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

Regionalised Impacts of Climate Change on Flood Flows:

Regionalising the Flood Response Types in Britain

R&D Milestone Report FD2020/MR4

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Joint Defra/EA Flood and Coastal Erosion Risk
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Regionalised impacts of climate change on flood flows: regionalising the flood response types in Britain

Milestone report 4 – Project FD2020

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

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Executive summary

The primary objective of this project is to assess the suitability of current FCDPAG3 guidance given the advances in climate change science since its publication. PAG3 requires an allowance of 20% to be added to peak flows for any period between 2025 and 2115 for any location across Britain. This guidance was considered a precautionary value and its derivation reflected the evidence available at that time. FD2020 has been designed to increase this evidence base, and it is anticipated that the research will lead to the development of regional, rather than national, guidelines for changes to peak flows due to climate change.

A **scenario-neutral** approach based on a broad sensitivity analysis to determine catchment response to changes in climate as chosen for FD2020. The method separates the climate change that a catchment may be exposed to **(the hazard)** from the catchment response (change in peak flows) to changes in the climate **(the vulnerability)**. By combining current understanding of climate change likelihood (the ‘hazard’) with the vulnerability of a given catchment, it is possible to evaluate the **risk** of flood flow changes.

The vulnerability of a catchment is to be characterised in two steps: first, the response of a set of catchments to a range of climatic changes are modelled, then analysed for similarity, and second the main responses are characterised according to catchment properties. This is possible by defining a sensitivity framework of changes to the mean and seasonality of precipitation and temperature and modelling the response of each catchment within this fixed framework.

This milestone report describes the second step of the vulnerability assessment. This is achieved by identifying the relationships identified between a catchment’s characteristics (geographic, geologic or climatic) and the vulnerability of its flood peak to changes in the climate. The work follows the identification of nine flood response types for catchments in Britain, after a comprehensive ‘scenario-neutral’ sensitivity study based on 4,200 patterns of changes in rainfall, temperature and potential evaporation.

These nine flood response types were found to fully describe the range of changes in flood peak obtained in 154 catchments, and represent five main families of behaviour from the most ‘damping’ (low vulnerability), through ‘neutral’, to the most ‘enhancing’ (high vulnerability) catchments. One of the response types, with a very damped response to changes in climate, was removed from the analysis, as the group was too small for a reliable model to be built; leaving eight flood response types to characterise. Using a hierarchical partitioning technique and digital catchment descriptors from the Flood Estimation Handbook and the Hydrometric Register databases, decision trees were identified to discriminate the flood response type from nine descriptors including mean annual rainfall, area, northing and easting, elevation, and measures of permeability and catchment losses.

At the 2-year return period level, all eight flood response types could be discriminated. For changes in the 20- and 50-year return period floods, the flood response types had to be merged into four main categories before they could be discriminated by the catchment characteristics. This merging was also necessary to ensure that uncertainty due to the impact of seasonality in rainfall change was fully incorporated into the flood response types. For the most enhancing catchments (i.e. where the changes in flood peak are proportionally much greater than the maximum increases in rainfall), the difference between the mean annual rainfall and the losses in the catchment was found to be an important discriminatory factor. For changes in higher return period floods, mean annual rainfall was found to be less critical. Wetter catchments were found to be in general less enhancing than drier catchments.

The decision trees were successful for between 67.5% and 84% of the study catchments, depending on the flood indicator. Amongst the misclassified catchments, a larger proportion was misclassified as more enhancing, resulting in a potential over-estimation of changes in flood peaks, or an over-precautionary assessment. When evaluating the ability to discriminate between the more general families of 'resilient/damping catchments' (i.e. associated with a damped flood response type), 'neutral catchments' and 'vulnerable/enhancing catchments' (i.e. associated with an enhanced response type), 80% of the catchments were found to be correctly classified across all four flood indicators. Large catchments seem to be slightly more difficult to classify, suggesting they might not be well represented by single value descriptors which smooth out spatial variations important in the response of the river to climatic changes.

Following the decision trees (sets of partitioning rules and paths for each of the flood response types), it is possible to quickly identify, for any catchment (gauged or ungauged but with available descriptors), the expected flood response type in response to climate change. This regionalised vulnerability assessment can be used in combination with an evaluation of potential climatic changes (or the hazard) to provide a measure of the risk of changes in flood peaks. In particular, this framework will enable a quick update of the potential risk of changes in peak floods when new climate change projections become available, such as for example the UKCP09 scenarios, without the need to undertake an extensive hydrological modelling and impact study.

Contents

1. Introduction

This milestone report describes the regionalisation of the levels of vulnerability of the flood regime to climate change identified for Britain. That is, it presents the method developed to estimate a catchment's response to climate change from its catchment characteristics. For any catchment in Britain, this methodology enables the rapid identification of likely flood response to climate change. It follows on from a previous milestone report describing the identification of the flood response types for Britain (Prudhomme *et al.* 2009). This report finalises the identification of the flood regime vulnerability to climate change from catchment properties.

A brief summary of flood response patterns and flood response types is given below. Section 2 describes the methodology used for the regionalisation of the flood regime response types, Section 3 the data used, and Section 4 the results obtained for the case study catchments. Section 5 presents a brief risk analysis of the method before a short conclusion in Section 6.

1.1 The sensitivity framework and flood response patterns: a brief overview

Projections from 17 Global Climate Models (GCMs) following three emission scenarios from the IPCC-AR4 were analysed on all land cells over Britain, and corresponding monthly change factors were calculated for the 2080s time horizon. It emerged that the monthly change factors could be summarised by a 3-parameter harmonic function (sinusoid with a single phase). These parameters represent the mean annual change, the amplitude of the sinusoid, and the time of the year with the maximum changes (called the phase). For precipitation, the phase was found to fall generally in winter and more particularly in January. For temperature changes, the phase was found to fall either in winter or in summer. For more details about the climate change scenarios, see Prudhomme and Reynard (2009).

The application of a harmonic function meant that the impact of a comprehensive range of climate change scenarios could be explored through a sensitivity analysis combining changes in precipitation with changes in temperature (and corresponding changes in potential evaporation PE), in the framework in Table 1.1.

From the sensitivity framework, a set of flood response patterns for each of the project's 154 catchments was simulated, described in another milestone report (Prudhomme *et al.* 2009). These present the modelled changes in a given flood indicator under a specific set of changes in rainfall and temperature/potential evaporation (T/PE). In other words, they represent the **vulnerability** of the flood regime of the catchment to climate change. An example flood response pattern for a catchment is shown in Figure 1.1.

Table 1.1 Sensitivity framework for precipitation and temperature changes

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

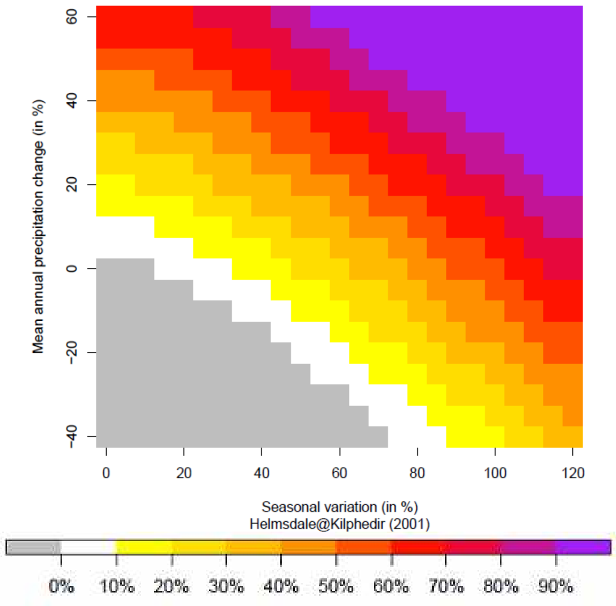


Figure 1.1 Example flood response pattern for changes in 20-year flood peak for the Helmsdale @ Kilphedir with the Medium-Aug temperature/PE scenario (maximum rainfall change in January).

1.2 Flood response types for Britain

Prudhomme *et al.* (2009) described the methodology used to group catchments according to similarity of their flood response patterns, and presented the resulting flood response types identified for Britain. A total of nine flood response types corresponding to nine key flood response patterns were identified for each flood indicator, represented by five main 'families'. The response types are listed in Table 1.2 with brief descriptions of change in flood peak for four categories of change in mean annual and seasonal precipitation. The response types are presented schematically in Figure 1.2 where boundaries between types are dividing a continuum. Response types are positioned relative to each other to represent the change in vulnerability to flooding from increase in rainfall, so that the least vulnerable type is on the left of the Figure and the most vulnerable on the right.

Table 1.2 Summary description of changes in flood peaks for flood response types in Britain from 154 catchments

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

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

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

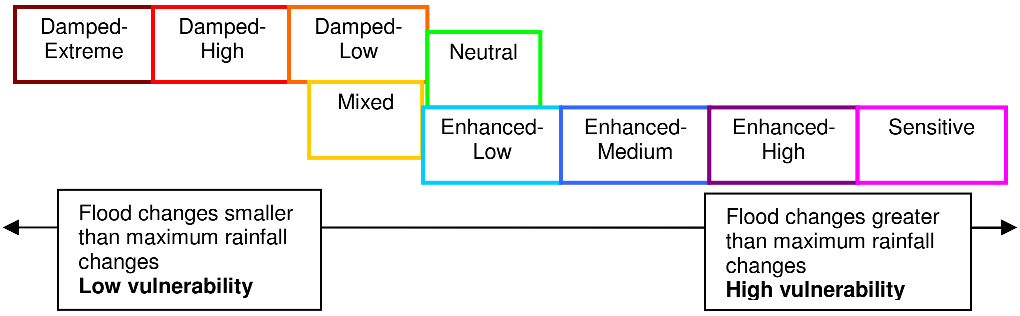


Figure 1.2 Schematic of the nine flood response types

The key flood response patterns (averaged over the 8 T/PE scenarios) for each flood response type and each of four flood indicators are shown in Figure 1.3.

1.3 Regionalisation of flood response types

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

For the regionalisation method to be widely applicable, it should exploit, as far as possible, catchment characteristics available for most catchments in Britain, gauged or ungauged. It is important for these relationships to be as reliable and robust as possible and that at least one relationship is identified to characterise each flood response type. The relative importance of transferability of the method to ungauged catchments and robustness of the relationships was carefully considered before finalising the regionalisation model.

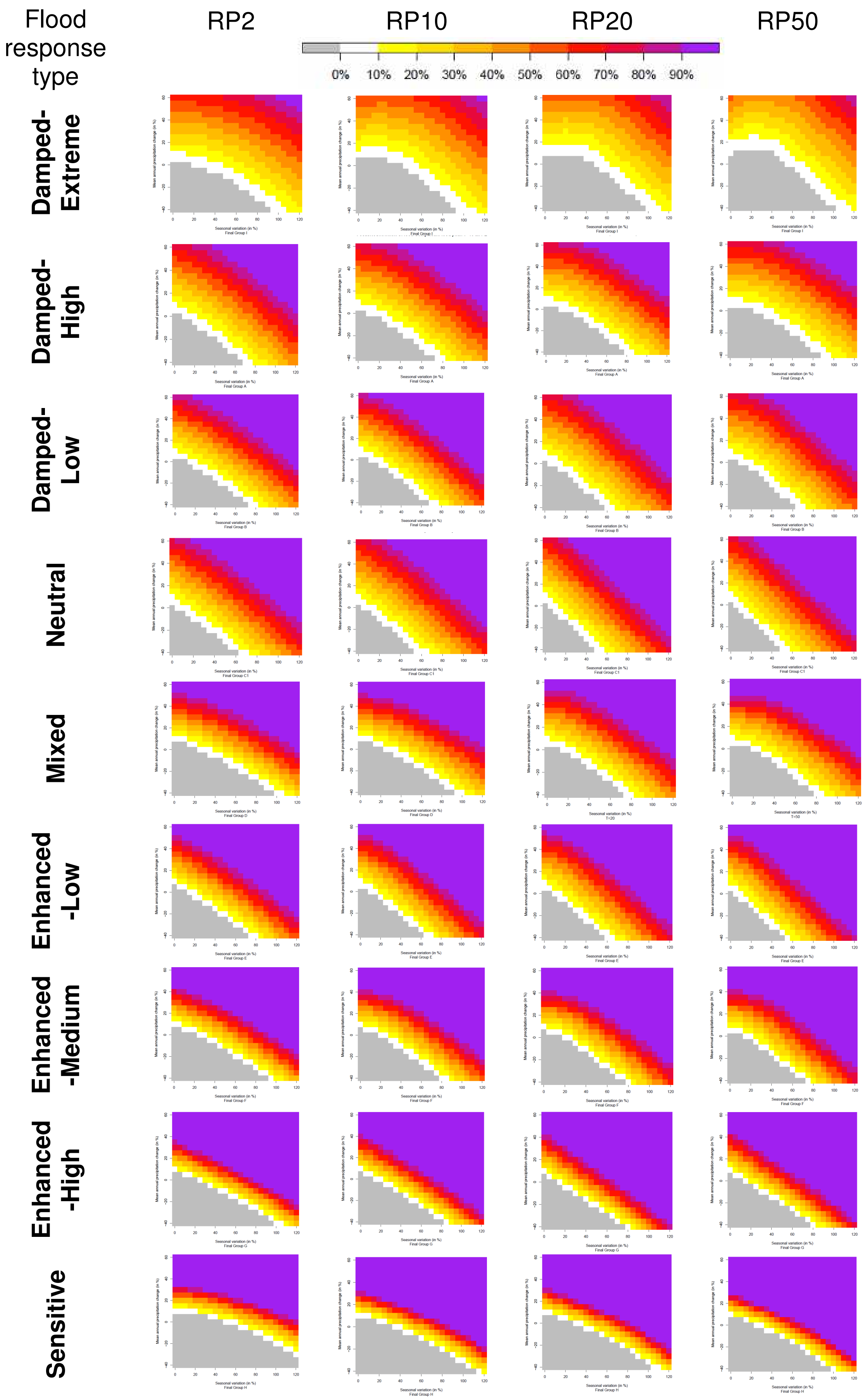


Figure 1.3 Key flood response patterns (averaged over the eight T/PE scenarios) for the four flood indicators for the nine flood response types

2. Methodology

This section presents the principle and main steps of the hierarchical partitioning method (or recursive partitioning) used to associate a set of catchment descriptors with a vulnerability type. This method is not yet very popular in statistics and pattern recognition, but is commonly used in medical science. However, it has been used to characterise UK rivers into ecological types from their physical characteristics (Acreman *et al.*, 2008), and expert systems, which also generate prediction rules in the form of decision trees, have been used for the seasonal forecasting of low summer flow in the river Thames (Wedgbrow *et al.*, 2005).

A summary of the basic principles is reported here, but more details can be found in Ripley (1996).

2.1 Principles of tree modelling

A decision tree divides the space of possible observations into sub-regions. The terminology and representation (Figure 2.1) of trees is graphic:

- The *root* is the top node and includes all samples to be classified.
- Data at each node are split into two *branches* according to binary tests, or rules, leading to the formation of two child nodes.
- A node becomes a *leaf* when no further split is possible or relevant.
- A leaf is reached by following a set of partitioning rules, termed a path.

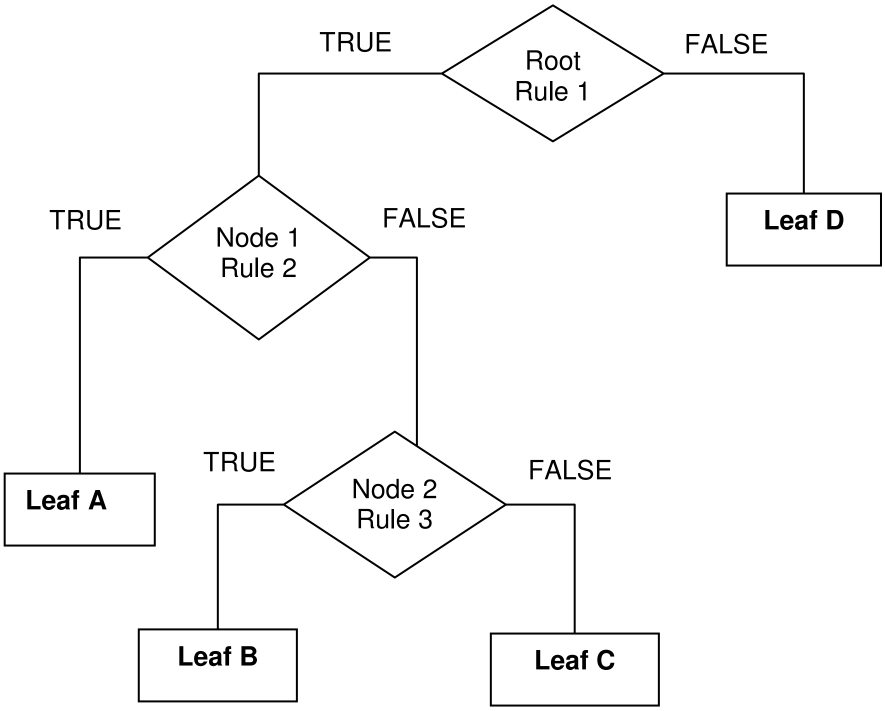


Figure 2.1 Example of decision tree diagram and partitioning rules

The terminology for the method states that we have elements with a number of ‘descriptors’ and an associated ‘category’ for each element. In our case, the elements are catchments and the category is the flood response type best describing the flood response pattern of the catchments. As the flood response type might not be the same for all flood indicators (see section 3), the four samples corresponding to results for the four flood indicators are treated separately and independently. The aim of a decision tree is to divide the elements of the original sample into groups of the same category according to their descriptors. The decision tree works as follows:

- the original sample contains all the catchments, each defined by a set of catchment descriptors and a flood response type
- catchments in a node are divided according to a binary test, or rule, on the catchment descriptors which aims to maximise the ‘purity’ of the two child nodes, i.e. resulting in as many catchments of the same flood response type as possible in the same node
- a node is pure if it contains only catchments with the same flood response type, and then becomes a leaf
- an impure node can either be further divided, or become a leaf if it contains too few catchments. In which case catchments will be of two, or more, flood response types
- each leaf has associated ‘flood response type probabilities’: the probability that a catchment following a path to a leaf belongs to a given flood response type. This probability is calculated as the proportion of catchments of that flood response type in that leaf, and is calculated for all flood response types represented in that leaf
- the flood response type associated with a leaf is that with the highest probability. When two, or more, flood response types have the same probability, the leaf flood response type is allocated at random

2.2 Model complexity

When growing a tree, the size of each node diminishes until, ultimately, each leaf becomes pure. This, however, would result in over fitting: the model would try to fit perfectly to a specific sample, but might not be representative of more general behaviour. Imposing a minimum leaf size is a common technique to limit the model complexity (i.e. number of splits/leaves). Another technique is known as ‘pruning’, where branches leading to leaves are cut to become leaves themselves.

There are many algorithms for calculating the purity of nodes, pruning or limiting tree growth. Cross validation is sometimes recommended to evaluate a model complexity. It is an iterative procedure where a sub-selection of the original sample is generated at random, a tree is grown from this root, and the number of misclassified elements calculated. The process is repeated K times, generating K pairs of [number of leaves, number of misclassified elements]. It is suggested that the ideal number of leaves is that of the least complex tree leading to the smallest number of misclassified elements.

The R freeware package `tree` was used for the modelling, and in particular the commands `tree`, `cv.tree`, `prune.tree` and `predict.tree` were used, with various combinations of pruning strategies and cross-validation methods explored. For all commands, the default options were used.

2.3 Evaluation

2.3.1 Overall

Once a decision tree and its corresponding paths have been defined, the resulting classification is assessed. In this project, the final decision tree was chosen according to the following qualitative and quantitative evaluations:

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

2.3.2 Contingency tables

In addition to the overall estimation of correctly classified elements (catchments), it is sometimes very useful to analyse the elements which have been misclassified. Contingency tables are good tools to summarise the results of a categorical classification in a simple 2-dimensional table, including how the misclassified elements were classified (Table 2.1). They are a very common way to present predicted results, in particular to evaluate forecasts. A description of contingency tables and their use can be found in Jolliffe and Stephenson (2003) and is summarised here:

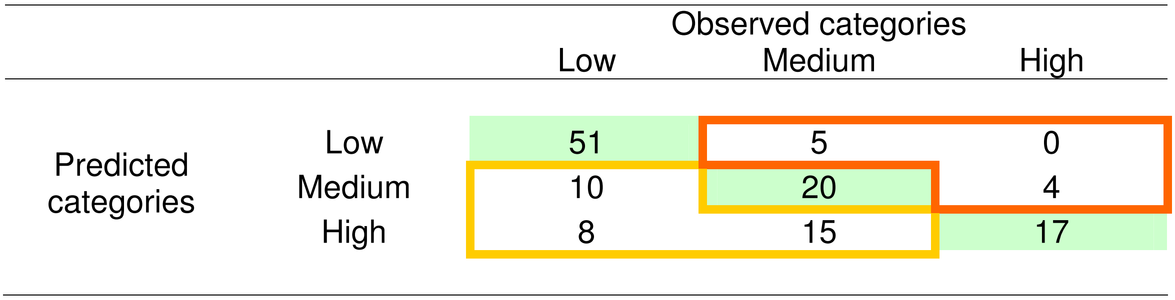
- The diagonal of the table shows the number of correct classifications for each category (flood response type). The sum in the diagonal is the total number of well classified elements, and sometimes called *hit rate* in forecasting studies

- The columns of the table represent how the observed categories are partitioned into predicted categories. The sum of each row is the total number of elements observed in the corresponding category
- The rows of the table represent how the predicted categories (i.e. obtained in the corresponding category using the paths) are distributed amongst the observations. The sum of each column is the total number of elements obtained using the paths
- Some misclassifications could have greater implications (or cost) than others. For example, precautionary forecasting would favour a medium flood risk to be classified high risk (i.e. implement protective measures) rather than low risk (i.e. do nothing) as flooding can be devastating when not forecast. The bottom half of the contingency table (surrounded in yellow) represents these precautionary forecasts, often called '*false alarms'* (or false positive) or the number of time the predicted category is worse than what has been observed. This is to be compared with the un-precautionary forecasts (surrounded in red), often called '*misses*' (or false negative) or the number of time the predicted category has a 'lower risk' than what has been observed. Where possible, the number of false alarms should be greater than the number of misses.

In the example of Table 2.1, for 130 elements:

- hit rate = 51+20+17 = 88 (= 88/130 = 67.7%)
- false alarms = 10+8+15 = 33 (= 33/130 = 25.4%)
- misses = 5+0+4 = 9 (= 9/130 = 6.9%)

Table 2.1 Example of contingency table for three categories with elements count rather than probabilities



		Observed categories		
		Low	Medium	High
Predicted categories	Low	51	5	0
	Medium	10	20	4
	High	8	15	17

In the FD2020 project, the main objective is to maximise the hit rate, and minimise the misses. However, the existence of a path for all flood response types and the logic of the hydrological processes of the tree take priority over any other statistics.

3. Data

3.1 Distribution of flood response types

Nine flood response types were identified for each flood indicator from the study catchments, described by specific flood response patterns. Not all catchments have the same flood response type for all four flood indicators (i.e. changes in flood peak of 2-, 10-, 20- and 50-year return period - respectively RP2, RP10, RP20 and RP50). The original distribution of the study catchments in these nine types by flood indicator is shown in Figure 3.1.

- More catchments are associated with a damped type for RP2 and RP10 than for RP20 and RP50 [red shades]
- The neutral and mixed types are larger at RP20 and RP50 than at RP2 [yellow and green]
- The number of catchments associated with an enhanced type is relatively independent of the return period [blue and purple shades]
- Few catchments belong to some of the enhanced types (less than 10)
- Only three catchments are of the Damped Extreme type

It was decided that the sample available for the Damped Extreme type was too small to allow a reliable classification, and the corresponding catchments were removed from the sample, leaving 151 catchments (and 152 flood response patterns, as one catchment was simulated by two hydrological models) to classify. The small size of some types is a problem for the classification algorithm, and it was necessary to regroup some of the types to achieve a better discrimination. The merging of the flood response types is discussed in the next sub-section.

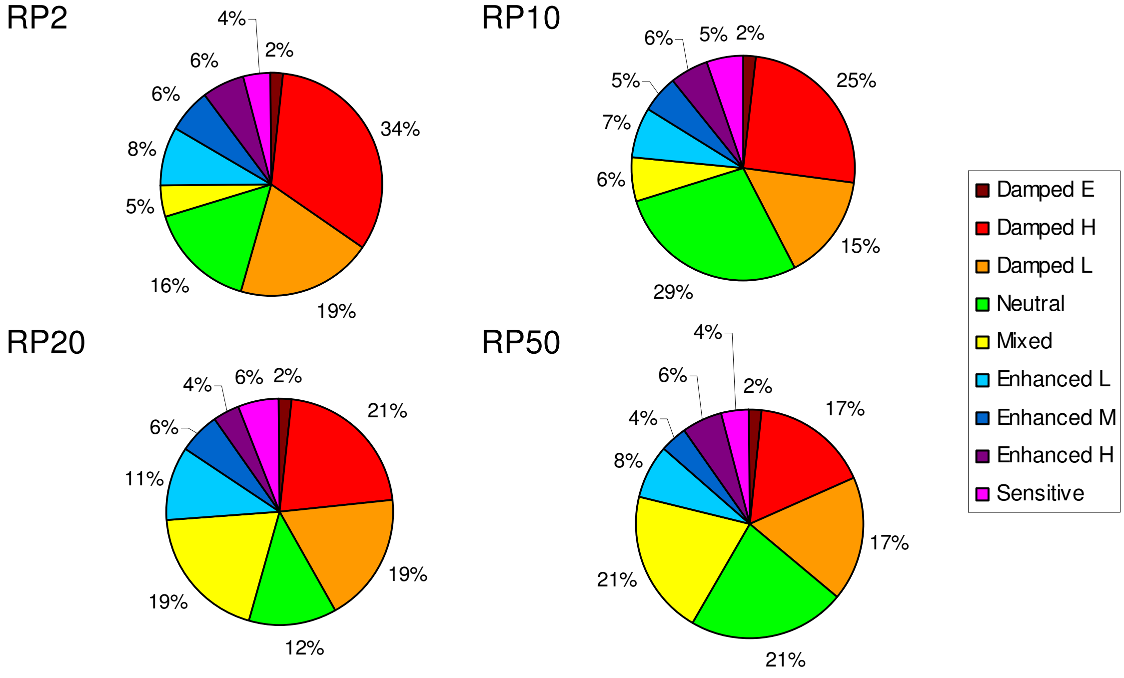


Figure 3.1 Original distribution of the flood response patterns in the nine flood response types for changes in flood peak for four return periods

3.2 Representation of flood response types and merged flood response types

The different flood response types identified have emerged from analysing changes in flood peak resulting from rainfall change scenarios with a smoothed variation through the year peaking in January. The impact of the month of the maximum rainfall change was investigated by Kay *et al.* (2009) who found that for catchments with damped types, the flood response pattern may be either less damped or neutral when peak changes in rainfall occur in the autumn, while for catchments with enhanced types the flood response pattern may be further enhanced. When the peak rainfall change occurs between February and mid-summer, the effect on changes in flood peaks is generally less. This impact is particularly applicable for RP20 and RP50.

In order to integrate the variation in the flood response type due to the month of maximum rainfall changes, and to address the issue of under-representation of some flood response types in the original sample of 152 patterns per flood indicator, the original eight main flood response types were merged into the following categories (see also Table 3.1):

- **RP2**: all eight main flood response types are partitioned.
- **RP10**: merge the flood response types Damped High and Damped Low, and associate the merged type with the composite key flood response pattern of the Damped Low catchments (i.e. with the higher overall flood increases). A total of seven types are partitioned.
- **RP20**: Merge the flood response types Damped High, Damped Low and Neutral and associate the merged type with the composite key flood response pattern of the Neutral catchments. Merge the flood response types Enhanced High, Enhanced Medium and Enhanced Low and associate the merged type with the composite key flood response pattern of the Enhanced High catchments. A total of four types are partitioned.
- **RP50**: same as RP20.

As a precautionary measure when merging types, it was decided to use the composite associated with the type showing the largest flood increases of the merged categories (Damped Low, Neutral and Enhanced High) for two reasons: (i) the change in the month of the rainfall peak might re-categorise a catchment to a more vulnerable type (i.e. further to the right in Figure 1.2; (ii) a new average composite would reduce the extremes (in particular high changes) compared to the pattern of the most vulnerable type in the merged group. This means that the response of catchments in more vulnerable types would be underestimated by the average pattern. The method applied favoured an overestimation of the vulnerability of the catchments instead of a potential underestimation.

Table 3.1 Combination of flood response types for higher return periods, along with the key flood response pattern to be applied for each combination

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

3.3 Catchment descriptors

The method developed in FD2020 should be able to define the vulnerability of a flood regime to climate change for as many catchments as possible in Britain, whether gauged or not. This means that relationships between flood regime vulnerability (i.e. flood response type) and catchment characteristics need to be defined using characteristics available for as many catchments as possible.

Two main sources of catchment properties are available digitally in Britain for a comprehensive number of catchments and these are described below. Additional specific hydroclimatic catchment properties were also tested, derived for the case study catchments, to evaluate whether they incorporate other processes necessary to characterise the flood response type and thus give improved tree model performance.

3.3.1 Flood Estimation Handbook catchment descriptors database

The Flood Estimation Handbook FEH (Reed, 1999) describes a standard method used to assess flood frequency and is widely used in flood design in the UK, for gauged or ungauged catchments. It is based on a number of statistics derived from gauged flood time series and catchment properties (called catchment descriptors in the FEH).

There are different sources for the FEH catchment descriptors (see Bayliss (1999) for complete description). They have been regrouped in a CD-ROM containing digital descriptors for over four million UK catchments that drain an area of at least 0.5 km^2. Twenty descriptors are fully described in Bayliss (1999), and a sub-selection has been considered here for inclusion in the regionalisation of the flood response types (Table 3.2).

Table 3.2 FEH catchment descriptors considered for the analysis

Acronym	**EAST**	**NORTH**	**AREA**	**BFIHOST**	**DPLBAR**
Variable	Easting of catchment outlet (in GB national grid)	Northing of catchment outlet (in GB national grid)	Catchment drainage area (km^2)	Base flow index derived using the HOST classification	Index describing catchment size and drainage path configuration (km)
Acronym	**DPSBAR**	**FARL**	**PROPWET**	**SAAR**	**SPRHOST**
Variable	Index of catchment steepness	Index of flood attenuation due to reservoirs and lakes	Index of proportion of time soils are wet	1961-90 standard period average annual rainfall (mm)	Standard percentage runoff derived using the HOST classification (%)
Acronym	**ALTBAR**	**ASPBAR**	**ASPVAR**	**LDP**	**RMED**
Variable	Mean catchment altitude (m above sea level)	Index representing the dominant aspect of catchment slopes	Index describing the invariability in aspect of catchment slopes	Longest drainage path (km)	Median annual maximum rainfall (mm)
Acronym	**SMDBAR**	**URBEXT**	**URBCONC**	**URBLOC**	
Variable	Mean soil moisture deficit defined by MORECS for 1961-90 (mm)	Index of fractional urban extent	Index of concentration of urban and suburban land cover	Index of location of urban and suburban land cover	

3.3.2 Hydrometric registry entries

The National River Flow Archive NRFA Hydrometric Register (Marsh and Hannaford, 2008) is a catalogue of river flow gauging stations in the UK holding summary hydrometric and spatial statistics for over 1,500 river basins. The Hydrometric Register is available in paper and digital format. For more information, see http://www.ceh.ac.uk/data/nrfa/publications.html.

Thirty eight descriptors are available, fully described in Marsh and Hannaford (2008), and a sub-selection has been considered here for inclusion in the regionalisation of the flood response types (Table 3.3).

Table 3.3 UK Hydrometric Register catchment descriptors considered for the analysis

Acronym	**MEAN ANN RUNOFF**	**BEDROCK HIGH PERMEBAILITY**	**BEDROCK MODERATE PERMEABILITY**	**BEDROCK VERY LOW PERMEABILITY**
Variable	Depth of water over the catchment equivalent to the mean annual flow (mm)	Proportion of the catchment underlain by rock formations of high permeability	Proportion of the catchment underlain by rock formations of moderate permeability	Proportion of the catchment underlain by rock formations of low permeability
Acronym	**MEAN ANNUAL LOSS**	**GEN HIGH PERMEABILITY**	**GEN LOW PERMEABILITY**	**MIXED PERMEABILITY**
Variable	Difference between mean annual catchment rainfall and mean annual catchment runoff (mm)	Proportion of the catchment underlain by superficial deposits of generally high permeability	Proportion of the catchment underlain by superficial deposits of generally low permeability	Proportion of the catchment underlain by superficial deposits of mixed permeability

3.3.3 Additional catchment descriptors

Additional statistics were considered to evaluate if the flood response type is influenced by the seasonality in the hydroclimatology of the catchments. Three types of variables were derived from the time series data for the case study catchments, presented in Table 3.4.

Table 3.4 Additional catchment descriptors considered for the analysis

Acronym	**Summer.PE**	**POT2.3m**	**POT2.2m**
Variable	average annual ratio between rainfall and potential evaporation for the 6 month period April to September	proportion of POT1 peaks observed in 3-month periods (NDJ, FMA, MJJ, ASO)	proportion of POT1 peaks observed in 2-month periods (DJ, FM, AM, JJ, AS, ON)

Summer.PE provides a measure of the average dryness of a catchment during the summer and therefore the impact of changing soil moisture deficit on flood potential during the autumn. The value of Summer.PE indicates how much changes in summer rainfall and PE are likely to impact on flood frequency. A value >> 1.0 indicates that autumn flood potential is unlikely to be affected by climate change (autumn floods will still be readily generated). Similarly autumn flood potential will be little changed with a Summer.PE value << 1.0 (autumn floods unlikely to be generated). However, if the ratio is close to 1.0 then changes to summer rainfall and PE will impact on the generation of floods during the following months with implications for changes in flood frequency.

POT1 is the sample corresponding to the Y highest independent daily flood peaks that have been recorded in the daily flow series, where Y is the number of years of available flow records. The POT1-type variables evaluate if the season of the main peak floods in the baseline has a significant influence on the flood response type. As the largest increase in rainfall is assumed to occur in winter, if the majority of baseline flood peaks occurred in winter, then the increase in flood discharge may be greater than if they occurred in the summer (see Prudhomme and Reynard (2009) for details of the rainfall change scenarios).

During preliminary testing of final paths in the decision trees, both Summer.PE and POT1 values were selected in possible paths but overall results were only marginally different from alternative paths which only used FEH and Hydrometric Register descriptors. Thus it was decided not to use these statistics as they would not be easily available for catchments not included in the project.

4. Results

The decision tree methodology was used to categorise the main flood response types for changes in four flood indicators over the study catchments. The techniques assume stationarity in the descriptors. All catchment descriptors presented in Table 3.2 to Table 3.4 were used during the development of the tree models. First, the partitioning aimed to characterise all eight main flood response types for each return period, but it proved not possible, or advisable, to discriminate all types for RP20 and RP50. The merged flood response types proved easier to characterise. Only the final partition trees are presented here, along with some evaluation criteria.

4.1 Catchment descriptors and partition rules to discriminate flood response types

Nine catchment descriptors were found to be necessary to characterise the flood response types of all four indicators, summarised in Table 4.1. Depending on the flood indicator, different partition rules were necessary to achieve total discrimination of the flood response types. The number of paths and overall performance of the selected tree model for each indicator are given in Table 4.2. Not surprisingly higher model performance is achieved with fewer groups.

Table 4.1 Catchment descriptors used in the flood response types characterisation

Descriptor	RP2	RP10	RP20	RP50
SAAR	Y	Y	Y	Y
Area	Y	Y	Y	Y
ALTBAR	Y	Y		Y
BFIHOST		Y		
North	Y	Y	Y	
East	Y			
Bedrock High Permeability (BHP)	Y	Y	Y	Y
Bedrock Very Low Permeability (BVLP)				Y
Mean Annual Loss (MAL)	Y		Y	Y

Table 4.2 Summary statistics of tree performance

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

Each path (leading to a leaf) is associated with a probability of belonging to a flood response type. Table 4.3 presents these probabilities for the selected decision trees. Most paths are not associated with a probability of one, i.e. do not contain catchments of a single flood response type. However, the majority of catchments generally belong to the same flood response type (given in column 3 of Table 4.3).

In addition to the probability for a path to categorise a single flood response type, it is possible to evaluate the confidence to be associated with the flood response type with the highest probability. An indicator of confidence has been developed, to be used for the highest probability of each path, combining how certain the probability estimate is with how robust it might be, where both concepts are defined as:

- **Certainty** of the probability estimate, measured by the difference between the two top probabilities for the path. A large difference indicates that the great majority of the catchments following the same path are from the same flood response type, and it is very likely that a new catchment with the same catchment descriptors would have the same flood response type. Conversely, a nil/small difference reflects that, when following the partitioning path, the two top flood response types are equally likely (in the case of two equal highest probabilities) or nearly as likely (if the probabilities of the two top categories are not very different).
- **Robustness** of the probability estimate, measured by the proportion of the original sample following the path. For a large group, the highest probability is unlikely to change much if one catchment is added or removed from the sample; for a small final group, the addition or removal of one catchment might significantly change the probability values, and even change the order of the top categories.

The product of certainty and robustness is an indication of the confidence in the flood response type associated with the highest probability. Values (in %) range from 0 (when the two top priorities are identical) to 100 (if a unique final sample exists). Thresholds of 2 and 5 were chosen to flag Low, Medium and High confidence levels. High confidence is given to estimates with high certainty and high robustness. Low confidence is given to estimates with low certainty and/or low robustness, as a slightly different sub-sample might have resulted in completely different categories using the same path. This indicates that care is needed when interpreting results, and it might be recommended to investigate possible alternatives for the final category. Medium confidence is given when the combination of both certainty and robustness is not very small or large, indicating some caution should be attached to the results. Important considerations when applying the method are listed in Section 5, along with some suggestions of how uncertainty might be reduced.

Table 4.3a Probability attached to each predicted flood response type and confidence levels for the highest probability, all paths for RP2. Highest probability in bold

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

Table 4.3b As Table 4.3a for RP10, for the merged flood response types (see Table 3.1)

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

Table 4.3c As Table 4.3b for RP20

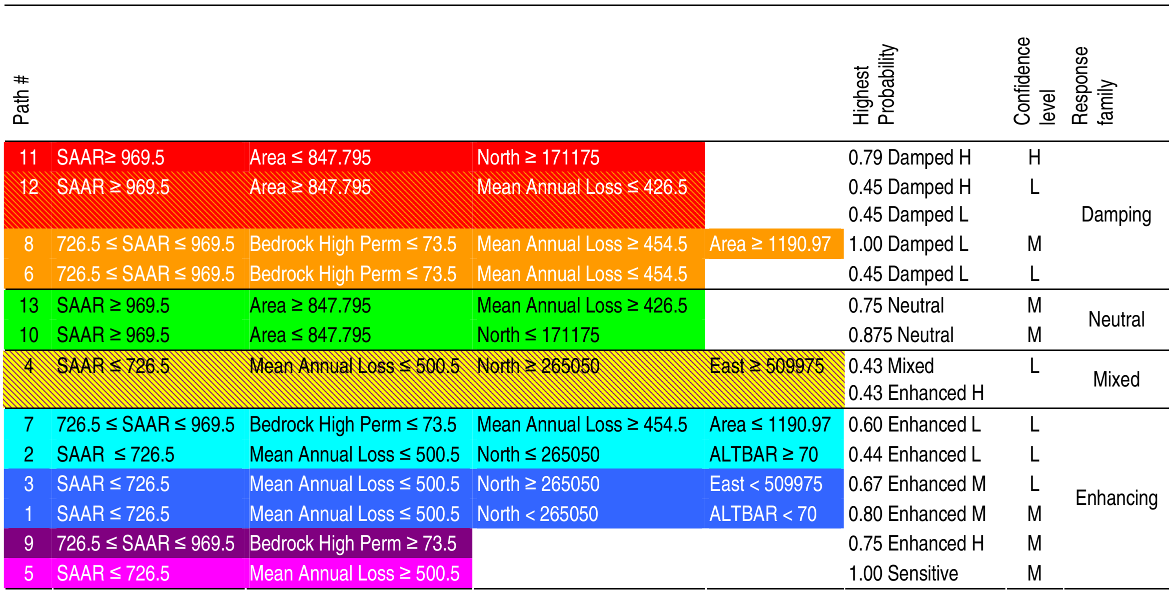
Path #	Size of leaf (number of elements from the sample)	Flood response type of path	Probability of flood response type				Confidence level
			Neutral	Mixed	Enhanced-H	Sensitive	
1	10	Neutral	**0.80**	0.20	0	0	**3.95 M**
2	18	Enhanced-H	0.17	0.17	**0.67**	0	**5.92 H**
3	21	Mixed	0	**0.91**	0.09	0	**11.33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

Table 4.3d As Table 4.3b for RP50

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

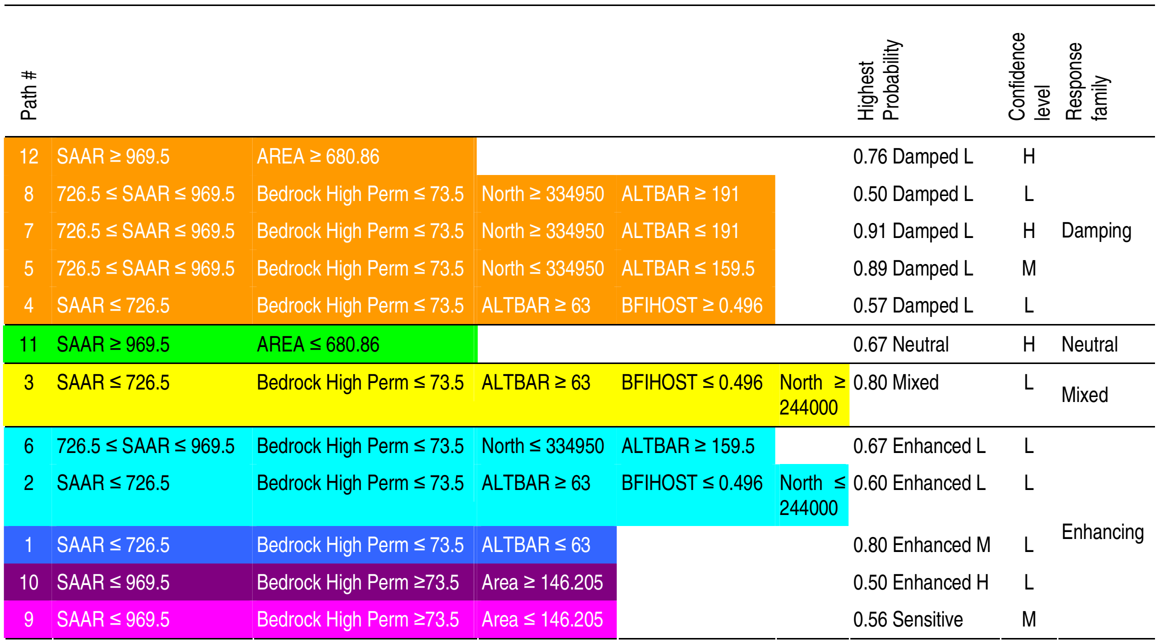
Figure 4.1 illustrates the paths found to discriminate the flood response types (original and merged depending on the return period) for the four flood indicators, colour-coded according to the flood response type with the highest probability. Some flood response types can be categorised by several paths. This shows that different combinations of catchment descriptors might represent catchments with similar flood change response to climate change. While decision trees summarise neatly the main relationships between catchment

descriptors and the vulnerability of the flood regime of a catchment to a range of climatic changes, they are probabilistic assessments, and all the flood response types with a non-nil probability should also be considered. The implications associated with different confidence levels are detailed in Section 5 and in the final report in the section application and worked examples.



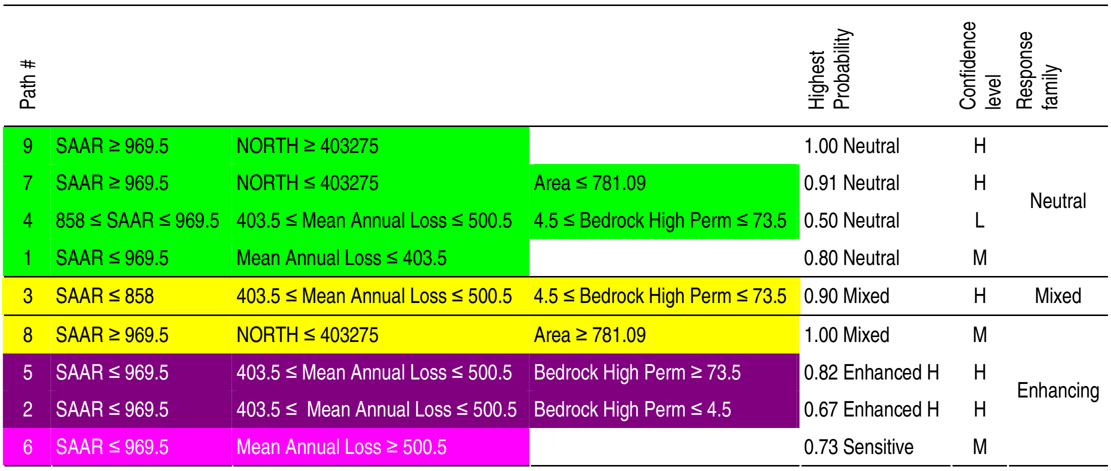
Path #					Highest Probability	Confidence level	Response family
11	SAAR≥ 969.5	Area ≤ 847.795	North ≥ 171175		0.79 Damped H	H	Damping
12	SAAR ≥ 969.5	Area ≥ 847.795	Mean Annual Loss ≤ 426.5		0.45 Damped H 0.45 Damped L	L	
8	726.5 ≤ SAAR ≤ 969.5	Bedrock High Perm ≤ 73.5	Mean Annual Loss ≥ 454.5	Area ≥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

Figure 4.1a Schematic of the decision tree for RP2 with associated highest probability and confidence level; coloured according to corresponding flood response type



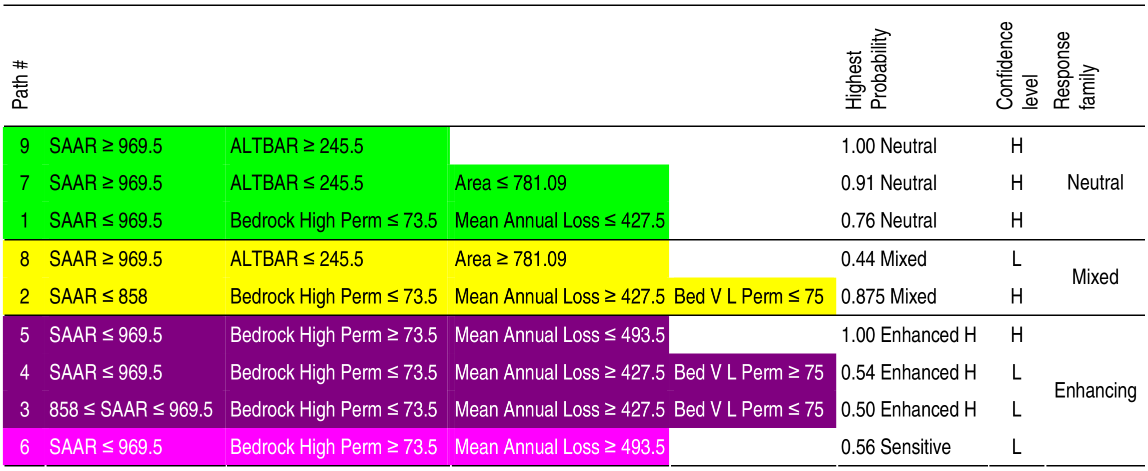
Path #						Highest Probability	Confidence level	Response family
12	SAAR ≥ 969.5	AREA ≥ 680.86				0.76 Damped L	H	Damping
8	726.5 ≤ SAAR ≤ 969.5	Bedrock High Perm ≤ 73.5	North ≥ 334950	ALTBAR ≥ 191		0.50 Damped L	L	
7	726.5 ≤ SAAR ≤ 969.5	Bedrock High Perm ≤ 73.5	North ≥ 334950	ALTBAR ≤ 191		0.91 Damped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

Figure 4.1b As Figure 4.1a for RP10



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

Figure 4.1c As Figure 4.1a for RP20



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

Figure 4.1d As Figure 4.1a for RP50

The decision trees defined by the hierarchical partitioning procedure were analysed across all return periods. One path for RP20 showed that large, wet catchments would be associated with Enhanced H flood response type (with Low confidence), which is inconsistent with results found for RP50 where these catchments are associated with a Mixed flood response type with a High confidence (path #8 in Figure 4.1d). For RP20, Enhanced H is a merged flood response, found for four catchments for path #8. The observed flood response type for these four catchments is Enhanced Low, all having catchment flood response patterns resembling more Mixed type than Enhanced H type. The three other catchments of path #8 are all of Mixed type. After expert judgment, similar to that used in the expert system tree partitioning of Wedgebrow et al. (2005), it was decided that all these seven catchments should be associated with a Mixed flood response type. This is equivalent to describing the Enhanced L category of the three catchments as Mixed rather than Enhanced H. It follows that the flood response type of path #8 of RP20 is Mixed type with a Medium confidence (Figure 4.1c and Table 4.3c).

4.2 Contingency tables and misclassification assessment

4.2.1 Summary statistics

Contingency tables compare the flood response types associated with the study catchments (observed categories) with the flood response type with the highest probability following the paths in the decision trees. Three parts of the tables are of particular interest (see Section 2.3.2):

- The diagonal (highlighted in green shading) shows the number of catchments correctly classified by the decision trees' paths.
- The bottom left hand side of the diagonal (surrounded by yellow border) shows the number of catchments classified by the decision tree in a flood response type with greater flood peak increases than observed: the misclassification is conservative, acceptable with a precautionary approach of over-estimating flood changes.
- The top right hand side of the diagonal (surrounded by red border) shows the number of catchments classified by the decision tree in a flood response type with smaller increases than observed: the misclassification of these elements tends to under-estimate flood changes

The partitioning approach used in the project aimed to maximise the number of catchments on the diagonal, and to minimise the number of catchments inside the red bordered areas. Table 4.4 summarises, for each flood indicator, the number of catchments in the diagonal, and in each of the yellow/red areas. It can be seen that:

- The proportion of catchments classified correctly is always greater than 50%, ranging from 67.5% for RP10 to 84% for RP20;
- When misclassified, 7.7% to 14% of catchments have a predicted flood response type more vulnerable than observed by one category according to Figure 1.2: e.g. observed Damped Medium but predicted Damped Low, or observed Enhanced Low and predicted Enhanced Medium. This number is reduced to 0% to 7% for a jump of two categories (e.g. observed Enhanced Low and modelled Enhanced High);
- The total percentage of catchments in the yellow area (also called 'false alarms') ranges from 8.4% (RP20) to 20% (RP10);
- In the red area (i.e. a less vulnerable flood response type is predicted, also called 'misses'), 5.8 to 7.1% of catchments are classified with a type less vulnerable by one category: e.g. observed Damped Medium but modelled Damped High, or observed Enhanced Low and modelled Mixed
- The total percentage of catchments in the red area (misses) ranges from 6.5% (RP20 and RP50) to 15% (RP2), always smaller than that of yellow areas (false alarms)

Table 4.4 Summary of misclassification statistics

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

1, 2 and >2 are the number of types between the observed flood response type and that predicted using Figure 4.1(configuration of types as in Figure 1.2, but allowing for merged types, as in Table 3.1)

Table 4.5a Contingency table for RP2. Cells shaded in green show the number of catchments correctly classified for each flood response type; areas surrounded in yellow highlight where the path ‘over-estimates’ the flood response type; areas surrounded in red highlight where the path ‘under-estimates’ the flood response type

	Observed flood response type							
Predicted flood response type	Damped-High	Damped-Low	Neutral	Mixed	Enhanced-Low	Enhanced-Medium	Enhanced-High	Sensitive
Damped-High	**43**	6	10	0	0	0	0	0
Damped-Low	7	**15**	2	2	0	0	0	0
Neutral	1	2	**13**	0	0	0	0	0
Mixed	0	0	0	**3**	1	1	2	0
Enhanced-Low	0	7	0	0	**10**	2	0	0
Enhanced-Medium	0	0	0	1	1	**8**	1	0
Enhanced-High	0	0	0	1	1	0	**6**	0
Sensitive	0	0	0	0	0	0	0	**6**

Table 4.5b as Table 4.5a for RP10

Predicted flood response type	Observed flood response type						
	Damped-Low	Neutral	Mixed	Enhanced-Low	Enhanced-Medium	Enhanced-High	Sensitive
Damped-Low	**43**	6	3	1	2	2	1
Neutral	18	**36**	0	0	0	0	0
Mixed	0	0	**4**	0	0	0	1
Enhanced-Low	2	1	1	**7**	0	0	0
Enhanced-Medium	0	0	1	0	**4**	0	0
Enhanced-High	0	0	1	3	0	**5**	1
Sensitive	0	0	0	0	2	2	**5**

Table 4.5c as Table 4.5a for RP20

Predicted flood response type	Observed flood response type			
	Neutral	Mixed	Enhanced-High	Sensitive
Neutral	**77**	5	2	0
Mixed	0	**19**	2	0
Enhanced-High	4	6	**25**	1
Sensitive	0	0	3	**8**

Table 4.5d as Table 4.5a for RP50

Predicted flood response type	Observed flood response type			
	Neutral	Mixed	Enhanced-High	Sensitive
Neutral	**77**	4	2	0
Mixed	4	**25**	3	1
Enhanced-High	6	2	**19**	0
Sensitive	0	1	3	**5**

4.2.2 Overall Performance

The prediction results from the decision trees were analysed by catchment across all four indicators to identify if there are underlying reasons for misclassification. Table 4.6 gives the number of catchments which were misclassified at one, two, three or all four indicators (return periods).

While only 35% are correct for all four indicators, this percentage increases to 80% with one misclassification. Two of the seven catchments misclassified for three indicators are ones identified during the model calibration phase (Crooks *et al.* 2009) as having substantial alteration to natural flow (67009 and 33035). The catchment incorrect for all four indicators (24005) also has alterations to natural flow, hence for these catchments, it is likely that flood response to change is not well represented by catchment characteristics.

There is no consistent reason for the remaining five catchments misclassified for three indicators. One catchment (54034) has several descriptor values close to threshold levels which results in different predicted flood response types for all indicators when the observed type is consistent across the four. One catchment (42008) is observed type Enhanced H but predicted Sensitive; two catchments (21013 and 54025) have observed and predicted types of damped, neutral and mixed but not matching, while the remaining catchment (37001) has observed mixed or neutral type at RPs 10, 20 and 50 but predicted Enhanced.

Table 4.6 Overall misclassified catchments

	Incorrect at all 4 RPs	Incorrect at 3 RPs	Incorrect at 2 RPs	Incorrect at 1 RP	Correct at all 4 RPs
No. of catchments	1	7	23	68	53
Percentage of catchments	0.66	4.6	15.1	44.7	34.9

Of the 152 catchments only 18 of these are predicted to have an enhanced flood response rather than a damped one for one or more indicators, or vice versa; that is a switch across the neutral/mixed line in Figure 1.2. Therefore, the overall type of flood response family is predicted correctly for 88% of catchments across all four indicators. The results also show that the selected catchment descriptors are able to predict variation in flood response type between indicators.

Large catchments seem to be slightly more difficult to classify, as half of the CLASSIC catchments are amongst those misclassified at one or two indicators, while a slightly smaller proportion of PDM catchments is associated with misclassifications. This would suggest that the response of the flood regime of large catchments to climate change might not be well represented by single value descriptors as they would smooth out spatial variations important in the response of the river to climatic changes.

4.2.3 Discussion of confidence levels and flood response types

A summary of confidence levels (from Table 4.3) associated with the flood response types is provided in Table 4.7 (more than one level per type and indicator shows where there is more than one path to that type). No type stands out as being associated consistently with lower confidence levels across the indicators but Neutral is the type associated most with high confidence. Group sizes are often less than 10 for Mixed and Enhanced types at RP2 and RP10 which contributes to the lower confidence levels for those indicators. There is evidence that confidence levels are higher at RP20 than RP50, probably associated with higher uncertainty in the overall estimation of RP50 events.

Table 4.7 Confidence levels associated with flood response types

Flood response type	RP2	RP10	RP20	RP50
Damped-High	L, H	N/A	N/A	N/A
Damped-Low	L, M	L, L, M, H, H	N/A	N/A
Neutral	M, M	H	L, M, H, H	H, H, H
Mixed	L	L	H	L, H
Enhanced-Low	L, L	L	N/A	N/A
Enhanced-Medium	L, M	L	N/A	N/A
Enhanced-High	M	L	L, H, H	L, L, H
Sensitive	M	M	M	L

4.3 Hydrological characteristics of flood response types

As outlined in Prudhomme *et al.* (2009), the differentiating factors between the nine flood response types can be understood in terms of the interaction between four main features of catchment hydrology and climatology, namely the water balance, catchment memory, natural variability and frequency of flood event. The fact that different decision trees and paths are required for the four indicators shows that a catchment may not exhibit the same response to climate change for all flood events. This is because floods typical of a 2-year return period frequency may have very different characteristics and causes, and response to change, to 50-year events. A catchment may, but may not, have a single flood response type to change. However, the values of the catchment descriptors in Figure 4.1 show two rules which are common to all four flood indicators. The first split always uses SAAR with a value of 969.5 mm and a Bedrock High Permeability of 73.5% occurs in all trees (2nd level split for RP10 and RP50). These two catchment descriptors are the key factors in the partitioning of the decision tree. Area is the other descriptor used for all indicators. The importance of the relative values of SAAR (rainfall) and Mean Annual Loss (a measure of water losses in the catchment, for example from evaporation and abstraction) in determination of the catchment flood response type is indicated in Table 4.8.

Table 4.8 Water balance rules for flood response types

Flood response type	RP2	RP10	RP20	RP50
Damped-High	SAAR ≥ 969.5	N/A	N/A	N/A
Damped-Low	726.5 ≤ SAAR ≤ 969.5	any	N/A	N/A
Neutral	SAAR ≥ 969.5	SAAR ≥ 969.5	Any	Any
Mixed	SAAR ≤ 726.5; MAL ≤ 500.5	SAAR ≤ 726.5	SAAR ≤ 858; MAL ≤ 500.5	Any
Enhanced-Low	726.5 ≤ SAAR ≤ 969.5; MAL ≥ 454.5 SAAR ≤ 726.5; MAL ≤ 500.5	SAAR ≤969.5	N/A	N/A
Enhanced-Medium	SAAR ≤ 726.5; MAL ≤ 500.5	SAAR ≤ 726.5	N/A	N/A
Enhanced-High	726.5 ≤ SAAR ≤ 969.5	SAAR ≤969.5	SAAR ≥ 969.5 SAAR ≤969.5; MAL ≤ 500.5	SAAR ≤ 969.5 MAL ≤ 493.5
Sensitive	SAAR ≤ 726.5 MAL ≥ 500.5	SAAR ≤969.5	SAAR ≤969.5 MAL ≥ 500.5	SAAR ≤ 969.5 MAL ≥ 493.5

The main features of Table 4.8 can be summarised by:

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

Guidelines for hydrological and climatological characteristics for each flood response type are given in Table 4.9 but flood response types do not have definitive boundaries applicable to all indicators.

Table 4.9 Dominant catchment characteristics for the nine flood response types

Flood response type	Dominant characteristics
Damped-Extreme	Medium to high SAAR, water balance affected by snowmelt, flood events have summer predominance
Damped-High	Generally high SAAR, water balance in spring may be affected by snowmelt, generally low permeability (short memory), flood events mainly not in winter (Dec – Feb)
Damped-Low	Medium to high SAAR, water balance not affected by change, generally low permeability
Neutral	Generally high SAAR, water balance not affected by change, low to medium permeability, flood events mainly in winter
Mixed	Generally low SAAR, summer water balance important, low to medium permeability
Enhanced-Low	Low to medium SAAR, not high permeability
Enhanced-Medium	Low SAAR, generally low-lying, not high permeability
Enhanced-High	Low to medium SAAR, generally high permeability but also low permeability with critical summer water balance
Sensitive	Low to medium SAAR, high Mean Annual Loss, summer water balance very sensitive to change, medium to high permeability
For definition of SAAR see Table 3.2, for definition of Mean Annual Loss and permeability see Table 3.3; permeability refers to bedrock permeability	

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

5. Predictions – Risk analysis

When applying the decision trees to identify the flood regime vulnerability to climate change of a catchment from its properties, it is important to remember that the results of the decision trees are probabilistic, i.e. they give the probability associated with all types predicted from following a certain path (see Table 4.3). While these probabilities are highly dependant on the size of the leaf they are derived for (in particular, these probabilities can change significantly if one extra element had been in a small-size leaf), they can inform how confident we might be in the partitioning rules. The confidence level calculated for each path provides a useful indicator of how reliable the prediction might be.

This section presents some examples of how to use and interpret the predictions, and practical recommendations of how to derive estimates of changes in flood peak.

5.1 Example for a path with High confidence level

Example for the Dove @ Rocester Weir (28008):

Descriptor	Value
SAAR	1020
Area	401
ALTBAR	269
BFIHOST	0.556
North	339750
East	411350
Bedrock High Permeability (BHP)	8
Bedrock Very Low Permeability (BVLP)	0.5
Mean Annual Loss (MAL)	445

In order to identify the flood response type of the Dove at Rocester Weir for changes in flood peak at the 50-year return period (RP50), the paths of Figure 4.1d are followed. The results are: $SAAR_{28008} = 1020 > 969.5$ and $ALTBAR_{28008} = 269 > 245.5$, hence the catchment follows path 9 of Figure 4.1d, indicating a flood response type Neutral, estimated with High Confidence.

This means that the Neutral composite flood response pattern for RP50 is appropriate to describe changes in flood peaks for the Dove at Rocester. Comparison of the flood response pattern of the catchment and the Neutral flood response type for two T/PE scenarios of the catchment shows good similarities (Figure 5.1).

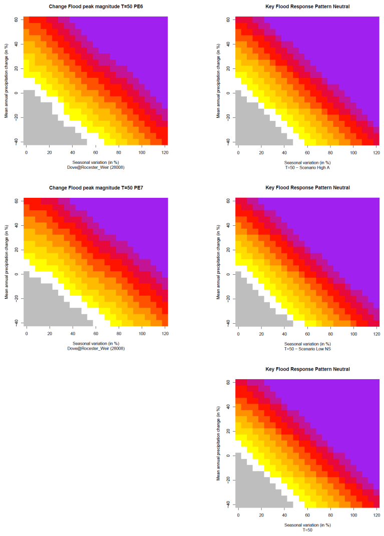


Figure 5.1 Flood response pattern for the Dove @ Rocester Weir and Neutral flood response patterns for two T/PE scenarios (High A and Low NS) for RP50. Bottom: composite of the Neutral flood response type.

5.2 Example for a path with Low confidence level

Example for Tay @ Ballathie (15006):

Descriptor	Value
SAAR	1424
Area	4587
ALTBAR	411
BFIHOST	0.473
North	736600
East	314700
Bedrock High Permeability (BHP)	0
Bedrock Very Low Permeability (BVLP)	83
Mean Annual Loss (MAL)	301

In order to identify the flood response type of the Tay at Ballathie for changes in flood peak at the 2-year return period (RP2), the paths of Figure 4.1a are followed. The results are: $SAAR_{15006} = 1424 > 969.5$ and $Area_{15006} = 4587 > 847.795$ and Mean Annual $Loss_{15006} = 301 < 426.5$, hence the catchment follows path 12 of Figure 4.1a, indicating a flood response type Damped L estimated with low confidence. Alternative flood response types given for this path are Damped H (45% of the sample) and Neutral (10% of the sample) (Table 4.3a)

This means that it is difficult to identify a unique flood response type for the Tay at Ballathie for RP2 as its catchment descriptors are shared equally by catchments of the Damped High and Damped Low flood response type, with some catchments of the Neutral flood response type. Evidence of this is seen in Figure 5.2, where patterns for each type are shown alongside the catchment flood response pattern for two T/PE scenarios. The Tay at Ballathie shares flood response pattern characteristics of all three flood response types, with the width of bands showing changes between 0 and 90% increase in flood peak (bands in yellow and red shades) lying between those of Damped H and Damped L. As a precautionary measure, one might prefer to consider the flood response type characterised by the highest changes, in this case Damped L or even Neutral, to avoid possible under-estimation of the changes for some scenarios.

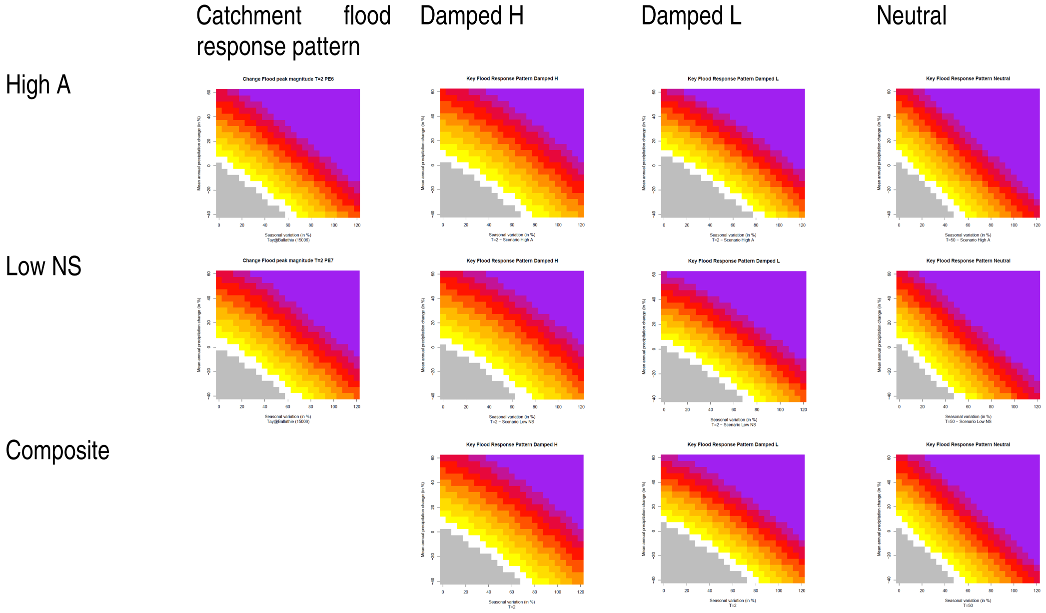


Figure 5.2 Flood response pattern for the Tay @ Ballathie and Damped H, Damped L and Neutral flood response patterns for the two T/PE scenarios for RP50. Bottom: composite of Damped H, Damped L and Neutral flood response types.

5.3 Example of a catchment with predicted vulnerability two types lower than observed

For RP10, the Stour at Throop (43007), an Enhanced Low catchment, was predicted to be of merged type Damped Low following path 5 of Figure 4.1b, thus two types different from its original type according to Figure 1.2. This is a path with Medium confidence level, hence where the prediction of the flood response type should be considered with some caution. The difference between the Damped Low composite and the flood response pattern of the catchment (of type Enhanced Low) for two T/PE scenarios can be seen in Figure 5.3.

There is a distinct difference between the catchment flood response patterns and the predicted Damped Low flood response pattern primarily in the slope of the bands showing same level changes (areas with yellow to red shades, steeper for the catchment flood response than for its predicted type), and the width of those bands. As described in Prudhomme *et al.* (2009), slope and location of those bands within the sensitivity framework is indicative of how fast the catchment responds to climatic changes, and whether the catchment can act as a buffer when rainfall increases. Such differences are unsurprising as they are the main criterion for the categorisation of the different flood response types. However, these differences are also where the largest internal variability of the original group describing the Damped Low flood response pattern, here illustrated with the Coefficient of Variation within the group[1]. Adding one or two SD to the estimate of flood peak change given by the composite flood response pattern will reduce the under-estimation in flood peak change generated by a prediction of a flood response type that is not high enough.

There is one alternative flood response type for this path, the Enhanced Low merged type (probability of 0.11). Because the path is associated with a Medium confidence (primarily due to the very small number of catchments from our sample with these combinations of descriptors), it is recommended to consider the type suggested by second highest probability. Its corresponding flood response patterns are shown in Figure 5.3, to be compared with the catchment's flood response patterns.

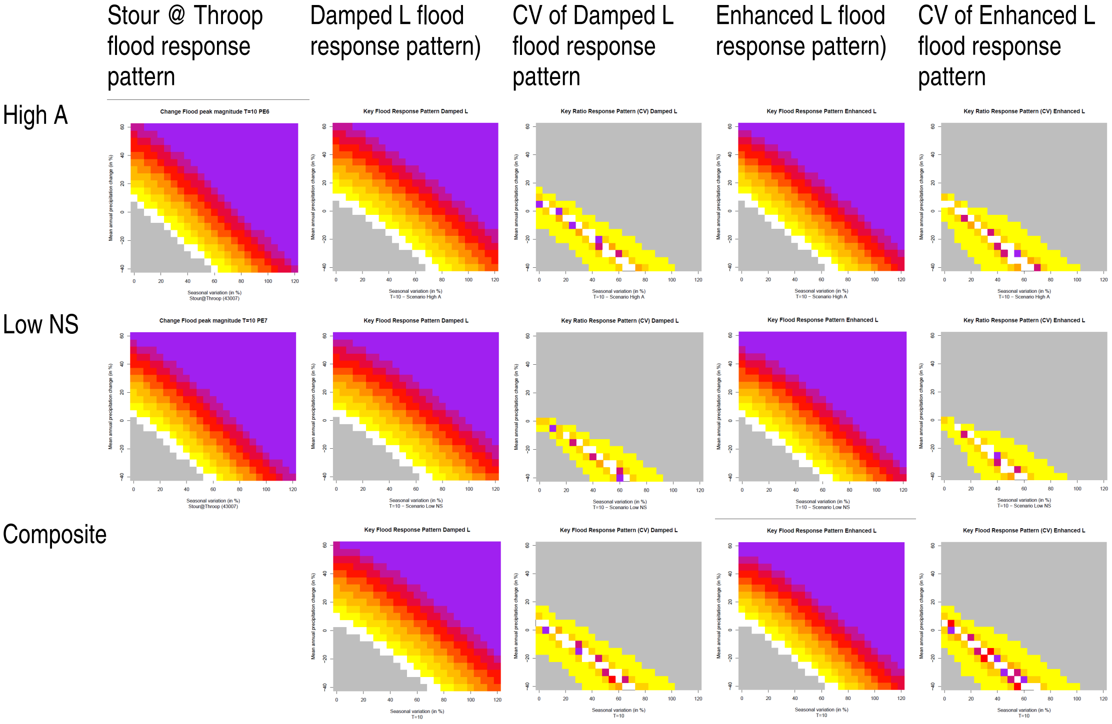


Figure 5.3 Flood response pattern and associated CV for the Stour @ Throop and predicted Damped Low flood response pattern for two T/PE scenarios for RP10. Bottom: composite of Damped Low and Enhanced Low flood response type.

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[1] the coefficient of variation, or CV, is the ratio between the average of the patterns of the original group and the standard deviation of the patterns of the original group. It is a non-dimensional value, which highlights areas of largest internal variation

When undertaking an impact study linked with Medium confidence path, it is recommended to investigate other types suggested by the highest probabilities (here there are only two flood response types suggested), in particular if they correspond to flood response types leading to larger flood changes.

5.4 Predictions for the Damped Extreme catchments

Three catchments were removed from the sample used to derive the decision trees as they formed a separate group described as the Damped Extreme flood response type which was not large enough to be discriminated by the technique. The three catchments categorised as Damped Extreme from their flood response pattern are: the Findhorn @ Forres (7002), the Avon @ Delhashaugh (8004) and the Dee @ Mar Lodge (12007). Here we compare which flood response types and corresponding patterns are indicated by the decision trees, and evaluate differences and similarities with the true catchment flood response types (Damped Extreme).

Descriptor	Findhorn @ Forres	Avon @ Delhashaugh	Dee @ Mar Lodge
SAAR	1064	1111	1335
Area	781.72	540.75	291.83
ALTBAR	442	525	683
BFIHOST	0.434	0.451	0.399
North	858350	835200	789500
East	301800	318500	309650
Bedrock High Permeability (BHP)	1	0	0
Bedrock Very Low Permeability (BVLP)	99	86	98
Mean Annual Loss (MAL)	318	235	82

The paths of Figure 4.1 must be followed to identify a flood response type according to the catchment properties, summarised below:

Catchment	RP2	RP10	RP20	RP50	Overall response
Findhorn @ Forres	Damped H (path 11, H)	Damped L (path 12, H)	Neutral (path 9, H)	Neutral (path 9, H)	Lowest vulnerability type predicted for 4 out of 4 indicators Overall level: lowest vulnerability flood response type
Avon @ Delhashaugh	Damped H (path 11, H)	Neutral (path 11, H)	Neutral (path 9, H)	Neutral (path 9, H)	Lowest vulnerability type predicted for 3 out of 4 indicators Overall level: lowest vulnerability flood response type
Dee @ Mar Lodge	Damped H (path 11, H)	Neutral (path 11,H)	Neutral (path 9, H)	Neutral (path 9, H)	Lowest vulnerability type predicted for 3 out of 4 indicators Overall level: lowest vulnerability flood response type

For RP20 and RP50, the flood response type predicted with high confidence is Neutral for all three catchments, which is the ‘lowest’ vulnerability flood response type of the merged levels for RP20 and RP50 (hence closest to Damped Extreme).

For RP10, Damped Low is predicted with High confidence for the Findhorn, but Neutral is predicted for the Avon and the Dee, also with high confidence. Damped Low is the 'lowest' vulnerability flood response type for RP10 (hence closest to Damped Extreme).

For RP2, all three catchments follow the same path, which predicts with high confidence the Damped High type, which is the 'lowest' vulnerability flood response type for RP2 (hence closest to Damped Extreme)

Considering all four flood indicators, the lowest vulnerability flood response type is predicted for three flood indicators out of four for all catchments (all flood indicators for the Findhorn @ Forres). When it is not the lowest, the second lowest level is predicted. This means that all decision trees correctly suggest that the flood response type of all three catchments generally shows a low vulnerability to climatic changes. This is consistent with the original flood response type of these catchments, which showed a very damped flood response to climate change.

5.5 Additional uncertainty

In Prudhomme *et al.* (2009), the internal variation in the patterns of a key flood response was analysed using the standard deviation and the coefficient of variation. They measure the variability in the group. In general, between 60 and 75% of the data is located within a distance of one standard deviation either side of the average (i.e. composite), and between 90 and 98% of the data located within two standard deviations either side of the average. Assuming the distribution in each of the groups is normal, 95% of the data is located within 1.96 times the standard deviation either side of the average.

In order to integrate the variability found in each of the key flood response patterns, it is recommended to add one or two standard deviations to the estimate given by the composite pattern of the flood response type found from the catchment descriptors.

5.6 Practical recommendations

When estimating the vulnerability of a catchment from its physical and climatological properties, the decision trees presented in this report provide a best-estimate of the flood response type, with an associated probability (Figure 4.1). Also provided is an indication of the confidence in that best-estimate (High, Medium or Low; Figure 4.1), given the probabilities associated with alternative flood response types (Table 4.3) and the potential robustness of the associated probabilities to changes in the catchment sample.

In order to incorporate these factors, and to minimise possible underestimation in the changes in flood peaks, Table 5.1 presents some practical recommendations on what course of action to take under various circumstances that may arise when applying the methodology. Estimating the possible impact for different return periods is also recommended, in the eventuality that the considered catchment is misclassified for only one flood indicator.

Table 5.1 Practical suggestions for predicting the flood response type of a catchment's flood regime from its descriptors

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

6. Conclusions

This report describes how to characterise the flood response type of a catchment flood regime to climatic changes from a set of catchment characteristics. The method follows a decision tree approach, where paths (or sets of partitioning rules) are associated with a predicted category, here the flood response type of a catchment response to climate change for specific flood indicators.

The decision trees developed showed very good prediction abilities, where more than 80% of catchments could successfully be categorised as ‘resilient’ to climatic changes (i.e. changes in their flood peaks are proportionally smaller than the maximum rainfall changes), ‘neutral’ or ‘enhancing’ to climatic changes. A finer level of vulnerability was determined for higher probability flood events (RP2 and RP10) than for more extreme events (RP20 and RP50). When incorrect, the predictions generally over-estimate the vulnerability, thus allowing for precautionary estimates to be made. With a probabilistic estimation embedded in the approach, a level of confidence was calculated for all predictions which can be used in the final assessment of uncertainty associated with the predicted catchment flood response type.

The decision trees finalise the regionalisation in Britain of the vulnerability of catchments (in term of their flood regime) to climate change, defined as the response of the catchments to 525 different rainfall change scenarios combined with 8 T/PE scenarios. It exploits nine catchment descriptors which are all available digitally for Britain for a large number of catchments. Combined with an estimation of the hazard, or which climate change scenario is predicted to be more likely, the framework enables an estimate risk in flood changes due to climate changes. In particular, this framework enables a quick update of potential risk in flood changes to be made when new climate change projections become available, such as for example the UKCP09 scenarios, without the need to undertake an extensive hydrological modelling and impact study. When flood response types are assessed nationally, they will support the testing of climate change allowances against the range of impacts due to different climate changes scenarios, and help revise policy guidance as climate science develops.

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8. Appendices

8.1 Key flood response types of changes in flood peak of four return periods for the study catchments

Catchment	River	Gauging station	Obs RP2	Pred RP2	Obs RP10	Pred RP10	Obs RP20	Pred RP20	Obs RP50	Pred RP50
2001	Helmsdale	Kilphedir	DpH	DpH	DpH	Neu	DpH	Neu	DpH	Neu
3003	Oykel	Easter_Turnaig	Neu	DpH	Neu	Neu	DpL	Neu	DpL	Neu
4005	Meig	Glenmeannie	DpH	DpH	Neu	Neu	Neu	Neu	Neu	Neu
6008	Enrick	Mill_of_Tore	Neu	DpH	Neu	Neu	DpL	Neu	Neu	Neu
7001	Findhorn	Shenachie	DpH	DpH	Neu	Neu	DpL	Neu	Neu	Neu
7002	Findhorn	Forres	DpE	DpH	DpE	DpL	DpE	Neu	DpE	Neu
7004	Nairn	Firhall	EnL	EnL	EnM	DpL	EnM	EnH	EnM	EnH
8004	Avon	Delnashaugh	DpE	DpH	DpE	Neu	DpE	Neu	DpE	Neu
8006	Spey	Boat_o_Brig	DpH	DpL	Neu	DpL	DpL	Neu	DpL	Neu
10002	Ugie	Inverugie	DpH	DpL	DpH	DpL	DpH	Neu	DpH	Neu
10003	Ythan	Ellon	DpH	DpL	DpH	DpL	DpH	Neu	DpL	Neu
11001	Don	Parkhill	DpH	DpL	DpH	DpL	DpH	Neu	DpH	Neu
12002	Dee	Park	DpH	DpH	DpH	DpL	DpH	Neu	DpH	Neu
12003	Dee	Polhollick	DpH	DpH	DpH	DpL	DpH	Neu	DpH	Neu
12007	Dee	Mar_Lodge	DpE	DpH	DpE	Neu	DpE	Neu	DpE	Neu
13001	Bervie	Inverbervie	DpL	DpL	Neu	DpL	DpL	Neu	DpL	Neu
13005	Lunan_Water	Kirkton_Mill	DpL	DpL	DpL	DpL	Mix	Neu	Neu	Neu
14001	Eden	Kemback	DpL	DpL	DpL	DpL	Mix	Mix	DpL	Neu
15006	Tay	Ballathie	Neu	DpH	Neu	DpL	Neu	Neu	Neu	Neu
16003	Ruchill_Water	Cultybraggan	DpH	DpH	Neu	Neu	Neu	Neu	Neu	Neu
17005	Avon	Polmonthill	DpH	DpH	DpH	Neu	DpH	Neu	DpL	Neu
19011	North_Esk	Dalkeith_Palace	DpH	DpL	DpH	DpL	DpH	Neu	DpH	Neu
20001	Tyne	East_Linton	Mix	EnM	Mix	Mix	Mix	Mix	Mix	Mix
21009	Tweed	Norham	DpL	DpL	DpL	DpL	Mix	Neu	Mix	Neu
21013	Gala_Water	Galashiels	DpL	DpL	Mix	DpL	Mix	Neu	Mix	Neu
21017	Ettrick_Water	Brockhoperig	Neu	DpH	Neu	Neu	Neu	Neu	Neu	Neu
21023	Leet_Water	Coldstream	EnM	EnM	EnM	Sens	EnM	EnH	EnM	EnH
22001	Coquet	Morwick	DpH	DpL	DpH	DpL	DpH	Neu	DpH	Neu
22006	Blyth	Hartford_Bridge	EnM	EnM	Mix	Mix	Mix	EnH	Mix	Mix
23001	Tyne	Bywell	DpL	DpH	DpH	DpL	DpH	Neu	DpL	Neu
23011	Kielder_Burn	Kielder	DpH	DpH	Neu	Neu	DpL	Neu	Neu	Neu
24005	Browney	Burn_Hall	Mix	DpL	Mix	DpL	DpH	EnH	DpH	Mix
24009	Wear	Chester_le_Street	Mix	DpL	Mix	DpL	Mix	Mix	Mix	Mix
25006	Greta	Rutherford_Bridge	DpH	DpH	DpH	Neu	DpH	Neu	DpH	Neu
27003	Aire	Beal_Weir	DpL	DpL	DpH	DpL	DpH	Neu	DpH	Mix
27007	Ure	Westwick_Lock	DpH	DpH/DpL	DpH	DpL	DpH	Neu	DpH	Neu
27009	Ouse	Skelton	DpL	DpL	DpH	DpL	DpH	Neu	DpH	EnH
27021	Don	Doncaster	DpH	DpL	DpH	DpL	DpH	Neu	DpL	Neu
27041	Derwent	Buttercrambe	DpL	DpL	DpL	DpL	Mix	EnH	Mix	Mix
27043	Wharfe	Addingham	DpH	DpH	DpH	Neu	DpH	Neu	DpL	Neu
27049	Rye	Ness	DpL	DpL	DpL	DpL	EnL	EnH	Mix	Neu
27051	Crimple	Burn_Bridge	Neu	DpL	DpH	DpL	DpH	EnH	DpH	Neu
27997	Ure (CLASSIC)	Westwick_Lock	DpL	DpH/DpL	DpH	DpL	DpH	Neu	DpH	Neu
28008	Dove	Rocester_Weir	Neu	DpH	Neu	Neu	DpL	Neu	DpL	Neu

Catchment	River	Gauging station	Obs RP2	Pred RP2	Obs RP10	Pred RP10	Obs RP20	Pred RP20	Obs RP50	Pred RP50
28015	Idle	Mattersey	Sens	Sens	Sens	EnH	Sens	Sens	Sens	Sens
28022	Trent	North_Muskham	DpL	DpL	DpL	DpL	Mix	Mix	Mix	Neu
28039	Rea	Calthorpe_Park	EnL	EnL	EnL	EnL	Mix	Mix	Mix	Mix
28046	Dove	Izaak_Walton	DpH	DpH	Neu	Neu	DpL	Neu	Neu	Neu
28066	Cole	Coleshill	Sens	Sens	Sens	Mix	Sens	Sens	EnH	EnH
29001	Waithe_Beck	Brigsley	Sens	Sens	Sens	Sens	Sens	Sens	Sens	Sens
30004	Lymn	Partney_Mill	EnL	EnH	DpL	DpL	Mix	Mix	Mix	Mix
30017	Witham	Colsterworth	Sens	Sens	Sens	Sens	Sens	Sens	EnH	Sens
31002	Glen	Kates_and_King_St_Brs	Sens	Sens	Sens	DpL	Sens	Sens	Sens	Mix
32003	Harpers_Brook	Old_Mill_Bridge	EnM	EnM	Mix	Mix	Mix	EnH	Mix	Mix
33012	Kym	Meagre_Farm	EnM	EnM	EnM	EnM	EnM	EnH	Mix	EnH
33019	Thet	Melford_Bridge	EnH	Mix	EnH	EnH	EnM	EnH	EnM	EnH
33026	Bedford_Ouse	Offord	Mix	Mix	Mix	Mix	Mix	Mix	Mix	Mix
33029	Stringside	Whitebridge	EnH	EnH	EnH	Sens	EnH	EnH	EnH	EnH
33035	Ely_Ouse	Denver_Complex	Mix	Mix	Mix	EnH	DpH	EnH	Mix	Sens
34003	Bure	Ingworth	Mix	Mix	Mix	EnM	Mix	Mix	Mix	Mix
34006	Waveney	Needham_Mill	EnH	Mix	EnM	EnM	EnM	Mix	Mix	Mix
36005	Brett	Hadleigh	EnM	EnM	EnH	EnH	EnH	EnH	EnH	EnH
36008	Stour	Westmill	EnL	EnL	EnL	EnH	EnL	EnH	EnL	EnH
36010	Bumpstead_Brook	Broad_Green	EnM	EnL	EnM	Sens	EnM	EnH	EnM	EnH
37001	Roding	Redbridge	EnM	EnM	Mix	EnL	DpH	EnH	DpH	EnH
37031	Crouch	Wickford	EnM	EnM	EnM	EnM	EnM	EnH	EnM	EnH
38003	Mimram	Panshanger_Park	Sens	Sens	Sens	Sens	Sens	Sens	Sens	Sens
38007	Canons_Brook	Elizabeth_Way	DpL	EnL	DpH	EnL	DpH	Neu	DpH	Neu
38020	Cobbins_Brook	Sewardstone_Road	EnL	EnL	EnL	EnL	EnL	EnH	Neu	EnH
39001	Thames	Kingston	DpL	EnL	DpL	DpL	Mix	Mix	Mix	Mix
39007	Blackwater	Swallowfield	EnL	EnL	DpL	DpL	Mix	Mix	Mix	Mix
39008	Thames	Eynsham	DpL	DpL	DpL	DpL	Mix	Mix	Mix	Mix
39016	Kennet	Theale	DpL	EnL	DpL	DpL	Mix	Mix	Mix	Mix
39017	Ray	Grendon_Underwood	EnL	EnL	EnL	EnL	EnL	EnH	Neu	EnH
39037	Kennet	Marlborough	EnH	EnH	Sens	Sens	Sens	Sens	Sens	Sens
39069	Mole	Kinnersley_Manor	DpH	DpL	DpH	DpL	DpH	Neu	DpH	Neu
39073	Churn	Cirencester	EnH	EnH	Sens	Sens	Sens	Sens	Sens	Sens
39081	Ock	Abingdon	DpL	EnL	DpL	DpL	Mix	Mix	Mix	Mix
39105	Thame	Wheatley	EnM	EnL	EnL	EnL	EnL	Mix	Neu	Neu
40003	Medway	Teston	DpL	DpL	DpH	DpL	Mix	Mix	Mix	Mix
40005	Beult	Stile_Bridge	EnL	EnM	EnM	EnM	Mix	Mix	Mix	Mix
40011	Great_Stour	Horton	Mix	EnH	EnL	EnH	EnL	EnH	EnL	EnH
42008	Cheriton_Stream	Sewards_Bridge	EnH	EnH	EnH	Sens	EnH	Sens	EnH	Sens
42012	Anton	Fullerton	EnH	EnH	EnH	EnH	Sens	EnH	EnH	EnH
43005	Avon	Amesbury	EnH	EnH	EnH	EnH	EnH	EnH	EnH	EnH
43007	Stour	Throop	EnL	EnL	EnL	DpL	EnL	Neu	EnL	EnH
43021	Avon	Knapp_Mill	DpL	DpL	DpL	DpL	Mix	Mix	Mix	Mix
44002	Piddle	Baggs_Mill	EnH	EnH	EnH	EnH	EnH	Sens	EnH	Sens
45003	Culm	Wood_Mill	Neu	Neu	Neu	Neu	DpL	Neu	DpL	Neu
45005	Otter	Dotton	Neu	Neu	Neu	Neu	DpL	Neu	DpL	Neu
47001	Tamar	Gunnislake	Neu	Neu	DpL	DpL	EnL	EnH	Mix	Mix
47007	Yealm	Puslinch	Neu	Neu	Neu	Neu	Neu	Neu	Neu	Neu

Catchment	River	Gauging station	Obs RP2	Pred RP2	Obs RP10	Pred RP10	Obs RP20	Pred RP20	Obs RP50	Pred RP50
47008	Thrushel	Tinhay	Neu	Neu	Neu	Neu	Neu	Neu	EnL	Neu
48003	Fal	Tregony	Neu	Neu	Neu	Neu	DpL	Neu	DpL	Neu
50002	Torridge	Torrington	DpH	Neu	Neu	Neu	Neu	Neu	Neu	Neu
50006	Mole	Woodleigh	Neu	Neu	Neu	Neu	DpL	Neu	DpL	Neu
52010	Brue	Lovington	DpL	EnL	DpH	DpL	DpH	Neu	DpH	EnH
53009	Wellow_Brook	Wellow	Neu	Neu	DpL	Neu	Mix	Neu	Neu	Neu
53018	Avon	Bathford	DpL	DpL	DpH	DpL	Mix	Mix	Mix	Mix
54001	Severn	Bewdley	DpL	DpL	DpL	EnL	EnL	Neu	EnL	EnH
54008	Teme	Tenbury	EnL	EnL	EnL	EnL	EnL	EnH	EnL	EnH
54018	Rea_Brook	Hookagate	EnL	EnL	EnL	EnL	EnL	EnH	Mix	Mix
54025	Dulas	Rhos-y-pentref	Neu	DpH	DpL	Neu	Mix	Neu	Neu	Neu
54027	Frome	Ebley_Mill	EnL	EnH	EnL	EnH	EnL	EnH	EnL	EnH
54034	Dowles_Brook	Oak_Cottage	EnH	EnM	EnH	DpL	EnH	EnH	EnH	Mix
54057	Severn	Haw_Bridge	DpL	DpL	DpL	DpL	Mix	Mix	Mix	Mix
54090	Tanllwyth	Tanllwyth_Flume	DpH	DpH	Neu	Neu	DpL	Neu	Neu	Neu
55002	Wye	Belmont	Neu	Neu	Neu	DpL	Mix	EnH	Neu	Neu
55008	Wye	Cefn_Brwyn	DpH	DpH	Neu	Neu	DpL	Neu	DpL	Neu
55013	Arrow	Titley_Mill	Neu	DpL	EnL	EnL	EnL	EnH	EnL	EnH
55023	Wye	Redbrook	DpL	Neu	DpL	DpL	EnL	EnH	EnL	Mix
55029	Monnow	Grosmont	DpL	EnL	Neu	EnL	EnL	EnH	EnL	EnH
57005	Taff	Pontypridd	DpH	DpH	Neu	Neu	Neu	Neu	Neu	Neu
57006	Rhondda	Trehafod	DpH	DpH	Neu	Neu	Neu	Neu	Neu	Neu
58005	Ogmore	Brynmenyn	DpH	DpH	Neu	Neu	DpL	Neu	Neu	Neu
58006	Mellte	Pontneddfechan	DpH	DpH	Neu	Neu	DpL	Neu	DpL	Neu
60002	Cothi	Felin_Mynachdy	Neu	DpH	DpH	Neu	DpH	Neu	DpH	Neu
60003	Taf	Clog-y-Fran	DpH	DpH	DpH	Neu	DpH	Neu	DpH	Neu
60010	Tywi	Nantgaredig	Neu	Neu	DpL	DpL	Mix	EnH	Mix	Mix
61001	Western_Cleddau	Prendergast_Mill	DpH	DpH	Neu	Neu	DpL	Neu	DpL	Neu
62001	Teifi	Glan_Teifi	DpL	DpH	DpL	DpL	EnL	EnH	EnL	Mix
64001	Dyfi	Dyfi_Bridge	DpH	DpH	Neu	Neu	Neu	Neu	Neu	Neu
65006	Seiont	Peblig_Mill	DpH	DpH	Neu	Neu	DpL	Neu	DpL	Neu
66011	Conwy	Cwm_Llanerch	DpH	DpH	Neu	Neu	DpL	Neu	DpL	Neu
67009	Alyn	Rhydymwyn	EnL	EnL	EnM	DpL	EnM	Sens	Mix	EnH
67033	Dee	Chester_Suspension_Br	Neu	Neu	DpL	DpL	Mix	EnH	Mix	Mix
68001	Weaver	Ashbrook	DpL	EnL	DpL	DpL	Mix	Mix	Neu	EnH
68005	Weaver	Audlem	EnM	EnM	EnH	DpL	EnM	EnH	EnM	EnH
69037	Mersey	Westy	DpL	Neu	DpL	DpL	EnL	EnH	Mix	Mix
69040	Irwell	Stubbins	DpH	DpH	DpH	Neu	DpL	Neu	DpL	Neu
71001	Ribble	Samlesbury	Neu	Neu	DpH	DpL	DpH	Neu	DpH	Mix
72004	Lune	Caton	DpH	DpL	Neu	DpL	Neu	Neu	Neu	Neu
73005	Kent	Sedgwick	DpH	DpH	Neu	Neu	Neu	Neu	EnL	Neu
74001	Duddon	Duddon_Hall	DpH	DpH	Neu	Neu	Neu	Neu	Neu	Neu
75017	Ellen	Bullgill	DpH	DpH	DpH	Neu	DpL	Neu	DpL	Neu
76007	Eden	Sheepmount	Neu	Neu	Neu	DpL	Neu	Neu	Neu	Neu
76014	Eden	Kirkby_Stephen	DpH	DpH	Neu	Neu	Neu	Neu	Neu	Neu
78003	Annan	Brydekirk	DpH	DpH	DpH	DpL	DpH	Neu	DpH	Mix
79002	Nith	Friars_Carse	DpH	DpH	DpH	DpL	DpL	Neu	DpL	Neu
79003	Nith	Hall_Bridge	DpH	DpH	Neu	Neu	DpL	Neu	Neu	Neu
79005	Cluden_Water	Fiddlers_Ford	Neu	DpH	Neu	Neu	Neu	Neu	Neu	Neu
81002	Cree	Newton_Stewart	DpL	DpH	DpH	Neu	DpH	Neu	DpH	Neu

Catchment	River	Gauging station	Obs RP2	Pred RP2	Obs RP10	Pred RP10	Obs RP20	Pred RP20	Obs RP50	Pred RP50
81006	Water_of_Minnoch	Minnoch_Bridge	DpH	DpH	DpH	Neu	DpH	Neu	DpL	Neu
83005	Irvine	Shewalton	DpH	DpH	DpH	Neu	DpL	Neu	DpL	Neu
84012	White_Cart_Water	Hawkhead	DpH	DpH	Neu	Neu	Neu	Neu	Neu	Neu
84013	Clyde	Daldowie	DpL	DpH	DpH	DpL	DpL	Neu	DpL	Neu
84030	White_Cart_Water	Overlee	DpH	DpH	Neu	Neu	Neu	Neu	Neu	Neu
85003	Falloch	Glen_Falloch	DpH	DpH	Neu	Neu	DpL	Neu	Neu	Neu
86001	Little_Eachaig	Dalinlongart	Neu	DpH	DpH	Neu	DpH	Neu	DpH	Neu
90003	Nevis	Claggan	DpH	DpH	DpH	Neu	DpL	Neu	Neu	Neu
93001	Carron	New_Kelso	DpH	DpH	DpH	Neu	DpL	Neu	DpL	Neu
94001	Ewe	Poolewe	Neu	DpH	Neu	Neu	Neu	Neu	Neu	Neu
95001	Inver	Little_Assynt	DpH	DpH	Neu	Neu	DpL	Neu	DpL	Neu
96001	Halladale	Halladale	DpH	DpH	DpH	Neu	DpH	Neu	DpH	Neu
97002	Thurso	Halkirk	DpH	DpH	DpH	Neu	DpH	Neu	DpH	Neu

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