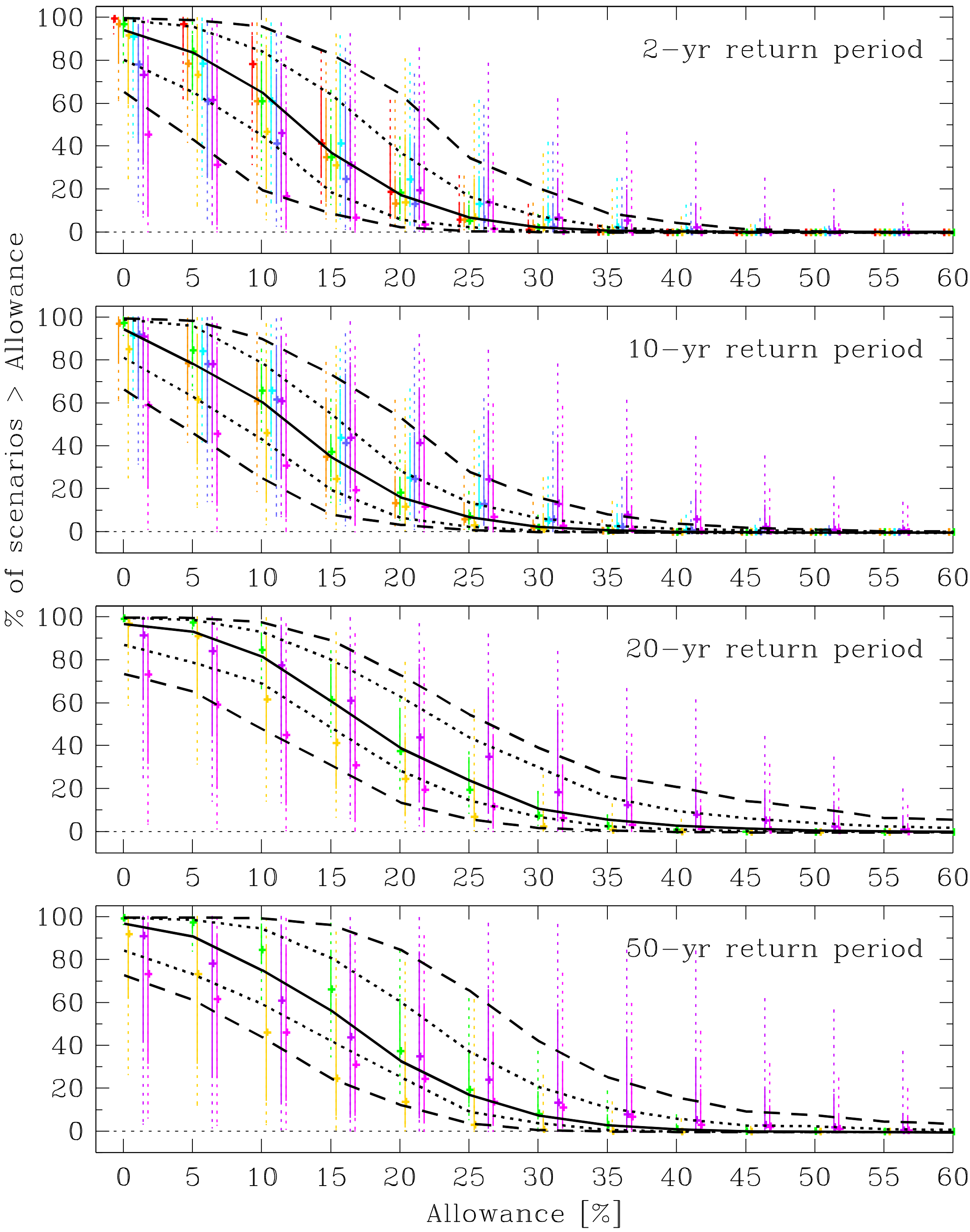


Figure B.6.13 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2050s A1B) for the Northumbria river-basin region. Response-type risk (colours): Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta); 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).

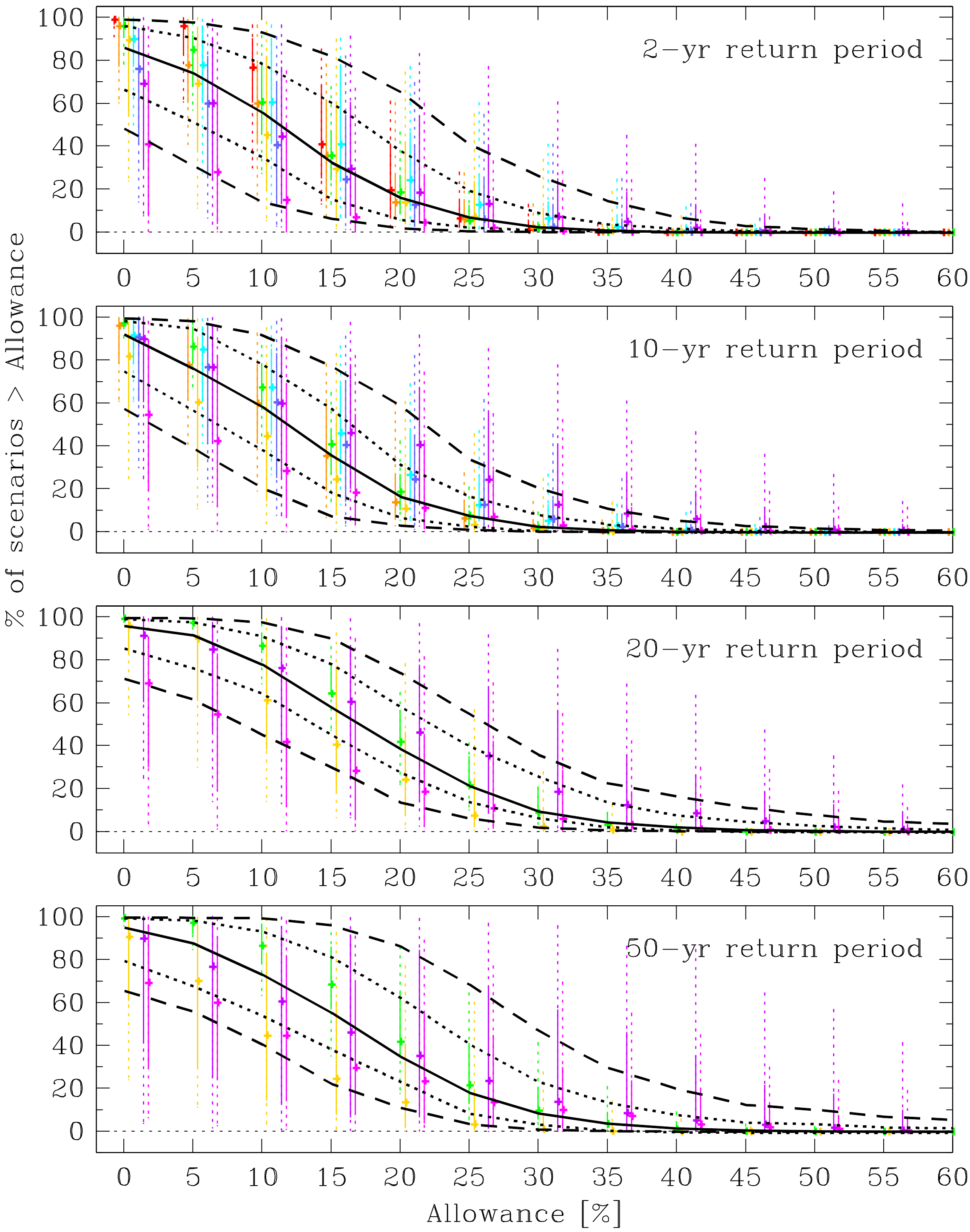


Figure B.6.14 As Figure B.13 but for the Humber river-basin region (2050s A1B).

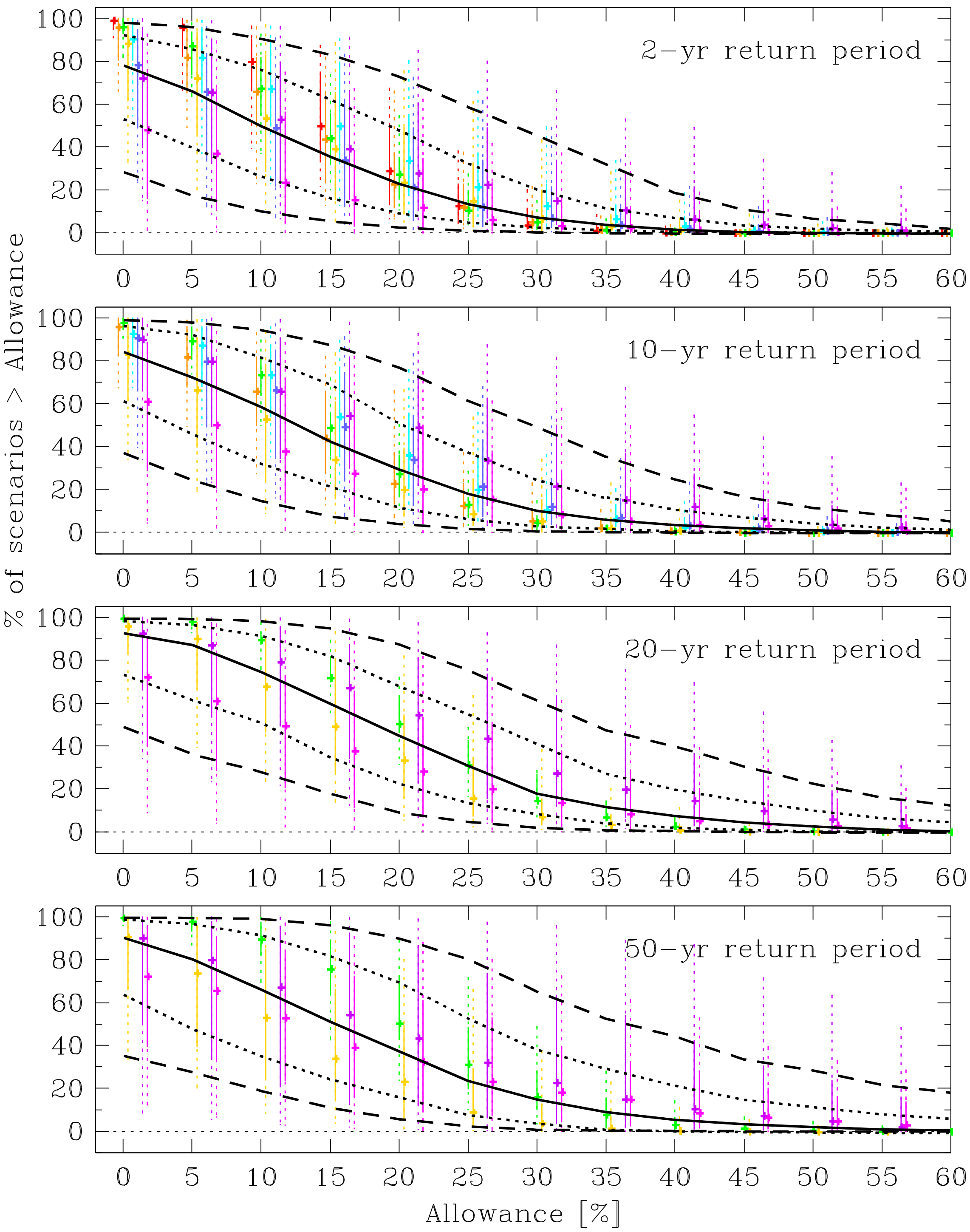


Figure B.6.15 As Figure B.13 but for the Anglian river-basin region (2050s A1B).

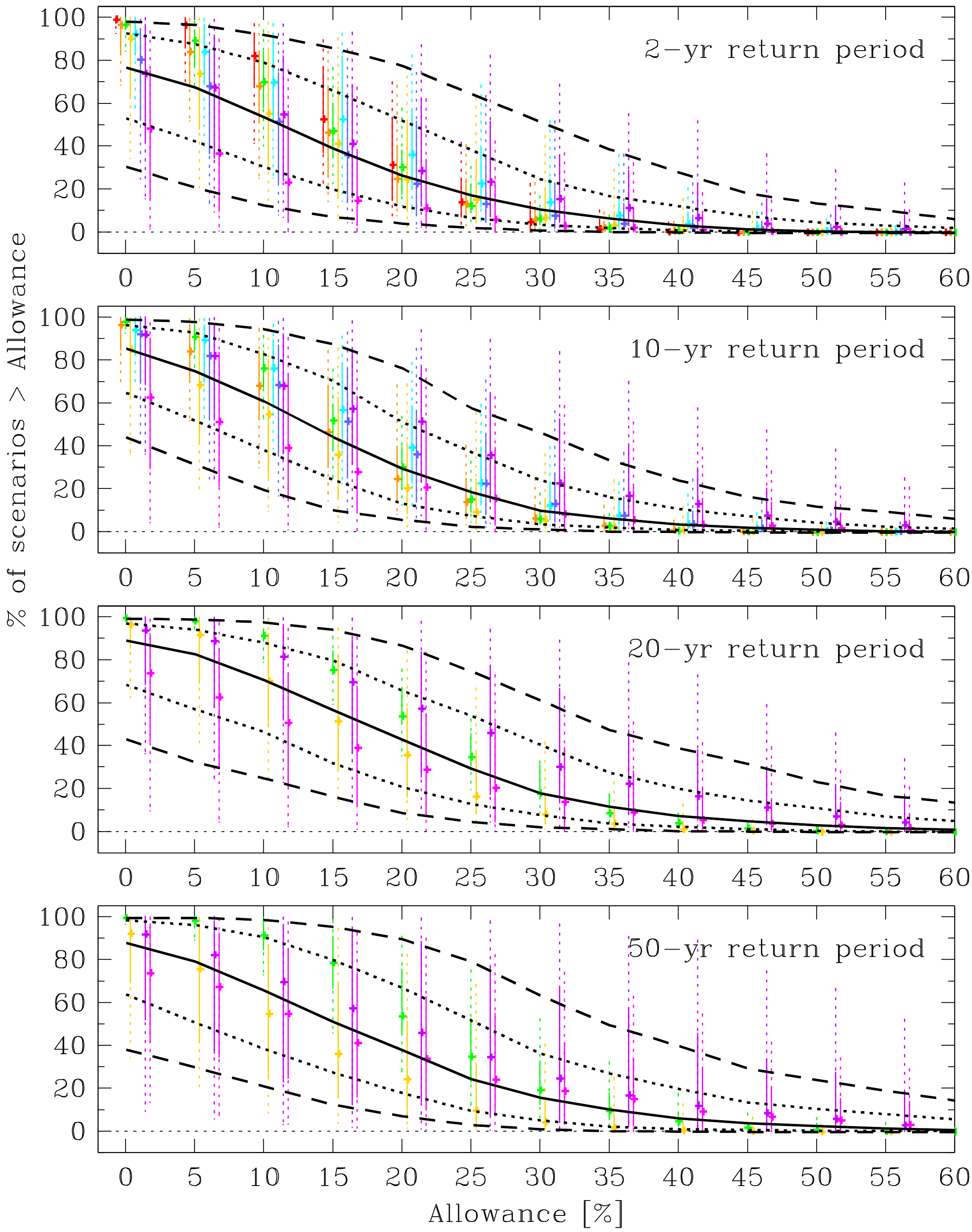


Figure B.6.16 As Figure B.13 but for the Thames river-basin region (2050s A1B).

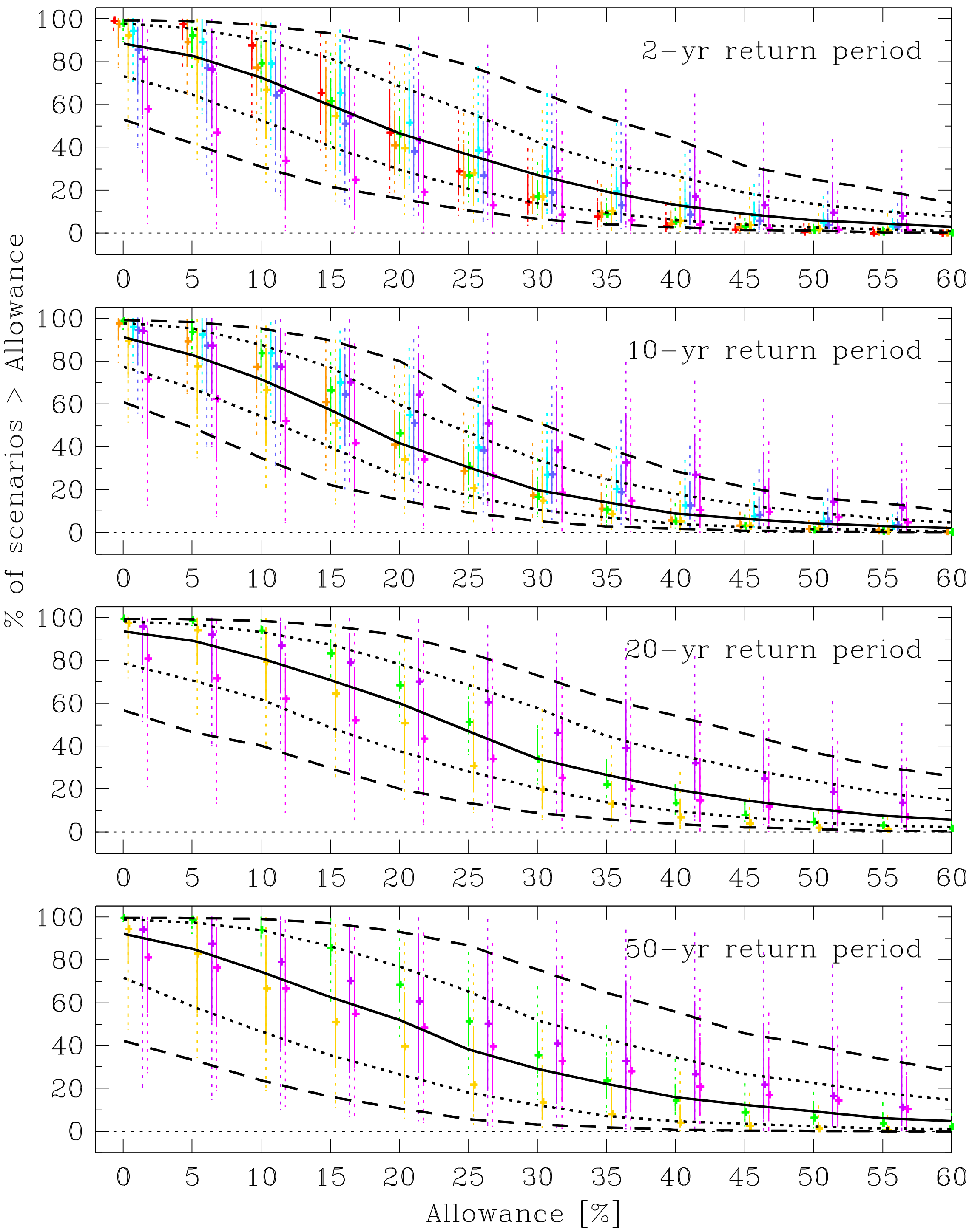


Figure B.6.17 As Figure B.13 but for the South-East England river-basin region (2050s A1B).

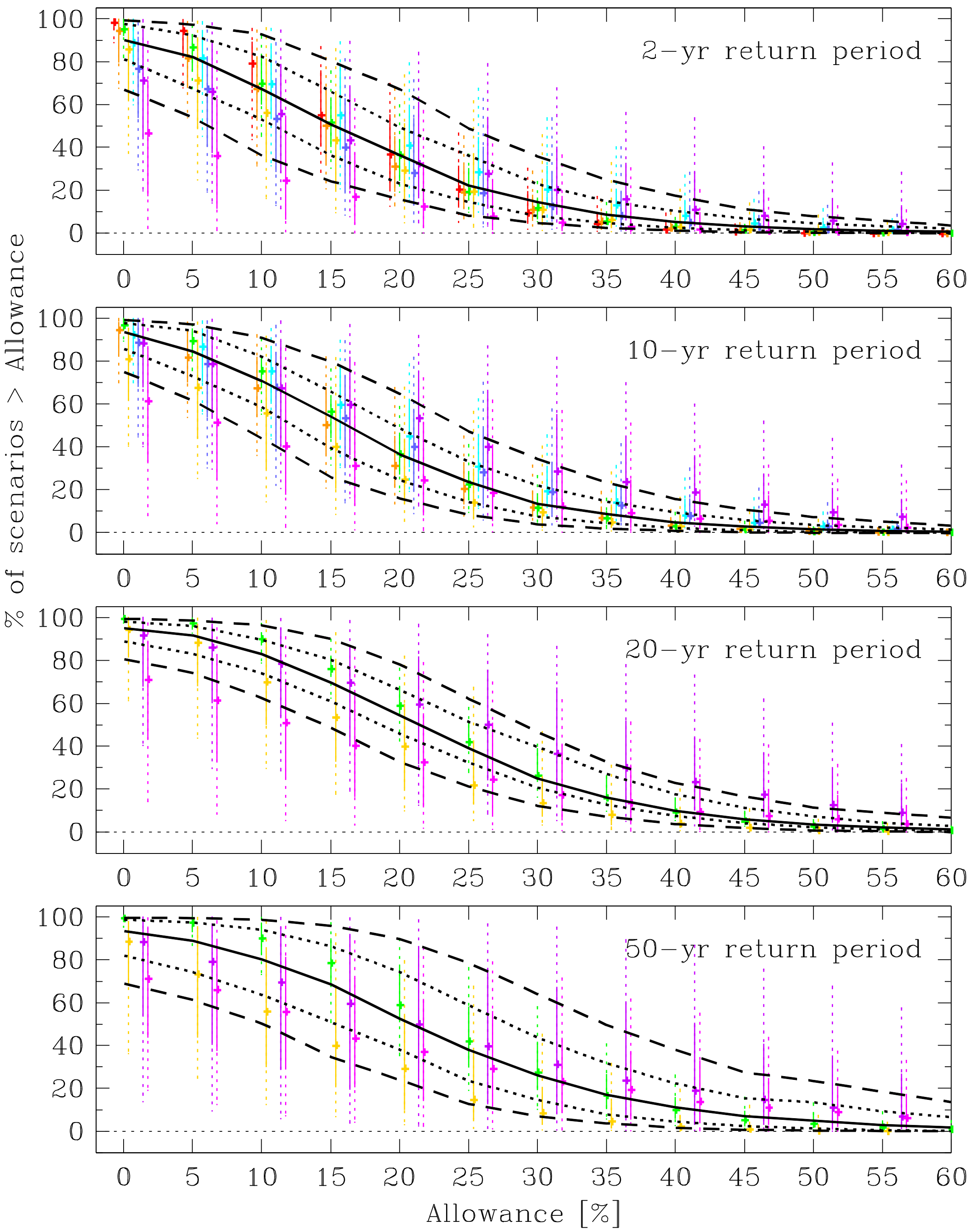


Figure B.6.18 As Figure B.13 but for the South-West England river-basin region (2050s A1B).

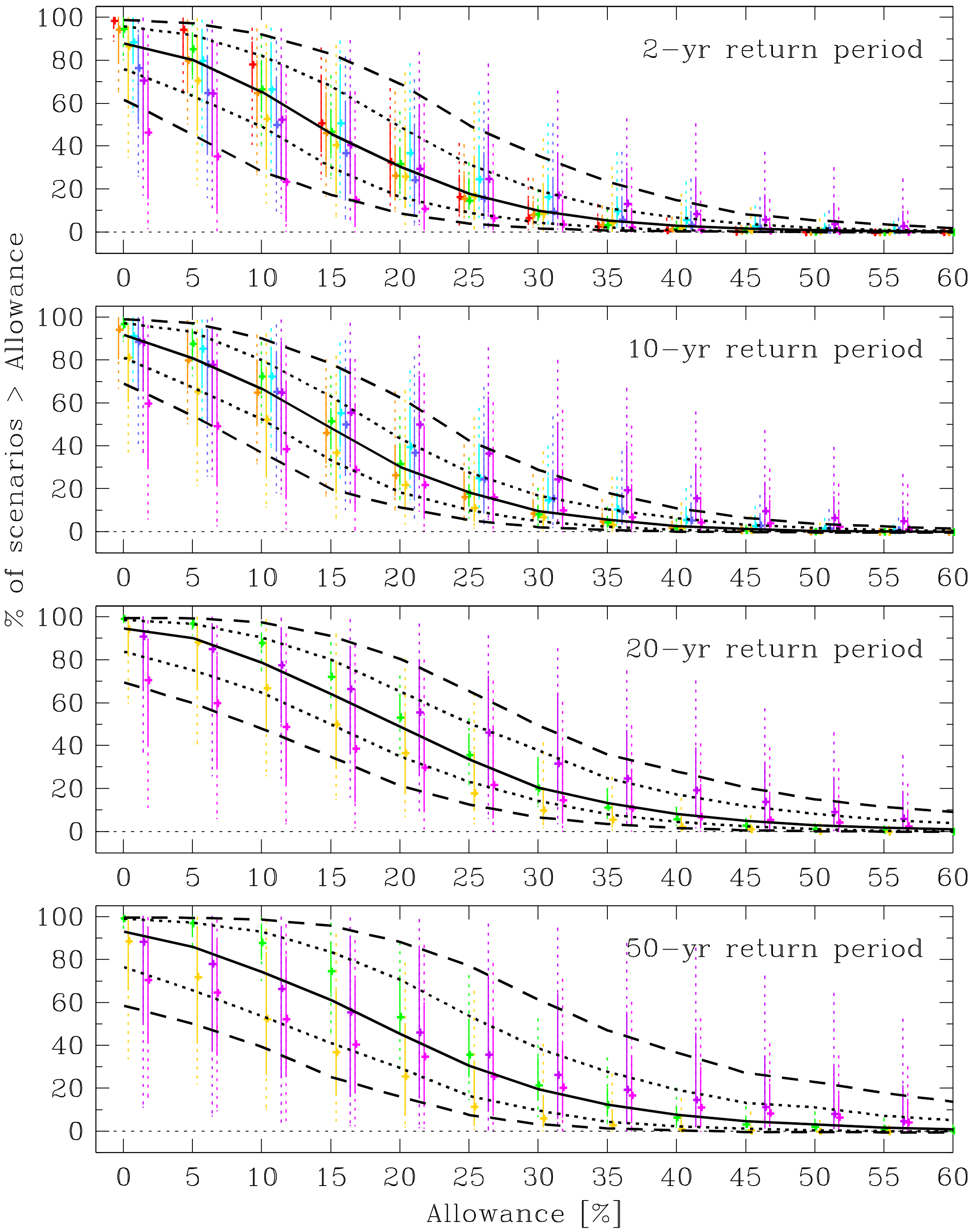


Figure B.6.19 As Figure B.13 but for the Severn England river-basin region (2050s A1B).

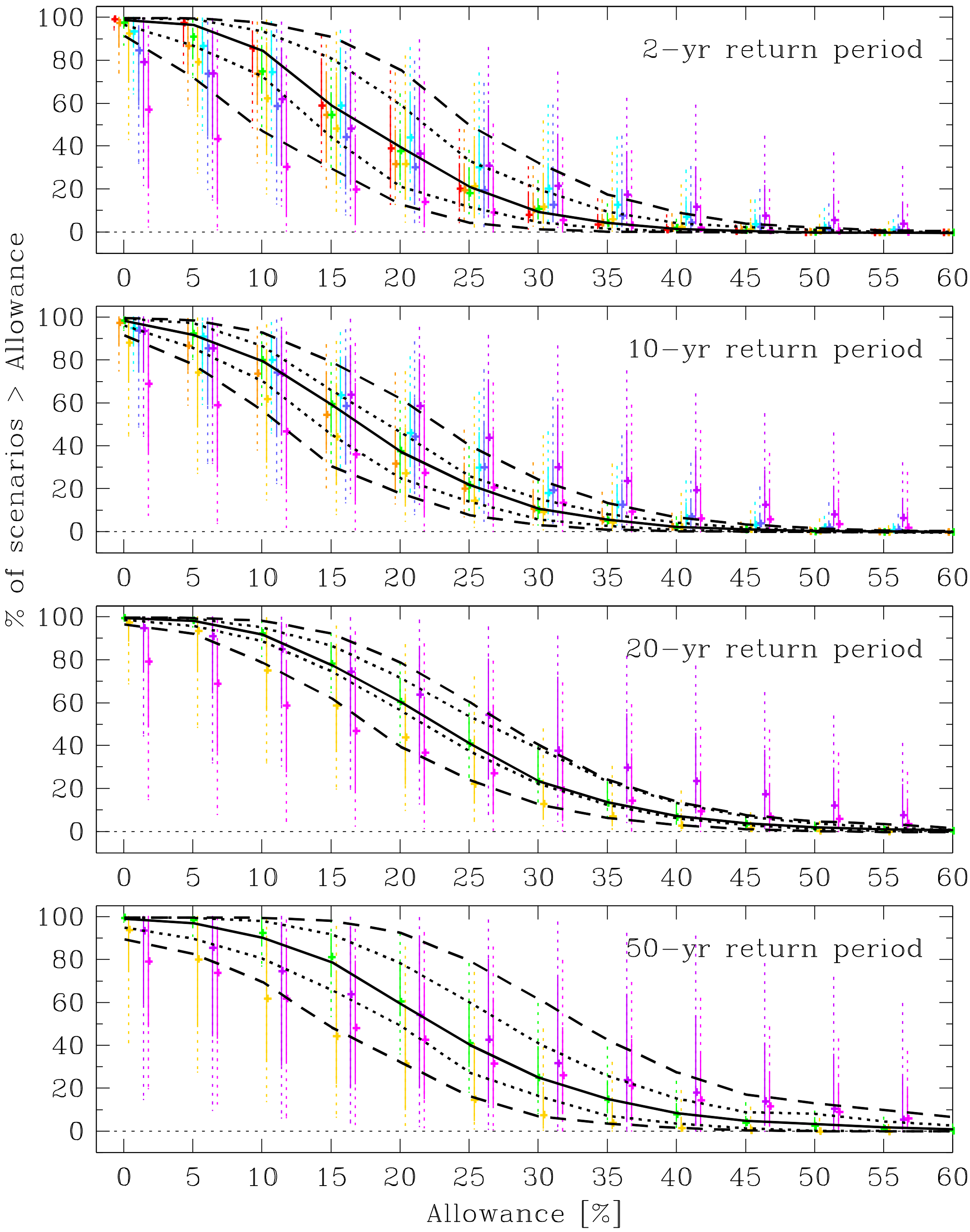


Figure B.6.20 As Figure B.13 but for the West Wales river-basin region (2050s A1B).

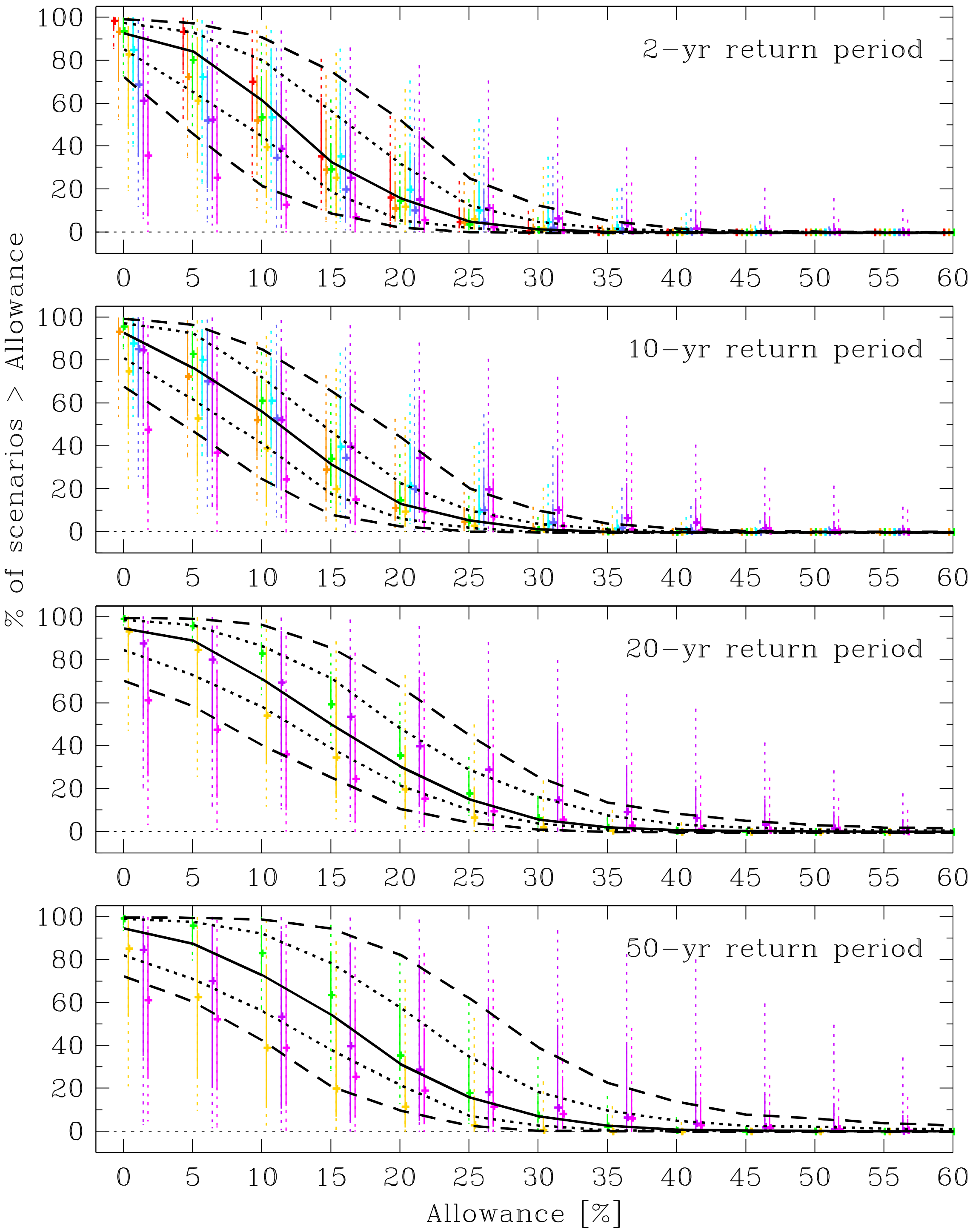


Figure B.6.21 As Figure B.13 but for the Dee river-basin region (2050s A1B).

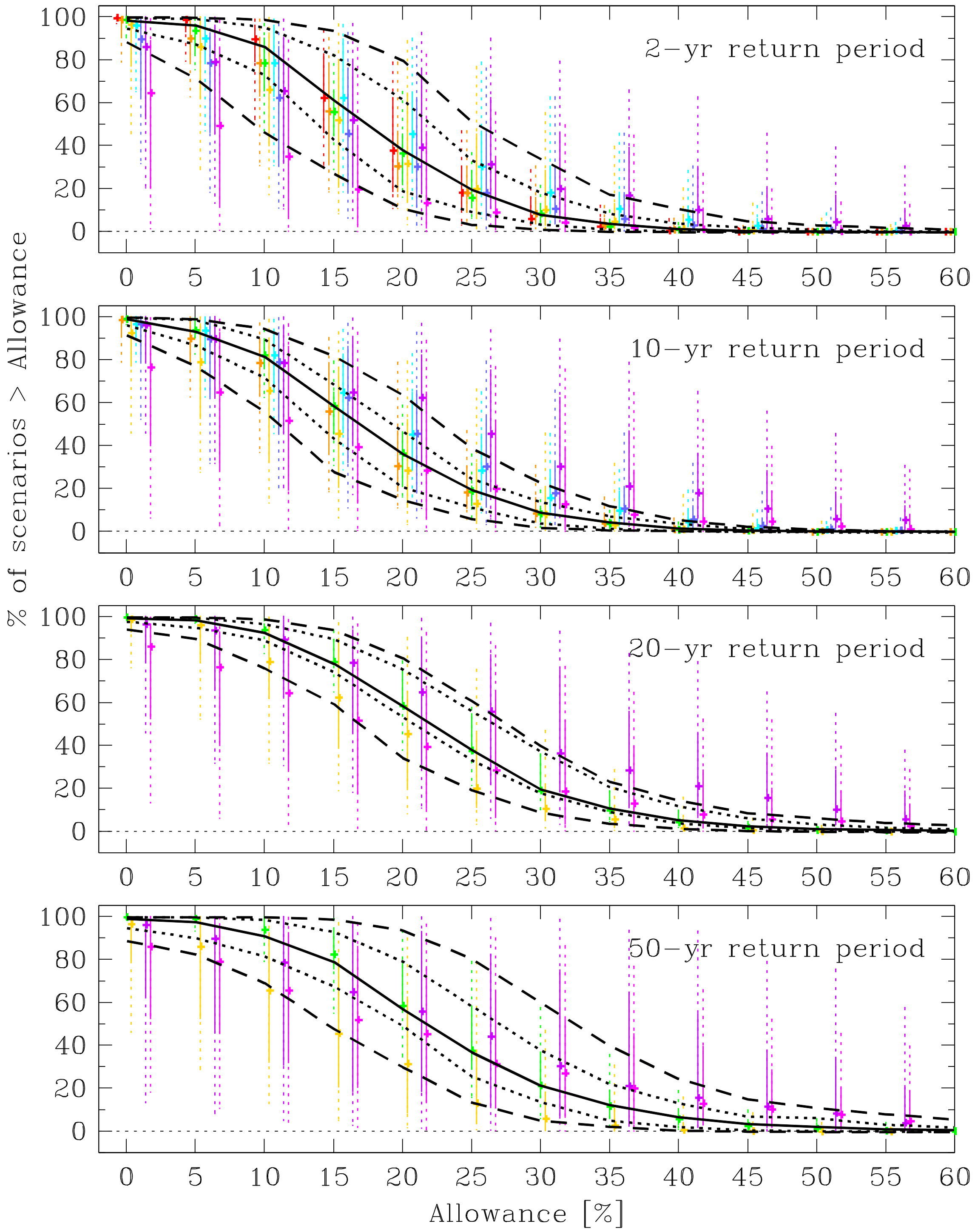


Figure B.6.22 As Figure B.13 but for the North-West England river-basin region (2050s A1B).

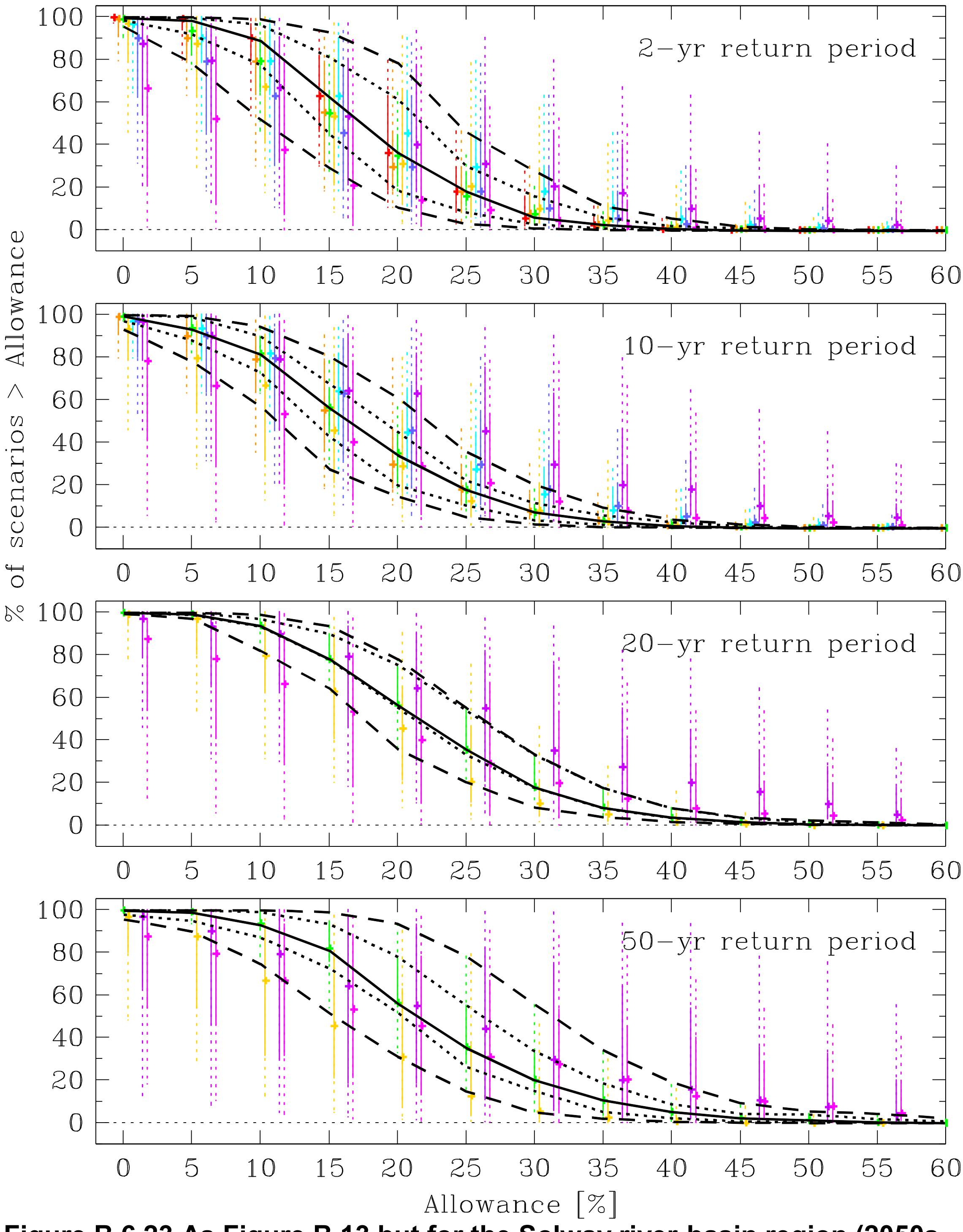


Figure B.6.23 As Figure B.13 but for the Solway river-basin region (2050s A1B).

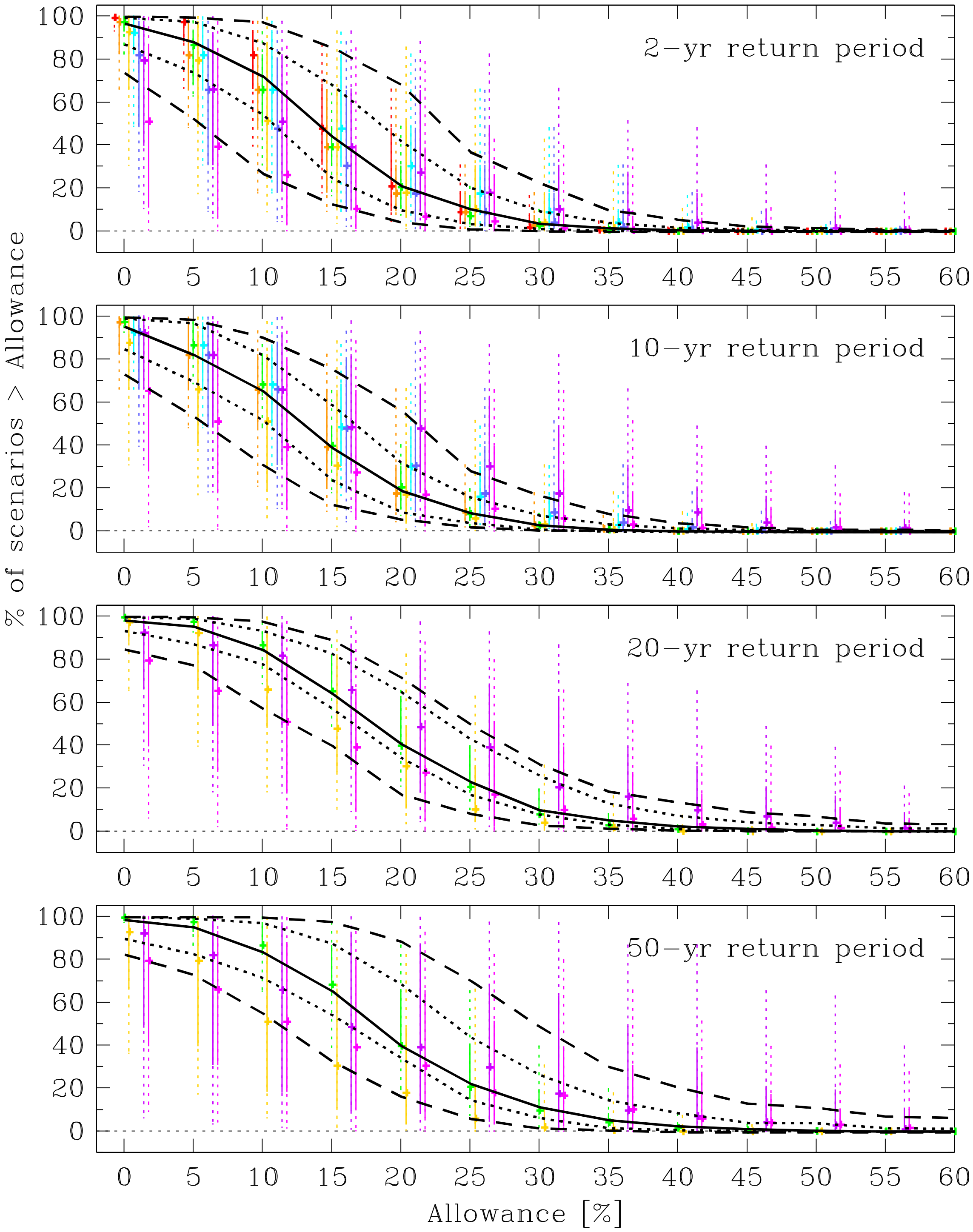


Figure B.6.24 As Figure B.13 but for the Tweed river-basin region (2050s A1B).

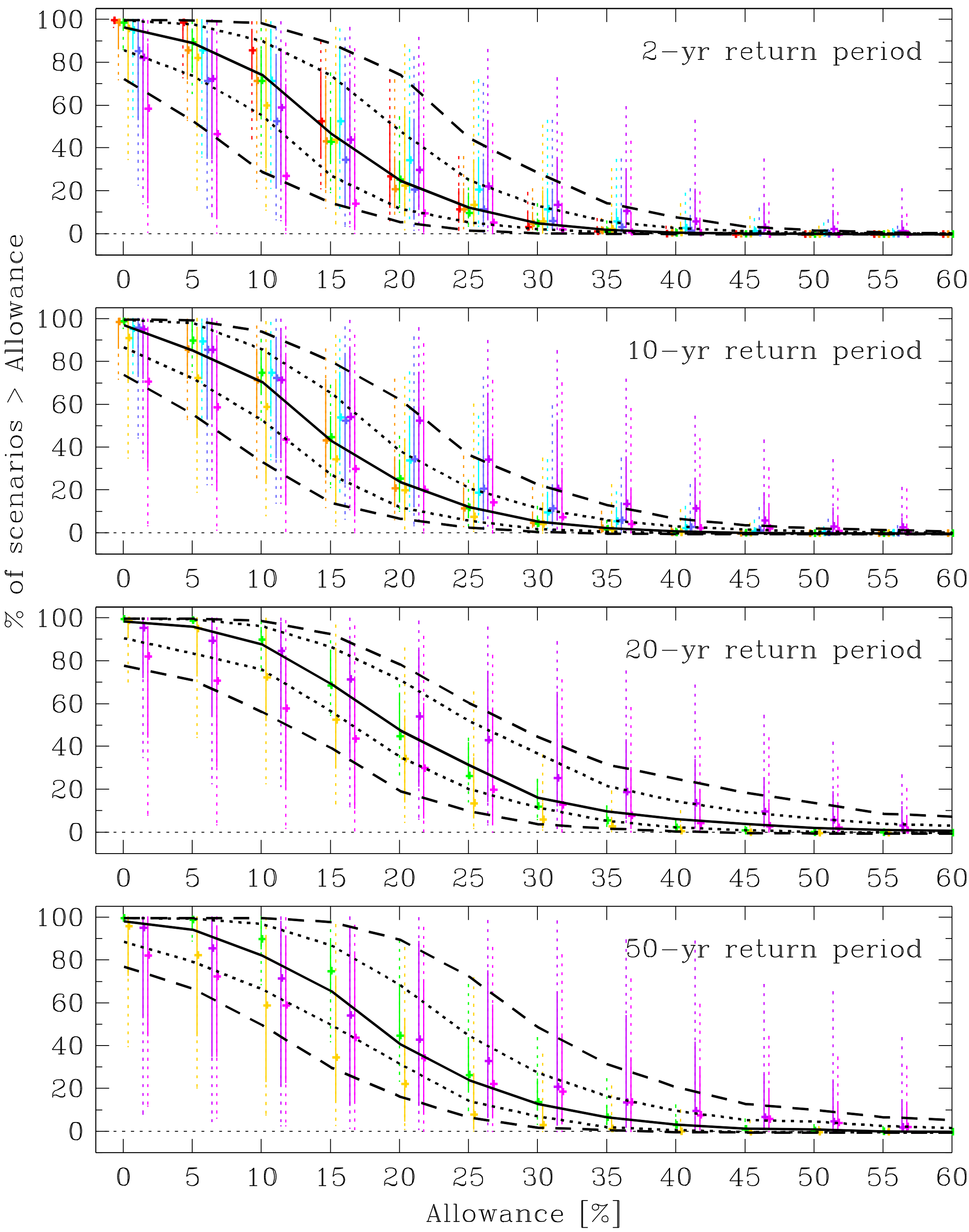


Figure B.6.25 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s B1) for the Northumbria river-basin region. Response-type risk (colours): Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta); 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).

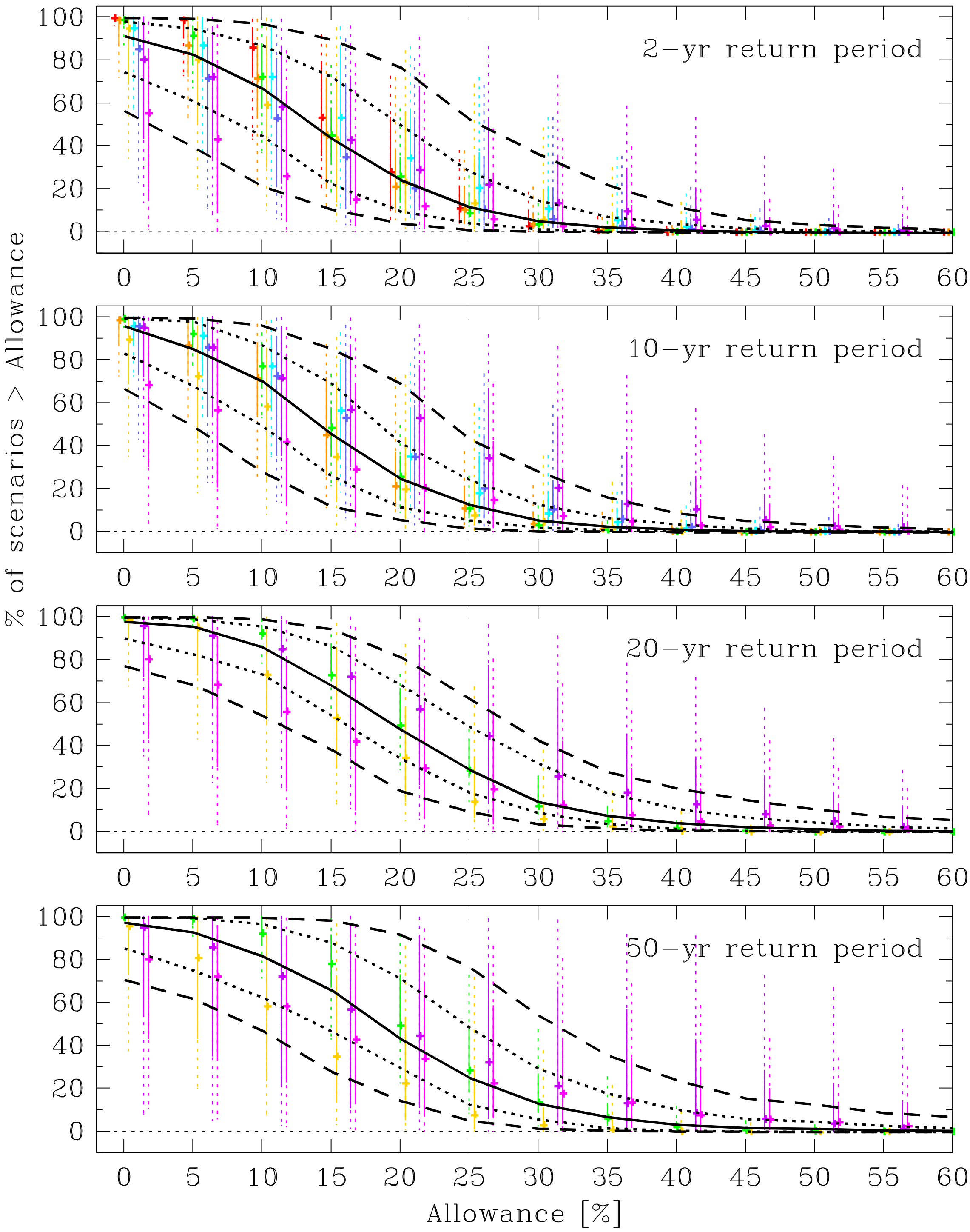


Figure B.6.26 As Figure B.25 but for the Humber river-basin region (2080s B1).

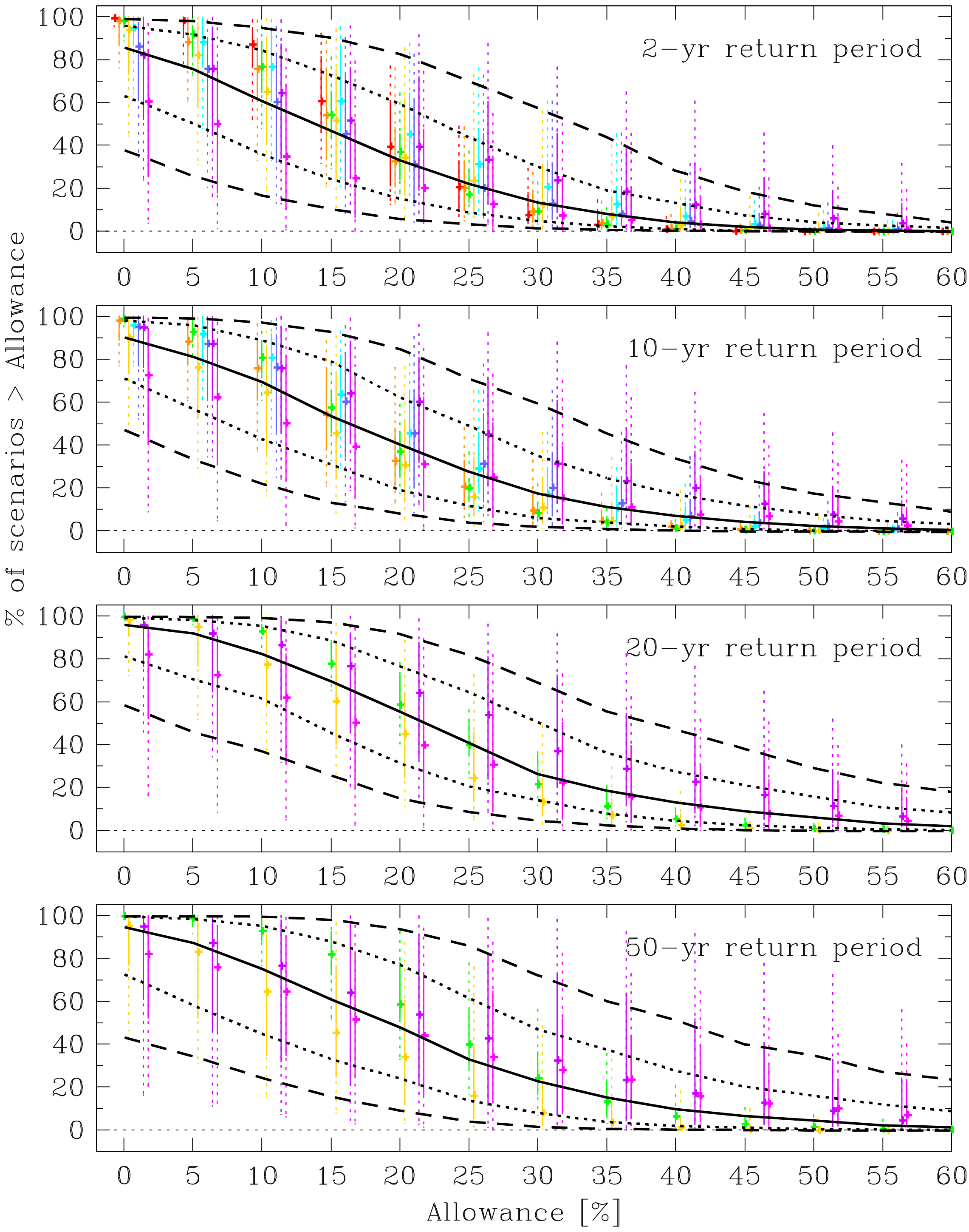


Figure B.6.27 As Figure B.25 but for the Anglian river-basin region (2080s B1).

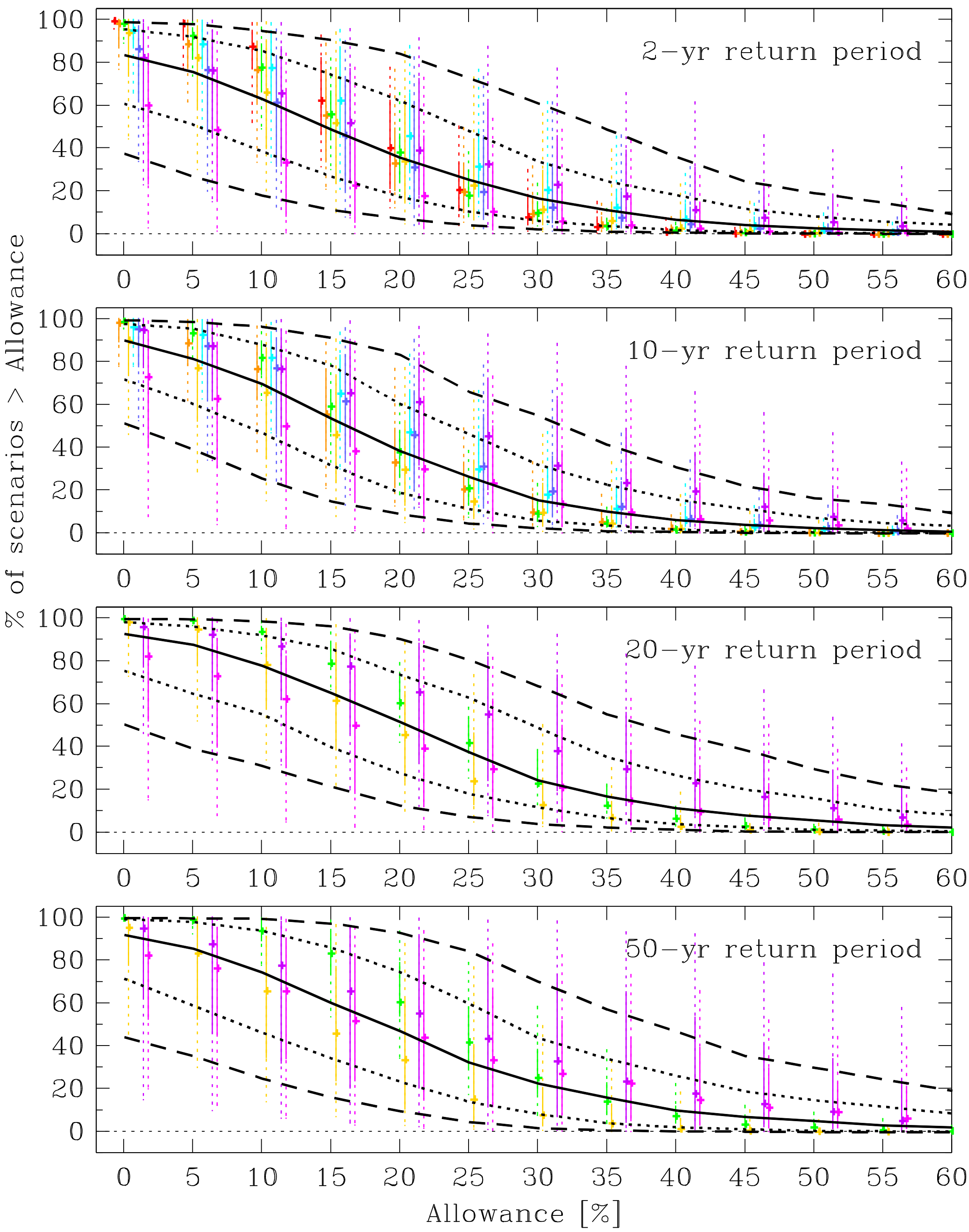


Figure B.6.28 As Figure B.25 but for the Thames river-basin region (2080s B1).

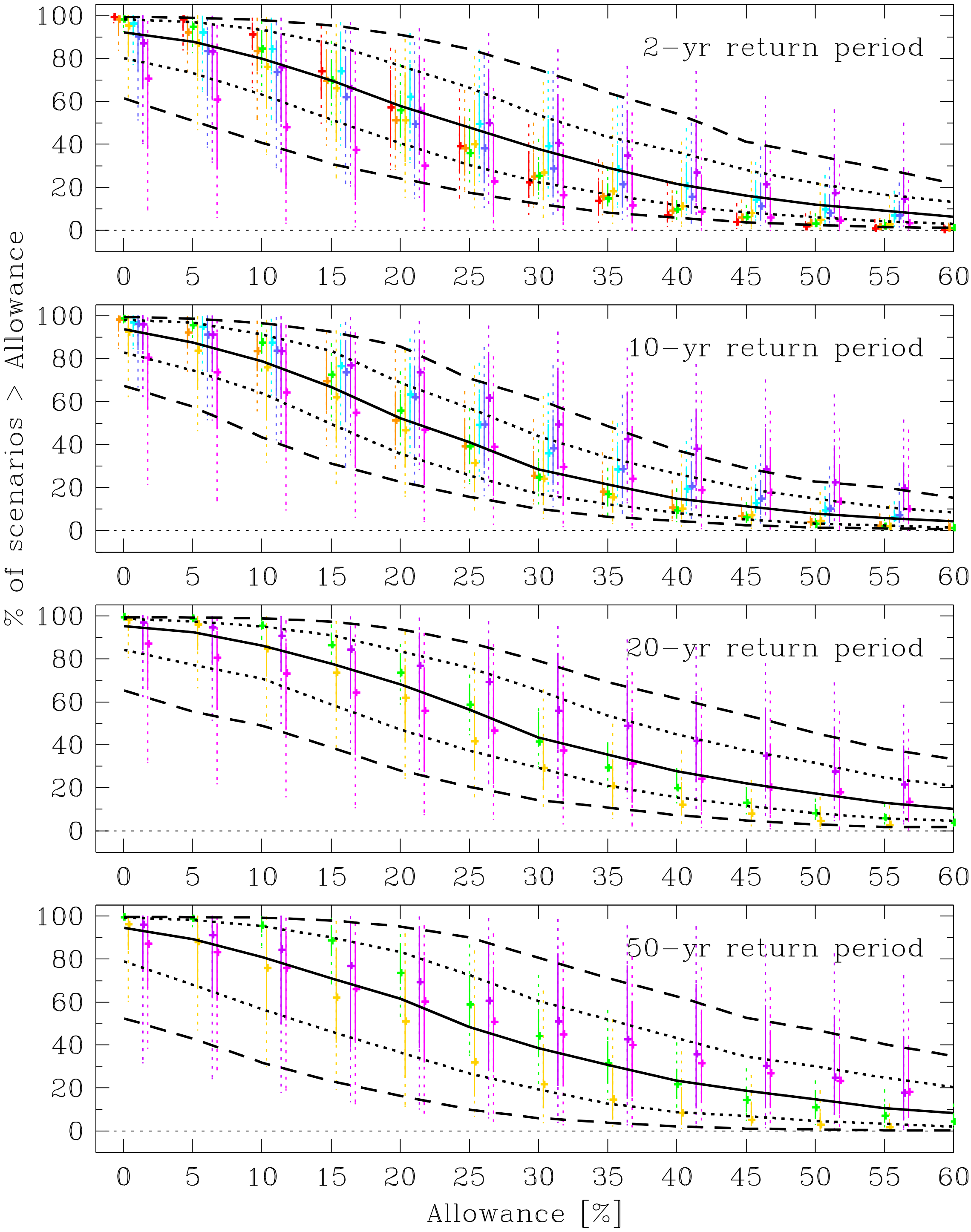


Figure B.6.29 As Figure B.25 but for the South-East England river-basin region (2080s B1).

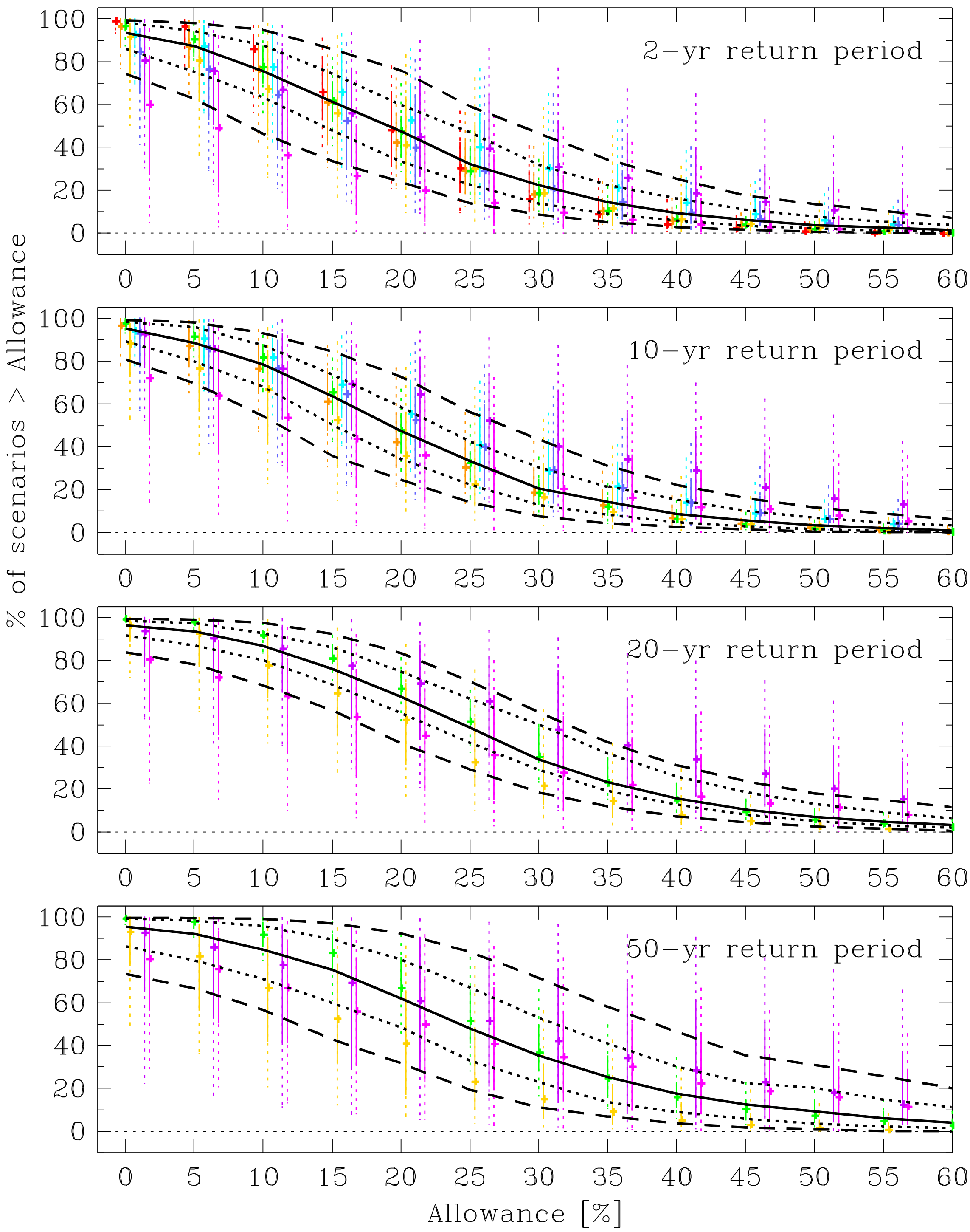


Figure B.6.30 As Figure B.25 but for the South-West England river-basin region (2080s B1).

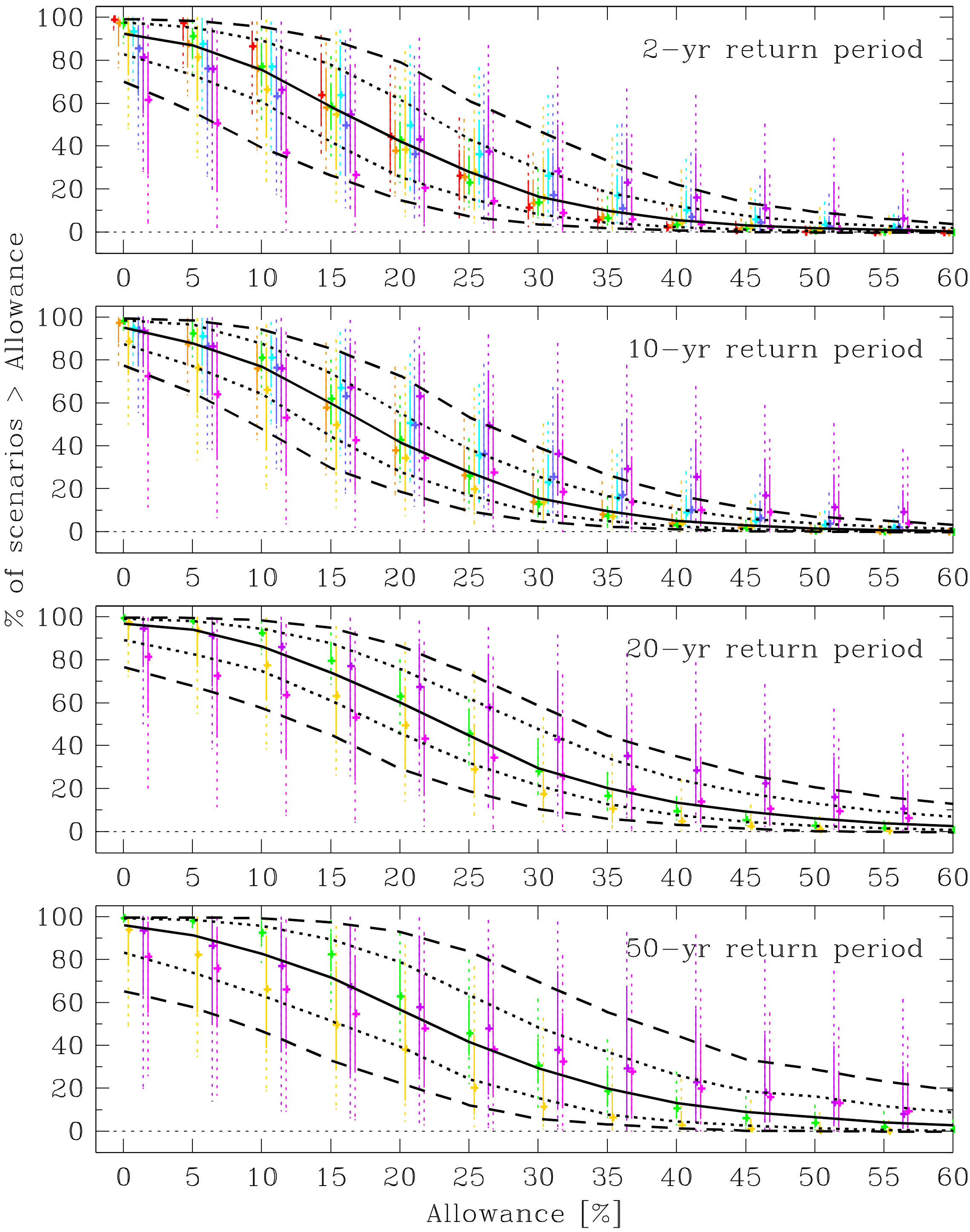


Figure B.6.31 As Figure B.25 but for the Severn England river-basin region (2080s B1).

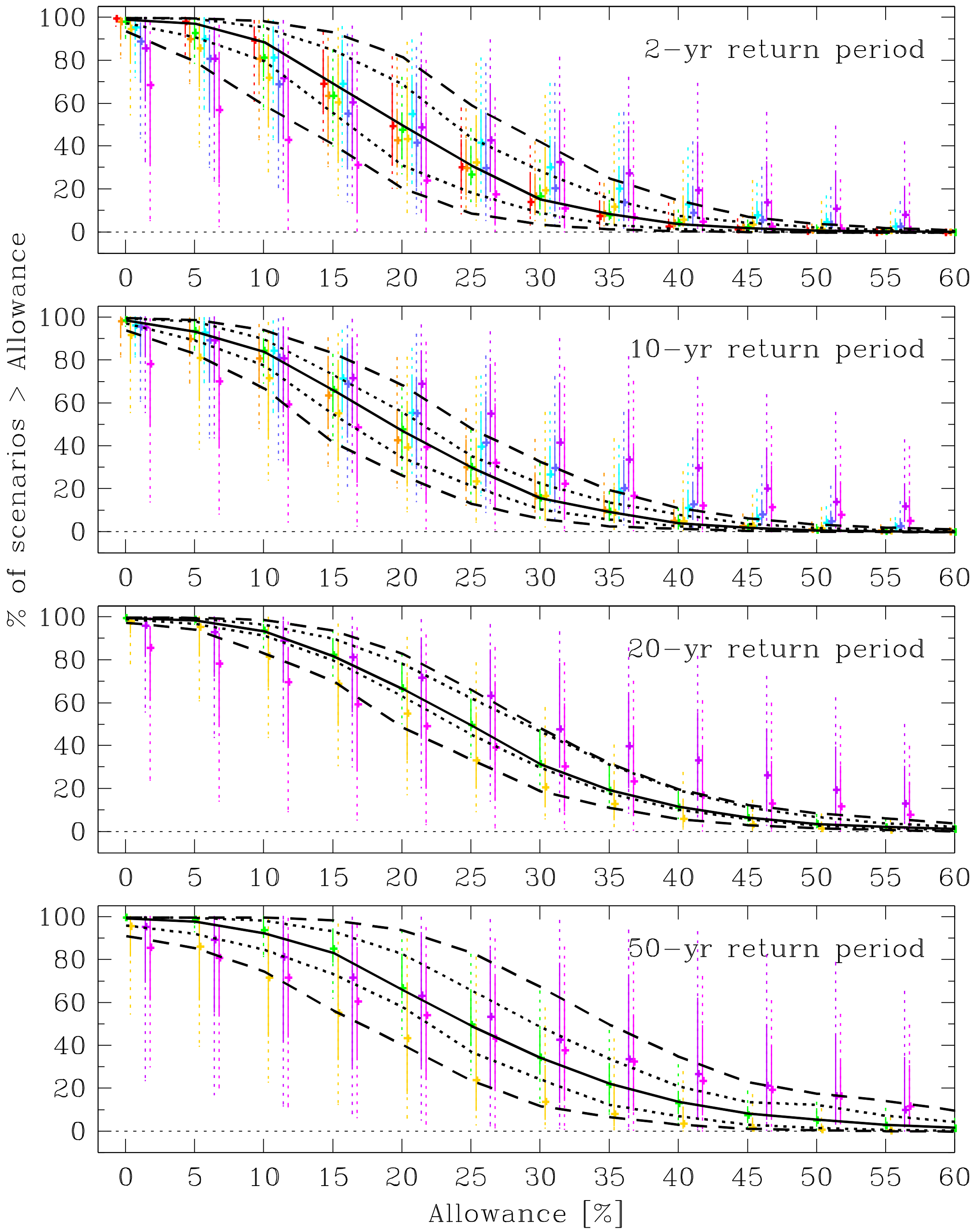


Figure B.6.32 As Figure B.25 but for the West Wales river-basin region (2080s B1).

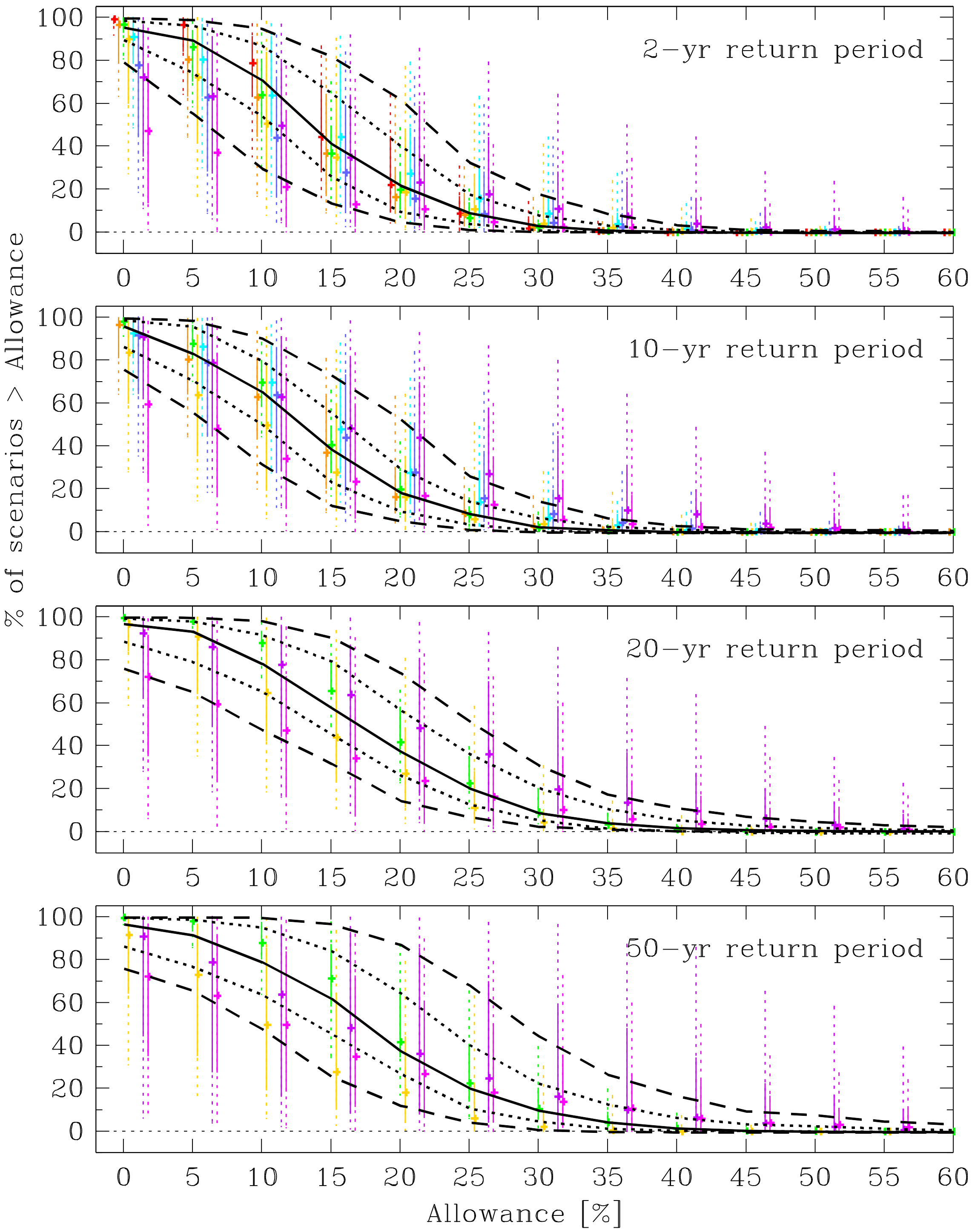


Figure B.6.33 As Figure B.25 but for the Dee river-basin region (2080s B1).

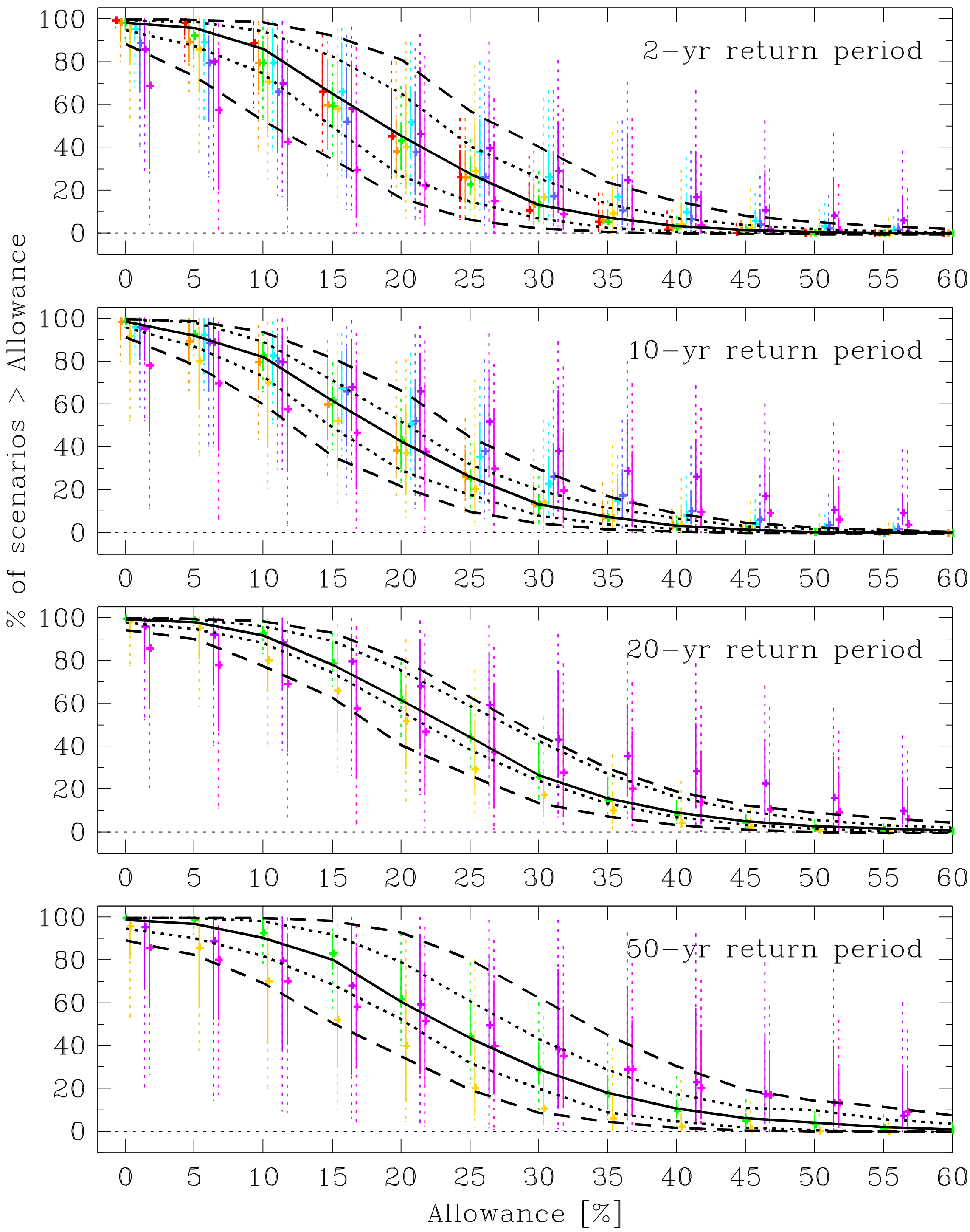


Figure B.6.34 As Figure B.25 but for the North-West England river-basin region (2080s B1).

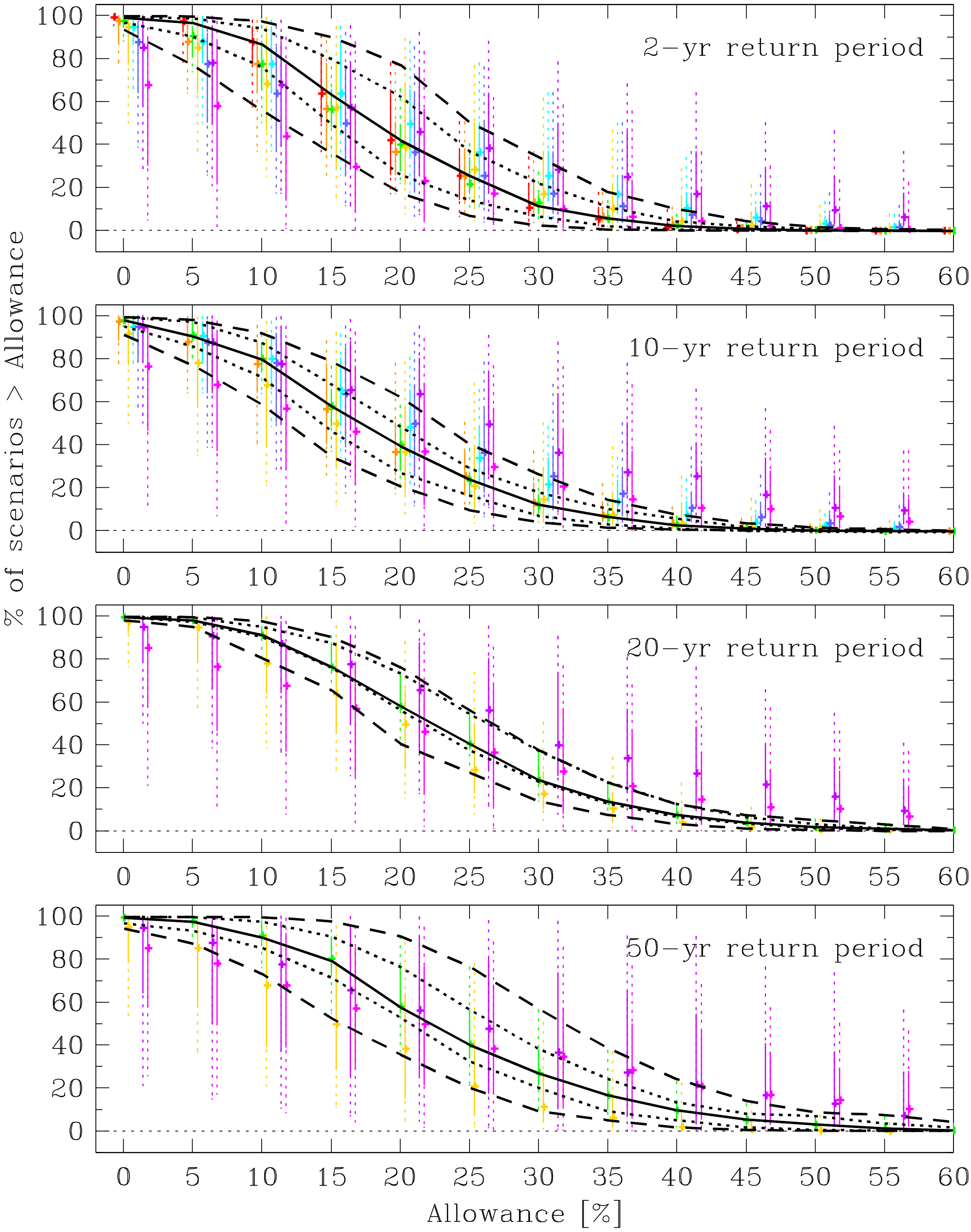


Figure B.6.35 As Figure B.25 but for the Solway river-basin region (2080s B1).

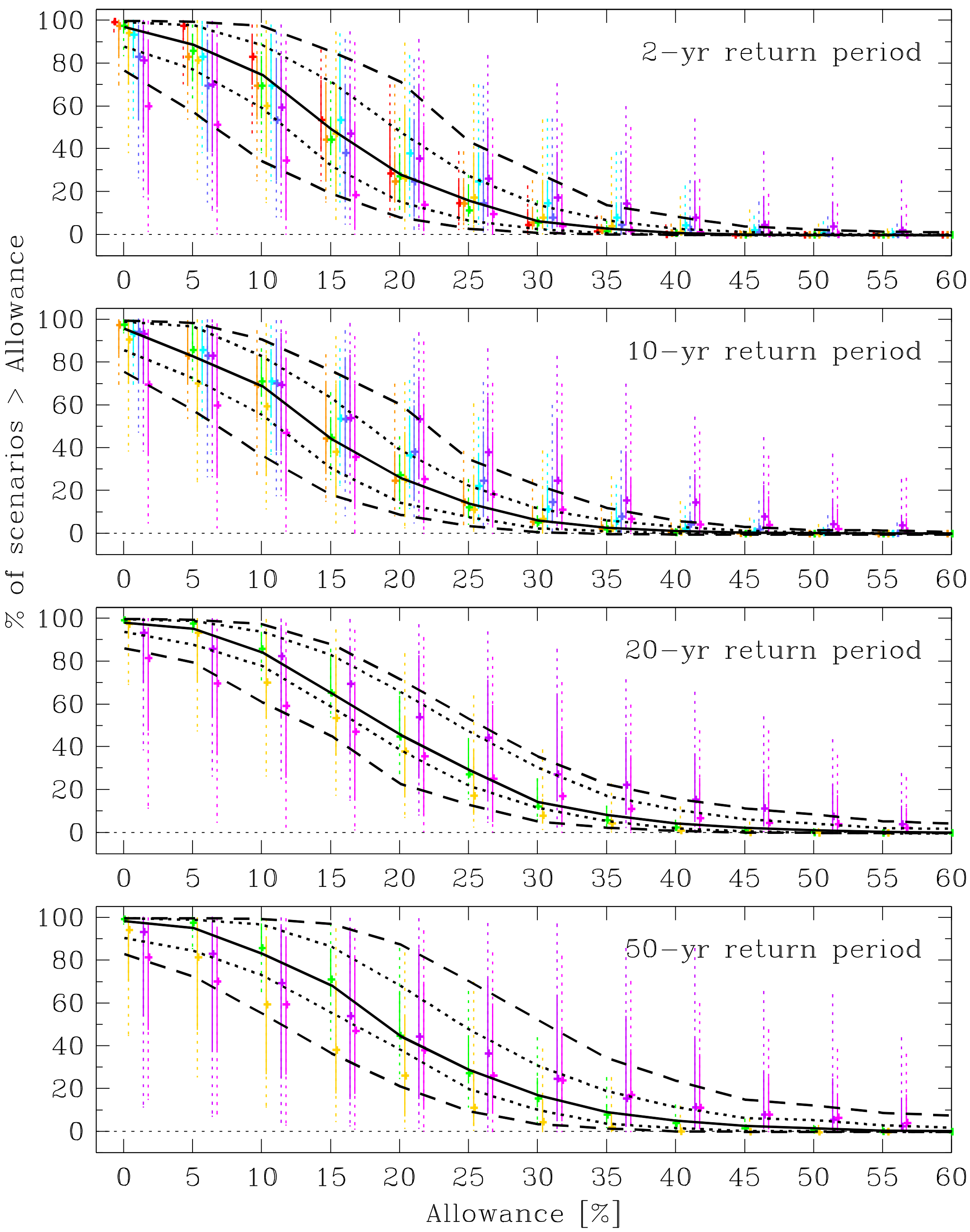


Figure B.6.36 As Figure B.25 but for the Tweed river-basin region (2080s B1).

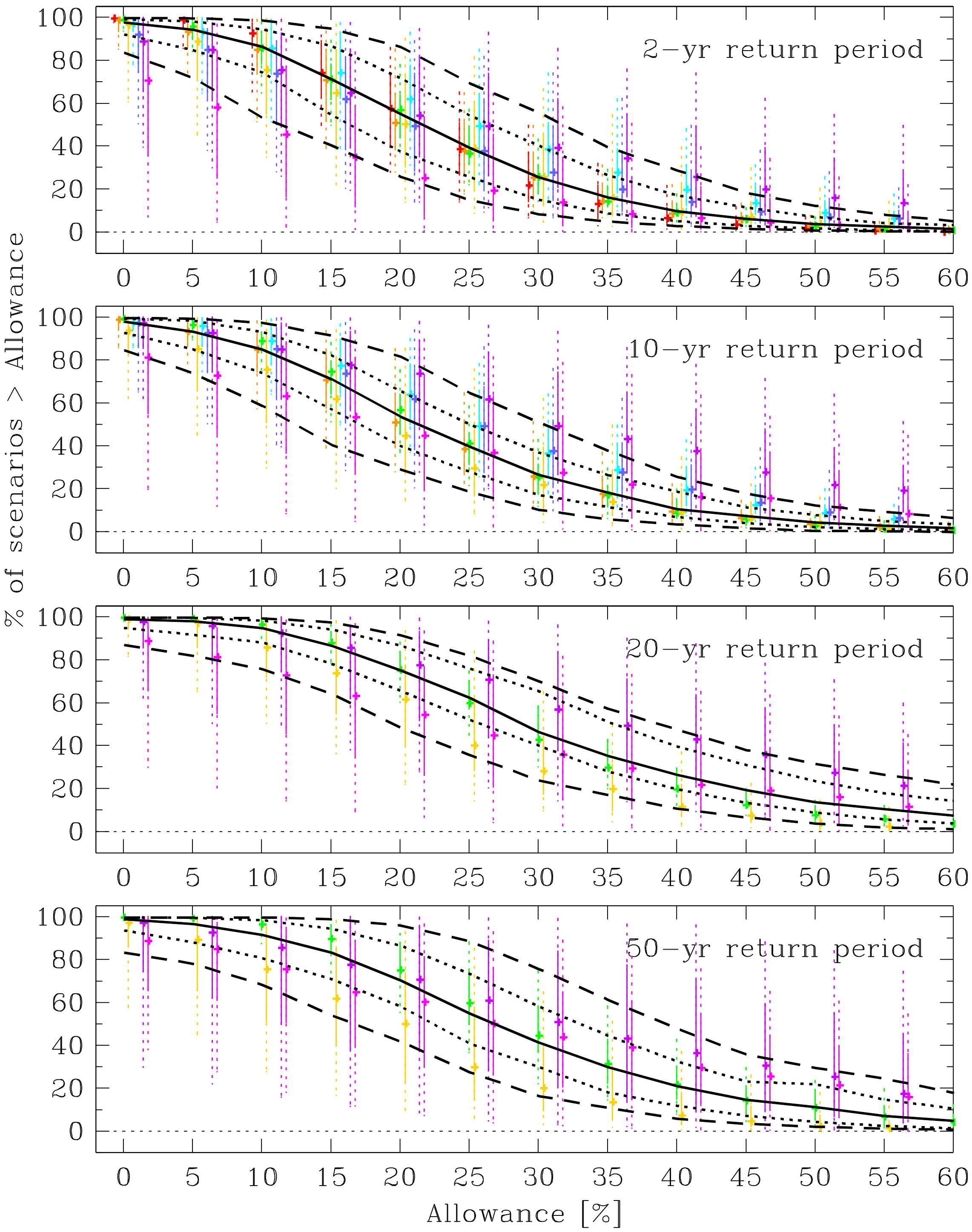


Figure B.6.37 Summary of the impacts obtained from each of the key response patterns using the UKCP09 Sampled Data (2080s A1F1) for the Northumbria river-basin region. Response-type risk (colours): Damped-High (red), Damped-Low (orange), Neutral (green), Mixed (gold), Enhanced-Low (cyan), Enhanced-Medium (blue), Enhanced-High (purple), Sensitive (magenta); 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).

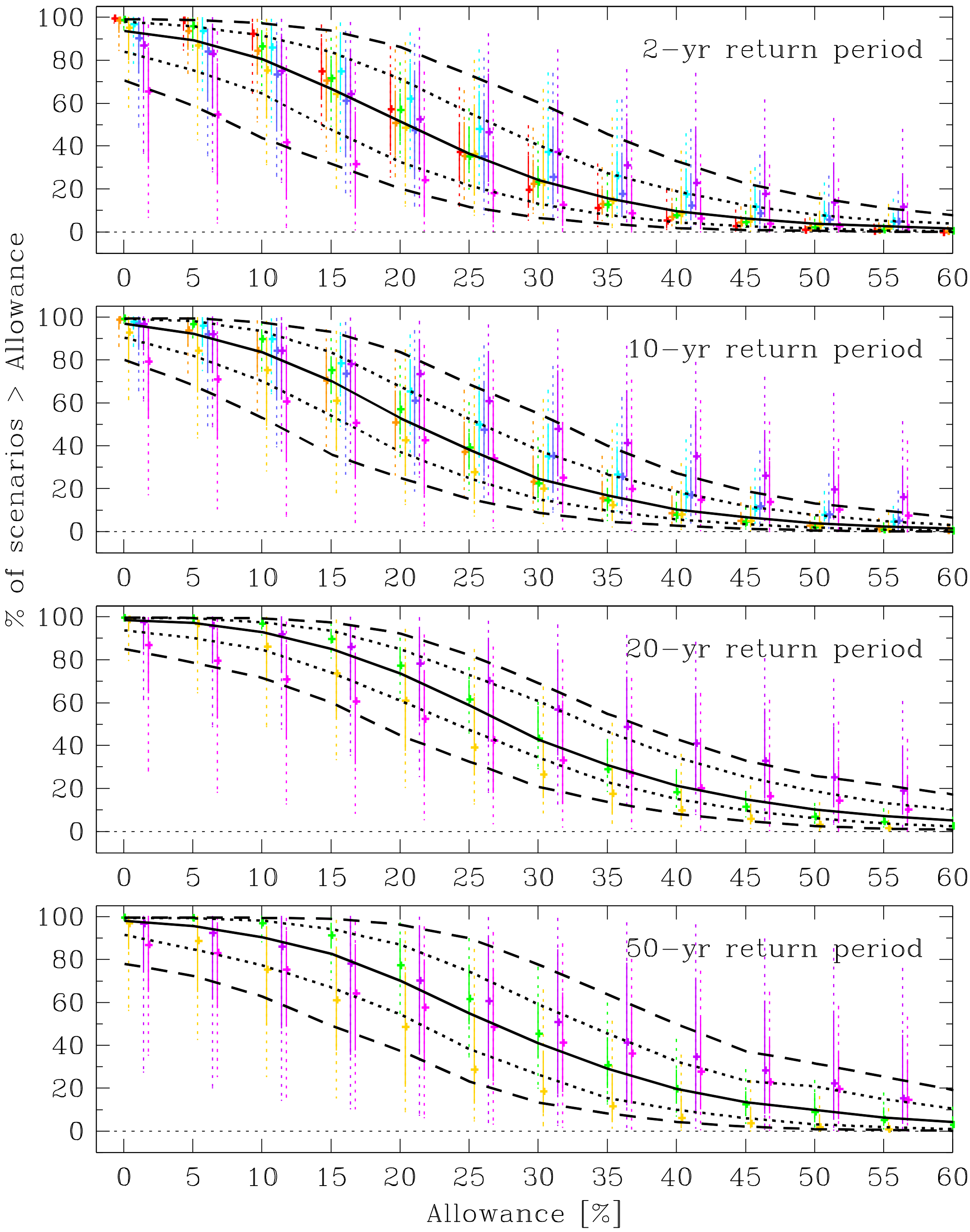


Figure B.6.38 As Figure B.37 but for the Humber river-basin region (2080s A1F1).

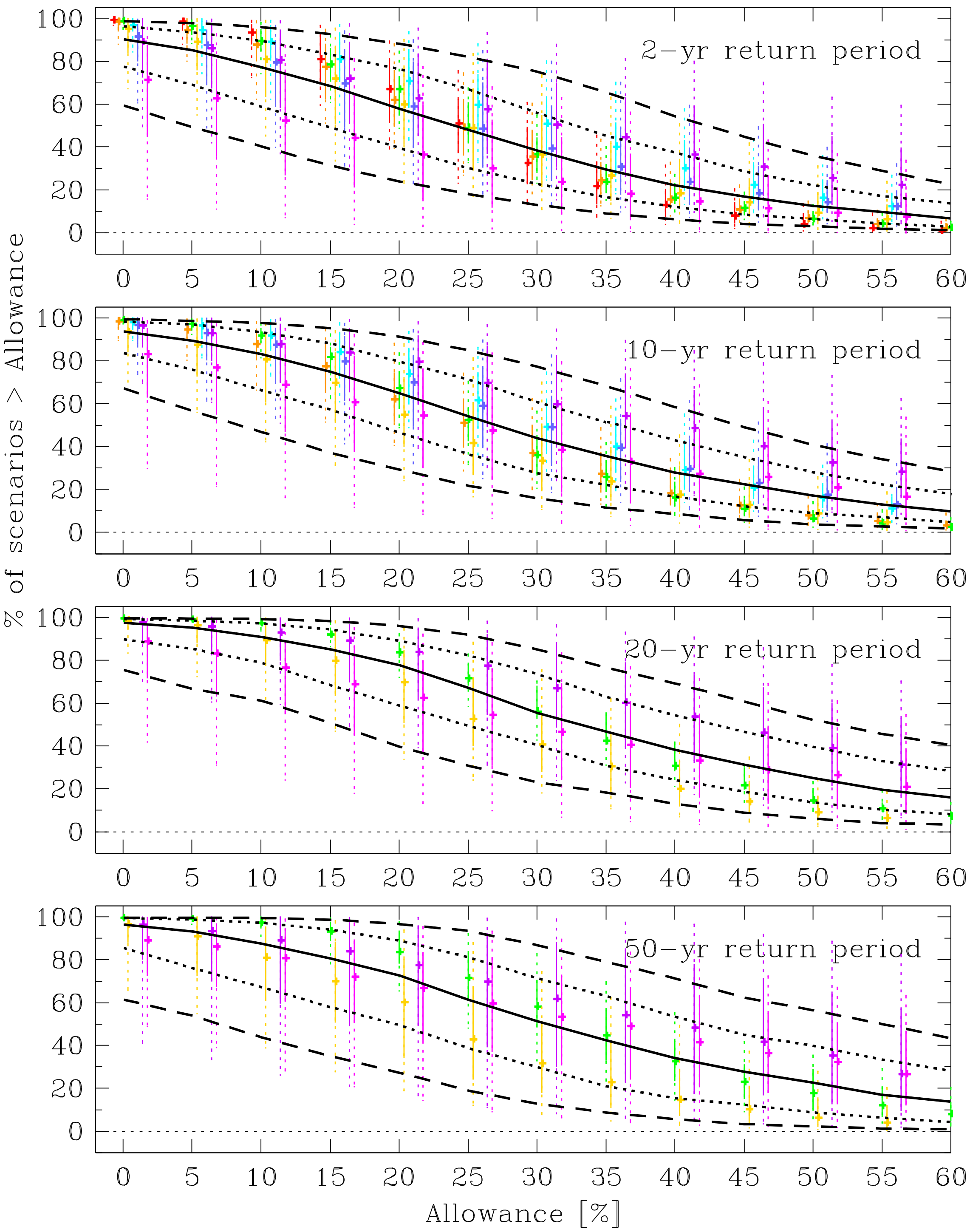


Figure B.6.39 As Figure B.37 but for the Anglian river-basin region (2080s A1F1).

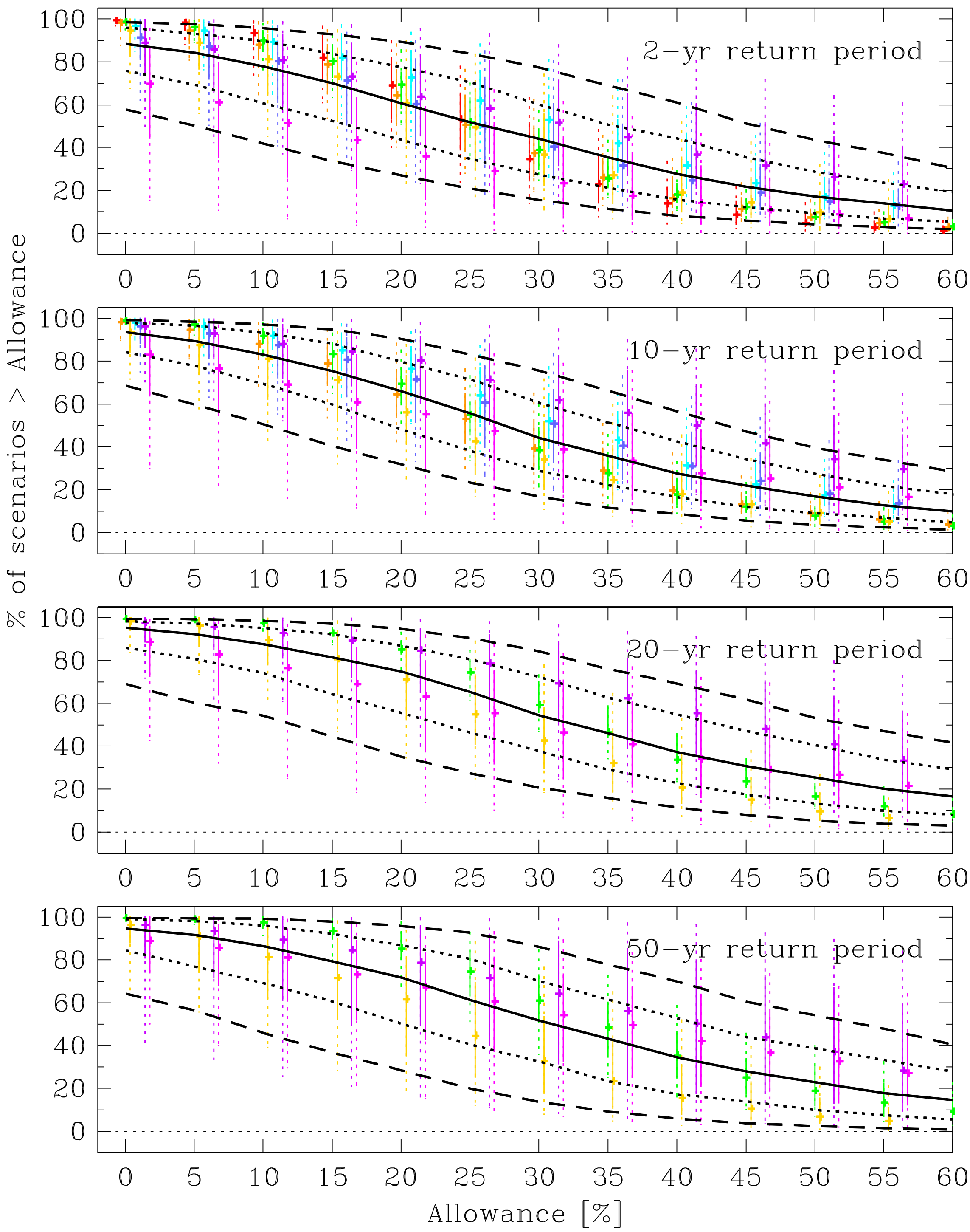


Figure B.6.40 As Figure B.37 but for the Thames river-basin region (2080s A1F1).

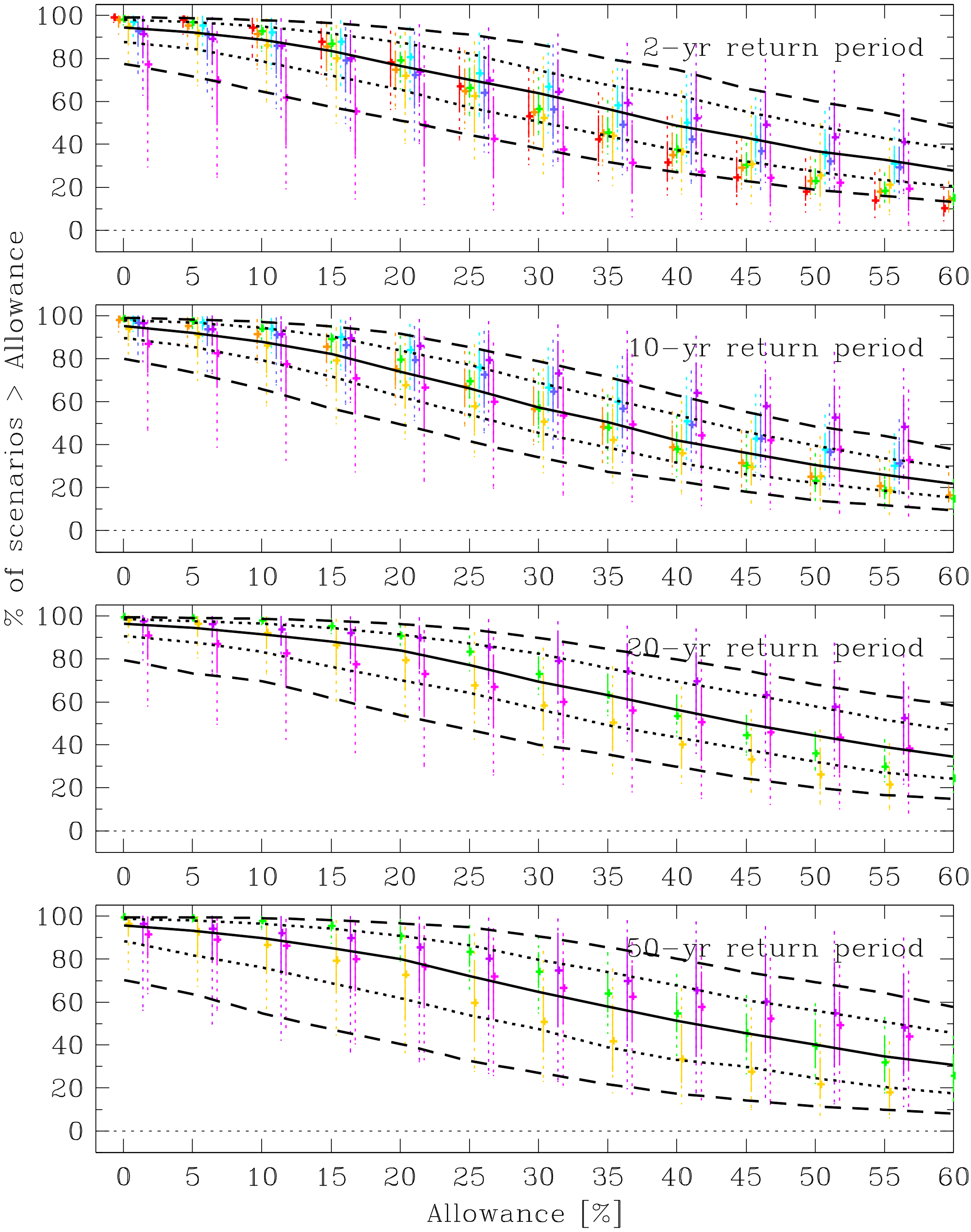


Figure B.6.41 As Figure B.37 but for the South-East England river-basin region (2080s A1F1).

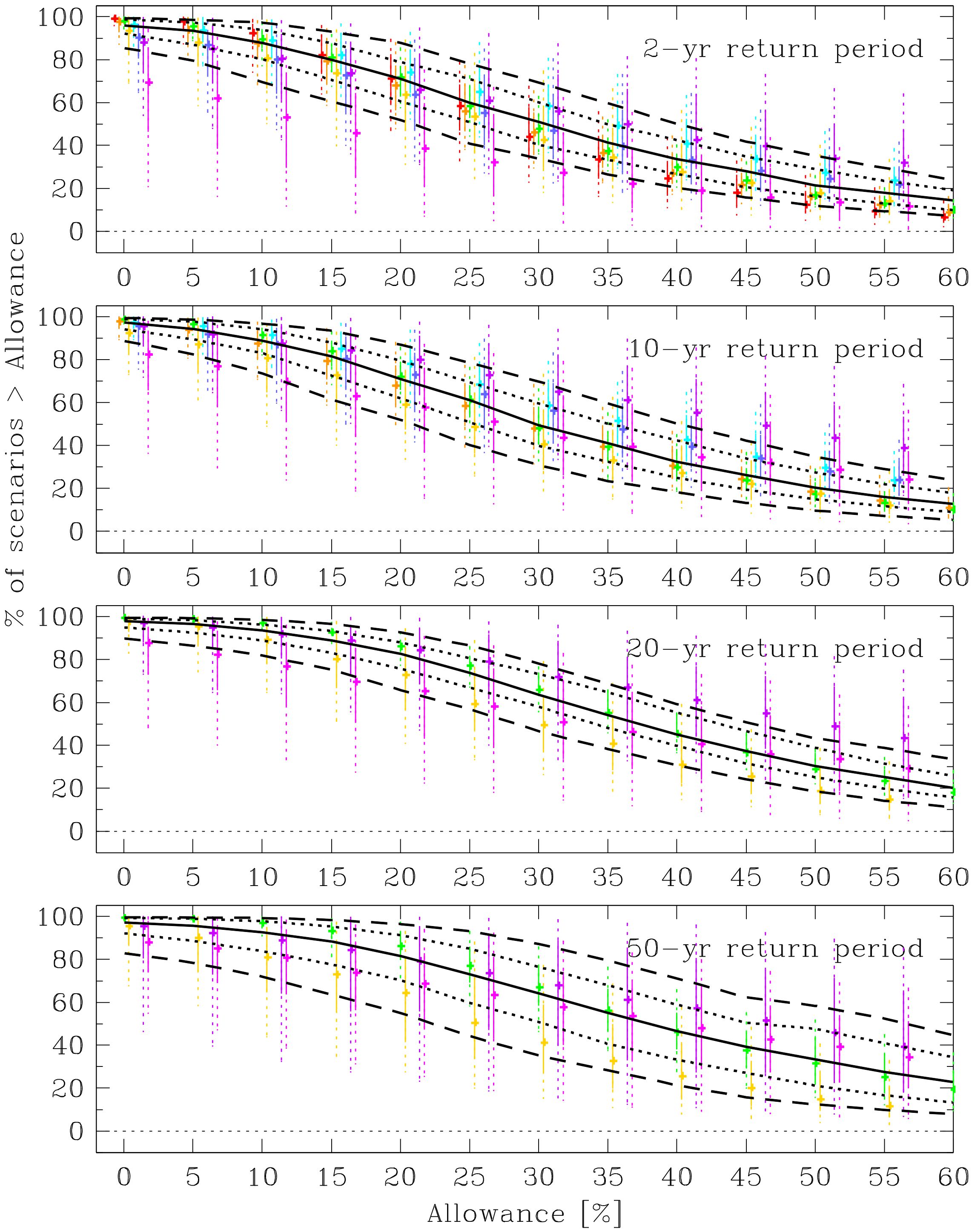


Figure B.6.42 As Figure B.37 but for the South-West England river-basin region (2080s A1F1).

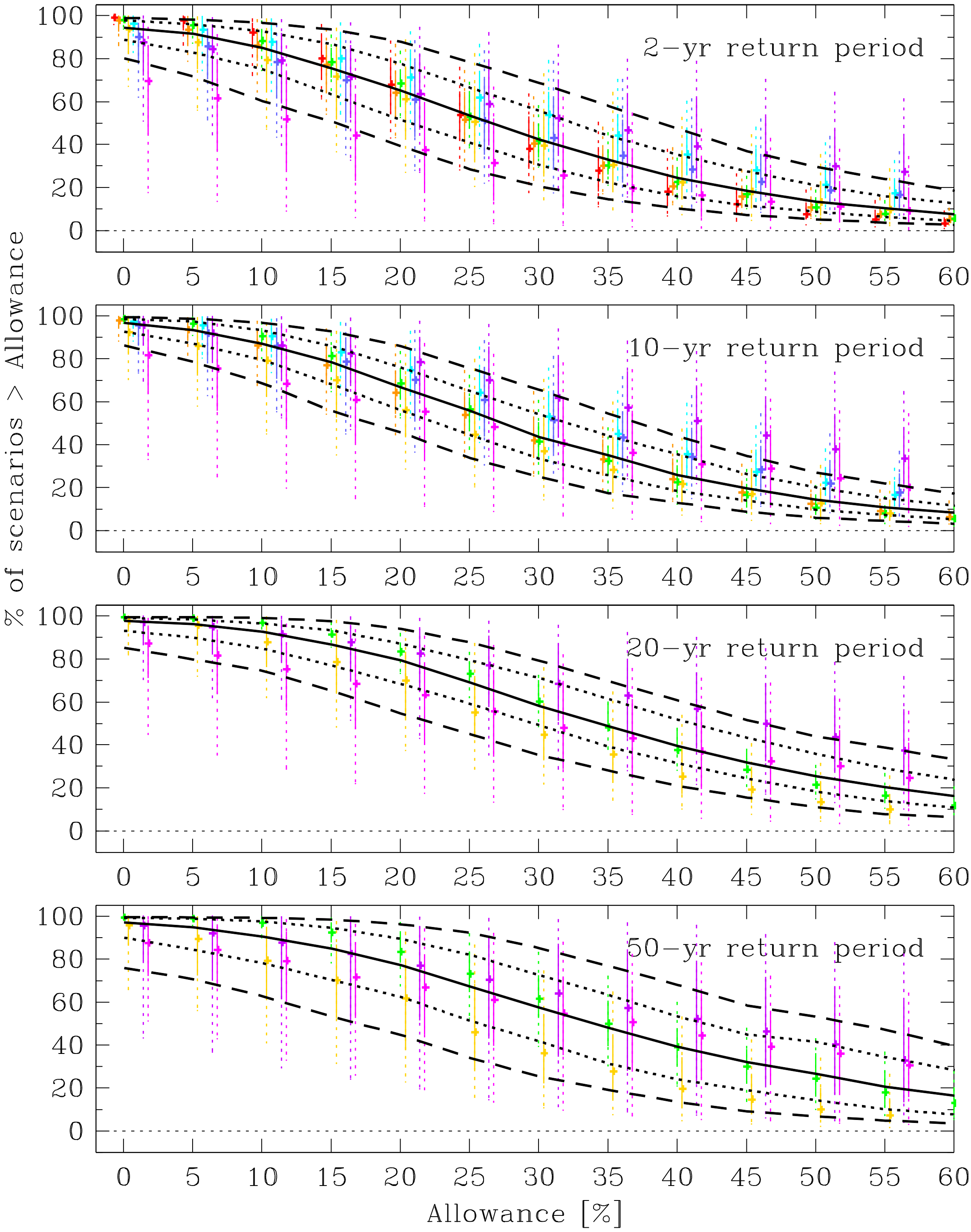


Figure B.6.43 As Figure B.37 but for the Severn England river-basin region (2080s A1F1).

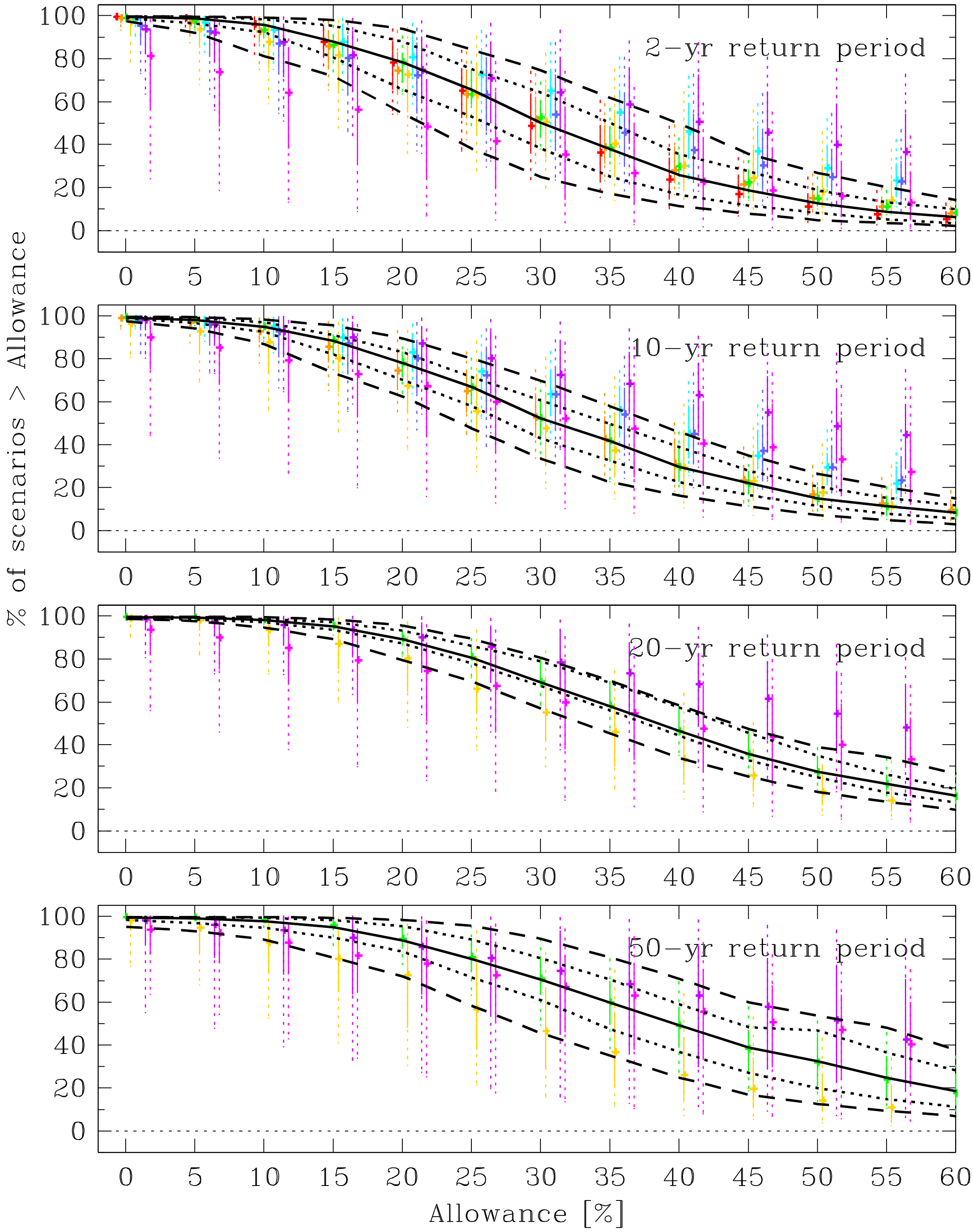


Figure B.6.44 As Figure B.37 but for the West Wales river-basin region (2080s A1F1).

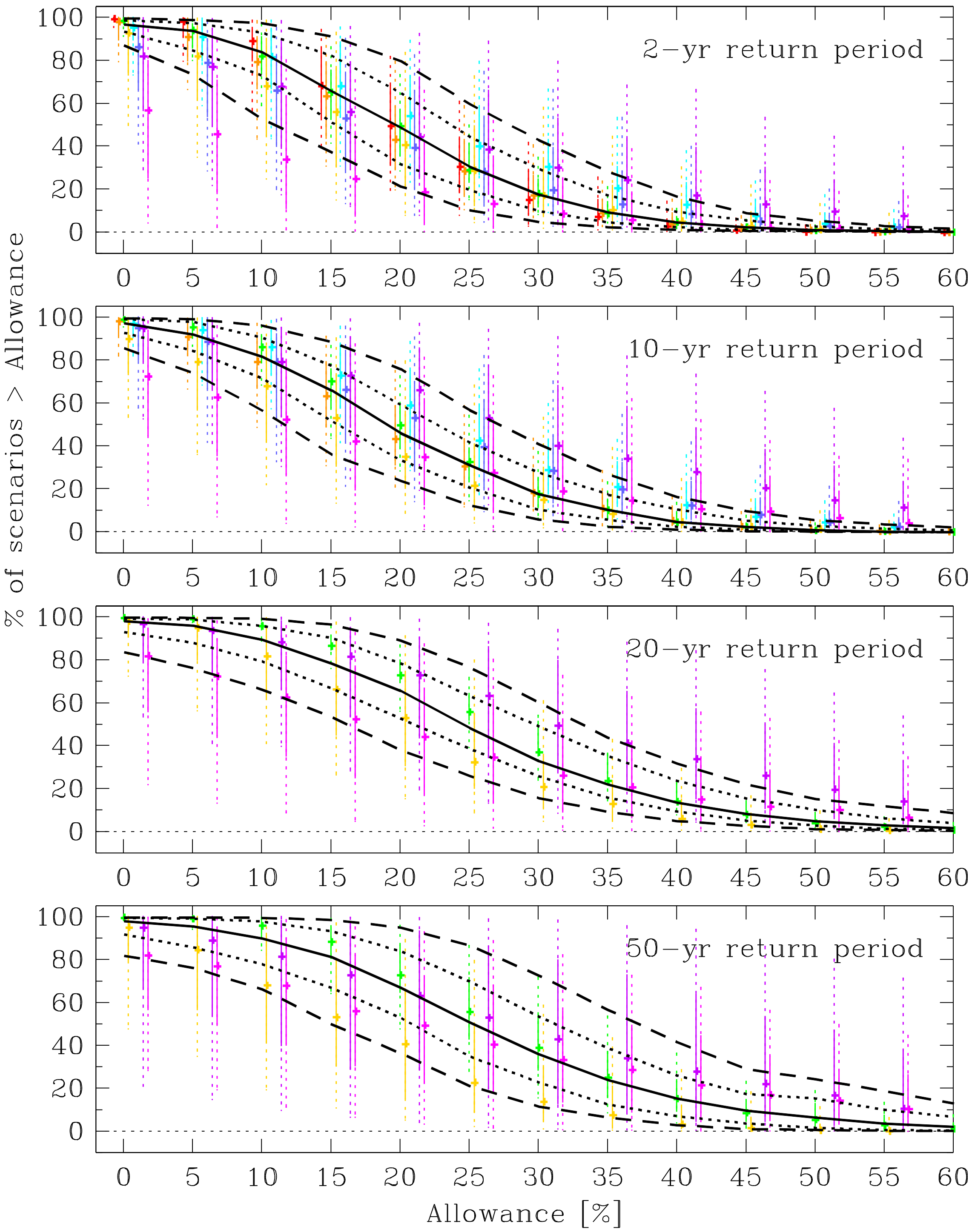


Figure B.6.45 As Figure B.37 but for the Dee river-basin region (2080s A1F1).

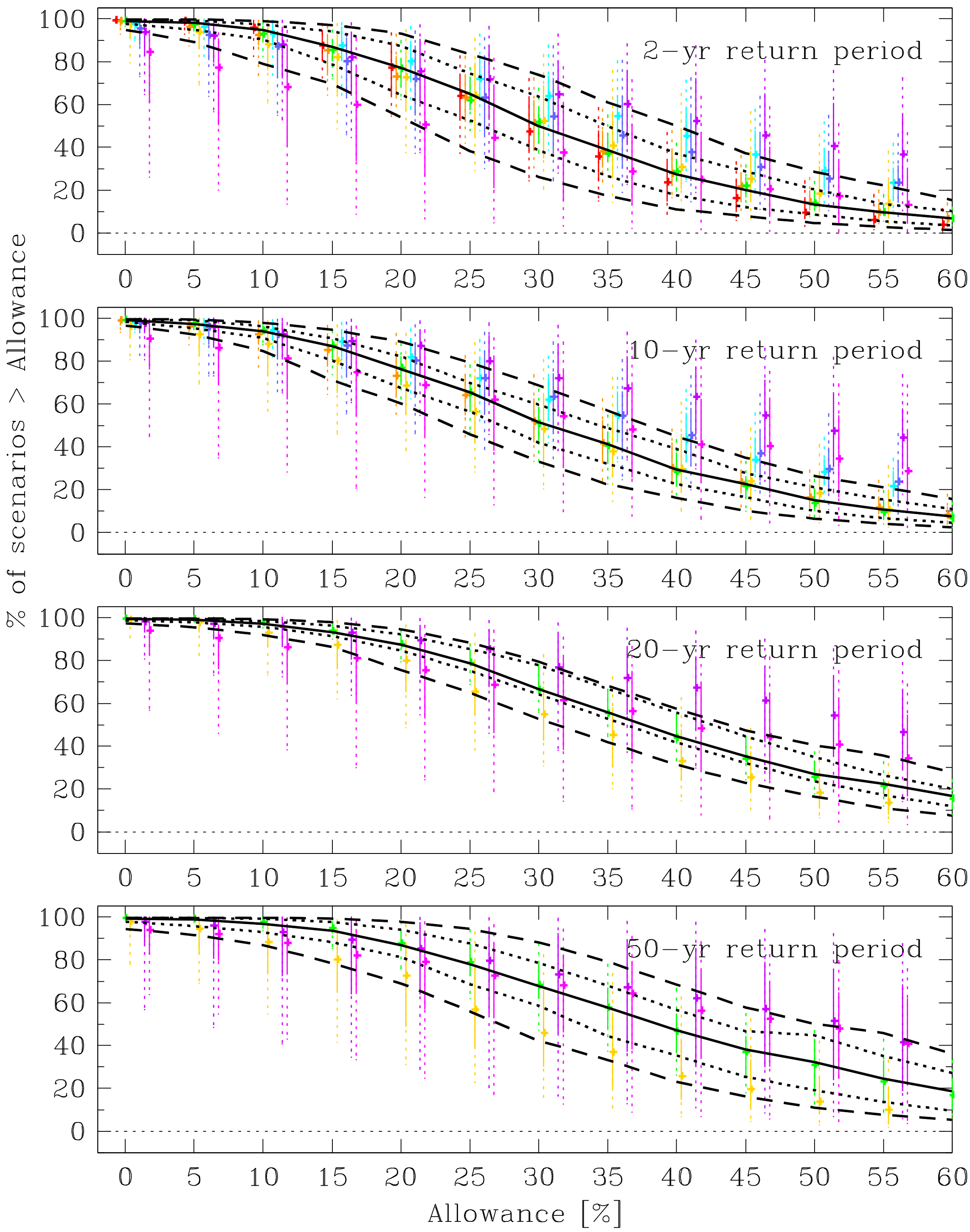


Figure B.6.46 As Figure B.37 but for the North-West England river-basin region (2080s A1F1).

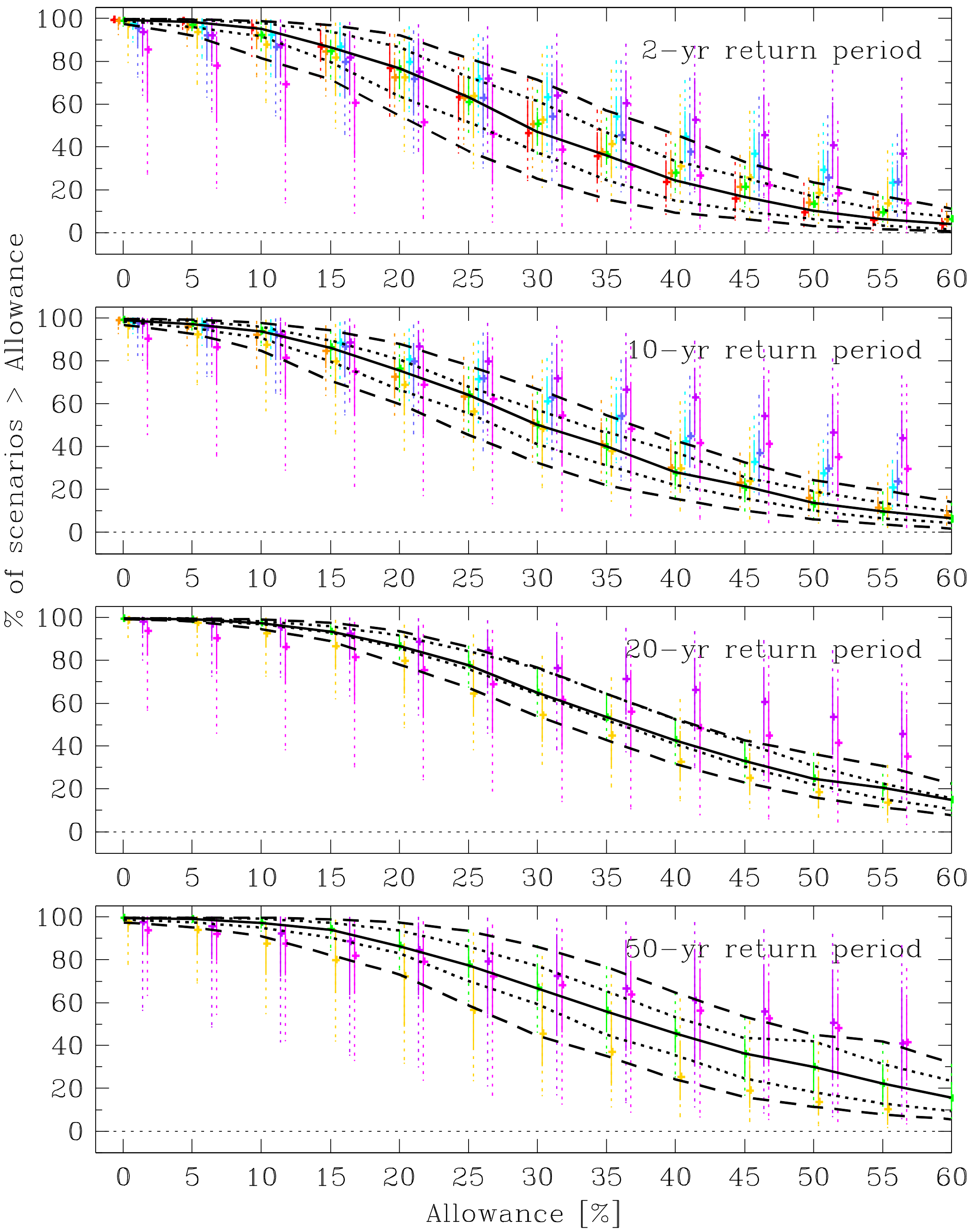


Figure B.6.47 As Figure B.37 but for the Solway river-basin region (2080s A1F1).

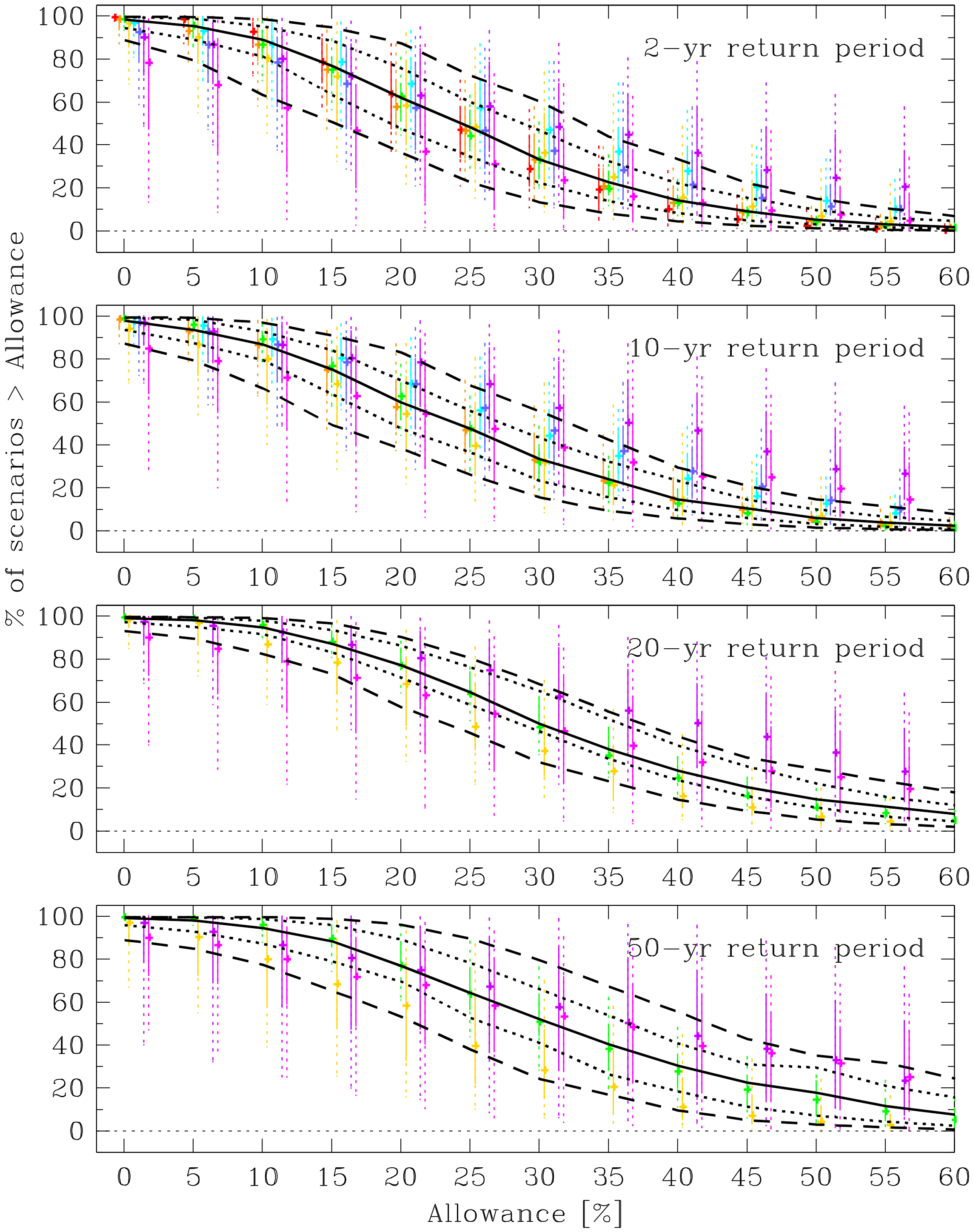


Figure B.6.48 As Figure B.37 but for the Tweed river-basin region (2080s A1F1).

B.2 Comparisons of regional risk curves between regions

The section presents plots comparing the central-estimates of the regional risk (i.e. without the uncertainty bands based on standard deviation) for the 12 river-basin regions in England and Wales, for each of four time-horizon and emissions scenario combinations:

- 2020s time-horizon under A1B (Medium) emissions (Figure B.49),
- 2050s time-horizon under A1B (Medium) emissions (Figure B.50),
- 2080s time-horizon under B1 (Low) emissions (Figure B.51),
- 2080s time-horizon under A1F1 (High) emissions (Figure B.52).

An equivalent plot for the 2080s time-horizon under A1B (Medium) emissions is presented in the main body of the report (Section 4.3; Figure 4.7).

The colour and line-type used to present the regional risk for each region in Figures B.49-B.52 is given in the table below. Note that cooler colours (cyan and blue) indicate more easterly regions, while hotter colours (orange and red) indicate more westerly regions. Similarly, darker colours (red and blue) indicate more northerly regions, while lighter colours (orange and cyan) indicate more southerly regions.

Key for Figures B.49-B.52:

Solway	red solid	Tweed	blue solid
North-West England	red dashed	Northumbria	blue dashed
Dee	red dotted	Humber	blue dotted
West Wales	orange solid	Anglian	cyan solid
Severn	orange dashed	Thames	cyan dashed
South-West England	orange dotted	South-East England	cyan dotted

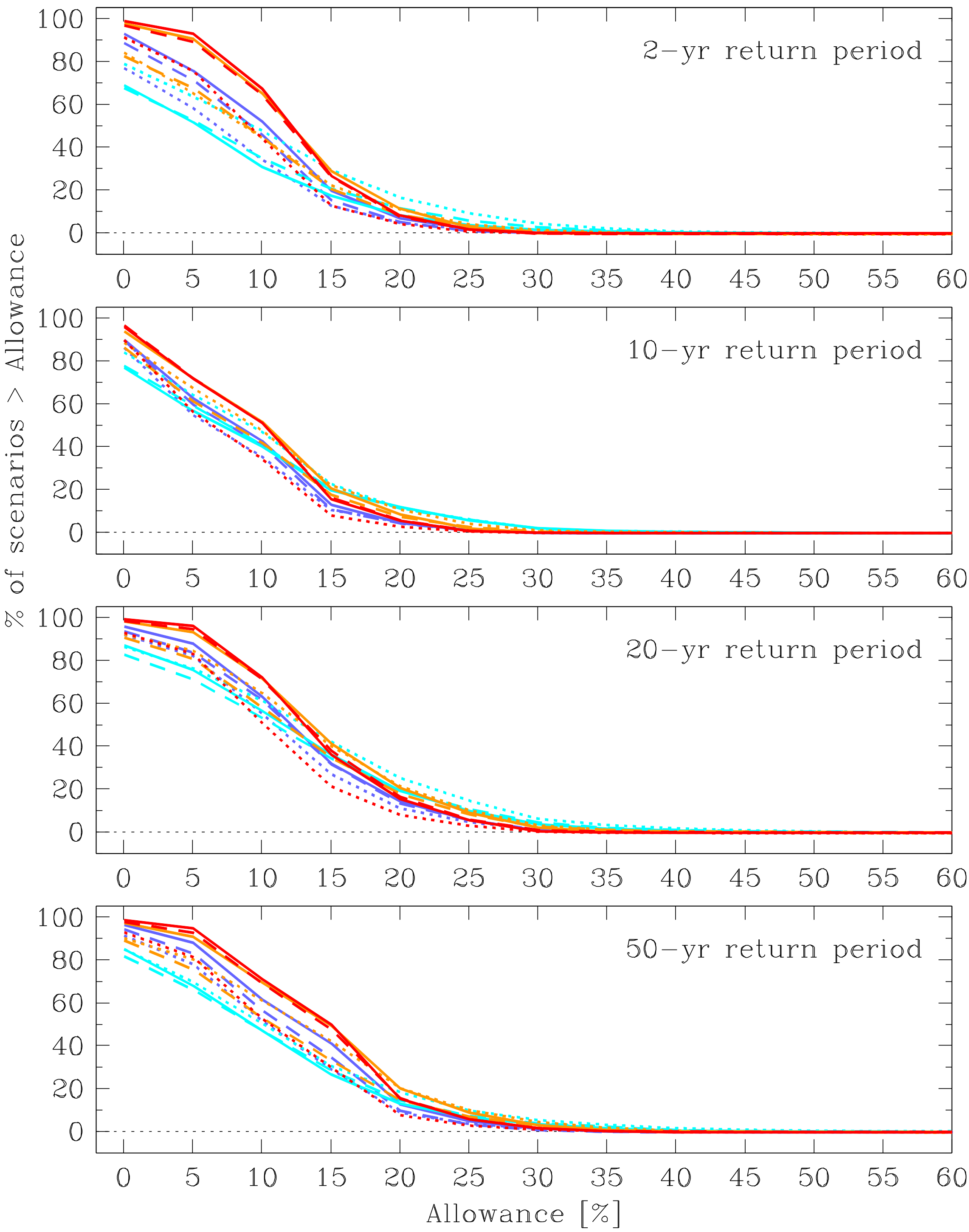


Figure B.6.49 Regional risk curves (central-estimates) for each of the 12 UKCP09 river-basin regions in England and Wales (2020s A1B). Key: Tweed – blue solid, Northumbria – blue dashed, Humber – blue dotted, Anglian – cyan solid, Thames – cyan dashed, South-East England – cyan dotted, Solway – red solid, North-West England – red dashed, Dee – red dotted, West Wales – orange solid, Severn – orange dashed, South-West England – orange dotted.

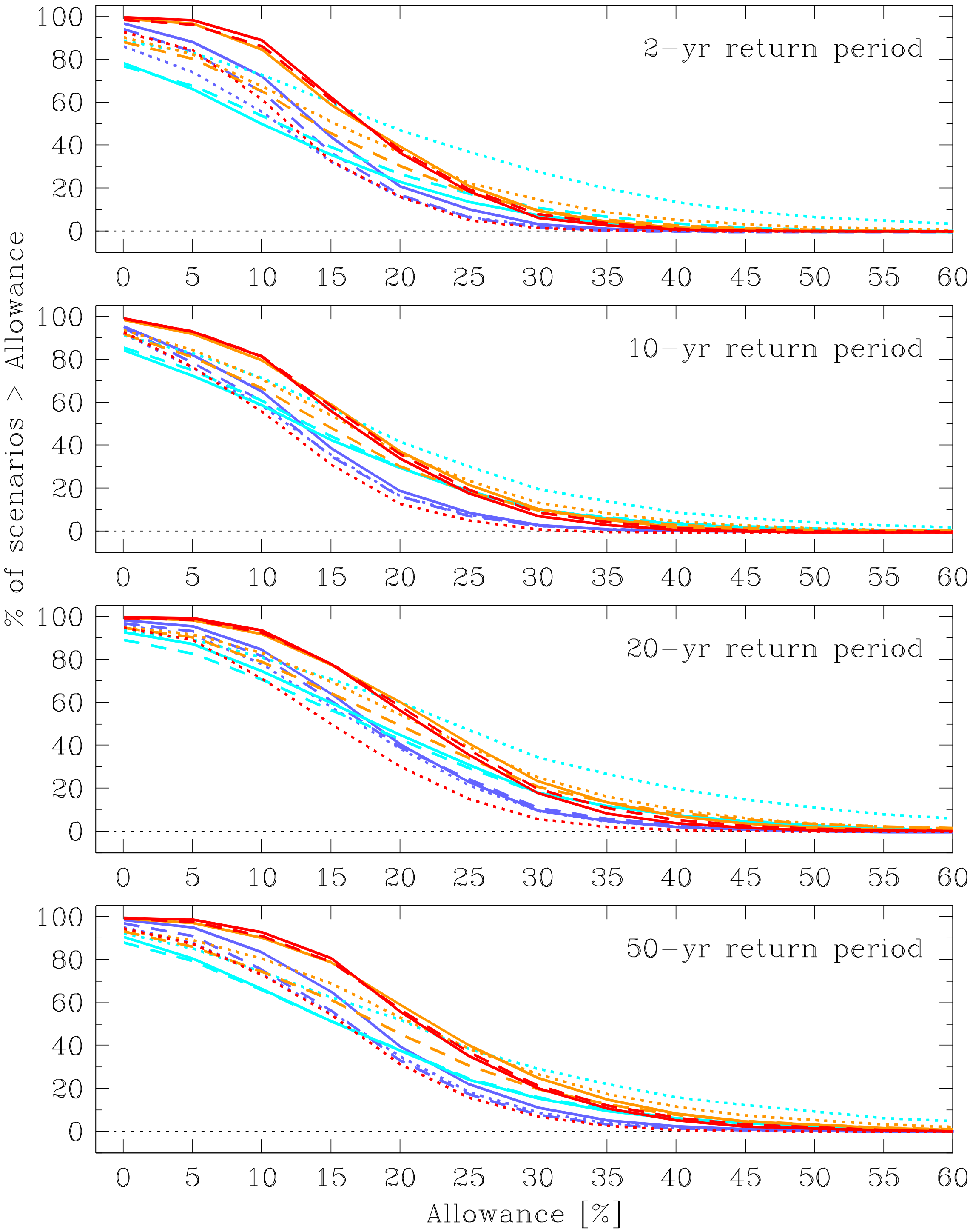


Figure B.6.50 As Figure B.49 but for the 2050s time-horizon under the A1B emissions scenario.

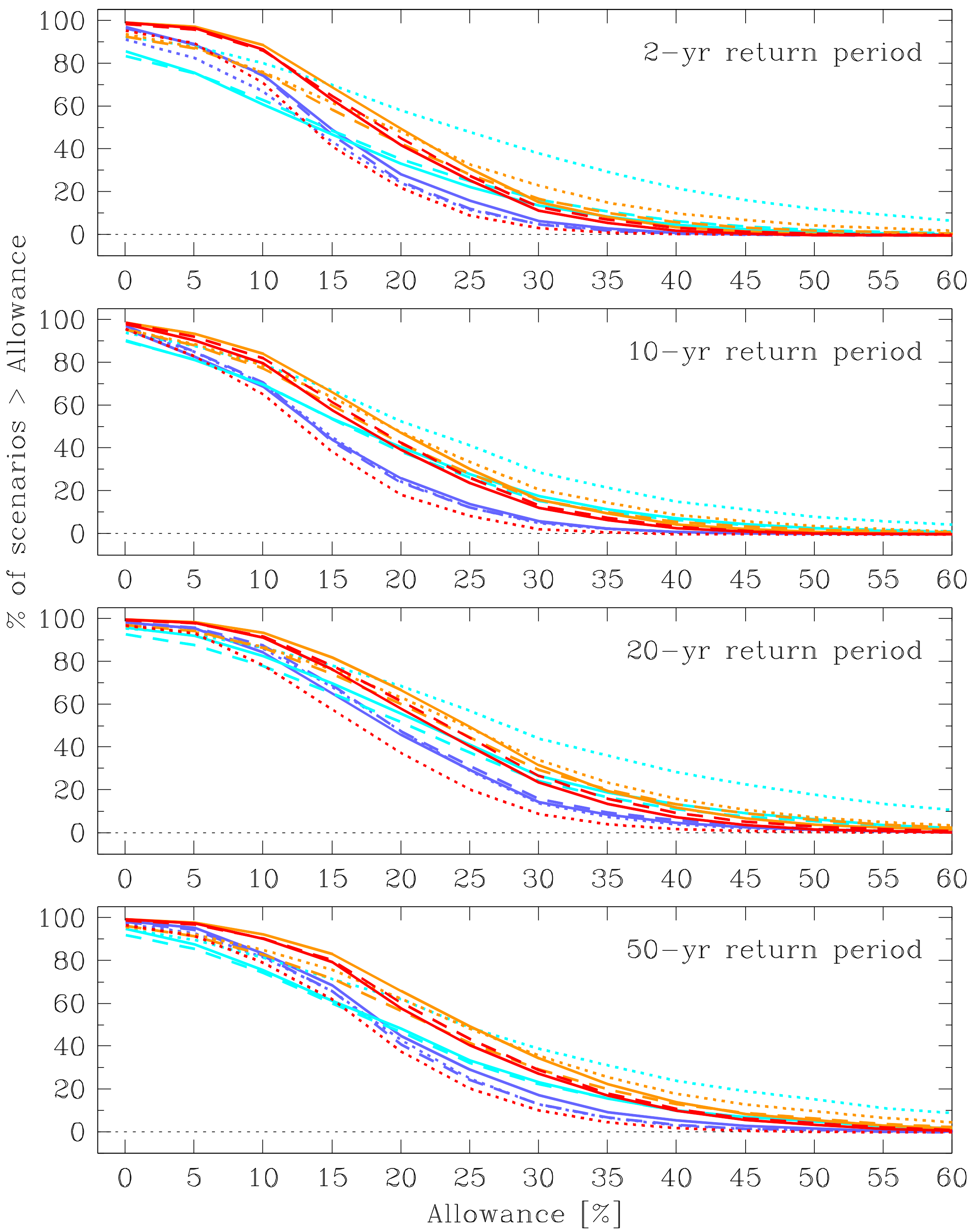


Figure B.6.51 As Figure B.49 but for the 2080s time-horizon under the B1 emissions scenario.

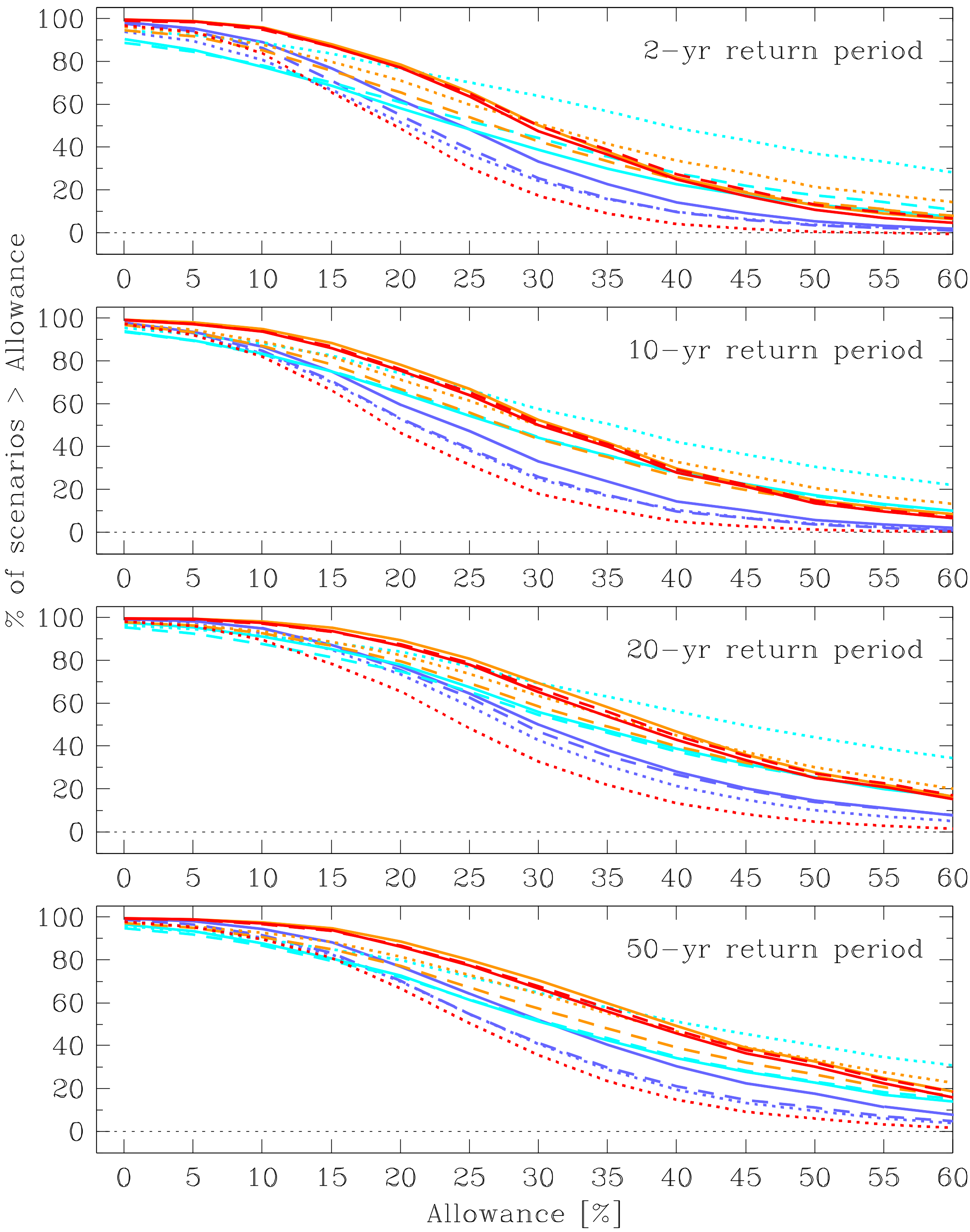
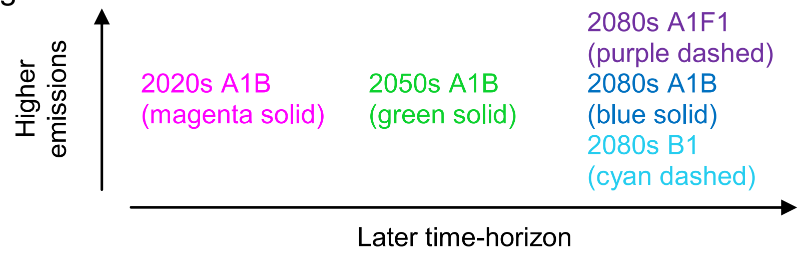


Figure B.6.52 As Figure B.49 but for the 2080s time-horizon under the A1F1 emissions scenario.

B.3 Comparisons of regional risk curves across time-horizons and emissions scenarios

This section presents plots comparing the central-estimates of the regional risk for the five time-horizon and emissions scenario combinations, for each of the 12 river-basin regions in England and Wales (Figures B.53-B.64). The colour and line-type used to present the regional risk curve for each time-horizon / emissions scenario combination is given in the table below.

Key for Figures B.53-B.64:



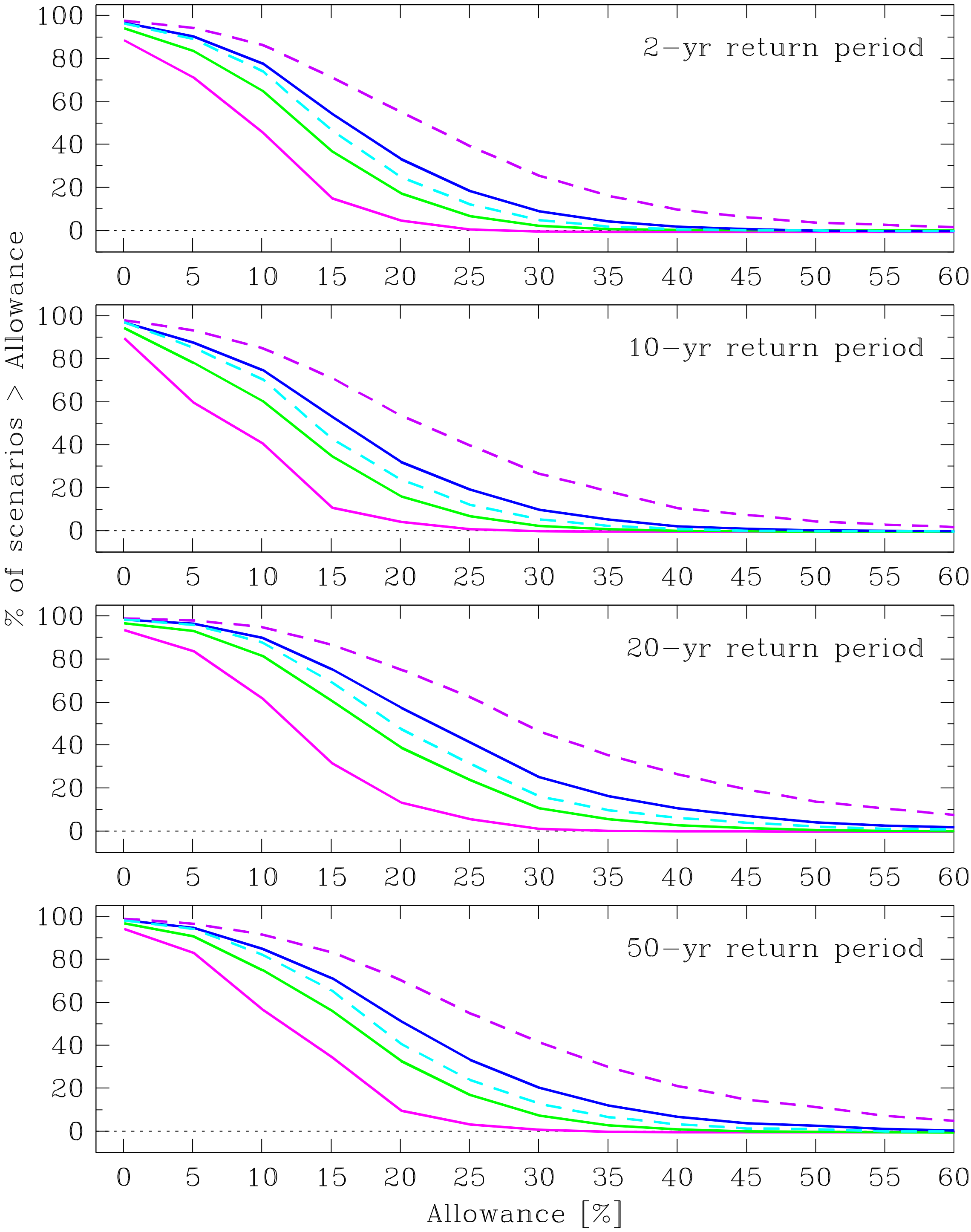


Figure B.6.53 Regional risk curves (central-estimates) for the Northumbria river-basin region, for five different time-horizons / emissions scenarios: 2020s A1B (magenta), 2050s A1B (green), 2080s A1B (blue), 2080s B1 (cyan dashed), 2080s A1F1 (purple dashed).

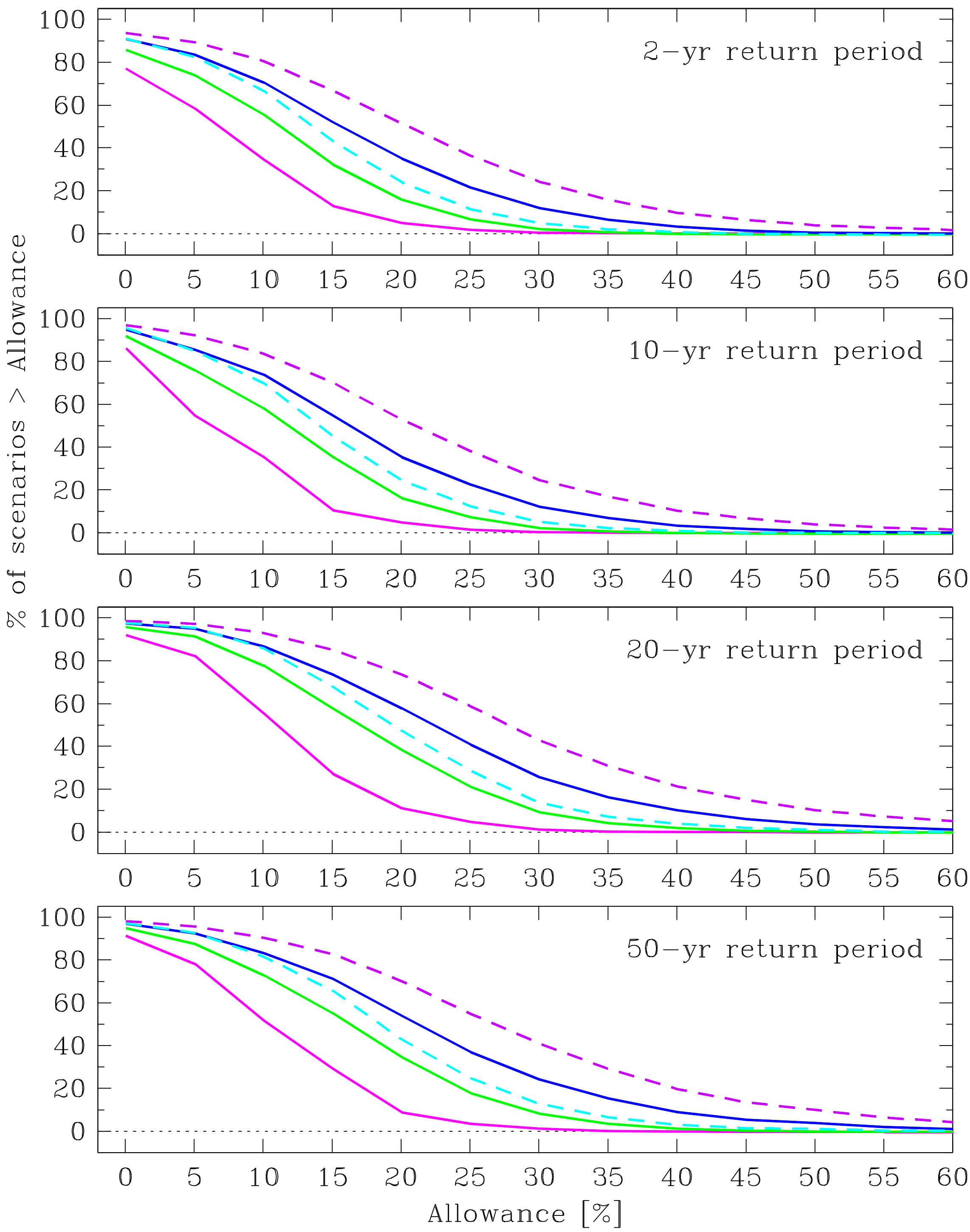


Figure B.6.54 As Figure B.53 but for the Humber river-basin region.

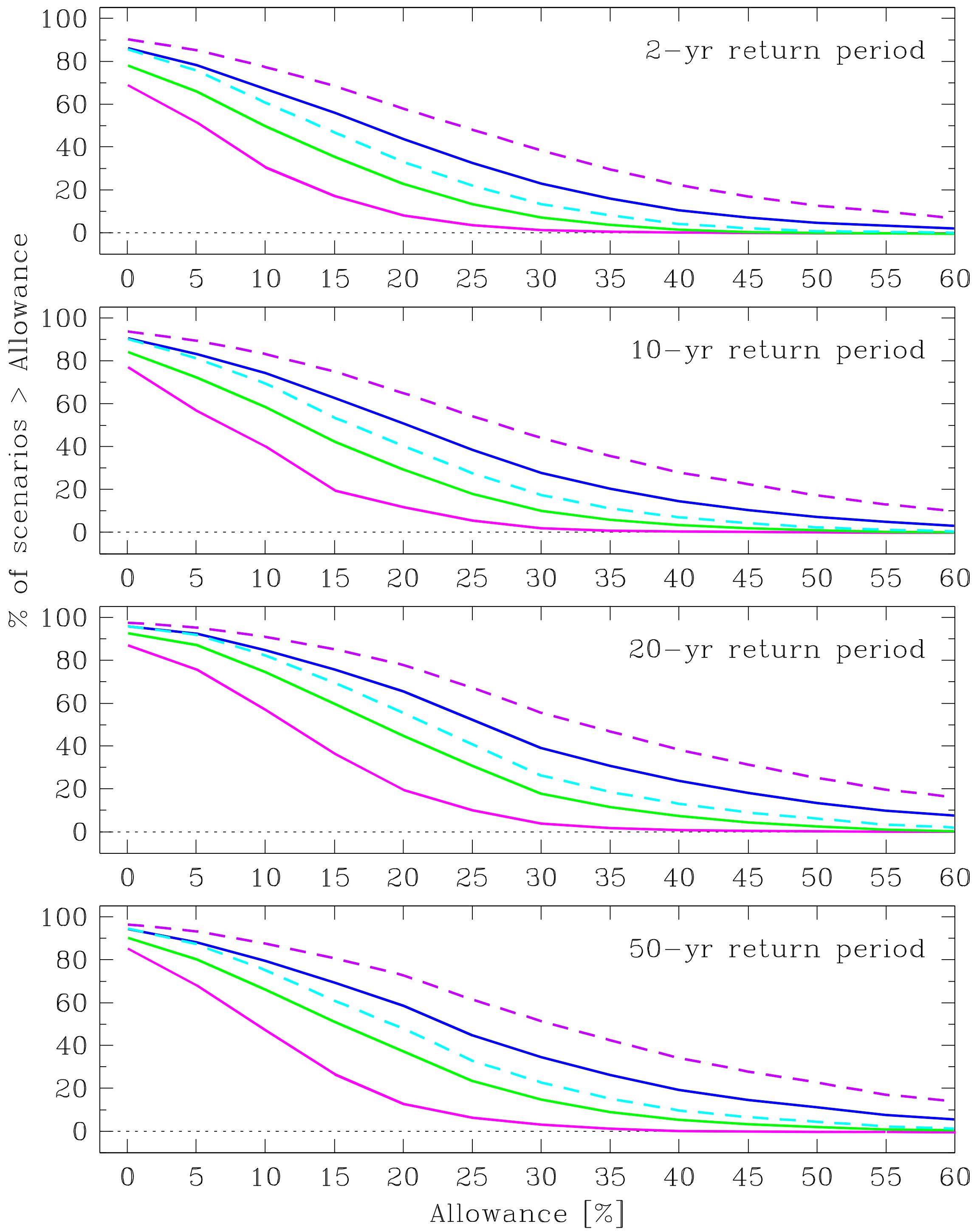


Figure B.6.55 As Figure B.53 but for the Anglian river-basin region.

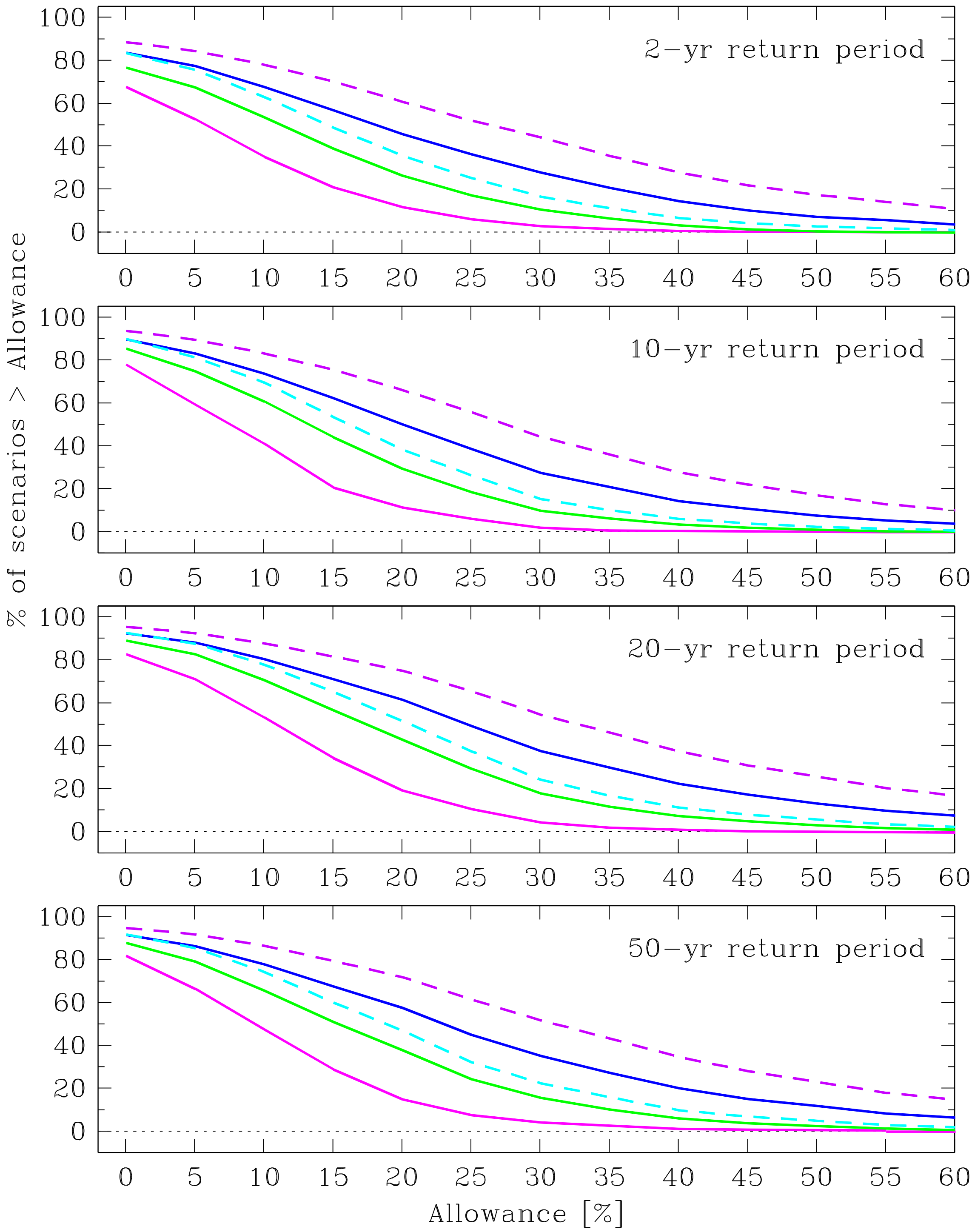


Figure B.6.56 As Figure B.53 but for the Thames river-basin region.

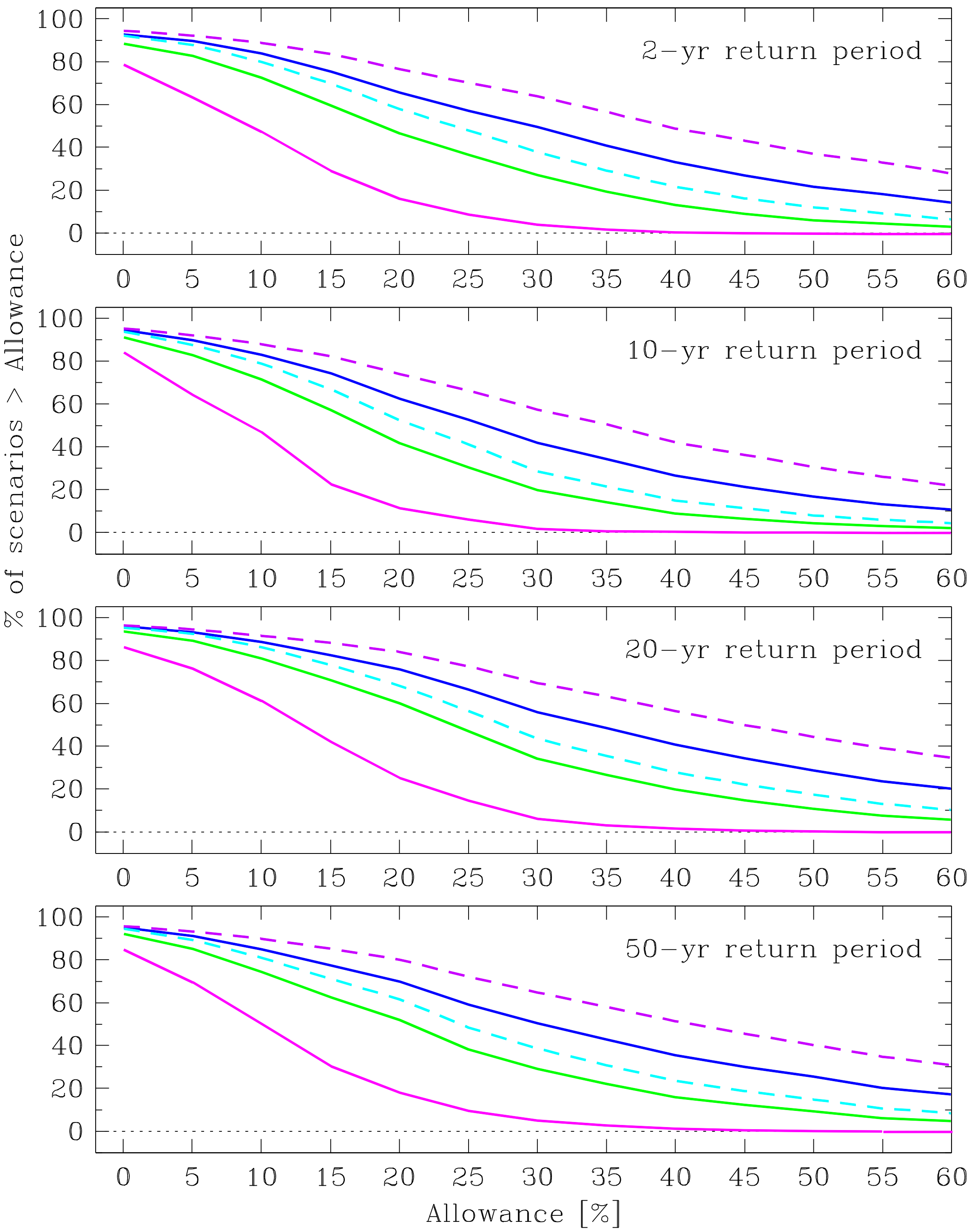


Figure B.6.57 As Figure B.53 but for the South-East England river-basin region.

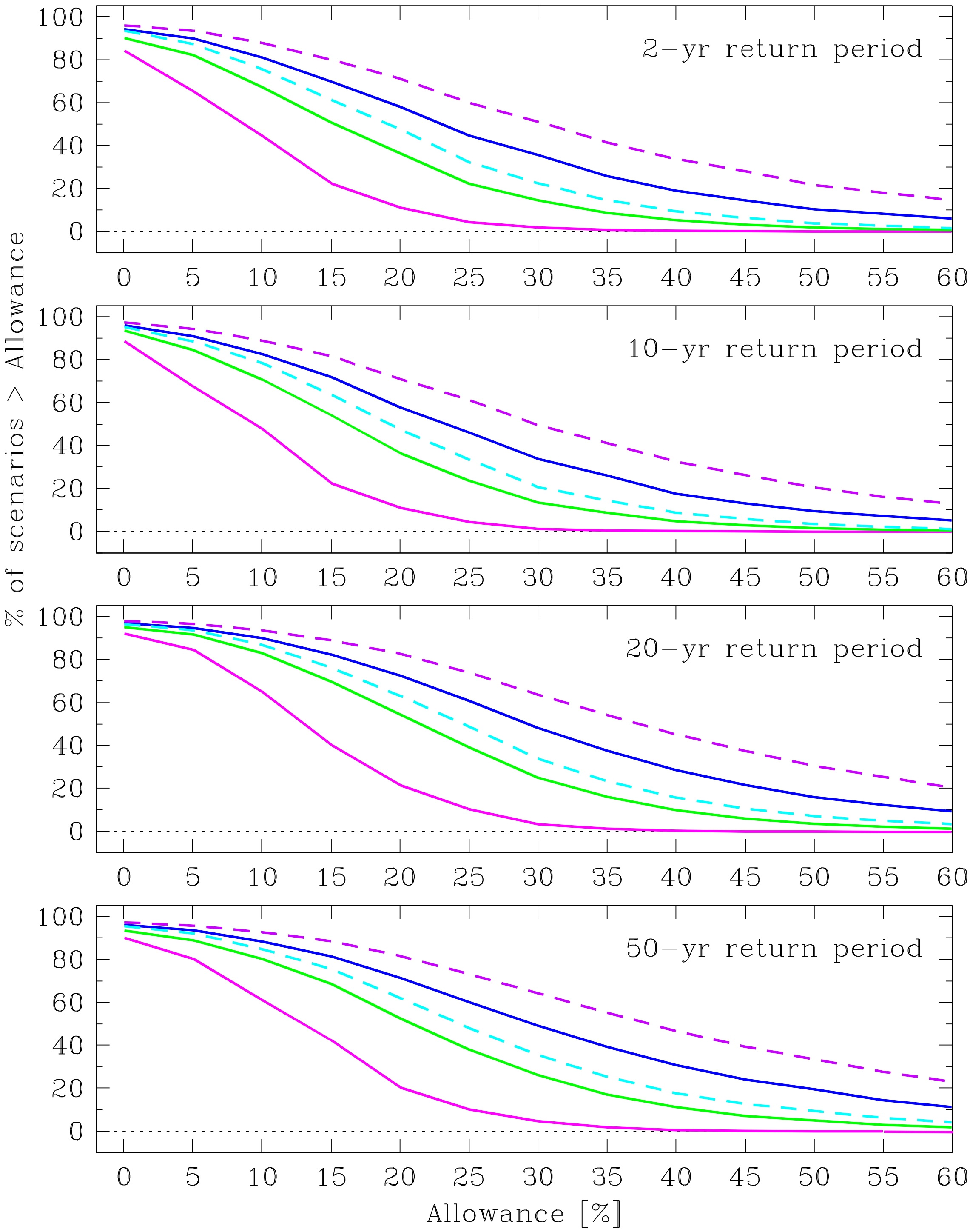


Figure B.6.58 As Figure B.53 but for the South-West England river-basin region.

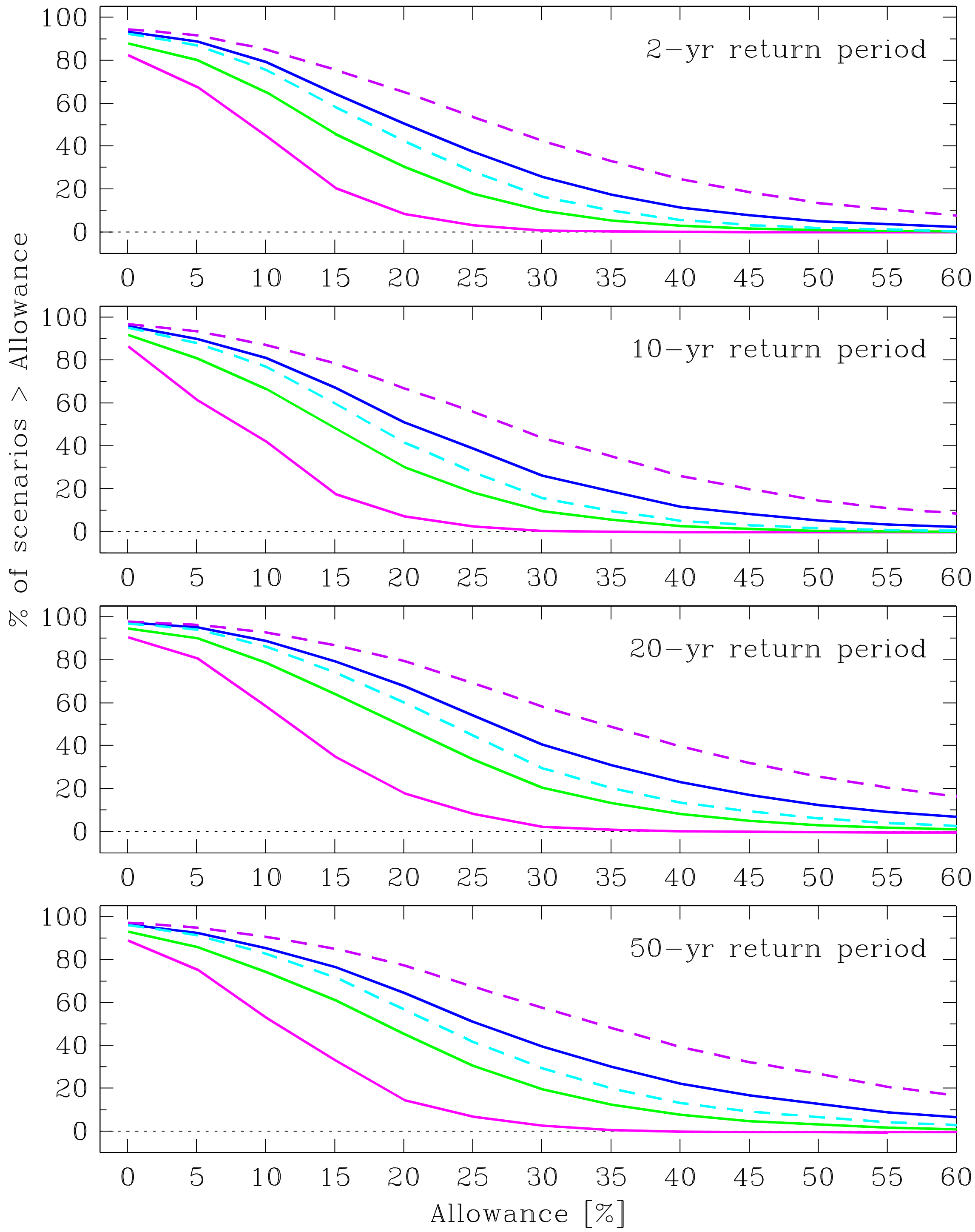


Figure B.6.59 As Figure B.53 but for the Severn river-basin region.

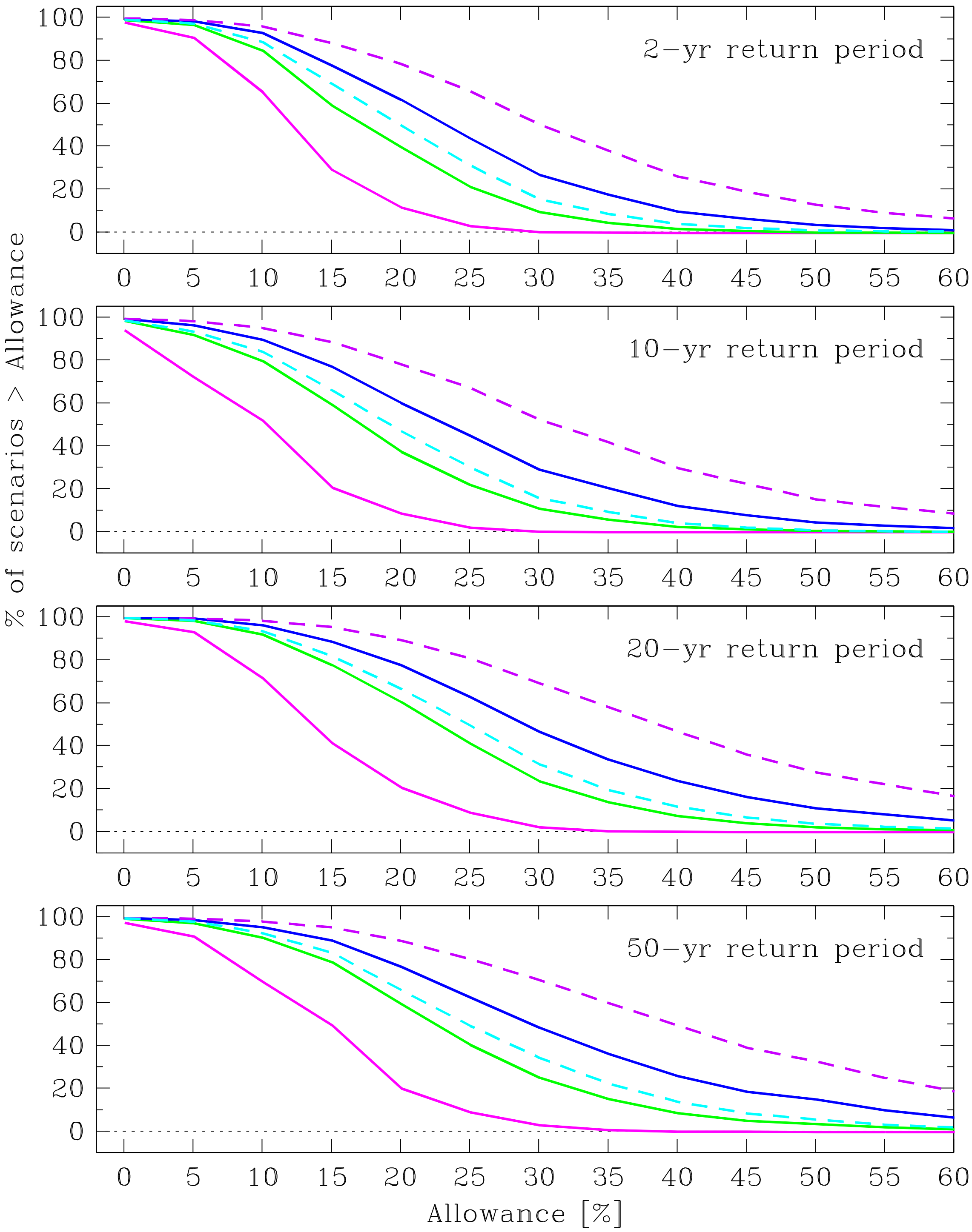


Figure B.6.60 As Figure B.53 but for the West Wales river-basin region.

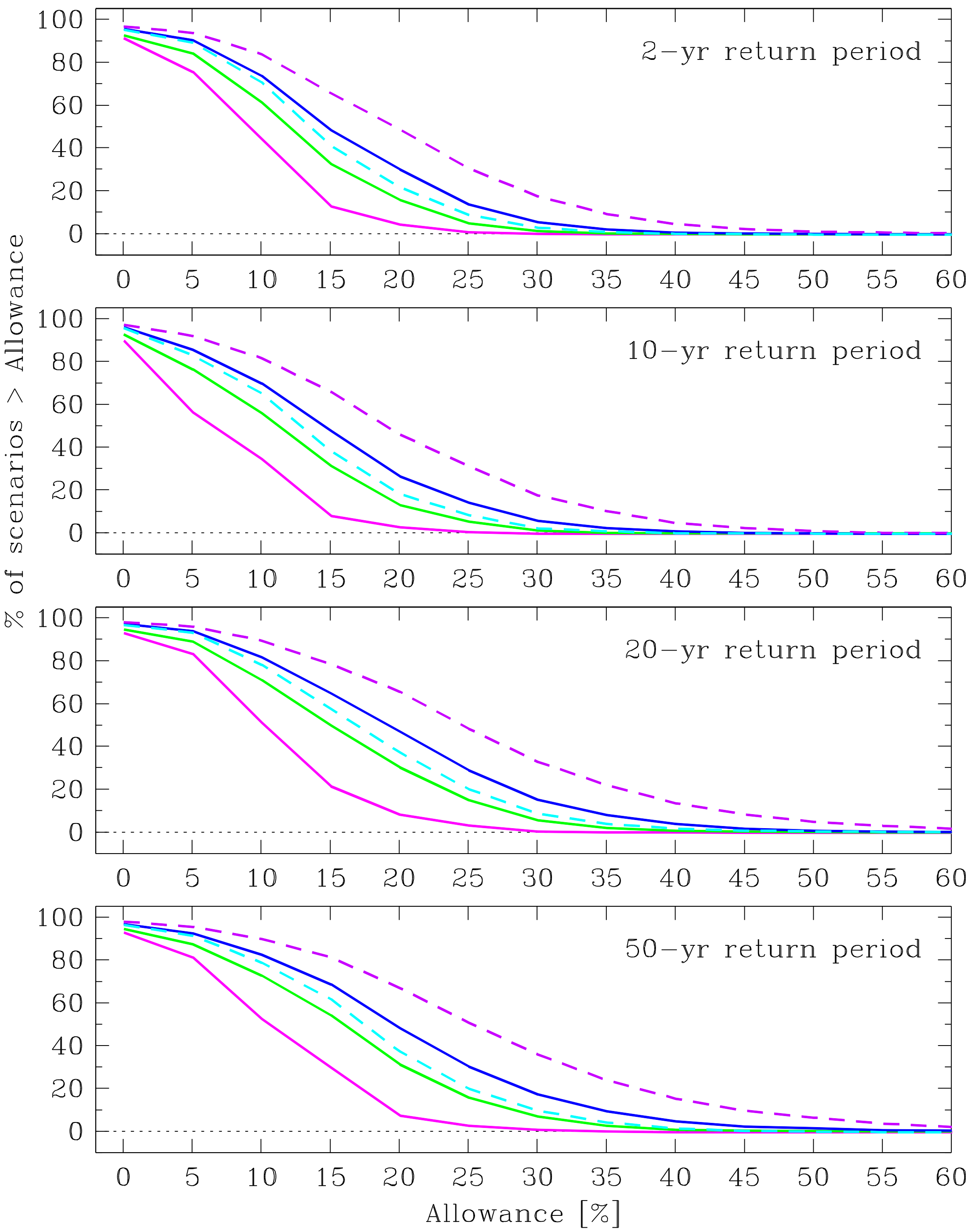


Figure B.6.61 As Figure B.53 but for the Dee river-basin region.

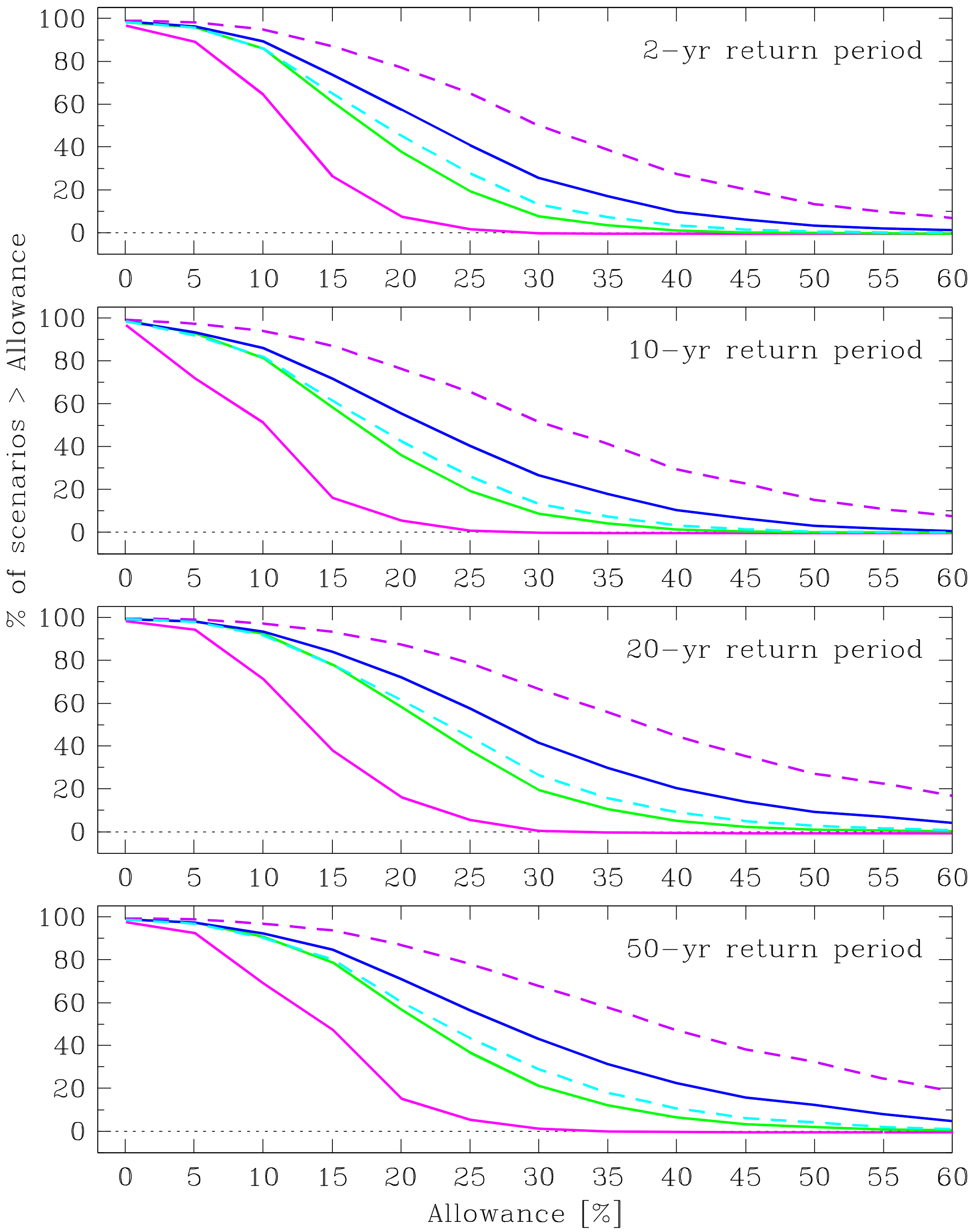


Figure B.6.62 As Figure B.53 but for the North-West England river-basin region.

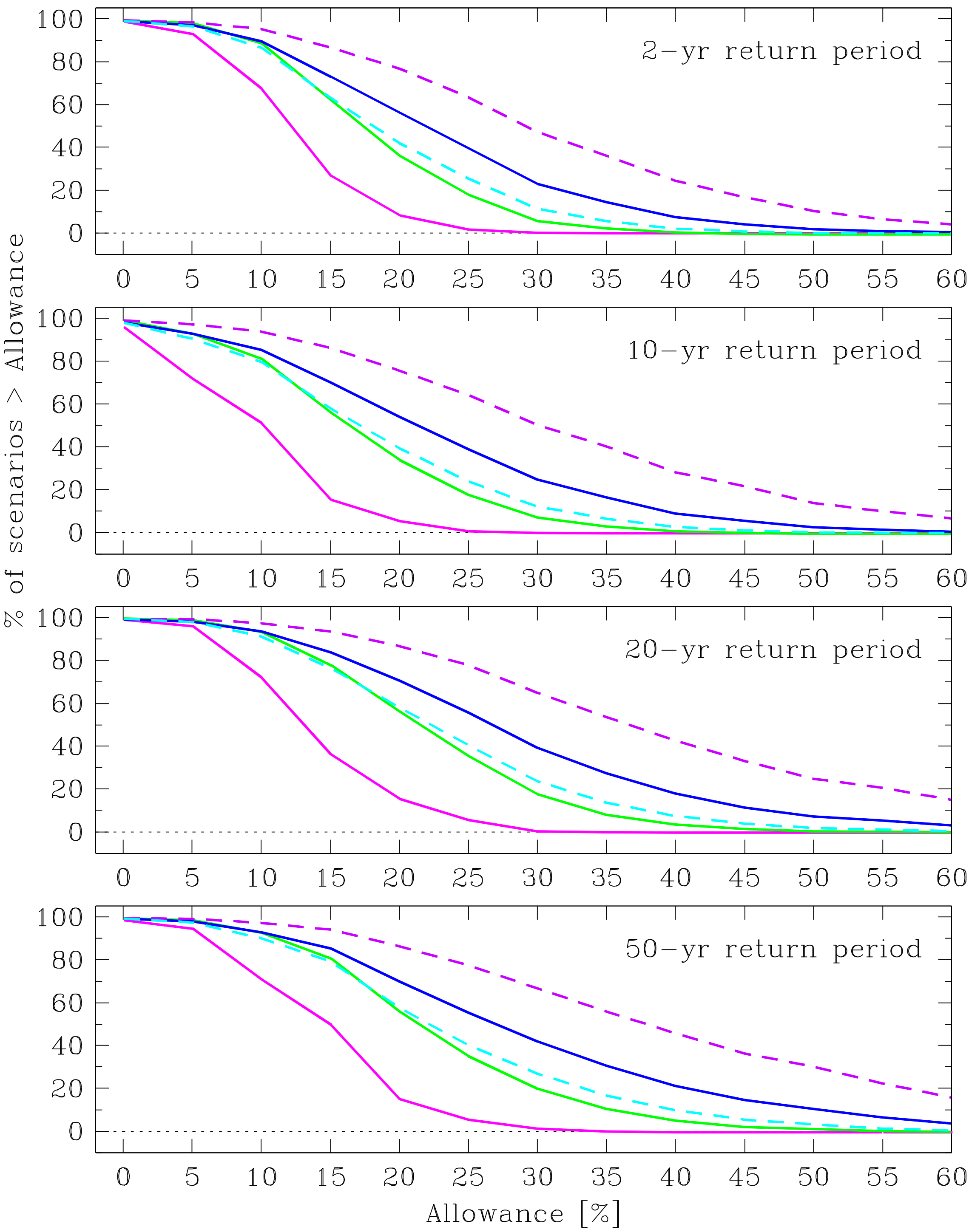


Figure B.6.63 As Figure B.53 but for the Solway river-basin region.

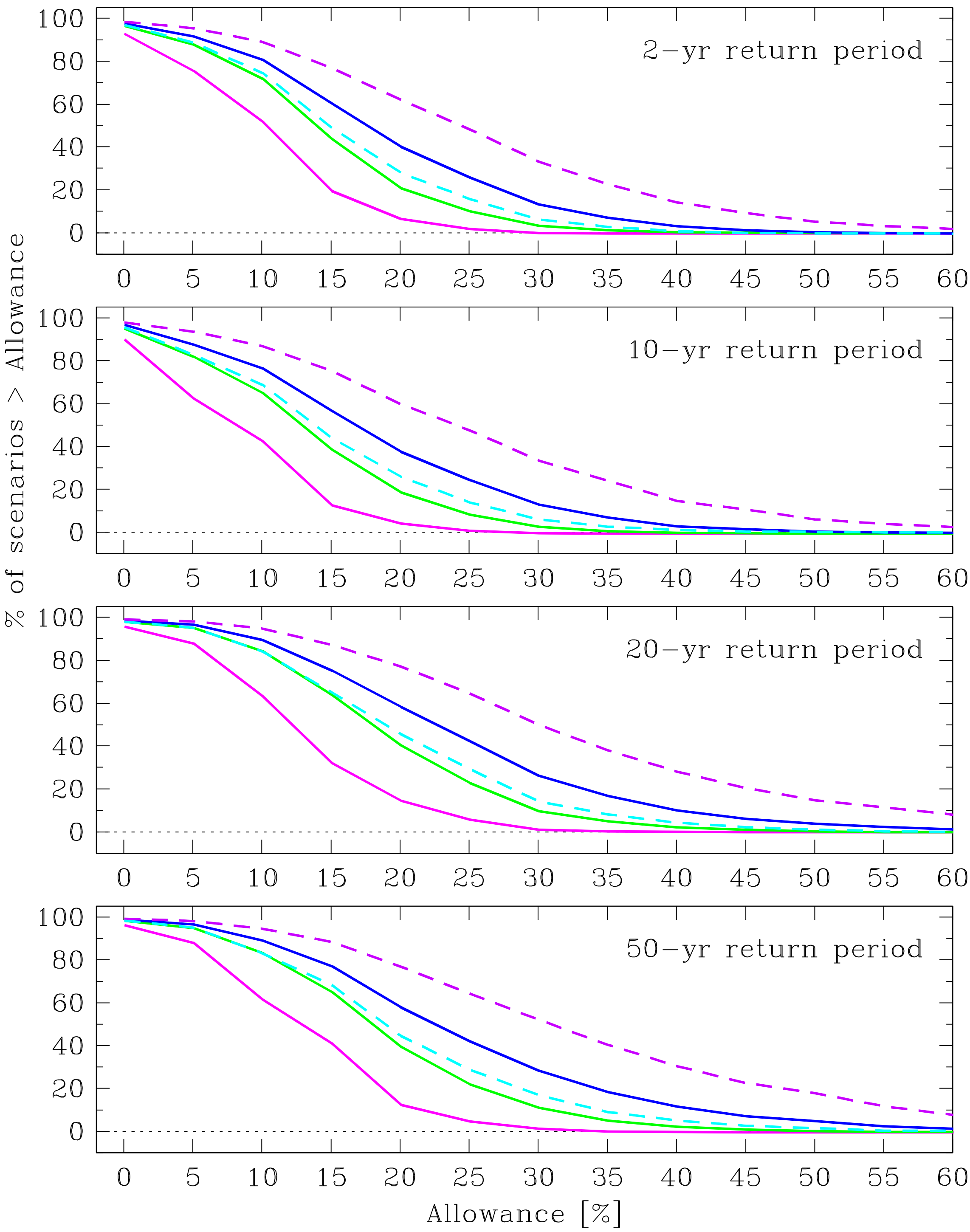


Figure B.6.64 As Figure B.53 but for the Tweed river-basin region.

Appendix C: Extension to higher return periods for alternative time-horizons and emissions scenarios

The section presents plots showing how the allowance may vary with return period for the 12 river-basin regions in England and Wales, for each of four time-horizon and emissions scenario combinations:

- 2020s time-horizon under A1B (Medium) emissions (Figure C.1),
- 2050s time-horizon under A1B (Medium) emissions (Figure C.2),
- 2080s time-horizon under B1 (Low) emissions (Figure C.3),
- 2080s time-horizon under A1F1 (High) emissions (Figure C.4).

An equivalent plot for the 2080s time-horizon under A1B (Medium) emissions is presented in the main body of the report (Section 4.5; Figure 4.8). The colours indicate which risk curve the allowance is derived from (see table below).

Key for Figures C.1-C.4:

Risk type	Colour
Neutral	green
Mixed	gold
Enhanced-High	purple
Sensitive	magenta
Regional	Black

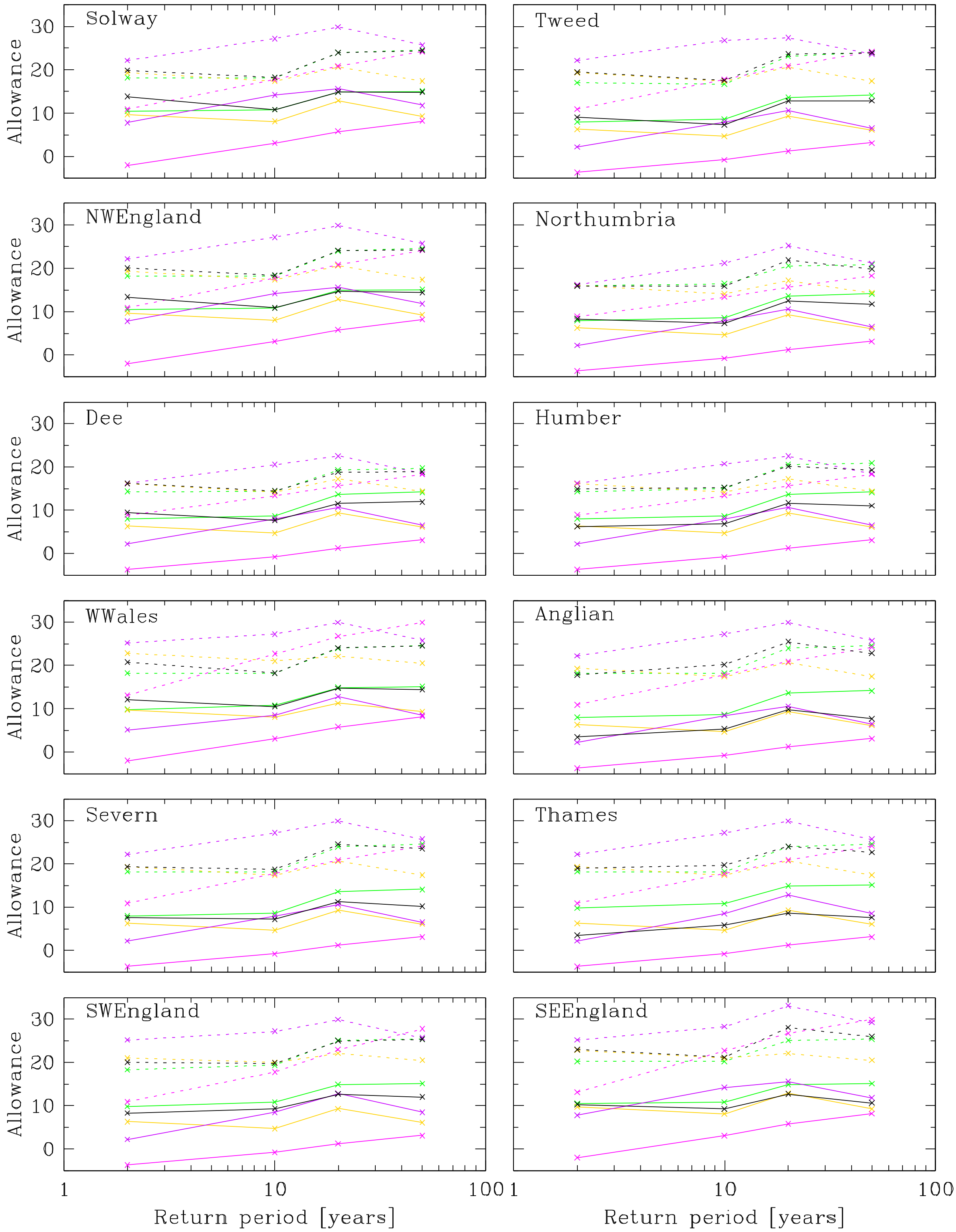


Figure C.1 Possible allowances versus return period, derived from the (2020s A1B) risk curves for the Neutral (green), Mixed (gold), Enhanced-High (purple) and Sensitive (magenta) response types and from the regional (weighted) risk curves (black). Allowances are shown for two 'protections levels', where i) 50% (solid lines) and ii) 10% (dotted lines) of scenarios exceed the allowance.

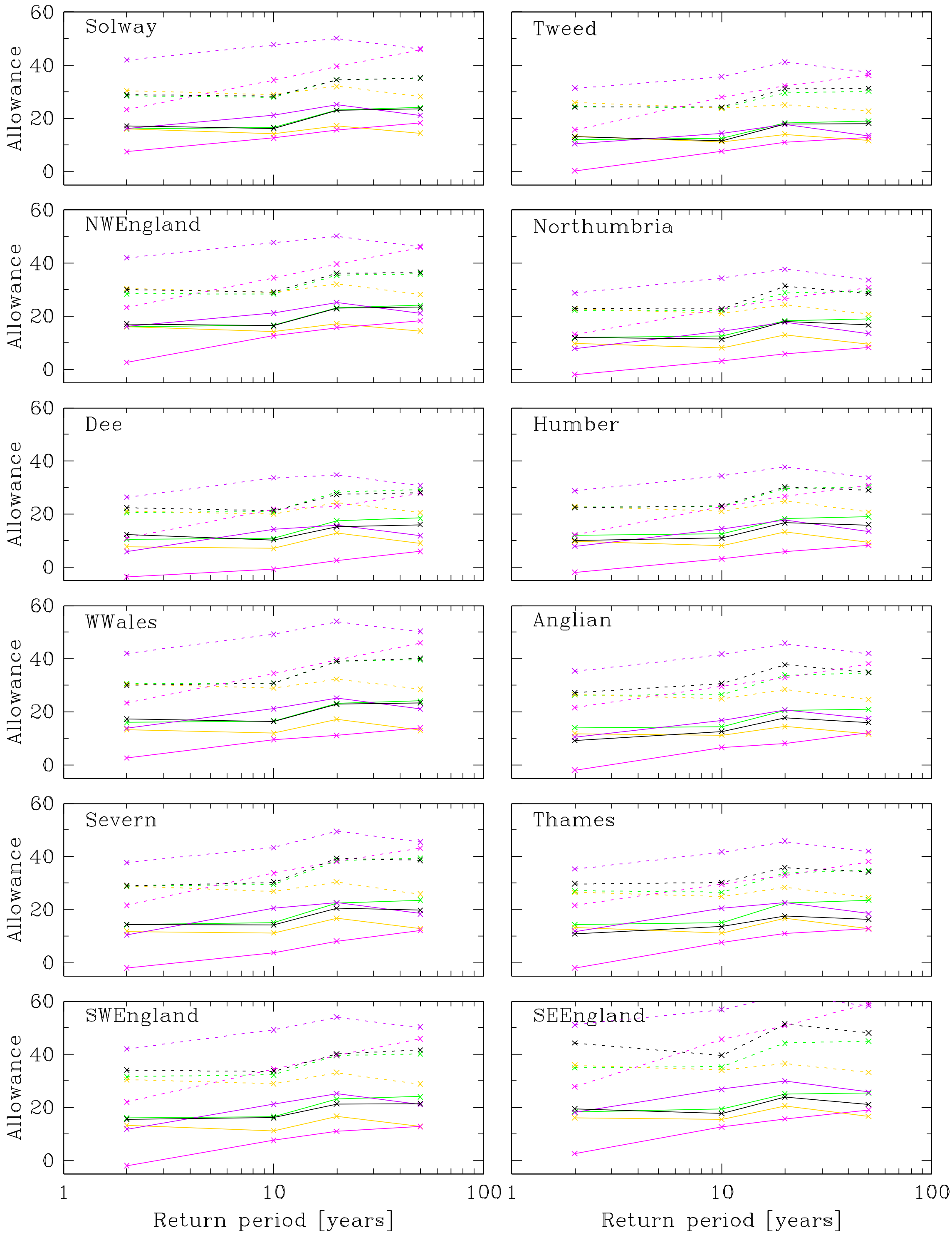


Figure C.2 As Figure C.1 but for the 2050s time-horizon under the A1B emissions scenario.

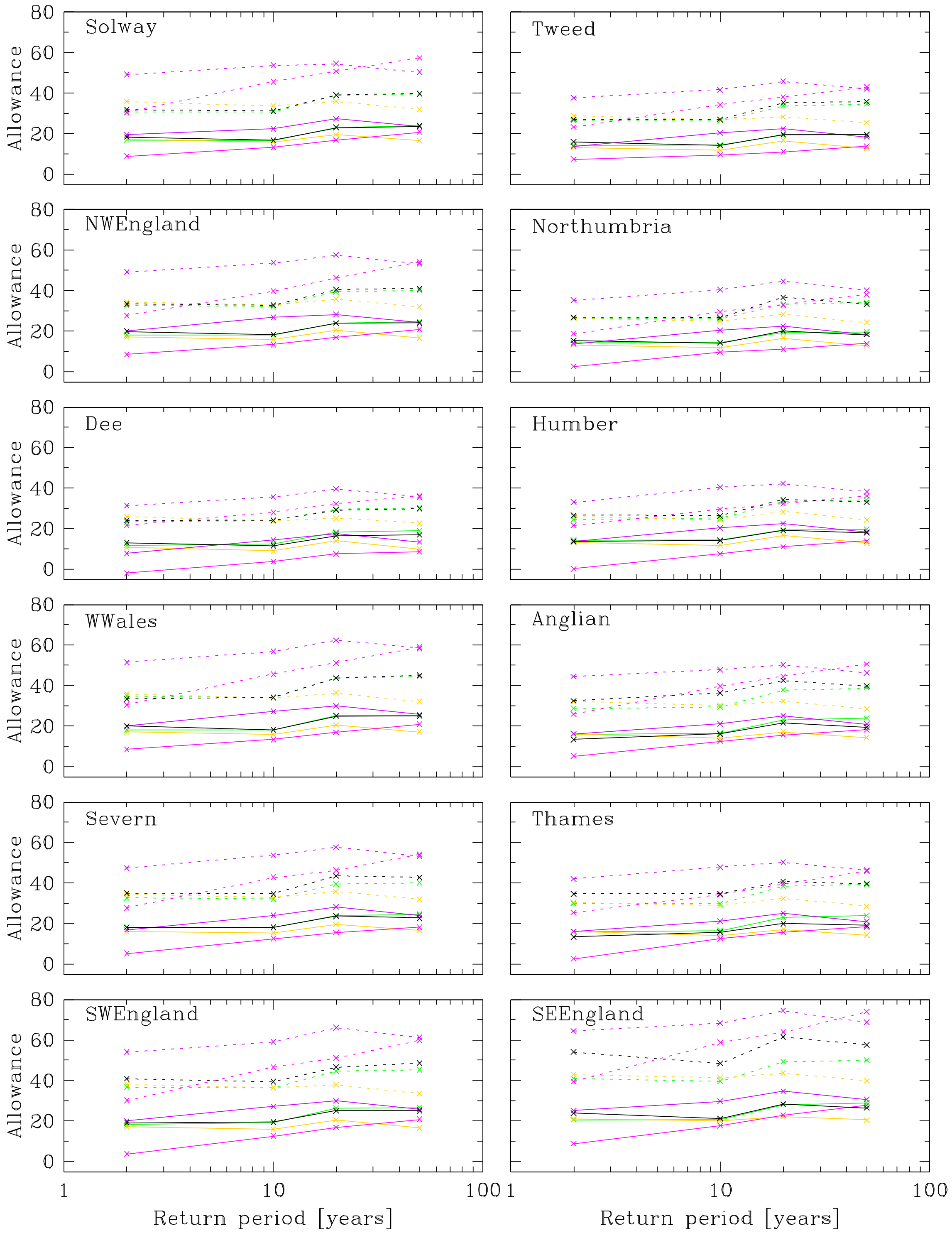


Figure C.3 As Figure C.1 but for the 2080s time-horizon under the B1 emissions scenario.

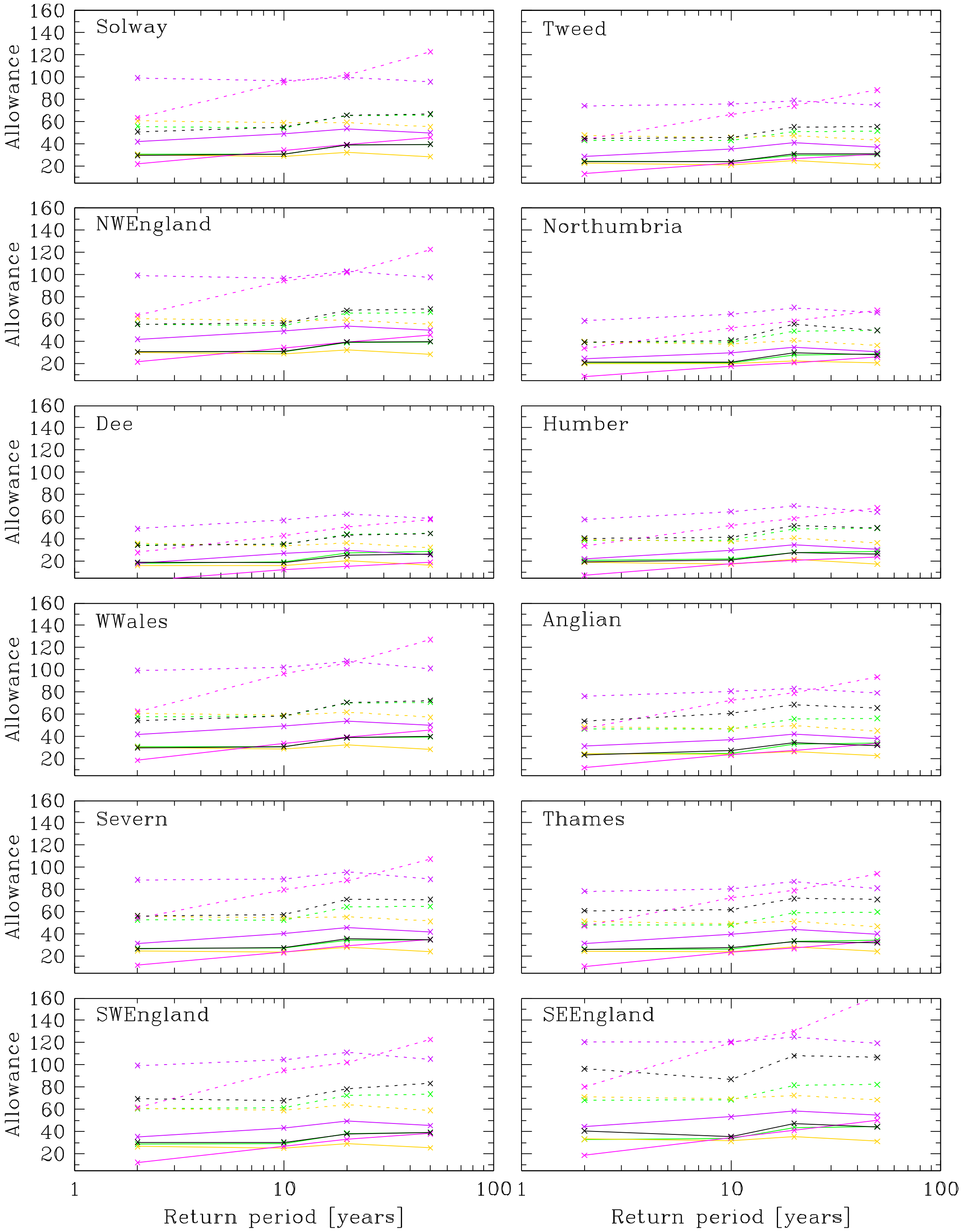


Figure C.4 As Figure C.1 but for the 2080s time-horizon under the A1F1 emissions scenario.