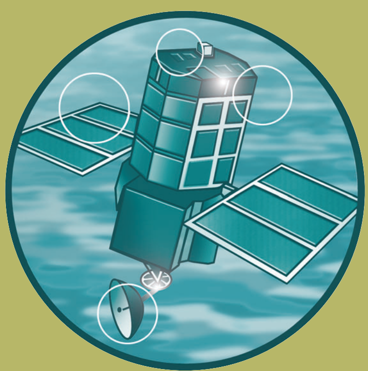
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Regionalised Impacts of Climate Change on Flood Flows:
Hydrological Models, Catchments and Calibration

R&D Milestone Report FD2020/MR1



Environment Agency

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Department for Environment Food and Rural Affairs

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

Regionalised impacts of climate change on flood flows: hydrological models, catchments and calibration

Milestone report 1 – Project FD2020

Produced: November 2008
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Statement of use

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

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Executive summary

The primary objective of this project is to assess the suitability of the PAG3 guidance of a 20% change to peak flows for any period between 2025 and 2115. The guidance was set as a precautionary upper limit to changes in river flows over the next 50 years, and was applicable to all regions of Britain. This has since been extended to the period up to 2115 reflecting the lack of scientific evidence to suggest any alternative figure. This project has been designed to provide this evidence. Furthermore, it is anticipated that the research will lead to the development of regional, rather than national, guidelines for changes to peak flows due to climate change.

The hydrological modelling tasks within this project provide the fundamental building blocks for the subsequent analysis of the potential implications of climate change on flood flows, and the regionalisation of those impacts. This means that it is essential that the hydrological models are set up and calibrated as robustly as possible. In particular, the inclusion of snowmelt within the hydrological models was considered crucial, given the project's aim to *regionalise* the impacts of climate change on flooding, as the winter flow regime of upland catchments can be considerably affected by snowfall and snowmelt, even in the UK, and changes in temperature will almost certainly alter the balance between snowfall and rainfall processes in such catchments in the future.

This milestone report describes the hydrological models (their structure and data requirements), details the 154 catchments to be modelled across Britain: 120 with the PDM (a lumped conceptual hydrological model), and 35 (generally larger) catchments with CLASSIC (a semi-distributed hydrological model), and presents their calibration results. One catchment is modelled by both hydrological models. The final calibrations include the use of a snowmelt module, which has been applied (with a fixed set of module parameters) for all catchments, to avoid an arbitrary decision on which catchments are affected. The hydrological models with the snowmelt module require input time-series of precipitation, potential evaporation and temperature to simulate mean daily flow. Overall, model performance improves when the snowmelt module is applied.

The calibrated models were used to simulate baseline time series of mean daily flows from which a set of independent flood peaks was extracted for each catchment. For the majority of catchments there is good comparison between flood frequency curves fitted to the observed and modelled mean daily flood peak data sets. Reasons are identified where there are considerable differences between the observed and modelled curves.

The final calibrated parameter sets are used in the next part of the project: the application of a large, regular, set of perturbations to observed precipitation time-series, alongside a smaller set of (linked) perturbations to potential evaporation and temperature time-series, to investigate the relative sensitivity of different catchments to the potential range of climate change. The development of this scenario method, and its application is described in milestone report 2 (Prudhomme & Reynard, 2009).

Contents

1. Introduction

This milestone report, for project FD2020 'Regionalised impacts of climate change on flood flows', describes the hydrological modelling of the project catchments. The project background and context are described below, along with descriptions of the hydrological models themselves. The catchments and input data described in Section 2 and initial calibrations (prior to the inclusion of a snowmelt module) described in Section 3. The snowmelt module, gridded temperature data, and their use with each of the hydrological models, is described in Section 4. Final calibrations, when the snowmelt module is included, are described in Section 5, with a short summary in Section 5.4.

1.1 Project context

Current Defra / Environment Agency guidance (PAG3 supplementary note) requires all flood management plans to allow for climate change by incorporating, within a sensitivity analysis, an increase in river flows of 20% for any period between 2025 and 2115. This guidance is the same for all of England and Wales, making no allowance for regional variation in climate change or catchment type. This is because the underpinning science has not been able to resolve the spatial distribution of climate change impact on flood flows with enough confidence to set such policy regionally. The recommendation for a 20% allowance was first raised in 1999 for MAFF and subsequently reviewed following the release of the UKCIP02 scenarios.

Defra and the Environment Agency have procured this project (FD2020) to provide more rigorous science evidence to consider whether the guidance within the PAG3 supplementary note can be improved. Although the 20% figure is a memorable precautionary target, there is the risk that it leads to a significant under- or over-estimating of future flood risk, and as yet there is not the confidence in the science evidence to support significant investment in adapting to future river flows above the current sensitivity approach. Ultimately, this may lead to the country being under-prepared for the future, a situation that must be quickly addressed if we are to put in place the measures to reduce the impact of river flooding driven by climate change.

The objectives of the FD2020 project are:

- Investigate the impact of climate change on a number of British catchments to assess the suitability of the PAG3 20% climate change allowance for river flows, given scientific developments since 2002.
- Investigate catchment response to climate change to identify any potential similarities such that the PAG3 nationwide allowance could be regionalised (the term regionalised is not limited here to location and could equally be a function of any catchment characteristic).
- Investigate the uncertainty in understanding changes to river flows from climate change.

1.2 Context for this milestone report

To understand the change to river flows driven by changes to the climate, the current or baseline flow regime for each catchment has to be determined. The objective of this milestone report is:

- To develop a set of models, for a representative number of catchments across England, Wales and Scotland, that accurately reproduce the relationship between the baseline climate and catchment characteristics.

The process to achieve this objective is illustrated in the schematic in Figure 1.1. The initial calibration of the models confirmed that the climate influence was underrepresented and that including snowmelt would significantly improve the reproduction of river flows during winter and spring months, and provide a better representation of changes in peak flows under climate change.

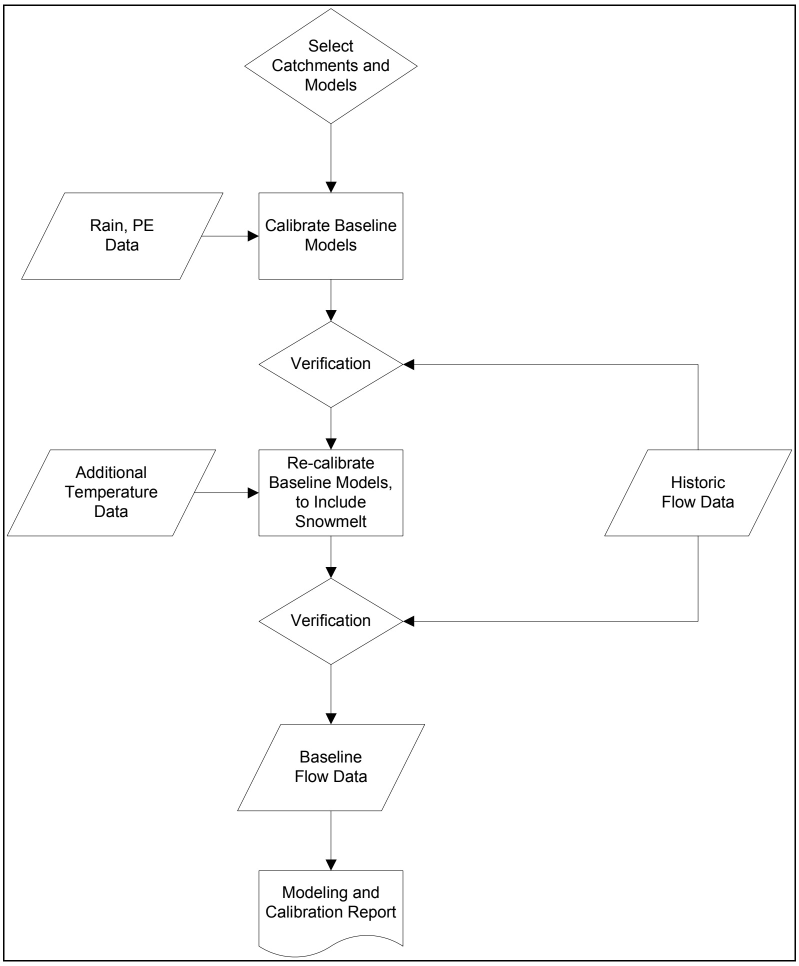

Figure 1.1 Schematic of the process underpinning the work leading to the delivery of this milestone report. The rectangles represent project processes, those with the wavy bottom line being reports. The diamonds are project decisions with trapeziums being data

1.3 Hydrological models and time-step issues

Two hydrological models were selected for use in the project:

- the Probability Distributed Model (PDM; Moore 1985, 1999, 2007), which is a lumped conceptual model.
- the Climate and Land-use Scenario Simulation In Catchments (CLASSIC) model (Crooks and Naden 2007), a semi-distributed, grid-based model.

Both are conceptual rainfall-runoff models developed for continuous simulation of river flow across the complete flow range. They incorporate soil moisture accounting processes, the primary component of non-linearity between rainfall and runoff, and routing procedures for converting effective rainfall (rainfall minus evaporative losses) to runoff. Smaller catchments are modelled with the PDM, which requires inputs of catchment-average rainfall and potential evaporation (PE), with flow data for calibration. Larger catchments are modelled with CLASSIC which requires gridded inputs of rainfall and PE, normally at a daily time-step, as well as land-use, soil and digital terrain data. A generalised method for determining parameter values from catchment properties makes it suitable for modelling catchments where direct calibration against observed flow is not suitable due to factors such as abstraction and river regulation. The methodology also ensures spatial consistency in flow simulation across the UK.

The greater spatial heterogeneity that can be expected in larger catchments, in terms of rainfall fields but also the differing responses of the range of soils and geological formations that may be present, means that the use of a lumped model is generally inappropriate for larger catchments. Conversely, the greater spatial homogeneity of smaller catchments means that a lumped model can provide a good fit to observations, and so the use of (semi-)distributed models, with their greater complexity and data requirements, is often not warranted.

A complication with the catchments to be modelled with the PDM is that some have hourly data available, whilst some only have daily data. The inclusion of catchments with daily data improves the spatial coverage of Britain as well as allowing the use of longer records (see Section 2), whilst the use of hourly data is more appropriate to capture the response of smaller, hydrologically-responsive catchments. Daily data are not used for catchments with an area less than 50 km^2.

Here, the hourly (daily) PDM catchments have been calibrated and run at the hourly (daily) time-step. However, the impact of the climate change scenarios for the hourly PDM catchments will be assessed on the flood frequency curve derived from daily mean flows, for consistency with the CLASSIC and daily PDM catchments.

1.4 PDM description

The Probability Distributed Model (PDM; Moore 1985, 1999, 2007) is typical of the relatively simple model structures that nevertheless can be applied effectively across the UK. It is based on conceptual stores, and represents non-linearity in the transformation from rainfall to runoff by using a probability distribution of soil moisture storage. This determines the time-varying proportion of the catchment that contributes to runoff, through either 'fast' or 'slow' pathways. The full PDM has a number of different formulations, but the version used here is simplified to allow automatic calibration for the majority of catchments. The reduction in the number of parameters is useful in limiting the problem of equi-finality, where a number of quite different parameter sets can result in very similar model performance. A brief description of the model and its remaining parameters is given below, along with a diagram illustrating its conceptual structure (Figure 1.2).

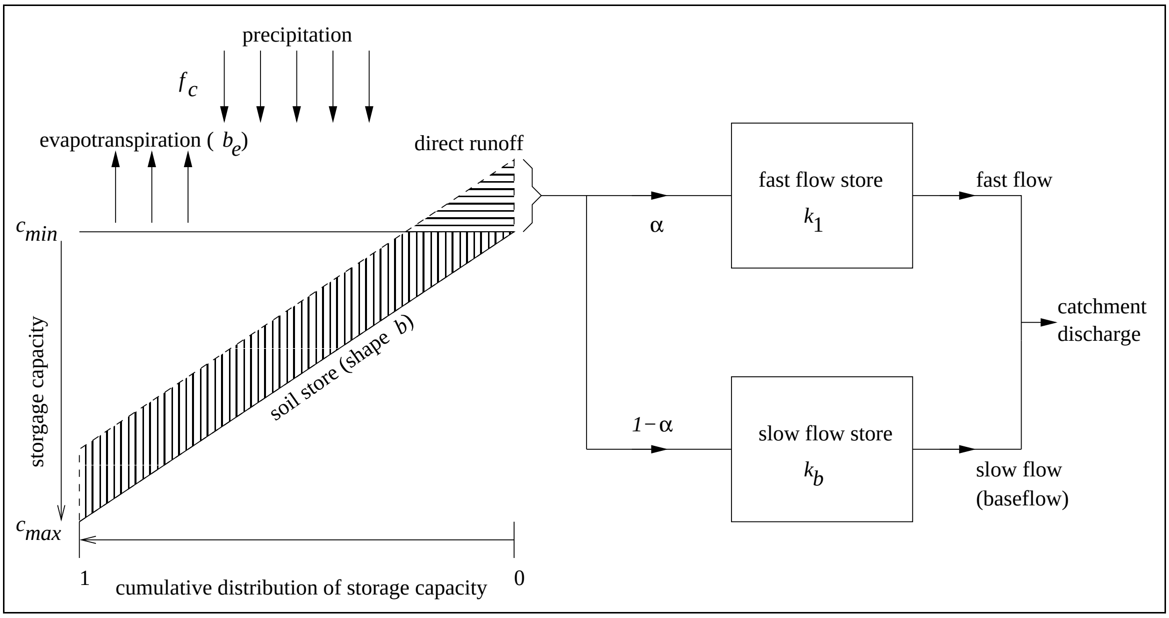

Figure 1.2 The conceptual structure of the version of the PDM rainfall-runoff model applied in the project

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

The soil store then generates direct runoff from a varying proportion of the catchment area, depending on how full it is. It is generally assumed, in the full PDM, that the direct runoff (overflow) from the soil store is routed through a fast flow store ([near-] surface storage), and that downward drainage from the soil store is routed through a slow flow store (groundwater storage). An alternative formulation, used here, is to assume that a proportion α of the direct runoff goes to the fast flow store, whilst $1-\alpha$ goes to the slow flow store. The value of α can then be estimated using soils data (see Section 3.2.2). Both fast and slow routing systems can be represented by a number of types of storage reservoir in the full PDM, but in this case a linear fast flow store and a cubic slow flow store are assumed. The time constants of the stores are k_1 and k_b respectively. The catchment discharge is then produced from a combination of fast flow (surface runoff) and slow flow (baseflow).

1.5 CLASSIC description

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 1.3; details of the model and how the parameters operate within the model structure are given in Crooks and Naden (2007).

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

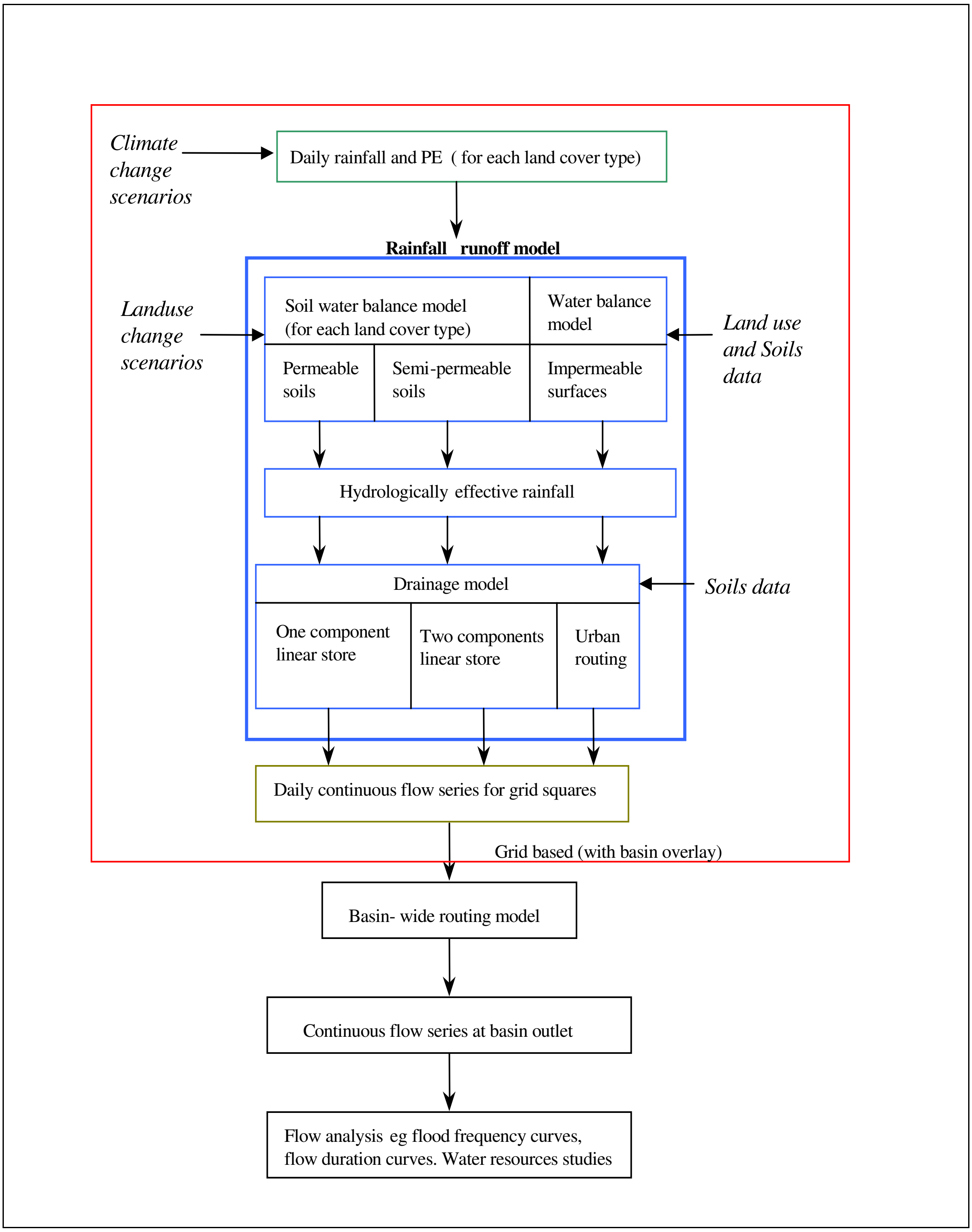

Figure 1.3 Conceptual structure of the semi-distributed hydrological model, CLASSIC

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

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

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

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 (Section 2.3.3), was used for the initial development of the model but smaller grid sizes have been used in later modelling. Figure 1.4 shows the Ouse catchment in Yorkshire overlain with the 10 km modelling grid used in this project. The robustness of the model structure and generalised method of calibration has been tested successfully by applying the model at different spatial and temporal scales.

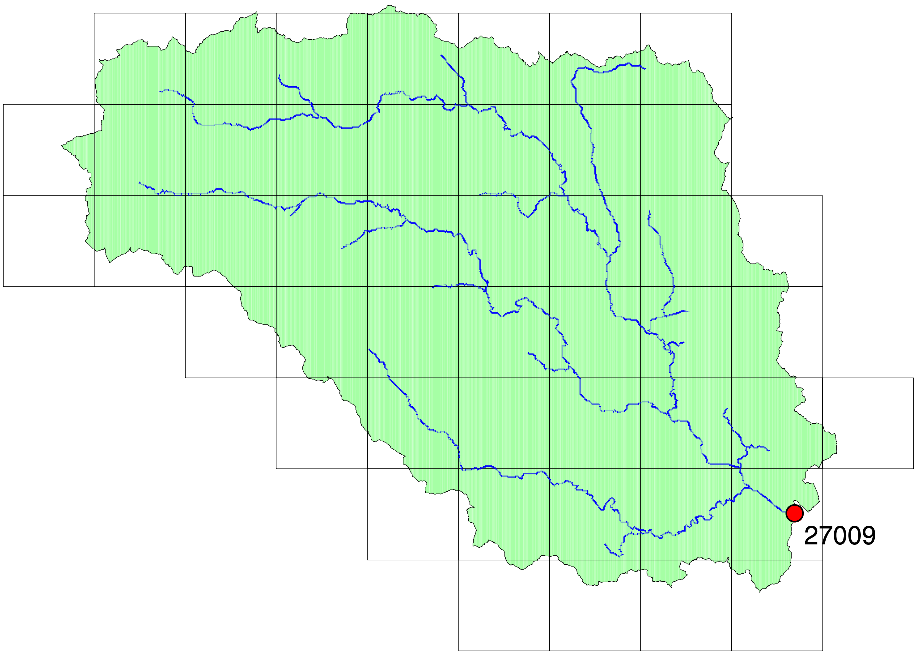

Figure 1.4 Ouse catchment in Yorkshire and 10 km CLASSIC modelling grid

The model is normally run at a daily time step using grid square averages of observed daily rainfall (Gannon 1995) and MORECS monthly PE, divided equally into daily values, to simulate mean daily flow. Monthly PE values for grid sizes less than 40 km are 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) are 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.

2. Catchments and data

This section details the catchments to be used in the project and demonstrates the coverage of Britain, both spatially and in terms of a selection of catchment properties. It also outlines the time-series data available for each catchment, which are used for calibration.

2.1 Catchments

2.1.1 PDM catchments

Table 2.1 and Table 2.2 list the hourly and daily catchments (respectively) modelled with the PDM, including the catchment number (according to the National River Flow Archive), the river name and location name of the flow gauging station, the catchment area, the 1961-1990 standard average annual rainfall ($SAAR_{61\text{-}90}$) and the baseflow index (BFI). The catchment outlets and boundaries are shown in Figure 2.1.

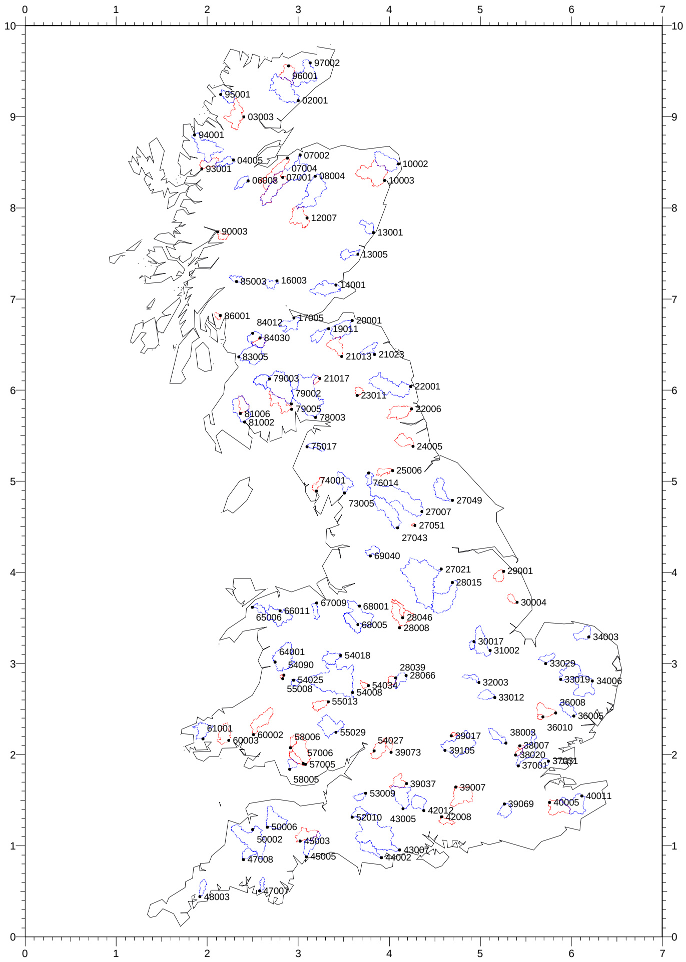

Figure 2.1 PDM catchment outlets and boundaries (hourly – red, daily – blue)

Table 2.1 Details of the PDM hourly catchments

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

Table 2.2 Details of the PDM daily catchments

Catchment Number	River	Location	Catchment Area (km^2)	SAAR$_{61-90}$ (mm)	BFI
02001	Helmsdale	Kilphedir	551.4	1117	0.48
04005	Meig	Glenmeannie	120.5	2145	0.26
06008	Enrick	Mill of Tore	105.9	1294	0.32
07002	Findhorn	Forres	781.9	1064	0.41
08004	Avon	Delnashaugh	542.8	1111	0.56
10002	Ugie	Inverugie	325.0	812	0.64
13001	Bervie	Inverbervie	123.0	890	0.56
13005	Lunan Water	Kirkton Mill	124.0	771	0.52
14001	Eden	Kemback	307.4	799	0.62
16003	Ruchill Water	Cultybraggan	99.5	1889	0.30

Catchment Number	River	Location	Catchment Area (km^2)	SAAR$_{61-90}$ (mm)	BFI
17005	Avon	Polmonthill	195.3	989	0.41
19011	North Esk	Dalkeith Palace	137.0	907	0.52
20001	Tyne	East Linton	307.0	713	0.52
21023	Leet Water	Coldstream	113.0	671	0.35
22001	Coquet	Morwick	569.8	850	0.45
27007	Ure	Westwick Lock	914.6	1118	0.39
27021	Don	Doncaster	1256.2	799	0.56
27043	Wharfe	Addingham	427.0	1383	0.33
27049	Rye	Ness	238.7	839	0.68
28015	Idle	Mattersey	529.0	650	0.79
28066	Cole	Coleshill	130.0	722	0.44
30017	Witham	Colsterworth	51.3	642	0.50
31002	Glen	Kates and King St Brs	341.9	608	0.59
32003	Harpers Brook	Old Mill Bridge	74.3	623	0.49
33012	Kym	Meagre Farm	137.5	585	0.26
33019	Thet	Melford Bridge	316.0	620	0.78
33029	Stringside	Whitebridge	98.8	629	0.85
34003	Bure	Ingworth	164.7	669	0.83
34006	Waveney	Needham Mill	370.0	594	0.47
36005	Brett	Hadleigh	156.0	580	0.46
37001	Roding	Redbridge	303.3	606	0.39
37031	Crouch	Wickford	71.8	572	0.30
38003	Mimram	Panshanger Park	133.9	656	0.94
39069	Mole	Kinnersley Manor	142.0	795	0.39
39105	Thame	Wheatley	533.8	644	0.63
40011	Great Stour	Horton	345.0	747	0.70
42012	Anton	Fullerton	185.0	773	0.96
43005	Avon	Amesbury	323.7	745	0.91
43007	Stour	Throop	1073.0	861	0.67
44002	Piddle	Baggs Mill	183.1	943	0.89
45005	Otter	Dotton	202.5	976	0.53
47007	Yealm	Puslinch	54.9	1410	0.56
47008	Thrushel	Tinhay	112.7	1143	0.39
48003	Fal	Tregony	87.0	1210	0.68
50002	Torridge	Torrington	663.0	1186	0.39
50006	Mole	Woodleigh	327.5	1306	0.47
52010	Brue	Lovington	135.2	867	0.47
53009	Wellow Brook	Wellow	72.6	998	0.62
54008	Teme	Tenbury	1134.4	841	0.57
54018	Rea Brook	Hookagate	178.0	756	0.51
54025	Dulas	Rhos-y-pentref	52.7	1269	0.37
55029	Monnow	Grosmont	354.0	955	0.59
58005	Ogmore	Brynmenyn	74.3	1976	0.49
61001	Western Cleddau	Prendergast Mill	197.6	1275	0.65
64001	Dyfi	Dyfi Bridge	471.3	1834	0.38
65006	Seiont	Peblig Mill	74.4	2278	0.40
66011	Conwy	Cwm Llanerch	344.5	2055	0.28
67009	Alyn	Rhydymwyn	77.8	969	0.40
68001	Weaver	Ashbrook	622.0	731	0.53
68005	Weaver	Audlem	207.0	719	0.50
69040	Irwell	Stubbins	105.0	~1405	0.44
73005	Kent	Sedgwick	209.0	1732	0.46
75017	Ellen	Bullgill	96.0	1110	0.49
76014	Eden	Kirkby Stephen	69.4	1483	0.24
78003	Annan	Brydekirk	925.0	1351	0.44
79002	Nith	Friars Carse	799.0	1460	0.39
79003	Nith	Hall Bridge	155.0	1505	0.27
81002	Cree	Newton Stewart	368.0	1760	0.27
83005	Irvine	Shewalton	380.7	1228	0.26
84012	White Cart Water	Hawkhead	234.9	1314	0.35
85003	Falloch	Glen Falloch	80.3	2842	0.17
94001	Ewe	Poolewe	441.1	2273	0.65
95001	Inver	Little Assynt	137.5	2211	0.64
97002	Thurso	Halkirk	412.8	1057	0.46

2.1.2 CLASSIC catchments

Table 2.3 gives details of the thirty-five catchments modelled with CLASSIC. The catchment outlets and boundaries are shown in Figure 2.2. The Ness at Ness-side (06007) was originally included in the list of CLASSIC catchments, but was removed as it was felt that the presence of Loch Ness immediately upstream of the gauging station, with complexities of routing and open-water evaporation rather than evapotranspiration from vegetated surfaces as given by MORECS, made a simple application of CLASSIC unrealistic. Other catchments include lakes, lochs and reservoirs but these are mostly in the headwaters and therefore their influence on catchment outflow is considerably dampened. All catchments have been modelled without any direct representation of these water-bodies.

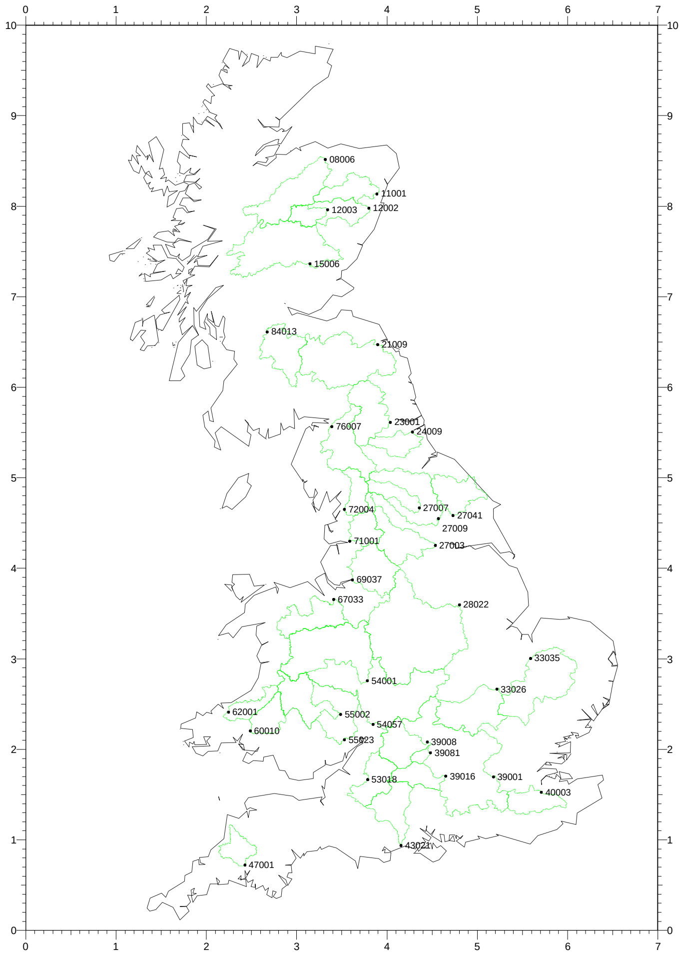

Figure 2.2 CLASSIC catchment outlets and boundaries

Table 2.3 Details of the CLASSIC catchments

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

2.2 Coverage of Britain

Figure 2.3 illustrates the spatial coverage of Britain provided by the project study catchments, by showing the boundaries and outlets of all of the catchments colour-coded by modelling method (see Figure 2.1 or Figure 2.2 for the associated catchment numbers). Note that one catchment (27007) is modelled with both the PDM (daily) and CLASSIC, but is only colour-coded for the PDM (daily) in Figure 2.3.

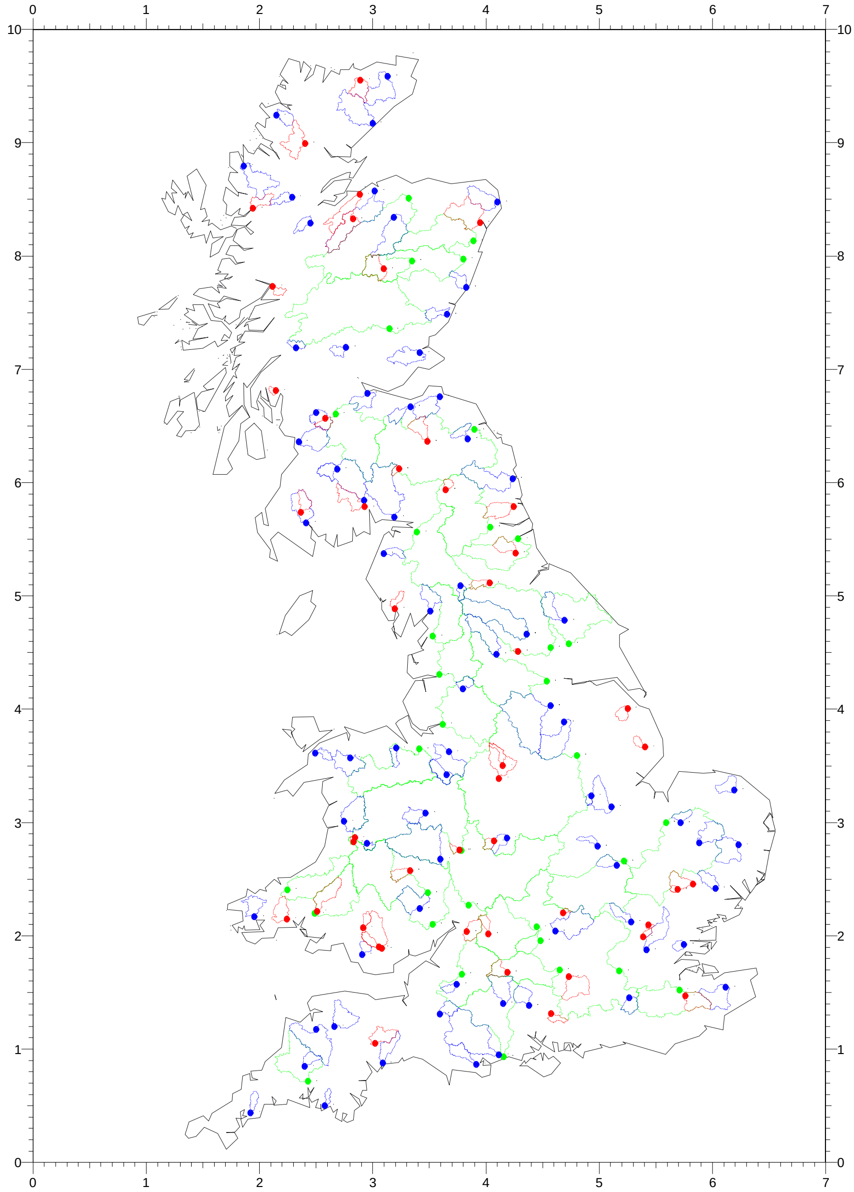

Figure 2.3 Map showing all catchment boundaries (PDM hourly – red, PDM daily – blue, CLASSIC – green)

Table 2.4 summarises the catchments according to the modelling method to be used, and shows that the main difference in the catchment sets is catchment area (by design); $SAAR_{61\text{-}90}$ and BFI have similar means and ranges. Figure 2.4 shows the distributions of these and other catchment properties, such as those from the Flood Estimation Handbook (Institute of Hydrology 1999), as well as those related to soils and land cover. This confirms that the main difference between the sets is catchment area and properties directly related to it, such as DPLBAR (mean drainage path length), with other catchment properties showing more similar distributions between the three sets of catchments. Figure 2.5 illustrates the joint coverage of the space of these catchment properties, by plotting pairs of properties against each other. Definitions of all of the catchment properties shown are given in Table 2.5, but note that some of the properties are transformed before plotting.

Table 2.4 Summary of catchments by modelling method

		PDM hourly	PDM daily	CLASSIC daily	Overall
# Catchments		46	74	35	155 (154 different)
Catchment area (km^2)	minimum	~1	51	234	~1
	mean	162	308	2610	762
	maximum	523	1256	9948	9948
$SAAR_{61\text{-}90}$ (mm)	minimum	589	572	587	572
	mean	1262	1107	1018	1117
	maximum	2913	2842	1595	2913
BFI	minimum	0.17	0.17	0.32	0.17
	mean	0.45	0.51	0.54	0.49
	maximum	0.97	0.96	0.90	0.97

Table 2.5 Definitions of catchment properties

Catchment property name	Range, units	Source	Notes
AREA	[0,∞] km^2	FEH	DTM-derived
ALTBAR	[0,∞] m	FEH	Mean altitude
BFIHOST	[0,1] -	FEH	Base flow index, calculated from weighted average of HOST classes over the catchment
DPLBAR	[0,∞] km	FEH	Mean drainage path length
DPSBAR	[0,∞] m/km	FEH	Mean slope of DTM drainage paths to site
FARL	[0,1] -	FEH	Index of flood attenuation due to reservoirs and lakes
SAAR	[0,∞] mm	FEH	Standard average annual rainfall, 1961-90
SPRHOST	[0,100] -	FEH	Standard percentage runoff derived from weighted average of HOST classes over catchment
URBEXT	[0,1] -	FEH	Extent of urban/suburban land cover ($URBEXT=URB_{FRAC}+0.5\times SUBURB_{FRAC}$)
HOSTGMIN	[0, 1] -	HOST	Proportion of catchment area covered by HOST classes 1-10,13,14 (mineral soils with underlying groundwater)
HOSTPEAT	[0, 1] -	HOST	Proportion of catchment area covered by HOST classes 11,12,15 ('peat soils with groundwater')
HOSTNG	[0, 1] -	HOST	Proportion of catchment area covered by HOST classes 16-29 (essentially 'non-groundwater')
LANDA	[0, 1] -	ITE	Proportion of catchment area covered by grassland, based on ITE land cover data (classes 5-8,19,23)
LANDB	[0, 1] -	ITE	Proportion of catchment area covered by upland, based on ITE land cover data (classes 9-13,17,24,25)
LANDC	[0, 1] -	ITE	Proportion of catchment area covered by trees, based on ITE land cover data (classes 14-16)
LANDD	[0, 1] -	ITE	Proportion of catchment area covered by 'arable', based on ITE land cover data (class 18)

Notes on sources:
FEH Properties appearing on the FEH CD-ROM (Institute of Hydrology 1999)
HOST Properties derived from the HOST soil classification system (Boorman *et al.* 1995)
ITE Properties derived from the ITE 1990 land cover classification (Fuller 1993)

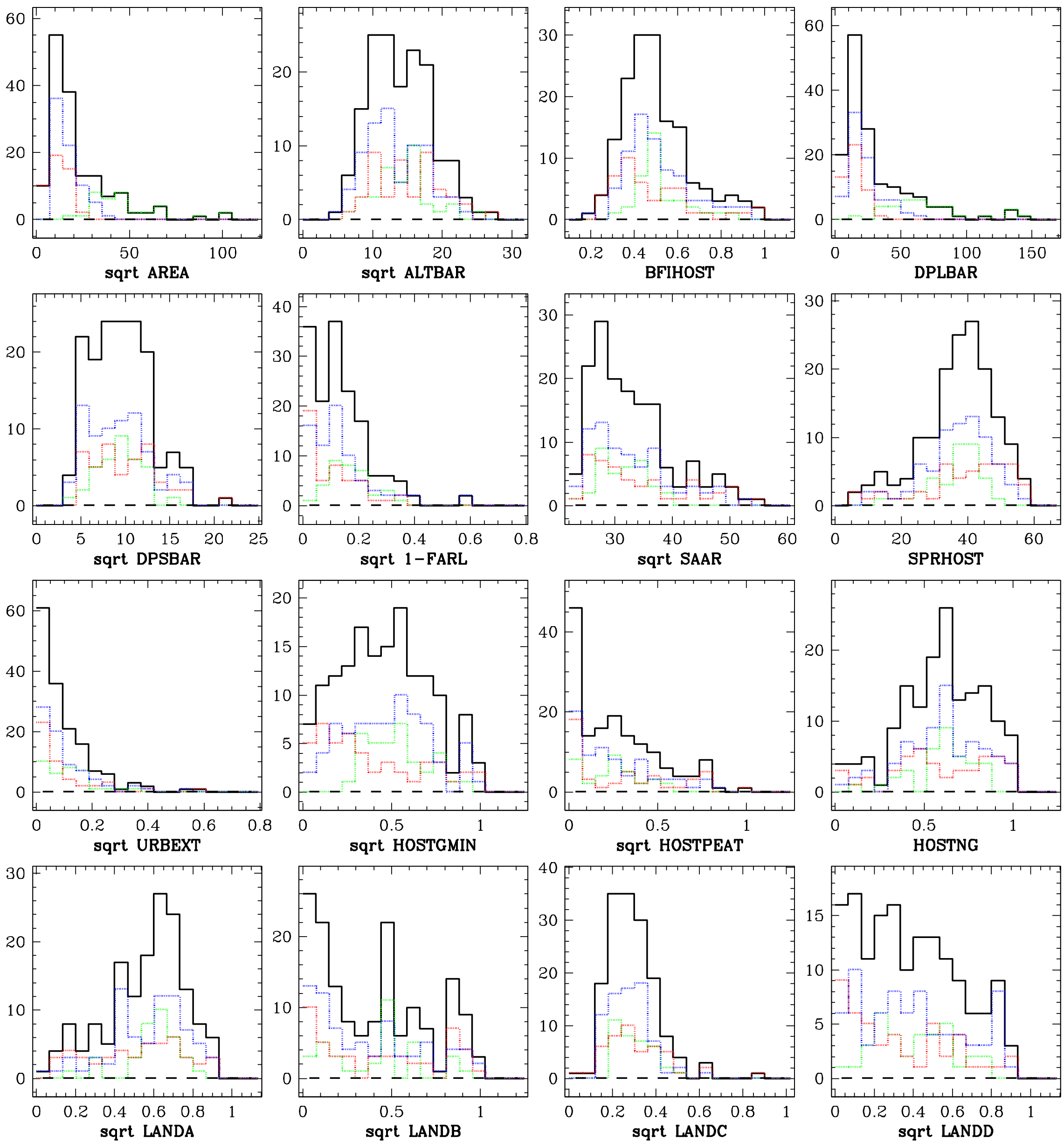

Figure 2.4 Distributions of catchment properties (PDM hourly – red, PDM daily – blue, CLASSIC – green, overall – black)

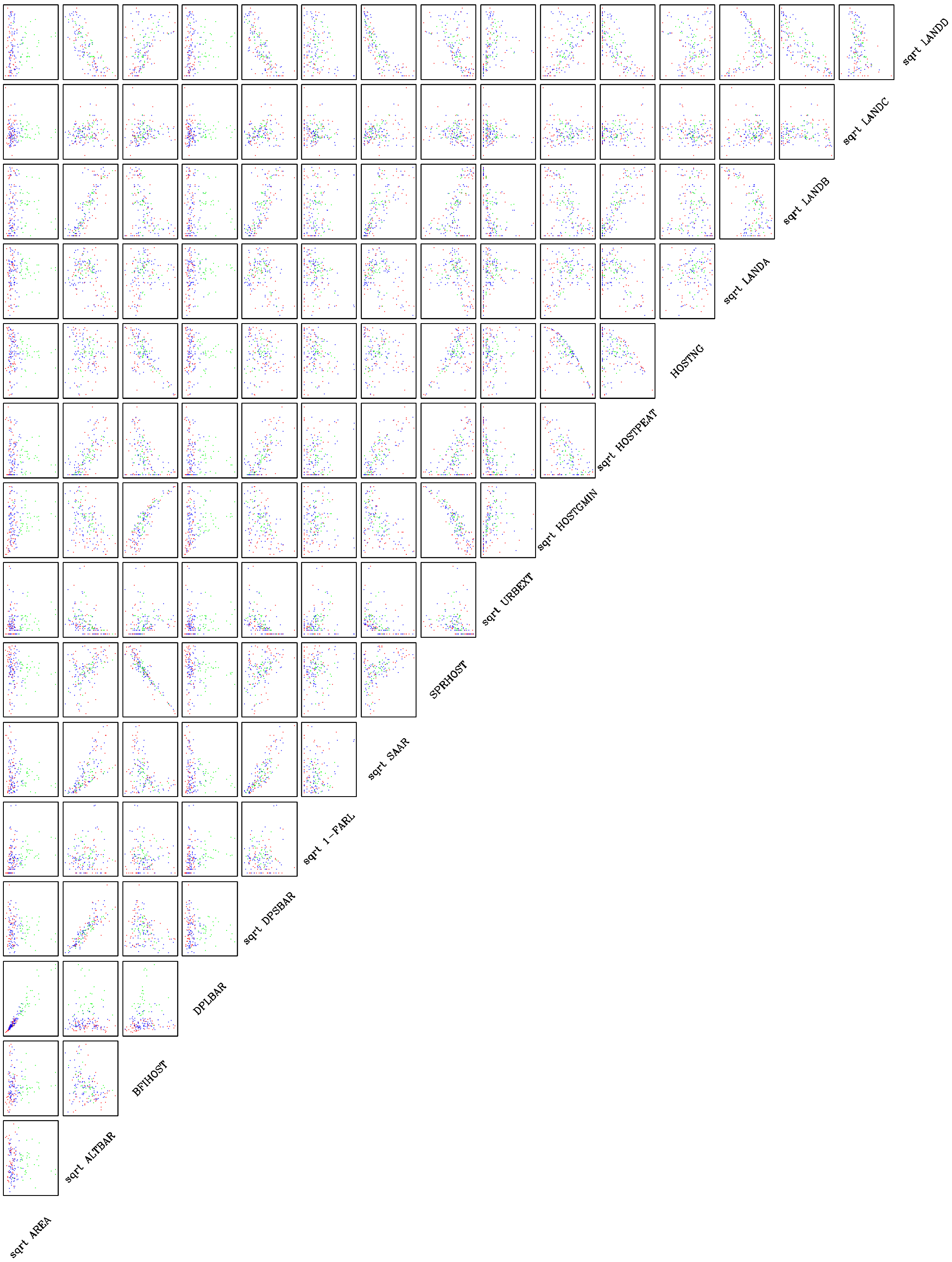

Figure 2.5 Coverage of the catchment property space (PDM hourly – red, PDM daily – blue, CLASSIC – green)

2.3 Baseline data

2.3.1 Availability of rainfall and flow data

Details of the period of concurrent flow and rainfall data available for each catchment are given in Table 2.6 (PDM hourly catchments), Table 2.7 (PDM daily catchments) and Table 2.8 (CLASSIC catchments).

Table 2.6 Data periods for the PDM hourly catchments

Catchment Number	Start date			End date			~# years
	day	month	year	day	month	year	
03003	1	1	1982	31	12	2001	20
07001	1	1	1985	31	12	2001	17
07004	1	2	1985	31	12	2001	17
10003	22	2	1989	31	12	2001	13
12007	13	10	1989	31	12	2001	13
21013	1	1	1986	31	12	2001	16
21017	1	1	1986	31	12	2001	16
22006	1	1	1985	31	12	2001	17
23011	1	1	1985	31	12	2001	17
24005	1	1	1982	31	12	2001	20
25006	1	1	1985	31	12	2001	17
27051	1	1	1985	31	12	2001	17
28008	1	1	1985	31	12	2001	17
28039	1	1	1985	31	12	2001	17
28046	1	1	1985	31	12	2001	17
29001	1	1	1985	31	12	2001	17
30004	1	1	1985	31	12	2001	17
36008	1	1	1985	31	12	2001	17
36010	1	1	1984	31	12	2001	18
38007	1	1	1985	31	12	2001	17
38020	1	11	1987	31	12	2001	15
39007	1	1	1985	31	12	2001	17
39017	1	1	1987	31	12	2001	15
39037	1	1	1985	31	12	2001	17
39073	1	2	1987	31	12	2001	15
40005	1	1	1985	31	12	2001	17
42008	1	1	1985	31	12	2001	17
45003	2	4	1985	31	12	2001	17
54027	1	1	1985	31	12	2001	17
54034	1	1	1985	31	12	2001	17
54090	1	1	1974	31	12	2001	28
55008	1	1	1969	31	12	2001	33
55013	1	1	1985	31	12	2001	17
57005	1	1	1985	31	12	2001	17
57006	1	1	1985	31	12	2001	17
58006	1	1	1985	31	12	2001	17
60002	1	1	1985	31	12	2001	17
60003	29	3	1985	31	12	2001	17
74001	1	1	1985	31	12	2001	17
79005	1	1	1988	31	12	2001	14
81006	1	1	1988	31	12	2001	14
84030	1	1	1992	31	12	2001	10
86001	1	1	1992	31	12	2001	10
90003	1	1	1993	31	12	2001	9
93001	1	1	1992	31	12	2001	10
96001	1	1	1985	31	12	2001	17

Table 2.7 Data periods for the PDM daily catchments

Catchment Number	Start date			End date			~# years
	day	month	year	day	month	year	
02001	1	1	1975	31	12	2001	27
04005	1	1	1986	31	12	2001	16
06008	1	1	1979	31	12	2001	23
07002	1	1	1961	31	12	2001	41
08004	1	1	1961	31	12	2001	41
10002	1	1	1971	31	12	2001	31
13001	1	1	1979	31	12	2001	23
13005	1	1	1981	31	12	2001	21
14001	1	1	1967	31	12	2001	35
16003	1	1	1970	31	12	2001	32
17005	1	1	1971	31	12	2001	31
19011	1	1	1963	31	12	2001	39
20001	1	1	1961	31	12	2001	41
21023	1	1	1970	31	12	2001	32
22001	1	1	1963	31	12	2001	39
27007	1	1	1961	31	12	2001	41
27021	1	1	1961	31	12	2001	41
27043	1	1	1973	31	12	2001	29
27049	1	1	1974	31	12	2001	28
28015	1	1	1982	31	12	2001	20
28066	1	1	1973	31	12	2001	29
30017	1	1	1978	31	12	2001	24
31002	1	1	1961	31	12	2001	41
32003	1	1	1961	31	12	2001	41
33012	1	1	1961	31	12	2001	41
33019	1	1	1962	31	12	2001	40
33029	1	1	1965	31	12	2001	37
34003	1	1	1961	31	12	2001	41
34006	1	1	1963	31	12	2001	39
36005	1	1	1962	31	12	2001	40
37001	1	1	1961	31	12	2001	41
37031	1	1	1976	31	12	2001	26
38003	1	1	1961	31	12	2001	41
39069	1	1	1976	31	12	2001	26
39105	1	1	1989	31	12	2001	13
40011	1	1	1964	31	12	2001	38
42012	1	1	1975	31	12	2001	27
43005	1	1	1965	31	12	2001	37
43007	1	1	1973	31	12	2001	29
44002	1	1	1963	31	12	2001	39
45005	1	1	1962	31	12	2001	40
47007	1	1	1963	31	12	2001	39
47008	1	1	1969	31	12	2001	33
48003	1	1	1978	31	12	2001	24
50002	1	1	1962	31	12	2001	40
50006	1	1	1965	31	12	2001	37
52010	1	1	1964	31	12	2001	38
53009	1	1	1966	31	12	2001	36
54008	1	1	1961	31	12	2001	41
54018	1	1	1962	31	12	2001	40
54025	1	1	1969	31	12	2001	33
55029	1	1	1961	31	12	2001	41
58005	1	1	1970	31	12	2001	32
61001	1	1	1965	31	12	2001	37
64001	1	1	1975	31	12	2001	27
65006	1	1	1976	31	12	2001	26
66011	1	1	1964	31	12	2001	38
67009	1	1	1967	31	12	2001	35
68001	1	1	1961	31	12	2001	41
68005	1	1	1961	31	12	2001	41
69040	1	1	1976	31	12	2001	26
73005	1	1	1968	31	12	2001	34
75017	1	1	1976	31	12	2001	26
76014	1	1	1971	31	12	2001	31

Catchment Number	Start date			End date			~# years
	day	month	year	day	month	year	
78003	1	1	1967	31	12	2001	35
79002	1	1	1961	31	12	2001	41
79003	1	1	1961	31	12	2001	41
81002	1	1	1963	31	12	2001	39
83005	1	1	1972	31	12	2001	30
84012	1	1	1961	31	12	2001	41
85003	1	1	1970	31	12	2001	32
90003	1	1	1982	31	12	2001	20
93001	1	1	1979	31	12	2001	23
94001	1	1	1970	31	12	2001	32
95001	1	1	1977	31	12	2001	25
97002	1	1	1972	31	12	2001	30

Table 2.8 Data periods for the CLASSIC catchments

Catchment Number	Start date			End date			~# years
	day	month	year	day	month	year	
08006	1	1	1961	31	12	2001	41
11001	1	12	1969	31	12	2001	33
12002	1	11	1972	31	12	2001	30
12003	1	7	1975	31	12	2001	27
15006	1	1	1961	31	12	2001	41
21009	1	10	1962	31	12	2001	40
23001	1	1	1961	31	12	2001	41
24009	1	9	1977	31	12	2001	25
27003	1	1	1961	31	12	2001	41
27007	1	1	1961	31	12	2001	41
27009	1	1	1969	31	12	2001	33
27041	1	10	1973	31	12	2001	29
28022	1	10	1968	31	12	2001	34
33026	1	2	1970	31	12	2001	32
33035	1	1	1961	31	12	2001	41
39001	1	1	1961	31	12	2001	41
39008	1	1	1961	31	12	2001	41
39016	1	10	1961	31	12	2001	41
39081	1	10	1962	31	12	2001	40
40003	1	1	1961	31	12	2001	41
43021	1	1	1975	31	12	2001	27
47001	1	1	1961	31	12	2001	41
53018	1	12	1969	31	12	2001	33
54001	1	1	1961	31	12	2001	41
54057	1	7	1971	31	12	2001	31
55002	1	1	1961	31	12	2001	41
55023	1	1	1961	31	12	2001	41
60010	1	1	1961	31	12	2001	41
62001	1	1	1961	31	12	2001	41
67033	6	1	1994	31	12	2001	8
69037	1	1	1986	31	12	2001	16
71001	1	1	1961	31	12	2001	41
72004	1	1	1961	31	12	2001	41
76007	1	10	1967	31	12	2001	35
84013	1	10	1963	31	12	2001	39

2.3.2 Sources and processing of rainfall and flow data

Daily mean flow and raingauge data are available from the National Water Archive, held at CEH Wallingford. The daily raingauge data are used to make catchment-average daily rainfall (CADR), using the Triangle Method of Jones (1983), for input to the PDM, and to make gridded rainfall inputs for CLASSIC.

For the hourly PDM catchments, hourly flow and raingauge data were obtained from the EA and SEPA for previous projects, and the hourly raingauge data were quality-checked against daily raingauge data. For days with good quality hourly rainfall data, this was used to distribute the CADR over the 24 hours of the day. For days without good quality hourly rainfall data, the CADR was distributed using average profiles derived for each catchment using the average variability method (Pilgrim *et al.* 1969). The result of this process is catchment-average hourly rainfall (CAHR). See Lamb and Gannon (1996) and Crooks *et al*. (2002) for more details of the processing of hourly data.

2.3.3 Potential Evaporation data

MORECS (Meteorological Office Rainfall and Evaporation Calculation System) monthly data (Thompson *et al.* 1982; Hough *et al*. 1997) are used to provide catchment potential evaporation (PE) inputs for the PDM and gridded PE inputs for CLASSIC. These data are based on the Penman-Monteith equation for PE (Monteith 1965) and are readily available as average values for 201 40 km × 40 km grid squares across Britain.

For a catchment, weighting the PE data for each MORECS grid square by the proportion of the catchment in that square, and then summing over the squares, produces the monthly PE data for that catchment. Gridded PE for CLASSIC is simply interpolated onto the appropriate catchment grid from the MORECS grid. For each model, the monthly values are then disaggregated equally down to the required input time-step.

3. Calibration (prior to inclusion of snowmelt)

This section describes the set-up and calibration of the models, including the formulation of the PDM to be used in the project, descriptions of how the PDM and CLASSIC are calibrated, and the performance of these calibrations, prior to the inclusion of the snowmelt module.

3.1 Aims and constraints of calibration

Calibration is the process of setting model parameter values which reproduce the characteristics of catchment rainfall-runoff response across the spectrum of hydrological conditions. Generally, calibration is achieved by comparing simulated flows with observed flows, with the difference between them taken as a measure of model performance. The difference can be calculated with a variety of objective functions, which can concentrate on different flow ranges (Madsen *et al.* 2002). Probably the most universally used objective function in hydrological modelling is the model efficiency of Nash and Sutcliffe (1970). A Nash-Sutcliffe value of 1 indicates a perfect fit, whilst a negative value indicates that the fit is worse than that of the mean value. The aim in this study is to obtain a Nash-Sutcliffe value of at least 0.6 for mean daily flows, at least 0.8 for 30-day mean flows and an overall volume error of less than 10%. Additional objective functions have been used during the calibration of the models.

The most important part of calibration, particularly when a hydrological model is used to assess the impact of climate change on a flow regime, is confidence in the modelled relationship between rainfall and runoff which may, or may not, be reflected by good objective function values. If modelled river flows are what would have actually occurred if the given inputs of rainfall and PE had been spatially uniform over the modelling area (catchment or grid) and temporally uniform over the model time step then the model is a good representation of hydrological processes in the catchment. In reality, spatial and temporal uniformity of rainfall is unlikely to occur (except over very small areas and time steps), hence this is one of the main reasons why modelled flows always differ from observed. Care is therefore required during the process of calibration in the interpretation of objective function values. Poor final objective function values should not be disregarded nor the calibration automatically discarded but all values must be evaluated with discretion. A visual comparison of observed and simulated hydrographs should be made to ensure the calibrated parameters result in a realistic temporal runoff response.

It is assumed that model parameters are stationary when calculating impacts of climate change. In this study all available data have been used in the calibration to include as wide a range of hydrological conditions as possible and help ensure that the choice of data period is not a factor in the following impact analysis (Brath *et al.* 2004; Wilby, 2005). Geology, topography, soil type and land use are the main catchment characteristics determining parameter values. Geology and topography are invariant (at least in this time-frame), and while land use and, to a lesser extent, soil characteristics may change with time, in response to human activity and climate, these factors are not within the scope of this study.

3.2 PDM

3.2.1 Background

In previous research (Defra/EA R&D project FD2106, 'National river catchment flood frequency method using continuous simulation') using a five-parameter version of the PDM model (Calver *et al.* 2005), an automatic calibration method was devised. This involved the sequential calibration of four of the parameters (f_c, c_{max}, k_1 and k_b) in a Monte-Carlo, two-pass approach (i.e. using random sampling of so-far uncalibrated parameters, with each parameter being calibrated twice), using a different objective function (measure of fit between simulated and observed flows) for each parameter. [The fifth parameter, α, was preset for each catchment using soils information, much as is being done here; see Section 1.4]. The aim of the project was to develop ways of estimating the parameters of hydrological models, specifically for the purpose of determining flood frequency curves for ungauged sites (those with insufficient concurrent rainfall and flow data to allow the direct calibration of a model), by developing relationships between calibrated parameters and catchment properties. In order to aid the development of such relationships (whether through regression or other means), it was considered necessary to use a model formulation with a reduced number of parameters (compared to the most complex version) so that an automatic calibration routine could be applied for all catchments. It is more appropriate to use a model with fewer parameters in which each parameter plays a more or less independent role than to try and include too much complexity in the model for which there is insufficient data for the model to be well calibrated. Complexity does not necessarily lead to improved model performance. Compatability of model formulation and data helps to minimise problems of equifinality in calibration (Beven, 2006).

The FD2020 project is using many of the same catchments as those used in FD2106, so the model formulation and its calibrations developed there could have been directly applied here. However, the differing aims of the two projects meant that the use of the same model formulation, in which some parameters were assigned the same values across the country, was not applicable. Hence, recalibration was undertaken to ensure the calibrations were appropriate for the climate change context of this project. In any case, the catchments with daily data would have to have been recalibrated for use at a daily time-step; FD2106 applied an hourly model time-step for all models, as the generalisation of model parameters meant that they had to be directly comparable between catchments with daily and hourly data. The automatic calibration method developed in project FD2106 has thus been adapted for use in this project.

3.2.2 Model formulation

The main change to introduce greater flexibility in the PDM was to allow the parameters controlling evaporation rates and soil moisture, principally *b* and b_e, to vary in different regions of the country (in FD2106 they were both set to the value 1, for every catchment). Ideally b and b_e would be included in the parameters calibrated for each catchment but because of the interdependence between the soil store parameters it is necessary when using the automatic calibration routine for them to be pre-set. Following sensitivity modelling using a range of values for b and b_e, the country was divided into two regions, one covering the South and East (S&E; hydrometric areas 22 to 54, up to catchment 54040), and one covering the rest of the country, to the North and West (N&W).

A value of b=0.5 (higher proportion of deep soil stores than shallow soil stores) provided good results for catchments in the S&E, whilst for catchments in the N&W, the original value of b=1 (equal proportion of soil stores of all depths between c_{min} and c_{max}) was retained. The maximum allowed value of c_{max} was increased from 300 to 600mm for catchments in the S&E. Also for catchments in the S&E the value of b_e was set to 2.5, with a value of 2 for the N&W. The value of b_e determines the ratio between actual and potential evaporation depending on soil moisture level. Both of these values give a higher ratio between actual and potential evaporation as the soil store fills, than was used previously (b_e=1). This change allowed higher rates of actual evaporation within the model than was possible with both b_e and b set to 1, with the result that a good fit between observed and simulated catchment water balances could be achieved without the use of a rainfall factor. It was decided that the rainfall factor, f_c, should, at least initially, be set to the value 1 for every catchment (i.e. no change to the calculated catchment average rainfall before input to the model), rather than it being an automatically calibrated parameter, as allowing f_c to take its preferred value through calibration can potentially mask other factors affecting the water balance.

The split parameter, α, is set to be 1-BFIHOST (previously SPRHOST/100), where BFIHOST is the catchment's baseflow index (BFI) as estimated through HOST (Boorman *et al.* 1995) soil classes (Institute of Hydrology 1999).

Catchments with a significant proportion of baseflow (BFI ≥ 0.80) are also treated separately in the initial automatic calibration, with b_e=6, c_{min}=50mm (as against c_{min}=0, which is used for the rest of the catchments), and an even higher maximum allowed value for c_{max} (1000mm). Just eight of the catchments being used in this project fall into this category (29001, 33029, 39037, 39073, 42008, 42012, 43005 and 44002); all are in the far south or east of England.

3.2.3 Automatic calibration method

Once the PDM formulation described above and in Section 1.4 is implemented for each catchment, three parameters remain to be determined by calibration against observed flows. These are c_{max} (the maximum depth of the soil store), and k_1 and k_b (the time-constants of the fast and slow flow stores respectively).

In the first pass, the first parameter to be calibrated is c_{max}, using the Nash-Sutcliffe efficiency measure for the whole flow series based on 30-day mean flows. This calibration is performed with k_1 and k_b taking random values in pre-specified ranges. The value of c_{max} is then set at its optimum value whilst the next parameter (k_1) is calibrated (with k_b taking random values in pre-specified ranges, as before), using an objective function based on the whole flow series but which gives more weight to high flows. Parameter k_b is then calibrated (with c_{max} and k_1 set at their previously calibrated values), using an objective function based on the whole flow series but which gives more weight to low flows.

The second pass allows parameter values to be adjusted based on the calibrated values of the other parameters. The first parameter is again c_{max}, using the same objective function as before, but with k_1 and k_b set at their calibrated values from the first pass. The parameter k_b is next, again using the same objective function as before, but with k_1 and c_{max} set at their latest calibrated values. The order of k_1 and k_b is opposite to that used in the first pass, to allow a final calibration of k_1 using an objective function which looks at the fit of the observed and simulated flood frequency curve, as flooding is the focus of this project. The final calibration of k_1 using the flood frequency fit generally results in an improvement in those measures at the expense of some deterioration in the objective functions that look at the whole time-series, and these two factors have to be balanced.

3.2.4 Results

The automatic calibration procedure described in Section 3.2.3 has been applied to all 120 PDM catchments, and the results have been considered in terms of the fit of the flow time-series, flood frequency curves and overall volume error. A summary of the results is given in Table 3.1, where column 8 indicates whether the catchment and its automatic calibration have been accepted as-is (A), requires some (minor) further investigation (I), is a groundwater-dominated catchment that is likely to benefit from a more manual approach to calibration (G) or requires a more thorough reassessment (R).

A calibration has generally been accepted as-is if the criteria stated in Section 3.1 (before the final calibration of k_1) have been achieved and if a visual inspection of time-series and flood frequency plots (after the final calibration of k_1) does not indicate any problems. Some calibrations meet the quantified criteria but the visual inspection suggests they could be improved, either through manual adjustment of the calibration or through the inclusion of snowmelt modelling, and these have been marked for further investigation. This is also the case for most of the catchments which fail to meet one or more of the quantified criteria, when a value of $f_c \neq 1$ may be appropriate. However, some calibrations have still been accepted as-is despite not meeting one or more of the quantified criteria. This has happened when, for instance, a visual inspection of plots has indicated that the fit is good except for a timing error (to which the Nash-Sutcliffe measure is rather sensitive), or if the catchment description in Hydrometric Data UK suggests a problem with observed data which means that the simulation is probably realistic (e.g. significant abstractions, or a new rating yet to be applied).

Out of 120 PDM catchments, 82 had their automatic calibration accepted as-is, 35 catchments require some further investigation (including 11 catchments which are groundwater-dominated) while three will be reassessed. The map in Figure 3.1 summarises these results spatially.

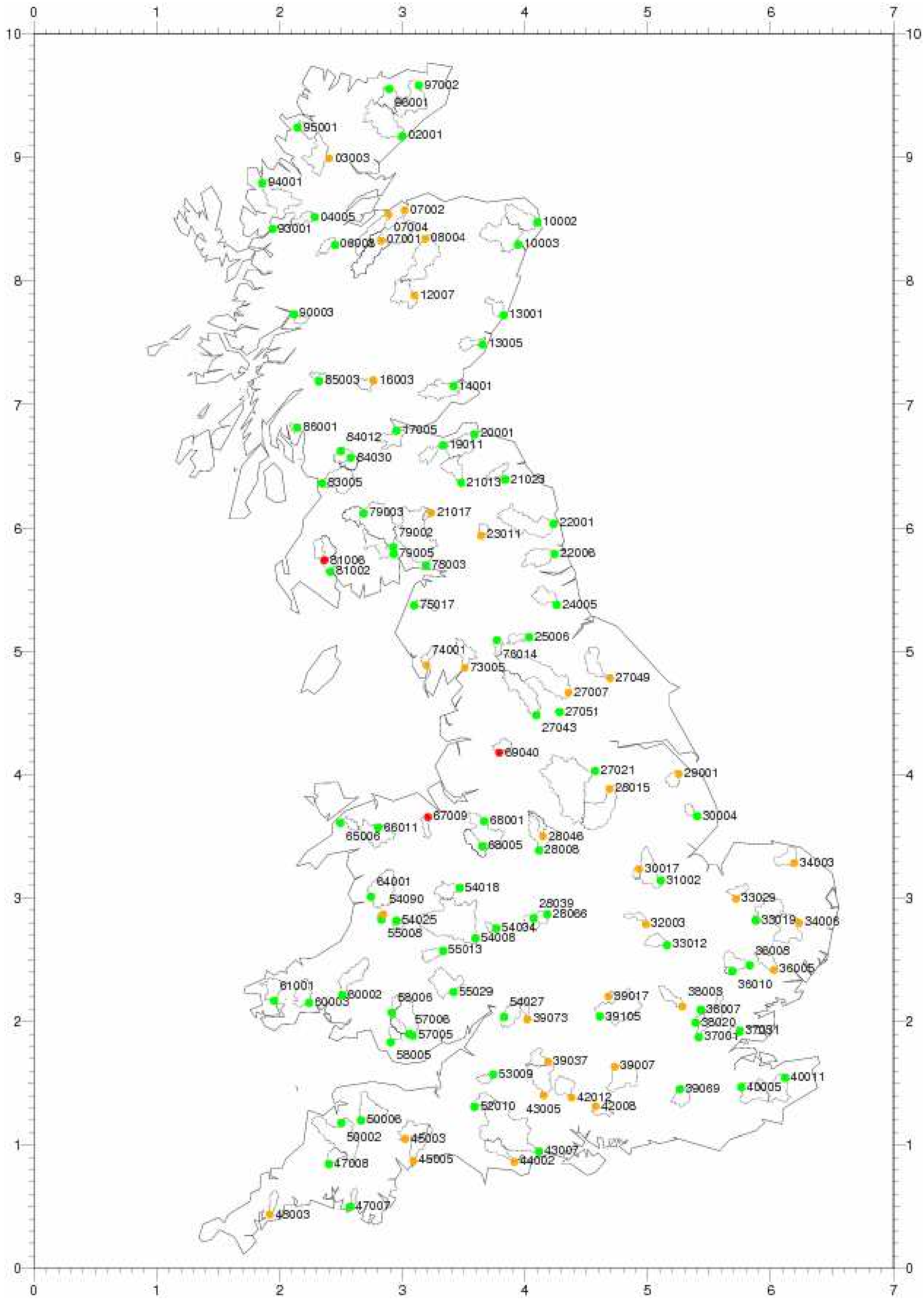

Figure 3.1 Map summarising the performance of the automatic calibration for the 120 PDM catchments. Green dots show catchments whose automatic calibration has been accepted as-is, amber dots show catchments whose calibration requires some further investigation, and red dots show catchments to be reassessed

Table 3.1 Summary of results from automatic calibration of the PDM catchments

Catchment number	full auto-calibration (with final ff fit)			auto-calibration before final ff fit			Decision: A – Accept I – Investigate G – Groundwater R – Reassess
	N&S (1-hour or 1-day)	N&S (30-day)	Volume error (%)	N&S (1-hour or 1-day)	N&S (30-day)	Volume error (%)	
02001	0.37	0.88	-0.64	0.59	0.89	-0.82	A
03003	0.30	0.90	2.05	0.54	0.90	1.41	I
04005	0.51	0.81	8.08	0.61	0.82	7.05	A
06008	0.52	0.90	6.50	0.67	0.91	2.29	A
07001	-0.04	0.56	-3.78	0.16	0.56	-3.44	I
07002	0.13	0.69	-3.38	0.37	0.69	-2.82	I
07004	0.23	0.75	15.57	0.47	0.84	11.67	I
08004	-0.22	0.44	0.52	0.14	0.45	0.84	I
10002	0.19	0.88	-6.64	0.72	0.88	-6.97	A
10003	0.73	0.84	-10.37	0.78	0.84	-10.43	A
12007	-0.04	0.57	-0.30	0.13	0.58	-2.57	I
13001	0.48	0.93	-4.05	0.80	0.93	-4.08	A
13005	0.48	0.90	-5.85	0.76	0.90	-6.01	A
14001	0.58	0.95	0.79	0.81	0.95	0.81	A
16003	0.65	0.91	3.43	0.69	0.91	3.09	I
17005	0.60	0.95	-3.62	0.78	0.95	-3.69	A
19011	0.24	0.87	2.42	0.62	0.87	0.74	A
20001	0.28	0.88	6.41	0.66	0.88	5.30	A
21013	0.51	0.90	-2.05	0.66	0.91	-1.87	A
21017	0.08	0.95	-2.36	0.59	0.95	-2.37	I
21023	0.41	0.84	3.12	0.67	0.84	2.22	A
22001	0.32	0.90	-7.44	0.65	0.90	-7.69	A
22006	0.60	0.91	7.71	0.67	0.91	7.60	A
23011	-0.12	0.89	-4.54	0.37	0.89	-4.50	I
24005	0.38	0.94	3.76	0.52	0.94	3.82	A
25006	0.25	0.92	-6.58	0.50	0.92	-6.62	A
27007	0.34	0.91	-0.88	0.71	0.91	-1.16	I
27021	0.54	0.83	-4.93	0.76	0.84	-5.17	A
27043	0.44	0.94	-1.86	0.75	0.94	-2.34	A
27049	0.19	0.88	-7.90	0.67	0.88	-8.08	I
27051	0.19	0.93	-2.94	0.41	0.93	-2.89	A
28008	0.60	0.97	-3.45	0.77	0.97	-3.56	A
28015	0.37	0.59	-8.06	0.61	0.58	-5.90	G
28039	0.24	0.61	-2.52	0.56	0.61	-2.51	A
28046	0.54	0.88	-8.07	0.80	0.89	-7.89	I
28066	0.57	0.77	-15.21	0.70	0.77	-14.86	A
29001	-0.85	-0.51	75.45	-	-	-	G
30004	0.60	0.85	0.41	0.66	0.85	0.46	A
30017	0.25	0.81	9.41	0.59	0.81	9.38	I
31002	0.38	0.76	23.27	0.59	0.73	21.70	A
32003	0.05	0.89	6.49	0.64	0.89	6.51	I
33012	0.38	0.88	17.66	0.66	0.88	16.64	A
33019	0.73	0.88	-4.32	0.76	0.88	-4.75	A
33029	0.66	0.72	-7.54	-	-	-	G
34003	0.43	0.52	0.71	0.55	0.46	-0.11	G
34006	0.25	0.85	7.24	0.62	0.86	6.94	I
36005	0.22	0.88	9.69	0.68	0.88	10.06	I
36008	0.63	0.75	-7.78	0.63	0.75	-7.89	A
36010	0.38	0.87	24.34	0.47	0.87	24.46	A
37001	0.57	0.92	-2.17	0.81	0.93	-2.33	A
37031	0.12	0.82	-7.76	0.54	0.83	-8.39	A
38003	0.10	0.35	22.12	-0.38	0.08	28.13	G
38007	0.59	0.92	-8.61	0.70	0.92	-8.61	A
38020	0.44	0.95	7.90	0.63	0.95	8.54	A
39007	0.85	0.93	-0.26	0.84	0.94	-0.14	I
39017	-0.34	0.86	4.97	0.49	0.86	4.95	I
39037	0.68	0.76	25.26	-	-	-	G
39069	0.27	0.87	-9.07	0.74	0.88	-9.54	A
39073	0.41	0.78	6.73	-	-	-	G
39105	0.67	0.96	-1.50	0.85	0.96	-1.46	A
40005	0.69	0.94	14.84	0.65	0.95	15.13	A
40011	0.61	0.91	3.90	0.82	0.90	4.13	A
42008	0.63	0.69	16.01	-	-	-	G
42012	0.53	0.55	-12.27	-	-	-	G
43005	0.77	0.88	-4.86	-	-	-	G
43007	0.55	0.97	0.18	0.85	0.97	-0.09	A
44002	0.84	0.88	3.39	-	-	-	G

Catchment number	full auto-calibration (with final ff fit)			auto-calibration before final ff fit			Decision: A – Accept I – Investigate G – Groundwater R – Reassess
	N&S (1-hour or 1-day)	N&S (30-day)	Volume error (%)	N&S (1-hour or 1-day)	N&S (30-day)	Volume error (%)	
45003	0.03	0.94	4.35	0.70	0.94	4.23	I
45005	0.26	0.90	7.86	0.68	0.90	7.76	I
47007	0.68	0.97	-4.05	0.84	0.97	-4.05	A
47008	0.76	0.93	0.46	0.81	0.93	0.19	A
48003	0.63	0.95	-2.42	0.84	0.96	-2.55	I
50002	0.40	0.97	-6.70	0.83	0.97	-6.89	A
50006	0.57	0.98	-1.14	0.87	0.98	-1.27	A
52010	0.41	0.93	-4.12	0.75	0.93	-4.37	A
53009	0.73	0.96	-0.92	0.91	0.96	-1.01	A
54008	0.69	0.95	-3.04	0.84	0.95	1.03	A
54018	0.63	0.93	0.92	0.76	0.93	6.23	A
54025	0.83	0.97	1.67	0.86	0.97	3.31	A
54027	0.84	0.93	-4.50	0.85	0.94	-0.67	A
54034	0.44	0.94	3.28	0.71	0.89	14.51	A
54090	0.04	0.94	-3.10	0.69	0.94	-3.32	I
55008	0.04	0.96	-2.28	0.69	0.96	-2.34	A
55013	0.48	0.93	8.50	0.77	0.94	8.03	A
55029	0.52	0.94	3.59	0.74	0.95	1.53	A
57005	0.52	0.97	-0.48	0.81	0.97	-0.47	A
57006	0.61	0.97	-2.14	0.81	0.97	-2.41	A
58005	0.40	0.90	-7.26	0.77	0.90	-7.56	A
58006	0.33	0.97	0.44	0.67	0.97	0.42	A
60002	0.55	0.96	-1.36	0.76	0.96	-1.39	A
60003	0.70	0.89	-11.24	0.77	0.89	-11.07	A
61001	0.67	0.92	-7.53	0.85	0.92	-7.62	A
64001	0.55	0.93	-5.30	0.83	0.93	-5.43	A
65006	0.23	0.89	-5.45	0.77	0.90	-6.27	A
66011	0.66	0.96	-2.65	0.78	0.96	-2.94	A
67009	0.02	-0.10	119.91	0.09	0.15	105.16	R
68001	0.55	0.90	-2.46	0.80	0.90	-2.48	A
68005	0.50	0.89	6.40	0.76	0.89	6.43	A
69040	0.54	0.79	-3.99	0.73	0.79	-10.67	R
73005	0.58	0.97	-4.83	0.82	0.97	-5.00	I
74001	-0.10	0.95	1.86	0.53	0.95	1.88	I
75017	0.49	0.93	-7.67	0.82	0.94	-7.64	A
76014	0.74	0.95	1.24	0.75	0.95	0.61	A
78003	0.40	0.96	-5.17	0.84	0.97	-5.32	A
79002	0.46	0.97	0.04	0.81	0.97	-0.11	A
79003	0.58	0.96	-2.04	0.80	0.96	-2.36	A
79005	0.69	0.97	-1.81	0.80	0.97	-1.77	A
81002	0.49	0.96	-0.83	0.79	0.96	-1.16	A
81006	-0.23	0.96	0.41	0.72	0.97	0.44	R
83005	0.52	0.90	1.14	0.76	0.91	0.76	A
84012	0.09	0.05	6.17	0.32	0.05	6.18	A
84030	0.24	0.97	-0.61	0.80	0.97	-0.54	A
85003	0.71	0.85	10.10	0.74	0.88	7.25	A
86001	0.47	0.86	10.12	0.58	0.87	9.50	A
90003	0.32	0.88	2.95	0.63	0.88	3.11	A
93001	0.37	0.93	-7.51	0.69	0.92	-8.83	A
94001	0.84	0.94	0.70	0.80	0.93	-3.17	A
95001	0.67	0.88	3.08	0.75	0.88	1.36	A
96001	0.40	0.89	-4.46	0.57	0.90	-4.65	A
97002	0.37	0.92	-3.01	0.66	0.92	-3.27	A

3.2.5 Manual calibration for groundwater catchments

Looking at the automatic calibration results for catchments with a significant proportion of baseflow, it was decided that this particular subset of 11 catchments (designated 'G' in Table 3.1, including the 8 catchments discussed at the end of Section 3.2.2) would benefit from manual calibration using an interactive version of the PDM. The regime of these catchments is groundwater-dominated with, as a general rule, at least 75% of the total flow being baseflow (see Figure 1.2) as determined by BFIHOST. Improvement in calibration was achieved through four main types of parameter change:

- Parameters controlling evaporation and water balance; c_{max}, c_{min} and b_e were allowed to vary from the selected values used in the initial calibration of the groundwater catchments. The maximum soil store depth c_{max} > 600 mm for five catchments; c_{min} = 50 mm for two catchments; b_e = 6 for four catchments.
- Parameter controlling proportion of baseflow; α. For three catchments a better fit was achieved using BFI rather than BFIHOST. (For most catchments these are, as expected, very similar but for some catchments, not just groundwater dominated, they are noticeably different).
- Time constant parameters; k_1 and k_b. In groundwater dominated catchments these may be very similar and for some of the catchments the values from the automatic calibration were manually adjusted to improve the fit of the baseflow.
- Rainfall factor; f_c. For four catchments, Hydrological Data UK (Marsh and Hannaford, 2008) indicates that the topographical catchment area differs significantly from that of the groundwater catchment, and for these a value of $f_c \neq 1$ was used (with $f_c > 1$ for two catchments and $f_c < 1$ for two catchments).

Criteria for calibration were visual fit of observed and modelled flow recessions, low flows and flood frequency curve using objective function values as a guide to overall model performance. Allowance was made for known factors affecting gauged flows, such as groundwater abstraction, by-passing of the flow gauge at high flows and seasonal weed growth affecting low flows.

Improved objective function values were achieved through manual calibration for 10 of the 11 catchments, with the calibration for the other catchment (34003) not changed (Table 3.2). Although not all target values have been met it was felt, from the hydrograph and flood frequency fit, that the calibrated parameter values provided an acceptable simulation of the catchment response. For catchment 29001, groundwater abstraction and abstraction for irrigation have a significant effect on low flows, contributing to the very poor objective function values.

Table 3.2 Results from manual calibration of groundwater catchments

Catchment number	Time-step	N&S (1-hour or 1-day)	N&S (1-day or 30-day)	Volume error (%)
28015	daily	0.47	0.66	-13.9
29001	hourly	0.02	0.01	57.4
33029	daily	0.74	0.77	14.1
34003	daily	0.44	0.51	0.0
38003	daily	0.75	0.79	0.6
39037	hourly	0.71	0.72	5.1
39073	hourly	0.70	0.70	-0.1
42008	hourly	0.82	0.82	4.3
42012	daily	0.77	0.78	-4.2
43005	daily	0.88	0.93	5.7
44002	daily	0.82	0.89	3.3

3.2.6 ‘I’ and ‘R’ catchments

As shown in Table 3.1 a number of catchments were designated ‘I’ (Investigate) or ‘R’ (Reassess) following the automatic calibration. Catchment history, data quality and calibrations for these catchments were investigated to ascertain if there were identifiable reasons for the lack of model performance, other than from snowmelt.

For the ‘I’ catchments, manual calibration was undertaken for those catchments where the automatic routine resulted in similar values of k_1 and k_b, or where BFI was noticeably different to BFIHOST. A number of catchments have rating problems including instability of the rated section and weed growth at low flows; rating uncertainty and bypassing at the high flow range are also factors in poor correspondence between observed and simulated flood frequency curves.

The three ‘R’ catchments were all reassessed and then two were manually calibrated to allow for known problems. Catchment 67009 has swallow holes upstream of the gauging station so low flows are frequently zero. Modelled hydrograph response for medium and high flows now compares well with observed, with good simulation of the flood frequency curve. Catchment 69040 is now a discontinued station due to a very variable rating so calibration aimed to represent overall response patterns without matching of peak flows, which are excessively high. Modelled peak flows are compatible with those at 69022 (the replacement station, 2 km upstream of 69040). The problem with catchment 81006 is simulation of the flood frequency curve. Overall hydrograph response is reasonable but extreme peak flows are underestimated.

3.3 CLASSIC

3.3.1 Calibration method

CLASSIC has been calibrated for 35 catchments. A major consideration when calibrating a hydrological model for these large catchments is that the gauged flow is rarely natural runoff; in most catchments the flow is affected by water utilisation within the catchment and many have river regulation and transfers of water into or out of the catchment. In one catchment, the Ely Ouse (33035), the observed flow from 1975 is frequently zero due to complex water management. The record for the Mersey (69037) is for only part of the total flow from the catchment. Therefore, criteria for calibration must make allowance for these factors and for other alterations to the natural flow regime. A few, notably the Thames (39001), have naturalised flow series allowing direct comparison between observed and modelled flows. Data for the short record for the Dee (67033) have been supplemented with data from earlier gauging stations 67020 and 67026 (all with the same catchment area).

Characteristic values for the soil water balance and drainage module parameters have been determined using land use, soil and DTM data during development of the model on catchments and sub-catchments with relatively natural, or naturalised, flow records. In calibration of CLASSIC for this project the catchments were divided into three groups:

1. 9 catchments which had been previously calibrated.
2. 13 catchments chosen to give a broad geographic and physiographic distribution and with reasonable quality flow data.
3. The remaining 13 catchments, including those with known data problems.

The aim of calibration was to simulate the flow regime as it would be with no human interference. Land-use data from the 1990 survey (Fuller 1993) have been used to provide the land use percentages for each grid square, as this is more appropriate to the time-scale of the flow data (up to 2001) than the more recent survey in 2000 (Fuller *et al.* 2002).

Calibration of the catchments in the second group was performed using the previously determined relationships between catchment properties and soil moisture and drainage module parameters. Routing parameters were determined by optimisation with a simplex routine with fine-tuning using visual fit of the flood frequency curve. Objective functions used to determine goodness-of-fit were Nash-Sutcliffe model efficiency for daily and monthly flows and monthly, annual and total time-period volume error. Minor adjustments were made to the parameter/catchment property relationships from the results of these 13 catchments and to extend the parameter space to include soil types not fully included in previous calibration work. Where appropriate, these adjustments were applied to re-calculate parameter values for the nine catchments in the first group. Finally, the catchments in the third group were set-up and calibrated using the adjusted parameter / catchment property relationships for the soil moisture and drainage modules, and by calibration against visual fit of the flood frequency curve combined with appropriate catchment properties for the routing parameters. [In general, high flows are the least affected by catchment water usage, but are subject to considerable measurement error]. Thus, all catchments modelled with CLASSIC have a common parameterisation based on physical catchment properties which ensures spatial consistency in simulated flows.

3.3.2 Results

Results from the calibration of catchments with CLASSIC are summarised spatially in Figure 3.2 and detailed in Table 3.3. However, in assessing the Nash-Sutcliffe values and volume error it must be remembered that these are against observed flows which may include considerable water usage. Catchment numbers in bold are those in the first group, those in ordinary type are in the second group and those in italics are catchments in the third group.

Despite the generalised method of calibration and the problems of water usage the results for the majority of catchments (25) are within the three criteria given in Section 3.1 for accepting the calibration (N&S 1-day ≥ 0.6, N&S 30-day ≥ 0.8 and volume error ≤ 10%). N&S values for catchments in Scotland (1-day and 30-day) and Northern England (1-day) are affected by timing-errors probably caused by snowfall and subsequent melt.

Table 3.3 Results from calibration of the CLASSIC catchments

Catchment number	N&S (1-day)	N&S (30-day)	Volume error (%)	Factors affecting gauged flow[1]
08006	0.39	0.57	-0.3	4
11001	0.67	0.82	-8.2	
12002	0.46	0.73	-6.2	1
12003	0.17	0.51	-8.8	
15006	0.75	0.90	-8.5	1 2 4
21009	0.76	0.93	0.6	1 2
23001	0.55	0.88	-10.3	2
24009	0.60	0.90	-1.3	4
27003	0.86	0.95	-1.8	1 2 3 5
27007	0.78	0.93	-4.2	1 2
27009	0.85	0.96	-0.2	1 2 4 5
27041	0.86	0.96	-2.8	1 4 5
28022	0.87	0.95	-5.4	1 2 3 4 5
33026	0.88	0.95	1.8	1 2 3 5
33035	0.55	0.85	-13.8	3 4 5
39001[2]	0.93	0.97	0.5	1 2 3 4 5
39008	0.89	0.95	7.0	1 2 3
39016	0.87	0.92	-1.7	4 5
39081	0.84	0.94	0.3	3 4
40003	0.80	0.92	3.3	1 2 4
43021	0.93	0.95	-2.7	1
47001	0.80	0.96	-6.1	1 2 3 4 5
53018	0.86	0.93	-8.3	1 3 4
54001	0.88	0.95	11.1	1 2 3 4 5
54057	0.91	0.97	5.5	1 2 3 4 5
55002	0.88	0.96	3.5	1 2
55023	0.83	0.95	-1.8	1 2 3
60010	0.83	0.96	-6.5	1 4
62001	0.87	0.93	-12.4	1 2
67033	0.88	0.90	18.0	1 2 3 4 5
69037	0.59	0.78	6.9	1 2 3 4 5
71001	0.66	0.95	-2.6	2 3
72004	0.59	0.97	-4.3	1 2 4
76007	0.84	0.97	7.2	1 2
84013	0.83	0.95	-5.9	3

[1] Factors affecting gauged flow (www.nwl.ac.uk/ih/nrfa/station_summaries):

1. abstraction for public water supply;
2. reservoir(s) in catchment;
3. runoff increased by effluent returns;
4. regulation from surface and/or groundwater;
5. abstraction for industrial/agricultural use.

[2] Results for naturalised flow record.

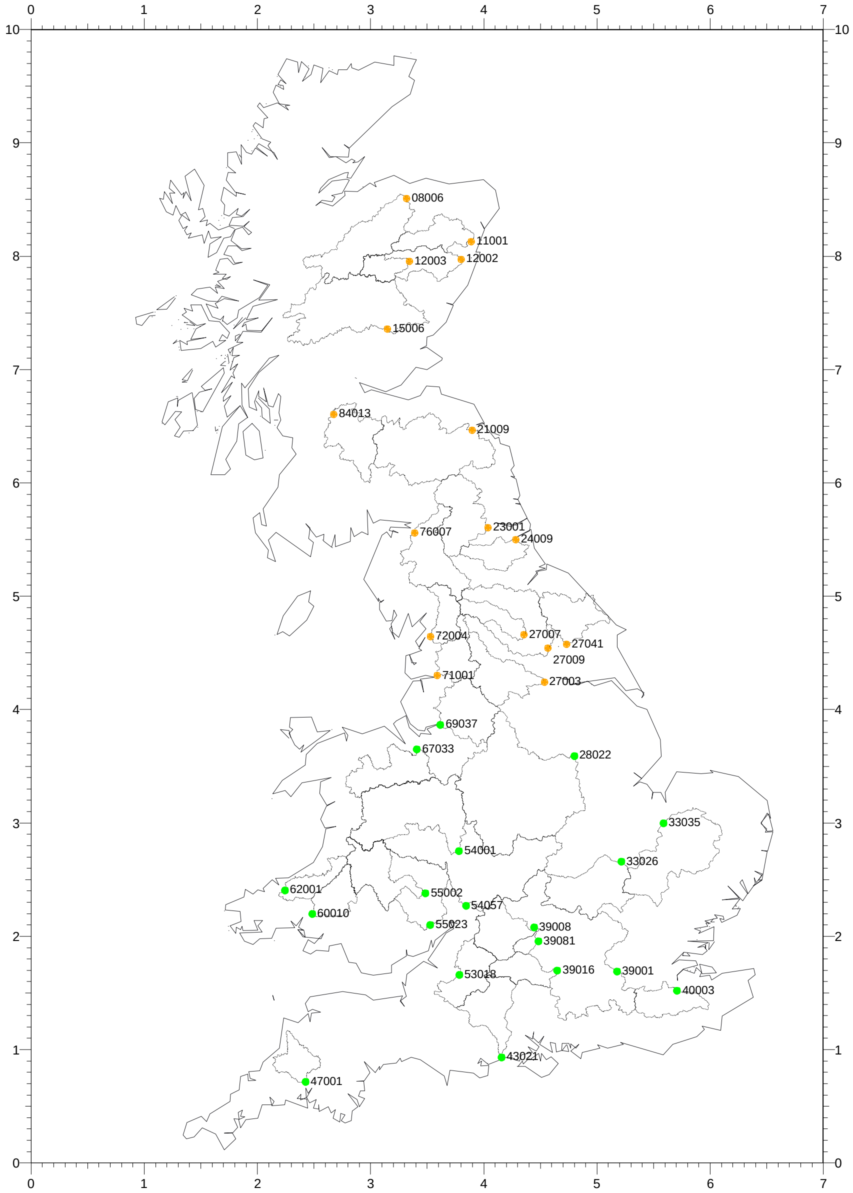

Figure 3.2 Map summarising the performance of the calibration for the CLASSIC catchments. Green dots show catchments whose calibration is acceptable, while amber dots show catchments whose calibration requires some further investigation with the inclusion of snowmelt

3.4 Discussion

The calibration procedure for both models aimed to ensure that the parameter values assigned for each catchment simulate river flow with similar rainfall-runoff response and statistical properties as those of the observed flow record, particularly within the high flow range. For catchments in Scotland (and to a lesser extent North-East England) timing effects on runoff from snowmelt and consequent impact on flood peaks are apparent during many winters. As timing between rainfall input and runoff output is a critical factor in calibration of flow routing parameters these catchments cannot be satisfactorily calibrated without including allowance for snowfall. It is also important when modelling impacts of climate change, which will affect the incidence of snowfall, that parameter values are not compromised by being calibrated with data that contain a range of timing patterns between precipitation and runoff. Therefore, to obtain flow routing values, k_1 in the PDM and the routing parameters in CLASSIC, which are appropriate for simulating flows with snow (20th century) and without (late 21st century?), it is necessary to calibrate with a snowmelt module. Details of the module and its calibration are given in the following sections.

The integrity of the calibration procedure in hydrological modelling is essential for meaningful interpretation of climate change impacts. The procedure followed in this project has endeavoured to ensure that calibrations are based on good quality data (or reasons known for anomalies) and that derived parameter values represent stable catchment rainfall-runoff processes. However, uncertainty affects all aspects of the modelling process including data accuracy of both climate and flow data, data periods used for calibration, spatial and temporal representation of hydrological processes and model structure and calibration. Much has been researched and written about uncertainty within hydrological modelling and the impacts of uncertainty on results and conclusions drawn from such modelling (e.g. Beven 2006, Wilby 2005). Effects of uncertainty within the hydrological modelling phase on results from the climate change impact assessment will be considered within the project milestone report on uncertainty (Kay *et al.* 2009).

4. Snowmelt modelling

4.1 Background

Many previous studies of the impact of climate change on river flows and flood frequency in Britain have ignored the role of precipitation falling as snow, and of subsequent snowmelt. However, given that this project aims to *regionalise* the impacts of climate change on flooding, it was considered important to include these processes as the winter flow regime of upland catchments can be considerably affected by snowfall and snowmelt, even in the UK (e.g. Archer, 1981; Ferguson, 1984), and changes in temperature will almost certainly alter the balance between snowfall and rainfall processes in such catchments in the future. A preliminary study was undertaken to assess the role of snowmelt by testing the inclusion of a snowmelt module on the Dee catchment in Scotland (Crooks 2006) using temperature data from synoptic sites. This study showed the improvement in temporal simulation of flows when including snowfall and snowmelt and gave an indication of the difference when determining impacts of climate change.

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

4.2 Temperature data

Time-series of daily minimum and maximum temperature data for the period 1960 to 2006 have been produced by the Met Office as one of the UKCP09 products, on a 5km grid over the UK. An example of these data is shown in Figure 4.1. These data, which are estimates of the temperature at the centre of each 5km x 5km grid box, have been used as input to the snowmelt module for the PDM and CLASSIC.

Also required is information on the altitude to which the temperatures relate. As this was not provided with the temperature data itself, altitudes have been taken from the corresponding points (grid box centres) within the IHDTM (Morris and Flavin 1990), which has a 50m horizontal resolution. The need to use altitude data from a different DTM to that which had been used by the Met Office in the production of the temperature data is not ideal, given that inconsistencies could be introduced. However, it was necessary in order for this project to progress, and any errors should be minimal given other assumptions.

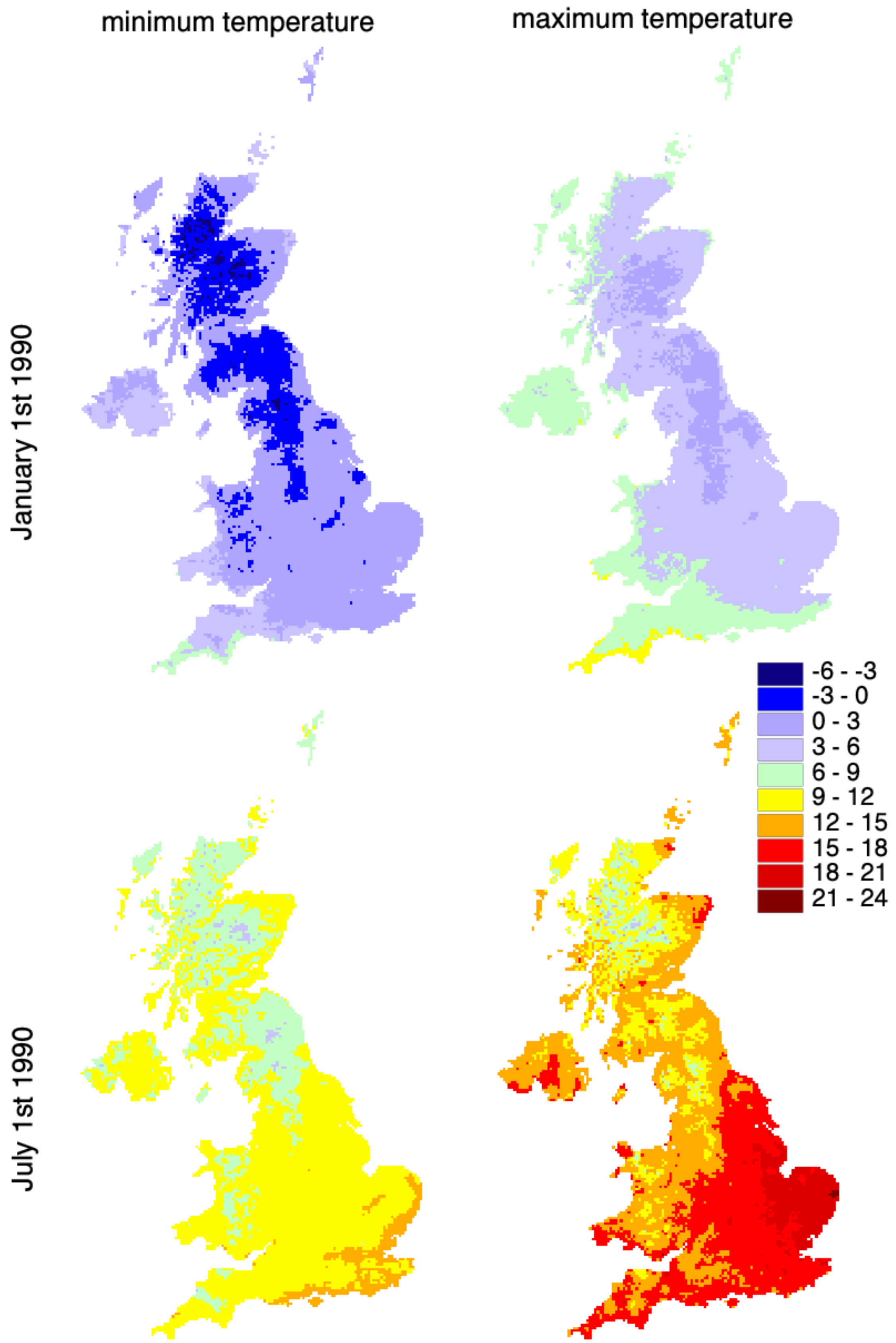

Figure 4.1 Example gridded daily minimum and maximum temperature data, for two days in 1990 (degrees celsius)

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

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

4.3 The snowmelt module

Snow hydrology covers a range of complex processes which impact particularly on timing of runoff, with the additional fact that snow and its subsequent melt are highly spatially variable, even more than for rainfall. In modelling these processes it is again important to keep model complexity compatible with available data and the purpose of the simulation. A model was required which was appropriate for all catchments and could be calibrated using only temperature and elevation data. Its main purpose is to improve timing in upland areas between precipitation and runoff when calibrating the main hydrological models and simulate impacts of changing temperature on flood events. A snow module devised by Bell and Moore particularly for improved snowmelt forecasting in Britain using the PDM (Moore *et al.* 1999; Bell and Moore 1999) was considered suitable for the purpose and was adapted to use with both the PDM and CLASSIC hydrological models. The module is essentially used as a pre-processor for the rainfall inputs to the PDM and CLASSIC, meaning that input of water is delayed if snowfall occurs. The version employed uses a simple temperature-related snow store and melt rate with eight parameters (Table 4.1).

The module operates within each catchment (PDM) or modelling grid square (CLASSIC) with separate accounting within elevation zones, using a DTM to determine the area for each elevation zone within a catchment/grid square. Mean daily temperatures for each zone are determined by $T_i = T_j - \alpha (z_i - z_j)$, where T is temperature, z is elevation, α is temperature lapse rate, and i and j are locations, in this case an elevation zone and centre of a temperature grid box respectively. A lapse rate of $\alpha = 0.0059\ ^{o}\mathrm{Cm}^{-1}$ was used.

Table 4.1 Snowmelt module parameters

Parameter	Description	Value used
T_{snow}	Threshold temperature below which precipitation is snow	1.0 °C
T_m	Threshold temperature for snow melt	0.0 °C
T_{drel}	Threshold temperature for drainage release	0.0 °C
mfac	Melt factor	6.0 mm/day/°C
k_{1s}	Storage time constant: lower outlet	0.5 day^{-1}
k_{2s}	Storage time constant: upper outlet	0.9 day^{-1}
s_c	Maximum liquid water content as proportion of total	0.18 -
rgfac	Correction factor for gauged rainfall when falling as snow	1.1 -

The elevation zone temperature, T_i, determines for that zone whether precipitation falls as rain or snow (by comparison with T_{snow}), whether melt can occur (by comparison with T_m), and how much of any snowpack is released as melt (by comparison with T_{drel}). The snowpack is represented conceptually as having two stores, a 'dry' store and a 'wet' store. Precipitation falling as snow is added to the dry store, and that falling as rain is added to the wet store unless the dry store is empty, in which case the wet store is bypassed and the rainfall is added directly to the output from the snowpack. Melt from the dry store, calculated as $mfac(T_i - T_m)$, is also added to the wet store. The wet store has lower and upper outlets with drainage rates given by k_{1s} and k_{2s}; drainage occurs at a faster rate from the upper outlet when a critical liquid water proportion, s_c, is exceeded. The combined drainage from the two wet store outlets (plus any rainfall bypassing the wet store) from all elevation zones becomes the input to the rainfall-runoff model.

Initial test runs of the snowmelt module over a number of catchments, with the gridded temperature data, used a set of typical parameter values taken from Bell and Moore (1999) and Moore *et al.* (1999), which were also used in the preliminary study for the Dee (Crooks 2006). Further calibration runs allowed the most sensitive parameters, T_{snow} and *mfac*, to vary between catchments but with the aim of determining a set of constant values which would provide reasonable results for all snowmelt flood events across all catchments. T_{snow} determines the time periods (and hence the volume) of incoming precipitation falling as snow while *mfac* is particularly critical for peak flows. Values of T_{snow} were tested between 0 °C and 3 °C, with *mfac* from 3 to 8 mm/day/°C. The final selected set of parameter values is given in Table 4.1 which are consistent with values from other studies (Fontaine *et al.* 2002).

A value of T_{snow} of 1 °C was generally found to give the best results (rather than the initial value of 3 °C) which is to be expected given the improved spatial representation from the gridded daily temperature data. An additional parameter, *rgfac*, was introduced in the calibration to allow for errors in measurement (underestimation) when precipitation falls as snow; when the temperature is less than T_{snow} the precipitation is multiplied by *rgfac*. Thus *rgfac* affects the volume of snowfall as well as T_{snow}, so the calibrated values of these two parameters aimed to balance timing of runoff with volume of flow.

Use of an overall average melt rate, *mfac,* is more problematic, as different rates are required for different events and different elevations to accurately simulate all flood events which include snowmelt. This range of rates is probably a consequence of many factors including variations in snow cover spatially and with aspect, the use of a constant temperature lapse rate, the type of snow and the temporal pattern of temperature during the 24-hour period. For example, the average of daily maximum and minimum temperatures may be close to 0 ^{o}C, but the temperature during the 24 hours may have been well above freezing for much of that time. Thus, in reality a considerable volume of melt may have occurred whereas the modelled volume, from the daily mean temperature, is small. A value of 6.0 mm/day/^{o}C provides a reasonable compromise slightly biased towards the higher flood events; but this rate is inevitably too fast for some events and too slow, in some cases much too slow, for others.

5. Final calibrations and flood frequency

5.1 PDM

Testing of the snowmelt module for catchment 12007 (the Dee at Mar Lodge, in Scotland), with the PDM, using station temperature data from Balmoral, indicated that simply including the snowmelt module without any adjustment of parameter values, gave a much improved fit to the observed flood frequency curve. However, slight adjustment of the parameters, in particular of the PDM's fast flow routing parameter k_1, gave a further improvement in the fit. Therefore it was necessary for the PDM calibrations, particularly for catchments in Scotland and northern England, to be briefly revisited after the inclusion of the snowmelt module.

Results for the catchments modelled with the PDM plus snowmelt module, including all manual adjustments to parameter values (Section 3.2), are given in Table 5.1. The short time-period objective function value is given as N&S 1-day for all catchments, rather than 1-hour for the catchments modelled at an hourly time-step (as in Table 3.1). This change allows direct comparison of model performance between all catchments. Almost all catchments (96%) show an improvement or no change in the N&S 1-day value; while of the five with a decline in performance the difference for four of them is only 0.01.

Table 5.1 Calibration results for PDM catchments, with the snowmelt module

Catchment number	N&S (1-day)	N&S (30-day)	Volume error (%)	Catchment number	N&S (1-day)	N&S (30-day)	Volume error (%)
02001	0.48	0.89	-0.6	40005	0.73	0.95	15.4
03003	0.69	0.90	2.0	40011	0.65	0.89	2.4
04005	0.64	0.86	7.7	42008	0.81	0.84	6.4
06008	0.66	0.93	2.4	42012	0.79	0.80	-6.7
07001	0.25	0.60	-5.4	43005	0.87	0.91	3.0
07002	0.42	0.80	-8.6	43007	0.59	0.97	0.0
07004	0.49	0.76	15.4	44002	0.85	0.92	1.7
08004	0.26	0.71	-6.0	45003	0.65	0.94	4.2
10002	0.26	0.83	-8.2	45005	0.48	0.90	6.8
10003	0.78	0.84	-11.2	47007	0.70	0.97	-4.0
12007	0.16	0.58	-1.6	47008	0.77	0.93	0.9
13001	0.46	0.90	-7.8	48003	0.61	0.94	-4.1
13005	0.58	0.90	-6.6	50002	0.55	0.98	-4.7
14001	0.67	0.95	-0.2	50006	0.62	0.98	-1.4
16003	0.67	0.92	-1.7	52010	0.45	0.94	-4.0
17005	0.60	0.94	-6.0	53009	0.72	0.96	-2.8
19011	0.36	0.89	0.6	54008	0.75	0.95	-3.2
20001	0.44	0.90	4.5	54018	0.70	0.95	2.5
21013	0.69	0.91	-2.4	54025	0.82	0.96	-1.1
21017	0.76	0.95	-2.5	54027	0.84	0.93	-4.8
21023	0.48	0.84	6.2	54034	0.77	0.94	3.1
22001	0.48	0.91	-8.7	54090	0.76	0.94	-3.4
22006	0.74	0.91	7.1	55008	0.77	0.96	-2.6
23011	0.58	0.90	-5.1	55013	0.70	0.93	8.5
24005	0.62	0.94	3.1	55029	0.67	0.95	-2.1
25006	0.68	0.94	-6.6	57005	0.81	0.97	-0.5
27007	0.48	0.93	-4.6	57006	0.82	0.97	-2.2

Catchment number	N&S (1-day)	N&S (30-day)	Volume error (%)	Catchment number	N&S (1-day)	N&S (30-day)	Volume error (%)
27021	0.64	0.90	-6.4	58005	0.39	0.92	-4.0
27043	0.58	0.96	-4.0	58006	0.76	0.97	0.4
27049	0.55	0.87	-6.7	60002	0.78	0.96	-1.4
27051	0.69	0.93	-3.2	60003	0.79	0.89	-11.2
28008	0.77	0.97	-3.8	61001	0.71	0.92	-7.3
28015	0.54	0.78	-3.5	64001	0.59	0.96	-6.4
28039	0.66	0.61	-3.4	65006	0.28	0.89	-5.9
28046	0.67	0.87	-8.8	66011	0.69	0.96	-3.9
28066	0.65	0.70	-13.1	67009	0.33	0.22	103.9
29001	-0.75	-0.46	75.3	68001	0.62	0.90	-2.9
30004	0.73	0.85	-0.2	68005	0.69	0.86	15.6
30017	0.41	0.81	6.8	69040	0.66	0.77	-6.2
31002	0.43	0.80	15.4	73005	0.66	0.98	-3.0
32003	0.28	0.90	3.9	74001	0.72	0.95	1.8
33012	0.43	0.89	12.7	75017	0.51	0.94	-7.2
33019	0.80	0.90	-4.7	76014	0.70	0.93	-6.4
33029	0.73	0.78	11.1	78003	0.53	0.97	-5.4
34003	0.54	0.64	-4.3	79002	0.60	0.97	-0.5
34006	0.41	0.88	5.4	79003	0.61	0.93	-5.0
36005	0.32	0.89	6.7	79005	0.86	0.97	-1.8
36008	0.69	0.74	-8.1	81002	0.56	0.95	0.9
36010	0.66	0.87	24.8	81006	0.81	0.97	0.4
37001	0.62	0.92	-3.6	83005	0.56	0.96	2.1
37031	0.13	0.79	-11.1	84012	0.63	0.97	0.0
38003	0.68	0.71	-8.2	84030	0.84	0.97	-0.7
38007	0.79	0.92	-9.0	85003	0.69	0.82	9.4
38020	0.74	0.95	7.7	86001	0.77	0.86	10.2
39007	0.90	0.93	-0.6	90003	0.79	0.90	1.6
39017	0.42	0.86	4.6	93001	0.72	0.93	-7.7
39037	0.73	0.80	5.3	94001	0.86	0.95	-0.2
39069	0.29	0.87	-9.6	95001	0.71	0.90	0.9
39073	0.72	0.77	4.9	96001	0.67	0.91	-4.4
39105	0.68	0.96	-1.6	97002	0.54	0.93	-3.5

After inclusion of the snowmelt module, and allowing for reasons given in Section 3.2.6, some catchments still have very low N&S 1-day values. Catchments with an overall poor performance are 07001, 08004 and 12007. These are all upland catchments in NE Scotland where it is likely that the poor raingauge network over the mountains is a factor in estimating catchment precipitation and thus being able to realistically model river flow. Two catchments have been assessed as having good quality high flow measurements which are not reproduced by modelled flows – 58005 and 81006 (as mentioned in Section 3.2.6).

5.2 CLASSIC

For CLASSIC the routing parameters for catchments where snowmelt is a major contributing factor in the runoff regime could not be properly calibrated until the temperature data were received and the model run with the snowmelt module. Most of the catchments shown with amber dots in Figure 3.2 required minor re-calibration of the routing parameters. In addition, the modelling of soil moisture was adjusted so that where the temperature is below freezing or a ‘dry’ snow store is present then there is no loss of soil moisture through evaporation. For mountainous catchments this adjustment considerably improves modelled flows in spring and the overall water balance (except 08006).

Results from calibration of the 35 catchments modelled with CLASSIC with the snowmelt module are given in Table 5.2. Almost all catchments other than 08006 have improved N&S values at both 1-day and 30-day time periods when including the snow module. There is only one catchment (39016) where the 1-day no snow N&S value (0.87) is higher than with the snow module (0.86), while exceptions for the 30-day period are all catchments with significant abstraction.

Table 5.2 Calibration results for CLASSIC catchments, with the snowmelt module

Catchment number	N&S (1-day)	N&S (30-day)	Volume error (%)	Factors affecting gauged flow[1]
08006	0.69	0.77	12.4	4
11001	0.84	0.94	-0.4	
12002	0.72	0.94	-0.4	1
12003	0.54	0.89	-1.5	
15006	0.86	0.96	-3.7	1 2 4
21009	0.86	0.97	5.4	1 2
23001	0.63	0.95	-5.3	2
24009	0.77	0.96	4.1	4
27003	0.89	0.96	2.1	1 2 3 5
27007	0.85	0.95	2.4	1 2
27009	0.92	0.97	5.6	1 2 4 5
27041	0.89	0.96	5.3	1 4 5
28022	0.90	0.96	-6.0	1 2 3 4 5
33026	0.89	0.94	6.1	1 2 3 5
33035				3 4 5
39001[2]	0.93	0.97	3.4	1 2 3 4 5
39008	0.90	0.95	10.2	1 2 3
39016	0.87	0.92	1.2	4 5
39081	0.87	0.94	2.6	3 4
40003	0.80	0.88	12.9	1 2 4
43021	0.93	0.95	-0.3	1
47001	0.82	0.98	-1.6	1 2 3 4 5
53018	0.87	0.93	-6.3	1 3 4
54001	0.89	0.94	13.7	1 2 3 4 5
54057	0.92	0.96	7.7	1 2 3 4 5
55002	0.90	0.96	5.9	1 2
55023	0.85	0.96	0.9	1 2 3
60010	0.83	0.96	-5.4	1 4
62001	0.87	0.94	-9.8	1 2
67033	0.89	0.88	20.8	1 2 3 4 5
69037	0.58	0.77	7.8	1 2 3 4 5
71001	0.66	0.96	-0.6	2 3
72004	0.60	0.97	-3.1	1 2 4
76007	0.84	0.96	9.0	1 2
84013	0.84	0.97	-4.4	3

[1] Factors affecting gauged flow (www.nwl.ac.uk/ih/nrfa/station_summaries):
1. abstraction for public water supply;
2. reservoir(s) in catchment;
3. runoff increased by effluent returns;
4. regulation from surface and/or groundwater;
5. abstraction for industrial/agricultural use.

[2] Results for naturalised flow record.

All catchments (excluding 33035 and 69037) now meet the criteria for calibration except the Spey (08006) over 30 days and the Dee (12003) over one day. Both of these catchments are in Scotland with considerable impact of snowfall in the runoff regime where the use of constant parameter values in the snowmelt module is one factor in the lower model performance values. The comparatively low N&S(1-day) value for the Lune (72004) is caused by intermittent timing errors rather than overall quality of performance.

5.3 Discussion of modelling with snowmelt

A comparison of results of mean N&S values for seven regions (labelled A-G; Figure 5.1), with and without the snowmelt module, is given in Table 5.3 for the PDM and Table 5.4 for CLASSIC (catchments in only six regions for CLASSIC). The regions are based on hydrometric areas: A, 01-18,97; B, 19-27; C, 28-39; D, 40-53; E, 54-67; F, 68-84; G,85-96 (note that the first two digits of the catchment number indicate the catchment's hydrometric area). The results show that the greatest improvement in model performance when including the snow module is for catchments draining the eastern side of Scotland (region A), followed by those in North-East England (region B). All regions show an improvement at the 1-day period and all an improvement, or no change, at the 30-day period. The greater contribution of snowmelt to rivers in the North-East compared to the North-West is evident from these results. The results concur with the fact that snow has affected runoff from all catchments at some time during their period of record, notably during the winters of 1962/63 and 1978/79.

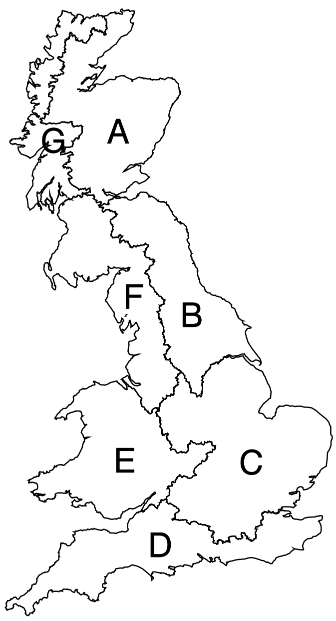

Figure 5.1 Regions used for the mean performance summaries given in Tables 4.3 and 4.4. The regions are based on hydrometric areas: A, 01-18,97; B, 19-27; C, 28-39; D, 40-53; E, 54-67; F, 68-84; G,85-96

Table 5.3 Comparison of average PDM performance by region (Figure 5.1), without and with the snowmelt module

Region (number of catchments)	Without snow module		With snow module	
	N&S (1-day)	N&S (30-day)	N&S (1-day)	N&S (30-day)
A (17)	0.40	0.81	0.51	0.84
B (15)	0.52	0.90	0.58	0.91
C (29)	0.52	0.79	0.54	0.79
D (16)	0.67	0.93	0.68	0.93
E (20)	0.66	0.91	0.69	0.91
F (16)	0.63	0.94	0.66	0.94
G (7)	0.73	0.89	0.74	0.89

Table 5.4 Comparison of average CLASSIC performance by region (Figure 5.1), without and with the snowmelt module

Region (number of catchments)	Without snow module		With snow module	
	N&S (1-day)	N&S (30-day)	N&S (1-day)	N&S (30-day)
A (5)	0.49	0.71	0.73	0.90
B (7)	0.75	0.93	0.83	0.96
C (6)*	0.88	0.95	0.89	0.95
D (4)	0.85	0.94	0.85	0.94
E (7)	0.87	0.94	0.88	0.94
F (4)*	0.73	0.96	0.74	0.97

* excluding 33035 and 69037, see Section 3.3.2

A considerable gradation of impact of snowmelt on flow is evident across Britain. For catchments in the south and west the impact is entirely historic (i.e. pre early-1990s) and with limited contribution to flood events (in the period from 1961). For catchments in the North-East of England most winters (pre-2001) have snowfall at some time and snowmelt has contributed to a number of 'top-10' flood events (Figure 5.2). In Scotland, however, particularly for catchments draining from the mountains of the Highlands and Cairngorms, accumulation of snowfall with subsequent melt occurring over several months is part of the normal flow regime (Figure 5.3). Flood peaks affected by snow may be either enhanced, where snowmelt combines with runoff from rain (Figure 5.2), or suppressed, when incoming precipitation falls as snow over the mountains and rain over lower ground, with the snow only melting gradually (Figure 5.3). Flood events (> 1-year return period) entirely from snowmelt are not a feature of British rivers.

Success in simulating flood events in which snowmelt is a dominant factor is mixed, those in catchments in NE England (Figure 5.2) being generally better simulated than many Scottish events (Figure 5.3). Two extreme snowmelt peaks on the Tay (15006) in 1990 and 1993 (Figure 5.4) are impossible to simulate using the set of parameter values in Table 4.1 and mean daily temperature. The sub-daily timing of precipitation and temperature in January 1993 was critical in the generation of the flood event.

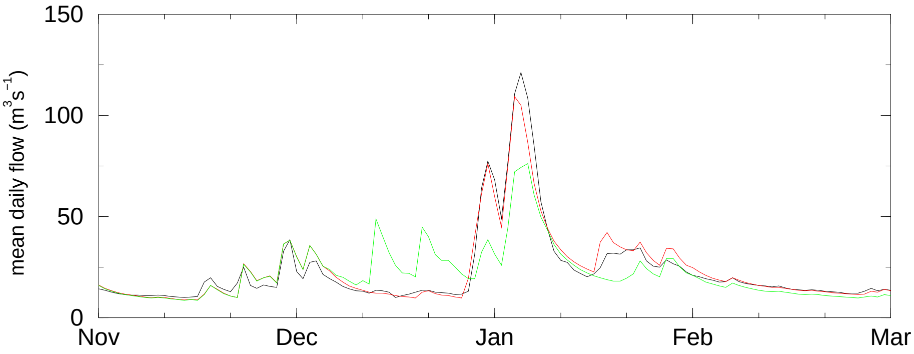

Figure 5.2 Hydrograph for the Derwent (27041) for November 1981 to March 1982, observed flow (black), modelled flow with snow module (red), modelled flow without snow module (green)

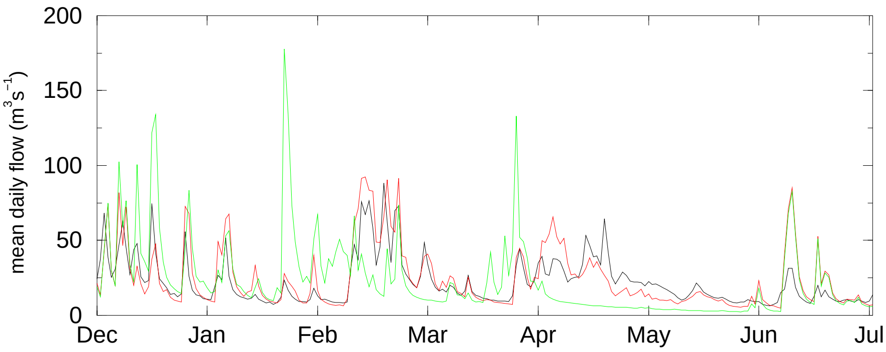

Figure 5.3 Hydrograph for the Dee (12003) for December 1979 to July 1980, observed flow (black), modelled flow with snow module (red), modelled flow without snow module (green)

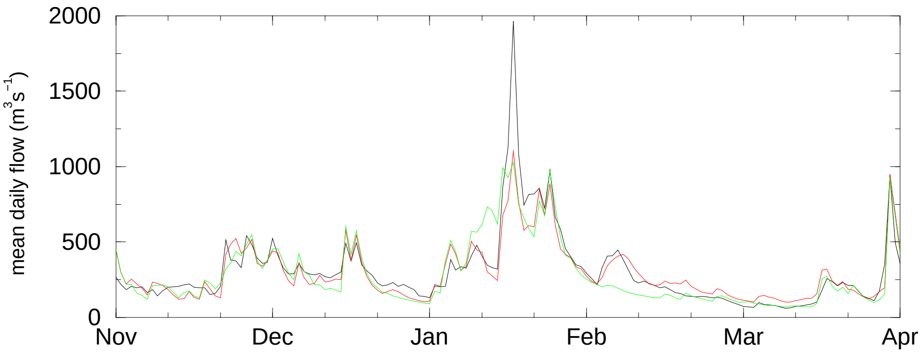

Figure 5.4 Hydrograph for the Tay (15006) for November 1992 to April 1993, observed flow (black), modelled flow with snow module (red), modelled flow without snow module (green)

5.4 Flood frequency

5.4.1 Flood frequency analysis

A major criterion in the calibration of the hydrological models is to achieve a good similarity between frequency of observed and modelled peak discharges. The statistical method that has been used to analyse the time-series of observed and modelled mean daily flows to provide flood data series, is the peaks-over-threshold (POT) method (Naden, 1993). The data period for comparison between observed and modelled flows for each catchment is as given in Tables 2.6, 2.7 and 2.8. The maximum data period is 41 years (1961 – 2001) with the minimum for one of the catchments with hourly data of nine years (1993 – 2001). The flood series contain all daily peak discharges above a threshold flow, with criteria on minimum time between peaks (determined from response time of the catchment) used to ensure that all selected peaks are independent (Bayliss and Jones, 1993). The threshold is set so that the series contains an average of a selected number of daily peaks per year. In this case an average of 2 peaks per year has been used (POT2) to provide a more complete picture of the flood history than is achieved with only 1 peak per year but without including many minor flood events. Having sufficient peaks to adequately define the flood frequency pattern is particularly important for many of the catchments with hourly data, which have less than 20 years of data.

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

As outlined in Section 3.1 there are many reasons why it is impossible to completely reproduce an observed flow series with modelled flows. These reasons are even more acute during flood events when high accuracy of measurement of precipitation and river flow is difficult to achieve. Apart from the catchments modelled with hourly data variation in intensity of sub-daily rainfall is not included in model response. In addition, rating curves for gauging stations, used to determine discharge from measured water levels, are often extrapolated beyond gauged flows to provide extreme flood discharges, where the accuracy of the extrapolation is not known. Hence, it is not surprising that modelled flood peaks may differ from observed ones but the aim of calibration is to achieve overall agreement in terms of frequency and magnitude of discharge and similarity of slope of the flood frequency curve.

Examples of observed and modelled flood frequency curves are given in Figure 5.5 for six catchments with contrasting hydrological response characteristics, as well as illustrating some of the reasons for differences between observed and modelled flood frequency curves. Distinguishing features for each of the six catchments are outlined in Table 5.5.

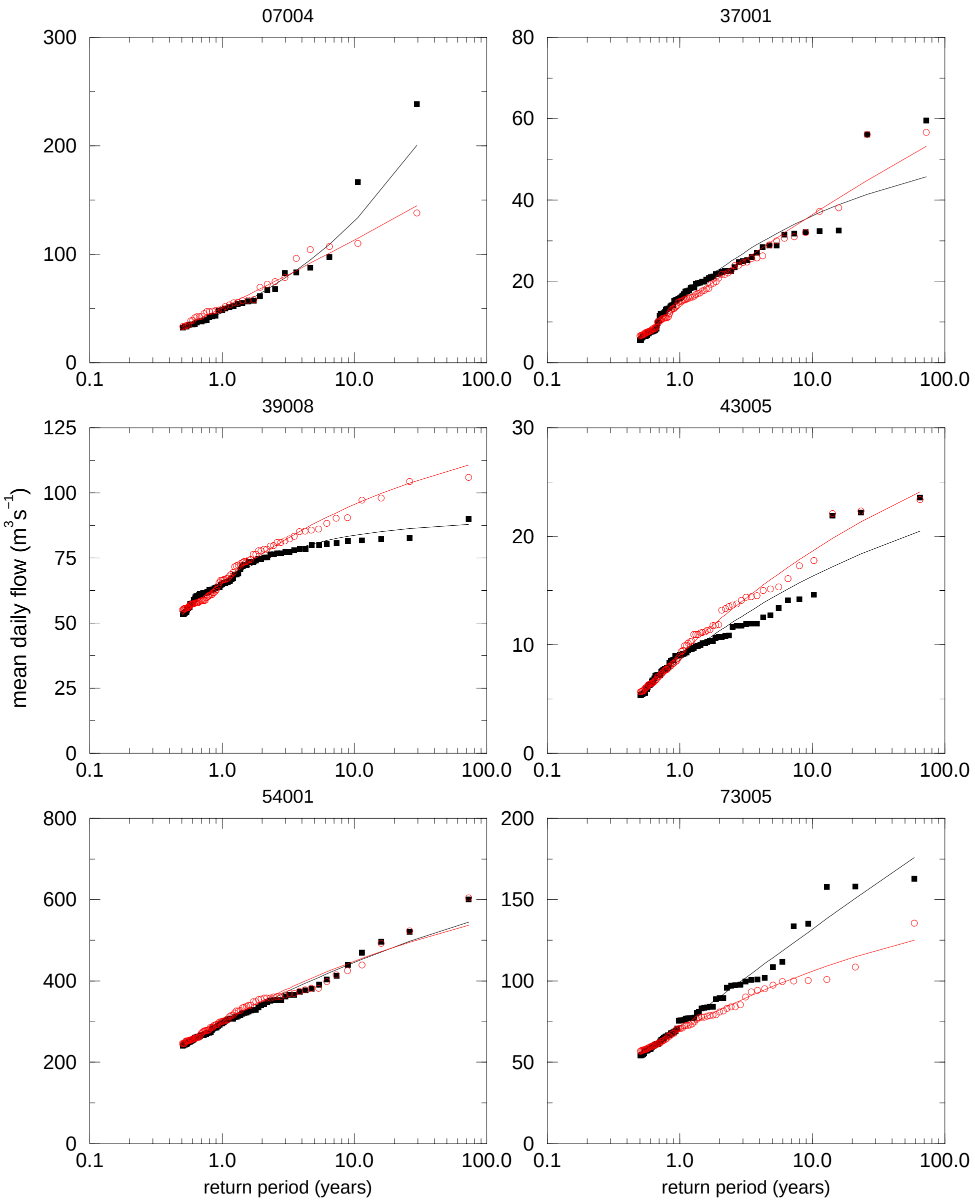

Figure 5.5 Observed (black) and modelled (red) flood frequency curves for six catchments. Fitted curves (solid lines), observed mean daily flow peaks (black squares), modelled mean daily flow peaks (red circles)

Table 5.5 Characteristics of catchments with flood frequency curves in Figure 5.5

Catchment number	Area (km^2)	SAAR (mm)	BFI	Comments (see www.environment-agency.gov.uk/hiflows for details on rating curves)
07004	313	940	0.45	Extrapolation of rating curve > 150 m^3s^{-1}. NE Scotland, upland catchment, snow in winter.
37001	303	606	0.39	Extrapolation > 35 m^3s^{-1} from model tests. S E England, urban development close to gauging station.
39008	1616	749	0.68	Bypassing of gauging station, S Central England.
43005	324	745	0.91	Good high flow rating. S England, groundwater catchment.
54001	4325	924	0.53	Ultrasonic gauge. Central Wales, diverse catchment.
73005	209	1732	0.46	Flashy, responsive catchment, all flows contained. NW England.

5.4.2 Characteristics of flood series

A dimensionless statistic which can be used to compare data series is the coefficient of variation, cv, defined as the ratio between the standard deviation and mean of the series (NERC, 1975). The coefficient of variation is a measure of the relative range, or dispersion, of the series. Therefore comparison between values of cv for the observed and modelled POT2 series for each catchment indicates how well the modelled flood peaks reproduce observed variation in daily flood peak response.

Values of the mean and coefficient of variation for the observed and modelled POT2 series for each of the 155 catchments are given in Table 5.6, and plotted against each other in Figure 5.6. The mean POT2 values (Figure 5.6a) show the overall range of flood discharges covered by the project and also illustrate the overlap in flood flows simulated by the three modelling methods — hourly PDM (red triangles), daily PDM (blue triangles) and CLASSIC (green circles). The 11 groundwater catchments, listed in Table 3.2, are indicated by open diamonds (red or blue). The two CLASSIC catchments with noticeably higher modelled mean POTs than observed are 33035, where gauged flows are affected by water management, and 69037, where the gauged record is for only part of the catchment (see Section 3.3.1).

The coefficient of variation values (Figure 5.6b) are more sensitive to factors affecting the flood peak series than the mean values. Accuracy of water level or discharge measurement at high flows, extrapolation of rating curves and bypassing of the gauging station are all factors which affect observed flood peak data series. The uncertainty related to high flow measurement is evident from the periodic review of peak flows (e.g. HiFlows) which may result in revision of discharges both upwards and downwards. Examples of catchments where these factors are evident are five of the six catchments in Figure 5.6b where the modelled coefficient of variation is noticeably lower than the observed. Factors for these five catchments are: considerable differences between observed and modelled peaks where the rating curve has been extrapolated (07004 (see Figure 5.5), 34006 and 58005); comparison with 15-minute instantaneous peaks in HiFlows indicates observed daily peaks too high (48003) and generally poor quality of gauged flows (69040, station discontinued). For the remaining station (12007) differences are related to modelling of snowmelt peaks, where timing of sub-daily changes in temperature is critical for accurate simulation of the flood hydrograph (see Section 5.3 and Figure 5.4). Bypassing of the gauging station at high flows causes a higher modelled coefficient of variation than observed (for example, the groundwater catchment 44002).

Of the six observed and modelled flood frequency curves shown in Figure 5.5 the catchment with the highest modelled cv is 37001 (0.597 modelled, 0.578 observed) where the runoff from urban areas contributes to the high variation in flood response. The lowest cv is for 39008 (0.184, 0.132) where the flood response is often constrained by the slow response from the substantial groundwater component of flow. Groundwater catchments often have a low flood range but under exceptional conditions high floods may be generated, as for 43005 (0.378, 0.406). Large catchments generally have a low flood peak range compared to the mean flood discharge (e.g. 54001, 0.208, 0.216).

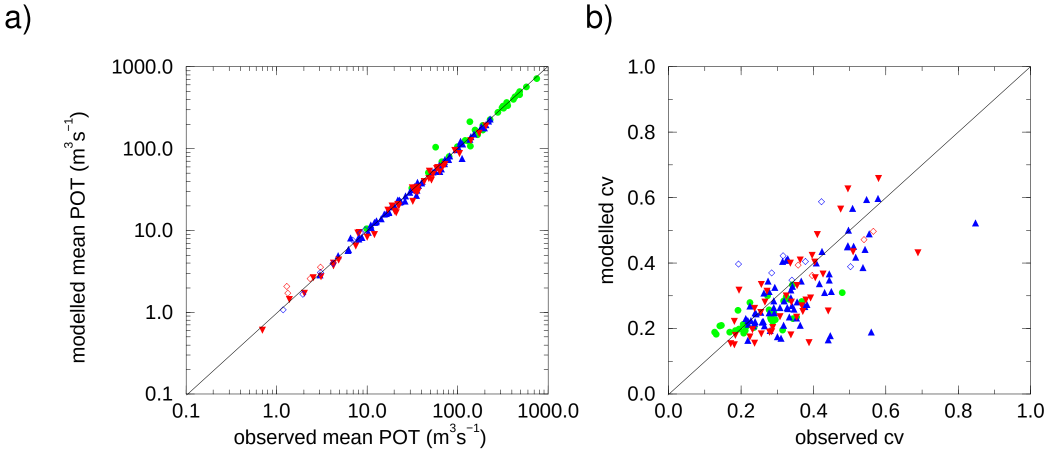

Figure 5.6 Comparison between observed and modelled values of a) the mean and b) the coefficient of variation (cv) of the POT2 series, for catchments modelled with the daily PDM (blue triangles), the hourly PDM (red triangles) and CLASSIC (green circles). Groundwater catchments are indicated by open diamonds of the appropriate colour

5.4.3 Baseline flood frequency curves

Flood frequency curves from modelled flows are the basis of the analysis to determine impacts of climate change on daily peaks. Therefore, it is important that the modelled curves are representative of catchment response under high mean daily (or mean hourly, where appropriate) rainfall conditions. Within the provisos outlined in the report regarding data measurement and spatial and temporal modelling issues, the modelled high flow response for each catchment is considered appropriate for assessing impacts of change in precipitation and temperature. However, uncertainty from calibration of model parameters, choice of sampling method and fitting of a frequency curve to the sampled set of flood peaks has not been included in subsequent analyses.

The calibrated models were run with 41 years of precipitation and PE data (1961 – 2001) for all catchments run with daily data and with the longest available data series (ending in 2001) for the catchments run with hourly data. These represent the baseline mean daily flows to which simulated flows from alternative climate scenarios are compared. Flood frequency analysis of the baseline simulated mean daily flows provides the POT2 flood series and baseline flood frequency curves used further in the project to develop the regionalised response to climate change (Prudhomme *et al.* 2009).

Table 5.6 Observed and modelled mean and coefficient of variation (cv) for POT2 flood peak series for the 155 catchments

Catchment number	Obs' mean	Obs' cv	Mod' mean	Mod' cv	Catchment number	Obs' mean	Obs' cv	Mod' mean	Mod' cv
02001	99.78	0.234	98.24	0.209	39081	9.99	0.184	10.46	0.195
03003	174.78	0.353	154.56	0.235	39105	22.87	0.494	23.51	0.45
04005	71.75	0.278	69.25	0.249	40003	129.95	0.325	124.68	0.297
06008	37.00	0.291	35.38	0.285	40005	32.31	0.495	22.79	0.628
07001	139.81	0.266	126.50	0.282	40011	17.22	0.329	16.64	0.413
07002	182.15	0.449	181.84	0.313	42008	1.34	0.565	1.72	0.498
07004	60.24	0.688	59.25	0.433	42012	3.06	0.316	3.07	0.423
08004	108.51	0.376	122.53	0.268	43005	9.48	0.378	10.17	0.406
08006	347.69	0.353	365.29	0.236	43007	81.66	0.408	81.07	0.401
10002	36.25	0.444	38.46	0.349	43021	47.89	0.142	50.99	0.209
10003	42.63	0.427	40.05	0.368	44002	6.95	0.193	7.61	0.398
11001	122.37	0.367	125.72	0.284	45003	35.25	0.339	30.21	0.282
12002	325.79	0.333	319.82	0.289	45005	32.44	0.333	31.78	0.235
12003	161.64	0.273	157.06	0.301	47001	191.36	0.282	169.11	0.234
12007	93.44	0.387	95.97	0.158	47007	12.14	0.219	12.53	0.164
13001	21.76	0.346	23.52	0.26	47008	22.94	0.327	22.15	0.265
13005	16.48	0.263	16.07	0.309	48003	12.77	0.559	13.05	0.19
14001	29.47	0.337	29.09	0.295	50002	152.24	0.329	150.41	0.261
15006	750.82	0.314	722.82	0.196	50006	72.70	0.354	73.29	0.233
16003	56.58	0.3	53.07	0.175	52010	18.48	0.355	19.34	0.282
17005	40.34	0.431	38.18	0.31	53009	8.12	0.237	8.38	0.216
19011	23.71	0.444	22.50	0.368	53018	137.98	0.288	107.98	0.221
20001	35.81	0.542	35.64	0.442	54001	311.73	0.216	316.74	0.208
21009	575.38	0.317	573.26	0.285	54008	99.28	0.342	98.39	0.329
21013	34.55	0.396	33.32	0.424	54018	15.51	0.278	15.81	0.313
21017	21.18	0.171	16.58	0.155	54025	12.64	0.292	12.76	0.248
21023	14.44	0.547	13.86	0.595	54027	7.97	0.307	9.34	0.238
22001	96.07	0.417	97.64	0.338	54034	4.85	0.256	4.40	0.335
22006	36.73	0.58	30.30	0.66	54057	486.71	0.168	496.91	0.189
23001	486.74	0.343	455.60	0.231	54090	0.70	0.256	0.61	0.185
23011	22.41	0.288	19.98	0.204	55002	356.72	0.195	334.62	0.199
24005	21.82	0.404	20.87	0.404	55008	7.57	0.279	6.47	0.19
24009	160.21	0.342	153.48	0.334	55013	19.01	0.368	19.93	0.271
25006	33.20	0.271	30.53	0.315	55023	469.08	0.236	462.09	0.204
27003	229.46	0.145	228.26	0.21	55029	66.35	0.338	56.65	0.318
27007	183.79	0.364	184.86	0.21	57005	205.98	0.284	191.16	0.191
27009	317.95	0.224	329.96	0.28	57006	59.17	0.238	57.20	0.157
27021	110.01	0.366	115.28	0.345	58005	30.84	0.441	31.39	0.166
27041	81.02	0.277	80.36	0.258	58006	31.88	0.225	33.34	0.175
27043	136.34	0.31	130.60	0.171	60002	105.69	0.441	87.79	0.255
27049	26.45	0.536	22.68	0.386	60003	51.60	0.181	41.65	0.223
27051	1.39	0.364	1.45	0.41	60010	278.75	0.283	278.01	0.228
27997[1]	190.05	0.29	191.67	0.25	61001	33.30	0.259	32.69	0.22
28008	49.08	0.392	53.42	0.295	62001	168.05	0.285	148.37	0.227
28015	8.52	0.341	9.34	0.349	64001	205.12	0.213	196.34	0.231
28022	434.22	0.281	433.58	0.233	65006	33.33	0.242	34.33	0.246
28039	10.10	0.238	8.32	0.262	66011	197.77	0.259	178.55	0.222
28046	8.25	0.371	9.56	0.253	67009	6.60	0.495	8.03	0.453

[1] 27997 refers to catchment 27007 simulated with CLASSIC

Catchment number	Obs' mean	Obs' cv	Mod' mean	Mod' cv	Catchment number	Obs' mean	Obs' cv	Mod' mean	Mod' cv
28066	8.81	0.225	8.15	0.269	67033	155.76	0.212	169.40	0.194
29001	1.30	0.358	2.09	0.395	68001	40.73	0.274	39.72	0.345
30004	4.26	0.336	4.00	0.4	68005	11.14	0.324	10.81	0.408
30017	3.04	0.314	2.87	0.405	69037	136.41	0.127	214.18	0.189
31002	11.02	0.554	11.58	0.49	69040	35.15	0.446	26.82	0.179
32003	6.24	0.424	5.83	0.435	71001	323.24	0.294	311.13	0.227
33012	10.35	0.496	9.53	0.5	72004	352.96	0.288	355.32	0.248
33019	6.21	0.508	5.72	0.568	73005	79.76	0.318	73.82	0.211
33026	99.62	0.191	105.30	0.256	74001	48.22	0.231	43.54	0.198
33029	1.95	0.422	1.67	0.588	75017	20.26	0.239	19.85	0.222
33035	57.55	0.48	104.20	0.311	76007	414.73	0.283	399.99	0.236
34003	4.23	0.503	3.93	0.389	76014	35.66	0.34	31.03	0.271
34006	17.43	0.847	16.71	0.523	78003	221.51	0.227	217.43	0.224
36005	8.11	0.511	7.83	0.452	79002	230.02	0.265	230.31	0.209
36008	12.11	0.475	8.97	0.566	79003	53.98	0.308	51.97	0.265
36010	3.12	0.509	2.73	0.436	79005	68.95	0.181	60.48	0.152
37001	17.31	0.578	16.63	0.597	81002	139.84	0.219	140.26	0.224
37031	4.81	0.517	4.91	0.418	81006	72.79	0.337	64.19	0.181
38003	1.19	0.284	1.07	0.371	83005	102.47	0.293	103.16	0.326
38007	2.54	0.41	2.65	0.488	84012	62.89	0.319	62.24	0.285
38020	4.28	0.355	3.72	0.332	84030	36.65	0.324	34.07	0.301
39001	320.92	0.206	333.91	0.214	85003	71.76	0.261	65.46	0.222
39007	20.31	0.195	17.21	0.319	86001	17.05	0.185	17.94	0.18
39008	67.09	0.132	69.11	0.184	90003	64.04	0.255	52.79	0.25
39016	31.34	0.207	33.13	0.186	90003	64.04	0.255	52.79	0.25
39017	2.04	0.405	1.72	0.357	93001	112.15	0.291	75.41	0.265
39037	3.06	0.54	3.58	0.473	94001	113.28	0.22	114.25	0.213
39069	26.56	0.382	26.35	0.274	95001	35.50	0.28	35.75	0.194
39073	2.36	0.397	2.60	0.362	96001	53.85	0.379	49.15	0.288
					97002	69.59	0.239	68.78	0.248

6. Summary

The outcome of this milestone report is a calibrated parameter set for each of 154 catchments spread across Britain: 120 modelled with the PDM, a lumped conceptual hydrological model, and 35 (generally larger) modelled with CLASSIC, a semi-distributed hydrological model. Note that the Ure at Westwick Lock (27007) has been calibrated for both the PDM and CLASSIC, hence generating 155 sets of river flow series.

The final calibration for each catchment includes the use of a snowmelt module (with a fixed set of module parameters), which requires time-series of temperature data in order to determine whether precipitation falls as rain or snow, and how much melt of lying snow occurs. Essentially, the snowmelt module is used as a pre-processor on the precipitation inputs, to delay the input of water in cold weather. The hydrological models with the snowmelt module thus require input time-series of precipitation, potential evaporation and temperature. Overall, model performance improves when the snowmelt module is applied. The target calibration aims on model performance have been achieved for the majority of catchments with reasons identified where the aims have not been met.

The peaks-over-threshold method of analysis was used to generate daily flood peak data sets. Observed and modelled flood frequency curves were compared to ensure that the calibrated models satisfactorily reproduce the high flow characteristics of each catchment.

The final calibrated parameter sets are used to simulate baseline flows and flood frequency curves required in the next part of the project. This is the application of a large, regular, set of perturbations to observed precipitation time-series, alongside a smaller set of (linked) perturbations to potential evaporation and temperature, to investigate the relative sensitivity of different catchments to the potential range of climate change. All catchments are included in the sensitivity modelling but model performance is considered in interpretation of the results. The development and method of application of the set of perturbations is described in the second milestone report of the project (Prudhomme and Reynard, 2009).

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