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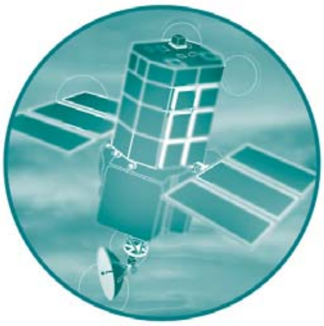

Impact of climate change on flood flows in river catchments – final report

R&D Technical Report W5-032/TR

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Food and Rural Affairs

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Impact of climate change on flood flows in river catchments – final report

R&D Technical Report W5-032/TR

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Statement of use
This document describes research undertaken during the 2 year project looking at the potential impact of climate change on flood flows in UK river catchments. The results will be used to inform Defra policy development on allowances for climate change in flood defence scheme appraisal.

Keywords
research; flood flows; climate change; Project Appraisal Guidance; UKCIP02 Scenarios, dynamic and statistical downscaling

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EXECUTIVE SUMMARY

This report details work undertaken during project W5-032. The objectives of the project are: To improve the scientific basis for the guidance on climate change to the flood management community, by applying climate change scenarios to a selected range of catchment types, making explicit use of UKCIP02 scenarios. The basic technical approach is to 'drive' hydrological models with input climate data that incorporates the changes indicated in the UKCIP02 Technical Report (Hulme *et al.* 2002).

Two types of hydrological model have been used, due to the wide range of catchment size, meaning that five of the study catchments have been modelled at the daily time step, and five at the hourly time step. The models, their calibration and performance are described, as are the uncertainties due to model calibration. Model simulations have assumed stationarity of all hydrological processes and land use between baseline and scenario time periods.

The UKCIP02 rainfall scenarios have been applied through the development of a "combined" scenario that incorporates both the percentage changes in average rainfall and the change in frequency of daily rainfall required for each month. Other scenarios have also been applied based on the use of statistical downscaling methods for rainfall, using the Statistical Downscaling Model (SDSM, Wilby 2002) and the direct use of data from the 25km Hadley Centre Regional Climate Model (RCM).

The results show the impacts of climate change on flood frequency in the study catchments, under the selected scenarios, to be considerably lower than those previously determined (Reynard *et al.* 1998, 2001). This is determined primarily by the fact that the current version of the Hadley Centre GCM, driving the climate changes, produces significantly drier and warmer summers and autumns, so that, despite the wetter winters (on average), flood frequencies in many catchments decrease. This does not necessarily apply to those catchments that are more responsive, i.e. steep-sided, small or urban catchments, but even in these the precise response is determined by the spatial and temporal detail of the climate changes.

For each of the catchments a range of climate impacts has been shown. In only a few of these are there obvious tendencies towards either a decrease (the Lymn - 30004 and the Beult - 40005) or an increase (the Duddon - 74001 and the Anton - 42012). All other catchments present a range of change, both positive and negative.

A wider range of impact was presented using resampled rainfall data, but even with these data the maximum impact from UKCIP02 scenarios was only above 20% for three of the catchments by the 2080s. In general, the range of impacts in this study is wide, across catchments, time slices and scenarios, but usually below the 20% increase. These results suggest that, under these scenarios, the current 20% sensitivity band appears appropriate as a precautionary response to the uncertainty of future climate change impacts on flood flows. To a very large degree this conclusion is determined by the dry and warm nature of the Hadley Centre model used to generate all the scenarios, and using other GCMs will undoubtedly produce different results.

The impact of climate change on the duration of high flows has been explored through the seasonal Q3 statistic (the flow exceeded 3% of the time). Most catchments show an increase in Q3 in the winter but a decrease in all other seasons, normally greatest in the summer. However, for the Anton (42012) and the Thames (39001), autumn shows a more extreme impact due to the contribution of baseflow sustaining runoff during the summer. Comparison of downscaling methods shows the pattern of change is similar across the seasons.

Some tentative relationships between catchment properties and the impact of climate change on flooding are suggested. These are not necessarily direct 'cause and effect' relationships. They could each be surrogates for something else, or for each other, and so the same relationships may not hold in other locations. For example, in the UK more westerly catchments are also more likely to have a lower BFI and a higher mean altitude. Thus it seems that location may be the dominant factor in determining the impact of climate change on flooding, but whether this is due to the spatial pattern of climate change or to the partial dependence of catchment type on location (or both) is difficult to distinguish given the relatively small number of catchments studied.

Finally, it is important to consider all the various sources of uncertainty involved in climate change impact studies, and how this uncertainty impacts on the decision that the research informs (Willows and Connell 2003). This research has, to a degree, addressed some of these uncertainties.

CONTENTS

1 INTRODUCTION

1.1 Background and project objectives

This is the final report for project W5-032: Impact of climate change on flood flows in river catchments. The project is in Theme 5.3 of the joint Defra / EA Flood and Coastal Defence R&D programme (within the Climate Change sub-theme within the Risk Evaluation and Understanding of Uncertainty theme). The project specifically addresses the following Scientific Objectives within the ROAME A Statement for the Theme:

- Provide information on climate change scenarios, impacts and uncertainties related to flood and coastal defence based on the best available scientific evidence, over a range of relevant parameters;
- Ensure that so-called 'climate surprises' and non-linearities are identified and possible implications are assessed, in order to understand more fully the possible implications of climate change.

Within the context of these ROAME Objectives the specific project objectives are:

- To help to meet the needs of the flood defence community for more sophisticated guidance on climate change impacts than are currently available;
- To provide a rapid and cost-effective case study assessment of climate change impacts on flood flows driven by the UKCIP02 scenarios;
- To demonstrate, and provide feedback on, the opportunities for impacts assessment presented by state-of-art detailed catchment modelling.

The interim report (report number W5-032/TR1), produced in March 2003, detailed the work undertaken during Year 1 of the project, concentrating on the description of the impact of the UKCIP02 scenarios on the flood flows of the Thames and Severn catchments. This constituted a re-working of the methodology described in Reynard *et al.* (1998, 2001) by applying the new UKCIP scenarios to the CLASSIC hydrological model in precisely the same way as was done before. It was that original work which under-pinned the 20% guidance in the Defra Project Appraisal Guidance (PAG) series for investigating potential sensitivities to climate change. The work described in the interim report therefore provided a direct comparison with the earlier work, while acknowledging the relatively simplistic way in which the scenarios of change, particularly for rainfall, were derived. For this report, a wider range of scenarios have been developed, particularly for precipitation, and applied for a larger number of catchments. These sources of precipitation include the use of both statistical and dynamic downscaling.

1.2 Report structure

This report first describes the catchments used in the study, detailing the reasons for selection and providing a range of catchment characteristics for each of them. The second section describes the hydrological models used. Due to the nature of the catchments selected it was necessary to use two models, essentially one "lumped" catchment model for the six smaller catchments and a semi-distributed model for the four larger catchments. The calibration of the models is described along with a discussion of the evaluation of model performance and an estimate of the hydrological (calibration) uncertainty.

Section 4 describes the range of climate change scenarios that have been used in the project, including the UKCIP02 scenarios, statistically downscaled scenarios and the direct use of information from the latest Hadley Centre regional climate model (RCM). The statistical and dynamic (use of RCM data) downscaling methods both generate daily (or hourly) rainfall series for the baseline as well as for scenario time periods. This section also includes a comparison of the baseline, 1961-1990 rainfall statistics from both of these sources, compared with the observed rainfall series for selected catchments. The impact on river flows of which of these sources of rainfall data is used is also illustrated.

Section 5 draws together the key flood frequency results under each of the scenarios, for selected catchments in terms of potential changes to the frequency and /or magnitude of flood flows (the full set of results for all scenarios, all future time horizons and for all catchments is given in Appendix I). In addition, there is an analysis of the impacts of climate change on the duration of flood flows, with regard to the particularly striking feature of the autumn / winter 2000 / 2001 floods in the UK (CEH-Wallingford / Met Office 2001), and an estimation of uncertainty in the impacts due to the rainfall data sources, through statistical resampling.

Section 6 provides the key set of outcomes from the results, highlighting the important messages for users and policy-makers. This section describes the effect of the choice of emission scenario and scenario downscaling technique and presents the results of the pair-wise comparison of catchment response to climate change. Finally, key conclusions are drawn in Section 7.

1.3 Uncertainty in climate change impact studies

There is, and always will be uncertainty in all aspects of a climate change impact study. The process whereby uncertainty accumulates throughout the process of climate change prediction and impact assessments has been described as a "cascade of uncertainty" (Schneider 1983) or the "uncertainty explosion" (Henderson-Sellers 1993). Figure 1.1 shows some of the major sources of uncertainty within an impact study such as this one, with the specific hydrological uncertainties at the end. Those areas in bold italics have been considered to some degree within the current project, those in normal text have not. The Figure represents the authors' subjective view of the relative contribution from each source of uncertainty (blue lines) to the overall uncertainty (red, dashed line), although Jenkins and Lowe (2003) suggest that the relative uncertainty due to the range of GCM simulations is greater than either emissions uncertainty or natural variability.

While some of these sources have been considered, the full range of uncertainty has not been sampled in any of the categories. For example, although the four UKCIP02 emissions scenarios have been used, they were all derived by rescaling the ensemble mean using one of the Intergovernmental Panel on Climate Change (IPCC) SRES (Special Report on Emissions Scenarios) scenarios; the A2 (IPCC 2000). Only one alternative emissions scenario has been used, that being the B2 scenario in conjunction with the statistical downscaling (see Section 4.3). Within the hydrological modelling, the uncertainty due to model calibration has been considered, but that due to data quality, model structure and the uncertainty from fitting a flood frequency curve to the points has not.

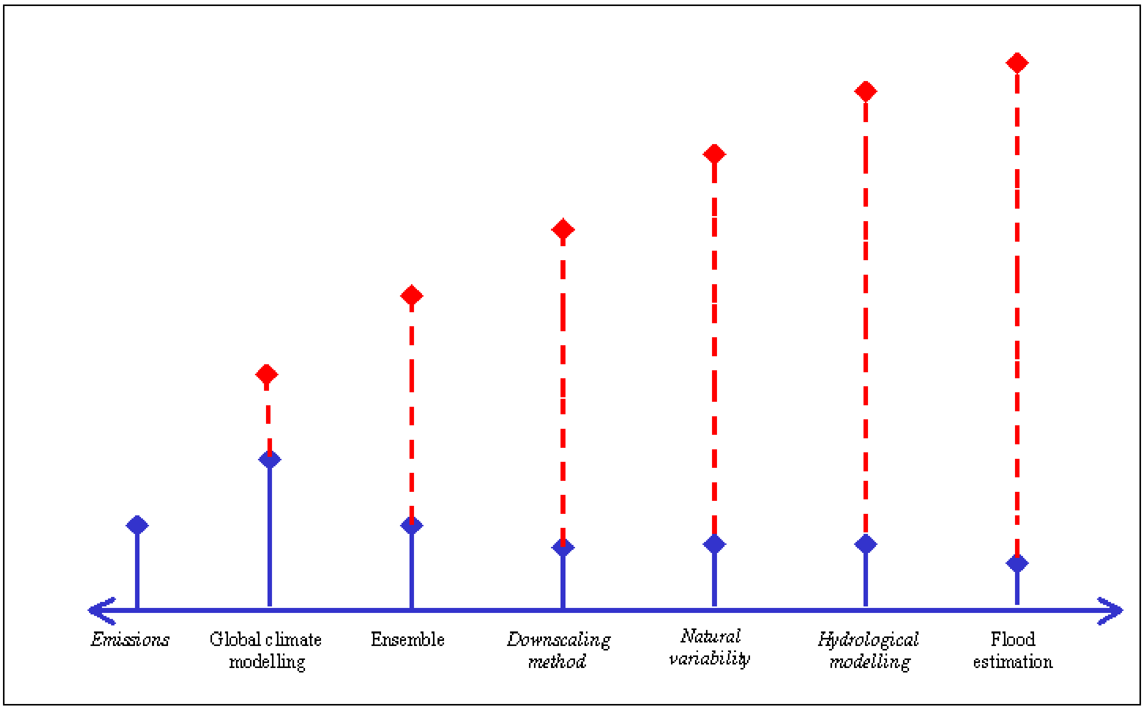


Figure 1.1 Some of the sources of uncertainty in a climate change impact study. Those labelled in italics have been addressed, to some degree, in this study. The blue spikes are the individual contributions to uncertainty with the red spikes showing the cumulative uncertainty. The relative sizes represent the expert opinion of the authors.

Furthermore, there is no accounting for the propagation of uncertainty through the phases of the project. Figure 1.1 presents this in simple cumulative sense, but this could equally be multiplicative.

1.4 Description of analysis tools

1.4.1 Frequency curves

The flood frequency curve, relating the peak flows (m^3s^{-1}) on the y-axis to the return period (years) on the x-axis, has been used throughout this report as an analysis tool. The return period is the average time interval, over a large number of years, between events exceeding a given size. Note that actual intervals between events of a given return period can vary. The partial duration, or peaks-over-threshold (POT), method (Naden 1993) was used to fit frequency distributions to the modelled baseline and scenario flow series. The magnitudes of the POT were fitted using the generalised Pareto distribution, with the peak arrival times assumed to correspond to a Poisson distribution. Fitting was carried out using the method of probability-weighted moments (Hosking and Wallis 1987). An average extraction rate of three events per year was used for the flood frequency analyses, with standard rules employed to ensure that extracted flood peaks were independent events (by imposing a minimum separation time period of three times a typical event time-to-peak, and specifying that the flow between two peaks must drop to at least two thirds of the higher peak).

A similar methodology has been used for comparing rainfall frequencies for one and five day periods. For these analyses an average rate of one event per year has been used with independence for the five day cumulated rainfalls achieved by avoiding overlapping periods.

1.4.2 Flow duration curves

The flow duration curve expresses the percentage of time that a given flow has been equalled or exceeded taken over a long time period, such as a 30-year time-slice. The percentile flow is commonly designated as Qn where, for example, Q5 is the flow that is equalled or exceeded 5% of the time. For looking at impacts of climate change on the high flow series, rather than just flood peaks, the Q3 statistic has been used. Q3 can be used to represent situations of potential flooding and has been used to quantify trends in high flows (CEH-Wallingford / Met Office 2001).

2 STUDY CATCHMENTS

The 10 catchments were selected to have a good geographical spread (Figure 2.1), and to incorporate different catchment areas, permeabilities and land uses. The selection aimed to provide a range of comparisons of catchment characteristics and locations. The list of catchment names, numbers and a description of the catchment land use and geology is given in Table 2.1, with Table 2.2 listing the catchment characteristics.

The Thames at Kingston (39001) and the similarly-sized Severn at Haw Bridge (54057) are included because they were used in earlier studies (Reynard *et al.* 1998, 2001, 2003). The Severn at Haw Bridge is also located within a catchment used for the Catchment Flood Management Plan study (HR Wallingford 2002), as is the Beult at Stile Bridge (40005; within the Medway catchment). The Anton at Fullerton (42012) provides an example of a highly permeable chalk catchment, whereas the upland Duddon at Duddon Hall (74001) in the Cumbrian Mountains has a low permeability. The Rea at Calthorpe Park (28039) is a highly urbanised catchment, contrasted with the rural Lymn at Partney Mill (30004). The Halladale at Halladale (96001) in northern Scotland was included for comparison with catchments having a more southern climate. Two middle-sized catchments were selected; the Ouse at Skelton (27009) in northern England and the Severn at Bewdley (54001) in the west.

Table 2.1 Catchment number, name and description

Catchment number	Catchment name	Comments
27009	Ouse at Skelton	Predominantly rural catchment with mixed geology, including limestones, grits, sandstones and clay.
28039	Rea at Calthorpe Park	Very responsive, almost totally urbanised catchment.
30004	Lymn at Partney Mill	Entirely rural catchment on sandstone and Boulder clay.
39001	Thames at Kingston	Diverse geology including Oolitic limestone, chalk and Oxford, London and Weald clay. Land use mainly agricultural but with substantial urban development particularly in the lower catchment.
40005	Beult at Stile Bridge	Predominantly rural catchment with scattered settlements on Weald clay.
42012	Anton at Fullerton	Unresponsive chalk catchment. Rural land use with some urban centres.
54001	Severn at Bewdley	Mixed geology with land use covering moorland, forestry and agriculture.
54057	Severn at Haw Bridge	As 54001 plus catchment of the Avon which includes substantial urban areas.
74001	Duddon at Duddon Hall	Steep impervious catchment with agricultural land use.
96001	Halladale at Halladale	Largely moorland with a peat based cover.

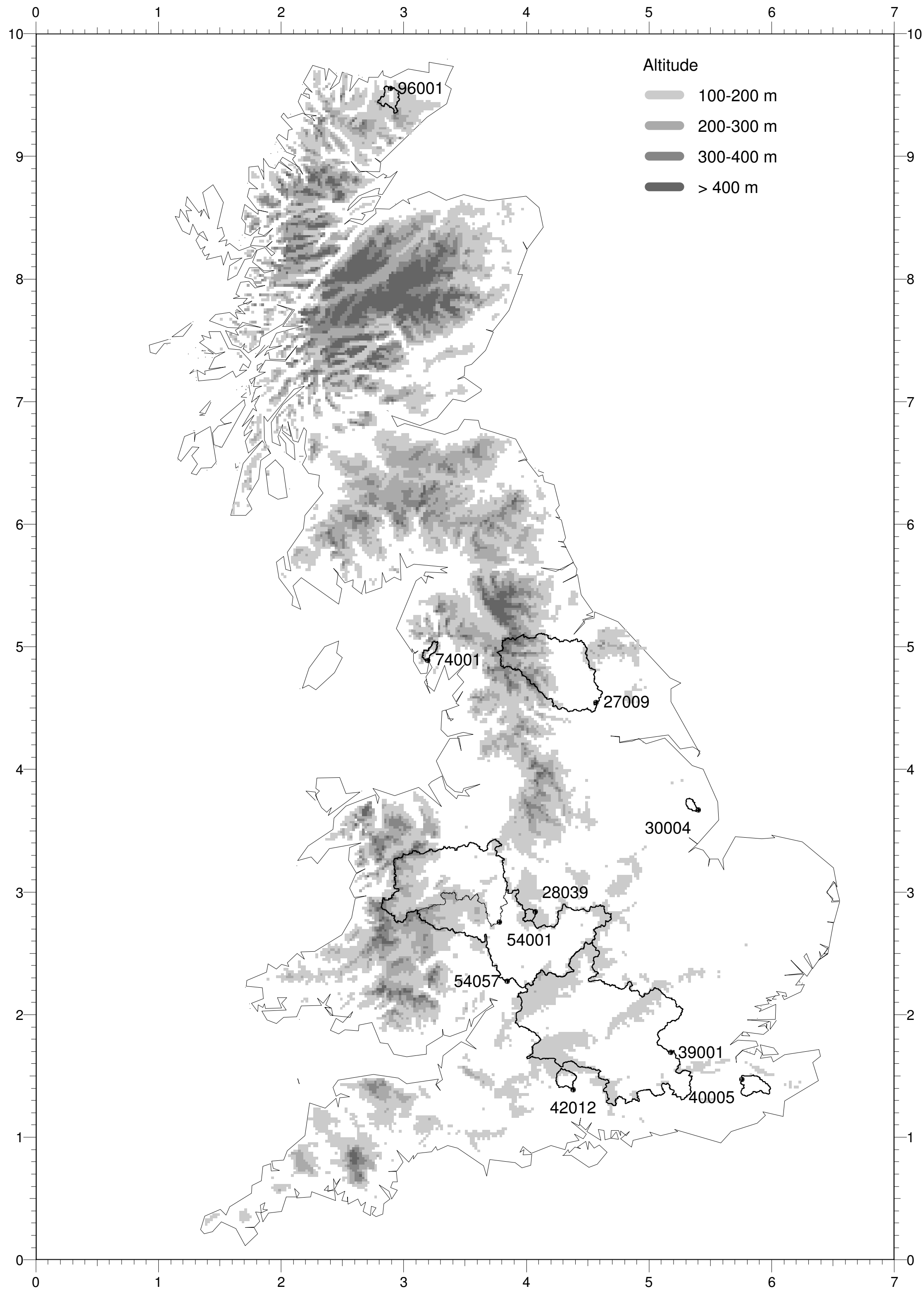


Figure 2.1 Topography and location of the 10 study catchments

Table 2.2 Catchment characteristics for the 10 study catchments

Catchment number	Catchment area (km^2)	Location of river flow gauge (m)		Range of altitude (m)	Mean altitude (m) (from FEH)	Base flow index	Urban extent (from FEH)	Mean flow (m^3s^{-1})	SAAR 1961-1990 (mm)
		Easting (km)	Northing (km)						
27009	3315	456.8	455.4	5 – 716	185	0.43	0.010	49.0	900
28039	74	407.1	284.7	104 – 286	168	0.48	0.331	0.8	781
30004	62	540.2	367.6	15 – 132	65	0.66	0.011	0.5	685
39001	9948	517.7	169.8	5 – 310	109	0.64	0.043	66.6	706
40005	277	575.8	147.8	12 – 50	45	0.24	0.006	2.1	690
42012	185	437.9	139.3	40 – 203	113	0.96	0.024	1.9	773
54001	4325	378.2	276.2	17 – 827	175	0.53	0.012	61.9	913
54057	9895	384.4	227.9	6 – 827	145	0.57	0.027	105.3	792
74001	86	319.6	489.6	15 – 810	315	0.28	0.000	5.0	2265
96001	205	289.1	956.1	23 – 580	175	0.25	0.000	5.0	1102

3 HYDROLOGICAL MODELLING

This section describes the hydrological models used in more detail. The model structures are presented and described as is the model parameterisation, calibration and the performance of the models in simulating the river flows in the study catchments. No allowance has been made for snowmelt, which is a factor in the timing and magnitude of observed flood peaks in several of the study catchments.

3.1 Hydrological models

Two hydrological models have been used in this study. For the larger catchments (the Ouse, the Severn at Haw Bridge and Bewdley and the Thames), the semi-distributed model, CLASSIC, was used, running at a daily time step. For the smaller catchments the PDM was used at an hourly or daily time-step, as data availability allowed (Table 3.1).

Table 3.1 Details of model and data availability for each catchment.

Catchment number	Model	Resolution	Data availability of hourly flow and catchment-average hourly rainfall	Data availability of daily mean flow
27009	CLASSIC	Daily		1969-2002
28039	PDM	Hourly	1985-2001	(1967-2002)
30004	PDM	Hourly	1987-2001	(1962-2002)
39001	CLASSIC	Daily		1883-2003
40005	PDM	Hourly	1985-2001	(1958-2001)
42012	PDM	Daily		1975-1999
54001	CLASSIC	Daily		1921-2003
54057	CLASSIC	Daily		1971-2002
74001	PDM	Hourly	1985-1994	(1968-2002)
96001	PDM	Hourly	1989-2001	(1976-2002)

3.1.1 CLASSIC

The semi-distributed continuous simulation rainfall-runoff model, CLASSIC, (Climate and Land-use Scenario Simulation In Catchments), was developed for estimating the impacts of climate and land use change in large catchments and was initially tested on the Thames, Severn and Trent drainage basins (Crooks *et al.* 1996). It has been further developed and used in the earlier climate change impact studies (Reynard *et al.* 1998, 2001). A schematic of the model structure is shown in Figure 3.1.

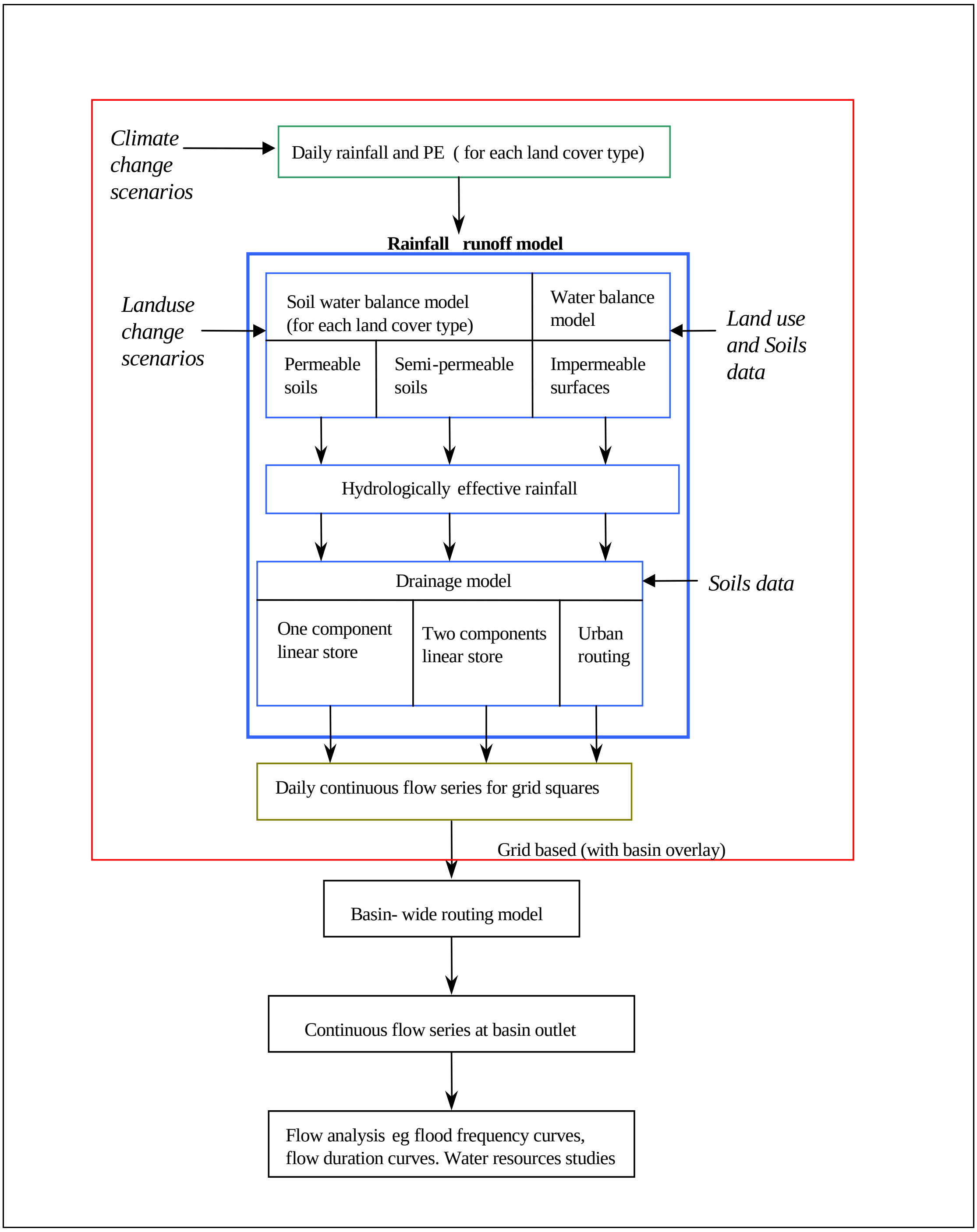


Figure 3.1 Conceptual structure of the CLASSIC semi-distributed hydrological model.

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

PE and SMD (Calder *et al*. 1983). The hydrologically effective rainfall generated by the soil water balance module forms the input to the drainage module in which the water is held in storage reservoirs. Soils overlying permeable substrata are modelled with a one-component store, with time constant T_s; soils overlying substrata with no significant underlying aquifer are modelled with two component stores, representing quick and slow flow, operating in parallel. These stores have time constants of t_q and t_s with the split between them given by *spl*. Urban areas have a separate water balance and drainage module and the total grid square outflow is given by the sum of the outflows from each storage reservoir operating within a particular grid square. The routing module convolves the grid square outflow with a measure of the catchment channel network determined from a DTM (Digital Terrain Model). This is further convolved with a routing function, which has two parameters, for wave velocity (*A*) and a coefficient of diffusion (*D*), which are determined by calibration with observed flow data. Individually routed grid square flows are summated to provide the total flow at the calibration site, normally a gauging station.

The main land use groups and soil types are incorporated into the parameterisation of each grid square for which characteristic values for the soil water balance and drainage modules parameters for different land use groups and soil classes were determined during development of the model. One of the fundamental principles of the modelling system, and important in the calibration of the model, is that the grid square parameter values are the same regardless of the downstream location of the point on the river at which the flow is simulated. This principle ensures that, although the total number of parameter values to be set is comparatively high, the resulting parameter space is quite tightly constrained. Once the model has been calibrated for a particular catchment it can be used to simulate flows at other ungauged locations within the catchment.

The grid square size is catchment-specific, depending on area and the variation of climatic and physiographic conditions within the catchment. A 40 km grid square, compatible with MORECS PE data (Thompson *et al.* 1982, Hough *et al.* 1997), was used for the initial development of the model, but smaller grid sizes have been used in later modelling. Figure 3.2 below shows the Ouse catchment overlain with the 10 km modelling grid used in this project. Applying the model at different spatial and temporal scales while keeping the same grid square parameterisations has tested the robustness of the model structure and calibration.

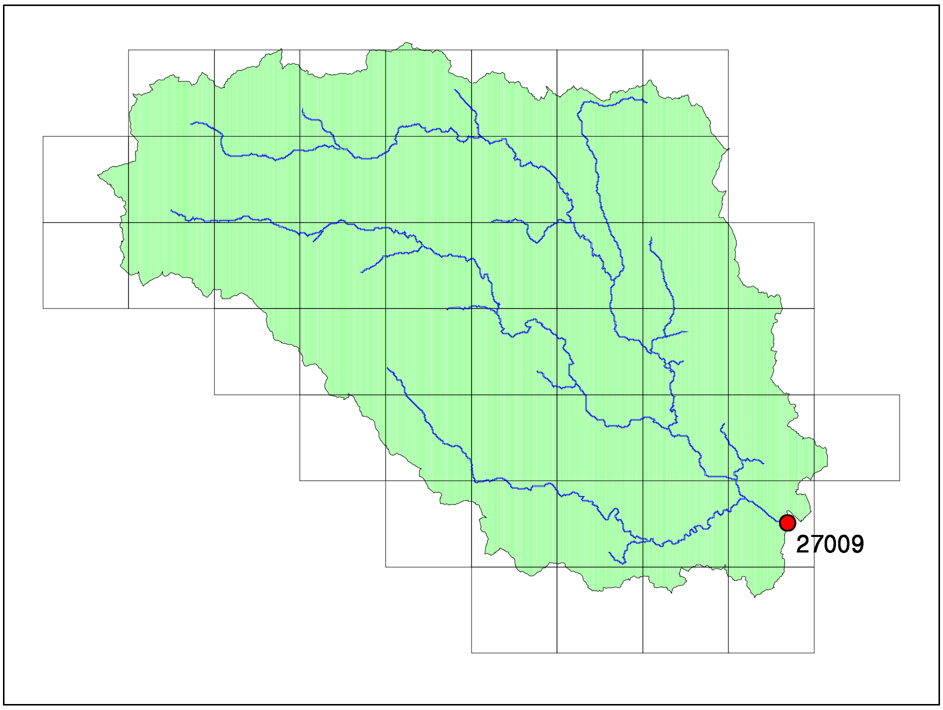


Figure 3.2 Ouse catchment and 10 km CLASSIC modelling grid.

The model was run at a daily time step using grid square averages of observed daily rainfall (Gannon 1995) and MORECS monthly PE, divided equally into daily values, to simulate mean daily flow. Monthly PE values for grid sizes less than 40 km were derived by interpolation. The MORECS data provide PE rates for a grass land cover; those for the other land use classes used in CLASSIC (deciduous woodland, coniferous woodland, upland and arable) were determined using regression relationships for each month, derived from daily data from the Met Office for a synoptic site relevant to each catchment being modelled. PE for urban areas is assumed to have a daily maximum of 0.5 mm depending on rainfall.

3.1.2 PDM

The Probability Distributed Model (PDM; Moore 1985, 1999) is typical of the relatively simple model structures that nevertheless can be applied effectively across the UK. It is based on conceptual stores, and attempts to represent non-linearity in the transformation from rainfall to runoff by using a probability distribution of soil moisture storage. This determines the time-varying proportion of the catchment that contributes to runoff, through either 'fast' or 'slow' pathways. The full PDM has a number of different formulations, but the version used here, with five parameters, is one that has proven useful for a wide range of catchments across the UK. The reduction in the number of parameters is useful in limiting the problem of equi-finality, where a number of quite different parameter sets can result in very similar model performance. A brief description of the model and its remaining parameters is given below, along with a diagram illustrating its conceptual structure (Figure 3.3).

Rainfall inputs to the soil store are first multiplied (at each time step) by a rainfall factor f_c. This serves as a volume adjustment factor to compensate, for instance, for loss or gain of water across the catchment boundary via subsurface pathways. The soil store can be depleted through evaporation, with content of the store determining the proportion of the potential evaporation that actually occurs (via a linear function). The distribution of the soil storage capacity can be described, in the full PDM, by any of a number of specified functions. In this case the distribution is assumed to be uniform. In addition, it is assumed that the minimum capacity of any point within the soil store is zero. The maximum capacity of any point is given by the parameter c_{max}. The soil store then generates direct runoff from a varying proportion of the catchment area, depending on how full it is. It is generally assumed, in the full PDM, that the direct runoff (overflow) from the soil store is routed through a fast flow store ([near-] surface storage), and that downward drainage from the soil store is routed through a slow flow store (groundwater storage). An alternative formulation, used here, is to assume that a proportion α of the direct runoff goes to the fast flow store, whilst $1-\alpha$ goes to the slow flow store. In this case the split parameter, α, is set to be 1/100 of the catchment's standard percentage runoff (SPR) as estimated through HOST (Boorman *et al.* 1995) soil classes (SPRHOST, Institute of Hydrology 1999). Both fast and slow routing systems can be represented by a number of types of storage reservoir in the full PDM, but in this case a linear fast flow store and a cubic slow flow store are assumed. The time constants of the stores are k_s and k_b respectively. The catchment discharge is then produced from a combination of fast flow (surface runoff) and slow flow (baseflow).

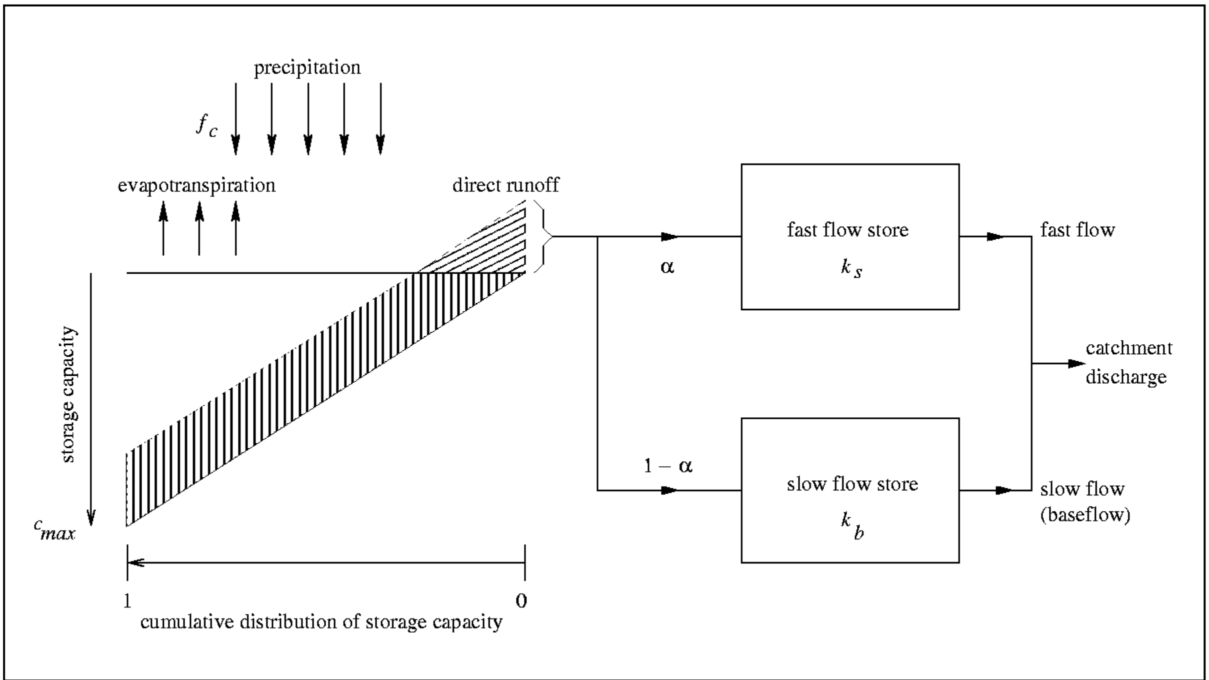


Figure 3.3 The conceptual structure of the five-parameter version of the PDM rainfall-runoff model.

The PDM rainfall-runoff model requires driving data as time series of catchment-average rainfall and PE. The model is capable of running with data at any time-discretisation. However, it is not appropriate to use a daily time-step for relatively small, or fast-responding, catchments, as there is too much smoothing of the peak flows (Spijkers and Naden 1994). Thus an hourly time-step is used for five of the six PDM catchments, for which hourly flow and rainfall data were readily available (collated for a previous Defra project, see Table 3.1 for a summary of data availability), whilst a daily time-step is used for the remaining catchment (42012). This latter catchment was specifically included as an example of a southern, groundwater dominated catchment, since no such examples were available in the hourly database of flow and rainfall data. As such, and considering the catchment's reasonably large catchment area, it is sufficient to use a daily model time-step. For flood estimation purposes at least, the time-step of the PE data is much less critical than that of the rainfall data, and as such monthly PE data (obtained from MORECS 40km squares; Thompson *et al.* 1982, Hough *et al.* 1997), is disaggregated uniformly down to the time-step of the input rainfall.

3.2 Model performance - calibration and validation

Model calibration (determining model parameter values to provide a good fit between observed and simulated flows) and model validation (testing of model performance using the calibrated parameter values with a different data period) are important criteria in the use of hydrological models. This is particularly the case when the models are used to predict the impact of changed input conditions on flows at extremes of the range. Ideally a model should be calibrated and tested over as wide a range of observed climatic conditions as possible to provide confidence in the modelled output. A description of the calibration and validation procedures used for the two hydrological models is given below.

3.2.1 CLASSIC

CLASSIC was used to model the four larger catchments in the project, namely the Thames at Kingston, the Severn at Haw Bridge and Bewdley and the Ouse at Skelton, all operating at a daily time step. The Thames had been calibrated during earlier studies (Crooks *et al.* 1996, Crooks *et al.* 2000), the latter using a 20 km grid structure (see section 3.1.1). The Severn at Haw Bridge had been calibrated with a 40 km grid size (Crooks *et al.* 1996), while a 10 km grid was used in the calibration of the Ouse catchment to Skelton (Crooks 2002). The Upper Severn to Bewdley was calibrated for this study using a 20 km grid, ensuring that parameter values for these grid squares were consistent with those for the catchment to Haw Bridge.

An initial calibration model run uses pre-set values of grid square parameters, determined using GIS data bases of soil type (Boorman *et al*. 1995) and land use (Fuller 1993), but these can be modified during further runs. Calibration is based on a range of criteria describing the fit between observed and modelled flows covering annual and monthly water balances, shape of recession curves, flood peaks and model efficiency (Nash and Sutcliffe 1970). The Thames and Severn were calibrated using data for 1981 to 1990, the Ouse 1986 to 1995, and validated with data both for earlier and later periods, covering both extreme dry summers, for example 1976, and wet winters, 2000/01.

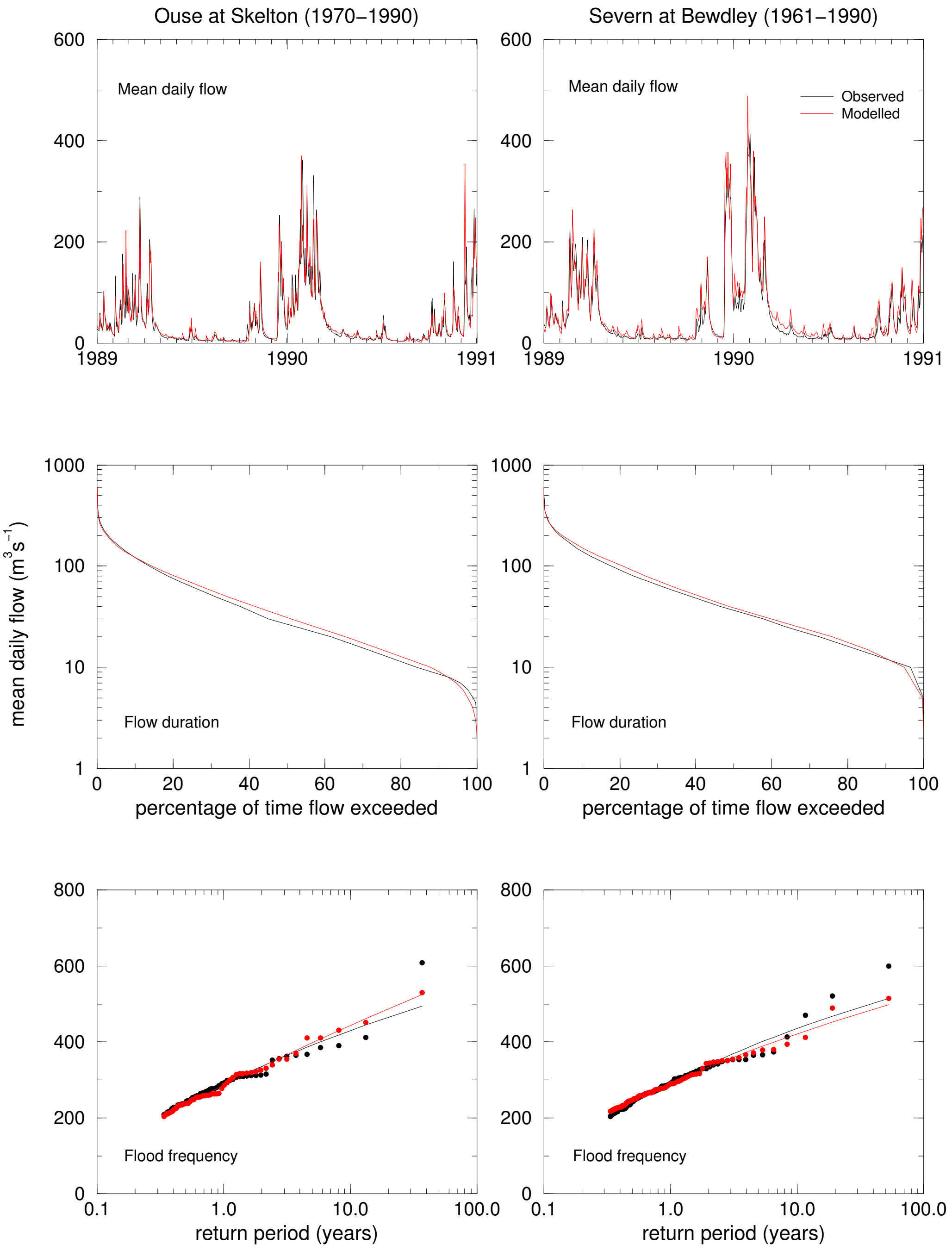


Figure 3.4 Examples of model fit, flow hydrographs, flow duration and flood frequency curves for the CLASSIC model in the Ouse and Severn catchments. The modelled flow is from a time series beginning in 1961, flow duration and flood frequency for the Ouse are for 1970 to 1990.

Examples of model fit, flow hydrographs, flow duration and flood frequency curves, were given in the interim report (W5-032/TR1) for the Thames and the Severn at Haw Bridge (Reynard *et al.* 2003) and in Figure 3.4 of this report for the Ouse and Severn at Bewdley. The modelled flow in Figure 3.4 for both these catchments is taken from a time series beginning in 1961, but the flow duration and flood frequency curves for the Ouse are for complete years from the start of the observed record, 1970, to 1990. It should be noted that observed flows for both these sites are gauged flows with modifications to the natural regime through abstraction for public water supply. The data base for land use was 1990 (Fuller 1993) which has been assumed to be constant for all baseline and scenario model runs.

3.2.2 PDM

For the PDM, the parameters were estimated through a combination of automatic and manual calibration, using the whole period of available data. The use of the whole data period was considered necessary, bearing in mind the shorter record available, in order to cover the widest range of observed conditions. Where a previous manual calibration existed, this was retained unless a subsequent automatic calibration proved to perform better. Automatic calibration in this case involves a two-pass sequential calibration of parameters. In the first stage, Monte-Carlo sampling of the remaining parameter space is performed at each step, and the selection of the best parameter value is based on optimising objective functions measuring the fit of observed and simulated flows (a different objective function is chosen, dependent on the parameter being fitted). A second-pass is then performed, to allow re-adjustment of the parameter values once each parameter has been calibrated once. Some manual tuning of parameter values can then be attempted, to obtain a final calibrated set. Figure 3.5 illustrates the fit of observed and simulated flood frequency curves for the six PDM catchments, with the calibrated parameter values.

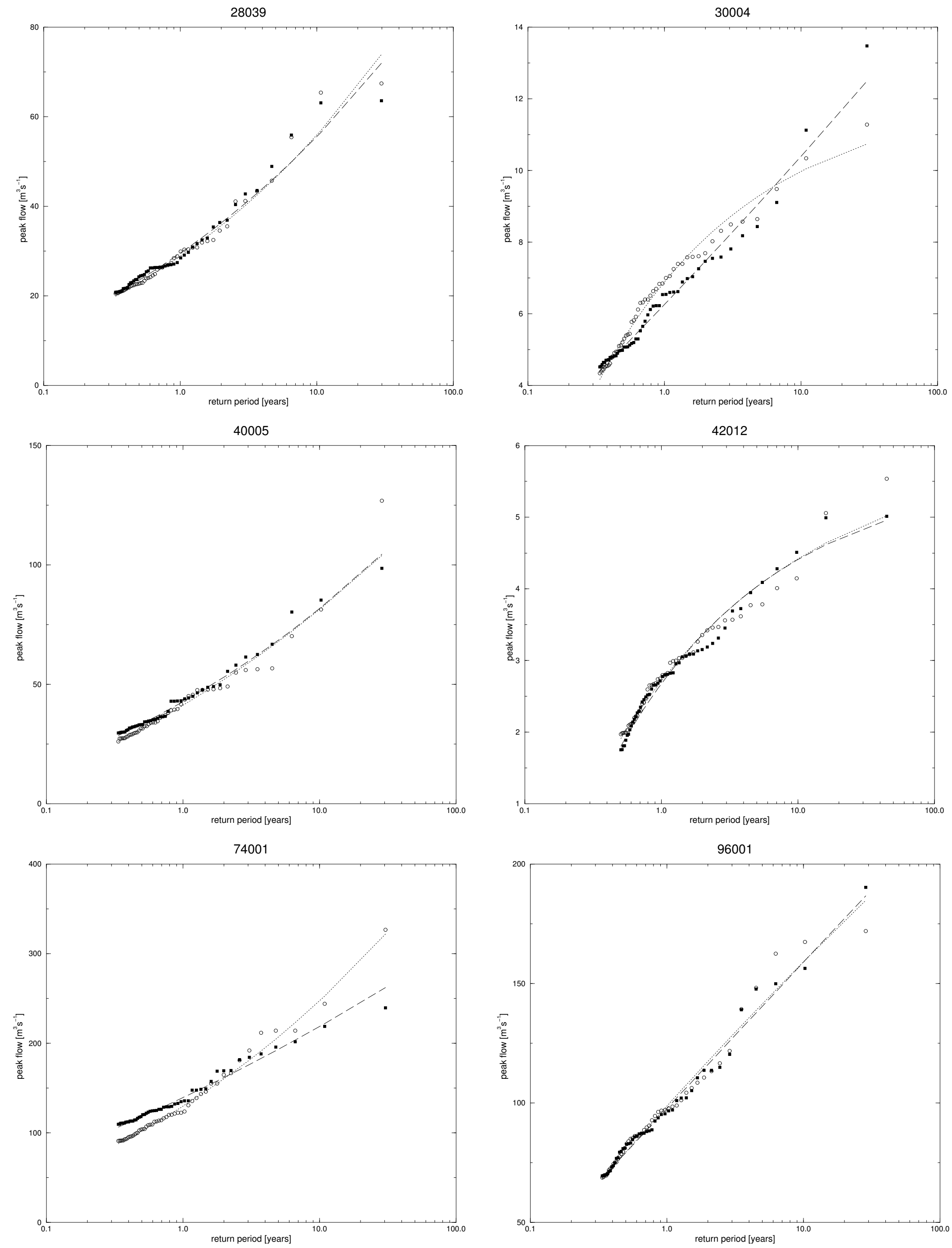


Figure 3.5 Comparison of modelled (dashed lines and filled squares) and observed (dotted lines and open circles) flood frequencies for the six PDM catchments.

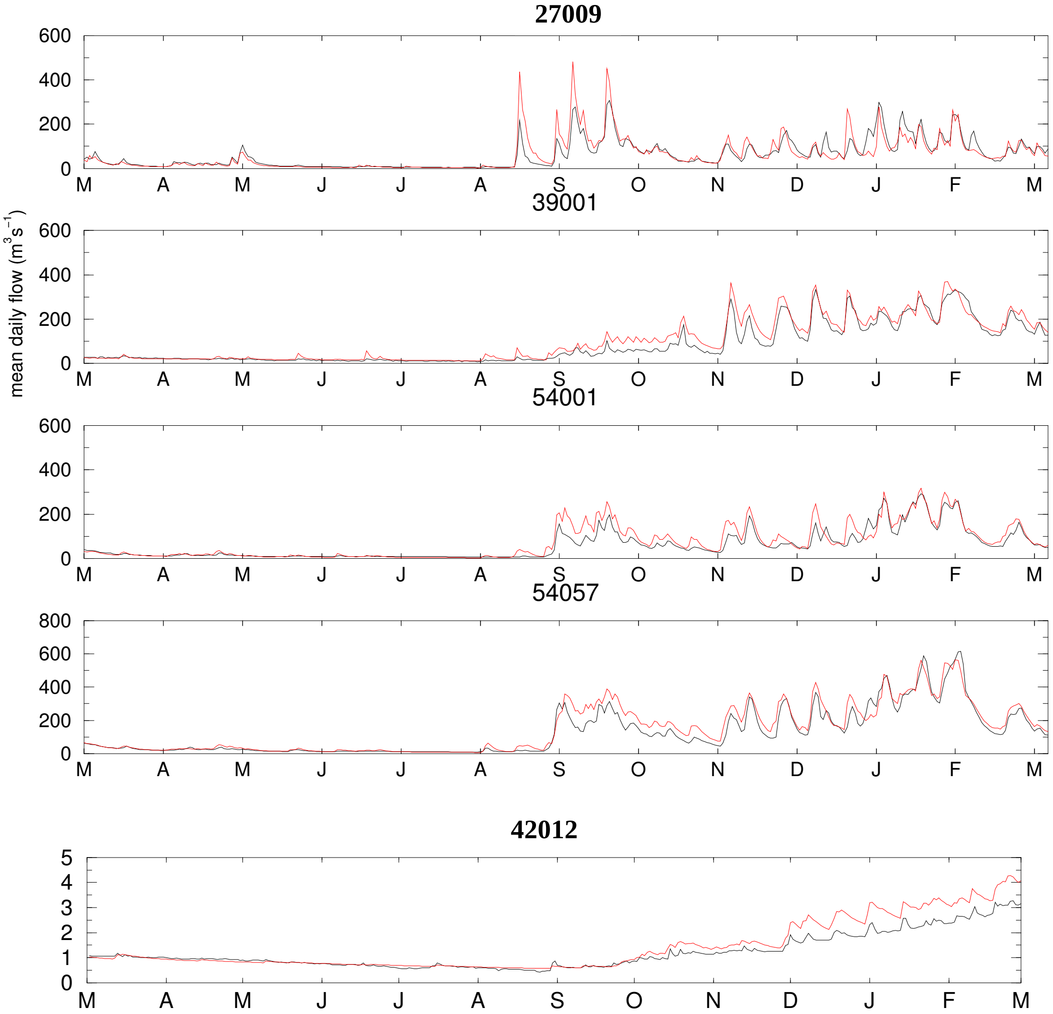
3.2.3 Validation of soil moisture replenishment

One of the main assumptions frequently made in the use of conceptual hydrological models to simulate rainfall-runoff systems under future climates is that the representation of hydrological processes by model parameters calibrated for conditions in the current climate is equally appropriate for the future climate. By calibrating and validating a model over a wide range of climatic conditions the performance of the model in extreme conditions can be assessed. Although it is flood frequency, and by implication changes in extreme rainfall, which is the concern of this investigation, the impact of hotter, drier, summers is also of importance. The continuation of depleted soil moisture levels through the autumn controls the flood potential of a catchment to autumn and winter rainfall. Realistic model performance during the autumn, and particularly following periods of drought, is therefore important for assessing future flood liabilities.

The driest conditions for much of the UK during the standard baseline period of 1961 to 1990 occurred in the summer of 1976, following on from the low rainfalls during the winter of 1975/76. The drought period ended very rapidly during the autumn of 1976. Observed and modelled flows for the year beginning in March 1976 are given in Figure 3.6a, for the four catchments modelled with CLASSIC. The Ouse (27009) demonstrates a rapid recovery of soil moisture levels and runoff response in contrast to the slower, more sustained recovery of the Thames (39001). Of the six catchments modelled with the PDM only the permeable, baseflow-dominated catchment of the Anton (42012) has data for the same period and is also shown in Figure 3.6a. All of these catchments show a similar tendency for modelled flows to exceed observed flows during such times of soil moisture replenishment, but the timing of modelled flow response is good. For the five remaining catchments modelled with the PDM a corresponding drought period within the hourly data record is the year beginning in March 1997. Figure 3.6b compares time series of observed and modelled flows for the Anton (42012) and Halladale (96001) for this period. The latter catchment remains responsive to rainfall, even within a generally dry period, due to the impermeability of the underlying geology and the lack of accumulation of large soil moisture deficits. The other four PDM catchments show similar response patterns related to their permeability.

Model performance thus indicates that simulations of flow under future climates, where conditions may not be more extreme than in 1976 but the frequency of such events may be different, is more likely to over- than under-estimate runoff during flood events following drought periods, assuming no other changes occur affecting hydrological response

a) March 1976 to February 1977



b) March 1997 to February 1998

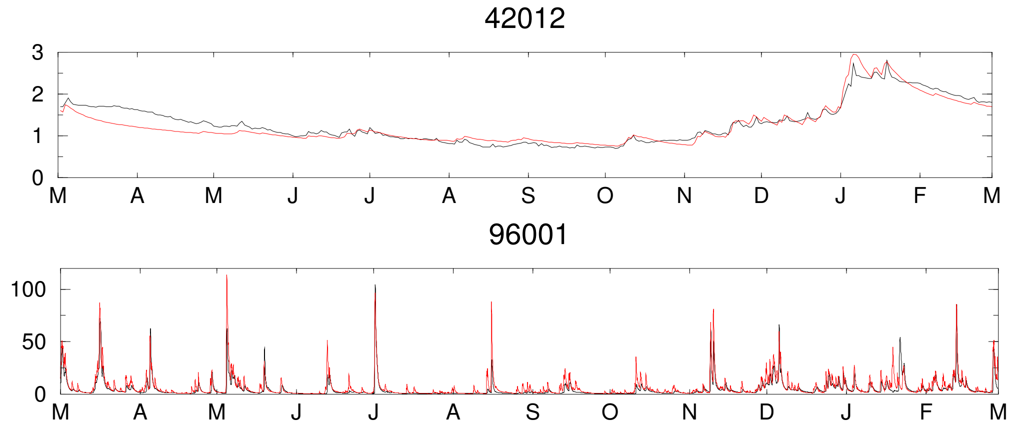


Figure 3.6 Time series plots comparing modelled (red) and observed flows (black) over a period of recovery from drought. Catchments 27009, 39001, 54001 and 54057 are modelled with CLASSIC; 42012 and 96001 are modelled with the PDM.

3.3 Uncertainty

Uncertainty in this aspect of the project might come from two sources: model structure and model parameter estimation. The first of these is not directly considered here, but the calibration uncertainty is discussed below for the PDM. The method of calibration (see Section 3.2.1) for CLASSIC uses an understanding of the physical nature of the parameters and their relationship to measured catchment data to determine parameter values.

PDM

For the PDM, the parameters are estimated through a combination of automatic and manual calibration for the whole data period. To obtain an estimate of calibration uncertainty, an adaptation of a statistical technique called jack-knifing (Shoa and Tu 1995) is applied using the automatic calibration method. This technique involves obtaining a number of different sets of calibrated parameters, each based upon leaving out one year of flow data when assessing model performance (the rainfall and PE data are all retained, so as to maintain the water balance throughout the run). Thus if there are N years of input data for a catchment, N sets of calibrated parameter values are obtained, each valid when a different year of flow data is discounted during the calibration process. The rainfall-runoff model can then be run for each set of parameter values, so that N flood frequency curves are produced.

Error bars can then be constructed for the flood frequency curves at specific return periods (or specific peak flow magnitudes), by calculating an estimate of the variance (σ^2) from the values of the N jack-knifed flood frequency curves at that return period (or peak flow magnitude). The 95% error bars can then be plotted as $\mu \pm 2\sigma$, where μ is the mean of the N jack-knifed values. However, jack-knife theory requires that the variance be calculated slightly differently to a usual sample, with a multiplier of (N-1)/N rather than 1/N (Shoa and Tu 1995). This inflates the size of the error bars somewhat, possibly over-exaggerating the calibration uncertainty. Figure 3.7 below shows the jack-knifed flood frequency curves for each of the six PDM catchments, with error bars at specific return periods determined by both the standard variance (solid lines) and jack-knife variance (dashed lines).

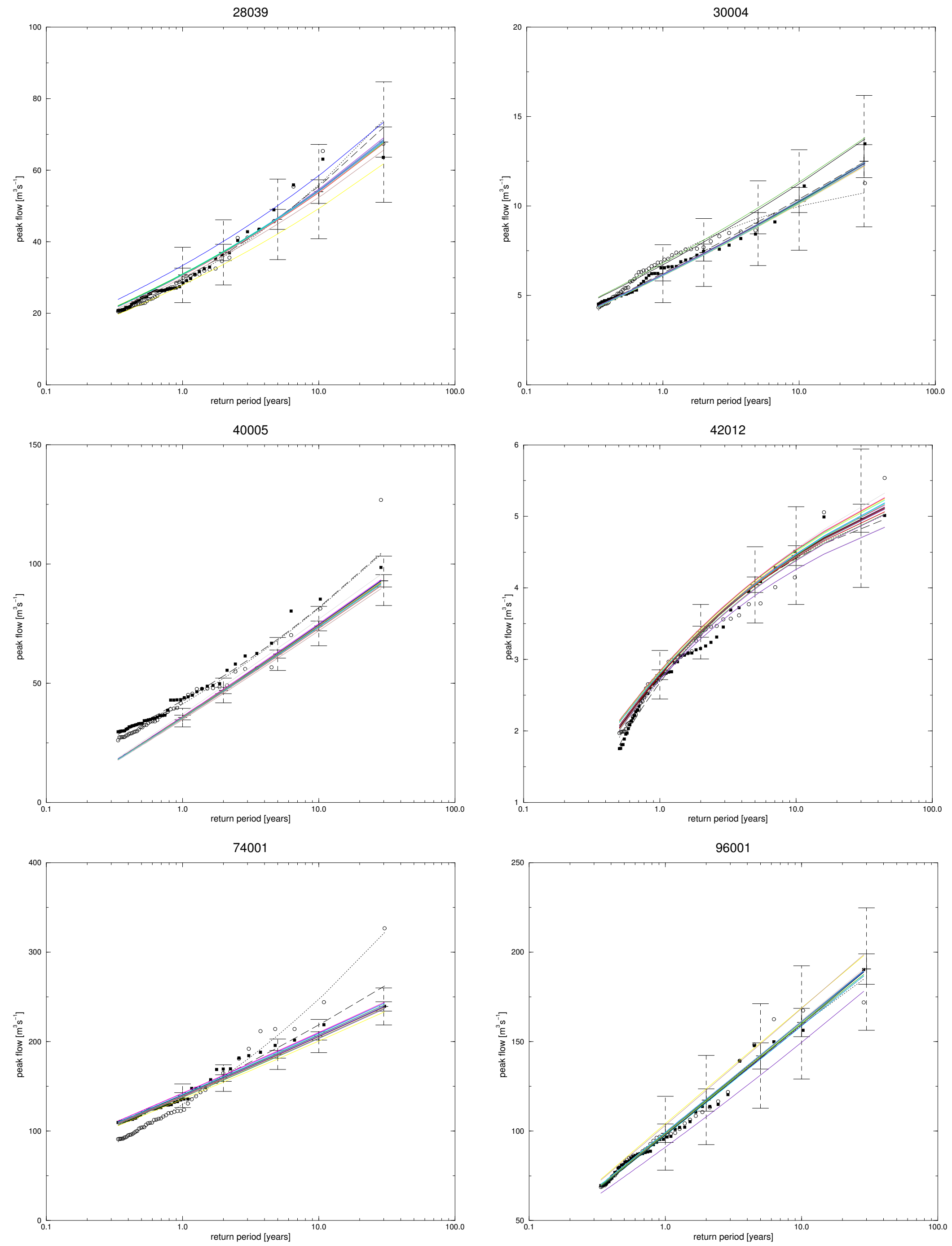


Figure 3.7 Illustration of the effect of calibration uncertainty (estimated through jack-knifing) on modelled flood frequency curves. Each coloured line represents a flood frequency curve modelled using a jack-knifed parameter set. Also shown is the flood frequency calculated from observed flows (dotted line and open circles), and that modelled with observed rainfall data using the 'proper' calibrated parameter set (dashed line and filled squares). Two sets of error bars are shown for each catchment, at return periods of 1, 2, 5, 10 and 30 years. The inner error bars use the standard estimate of variance, whilst the outer ones use the jack-knife estimate of variance.

4 CLIMATE CHANGE SCENARIOS

4.1 Introduction

A range of techniques has been used to derive climate change scenarios for application in this project.

1. For the **UKCIP02** scenarios the changes in monthly rainfall have been applied to the daily rainfall baseline time series in such a way as to reproduce the changes in seasonal daily rainfall frequency described in the UKCIP02 Technical Report (Hulme *et al.* 2002).
2. The **Statistical Downscaling** Model (SDSM), developed by Wilby (1998, 2003), has been used to provide daily time series of rainfall to drive the hydrological model CLASSIC (Wilby 2003; McSweeney 2003).
3. For **dynamic downscaling**, links with a Defra-funded Hadley Centre Annex 15 project "Change in Flood Prediction using a RCM", have allowed the use of hourly output from the ~25 km RCM directly to drive the PDM and CLASSIC.

All these downscaling techniques are described in more detail in this section. In addition there is a comparison of the rainfall data (both for the baseline and the future) derived using each of these methods and the effects of these different data series on the flow simulation in the study catchments.

4.2 UKCIP02 scenarios

Previous work on modelling the impacts of climate change on flood frequency used scenarios derived from the HadCM2 Global Climate Model (GCM) developed by the UK Hadley Centre. The more recent, UKCIP02, scenarios (Hulme *et al.* 2002) were developed using a combination of the HadCM3 GCM and the HadRM3 RCM (Regional Climate Model). They are based on new global emissions scenarios and the use of the RCM, which adds physically based information to the GCM results.

There are significant differences in seasonal temperature and precipitation changes between HadRM2 and HadRM3, notably a warmer and drier summer over southern England with HadRM3, and smaller increases in precipitation in spring and autumn with, in some areas, a decrease in these seasons. Increases in winter precipitation are also smaller for most areas with HadRM3 (see Figure 81 in Hulme *et al.* 2002). These differences between the old and new scenarios result in quite different impacts on flooding, as will be seen.

The UKCIP02 scenarios comprise a set of four alternative future climates spanning a range of global emissions, namely the Low, Medium-Low, Medium-High and High Emissions scenarios, for three future 30-year time-slices, the 2020s, 2050s and 2080s. The climate change pattern for each set of emissions within each time-slice has been derived from a single master set of patterns, which is the average of three climate change simulations made by HadRM3 using the Medium-High emissions scenario for the 2080s. All the other scenarios are derived by applying scaling factors to this one averaged set. Therefore, the patterns associated with each time-slice and emissions scenario are the same but the magnitudes are different. Annual and seasonal comparisons between a 2080s HadRM3 B2 (Medium-Low) emissions simulation and a Medium-low scenario obtained from pattern-scaling the A2 scenario are shown in Hulme *et al.* 2002 (Figure 80). Differences are generally small but changes for the autumn have opposite signs; negative with scaled A2 but positive with B2, which has considerable hydrological implications for satisfying summer soil moisture deficits and the consequent flood-producing potential of autumn and winter rainfall.

The UKCIP02 scenarios are presented as monthly changes, compared with the 1961-90 baseline, either percentage or absolute, in 15 climatic variables, for a 50 × 50 km grid across the UK. This resolution means that 104 grid boxes represent the UK (rather than just four under HadCM2). For hydrological purposes changes in rainfall and potential evapotranspiration (PE) are required. Changes in PE have been calculated using the Penman-Monteith equations with climatic variables of monthly mean temperature, wind speed, relative humidity, and net surface longwave and shortwave radiation. PE was calculated for the baseline period, and after applying the scenario changes to the monthly baseline climatic variables. The percentage change in PE is then derived for each time horizon and emissions scenario. Calculated percentage changes in seasonal PE (winter (DJF), spring (MAM), summer (JJA), and autumn (SON)) for the Medium-High 2080s scenario are shown in Figure 4.1. It should be noted that, quantitatively, a 50% increase in PE in winter may be only a few millimetres a month but 40 to 50 mm in summer. Percentage changes in precipitation are directly available as one of the climatic variables. Examples of the impact of the High 2080s climate change scenario on average baseline monthly rainfall and PE for two UKCIP02 grid squares were given in the Interim Report (Reynard *et al.* 2003).

4.2.1 Downscaling UKCIP02 scenarios

The use of monthly percentage change scenarios with modelling of daily data requires a method for downscaling between monthly and daily timescales. For PE, a simple proportional change throughout the month is acceptable but for rainfall an alternative approach is required. In earlier work (Reynard *et al.* 1998, 2001) three perturbation methods (proportional, day change and enhanced storm) were applied to observed daily rainfall. However, as described in the Interim Report to this project, none of these methods on their own resulted in a satisfactory translation to the required patterns of seasonal daily rainfall frequency and intensity, as defined in Hulme *et al.* (2002). This is particularly the case where the monthly percentage change for a grid square is negative but daily rainfall for a specified return period shows an increase. Therefore, a new method was devised to perturb the observed daily rainfall series to broadly achieve the overall percentage change and change in frequency of daily rainfall required for each month.

Seven categories for perturbing the observed rainfall series were defined and applied to each month of rainfall data. The method requires the monthly scenario percentage change in rainfall and an indicator of change in frequency of the 20-year return period rainfall (www.ukcip.org.uk/scenarios/maps/daily) for each season (winter, spring, summer and autumn) for the specified scenario and time horizon. The indicator took one of four values as defined in Table 4.1. The method for perturbing the observed daily rainfall for each category is described in Table 4.2.

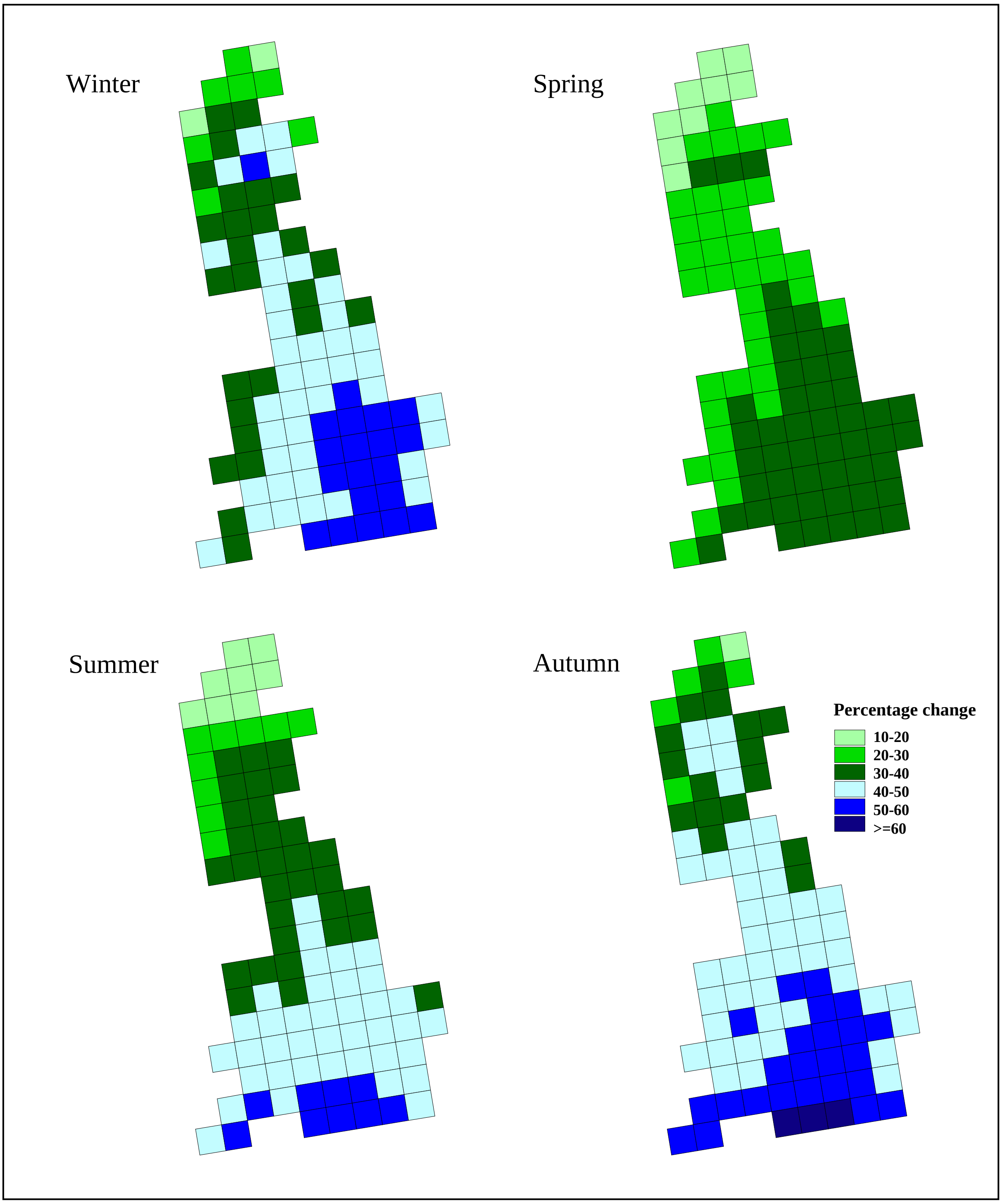


Figure 4.1 Percentage change in seasonal potential evapotranspiration for the Medium-High emissions scenario, 2080s, UKCIP02.

Table 4.1 Indicator values for the percentage changes in the 20-year return period daily rainfall.

Percentage change in 20-year return period daily rainfall	Indicator value
> 5	1
-5 to +5	0
-20 to -5	-1
< -20	-2

Table 4.2 Method for perturbing the observed daily rainfall for each category of change.

Scenario percentage change in rainfall	Indicator value	Method of change
Positive	1	For winter: sliding scale (P1) between 100% proportional and 100% rain day change depending on average winter percentage change. Spring and autumn: increase added to wettest day in month if this is > P2, otherwise as winter.
Positive	0	Rain day change (increase added equally to every third day where rainfall < P3).
Positive	-1	Maximum daily rainfall in month decreased by 20% and this amount added to the increase for the month. Then rain day change.
Negative	1	If the wettest day in the month is > P2 then days with rainfall < P4 changed to dry and the value S added to the wettest day, otherwise proportional decrease.
Negative	0	Summer: days with rainfall < 5.0 mm changed to dry otherwise (up to monthly decrease) $R_t = R_t{*}R_t/R_{max}$. Spring and autumn: days with rainfall < 10.0 mm changed to dry (up to monthly decrease).
Negative	-1	The average decrease (decrease for month/days in the month) subtracted from daily rainfall (not < 0.0). Any deficit carried forward to next day and at end of month to corresponding month of following year.
Negative	-2	As for indicator of -1 but daily rainfall decreased by 25% if this was more than the average decrease (up to monthly decrease).

The monthly increase or decrease is the total rainfall for the month multiplied by the scenario percentage change. P1, P2, P3 and P4 are model parameters where:

- P1 is the percentage of the change to be achieved by the proportional method;
- P2 is a threshold daily rainfall above which the frequency is likely to increase, approximately given by the 1-year return period rainfall for autumn;
- P3 is a rainfall threshold (e.g. 0.2 mm) for creating new wet days;

- P4 is an initial threshold for creating new dry days (e.g. 3.0 mm), which may be increased during the model run.

S is the sum of R minus the monthly decrease (where R < P4). R_t is the rainfall on day t and R_{max} is the maximum rainfall in the 30 year record for that month.

The rainfall perturbation model, termed the "combined method", was tested on several grid boxes for the Thames and Severn catchments. Examples of rainfall frequency curves using the combined method, the original proportional method and the observed baseline series for each season are shown in Figure 4.2 and Figure 4.3. These compare with Figures 8 and 9 of the Interim Report. This "combined method" provides a way of applying the UKCIP02 percentage changes to an observed baseline and generating a rainfall time series representative of an emissions scenario and time horizon. However, it is still based on the observed data series and changes in other facets that may affect future spatial and temporal distribution of rainfall are not included.

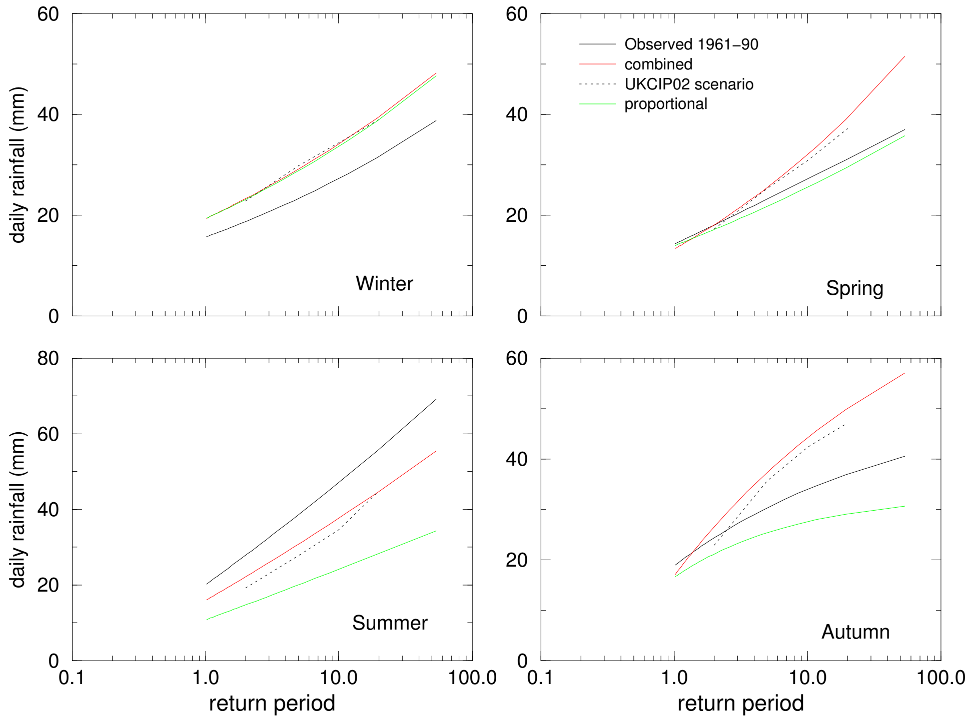


Figure 4.2 Daily rainfall frequency for observed rainfall, 1961-90, and perturbed using the combined and proportional methods for the UKCIP02 High 2080s scenario, compared with corresponding percentage changes for the 2, 5, 10 and 20-year return periods applied to the observed rainfall frequency for a grid box in the Thames catchment.

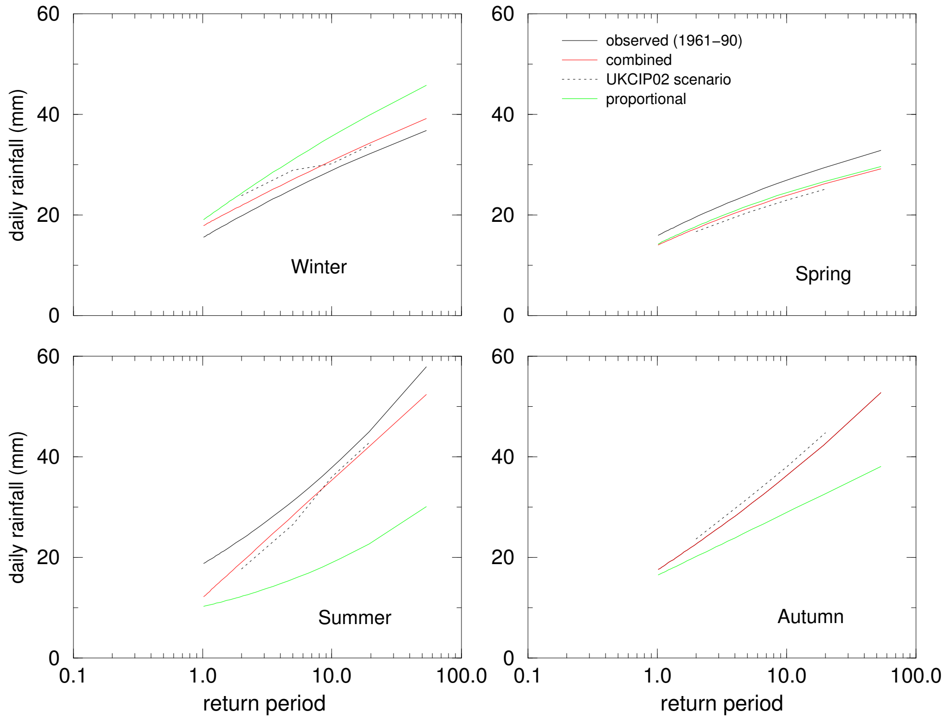


Figure 4.3 Daily rainfall frequency for observed rainfall, 1961-90, and perturbed using the combined and proportional methods for the UKCIP02 High 2080s scenario, compared with corresponding percentage changes for the 2, 5, 10 and 20-year return periods applied to the observed rainfall frequency for a grid box in the Severn catchment.

The combined method was used with the UKCIP02 scenarios to model runoff series for all the catchments and four emission scenarios for the 2050s and 2080s. Where the method was used for the four large catchments modelled with CLASSIC, a simple GIS technique was used to downscale the climate change percentages between the two grid systems. Seasonal indicator values (Table 4.1) were specified for each CLASSIC grid square but the same parameter values were used for the whole catchment. The aim was to reproduce an overall perspective of geographical variation in changes in rainfall without adhering rigidly to frequency changes for individual UKCIP02 grid boxes. For application to the catchments modelled with hourly data, the hourly data were summated to daily values, and the combined method used to perturb the daily data. This series was then disaggregated back to hourly values using the same temporal pattern through the day as the original data set. The climate change percentages for the smaller catchments were determined by area-weighting the values from the UKCIP02 grid boxes covering each catchment.

4.3 Statistical downscaling

The Statistical Downscaling Model (SDSM) was used to generate independent time series of daily rainfall data using the A2 and B2 emissions simulations. SDSM represents the hybrid of regression-based and stochastic weather generator statistical downscaling techniques (Wilby *et al.* 2002, 2003). The technique develops a relationship between the observed, single-site daily precipitation series and large-scale atmospheric variables (simulated by the GCM), together with a stochastic element to generate an ensemble of daily rainfall time series. For precipitation, SDSM is run conditionally, such that the final time series is based on two models, the first determining whether rain falls or not (the event threshold can be specified, in this case at 0.3mm) and the second determining the rainfall amount on wet days.

This downscaling method was used to derive a continuous time series of daily rainfall data for the 20 km grid squares used for the Severn at Bewdley and the 10 km grid squares for the Ouse at Skelton from 1961 to 2099 for the A2 and B2 emissions scenarios. These rainfall series were used as direct input to CLASSIC. Initial use of SDSM generated time series of rainfall individually for each grid square (McSweeney 2003) treating each as a single-site application. The method was enhanced for this project using multi-site generation to include spatial correlation in rainfall between grid squares over a catchment.

For PE, the same data sets were used as for modelling with the observed rainfall series and UKCIP02 scenarios, that is, MORECS monthly data for 1961-1990, and after applying UKCIP02 Medium-High (A2) and Medium-Low (B2) percentage changes for the 2050s (2041-2070) and 2080s (2070-2099).

4.4 Dynamic downscaling

As stated previously, the Hadley Centre RCM for Europe used to produce the UKCIP02 scenarios has a spatial resolution of about 50 km over the UK. However, this project also had access to data from a further-improved Hadley Centre RCM (through Annex 15 of the Hadley Centre's Defra-funded Climate Prediction Programme), which is otherwise the same as that used in UKCIP02, except that it has a spatial resolution of about 25 km over the UK. Rainfall data from the control and enhanced-greenhouse gas/sulphate aerosol runs of this RCM (Table 4.3) were used directly to drive both rainfall-runoff models. This is additional to work done for the Hadley Centre under the Defra Climate Prediction Programme, using a spatially generalised version of the PDM rainfall-runoff model (Kay *et al.* 2003, Kay 2003).

Table 4.3 RCM runs

Reference Name	Hadley Centre run name	Boundary conditions	Time-period	Emissions scenario
Current	ACQQA	GCM	Jan 1961 - Dec 1990	Observed greenhouse gases and sulphur
Future	ACQQB	GCM	Jan 2071 - Dec 2100	SRES A2 (IPCC 2000)

4.4.1 Production of rainfall-runoff model inputs from RCM data

As RCMs do not output PE data directly, it was first necessary to construct time series of PE for each RCM grid-square. This was done using the Penman-Monteith equation (Monteith 1965), which estimates PE via a calculation involving temperature, humidity, wind speed and net radiation, each of which can be obtained from the RCM (more details are given in Appendix D of Kay *et al.* 2003). Note that the Penman Monteith equation is also used within MORECS (Thompson *et al.* 1982, Hough *et al.* 1997).

CLASSIC

As CLASSIC is a grid-based model the RCM rainfall and PE data were used to directly drive the model runs. The model parameterisations for the catchments modelled with CLASSIC, derived from DTM, soils and land use databases, were re-configured for the RCM grid boxes (~25 km). This gives a slightly coarser grid than used with observed data for the Thames and Severn at Bewdley (20 km), much coarser grid for the Ouse (10 km) and finer grid for the Severn at Haw Bridge (40 km). Checks were made with observed data to ensure that the flows simulated with the different grid scales were compatible with small adjustments made to the channel routing parameters, where necessary. When comparing results from different downscaling methods it is the differences between time periods or scenarios, modelled with the same grid framework, which are compared.

The hourly data from the RCM were aggregated to give daily values to use with CLASSIC. The model also requires PE for six land use groups. Monthly totals of PE from the RCM were used in previously determined regression equations relevant to each catchment to calculate monthly PE for each group. These were disaggregated evenly through the month to provide daily values.

PDM

The PDM rainfall-runoff model requires driving data as time series of catchment-average rainfall and potential evaporation (PE). Since the RCM's outputs are averaged over RCM grid-squares, methods are needed to convert from grid-averaged to catchment-averaged values.

Combining the two grid-square PE time series using area-weightings produces a catchment-average PE. This is achieved by multiplying by the proportion of the catchment area in each grid-square. This method is sufficient for PE since it only changes slowly with spatial position.

Total precipitation is a direct output from the RCM. However, rainfall can be highly spatially variable, and some areas can receive consistently more rainfall than others, due to topography and the direction of travel of weather systems. A method that can take some account of these additional factors affecting the spatial variability of rainfall is therefore needed. Standard average annual rainfall (SAAR) data gives an indication of consistently differing amounts of rainfall in different areas, and the availability of a 1 km grid of SAAR values for the UK for the period 1961-1990 means that an average SAAR can be calculated for any area. This information can be used during the production of catchment-average rainfall from grid-average rainfall. The method used was to multiply each grid-square rainfall by the ratio of catchment SAAR to grid-square SAAR, before combining data from each grid-square using area-weightings, to give the catchment-average rainfall.

The use of SAAR values to scale the rainfall should compensate, to a large extent, for differing topography between squares, although it may not fully compensate for the topographic variability *within* grid-squares. Note that this method of spatial downscaling has been chosen in order to have as much comparability as possible with the method used to produce catchment-average rainfall from observed (raingauge) rainfall data, bearing in mind the size of the catchments used with the PDM. Slightly different methods may be more appropriate for larger catchments, with more internal variability in SAAR values.

4.5 Baseline and scenario inter-comparison

Before using these alternative "baselines" and applying the scenarios an inter-comparison exercise was undertaken to assess the differences between these data sets. In addition, the alternative baselines are also compared in terms of the impact on the simulation of the baseline flows. The statistical and dynamic downscaling methods both generate daily rainfall series for the baseline as well as for scenario time periods. The statistics of any generated rainfall series will differ to some extent from those of an observed series for the same time period. When comparing the results of hydrological modelling using these different series it is important to be aware of the variation between the baseline series. In addition, although all three downscaling methods use the same GCM, there are differences in the mean monthly percentage changes between scenario timeslice and baseline and in the seasonal variation of these changes, which can all have an impact on the statistics of flow modelled with these rainfall series.

4.5.1 Monthly rainfall

Figure 4.4 shows a comparison of mean monthly rainfall for the three baseline series (top histogram) and for the Medium-High 2080s scenario (bottom histogram) for the Upper Severn. The indicator bars show the range between the 2nd highest and 2nd lowest monthly rainfalls. It shows the observed/perturbed series (black) to be the wettest of the three methods in the autumn, the RCM (red) the wettest during the winter and the statistically downscaled series (green) the wettest during the summer.

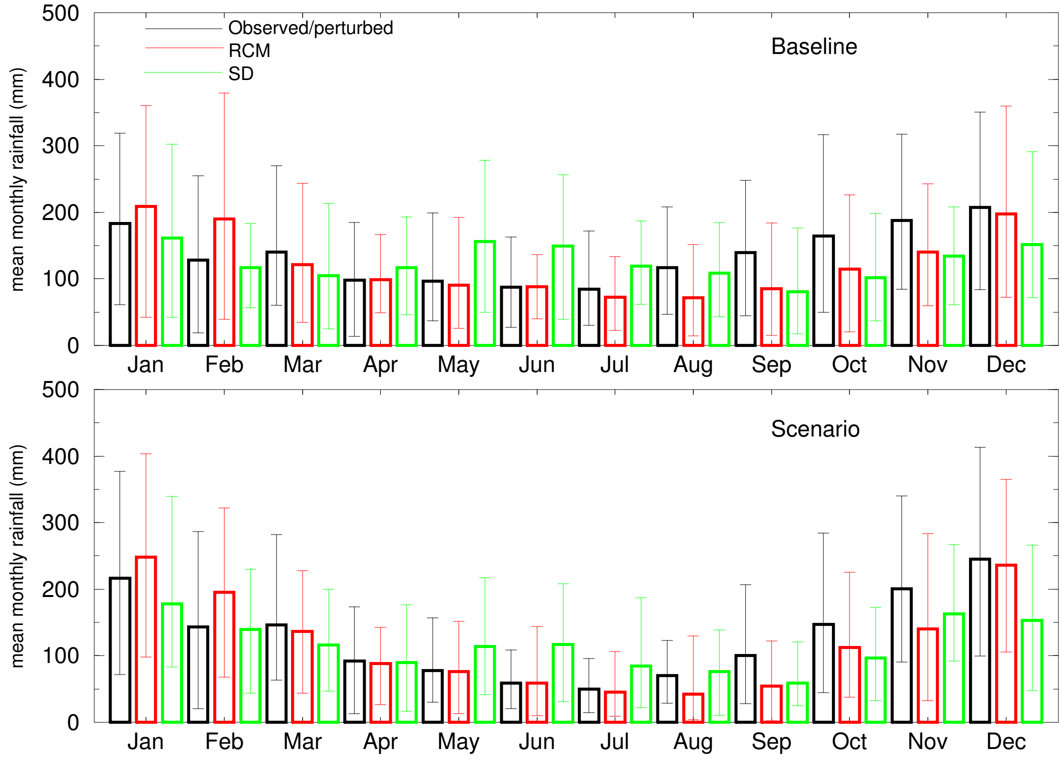


Figure 4.4 Comparison of mean monthly rainfall for the three baseline series and for the Medium-High 2080s scenario.

4.5.2 Rainfall frequency

Differences in the frequency of 1-day rainfall, and longer time intervals for the larger catchments, impact more on flood frequency than changes in monthly rainfall. Comparisons of 1-day rainfall for catchment-averaged rainfall for the Thames (39001) for the two baseline series (observed and RCM) and two downscaling methods (UKCIP02 "combined" scenario and RCM) are given in Figure 4.5 (Medium-High 2080s). Comparisons of the 5-day rainfall for the three baselines (observed, statistical and RCM) and three scenarios (UKCIP02 "combined", statistical and RCM) for the Upper Severn (54001) are shown in Figure 4.6. These figures highlight the differences (and similarities) between the methods, with no overall trend apparent. On the whole, catchment 1-day and 5-day rainfall frequencies for the two generated rainfall series compare well with observed data for the baseline period although the RCM has higher intensity rainfall in the spring and autumn than observed for the Thames (39001) and two Severn catchments (54001 and 54057) and the SDSM has lower intensities in the autumn.

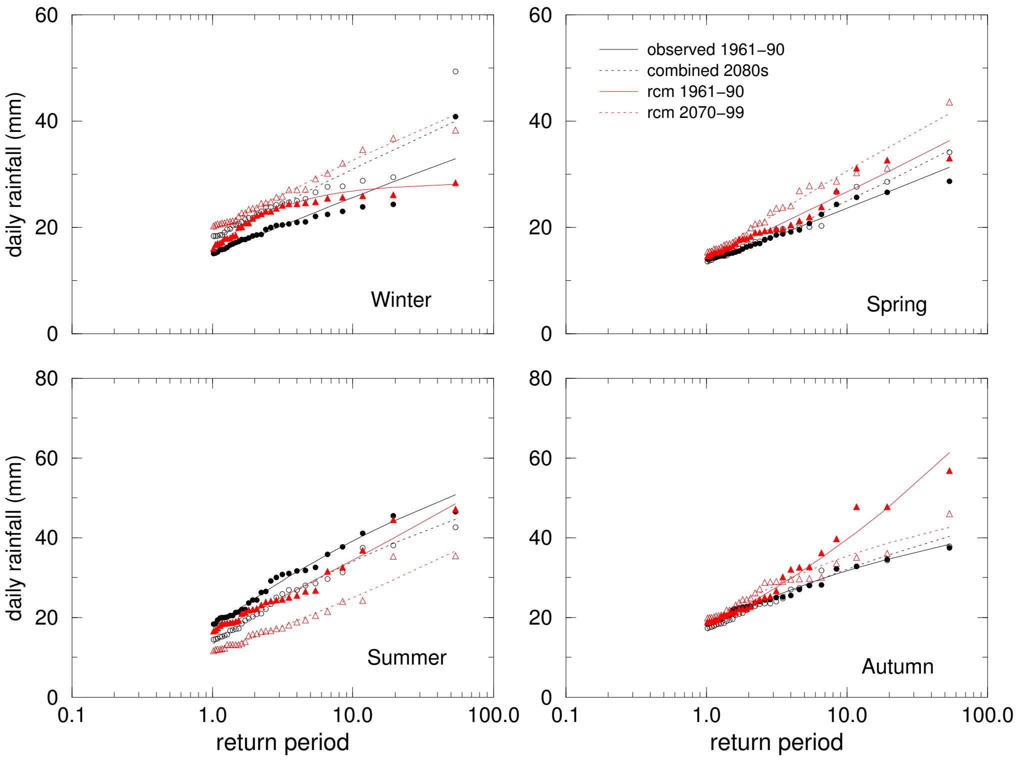


Figure 4.5 Seasonal comparison of the 1-day rainfall for the Thames for two baseline series: observed (black solid lines and filled circles) and RCM (red solid lines and filled triangles), and two downscaling methods: UKCIP02 "combined" (black dashed lines and open circles) and RCM (red dashed lines and open triangles).

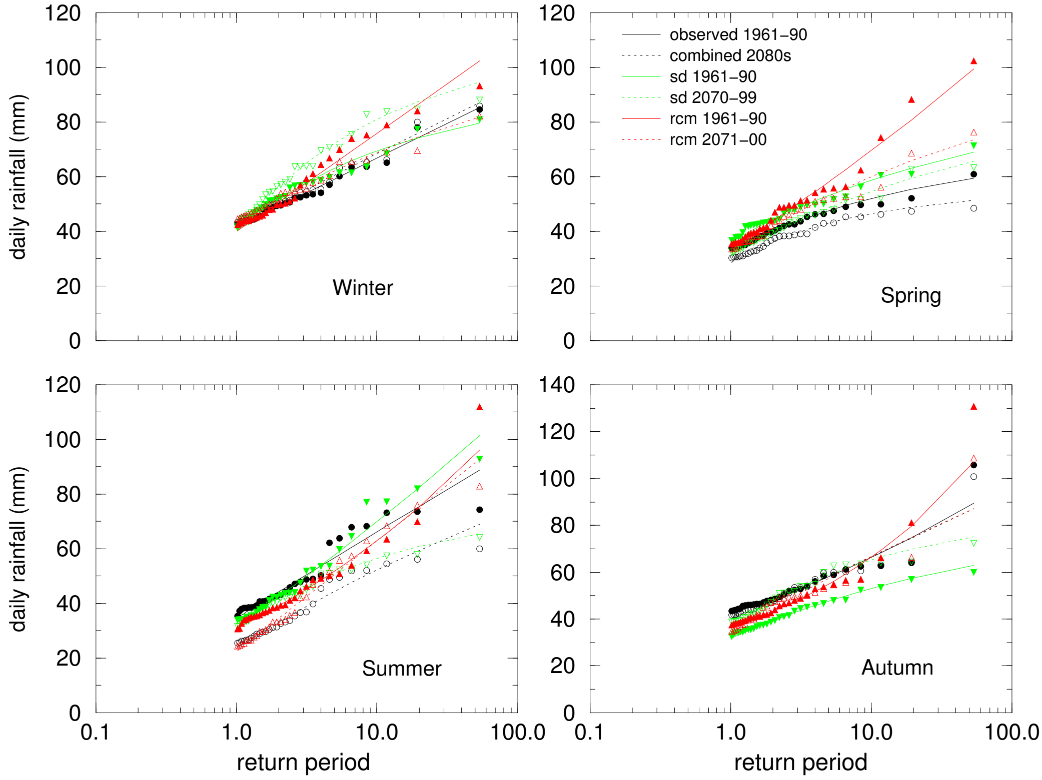


Figure 4.6 Seasonal comparison of the 5-day rainfall for the Upper Severn for three baselines: observed (black solid lines); statistical (green solid lines) and RCM (red solid lines), and three scenarios: UKCIP02 "combined" (black dashed lines); statistical (green dashed lines) and RCM (red dashed lines).

4.5.3 Flow simulation

The SDSM and RCM generate rainfall for the baseline period and as outlined above there are spatial and temporal differences between these data series and observed rainfall. Therefore, baseline flow series simulated from generated rainfall may have different statistics to those simulated from observed rainfall. Impact of these different rainfall series on flow simulation during the baseline is illustrated by differences between the respective flood frequency curves. These are given in Figures 5.3 and 5.4 for the SDSM and Figures A13 to A23 for the RCM (further explanation of these Figures is provided in Section 5).

The RCM baseline flood frequency curve for several catchments (28039, 30004, 54001, 54057 and 96001) is considerably more extreme than the observed baseline curve, though the opposite is true for others, notably the Anton (42012). Only the Thames (39001) shows a good fit between observed and RCM baseline curves. It should, however, be noted that the time periods for catchments modelled with hourly data are different as the RCM data is for the standard 30-year period whereas the observed record is shorter and includes data outside the 1961-90 period. For the two catchments modelled with the SDSM, the correspondence between the baseline series is quite good for return periods above 1 year, particularly for the Severn at Bewdley (54001). A comparison of flood frequency curves for the baseline period (observed flow, modelled from observed rainfall, SDSM A2 and B2 and RCM) is given in Figure 4.7 for the Severn at Bewdley (54001).

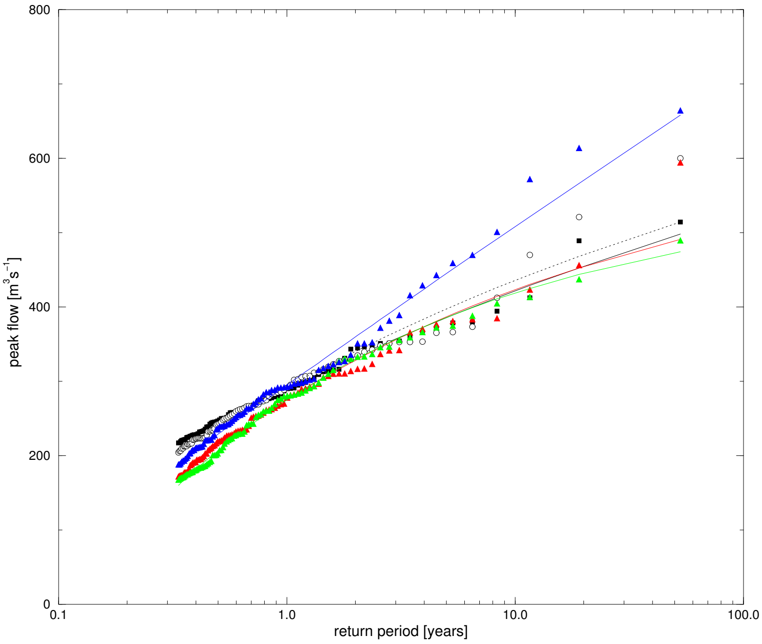


Figure 4.7 Comparison of baseline (1961-1990) flood frequency curves for the Severn at Bewdley, observed flows (black dotted), modelled from observed rainfall (black solid), SDSM A2 (red), SDSM B2 (green), RCM (blue)

4.6 Discussion

Three alternative sets of scenarios have been presented based on the UKCIP02 scenarios, and statistical and dynamic downscaling. As the two downscaling methods also produce alternative baseline series the characteristics of the rainfall, and the flow series they generate, have also been analysed.

While various methods for generating scenarios have been used, the use of alternative emissions scenarios has been limited to just two (A2 and B2), and this has been further limited by their application to only the statistical downscaling method (all other scenarios have been generated, or re-scaled, from the A2 emissions scenario).

Also, the uncertainty due to the choice of GCM or RCM is not considered in this project as all the scenarios have been generated from the Hadley Centre models. Inclusion of the output from more GCMs would provide a much wider range of impact on river flows. For example Figure 4.8 shows the range of changes in average winter over the British Isles as predicted by nine different of GCMs. While all models predict an increase in winter rainfall, the changes range from 1% to 60% (Jenkins and Lowe 2003).

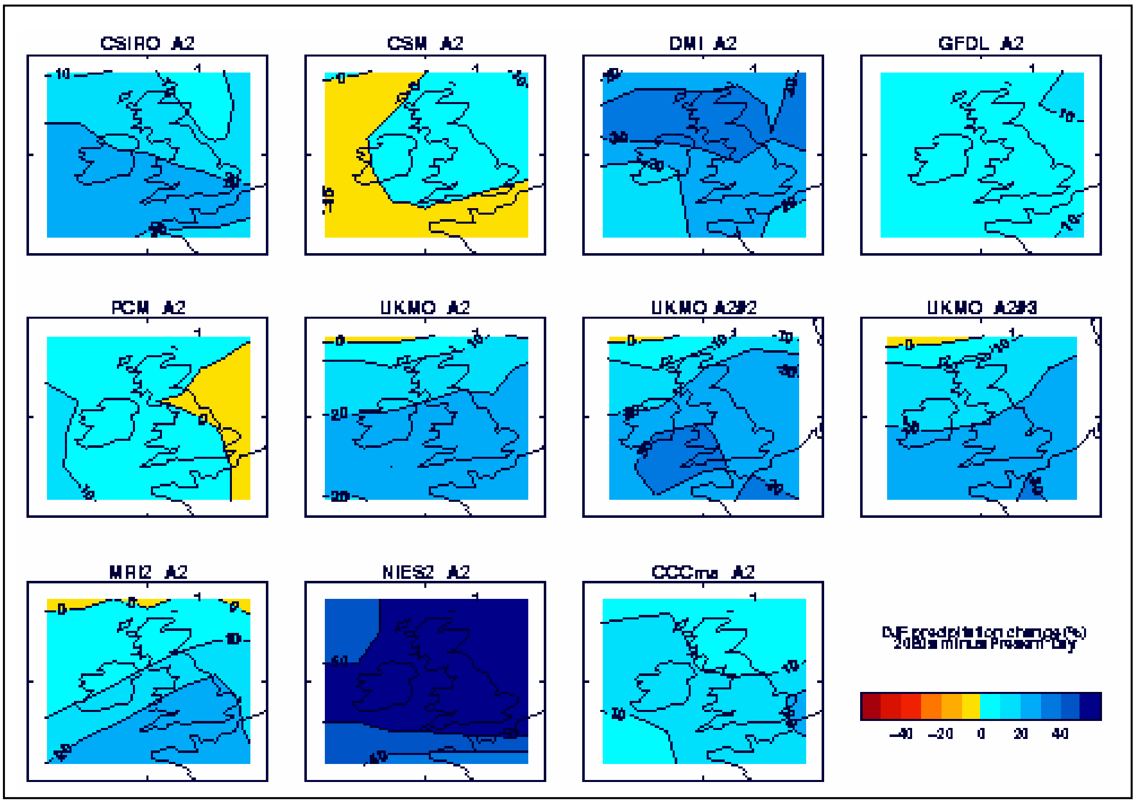


Figure 4.8 Change in average winter rainfall over the British Isles for the 2080s for nine GCMs forced with the A2 emissions scenario (from: Jenkins and Lowe 2003).

5 RESULTS

5.1 Introduction

This results section draws on the full set of graphical and tabular results in the Appendix. The results are presented in a method-based way, according to the scenario generation method. The impacts have been analysed in two ways: the changes in the frequency and magnitude of flood flows, using flood frequency curves; and the impacts on the duration of high flows. The impacts on flows have been calculated purely through changes in rainfall and PE; no allowance has been made in the modelling for other impacts that might arise through changes in climate. These include changes in land cover, cropping patterns, soil properties and their hydrological behaviour, relationships between potential and actual evapotranspiration, and relationships for PE between grass and other vegetation types. Finally in this section a monthly rainfall resampling technique was used to estimate the uncertainty in the impacts due to “natural variability”. This technique was used to produce 100 ensembles of the future rainfall series.

5.2 Flood frequency results

Flood frequency curves for the 10 catchments for four emission scenarios for the 2050s and 2080s using UKCIP02, two catchments using SDSM and for 10 catchments using RCM data are given in the Appendix. Percentage changes between baseline (1961–1990) and scenario flood frequencies for a range of return periods between 1 and 50 years are also given in the Appendix. These percentages have been used to determine the pattern of impact for each catchment for each downscaling method, described in the following sections. Generally, the impact falls into one of two patterns:

- **Type 1** - the percentage change has a positive gradient (i.e. the 50 year return period change is higher, numerically, than the 1 year return period change);
- **Type 2** - the percentage change has a negative gradient (i.e. the 50 year return period change is lower than the 1 year return period change).

For Type 1 the change may be negative at low return periods and positive at high return periods and vice versa for Type 2. The return period at which there is zero change varies between catchments and scenarios, and some catchments have an increase or decrease for all plotted return periods.

5.2.1 UKCIP02

The flood frequency curves for the impacts under all the UKCIP02 scenarios, for all catchments are given in the Appendix in Figures A1.1 to A1.10. Percentage changes between baseline and scenario flood frequencies are given in Table A1.1 for the catchments modelled with CLASSIC and in Table A1.2 for the PDM catchments. The combined method (see Section 4.2) was used to apply the UKCIP02 monthly percentage changes to the observed baseline rainfall series. The results are summarised in Table 5.1 for the Medium-High scenario for the 2050s and 2080s.

Table 5.1 Summary of percentage changes for UKCIP02 scenarios (Medium-High 2050s and 2080s)

Catchment	2050s			2080s		
	Impact Type	5-year	50-year	Impact Type	5-year	50-year
27009	2	-0.3	-3.9	2	0.4	-7.1
28039	2	7.3	-1.3	2	2.8	-7.6
30004	2	-4.0	-8.3	2	-4.5	-13.9
39001	1	-2.9	-1.2	1	-2.5	0.6
40005	2	5.1	-4.6	2	9.8	-11.2
42012	1	-1.8	4.7	1	-1.7	8.5
54001	1	-3.0	-0.9	2	-4.7	-6.7
54057	1	-1.6	1.0	1	-0.5	4.2
74001	2	6.9	4.2	1	10.1	21.9
96001	1	-2.1	2.0	2	-2.8	-2.9

The results show:

- There is an overlap in impact between the 2050s and 2080s, with the high of the 2050s generally similar to the medium-low of the 2080s.
- Four catchments have an increase in the 50-year (2050s and 2080s) return period flows (42012, 74001, 39001 and 54057).
- Four catchments have an increase in the 5-year (2080s) return period flows (28039, 40005, 74001, and 27009).
- Only one catchment has an increase at all return periods (74001).
- For most catchments the percentage changes follow a similar pattern across the four emission scenarios and time-slices. The main exception is 28039 (the urban catchment) where the Medium-Low and Low scenarios for the 2050s and Low scenario for the 2080s show an increase at the 50-year return period, whereas the other scenarios show a decrease.
- Half the catchments show a Type 2 impact on flood frequency for the 2050s, where the percentage change decreases with increasing return period (60% for the 2080s).
- Two catchments, 39001 (Thames) and 27009 (Ouse), have an “outlier” highest peak, particularly for the 2080s, with a return period in excess of 100 years.
- For most catchments the impact of the increase in winter rainfall is offset by the increase in PE (see Figure 4.1) and generally hotter, drier conditions during the summer and autumn.

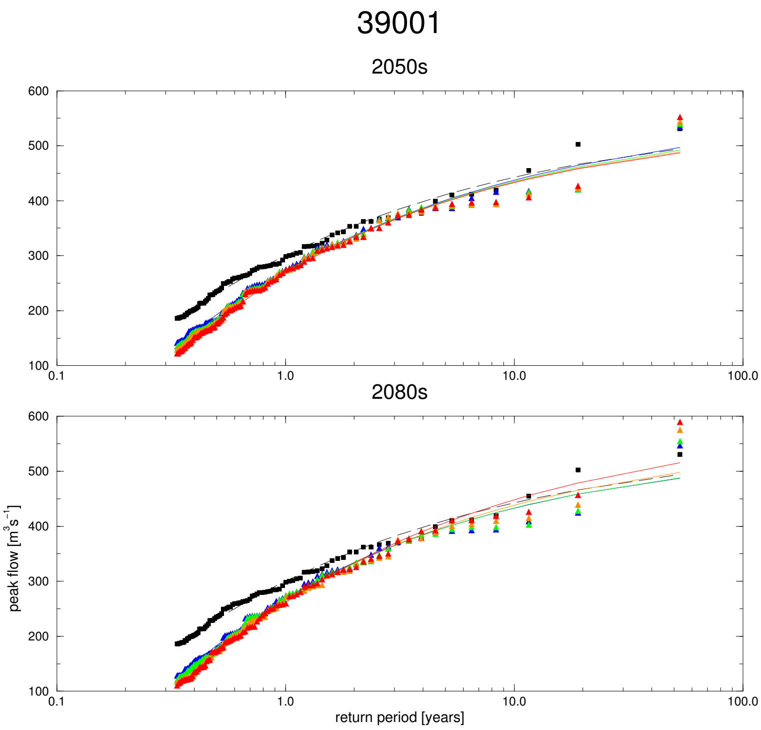


Figure 5.1 Flood frequency curves for the Thames (39001) for the baseline (black dashed line) and the four emissions scenarios (Low – blue, Medium-Low – green, Medium-High – orange, High – red) for the 2050s and the 2080s.

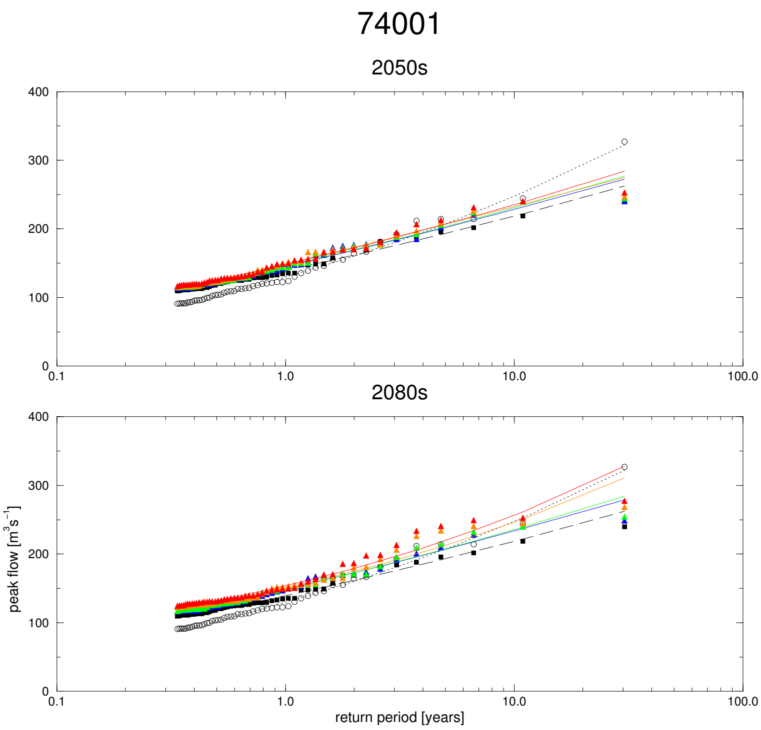


Figure 5.2 Flood frequency curves for the Duddon (74001) for the baseline (black dashed line) and the four emissions scenarios (Low – blue, Medium-Low – green, Medium-High – orange, High – red) for the 2050s and the 2080s.

Figure 5.1 shows the flood frequency curves for the Thames (39001) with little change at the higher return periods by the 2050s, but some increases by the 2080s. The reduction in lower flows is quite evident, arising from the prolonged, warmer and drier summers and autumns. Figure 5.2 shows the same results for the Duddon (74001). This is a quite different, smaller, more responsive catchment in the north west of England. For this type of catchment the impact of the wetter winters to the north and west of the country becomes apparent, as long-term antecedent conditions are less critical to this type of catchment. Hence a more marked increase in flood frequencies is evident under all scenarios, particularly for the 2080s.

The impact of the UKCIP02 scenarios on flood frequency is dependent on the month of occurrence of the main flood events in the baseline series. Due to the nature of this type of scenario application (perturbing the current 1961-1990 series) there is no allowance for changes in these seasonal patterns or the annual sequences of rainfall, or for changes in the spatial distribution.

5.2.2 Statistical downscaling

Flood frequency curves were derived for the two emission scenarios, A2 and B2, and three time-slices, the baseline period of 1961-1990, the 2050s and the 2080s. The flood frequency curves for the impacts of the SDSM data are given in Figure 5.3 for the Ouse (27009) and Figure 5.4 for the Severn at Bewdley (54001). In addition a flood frequency curve was also derived for the single-site (independent grid square) rainfall time series for the baseline period. The difference between the two blue lines in Figures 5.3 and 5.4, and comparing these curves to the black “observed” baseline, gives an indication of the positive contribution of using spatially correlated, multi-site, rainfall fields from SDSM in generating flood runoff. The uncorrelated, single-site, rainfall for the model grids greatly under-estimates the baseline flood frequencies as the large-scale rainfall events, which are more likely to produce floods in catchments as large as the Ouse or the Severn, are not being simulated. The percentage changes between baseline and scenario flood frequencies are given in Table A2.1 of the Appendix. The results are summarised in Table 5.2.

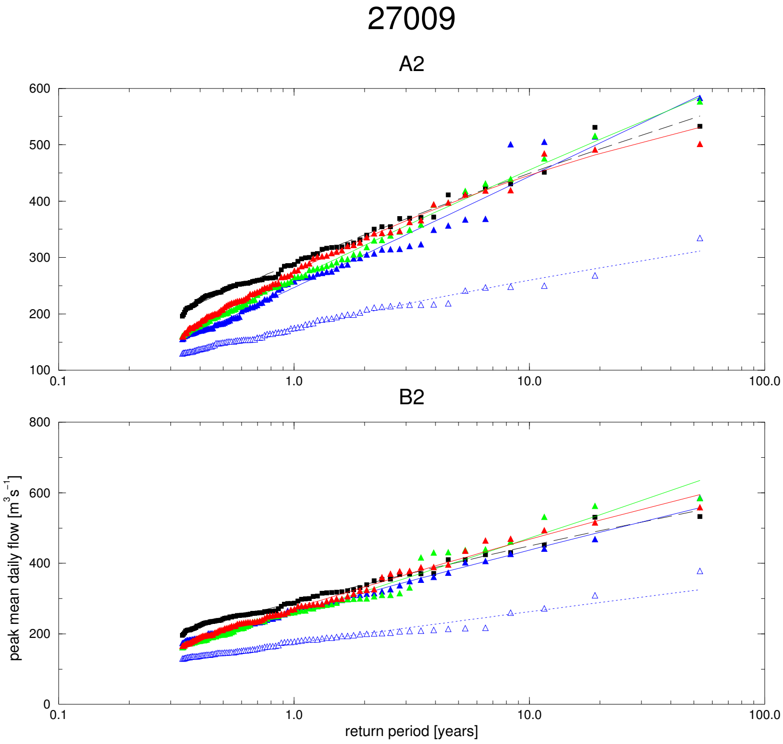


Figure 5.3 Flood frequency curves for the Ouse at Skelton (27009) under the A2 and B2 scenarios. The black dashed line is the 1961-1990 baseline from observed rainfall, the blue dashed line is the baseline using single site SDSM and the blue solid line is the baseline using the spatially correlated SDSM. The green line is for the SDSM 2050s and the red line is the SDSM 2080s.

54001

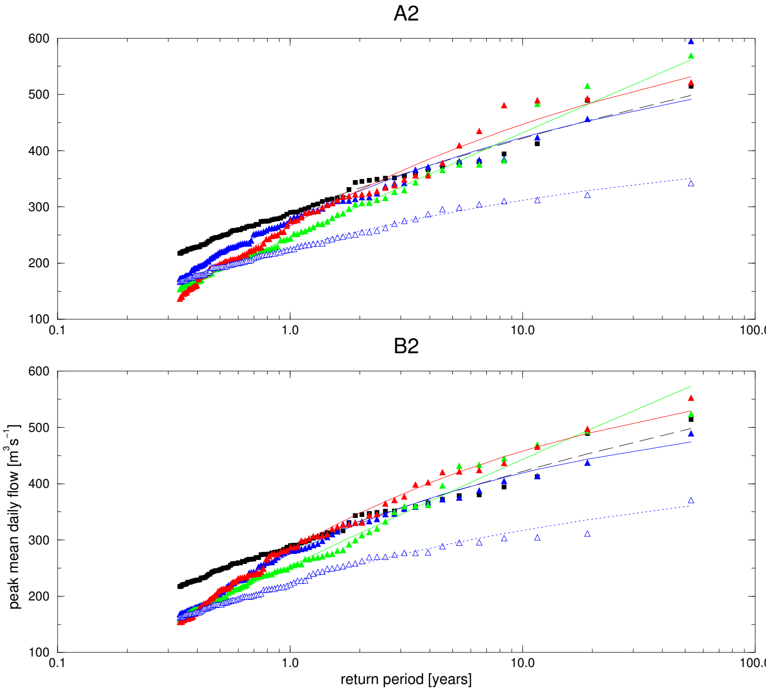


Figure 5.4 Flood frequency curves for the Severn at Bewdley (54001) under the A2 and B2 scenarios. The black dashed line is the 1961-1990 baseline from observed rainfall, the blue dashed line is the baseline using single site SDSM and the blue solid line is the baseline using the spatially correlated SDSM. The green line is for the SDSM 2050s and the red line is the SDSM 2080s.

Table 5.2 Summary of percentage changes for SDSM scenarios (Medium-High, A2, and Medium-Low, B2, for the 2050s and 2080s)

Catchment	Timeslice	2050s			2080s		
		Impact Type	5-year	50-year	Impact Type	5-year	50-year
27009	A2	2	3.9	-0.5	2	4.6	-9.3
	B2	1	5.2	13.7	1	6.7	6.8
54001	A2	1	-2.8	13.9	1	3.7	8.2
	B2	1	0.4	20.3	1	7.9	11.6

The results show:

- The B2 scenario shows an increase in flood frequency for all return periods greater than 5 years.
- For the Ouse (27009) the two emissions scenarios have an opposite impact.
- The highest increase for both catchments is shown to be for the B2 scenario for the 2050s for return periods greater than 20 years

5.2.3 Dynamic downscaling – use of RCM data

The flood frequency curves for the impacts of the RCM data are given in full in the Appendix in Figures A3.1 to A3.11. Percentage changes between baseline and scenario flood frequencies are given in Table A3.1 for the catchments modelled with CLASSIC and Table A3.1 for the PDM catchments. The percentage change results are summarised in Table 5.3 below.

The generation of a high flood peak for the Thames (39001) in the baseline period using RCM data is caused by extreme rainfall over the catchment over a critical 5-day period (see Figure A3.2 of the Appendix). Because this peak distorts the baseline flood frequency curve, curves have been calculated omitting the highest peak from each series to provide a more realistic estimate of the percentage change between the baseline and scenario time periods, (Figure A3.3). However, the generation of such an event underlines the limitation, and dangers, of basing estimates of impacts of climate change on only one model run for 30-year time periods. The generated peak flow is more extreme than anything that occurred between 1900 and 2000, but is similar to one that occurred in 1894. In comparison, the estimated return period for the highest peak on the Thames during October/November 2000 was five years (CEH-Wallingford / Met Office 2001).

Table 5.3 Summary of percentage changes for the RCM (Medium-High, 2080s).

Catchment	Impact Type	1-year	5-year	50-year
27009	1	5.0	8.7	11.7
28039	2	13.7	0.3	-23.4
30004	2	6.1	-2.7	-18.4
39001*	1	7.0	14.2	17.7
40005	2	9.3	-2.3	-21.5
42012	2	12.4	10.8	-2.2
54001	2	-3.3	-12.1	-23.8
54057	2	-4.0	-9.9	-17.8
74001	2	17.3	16.9	15.7
96001	2	14.5	5.0	-15.2

* Percentages for flood frequency curves omitting the highest peak.

The results show:

- Eight of the catchments show a Type 2 impact on flood frequency, with all but two of these having a decrease in excess of -15% at the 50-year return period. Only three catchments show an increase at the 50-year return period. The results for the Lymn (30004) are re-produced in Figure 5.5 to illustrate this change.
- Most catchments show a significant increase at the 1-year return period.
- The results are for only one scenario for one time-slice, so how the change for the 2080s relates to change in the intervening period cannot be identified. Neither can the variability in the change, had an ensemble of RCM data been available.

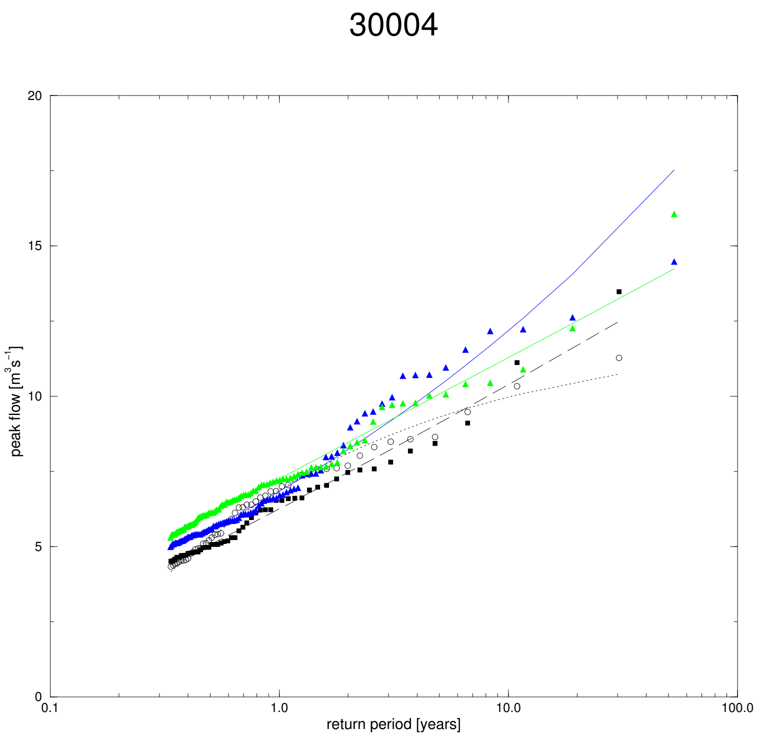


Figure 5.5 Flood frequency curves for the Lymn at Partney Mill (30004). The black dotted line is the curve generated from observed flows. The black dashed line is the curve for modelled flows from observed rainfall for the 1961-1990 period. The blue line is modelled using the RCM baseline data, and the green line is modelled using the 2080s RCM data.

5.3 Impact on duration of high flows

Climate change has an impact on all aspects of the flow regime. To examine the impact on the length of time high flows are sustained in catchments, the percentage change in the Q3 flow (see Section 1.4) was calculated. This is the flow that is equalled or exceeded just 3% of the time. It has been calculated separately for the four seasons, to highlight the impact of the increased winter and decreased summer rainfall. The Q3 flow was calculated for four emissions scenarios for 2050s (UKCIP02) and two or three methods for the 2080s (depending on the catchment). The percentage changes are given in Table 5.4 for the CLASSIC catchments and Table 5.5 for those modelled with the PDM. It should be noted that the magnitudes of these changes in Q3 may be less reliable for the catchments modelled with the PDM than for those modelled with CLASSIC, for a number of reasons: the PDM is a parameter-sparse, lumped model, calibrated with regard to peak flows in particular, and running (usually) at a finer time-step than CLASSIC. Reproducing the whole range of flows well is thus more difficult, particularly in the drier seasons. However, the results for the PDM are consistent with those for CLASSIC in that they show the same type of seasonal pattern, as discussed below.

Almost all the catchments show a decrease in the Q3 flow for the spring, summer and autumn. Almost the only exceptions to this occur in the spring for the Thames (39001 -

2080s, RCM), the Ouse (27009 - 2080s, SDSM), the Beult (40005 - 2080s, RCM) and the Duddon (74001 - 2080s, RCM). The two catchments on the Severn, 54001 and 54057, both also show a decrease in the Q3 winter flow. The catchments modelled with the PDM generally show larger increases in the winter Q3 flow than the CLASSIC catchments, which may reflect the modelling method as much as the catchment size. For most catchments the biggest decrease occurs in the summer, but for the Thames (39001) and the Anton (42012) autumn shows a more extreme impact due to the contribution of baseflow sustaining runoff during the summer. Examples of seasonal flow duration curves are given in Figure 5.6 for the Thames and Severn at Bewdley (2050s) and Figure 5.7 for the Anton (2050s and 2080s).

Comparison of downscaling methods for the 2080s on the Q3 flow shows that the pattern of change across the seasons is generally consistent though the level of change may differ.

Table 5.4 Percentage change in Q3, by season, for the four CLASSIC catchments

Catchment	Timeslice	Scenario	Winter	Spring	Summer	Autumn
39001	2050s	High	0.3	-7.1	-31.2	-53.8
		M-High	0.3	-6.6	-29.2	-50.0
		M-Low	0.7	-5.8	-27.8	-46.7
		Low	0.0	-4.9	-25.0	-41.8
	2080s	M-High	0.0	-8.8	-37.5	-59.9
		RCM	9.2	7.4	-21.1	-48.9
27009	2050s	High	3.8	-3.8	-50.7	-12.4
		M-High	3.8	-3.1	-44.8	-10.8
		M-Low	3.4	-2.5	-41.1	-9.1
		Low	3.0	-1.9	-36.8	-8.1
	2080s	M-High	6.8	-5.7	-63.2	-22.4
		RCM	7.1	-13.1	-42.9	-5.1
		SD A2	18.1	8.2	-15.3	1.0
54001	2050s	High	-3.5	-10.1	-46.5	-30.8
		M-High	-2.4	-9.6	-42.3	-26.9
		M-Low	-1.7	-7.4	-39.4	-24.4
		Low	-1.0	-6.4	-35.2	-21.4
	2080s	M-High	-4.2	-13.3	-56.3	-38.8
		RCM	-5.7	-19.4	-42.9	-18.4
		SD A2	4.8	-14.7	-53.6	-32.5
54057	2050s	High	-2.6	-8.1	-41.1	-45.4
		M-High	-2.4	-7.8	-37.8	-41.7
		M-Low	-1.9	-7.5	-35.1	-38.3
		Low	-1.5	-7.2	-32.4	-33.9
	2080s	M-High	-0.9	-11.2	-50.4	-52.2
		RCM	-3.2	-21.8	-55.7	-29.0

Table 5.5 Percentage change in Q3, by season, for the six PDM catchments

Catchment	Timeslice	Scenario	Winter	Spring	Summer	Autumn
28039	2050s	High	5.4	-19.6	-40.1	-13.0
		M-High	4.8	-16.7	-34.5	-11.3
		M-Low	-0.5	-10.4	-30.7	-10.4
		Low	-0.6	-8.7	-26.2	-8.6
	2080s	M-High	8.2	-26.5	-54.7	-18.7
		RCM	16.4	-12.1	-47.5	-9.9
30004	2050s	High	1.6	-8.5	-40.9	-24.7
		M-High	1.3	-7.2	-35.3	-21.0
		M-Low	1.3	-6.3	-32.5	-19.0
		Low	1.1	-5.7	-27.1	-16.1
	2080s	M-High	2.5	-12.1	-53.0	-34.6
		RCM	17.3	-1.6	-44.1	-16.7
40005	2050s	High	12.7	-2.6	-42.5	-17.9
		M-High	10.6	-2.3	-36.7	-15.1
		M-Low	9.7	-2.0	-33.4	-13.5
		Low	8.2	-1.9	-28.9	-11.7
	2080s	M-High	18.5	-3.7	-55.4	-26.9
		RCM	12.6	14.8	-47.6	-21.2
42012	2050s	High	3.1	-0.9	-9.9	-25.7
		M-High	2.6	-1.0	-8.6	-22.4
		M-Low	2.6	-0.8	-7.5	-20.2
		Low	2.4	-0.7	-6.5	-17.9
	2080s	M-High	3.7	-1.0	-13.0	-33.5
		RCM	19.5	-10.9	-51.3	-32.7
74001	2050s	High	13.4	-3.1	-37.6	-4.6
		M-High	11.3	-2.8	-33.2	-2.6
		M-Low	10.1	-2.5	-29.8	-2.1
		Low	8.4	-2.1	-24.2	-1.1
	2080s	M-High	19.6	-4.1	-53.5	-8.1
		RCM	19.2	8.5	-51.9	1.6
96001	2050s	High	2.6	-1.2	-19.4	-2.7
		M-High	1.4	-1.3	-13.7	-1.7
		M-Low	1.2	-1.3	-12.0	-1.6
		Low	0.9	-1.0	-9.6	-1.3
	2080s	M-High	10.0	-1.8	-25.0	-3.2
		RCM	7.2	-10.5	-31.6	3.4

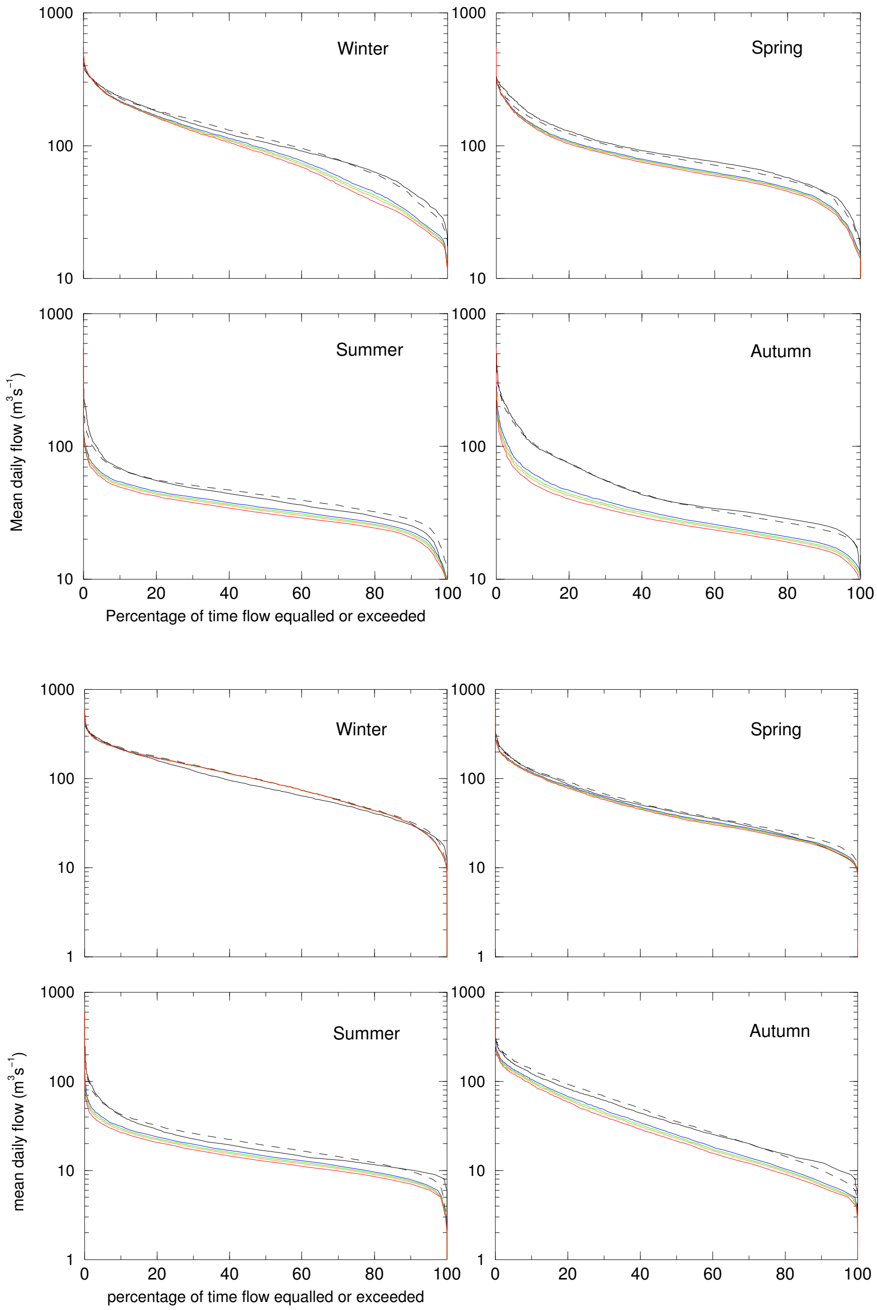


Figure 5.6 Seasonal flow duration curves for the Thames (39001), top, and Severn at Bewdley (54001), bottom, for baseline series – observed flow (black solid), modelled from observed rainfall (black dashed), and UKCIP02 2050s four emissions scenarios (Low — blue, Medium-Low — green, Medium-High — orange, High — red).

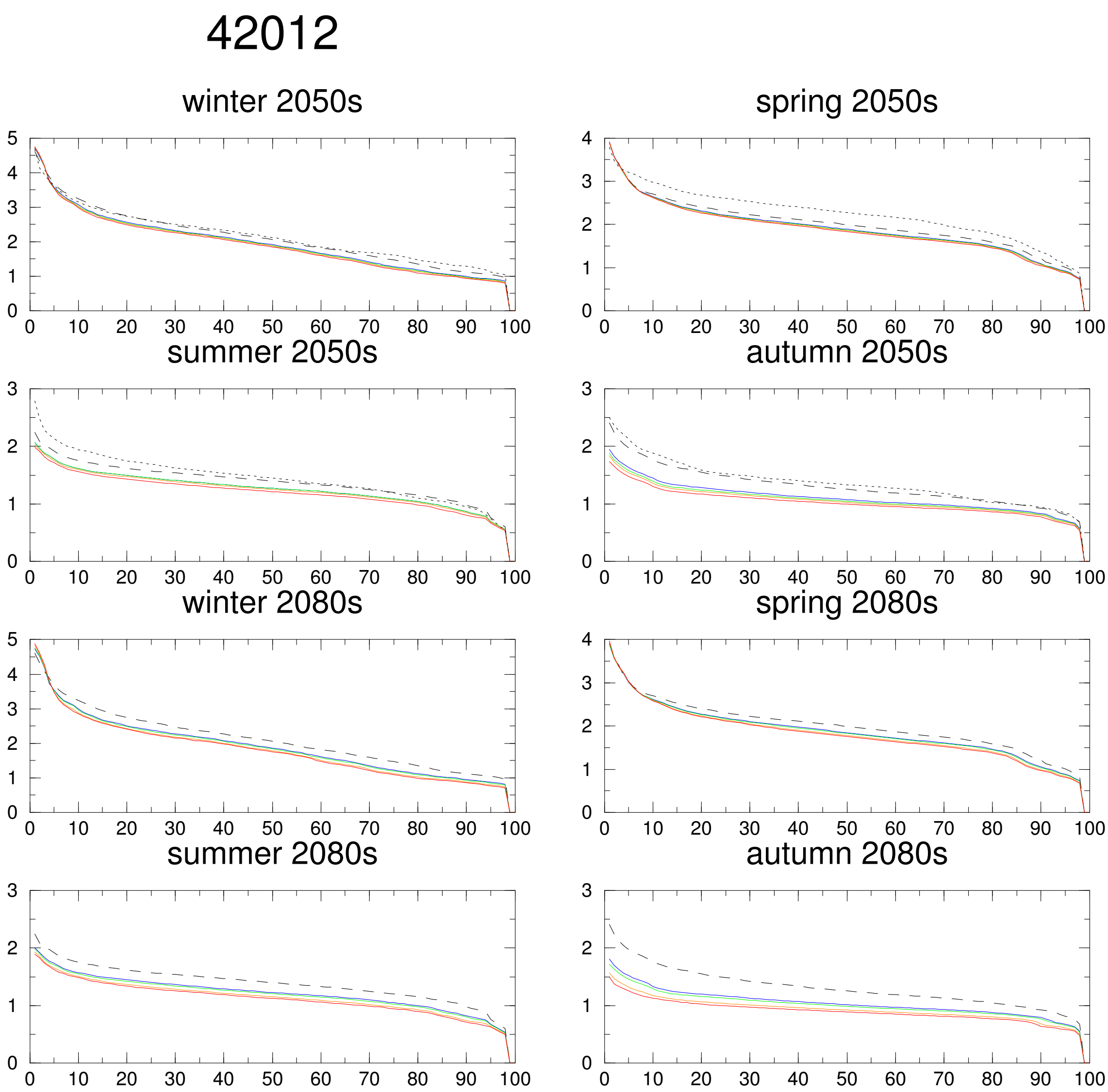


Figure 5.7 Seasonal flow duration curves for the Anton (42012), comparing baseline observed (dotted black line) and modelled (dashed black line) with those modelled under the four UKCIP02 emissions scenarios (solid lines; Low — blue, Medium-Low — green, Medium-High — orange, High — red) for the 2050s and 2080s.

5.4 Rainfall resampling

An attempt was made to give some allowance for "natural variability" in the future rainfall series by developing a method of resampling the rainfall, whether derived from UKCIP02 percentage changes or from the RCM. This involved making a number of different time series from the original rainfall series, by selecting the rainfall month-by-month, with replacement. That is, the rainfall for, say, "January 1961" of a series being constructed is taken from a randomly selected January of the original series; "February 1961" is taken from a randomly selected February, and so on. This method obviously does not change the sub-monthly variability (for example the hourly or daily intensities), but does allow changes in rainfall accumulations over a number of months. It is this that can result in quite different flood frequencies from the resampled series to those from the original series. For instance, a wet winter, which was preceded by a dry autumn in the original series, could be preceded by a wet autumn in a resampled series, thus greatly increasing the chance of flooding during that winter period. Assuming independence between monthly, and particularly seasonal, rainfall these resamples could have occurred in reality, therefore the flood frequencies that result from the use of any resample to drive the rainfall-runoff model are all possible distributions.

If a large number of resampled series are used to produce a large number of flood frequency curves, an average flood frequency can be calculated, along with uncertainty bounds. Here, 100 resampled rainfall series were generated so 101 series were used to produce flood frequencies (including the original series). At each return period plotting position, the 101 flood peak values are then ordered, so that the 51st value at each position gives the median. These points are then linearly interpolated, to give the median flood frequency 'curve'. Similarly, the 5th and 96th values can be selected and interpolated, to give the 90% upper and lower bounds.

Note that this resampling method has only been applied with the PDM, which requires catchment-average rainfall. It is a non-trivial exercise to apply this technique to the gridded rainfall required by CLASSIC. It should also be noted that the 90% upper and lower bounds represent a description of the more extreme scenarios, rather than assigning any measure of likelihood.

Table 5.6 summarises the results from resampling the UKCIP02 data for the 2050s and the 2080s (the baseline rainfall data perturbed according to the "combined" scenario). It gives the percentage changes in flood peaks at the 20-year return period, comparing the mean of the change for the four single UKCIP scenarios (from the figures in section A1 of the Appendix) with the mean, minimum and maximum changes when using 100 resamples for the four scenarios (from the figures in section A4.1 of the Appendix). The results are summarised across all four scenarios, rather than separately, to simplify their interpretation, and because the differences between emissions scenarios are small relative to the uncertainty bounds produced by the resampling. The minima and maxima are thus taken as the percentage change to the lowest lower 90% bound of the four scenarios, and the highest upper 90% bound of the four scenarios, respectively. The mean is that of the four scenario medians, and a comparison of this value with the mean from the four single scenarios shows where the latter lie in the distribution.

These results demonstrate that it would only take a slightly different sequencing of events to push some catchments into rather higher percentage changes in flood frequency (note, though, that resampling the observed rainfall time series could also result in quite a range of flood frequencies). The maxima suggest that highly urbanised catchments (e.g. 28039), groundwater catchments (e.g. 42012), and hilly catchments in the north west (e.g. 74001) may be generally more susceptible to changes in climate of this nature.

Figure 5.8 shows the median, maximum and minimum flood frequency curves generated from the 101 UKCIP02 rainfall series for the 2050s under the four emissions scenarios for the urbanised catchment, the Rea at Calthorpe Park (28039). The full explanation of the line colours is in the box below the figure.

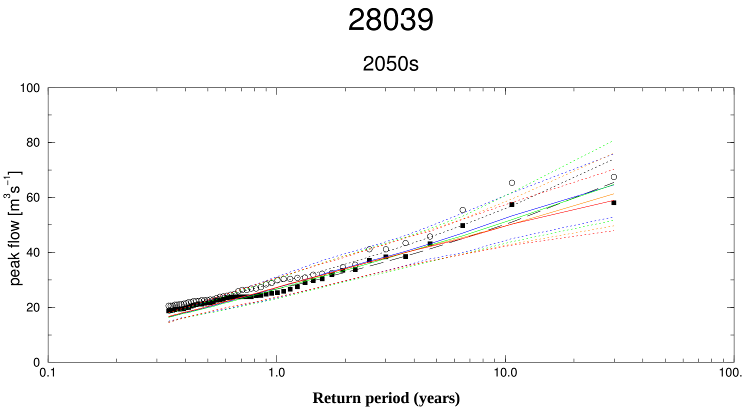


Figure 5.8 Flood frequency curves for the Rea at Calthorpe Park (28039) for median, maximum and minimum changes from the 101 resampled rainfall series for the 2050s under the four UKCIP02 emissions scenarios. (full explanation of the line colours is given in the text box below).

Black dotted line and open circles — from observed flows.
Black dashed line and filled squares — modelled using observed rainfall.
Red solid line — median modelled, using 100 resamples under UKCIP02 high emissions scenario. Dotted lines — 90% upper and lower uncertainty bounds, using 100 resamples under UKCIP02 high emissions scenario.
Orange solid line — median modelled, using 100 resamples under UKCIP02 medium-high emissions scenario. Dotted lines — 90% upper and lower uncertainty bounds, using 100 resamples under UKCIP02 medium-high emissions scenario.
Green solid line — median modelled, using 100 resamples under UKCIP02 medium-low emissions scenario. Dotted lines — 90% upper and lower uncertainty bounds, using 100 resamples under UKCIP02 medium-low emissions scenario.
Blue solid line — median modelled, using 100 resamples under UKCIP02 low emissions scenario. Dotted lines — 90% upper and lower uncertainty bounds, using 100 resamples under UKCIP02 low emissions scenario.

Table 5.6 Summary of results (at the 20-year return period) using 100 resamples of the UKCIP02 data.

Catchment number	Time-slice	Mean UKCIP02 scenario change	100 resamples for UKCIP02 minimum of scenario minima (within 90% bounds)	mean of scenario medians	maximum of scenario maxima (within 90% bounds)
28039	2050s	5.1	-22.5	-1.5	24.2
	2080s	-1.1	-28.5	-6.0	20.5
30004	2050s	-5.0	-24.9	-7.6	9.5
	2080s	-8.0	-28.3	-10.6	7.1
40005	2050s	0.1	-22.8	-4.9	9.9
	2080s	-2.4	-24.7	-5.3	9.4
42012	2050s	2.1	-8.5	6.6	25.7
	2080s	3.8	-8.4	6.9	29.6
74001	2050s	5.8	-14.4	2.6	17.0
	2080s	13.2	-13.0	9.3	30.4
96001	2050s	-0.1	-20.4	-2.3	16.2
	2080s	-2.1	-22.1	-4.6	16.0

Table 5.7 summarises the results from resampling the baseline (acqqa) and the 2080s (acqqb) RCM rainfall data. It gives the percentage changes in flood peaks at the 20-year return period, using the RCM data directly (from the figures in section A3 of the Appendix) and when using 100 resamples of the RCM data (from the figures in section A4.2 of the Appendix). In this case the minima and maxima are taken as the percentage change from, respectively, the upper 90% bound for acqqa to the lower 90% bound for acqqb, and the lower 90% bound for acqqa to the upper 90% bound for acqqb.

Table 5.7 Summary of results (at the 20-year return period) using 100 resamples of the RCM data (Medium-High, 2080s).

Catchment number	RCM data	100 resamples of RCM data minimum (within 90% bounds)	median	maximum (within 90% bounds)
28039	-14.0	-35.6	-5.7	38.6
30004	-12.0	-30.0	-6.8	29.7
40005	-13.8	-38.4	-13.3	20.3
42012	3.5	-73.0	20.9	474.3
74001	16.3	-2.9	15.9	39.6
96001	-6.9	-28.7	-7.3	30.6

These results are rather more difficult to interpret than those where the UKCIP02-derived data have been resampled, due to the fact that it is necessary to perform resampling for the baseline period as well as for the future period, thus the minimum and maximum percentage changes for each catchment give a very wide range. The results for the Halladale at Halladale (96001) are shown in Figure 5.9 as illustrative of this set of resampling results.

The maxima are somewhat consistent with those for the UKCIP02 resampling, as they suggest there may be a particular susceptibility for groundwater catchments like 42012, for urbanised catchments like 28039, and for hilly catchments in the north west like 74001, since these have the highest maximum percentage changes. Catchments 30004 and 40005 (rural catchments in eastern and southern England) appear to be the least susceptible for both the UKCIP02 and RCM resampling.

The particularly large maximum for catchment 42012 is due to the upper 90% bounds being significantly higher than the medians for both the baseline and future time-slices. This is likely to be because 42012 is a groundwater catchment, and so a few resampled-series may give sufficient rainfall over a sustained period of several months to fill up the groundwater store and cause significant flooding, whereas the majority will allow sufficient respite between events for the groundwater level to fall again. As such, the extremely high maximum percentage change given in the table could represent a real susceptibility of such catchments. (Alternatively, it could be a model structure issue in that the model is over-predicting flows when the high, longer duration accumulations of rainfall are presented to it. Also, note that the RCM is not doing a particularly good job of modelling the rainfall for that catchment anyway, as the RCM-modelled flood frequency for 1961-90 is significantly lower than the observed flood frequency. See Figure A3.9 in the Appendix).

It is useful also to look at the absolute changes in flows as well as the percentage changes, especially for the particularly high percentage changes in flow shown in Table 5.7 and in the tables A6.1 to A6.4 in the Appendix section A.6. Table 5.8 below shows changes in flow, in m^3s^{-1}, for the six PDM catchments under the maximum and minimum resampled scenarios from UKCIP02 and RCM information.

Table 5.8 Summary of absolute changes in flow (m^3s^{-1}) at the 20-year return period using 100 resamples of the UKCIP02 and RCM data for the 2080s.

Catchment	UKCIP02 minimum (within 90% bands)	UKCIP02 maximum (within 90% bands)	RCM minimum (within 90% bands)	RCM maximum (within 90% bands)
28039	-18.7	13.5	-30.4	22.7
30004	-3.3	0.8	-4.5	3.3
40005	-23.8	9.1	-36.9	13.0
42012	-0.4	1.4	-3.3	4.8
74001	-31.9	74.6	-4.7	54.1
96001	-39.1	28.4	-72.5	56.7

The very high percentage changes in flow, for example for the Anton (42012) under the RCM maximum resampling scenario (a 474% increase) only represents an increase of about 5 m^3s^{-1}.

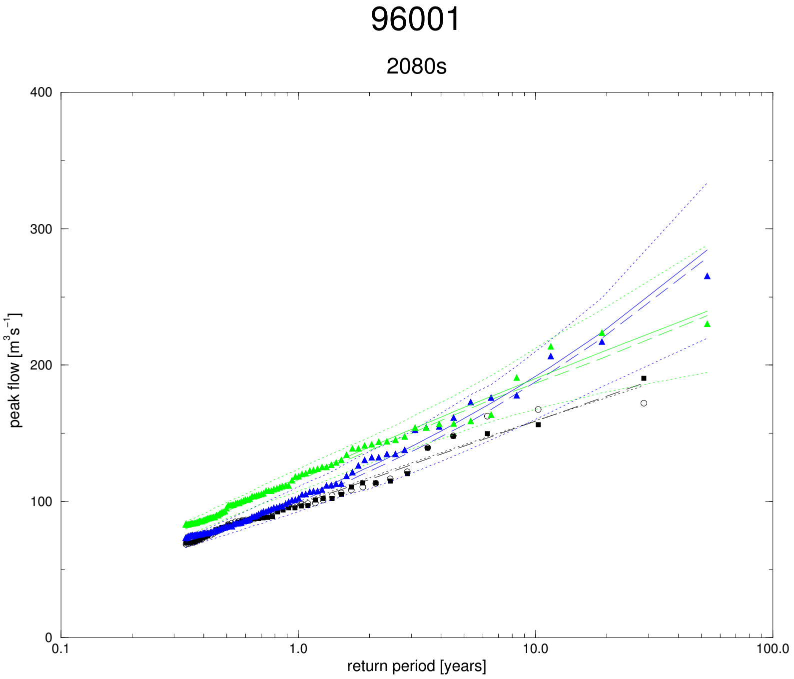


Figure 5.9 Flood frequency curves for the Halladale at Halladale (96001) for median, maximum and minimum changes from the 101 resampled RCM rainfall series for the baseline and the 2080s (full explanation of the line colours in text box below).

Black dotted line and open circles — from observed flows
Black dashed line and filled squares — modelled using observed rainfall.
Blue solid line and filled triangles — modelled using 1961-1990 RCM data (acqqa).
Blue dashed line — median modelled, using 100 resamples of the acqqa data.
Blue dotted lines — 90% upper and lower bounds, using 100 resamples of the acqqa data.
Green solid line and filled triangles — modelled using 2071-2100 RCM data (acqqb).
Green dashed line — median modelled, using 100 resamples of the acqqb data.
Green dotted lines — 90% upper and lower bounds, using 100 resamples of the acqqb data.

6 INTERPRETATION FOR USERS AND POLICY-MAKERS

6.1 Introduction

This section of the report brings together the results from each of the scenarios presented in Section 5 to provide an overview of more relevance to the potential users of these research results. The impacts on flood flows are compared across scenario methods to draw out key messages about the modelled responses to climate change in this project. This Section briefly discusses absolute changes in flows, particularly where the percentage changes are high and, through the application of simple stage-discharge relationships, potential changes in flow levels. There is also a discussion of responses due to catchment characteristics.

6.2 Comparison across methods

The seasonal distribution of rainfall, and the sequence of wet and dry periods over a range of time scales, is of critical importance in determining the impact on flood frequency. Throughout the UK the dominant impact of the climate change scenarios used in this study is to impose a greater seasonality on the hydrological year. The ability to realistically model replenishment of soil moisture following hot, dry summers, as shown in Section 3.2.3, is therefore important for minimising the uncertainty in the calculated percentage changes in flood frequency due to the hydrological modelling.

Differences in flood frequency between the UKCIP02 scenarios and those from the RCM may reflect differences between the two rainfall series for the baseline period as well as changes in rainfall patterns over a range of temporal and spatial scales. For example, the RCM produces wetter 1- and 5- day cumulated catchment rainfalls in spring and autumn than the observed / perturbed record. Geographic variation in changes in longer duration rainfall with return period may also be a factor. Increases in flood frequency using RCM data for the larger catchments of the Thames (39001) and Ouse (27009) may reflect changes in frequency of n-day rainfall where longer durations show a bigger increase for a given return period. Such changes in multi-day rainfall events over the UK between 1961 and 2000 have been investigated by Fowler and Kilsby (2003) and show little change for 1- and 2- day rainfalls, but significant increases in 5- and 10-day annual maxima during the 1990s over Scotland and Northern England. Decreases in RCM flood frequency for both Severn catchments (54001 and 54057) may reflect other influences such as rain shadow effects from mountains in the headwaters of the catchment. Central Wales also shows (UKCIP02) larger decreases in spring and autumn rainfall than areas around, as well as decreases in daily rainfall frequency in these seasons.

For the Thames, the increase in flood frequency under the RCM scenario, compared with very little change under UKCIP02, is also partly a result of the more extreme rainfalls occurring in January and February, rather than December, particularly when these fall within a wetter winter following a not-spectacularly dry autumn, i.e. these events have more impact when there is no soil moisture deficit to be replenished.

The impact on urban catchments (the example here being the Rea at Calthorpe - 28039) depends on the seasonality of the flood events in baseline period. High return period floods in summer from convective rainfall may decrease but there may be an increase in the flood frequency curve at lower return periods from the average increase in winter rainfall, coupled with the increased intensity of winter rainfall. The increased winter rainfall has a direct impact on impermeable catchments (74001) as there is no accumulation of large soil moisture deficits during the summer. Therefore the flood regimes of these catchments are highly susceptible to increases in rainfall, as is seen in the increase in flood peaks for all methods, time-slices and return periods. In contrast, the impacts on permeable catchments (42012) are highly dependent on precise sequencing of wet and dry summers, autumns and winters.

The impacts discussed above are all highlighted in the results from the rainfall resampling which demonstrate that it would only take a slightly different sequencing of events to push some catchments into rather higher percentage changes in flood frequency. The maximum values in Table 5.6 show that highly urbanised catchments (e.g. 28039), groundwater catchments (e.g. 42012), and catchments in the north west (e.g. 74001) may be generally more susceptible to changes in climate of this nature.

From the statistically downscaled scenarios it is possible to look at impacts due to different emission scenarios. The B2 scenario shows a larger impact than the A2 as there is less of a decrease in summer rainfall and less summer warming under this scenario, therefore the increases in winter rainfall have more of an effect.

Many of these key points can be seen in Table 6.1. This shows a summary of the impacts across scenarios for the ten catchments for the 2080s for the 20-year return period flow. The gaps occur as all scenario methods could not be applied to all catchments, for example the statistical downscaling was only undertaken for the Ouse (27009) and the Severn at Bewdley (54001), and the resampling technique was only applied to the six PDM catchments. Equivalent tables for the 2050s and for the 50-year return period flows are given in the Appendix (Section A6).

Table 6.1 Summary of the percentage changes in the 20-year return period flows for the 2080s.

Catchment	UKCIP02				Resampling UKCIP		SDSM		RCM	Resampling RCM	
	Low	Med Low	Med High	High	Min	Max	B2	A2	A2	Min	Max
27009	-2.2	-3.6	-3.8	-4.2			7.0	-3.8	10.7		
28039	6.4	-2.5	-2.6	-5.5	-28.5	**20.5**			-14.0	-35.6	**38.6**
30004	-3.5	-5.6	-9.9	-13.1	-28.3	7.1			-12.0	-30.0	**29.7**
39001	-1.6	-1.6	0.0	2.8					16.7		
40005	-0.5	-1.5	-3.9	-3.7	-24.7	9.4			-13.8	-38.4	**20.3**
42012	2.5	3.2	4.6	5.0	-8.4	**29.6**			3.5	-73.0	**474.3**
54001	-2.1	-2.7	-5.4	-6.7			10.4	6.8	-19.4		
54057	1.2	1.2	3.0	4.4					-14.5		
74001	6.6	8.3	16.1	**21.9**	-13.0	**30.4**			16.3	-2.9	**39.6**
96001	0.1	-0.9	-3.1	-4.6	-22.1	16.0			-8.9	-28.7	**30.6**

The CFMP catchments used in this study are the Severn at Haw Bridge (54057) and the Beult at Stile Bridge (40005), within the Medway. The Severn shows an increase in flood flows under the UKCIP02, but a decrease using the RCM data. By comparison with the impacts for the upper Severn (54001) however, larger increases might be expected for the Severn at Haw Bridge under the statistical downscaling method, particularly the B2 scenario. These catchments differ in their impacts as the larger Severn catchments includes significant areas of the Midlands, where the climate change scenarios suggest somewhat larger increases in winter rainfall than they do for central Wales.

For the Beult at Stile Bridge (40005) all scenarios show decreases in flood flows. This change is driven fundamentally by the location of the catchment in the south-east, where the scenarios suggest the greatest warming and drying. It is only by looking at the maximum change from the resampled data that any increase in flood flows is seen for this catchment.

6.3 Absolute changes and changes in levels

Simply analysing percentage changes in flows can be misleading, particularly when the baseline flows are low. The Anton (42012) has a current 20-year flow of just 1.0 m^3s^{-1}, under the minimum (5%) resampled baseline, so even the 500% increase simulated under the maximum (95%) resampled scenario equates to an increase in flows of just 4.8 m^3s^{-1}. For some of the larger catchments this relationship is, of course reversed. The absolute changes for the six PDM catchments under the resampled scenarios are summarised in Table 5.8.

Of course, the impacts on flood flows provide an indication of change in flood frequency, but do not tell us of possible changes in flood risk. To gain an understanding of this impact a simple stage-discharge relationship has been applied to the flows in the Anton (42012) to assess the potential change in river flow levels. The 500% increase in flows discussed above means a 420 mm increase in the current 20-year level of 212 mm.

6.4 Catchment intercomparison

As part of the analysis of these results, it was hoped that critical responses to climate change could be drawn out through comparison of pairs of catchments. For example, the effects of catchment location might be examined by comparing catchments with similar properties, such as size and geology, in different parts of the country. This analysis proved difficult for several reasons. First, there are too few catchments in the study to allow this type of analysis and second, there are too many variables changing at the same time.

In order to try to extract any relationships between catchment type and the impact of climate change on flooding, various measures of the impact were plotted against various catchment properties (see Section A5 and Figure A5.1 of the Appendix for the full comparison). Most plots do not show any clear dependencies, particularly when using measures of climate change impact based on use of RCM data. However, a small number of plots may hint at the existence of some sort of dependence, and these are discussed below. Note that this is a preliminary exploration of a methodology that may eventually lead to a regionalisation of flood frequency changes, but that the sample size used here is too small to elicit truly reliable relationships at this stage.

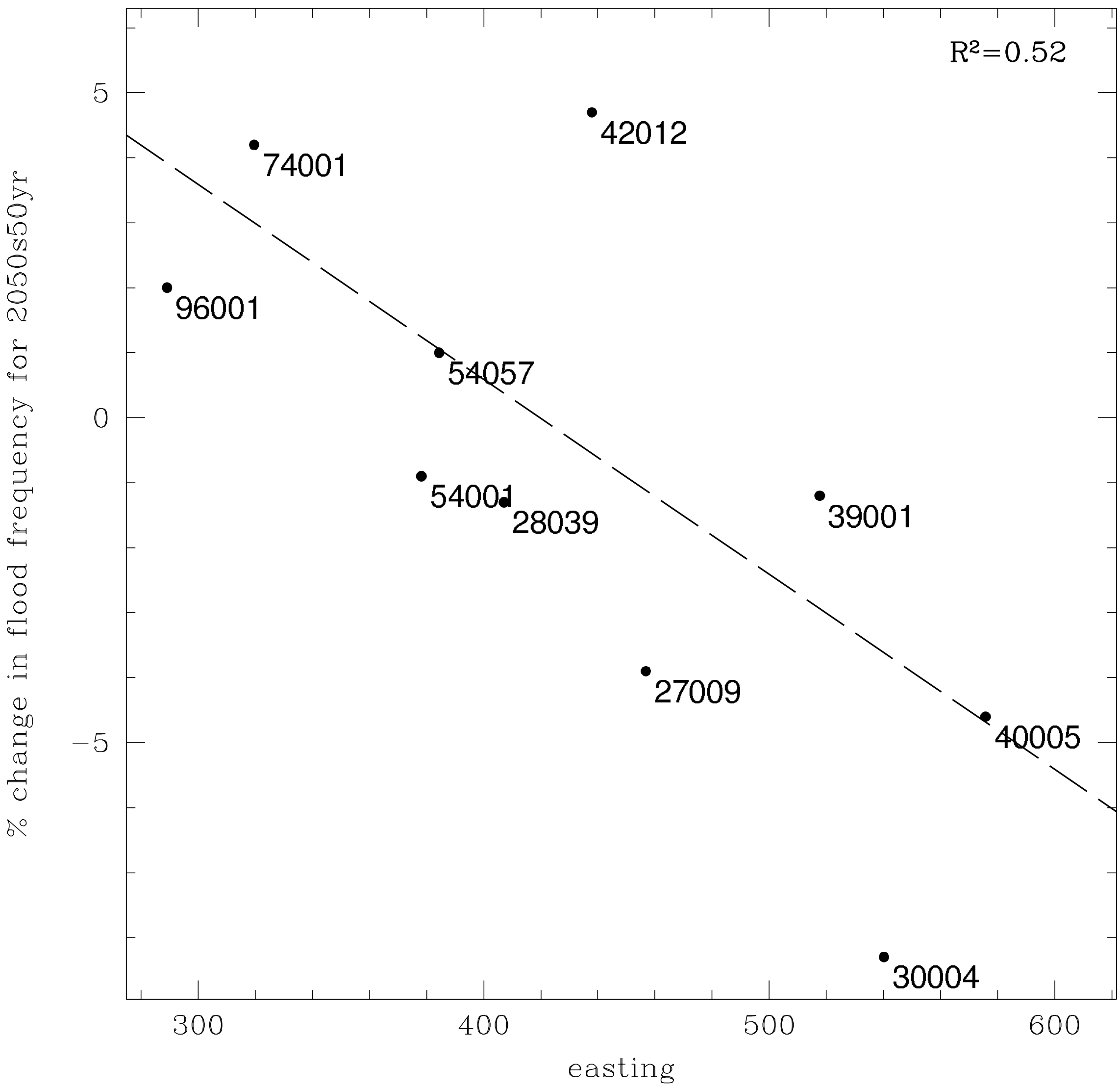


Figure 6.1 Plot of the 2050s impact on the 50-yr return period flood peak versus easting, illustrating a possible dependence between the two (R^2=0.52).

The first possible relationship is in terms of Easting (of the catchment outlet), for higher return period floods. As shown in Figure 6.1, it is suggested that more westerly catchments (lower easting value) may experience a greater impact than more easterly catchments. For the 2050s at the 50-year return period, the best fit line for this relationship has an R^2 of 0.52. This reduces to 0.32 for the impact at the 20-year return period. The corresponding values for the impact in the 2080s are 0.30 and 0.22.

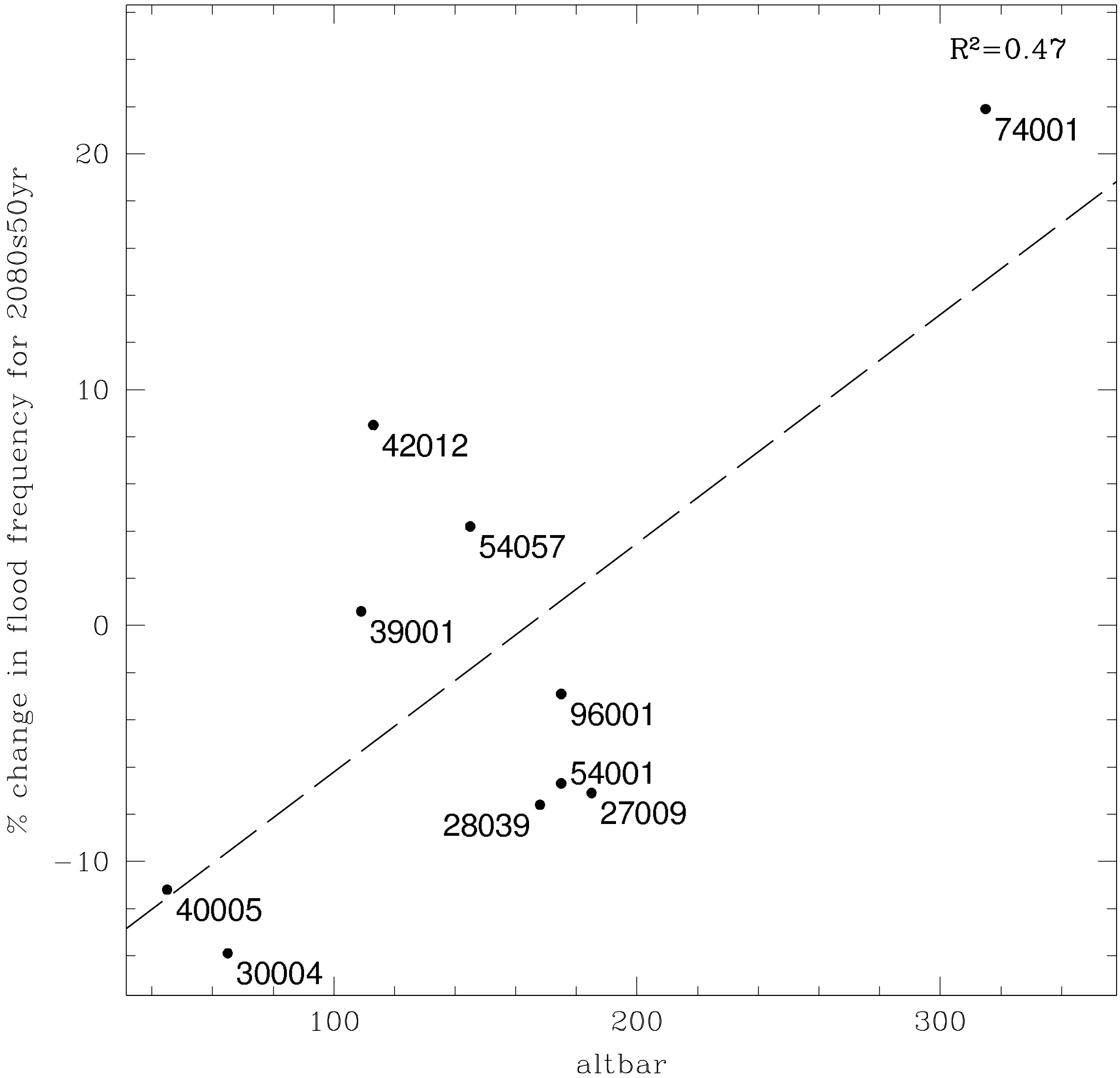


Figure 6.2 Plot of the 2080s impact on the 50-yr return period flood peak versus mean catchment altitude, illustrating a possible dependence between the two (R^2=0.47).

The second possible relationship is in terms of mean catchment altitude (altbar) for higher return period floods. As shown in Figure 6.2, it is suggested that more low-lying catchments may experience a lesser impact than catchments with more high-ground within them. For the 2080s at the 50 or 20-year return period, the best fit line for this relationship has an R^2 of 0.47. This reduces to 0.21 for the impact at the 5-year return period. The corresponding values for the impact in the 2050s are 0.35, 0.40 and 0.15.

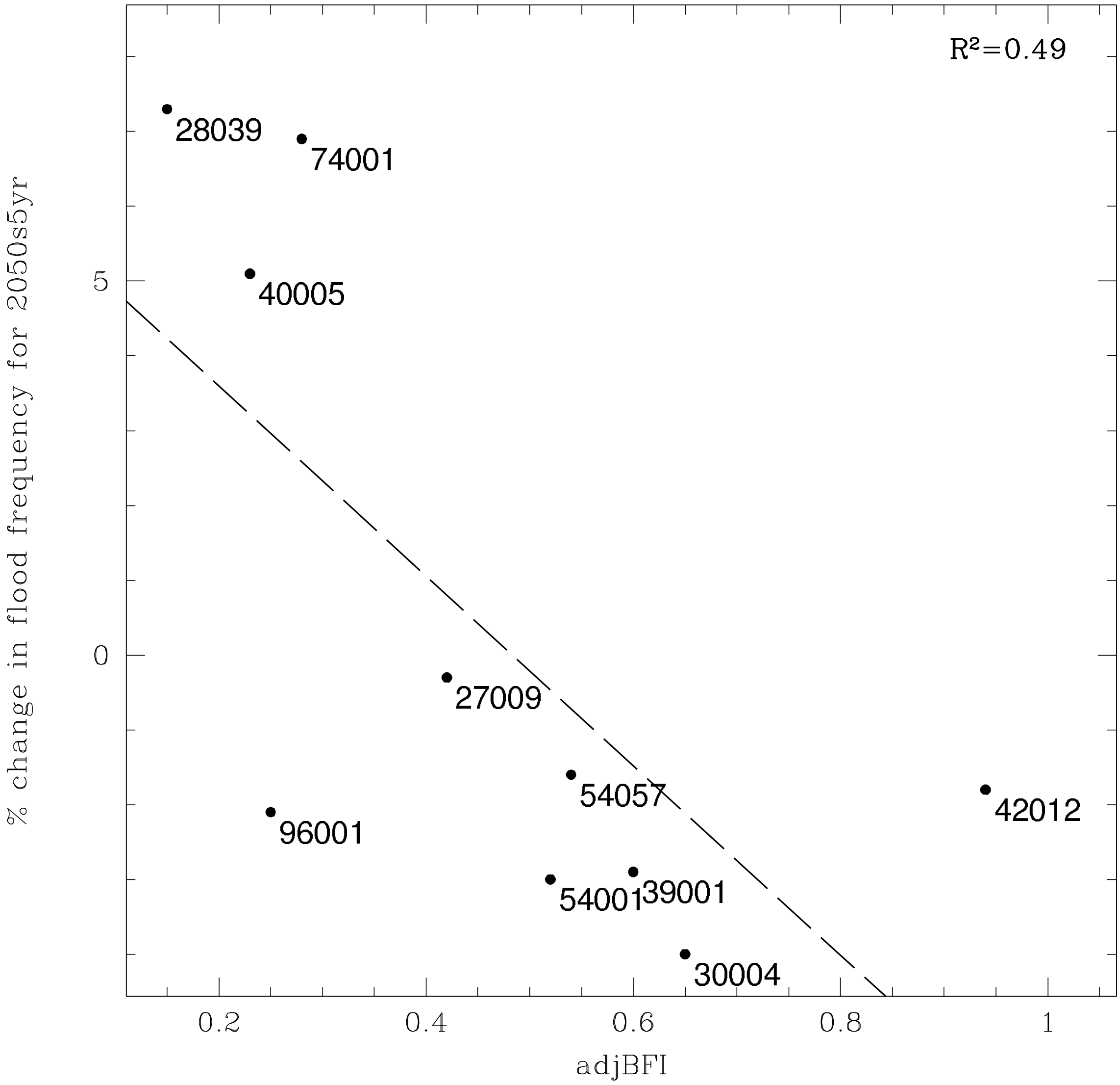


Figure 6.3 Plot of the 2050s impact on the 5-yr return period flood peak versus an adjusted baseflow measure, illustrating a possible dependence between the two (R^2=0.49).

The third possible relationship is in terms of the adjusted baseflow measure (adjBFI) for lower return period floods. As shown in Figure 6.3, it is suggested that catchments with a lower effective baseflow (either through a low BFI or, possibly, a high amount of urbanisation) may experience a greater impact than catchments with a higher baseflow. For the 2050s at the 5-year return period, the best fit line for this relationship has an R^2 of 0.49. Initially this relationship does not appear to hold at higher return periods, but this appears to be due to the somewhat anomalous behaviour of just one catchment; the Anton (42012). This catchment has an extremely high baseflow (BFI = 0.96), but shows large increases in flood peaks at higher return periods. The R^2 values, at the 5 and 20-year return period, when catchment 42012 is excluded from the fit are 0.67 and 0.50 respectively. The explanation for this could either lie in a real susceptibility of catchments with such a high groundwater element, or be an artefact of the modelling.

It is important to say that none of these suggested relationships between catchment properties and the impact of climate change on flooding are necessarily direct 'cause and effect' relationships. They could each be surrogates for something else, or for each other, and so the same relationships may not hold in other locations. For example, in the UK, given the geological gradient across the country, more westerly catchments (lower easting) are also more likely to have a lower BFI and a higher mean altitude than those in the south and east. Thus it seems that location may be the dominant factor in determining the impact of climate change on flooding, but whether this is due to the spatial pattern of climate change or to the partial dependence of catchment type on location (or both) is difficult to distinguish given the relatively small number of catchments studied.

6.5 Uncertainty

The results presented in this report should be interpreted in light of the uncertainty in a climate change impact study. This uncertainty comes from a variety of sources:

- future emissions of greenhouse gases;
- the representation of physical processes within the global climate model (GCM);
- natural climate variability;
- scenario development (downscaling);
- hydrological impact model (model structure and parameterisation).

Some of these sources of uncertainty have, to a degree, been addressed in the current study. Four of the IPCC SRES emissions scenarios (IPCC 2000) have been used with the UKCIP02 data, but these are actually scaled from the A2 ensemble mean, so that the spatial patterns of change are the same under each emissions scenario. Two of the IPCC SRES emissions scenarios have been used in conjunction with the statistical downscaling method for two catchments. In this case the B2 scenario is actually modelled rather than scaled from the A2 scenario, and behaves somewhat differently to how a scaled A2 would be expected to behave. The rainfall resampling technique has considered an aspect of natural climate variability. Three downscaling techniques (adjusted baseline, statistical and dynamic) have been used but there are other statistical downscaling methods that could be explored and the output from alternative RCMs could also be used. The hydrological model uncertainty due to calibration has been discussed and quantified, but other sources of hydrological uncertainty, such as the model structure, or the flood estimation from the flow time series have not. Also, the effect of this hydrological uncertainty on the range of impacts due to climate change has not been addressed.

Other sources of uncertainty have not been addressed. The output from only one GCM has been used, and only the UKCIP02 scenarios represent any use of ensembles of results from an individual model (they were derived as the mean of three ensemble runs from the Hadley Centre model). It is worth noting that Jenkins and Lowe (2003) suggest that the relative uncertainty due to the range of GCM simulations is greater than either emissions uncertainty or natural variability. Indeed the current estimate is that the range of change in global-mean precipitation is ±70% depending on the choice of GCM, compared with ±25% for the choice of emissions scenario (Jenkins and Lowe 2003).

7 CONCLUSIONS

7.1 Summary

The results of this study show the impacts of climate change on flood frequency in the study catchments, under the selected scenarios, to be considerably lower than those previously determined (Reynard *et al.* 1998, 2001). This is determined primarily by the fact that the current version of the Hadley Centre GCM, driving the climate changes, produces significantly drier and warmer summers and autumns, so that, despite the wetter winters (on average), flood frequencies in many catchments decrease. This does not necessarily apply to those catchments that are more responsive, i.e. steep-sided, small or urban catchments, but even in these the precise response is determined by the spatial and temporal detail of the climate changes.

For each of the catchments a range of climate impacts has been shown. In only a few of these are there obvious tendencies towards either a decrease (30004 and 40005) or an increase (74001 and 42012). All other catchments present a range of change, both positive and negative.

A wider range of impact was presented using resampled rainfall data, but even with these data sources the maximum impact from UKCIP02 scenarios was only above 20% for three of the catchments by the 2080s. In general, the range of impacts in this study is wide, across catchments, time slices and scenarios, but usually below the 20% increase. These results suggest that, under these scenarios, the current 20% sensitivity band appears appropriate as a precautionary response to the uncertainty of future climate change impacts on flood flows. To a very large degree this conclusion is determined by the dry and warm nature of the Hadley Centre model used to generate all the scenarios, and using other GCMs will undoubtedly produce different results.

The suggested relationships between catchment properties and the impact of climate change on flooding are not necessarily direct ‘cause and effect’ relationships. They could each be surrogates for something else, or for each other, and so the same relationships may not hold in other locations. For example, in the UK, given the geological gradient across the country, more westerly catchments are also more likely to have a lower BFI and a higher mean altitude. Thus it seems that location may be the dominant factor in determining the impact of climate change on flooding, but whether this is due to the spatial pattern of climate change or to the partial dependence of catchment type on location (or both) is difficult to distinguish given the relatively small number of catchments studied.

Finally, it is important to consider all the various sources of uncertainty involved in climate change impact studies, and how this uncertainty impacts on the decision that the research informs (Willows and Connell 2003). This research has, to a degree, addressed some of these uncertainties, but not all.

7.2 Development of a strategy for research into climate change impacts on flooding

The modelling methodology developed for this project provides the framework for future developments. Scenarios of climate change will continue to be updated, from a range of GCMs and RCMs and from improved downscaling techniques and these will need to be applied to assess their impact of flood flows. It is important that studies such as these sample from as much of the uncertainty as is possible, and it is particularly vital to consider those areas where uncertainty is large enough to influence the decision or development of policy that the science has been designed to inform. This is particularly the case for using the outputs from more than one GCM.

The results from this project are finding a higher degree of spatial variability and catchment response than was initially anticipated. To further develop this, the need to extend the basic research to more catchments remains. This variability has been additionally borne out by the ongoing work under the Hadley Centre Annex 15a project, directly using the RCM data for 15 other UK catchments. The need to expand the spatial representation of these impacts will also need to do dovetail with FD2106 (National system for flood frequency estimation using continuous flow simulation) funded under the BSM Theme of the joint program, which can provide a method for estimating impacts across the country using hydrological models with generalised parameters, and quantified uncertainty, for ungauged sites.

These impact analyses need also to move on from just changes in peak flows and durations to the wider flood risk measures of the impacts on future timing of flood peaks, flood levels and extents through linking hydrological with hydraulic models. Estuaries are at risk from flooding both from high river flows and from coastal variables such as sea surges and waves. The new RCM and shelf-seas model outputs arising from UKCIPnext may be used to estimate the joint probability of coastal and river flooding in the fluvial-tidal river reach.

Climate change over the next 100 years cannot be treated as separate from other environmental change. Changes in land use need to be modelled in combination with changes in climate, therefore requiring the alignment of the science in this type of study with the research in projects such FD2114 within the Defra / EA joint R&D programme.

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APPENDIX: RESULTS IN FULL

This appendix contains the full set of all catchment results under all the climate change scenarios that have been applied in the analysis. It is divided along the lines of the Results section in the main report, i.e. according to the scenario-type. The first section describes the impacts under the UKCIP02 scenarios, the second describes the results using the statistically downscaled rainfall series and the third section describes the results from applying the rainfall data from the Hadley Centre Regional Climate Model. The fourth section presents the full set of resampling results, while the fifth presents the full set of graphs looking for dependence between climate change impact on flood frequency and various catchment properties. The sixth section presents tables summarising the impact for each catchment under the various scenarios and methods, for the 2050s and 2080s and at the 20 and 50-year return period, in terms of percentage changes. The seventh section presents some of the percentage changes given in section A6 in terms of absolute changes to flows, in m^3s^{-1}.

A1 UKCIP02

Key for figures in this section:
Black dotted line and open circles — from observed flows.
Black dashed line and filled squares — modelled using observed rainfall.
Red solid line and filled triangles — modelled under UKCIP02 high emissions scenario.
Orange solid line and filled triangles — modelled under UKCIP02 medium-high emissions scenario.
Green solid line and filled triangles — modelled under UKCIP02 medium-low emissions scenario.
Blue solid line and filled triangles — modelled under UKCIP02 low emissions scenario.

CLASSIC

Table A1.1

Catchment	Time-slice	Scenario	Return period (years)								
			1	2	5	10	15	20	25	30	50
27009	2050s	High	-1.0	0.2	-0.3	-1.5	-2.4	-3.2	-3.7	-4.2	-5.6
		M-High	-1.2	0.0	-0.3	-1.1	-1.7	-2.2	-2.6	-2.9	-3.9
		M-Low	-1.0	0.0	-0.4	-1.2	-1.8	-2.3	-2.6	-3.0	-4.0
		Low	-0.9	-0.1	-0.4	-1.2	-1.8	-2.3	-2.7	-3.0	-3.9
	2080s	High	5.4	6.9	5.6	3.5	2.0	0.9	0.0	-0.7	-2.8
		M-High	0.3	1.6	0.4	-1.4	-2.1	-3.8	-4.6	-5.2	-7.1
		M-Low	-0.9	0.3	-0.4	-1.8	-2.8	-3.6	-4.2	-4.8	-6.2
		Low	-1.2	0.0	-0.3	-1.1	-1.7	-2.2	-2.6	-2.9	-3.9
39001	2050s	High	-10.8	-5.9	-3.0	-2.1	-1.8	-1.7	-1.6	-1.6	-1.5
		M-High	-10.1	-5.6	-2.9	-1.9	-1.6	-1.4	-1.3	-1.3	-1.2
		M-Low	-9.6	-5.4	-2.7	-1.6	-1.2	-1.0	-0.8	-0.7	-0.5
		Low	-9.0	-5.2	-2.4	-1.2	-0.6	-0.3	0.0	0.0	0.4
	2080s	High	-12.9	-6.0	-1.0	-1.3	-2.3	2.8	3.2	3.5	4.2
		M-High	-12.6	-6.5	-2.5	-0.9	-0.3	0.0	0.2	0.3	0.6
		M-Low	-11.2	-6.2	-3.1	-2.1	-1.8	-1.6	-1.5	-1.4	-1.4
		Low	-10.4	-5.8	-3.0	-2.1	-1.8	-1.6	-1.6	-1.5	-1.4
54001	2050s	High	-8.3	-5.5	-3.4	-2.5	-2.2	-2.0	-1.9	-1.8	-1.6
		M-High	-7.6	-5.1	-3.0	-2.1	-1.7	-1.4	-1.3	-1.2	-0.9
		M-Low	-7.1	-4.6	-2.8	-2.0	-1.7	-1.5	-1.4	-1.3	-1.1
		Low	-6.3	-4.1	-2.5	-1.8	-1.5	-1.4	-1.3	-1.3	-1.2
	2080s	High	-9.1	-5.9	-5.0	-5.5	-6.2	-6.7	-7.1	-7.5	-8.7
		M-High	-9.2	-6.1	-4.7	-4.8	-5.1	-5.4	-5.7	-6.0	-6.7
		M-Low	-8.5	-5.8	-3.8	-3.1	-2.9	-2.7	-2.7	-2.7	-2.6
		Low	-7.8	-5.3	-3.4	-2.6	-2.3	-2.1	-2.0	-1.9	-1.8
54057	2050s	High	-9.7	-5.0	-1.6	-0.2	0.4	0.7	0.9	1.0	1.4
		M-High	-8.7	-4.5	-1.6	-0.4	0.1	0.4	0.6	0.7	1.0
		M-Low	-8.0	-4.2	-1.5	-0.4	0.0	0.3	0.5	0.6	0.9
		Low	-7.0	-3.6	-1.3	-0.4	0.0	0.1	0.3	0.4	0.6
	2080s	High	-12.5	-5.3	0.1	2.6	3.7	4.4	4.8	5.1	5.9
		M-High	-11.5	-5.2	-0.5	1.5	2.4	3.0	3.3	3.6	4.2
		M-Low	-9.5	-4.5	-1.0	0.3	1.0	1.2	1.3	1.5	1.8
		Low	-8.6	-4.1	-1.0	0.3	1.0	1.2	1.3	1.5	1.8

PDM

Table A1.2

Catchment	Time-slice	Scenario	Return period (years)								
			1	2	5	10	15	20	25	30	50
28039	2050s	High	4.4	7.3	6.4	3.7	1.5	-0.2	-1.6	-2.7	-6.2
		M-High	3.8	7.0	7.3	5.7	4.3	3.1	2.1	1.2	-1.3
		M-Low	1.5	5.5	8.1	8.7	8.6	8.4	8.2	8.0	7.2
		Low	3.1	7.2	9.5	9.7	9.4	9.1	8.7	8.4	7.2
	2080s	High	-1.8	-0.4	-1.2	-3.0	-4.4	-5.5	-6.4	-7.2	-9.5
		M-High	1.5	3.6	2.8	0.6	-1.2	-2.6	-3.7	-4.7	-7.6
		M-Low	4.1	6.6	5.1	1.9	-0.6	-2.5	-4.0	-5.3	-9.1
		Low	4.7	8.6	9.7	8.6	7.4	6.4	5.5	4.8	2.4
30004	2050s	High	0.3	0.2	-1.2	-2.8	-3.9	-4.7	-5.4	-5.9	-7.5
		M-High	-2.5	-2.9	-4.0	-5.1	-5.9	-6.4	-6.9	-7.2	-8.3
		M-Low	-2.1	-2.3	-3.1	-4.1	-4.7	-5.2	-5.6	-5.9	-6.8
		Low	-1.3	-1.3	-1.9	-2.6	-3.1	-3.5	-3.8	-4.1	-4.8
	2080s	High	-1.7	-3.3	-6.7	-9.8	-11.7	-13.1	-14.2	-15.1	-17.5
		M-High	-0.9	-1.8	-4.5	-7.1	-8.7	-9.9	-10.9	-11.7	-13.9
		M-Low	0.1	-0.1	-1.7	-3.5	-4.7	-5.6	-6.3	-6.8	-8.5
		Low	0.5	0.6	-0.5	-1.9	-2.8	-3.5	-4.1	-4.6	-5.9
40005	2050s	High	6.9	7.5	5.3	2.4	0.4	-1.1	-2.4	-3.4	-6.4
		M-High	5.9	6.7	5.1	2.8	1.1	-0.2	-1.2	-2.1	-4.6
		M-Low	5.5	6.3	5.0	2.9	1.5	0.3	-0.6	-1.4	-3.7
		Low	4.8	5.6	4.8	3.3	2.2	1.3	0.6	-0.1	-1.9
	2080s	High	11.1	10.8	6.5	1.7	-1.4	-3.7	-5.5	-7.0	-11.3
		M-High	9.9	9.8	5.8	1.3	-1.7	-3.9	-5.7	-7.1	-11.2
		M-Low	7.2	7.8	5.4	2.3	0.2	-1.5	-2.7	-3.9	-7.0
		Low	6.2	6.9	5.2	2.6	0.9	-0.5	-1.6	-2.5	-5.2
42012	2050s	High	-6.8	-5.0	-1.9	0.6	2.0	3.0	3.8	4.4	6.0
		M-High	-5.8	-4.4	-1.8	0.2	1.4	2.2	2.9	3.4	4.7
		M-Low	-5.2	-4.0	-1.8	0.0	1.1	1.8	2.3	2.8	4.0
		Low	-4.4	-3.5	-1.7	-0.2	0.6	1.2	1.6	2.0	2.9
	2080s	High	-8.0	-5.1	-1.0	2.0	3.8	5.0	5.9	6.6	8.6
		M-High	-7.9	-5.6	-1.7	1.5	3.3	4.6	5.5	6.3	8.5
		M-Low	-7.0	-5.2	-1.9	0.7	2.2	3.2	4.0	4.6	6.4
		Low	-6.2	-4.6	-1.9	0.4	1.6	2.5	3.2	3.7	5.2
74001	2050s	High	6.2	6.4	7.0	7.5	7.8	8.0	8.2	8.4	8.9
		M-High	6.6	7.1	6.9	6.4	5.9	5.5	5.2	5.0	4.2
		M-Low	4.4	4.8	5.2	5.4	5.5	5.6	5.7	5.7	5.8
		Low	4.0	4.4	4.5	4.4	4.3	4.1	4.0	4.0	3.7
	2080s	High	10.4	10.8	13.6	17.2	19.8	21.9	23.6	25.1	29.7
		M-High	8.3	8.2	10.1	12.7	14.6	16.1	17.4	18.5	21.9
		M-Low	6.7	6.9	7.3	7.8	8.0	8.3	8.4	8.6	9.0
		Low	6.3	6.8	6.9	6.8	6.7	6.6	6.6	6.5	6.2
96001	2050s	High	-3.3	-3.6	-2.9	-1.8	-1.1	-0.5	0.0	0.4	1.7
		M-High	-2.5	-2.7	-2.1	-1.1	-0.4	0.1	0.5	0.9	2.0
		M-Low	-2.3	-2.5	-1.9	-1.0	-0.4	0.1	0.5	0.8	1.8
		Low	-2.0	-2.1	-1.6	-0.9	-0.3	0.1	0.4	0.7	1.6
	2080s	High	-0.5	-1.9	-3.3	-4.0	-4.4	-4.6	-4.8	-5.0	-5.3
		M-High	-0.9	-2.0	-2.8	-3.0	-3.1	-3.1	-3.1	-3.0	-2.9
		M-Low	-1.1	-2.0	-2.1	-1.7	-1.3	-0.9	-0.6	-0.4	0.4
		Low	-2.6	-2.9	-2.2	-1.2	-0.4	0.1	0.6	1.0	2.2

CLASSIC

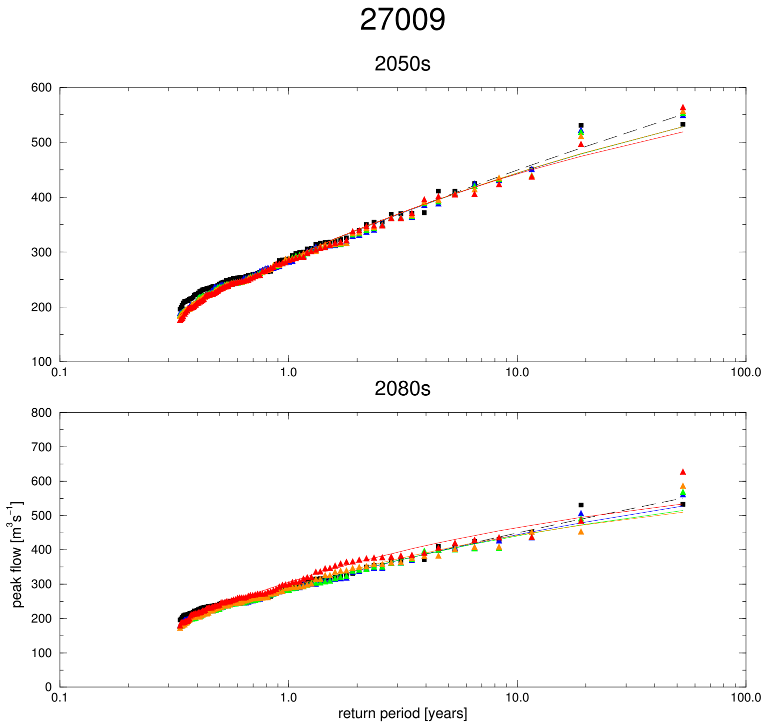


Figure A1.1

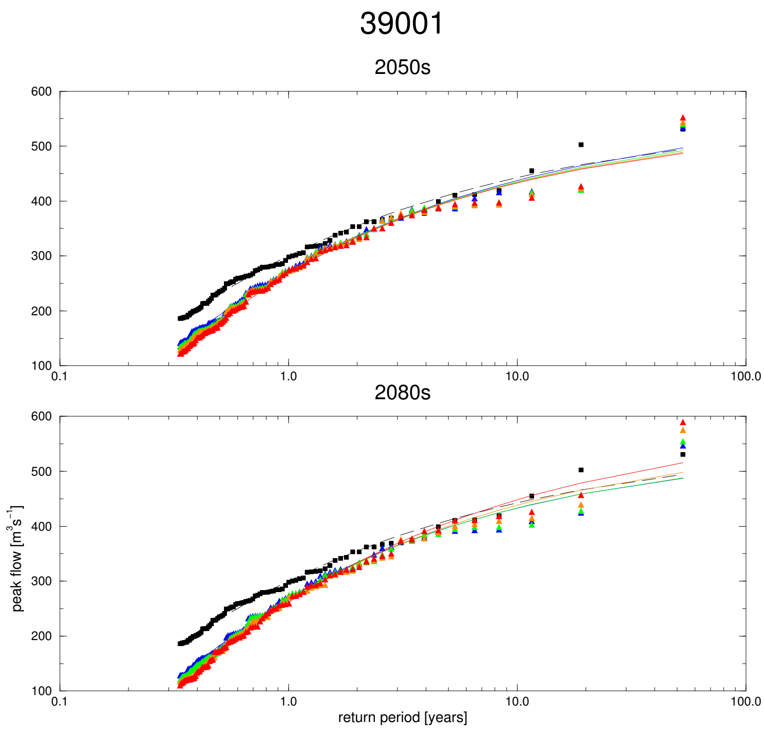
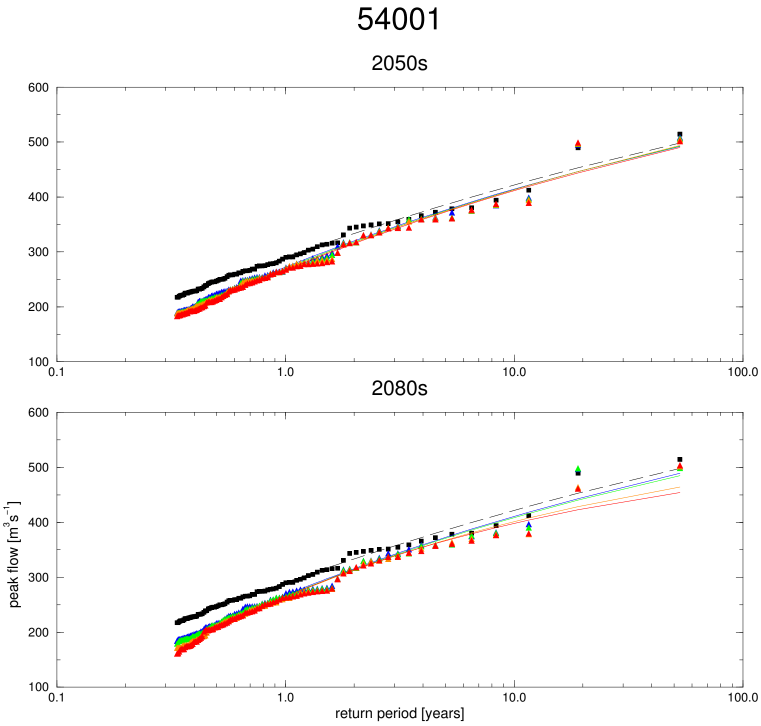


Figure A1.2



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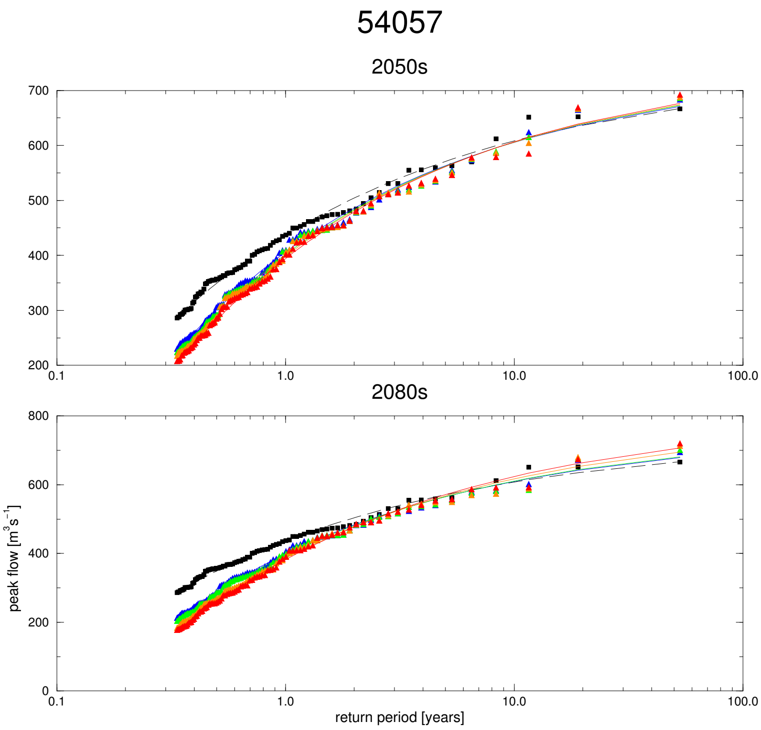

Figure A1.4

PDM

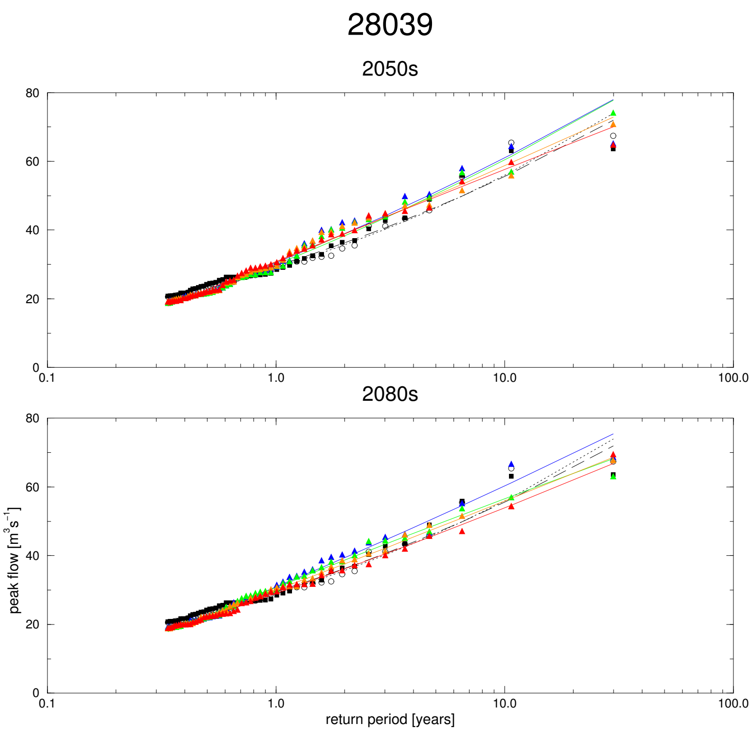

Figure A1.5

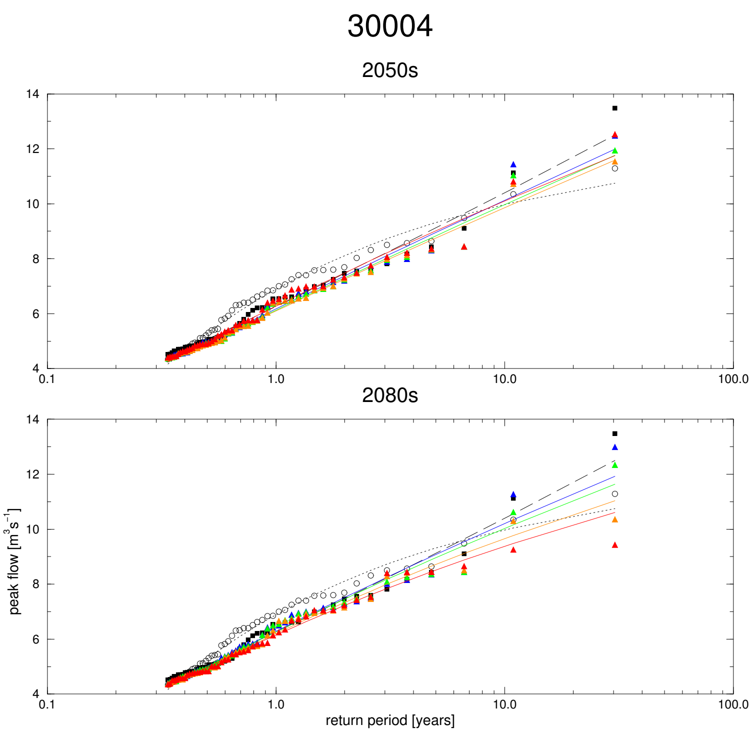

Figure A1.6

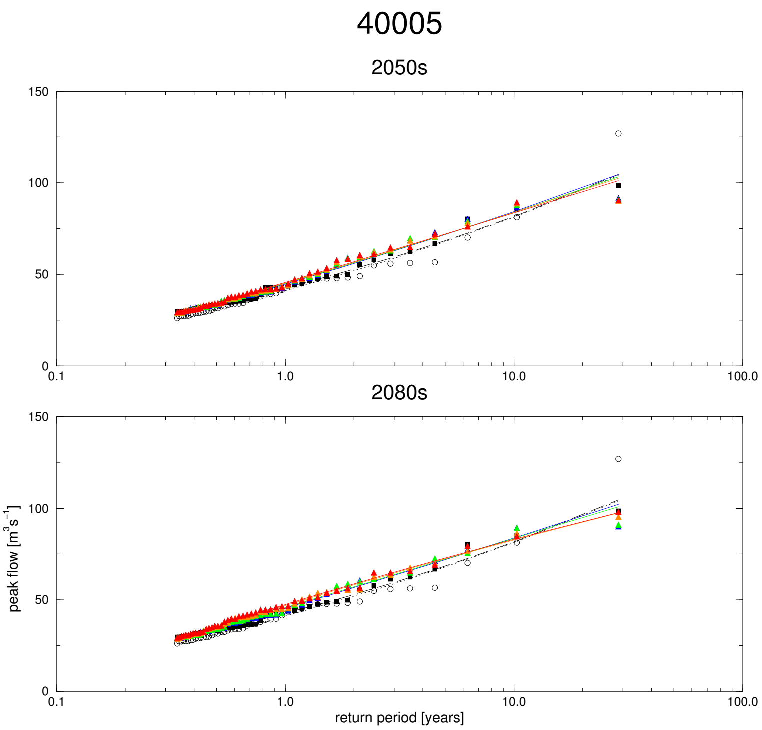

Figure A1.7

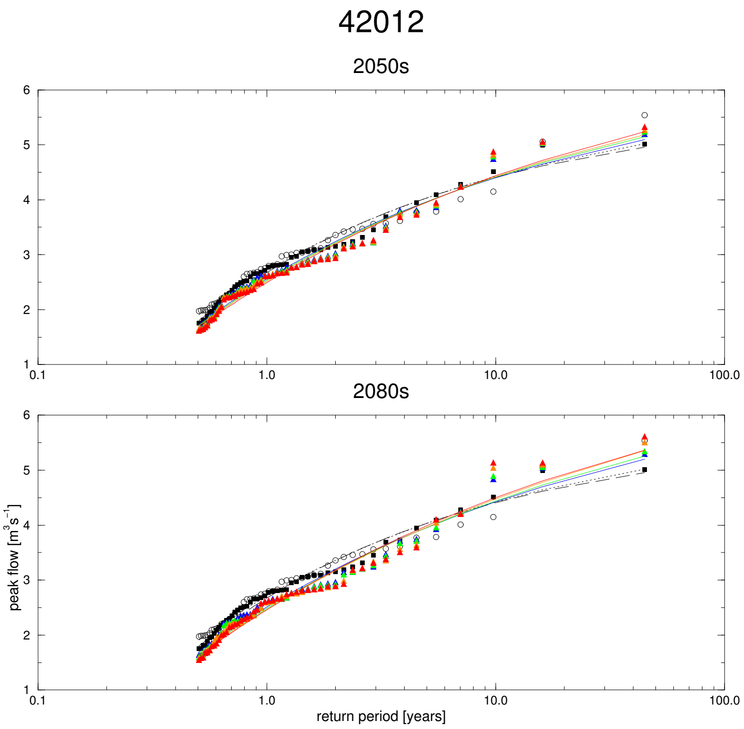

Figure A1.8

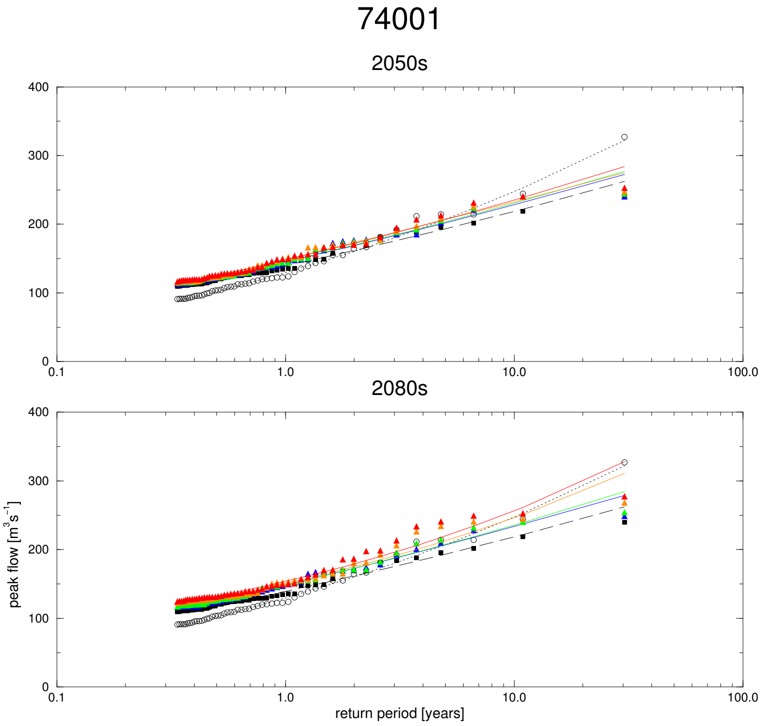

Figure A1.9

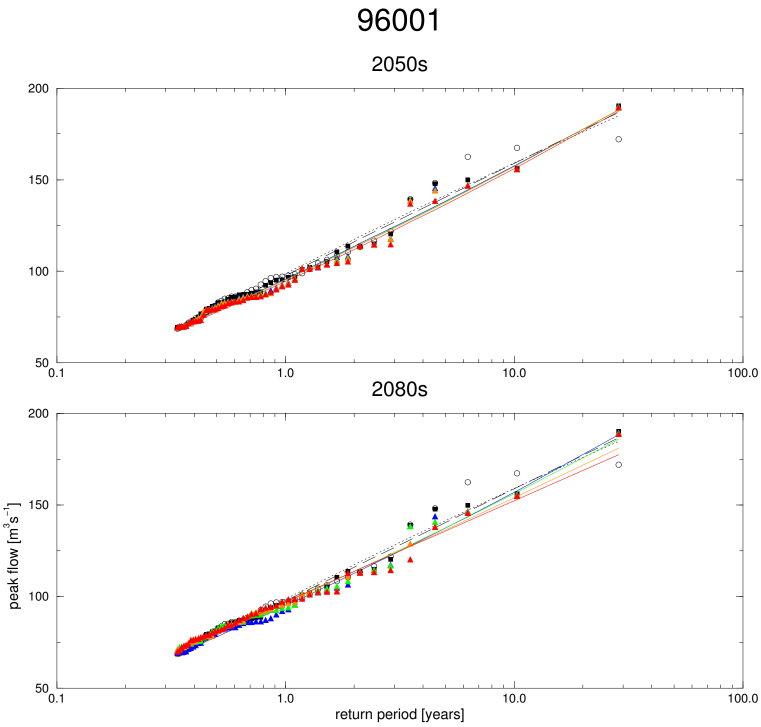

Figure A1.10

A2 Statistical downscaling

This method was only used for the two smaller catchments modelled with CLASSIC – the Ouse at Skelton (27009) and the Severn at Bewdley (54001). Figures are given for two emissions scenarios A2 (Medium-High) and B2 (Medium-Low).

Key for figures in this section:
Black dashed line and filled squares – modelled using observed rainfall 1961-1990.
Blue solid line and filled triangles – modelled using 1961-1990 SDSM data with spatial correlation.
Green solid line and filled triangles – modelled using 2041-2070 SDSM data with spatial correlation.
Red solid line and filled triangles – modelled using 2070-2099 SDSM data with spatial correlation.
Blue dotted line and open triangles – modelled using 1961-1990 single site SDSM data.

Table A2.1

Catchment	Time-slice	Scenario	Return period (years)								
			1	2	5	10	15	20	25	30	50
27009	2050s	A2	6.0	5.3	3.9	2.7	1.9	1.3	0.9	0.5	-0.5
		B2	-0.8	1.8	5.2	7.7	9.2	10.3	11.1	11.8	13.7
	2080s	A2	11.2	9.2	4.6	0.5	-2.0	-3.8	-5.1	-6.2	-9.3
		B2	3.8	5.6	6.7	7.0	7.1	7.0	7.0	6.9	6.8
54001	2050s	A2	-10.9	-8.0	-2.8	1.9	4.7	6.9	8.5	9.9	13.9
		B2	-7.7	-5.3	0.4	5.8	9.2	11.8	13.8	15.5	20.3
	2080s	A2	-3.5	0.5	3.7	5.5	6.3	6.8	7.2	7.5	8.2
		B2	2.8	5.5	7.9	9.3	9.9	10.4	10.7	10.9	11.6

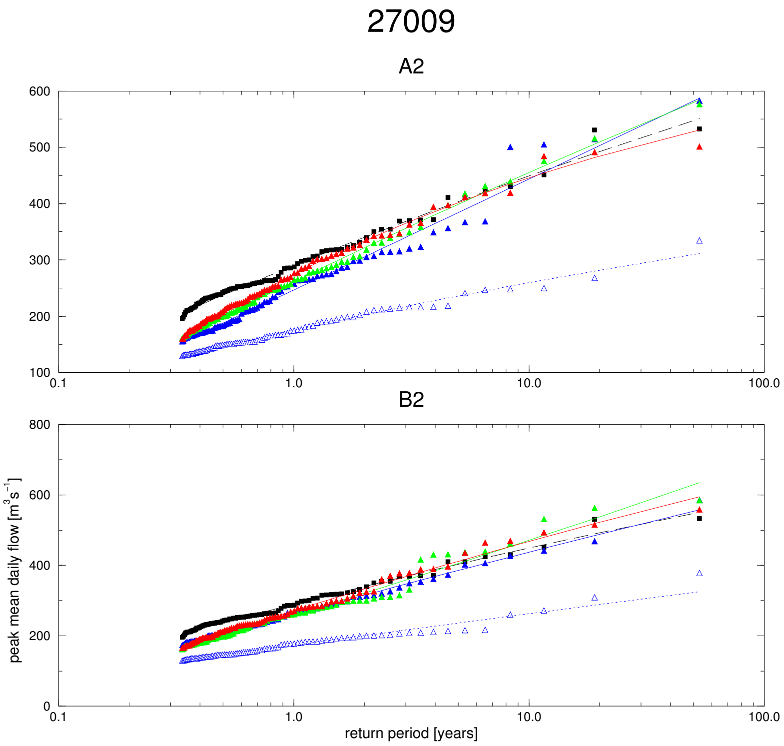

Figure A2.1

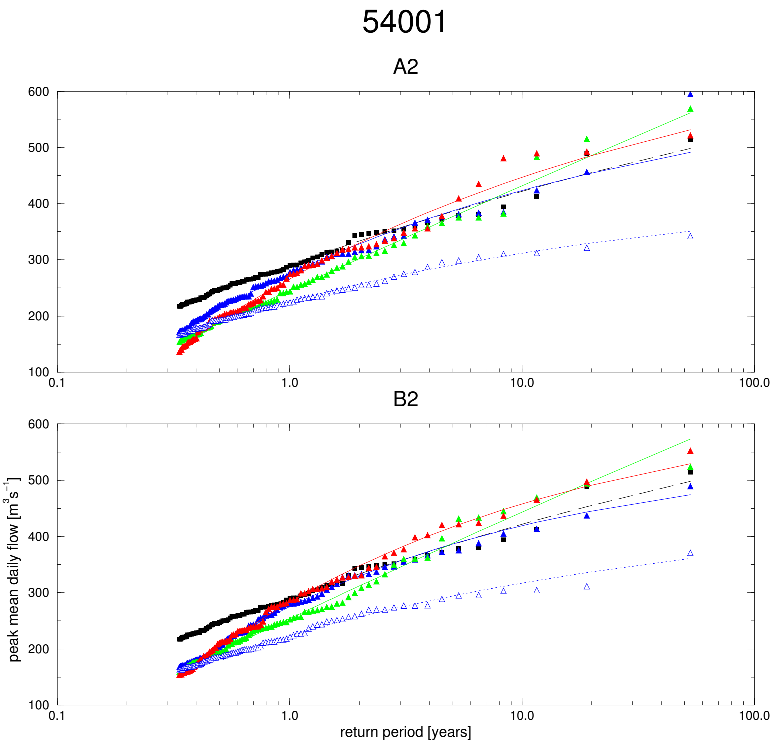

Figure A2.2

A3 Dynamic downscaling – use of RCM data

Key for figures in this section:
Black dotted line and open circles — from observed flows
Black dashed line and filled squares — modelled using observed rainfall.
Blue solid line and filled triangles — modelled using 1961-1990 RCM data (acqqa).
Green solid line and filled triangles — modelled using 2071-2100 RCM data (acqqb).

CLASSIC

Table A3.1

Catchment	Return period (years)								
	1	2	5	10	15	20	25	30	50
27009	5.0	6.8	8.7	9.7	10.3	10.7	11.0	11.2	11.7
39001	7.0	11.1	14.2	15.7	16.3	16.7	17.0	17.2	17.7
54001	-3.3	-7.0	-12.1	-15.8	-17.9	-19.4	-20.5	-21.4	-23.8
54057	-4.0	-6.0	-9.9	-11.9	-13.5	-14.5	-15.4	-16.0	-17.8

PDM

Table A3.2

Catchment	Return period (years)								
	1	2	5	10	15	20	25	30	50
28039	13.7	8.7	0.3	-6.8	-11.0	-14.0	-16.3	-18.2	-23.4
30004	6.1	2.8	-2.7	-7.3	-10.0	-12.0	-13.6	-14.8	-18.4
40005	9.3	4.8	-2.3	-8.0	-11.4	-13.8	-15.7	-17.3	-21.5
42012	12.4	13.2	10.8	7.5	5.2	3.5	2.2	1.0	-2.2
74001	17.3	17.2	16.9	16.6	16.4	16.3	16.2	16.0	15.7
96001	14.5	11.5	5.0	-0.8	-4.3	-6.9	-8.9	-10.6	-15.2

CLASSIC

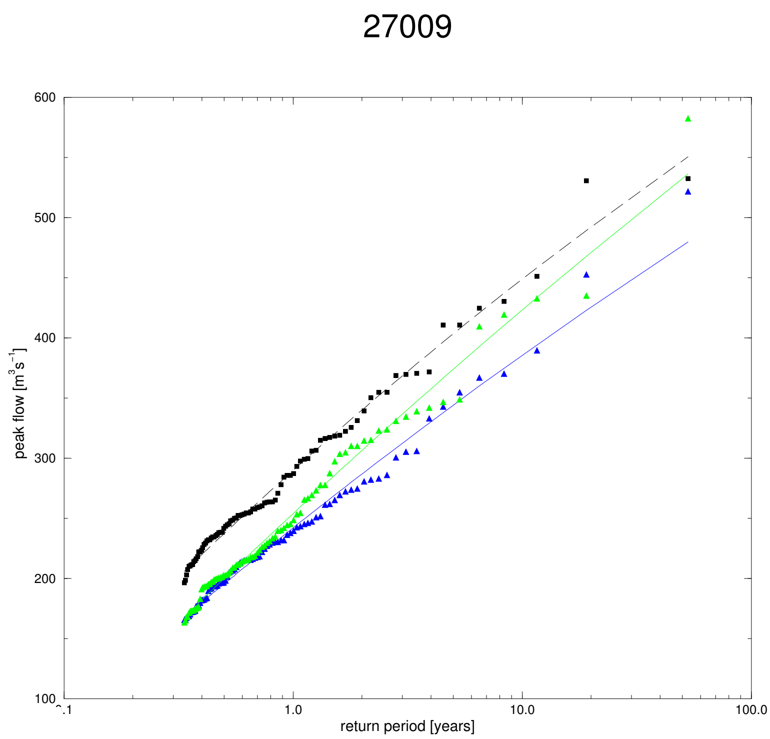

Figure A3.1

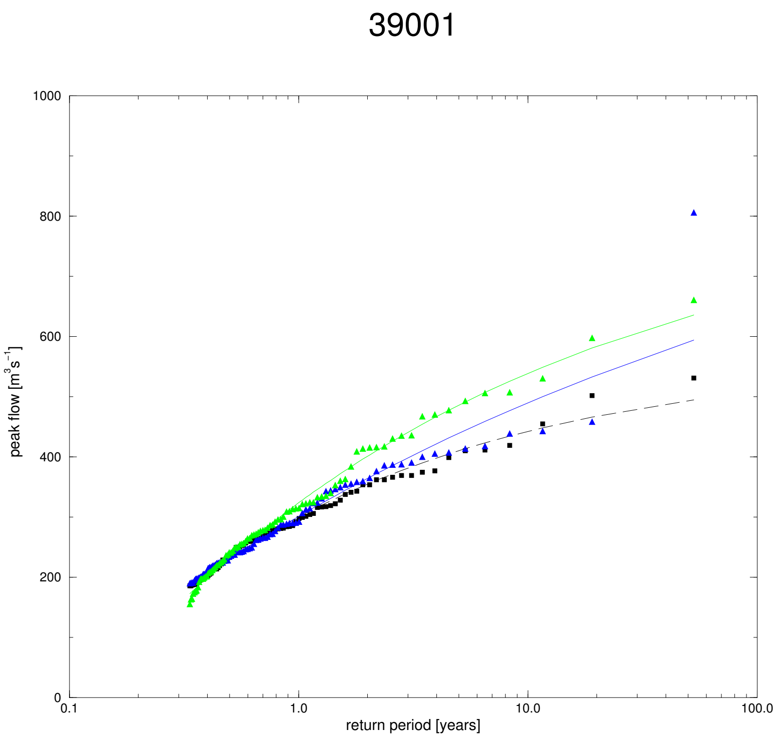

Figure A3.2

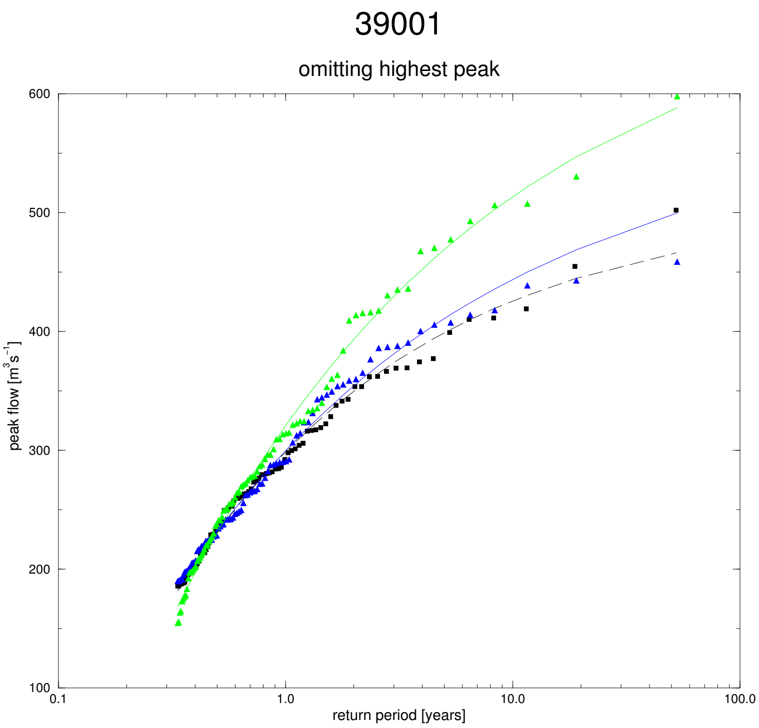
39001
omitting highest peak
600
500
400
300
200
100
peak flow [m^{3}s^{-1}]
0.1
1.0
10.0
100.0
return period [years]

Figure A3.3

54001

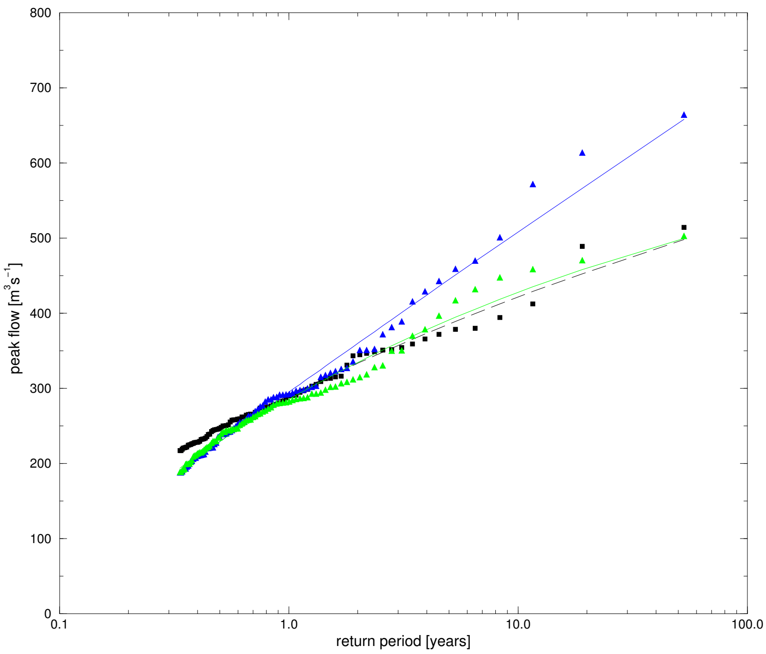

Figure A3.4

54057

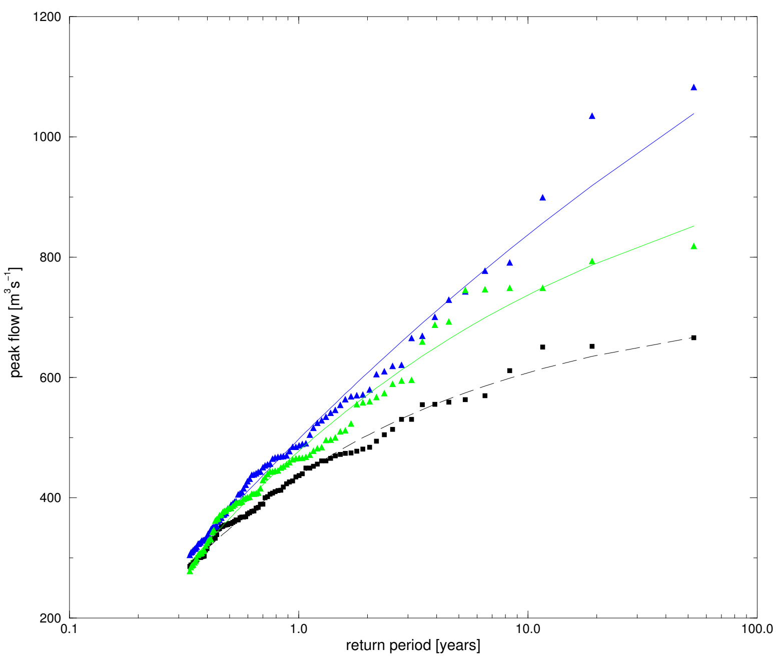

Figure A3.5

PDM

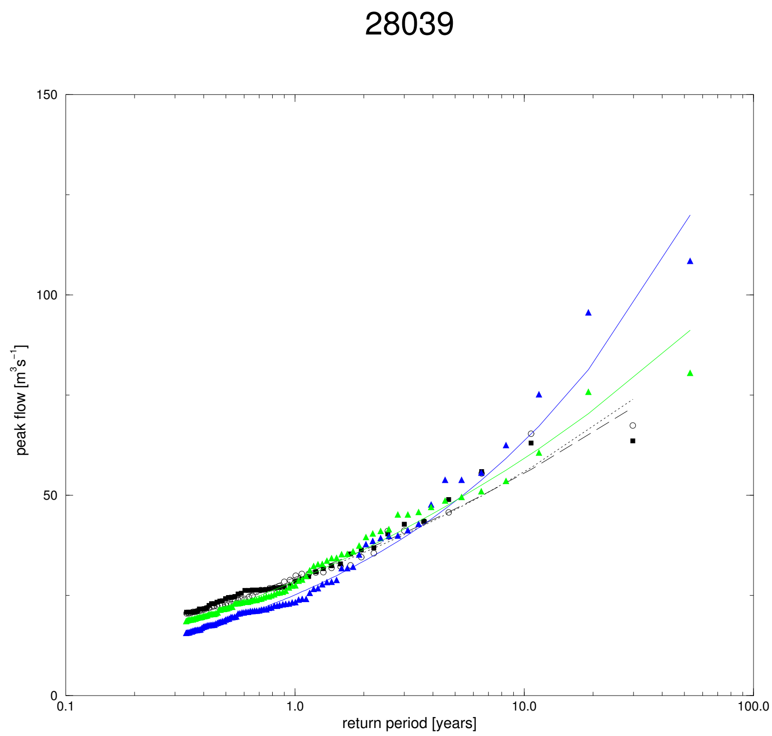

Figure A3.6

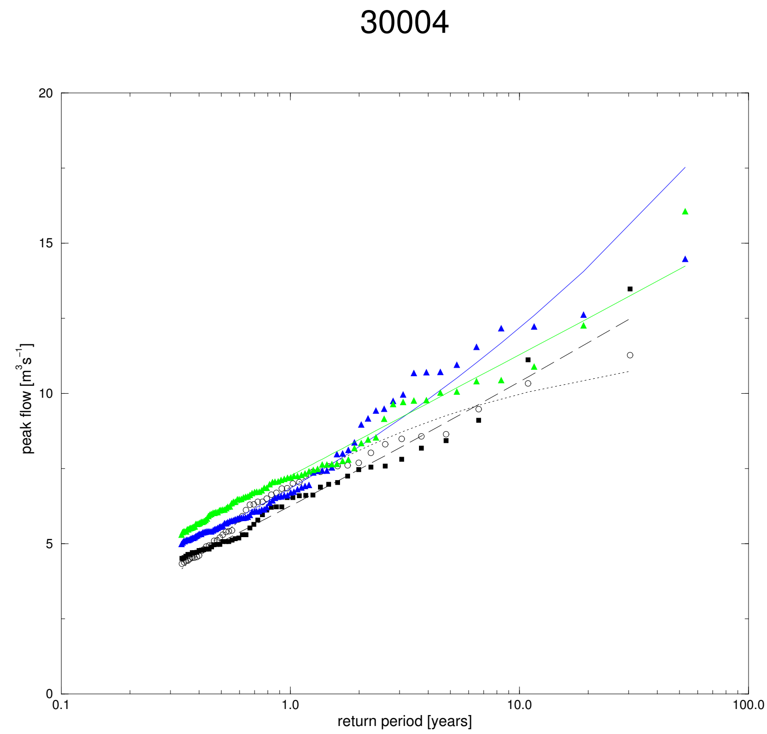

Figure A3.7

40005

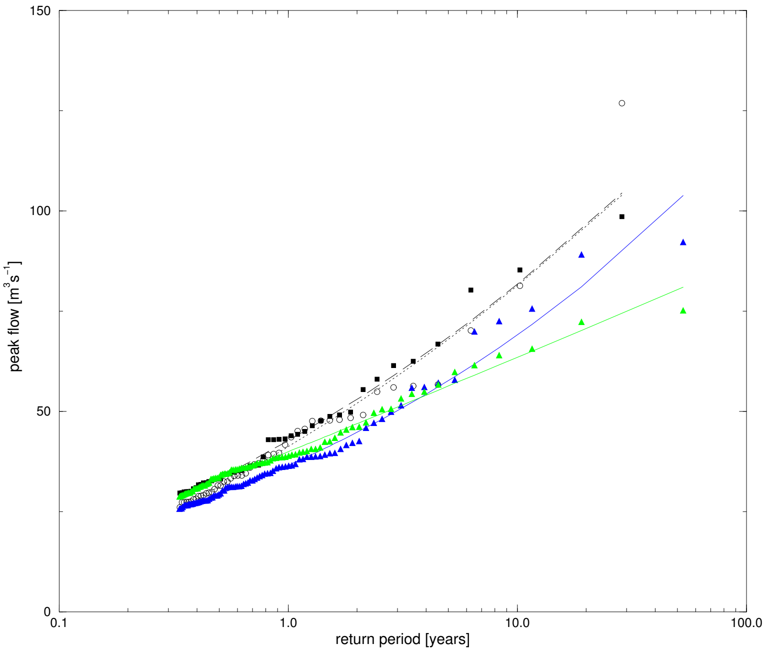

Figure A3.8

42012

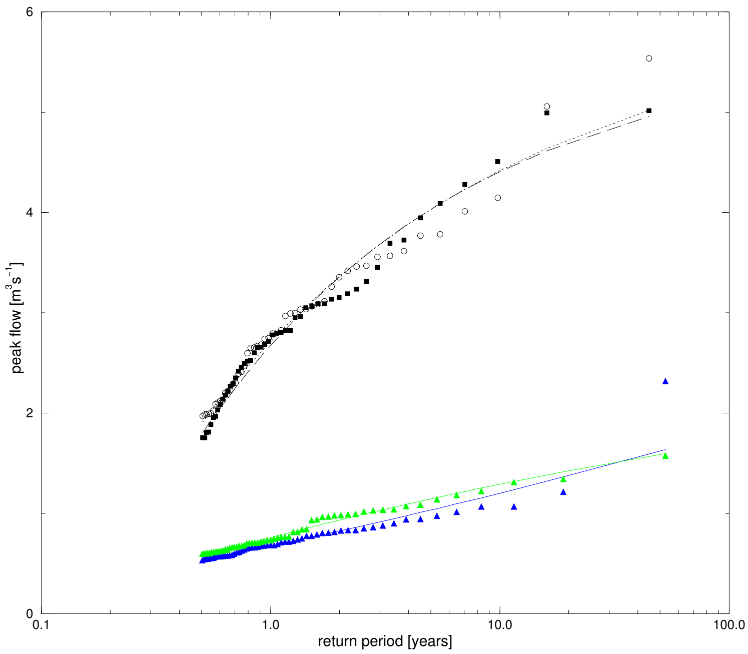

Figure A3.9

74001

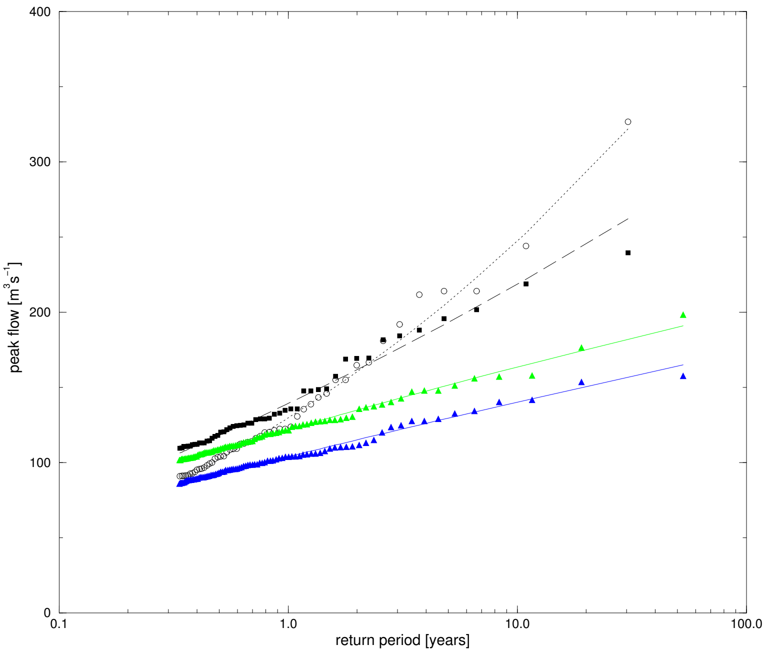

Figure A3.10

96001

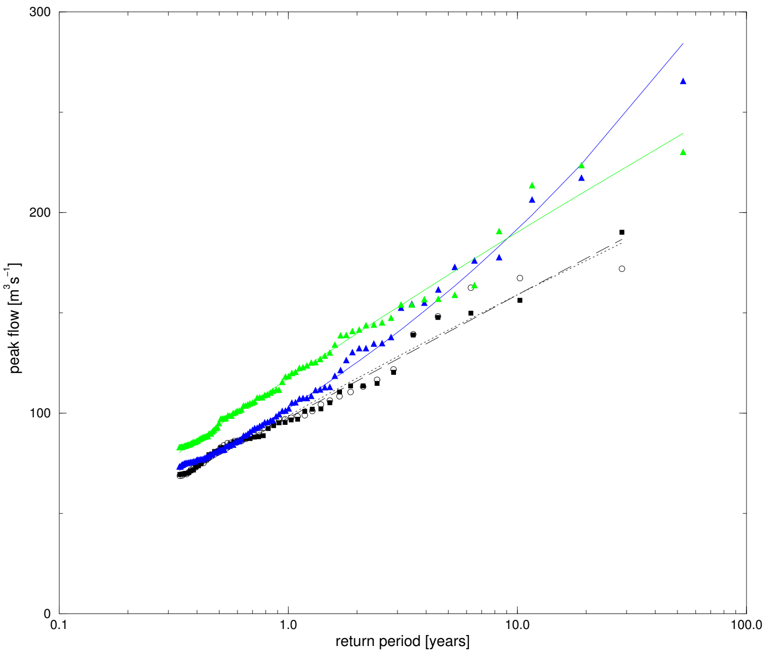

Figure A3.11

A4 Resampling rainfall

A4.1 UKCIP02 resampling

Key for figures in this sub-section:
Black dotted line and open circles — from observed flows.
Black dashed line and filled squares — modelled using observed rainfall.
Red solid line — median modelled, using 100 resamples under UKCIP02 high emissions scenario.
Red dotted lines — 90% upper and lower uncertainty bounds, using 100 resamples under UKCIP02 high emissions scenario.
Orange solid line — median modelled, using 100 resamples under UKCIP02 medium-high emissions scenario.
Orange dotted lines — 90% upper and lower uncertainty bounds, using 100 resamples under UKCIP02 medium-high emissions scenario.
Green solid line — median modelled, using 100 resamples under UKCIP02 medium-low emissions scenario.
Green dotted lines — 90% upper and lower uncertainty bounds, using 100 resamples under UKCIP02 medium-low emissions scenario.
Blue solid line — median modelled, using 100 resamples under UKCIP02 low emissions scenario.
Blue dotted lines — 90% upper and lower uncertainty bounds, using 100 resamples under UKCIP02 low emissions scenario.

Table A4.1 gives percentage changes in flood peaks at the 20-year return period, comparing the mean of the change for the four single UKCIP scenarios (from figures in section I.1) with the mean, minimum and maximum changes when using 100 resamples of the adjusted-baseline data for the four scenarios (figures in this section). As the results for the four scenarios in each time-slice are so close, the results are summarised across all four scenarios, rather than separately. The minima and maxima are thus taken as the percentage change to the lowest lower 90% bound for the four scenarios, and the highest upper 90% bound for the four scenarios, respectively. The mean is that of the four scenario medians, and a comparison of this value with the mean from the four single scenarios shows where the latter lie in the distribution.

Table A4.1

Catchment number	Time-slice	Mean UKCIP02 scenario change	100 resamples from UKCIP02		
			Minimum of scenario minima (within 90% bounds)	Mean of scenario medians	Maximum of scenario maxima (within 90% bounds)
28039	2050s	5.1	-22.5	-1.5	24.2
	2080s	-1.1	-28.5	-6.0	20.5
30004	2050s	-5.0	-24.9	-7.6	9.5
	2080s	-8.0	-28.3	-10.6	7.1
40005	2050s	0.1	-22.8	-4.9	9.9
	2080s	-2.4	-24.7	-5.3	9.4
42012	2050s	2.1	-8.5	6.6	25.7
	2080s	3.8	-8.4	6.9	29.6
74001	2050s	5.8	-14.4	2.6	17.0
	2080s	13.2	-13.0	9.3	30.4
96001	2050s	-0.1	-20.4	-2.3	16.2
	2080s	-2.1	-22.1	-4.6	16.0

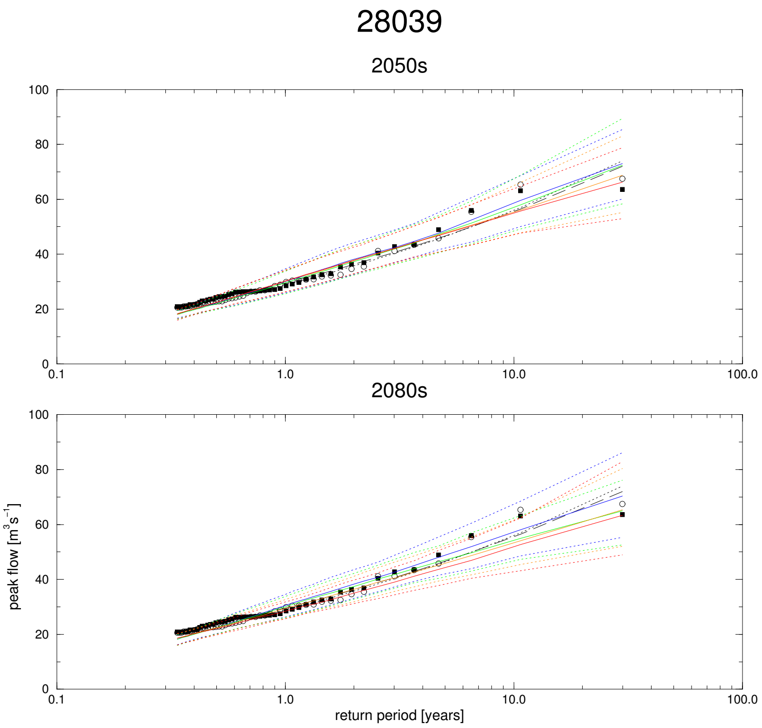

Figure A4.1

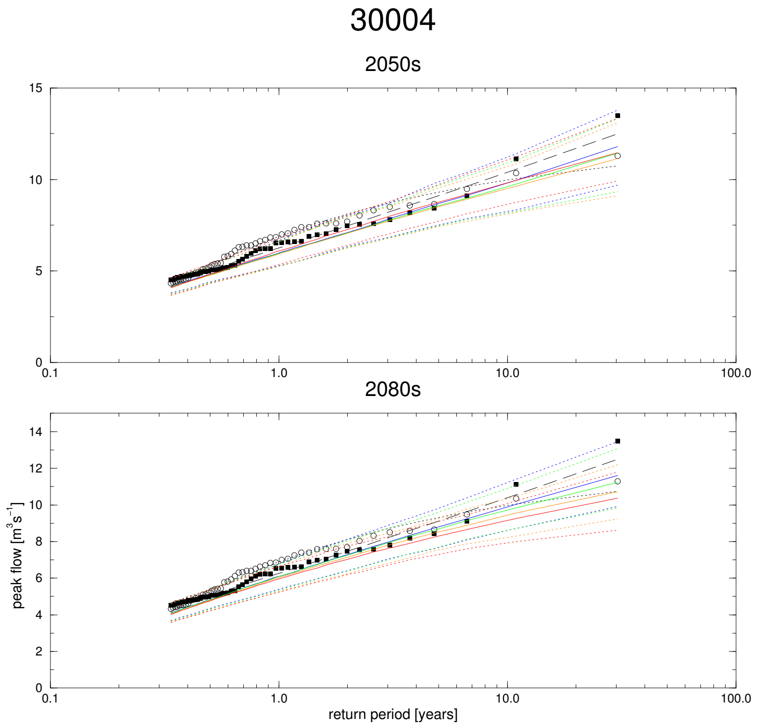

Figure A4.2

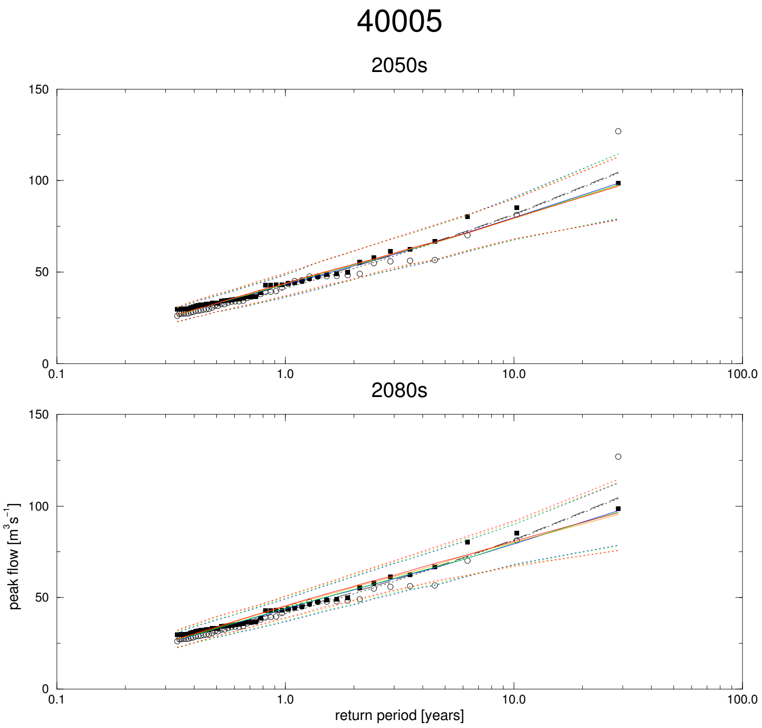

Figure A4.3

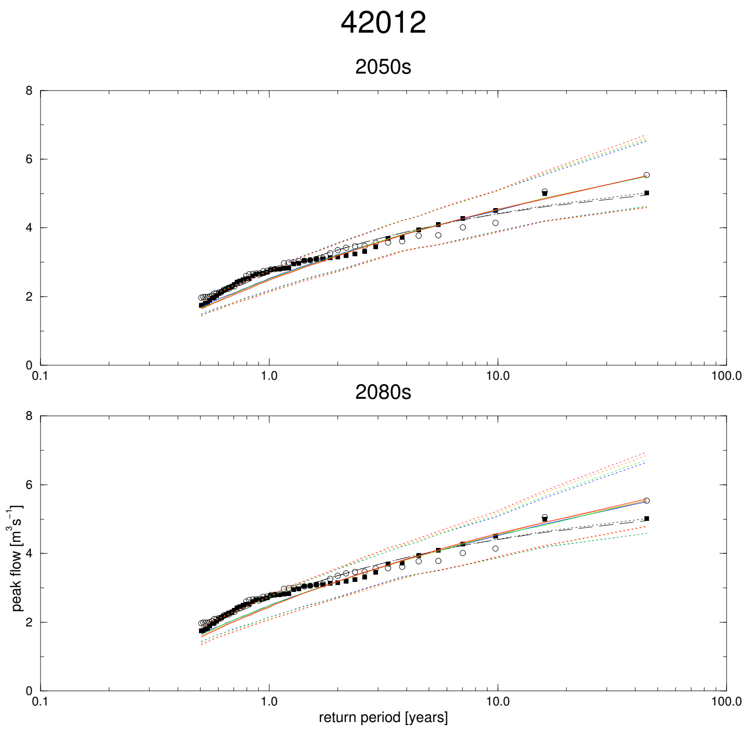

Figure A4.4

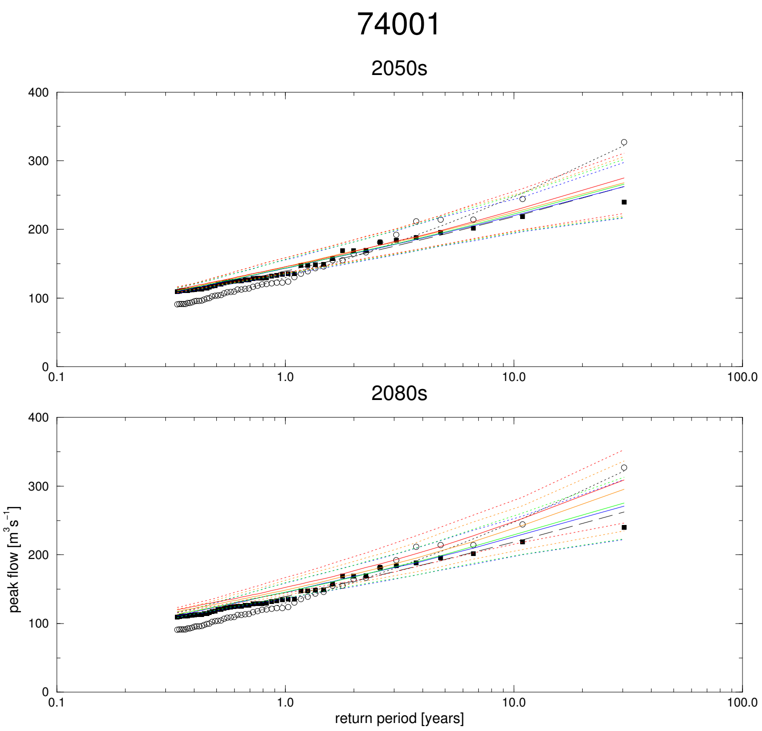

Figure A4.5

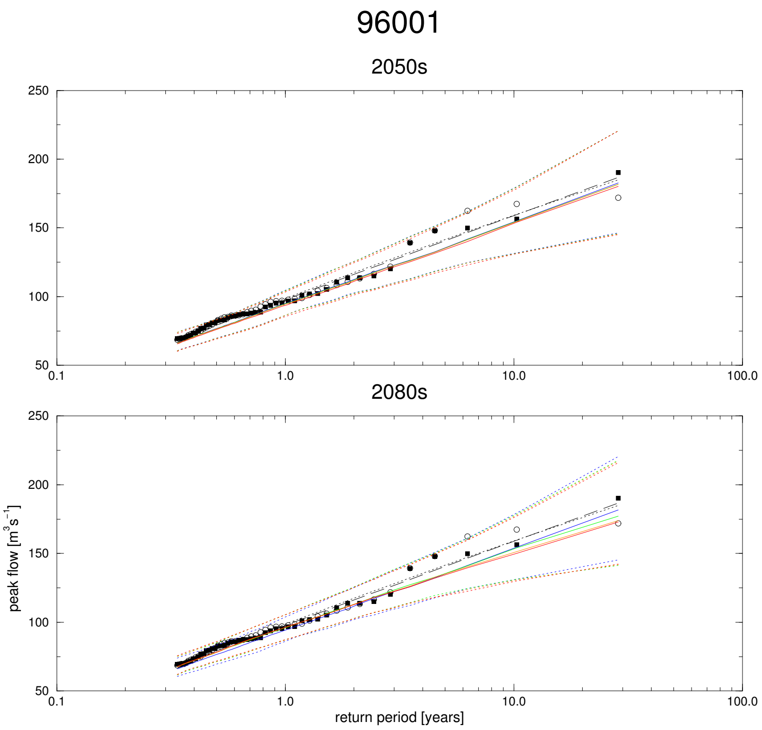

Figure A4.6

A4.2 RCM resampling

Key for figures in this sub-section:
Black dotted line and open circles — from observed flows
Black dashed line and filled squares — modelled using observed rainfall.
Blue solid line and filled triangles — modelled using 1961-1990 RCM data (acqqa).
Blue dashed line — median modelled, using 100 resamples of the acqqa data.
Blue dotted lines — 90% upper and lower bounds, using 100 resamples of the acqqa data.
Green solid line and filled triangles — modelled using 2071-2100 RCM data (acqqb).
Green dashed line — median modelled, using 100 resamples of the acqqb data.
Green dotted lines — 90% upper and lower bounds, using 100 resamples of the acqqb data.

Table A4.2 gives percentage changes in flood peaks at the 20-year return period, using the RCM data directly and when using 100 resamples of the RCM data. The minima and maxima are taken as the percentage change from, respectively, the upper 90% bound for acqqa to the lower 90% bound for acqqb, and the lower 90% bound for acqqa to the upper 90% bound for acqqb.

Table A4.2

Catchment	RCM data	100 resamples of RCM data		
		Minimum (within 90% bounds)	Median	Maximum (within 90% bounds)
28039	-14.0	-35.6	-5.7	38.6
30004	-12.0	-30.0	-6.8	29.7
40005	-13.8	-38.4	-13.3	20.3
42012	3.5	-73.0	20.9	474.3
74001	16.3	-2.9	15.9	39.6
96001	-6.9	-28.7	-7.3	30.6

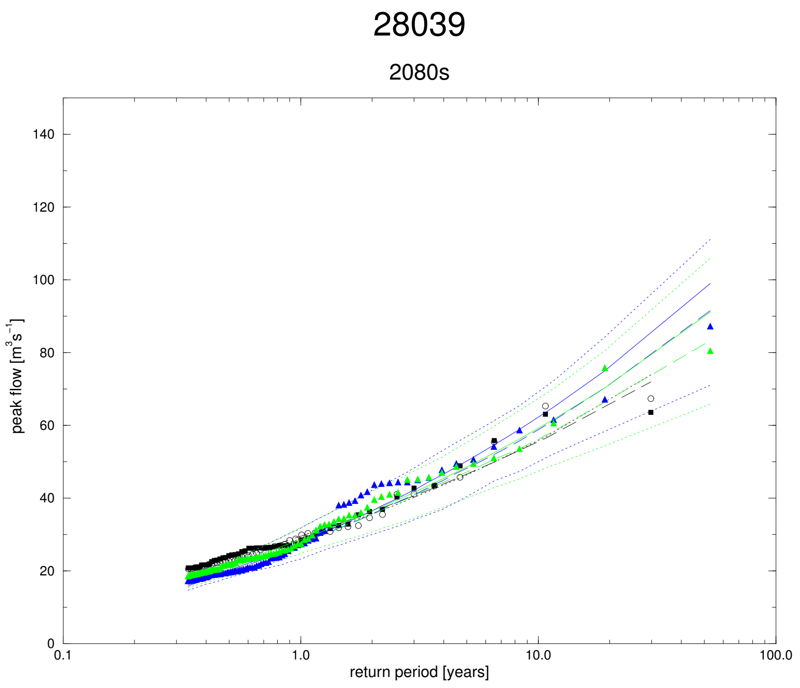

Figure A4.7

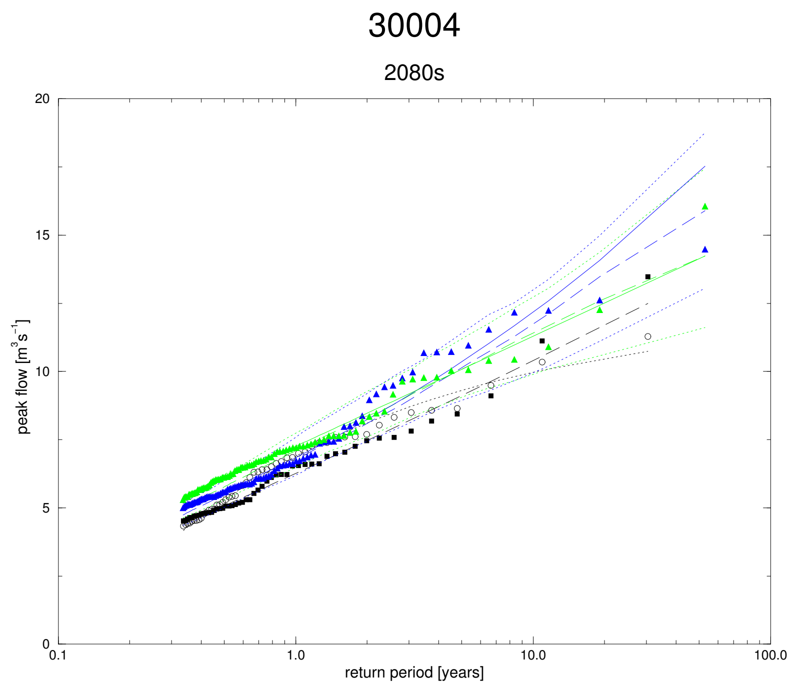

Figure A4.8

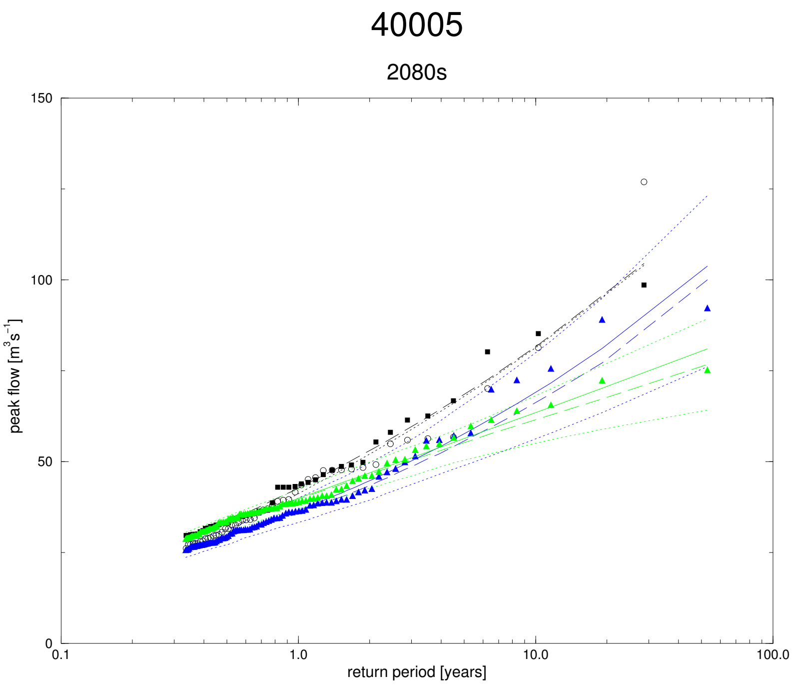

Figure A4.9

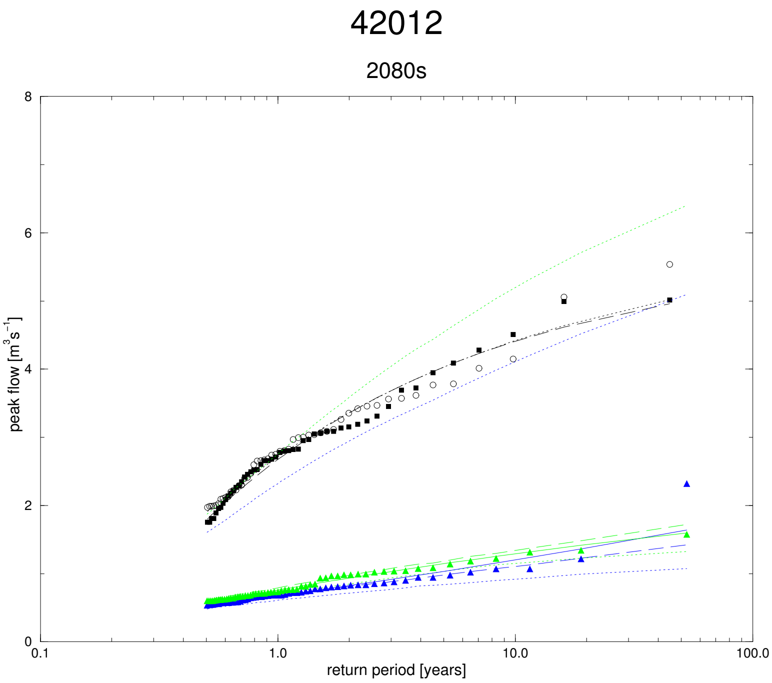

Figure A4.10

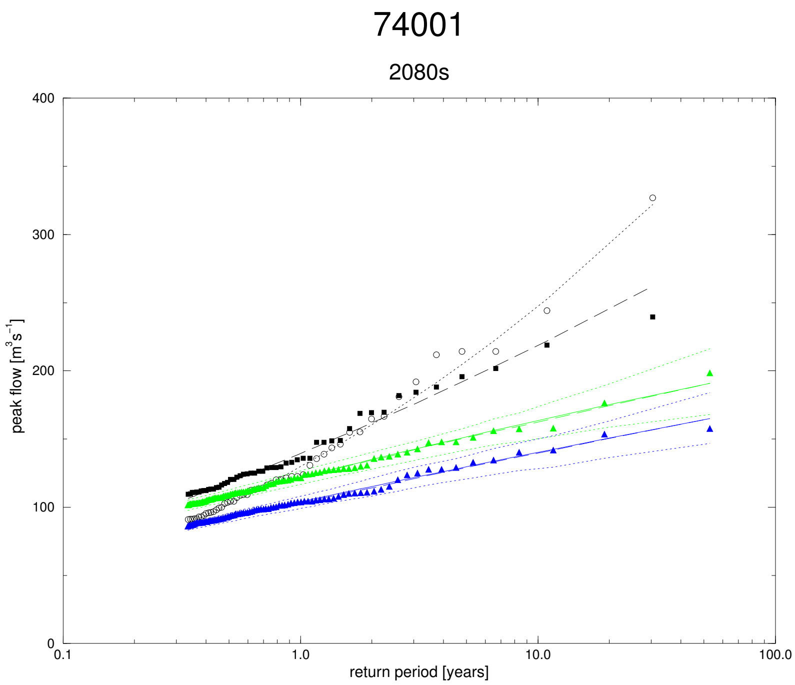

Figure A4.11

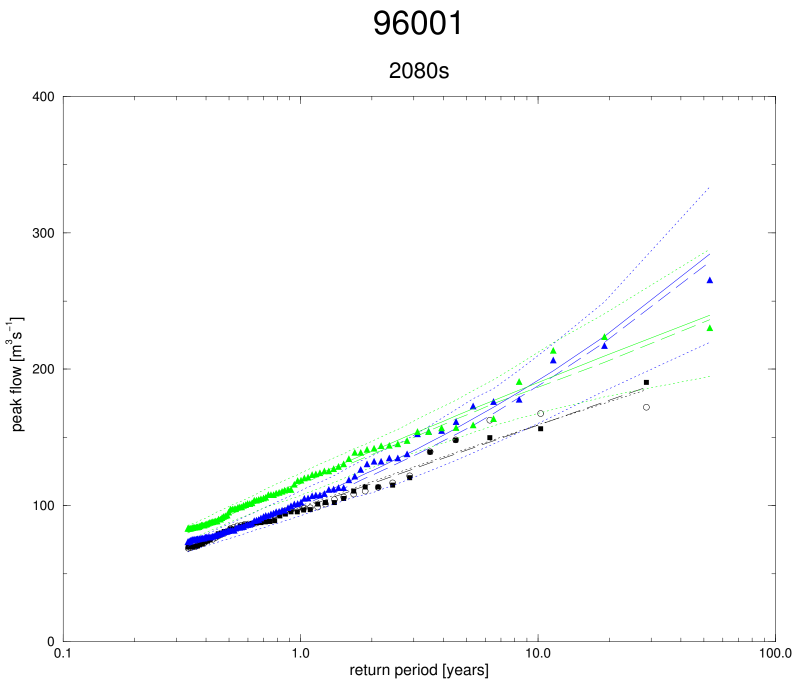

Figure A4.12

A5 Catchment intercomparison

Figure A5.1 show various measures of the impact of climate change on flood frequency plotted against various catchment properties.

The impact measures are the percentage change in flood frequency under three scenarios:

- 2050s UKCIP02,
- 2080s UKCIP02, and
- RCM (2080s A2).

Each taken at the 5, 20 and 50-year return period.

The catchment properties are

- easting of catchment outlet (in km),
- northing of catchment outlet (in km),
- catchment area (in km^2),
- mean catchment altitude (altbar, in m),
- mean flow (qbar, in m^3s^{-1}),
- catchment standard average annual rainfall (SAAR, in mm),
- baseflow index (BFI),
- FEH's extent of urban and suburban development (URBEXT1990), and
- an adjusted BFI (adjBFI), which is calculated as BFI – URBEXT1990, to take account of the fact that more highly urbanised catchments will have a quicker response than their BFI may indicate.

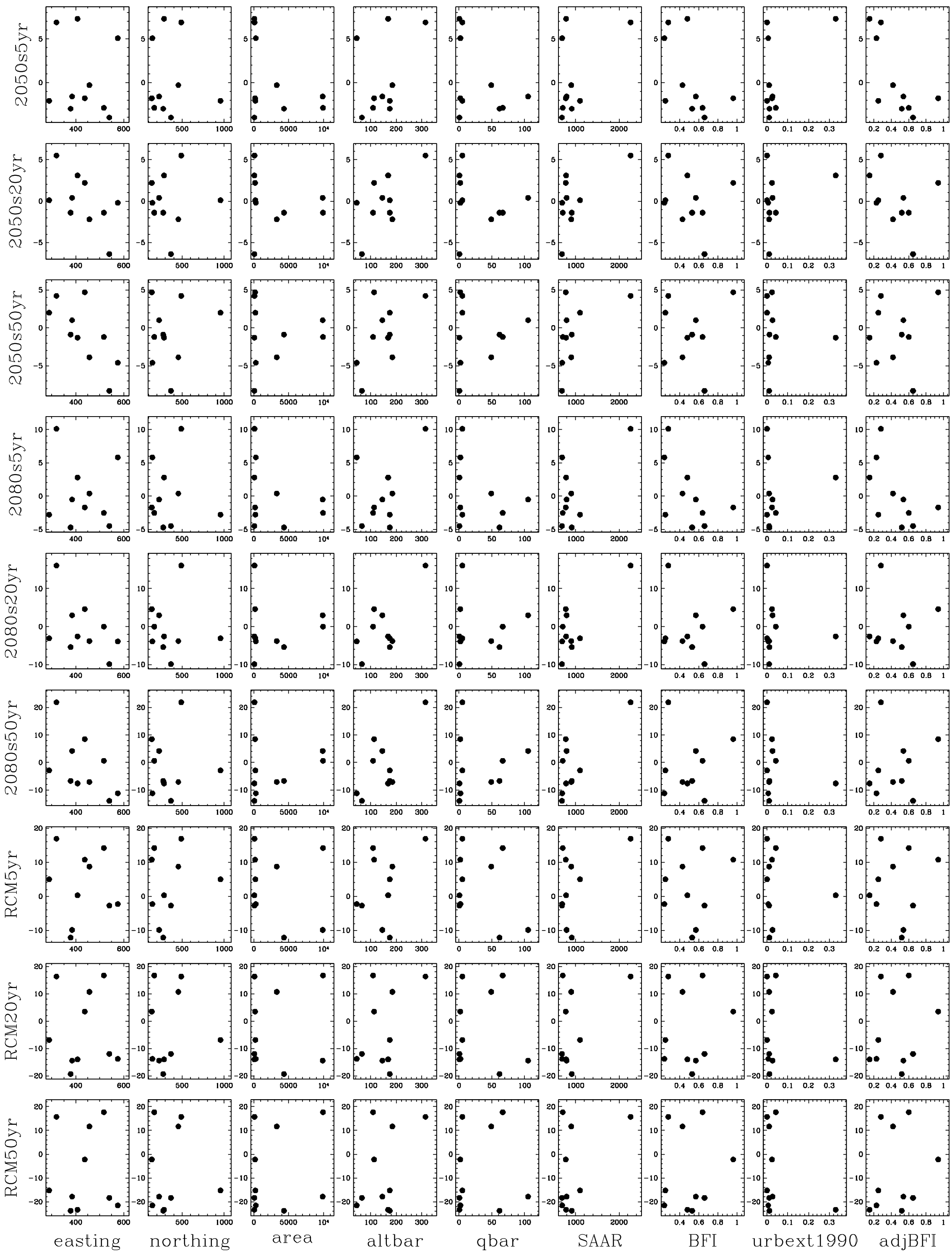
2050s5yr
2050s20yr
2050s50yr
2080s5yr
2080s20yr
2080s50yr
RCM5yr
RCM20yr
RCM50yr
easting
northing
area
altbar
qbar
SAAR
BFI
urbext1990
adjBFI

Figure A5.1

A6 Summary tables for percentage change in flows

2050s:

Table A6.1 Range of 2050s impacts for the 20-year return period flow.

Catchment	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
27009	-2.3	-2.3	-2.2	-3.2	10.3	1.3					
28039	9.1	8.4	3.1	-0.2				-22.5	**24.2**		
30004	-3.5	-5.2	-6.4	-4.7				-24.9	9.5		
39001	-0.3	-1.0	-1.4	-1.7							
40005	1.3	0.3	-0.2	-1.1				-22.8	9.9		
42012	1.2	1.8	2.2	3.0				-8.5	**25.7**		
54001	-1.4	-1.5	-1.4	-2.0	11.8	6.9					
54057	0.1	0.3	0.4	0.7							
74001	4.1	5.6	5.5	8.0				-14.4	17.0		
96001	0.1	0.1	0.1	-0.5				-20.4	16.2		

Table A6.2 Range of 2050s impacts for the 50-year return period flow.

Catchment	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
27009	-3.9	-4.0	-3.9	-5.6	13.7	-0.5					
28039	7.2	7.2	-1.3	-6.2				-31.7	**27.4**		
30004	-4.8	-6.8	-8.3	-7.5				-29.9	12.7		
39001	0.4	-0.5	-1.2	-1.5							
40005	-1.9	-3.7	-4.6	-6.4				-30.6	9.1		
42012	2.9	4.0	4.7	6.0				-7.6	**36.6**		
54001	-1.2	-1.1	-0.9	-1.6	**20.3**	13.9					
54057	0.6	0.9	1.0	1.4							
74001	3.7	5.8	4.2	8.9				-20.1	**23.0**		
96001	1.6	1.8	2.0	1.7				-25.3	**23.3**		

Key:
1 UKCIP02 low
2 UKCIP02 medium-low
3 UKCIP02 medium-high
4 UKCIP02 high
5 SDSM B2 (medium-low)
6 SDSM A2 (medium-high)
7 RCM (medium-high)
8 UKCIP02 resampling minimum
9 UKCIP02 resampling maximum
10 RCM resampling minimum (medium-high)
11 RCM resampling maximum (medium-high)

2080s:

Table A6.3 Range of 2080s impacts for the 20-year return period flow.

Catchment	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
27009	-2.2	-3.6	-3.8	-4.2	7.0	-3.8	10.7				
28039	6.4	-2.5	-2.6	-5.5			-14.0	-28.5	**20.5**	-35.6	**38.6**
30004	-3.5	-5.6	-9.9	-13.1			-12.0	-28.3	7.1	-30.0	**29.7**
39001	-1.6	-1.6	0.0	2.8			16.7				
40005	-0.5	-1.5	-3.9	-3.7			-13.8	-24.7	9.4	-38.4	**20.3**
42012	2.5	3.2	4.6	5.0			3.5	-8.4	**29.6**	-73.0	**474.3**
54001	-2.1	-2.7	-5.4	-6.7	10.4	6.8	-19.4				
54057	1.2	1.2	3.0	4.4			-14.5				
74001	6.6	8.3	16.1	**21.9**			16.3	-13.0	**30.4**	-2.9	**39.6**
96001	0.1	-0.9	-3.1	-4.6			-8.9	-22.1	16.0	-28.7	**30.6**

Table A6.4 Range of 2080s impacts for the 50-year return period flow.

Catchment	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
27009	-3.9	-6.2	-7.1	-2.8	6.8	-9.3	11.7				
28039	2.4	-9.1	-7.6	-9.5			-23.4	-36.3	19.5	-40.0	**47.4**
30004	-5.9	-8.5	-13.9	-17.5			-18.4	-34.3	10.2	-37.7	**33.1**
39001	-1.4	-1.4	0.6	4.2			17.7				
40005	-5.2	-7.0	-11.2	-11.3			-21.5	-32.9	8.6	-47.3	17.6
42012	5.2	6.4	8.5	8.6			-2.2	-7.5	**41.6**	-74.0	**494.1**
54001	-1.8	-2.6	-6.7	-8.7	11.6	8.2	-23.8				
54057	1.8	1.8	4.2	5.9			-17.8				
74001	6.2	9.0	**21.9**	**29.7**			15.7	-19.3	**37.2**	-8.5	**46.5**
96001	2.2	0.4	-2.9	-5.3			-15.2	-27.6	**22.6**	-40.9	**31.2**

Key:

1 UKCIP02 low
2 UKCIP02 medium-low
3 UKCIP02 medium-high
4 UKCIP02 high
5 SDSM B2 (medium-low)
6 SDSM A2 (medium-high)
7 RCM (medium-high)
8 UKCIP02 resampling minimum
9 UKCIP02 resampling maximum
10 RCM resampling minimum (medium-high)
11 RCM resampling maximum (medium-high)

A7 Summary tables for absolute (m^3s^{-1}) change in flows under resampling

2050s:

Table A7.1 Range of 2050s impacts for the 20-year return period flow.

Catchment	1	2	3	4
27009				
28039	-14.7	15.9		
30004	-2.9	1.1		
39001				
40005	-21.9	9.5		
42012	-0.4	1.2		
54001				
54057				
74001	-35.2	41.6		
96001	-36.2	28.8		

Table A7.2 Range of 2050s impacts for the 50-year return period flow.

Catchment	1	2	3	4
27009				
28039	-25.6	22.2		
30004	-4.0	1.7		
39001				
40005	-36.2	10.8		
42012	-0.4	1.8		
54001				
54057				
74001	-56.8	65.0		
96001	-51.0	47.0		

Key:
1 UKCIP02 resampling minimum
2 UKCIP02 resampling maximum
3 RCM resampling minimum (medium-high)
4 RCM resampling maximum (medium-high)

2080s:

Table A7.3 Range of 2080s impacts for the 20-year return period flow.

Catchment	**1**	**2**	**3**	**4**
27009				
28039	-18.7	13.5	-30.4	22.7
30004	-3.3	0.8	-4.5	3.3
39001				
40005	-23.8	9.1	-36.9	13.0
42012	-0.4	1.4	-3.3	4.8
54001				
54057				
74001	-31.9	74.6	-4.7	54.1
96001	-39.1	28.4	-72.5	56.7

Table A7.4 Range of 2080s impacts for the 50-year return period flow.

Catchment	1	2	3	4
27009				
28039	-29.4	15.8	-43.7	33.5
30004	-4.6	1.4	-7.0	4.3
39001				
40005	-38.9	10.2	-57.4	13.3
42012	-0.4	2.1	-3.80	5.3
54001				
54057				
74001	-54.5	105.1	-15.5	68.1
96001	-55.7	45.5	-134.5	67.8

Key:
1 UKCIP02 resampling minimum
2 UKCIP02 resampling maximum
3 RCM resampling minimum (medium-high)
4 RCM resampling maximum (medium-high)