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Article

From Catchment to National Scale Rainfall-Runoff Modelling: Demonstration of a Hydrological Modelling Framework

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Abstract: The increasing availability of digital databases (e.g., of climatology, topography, soils and land use) has enabled research into the generalisation of hydrological model parameter values from physical properties and the development of grid-based models. A hydrological modelling framework (HMF) is being developed to exploit this generalisation and provide a flexible gridded infrastructure, operational over regional, national or larger scales at a range of spatial and temporal resolutions. The capability of the framework is demonstrated through adaptation of an existing semi-distributed catchment-based rainfall-runoff model, CLASSIC, for which a generalised methodology exists to determine parameter values. The main change required was to ensure consistency of parameter values between the runoff procedure in CLASSIC and flow routing in the HMF. Assessment is by comparison of modelled and observed flow at grid points in Britain corresponding to gauging stations, both for catchments previously modelled and for new locations, for a range of catchment areas and physical properties and for four spatial resolutions (10, 5, 2.5 and 1 km). Good model performance is achieved for 90% of catchments tested, with a 5 km resolution proving adequate for catchments larger than 500 km^2. Applications are outlined for which the framework could be used to test alternative modelling approaches or undertake consistent studies across the range of resolutions.

Keywords: rainfall-runoff; digital databases; generalised parameterisation; gridded flow routing; modelling framework; HOST soils

1. Introduction

Hydrological models for simulating river flow from rainfall have evolved over many decades [1] into a wide range of representations in terms of structure, complexity, data requirements, and scale of application from field plot to global, with a similarly wide range of purposes from floods to droughts, past to future climate, water resources and water quality. Much hydrological research has been based on catchment studies using models calibrated to observed flow (e.g., [2–4]), as well as continued exploration and evolving understanding of hydrological processes to enable more reliable simulation in ungauged catchments [5]. Generalisation of relationships between catchment properties, hydrological response and model parameters allows estimation of flow metrics in data-scarce areas [6], and flow simulation for gauged catchments with little or no direct calibration [7–9] as well as for ungauged locations within gauged catchments [10]; although use of such relationships implies that similarity between catchments can be defined [11]. Grid-based hydrological models (e.g., [12,13]) have exploited the advantages of digital databases and broadened the spatial scale of model application. Modelling systems have been designed to incorporate components from different models to customise a structure appropriate for individual catchments (e.g., [14,15]).

While the wealth of available hydrological models provides tailored solutions to a range of hydrological problems they often have very individual requirements, in terms of their supporting spatial and configurative datasets, drivers, data-format resolution and internal structure. Calibrated catchment models can capture the key behaviour of the area to which they are applied, but often say little about how the model can be applied to other catchments without recalibration. The overall aim of the generic Hydrological Modelling Framework (HMF) introduced here is to support and enhance existing models used for a range of water-management applications, by providing a single GIS-based data and spatial configuration framework. Potentially, existing models can be adapted to run within this spatial configuration, allowing a previously catchment-based model to operate in a gridded framework over a wide area and at a range of spatial resolutions. Although, a pre-requisite for transfer of a model to the HMF is methodology to calculate model parameter values from physical properties. The concept recognises that hydrological (and land-surface) models increasingly share a common spatial representation of the landscape provided by digital datasets, and that some of this functionality can be shared without necessarily losing the unique characteristics that a specialised model can provide. The HMF enables models to be applied across Great Britain, or a wider area, and enables users to focus resources on a specialist science question, or model application, while relying on an existing framework for underpinning data and spatial information.

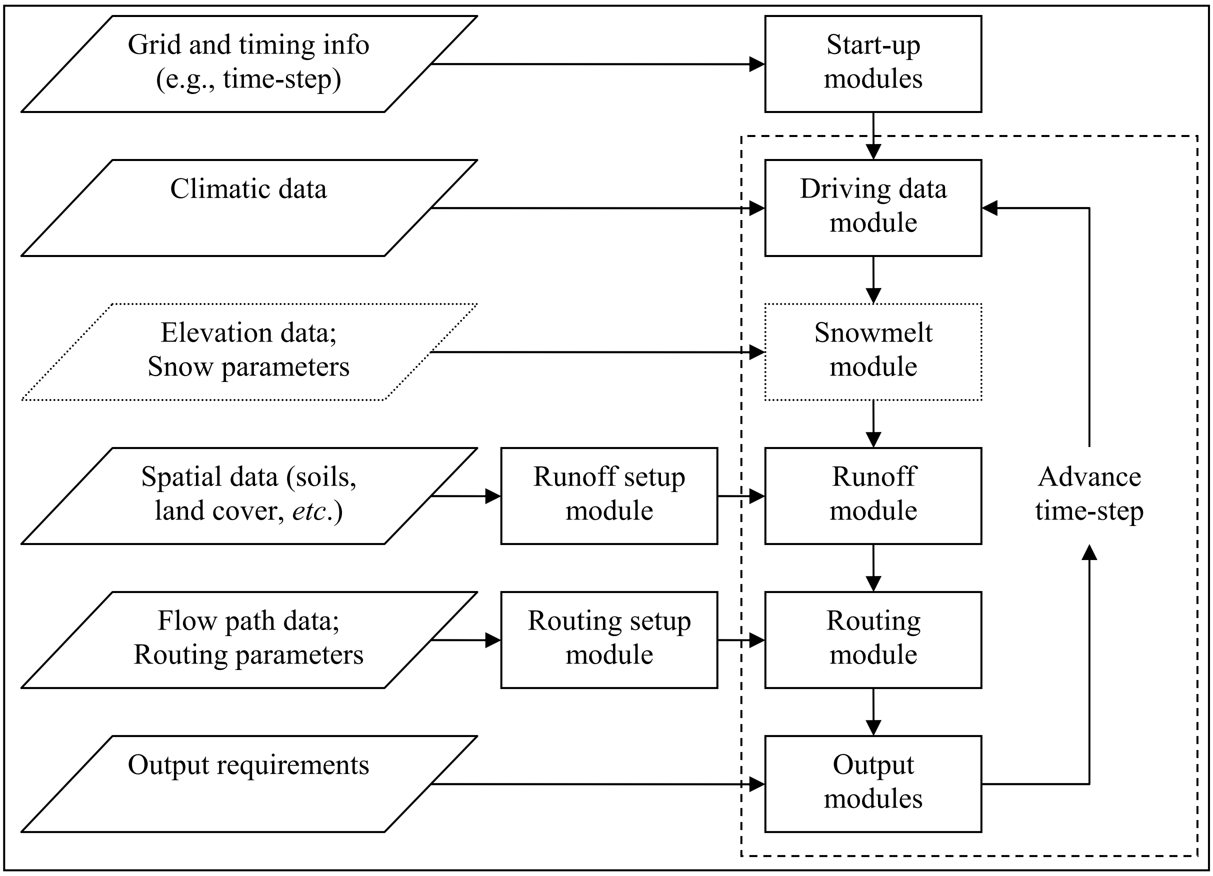
The aim of this paper is to demonstrate, as an example, the transfer of one existing catchment-based model, CLASSIC [16], to operation in the HMF. Transfer of other models may require different changes, dependent on the model, but could follow a similar procedure and analysis of results. The paper gives a description of the structure of the HMF, background information on CLASSIC (for which a generalised methodology exists to determine parameter values from physical properties), followed by details of transfer of CLASSIC from simulation of individual catchments to simulation of gridded river flows across the whole of Britain. Final model performance is discussed for over 50 catchments and analysed to show the effect of spatial resolution and demonstrate how the HMF can be used to further model understanding, development and application.

2. Background and Methodology

2.1. Description of the Hydrological Modelling Framework

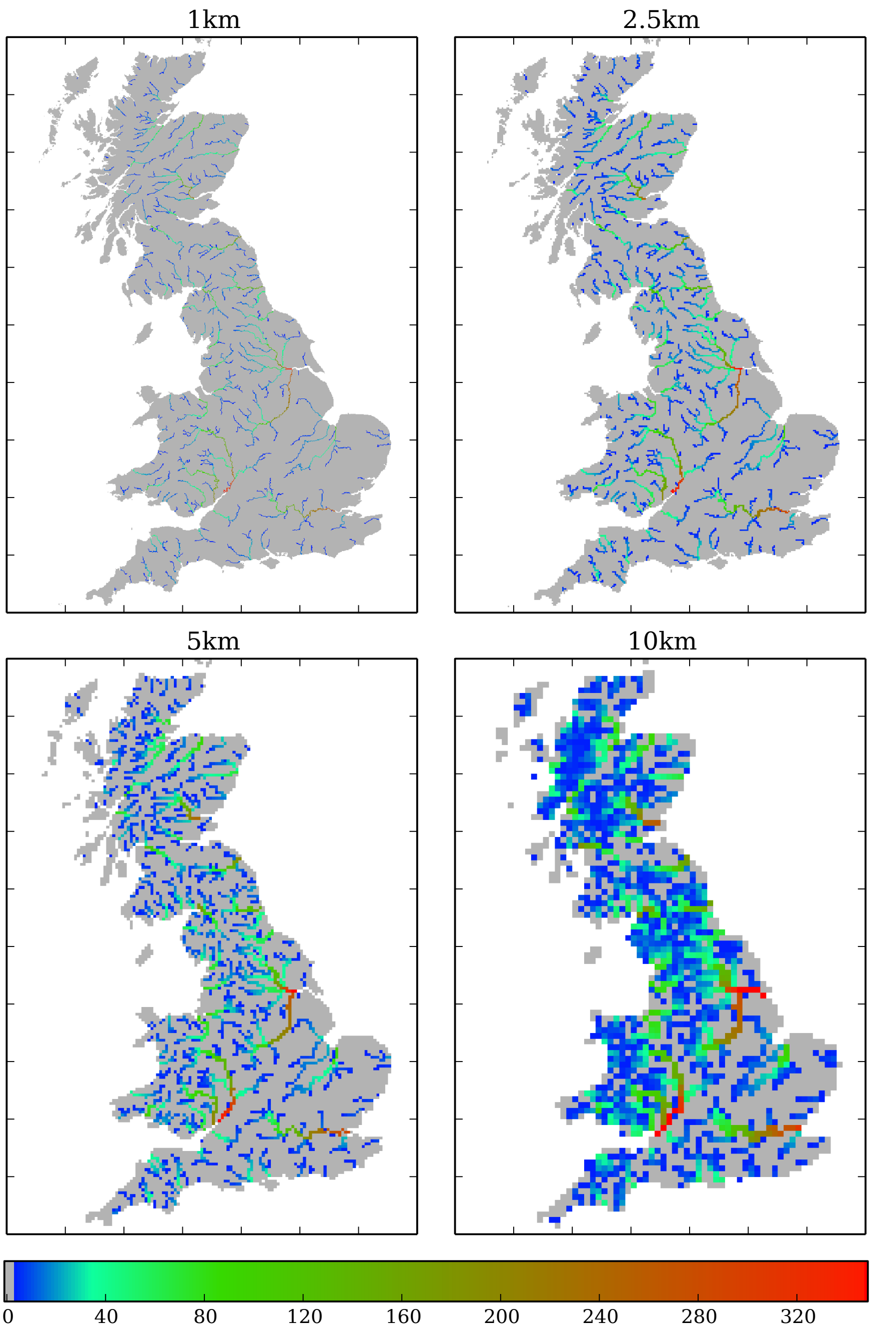
The HMF essentially comprises a set of modules for: model set-up; input of gridded driving data; production of gridded runoff (including optional use of a snow module); routing runoff along a network of flow paths to produce river flows; and output of simulated variables such as flow or soil-moisture (Figure 1). The modular nature of the HMF ensures flexibility, by allowing substitution or addition of modules. For example, the main driving data module provides observed climate data but could be replaced by a module providing projected climate data for a future period (taken from a regional climate model for instance). Similarly, alternative snowmelt, runoff-production or routing modules could be applied. Modules could be added to provide information on groundwater abstractions or to simulate water quality for example, thus more easily enabling sharing of existing model expertise.

Figure 1. Schematic of the Hydrological Modelling Framework, showing modules (rectangles) and data requirements (parallelograms), with optional parts indicated by dotted lines. The parts within the dashed box are performed at each time-step.



There are currently two domain applications of HMF. The first (HMF-GB) was set up for use over Great Britain, with kilometre-scale grids aligned with the GB national grid. The second (HMF-GLOBAL) was set up for use over a user-defined region up to global scale, with degree-scale grids aligned with standard latitude and longitude. For each variant a key requirement is derivation of the network of flow paths along which runoff is routed, and definition of a land-sea mask; sea boxes are subsequently ignored (all data set to missing values). Flow path delineation for a range of spatial resolutions has been undertaken using the COTAT+ method for deriving lower-resolution river networks from higher-resolution Digital Terrain Model (DTM) data [17], which assumes that flows are routed in one of eight directions. Currently, HMF-GB can operate at four spatial resolutions (10, 5, 2.5 and 1 km) while HMF-GLOBAL can operate at three spatial resolutions (0.25, 0.125 and 0.05 deg). Hereafter, this paper focuses on HMF-GB; the representation of river flow at the four spatial resolutions is shown in Figure 2. The introduction and testing of the runoff-production scheme from a semi-distributed catchment-based model, CLASSIC [16], into HMF-GB (called CLASSIC-GB) are described later in this paper. Other key features of the HMF are briefly described below.

Figure 2. Representation of river flow in Britain at four spatial resolutions; mean monthly flow ($m^3 \cdot s^{-1}$) in January 1982.



The routing module currently in HMF-GB is based on a kinematic wave scheme [18], and allows parallel routing of surface and sub-surface runoff. In addition, each (non-sea) grid box is designated as either 'land' or 'river' using a cumulative catchment area threshold of 20 km^2 [18]; at lower resolutions (10 and 5 km) all grid boxes are designated as 'river', whereas for the higher resolutions (2.5 and 1 km) boxes can be either 'land' or 'river'. Thus four wave speeds are defined (for land surface, land sub-surface, river surface and river sub-surface runoff), with slower speeds for land boxes and sub-surface runoff. There is also a fractional return flow, similar to [18], from sub-surface to surface runoff, for land and river grid boxes. Lakes and reservoirs are not currently differentiated. For stability of the routing scheme, the routing time-step must be sufficiently small in relation to the spatial grid size, meaning that a sub-daily time-step is necessary for the routing module. The main HMF-GB time-step is generally the same as the routing time-step, although it can be a multiple of the routing time-step if faster run-times are required.

The optional snowmelt module in HMF-GB currently uses a simple temperature-related snow store and melt rate with eight parameters (based on [19]), and operates with separate accumulation and melt in different elevation zones. Apart from temperature the module also requires the altitude to which the temperature relates, and information on fractional grid-box area within the different elevation zones.

Spatial outputs from HMF-GB are generally produced by an output module as netcdf files. The HMF can also be used in validation mode, in which simulated flow time-series are output for grid boxes corresponding to the locations of river flow gauging stations, along with observed flow time-series for those stations. Other variables, like soil-moisture, can also be output, allowing extended model validation.

The climate data provided by HMF-GB are rainfall, potential evaporation (PE) and temperature. The GB application presented here uses observed data; daily rainfall on a 1 km grid [20], monthly total PE on a 40 km grid provided by the Met Office Rainfall and Evaporation Calculation System (MORECS [21]) and daily minimum and maximum temperature on a 5 km grid [22]. Rainfall and PE are averaged up or copied down to the HMF-GB grid, as required, and divided equally down to the HMF-GB time-step. The daily minimum and maximum temperatures are lapsed to the required HMF-GB elevations and interpolated through the day using a sine curve, assuming that the minimum occurs at 2am and the maximum at 2pm [23].

Other datasets provided by HMF-GB, as 500 m grids, include: percentages of each soil class in the Hydrology of Soil Types (HOST [24]), percentages of each land cover class in the Land Cover Map 2007 (LCM2007 [25]), and mean slope derived from the Integrated Hydrological Digital Terrain Model (IHDTM [26]) which has a 50 m horizontal resolution. Each of these is spatially averaged to the required HMF-GB grid size. Also provided is mean altitude on a 100 m grid, derived from the IHDTM, which can be averaged as required, or used to determine the proportion of each HMF grid square in different elevation zones for use with the snowmelt module.

2.2. Background on CLASSIC

The semi-distributed continuous simulation model CLASSIC (Climate and Land-use Scenario Simulation in Catchments) was originally developed in the mid-1990s for estimating the impacts of climate and land use change in three large catchments in Britain (~10,000 km^2). The model is described in detail in [16] with the main features outlined below.

CLASSIC is applied on a grid framework superimposed on a catchment, defined by a topographic boundary. The grid size is not fixed but selected so as to be compatible with the catchment area and heterogeneity of the physical and climatic characteristics of the catchment. Grid sizes of 40 km (original size), 20 km (suitable for large catchments e.g., > 5000 km^2), 10 km (normally used) and 5 km have all been used. The model is normally run at a daily time-step. The model's three component modules are soil-moisture accounting, soil-drainage and channel routing. Inputs of rainfall and PE to the soil-moisture accounting module determine effective rainfall, which provides the input to the soil-drainage module, the output from which enters the channel routing module. The soil-moisture accounting and soil-drainage modules operate in each grid square, while the channel routing module transfers runoff from each grid square directly to the catchment outlet. The river flow at the outlet (normally a river gauging station) is the summation of the routed flow from all contributing grid squares. An optional fourth module, a snowmelt module, can be used as a precursor to the soil-moisture accounting. This catchment-based version of CLASSIC is referred to in subsequent sections as CLASSIC-catchment.

A generalised methodology [16] has been developed to allow parameter values in the soil-moisture and soil-drainage modules to be determined from physical properties, with only the two routing parameters determined by calibration against gauged flows. Parameter values in the soil-moisture module are derived from land cover type, soil type, slope and altitude, while those in the soil-drainage module are derived from soil type. Land cover is from CEH digitised databases, of which three are currently available (for years 1990 [27], 2000 [28] and 2007 [25]). Land cover types are amalgamated into six groups for use in CLASSIC; grass, deciduous woodland, coniferous woodland, arable, upland and urban. The arable group contains a seasonal growth cycle from bare ground in the autumn to maximum growth in early summer. Information on soils is from the HOST soil classification system, which has been shown to provide a meaningful approach to hydrological generalisation [29,30]. HOST groups soils into 29 classes based on the dominant features controlling water movement through the soil. Determining characteristics are whether the soil is mineral based or peat, whether there is an underlying aquifer, and the presence, or not, of an impermeable layer within the top metre (Figure 3.3 from [24]) Parameter generalisation was initiated through the calibration of a range of catchments with predominantly one HOST class and natural flow (*i.e.*, without artificial influences through abstraction, regulation or augmentation). The channel routing module uses network width functions (the number of drainage channels at kilometre distances from the catchment outlet, derived from the 50 m IHDTM) to represent the drainage network, combined with calibrated parameters for wave velocity and attenuation.

The aim of the generalised method for determining grid square parameter values is to simulate the natural flow regime, rather than the gauged flow. Few catchments in Britain, apart from headwater catchments, have natural flow so the generalised methodology provides a more stationary approach to model parameterisation than is obtained with calibration against observed flow, which is often performed over a time period of only a few years and can be affected by time-varying changes in water usage. The method also ensures spatial continuity of flow simulation within and between river basins. When CLASSIC is applied, although the generalised methodology for setting grid square parameter values is used to start with, there is the option to adjust parameter values if appropriate. Catchments where this option has been implemented are those with soils overlying aquifers of chalk, limestone and sandstone (HOST classes 1, 2 and 3 respectively). One representative response time is assigned for each of these

HOST classes (default value) but, as there is considerable regional variation in response rate within each class, more appropriate response times have been determined for defined groundwater regions to match recession curves and improve simulation of the dominant baseflow in relevant catchments.

CLASSIC-catchment has been set up for over 30 catchments across Britain with catchment areas ranging from 200 km^2 to 10,000 km^2. It has been used for a range of studies including: assessing the effect of land-use change on Thames floods [31]; investigating transient climate change and snowmelt in the Dee, north-east Scotland [23]; event attribution for the Autumn 2000 floods in England [32]; regionalising the impacts of climate change on flooding in Britain [33]; assessing impact uncertainty for larger catchments [34]. It is also one of a suite of models used to provide consistent sets of transient daily river flow projections across Britain for 1950–2098 [35].

2.3. Setting up CLASSIC-GB

Given the generally successful application of CLASSIC-catchment to catchments across Britain [33,35], the model was used to test the concept of the HMF and demonstrate the steps undertaken to reconfigure CLASSIC-catchment for use in HMF-GB (CLASSIC-GB). The generalised method for assigning parameter values from physical catchment properties in the soil-moisture and soil-drainage modules of CLASSIC-catchment is a key aspect in the transfer. These modules are used directly in the runoff module in HMF-GB and operate in the same way in both CLASSIC-catchment and CLASSIC-GB. However, the routing method is different. As the network width functions used in CLASSIC-catchment are not compatible with the structure of HMF-GB, CLASSIC-GB uses the kinematic wave routing scheme instead.

CLASSIC-GB uses the HMF-GB climate and physiographic datasets. Two further datasets have been created to implement other operations developed for CLASSIC-catchment; a PE station index and a response-time index. In CLASSIC-catchment, estimation of PE rates for different land cover types is derived from a set of 12 monthly regression equations between monthly MORECS PE for a short grass land cover and five other land cover types (deciduous woodland, coniferous woodland, upland, winter and spring sown grain crops). The regression equations were calculated for 10 climate stations, from daily data provided by the UK Met Office for each station derived for the six land cover types for eight years (1985–1992). The PE Index specifies which climate station to use for each grid square in HMF-GB. Boundaries between the stations have been mainly determined using appropriate catchment boundaries. The response-time index is described in Section 3.2.

To compare simulated discharge with observed, a grid square is selected as appropriate for a gauging station. The upstream contributing area and flow direction associated with each grid square are obtained from the network of flow paths; this information allows the contributing area for these grid squares to be compared with the required catchment area and drainage pattern to ensure that the most relevant square is selected for comparison of discharges. An advantage of CLASSIC-GB is that simulated river flow can be extracted for multiple grid cell locations (catchments) on the drainage network without setting up CLASSIC-catchment separately for each one. But, as catchment boundaries are not used, the upstream area contributing to a particular grid square is affected by the framework resolution—the finer the grid the more accurate the contributing area and potentially the more accurate the volume of simulated discharge.

2.4. Catchments

Details of the catchments used to assess the performance of CLASSIC-GB are given in Table 1, with their boundaries mapped in Figure 3 (for further catchment details see [36]). Table 1 is in two parts; the first 13 catchments are those used in the initial testing of CLASSIC-GB (with boundaries in cyan in Figure 3), the following 41 were used in further development and testing (boundaries in blue). Catchments were selected to give a range of areas, geographical location, climatic properties and HOST classes. The HOST classes listed in Table 1 each have at least 10% catchment coverage and are given in order of decreasing percentage. Also in the table are $SAAR_{61–90}$, the standard average annual rainfall for 1961–1990, and BFI, the baseflow index, described as an effective measure of indexing catchment geology [37] and used here as a combined measure of soil type.

Table 1. Details of catchments used to test CLASSIC-GB (the first 13, above the dashed line, are used for the initial assessment).

Station Number	River	Area (km^2)	$SAAR_{61–90}$ (mm)	Altitude range (m)	BFI	HOST
12002	Dee @ Park[1]	1844	1081	23–1309	0.53	17, 15, 29
15006	Tay @ Ballathie[1]	4587	1425	26–1210	0.64	17, 15
27009	Ouse @ Skelton[1]	3315	900	5–714	0.39	24, 29, 26
27034	Ure @ Kilgram[1]	510	1342	88–710	0.32	29, 26, 6
27041	Derwent @ Buttercrambe[1]	1586	765	10–452	0.69	24, 4, 2
39001	Thames @ Kingston[1]	9948	706	5–330	0.63	25, 1, 2
39081	Ock @ Abingdon[1]	234	639	51–260	0.64	25, 2, 3
43021	Avon @ Knapp Mill[1]	1706	810	1–294	0.86	1
47001	Tamar @ Gunnislake[1]	917	1216	8–580	0.46	17, 24, 21
54001	Severn @ Bewdley[1]	4325	913	17–826	0.53	24, 17, 18
54057	Severn @ Haw Bridge[1]	9895	792	11–826	0.56	24, 18
71001	Ribble @ Samlesbury[1]	1145	1353	10–688	0.33	24, 26, 29
84013	Clyde @ Daldowie[1]	1903	1129	8–745	0.46	24, 15, 29
04001	Conon @ Moy Bridge	962	1770	10–1100	0.57	15, 19, 29, 12
10002	Ugie @ Inverugie	325	812	9–234	0.63	17, 24
11001	Don @ Parkhill[1]	1273	885	32–874	0.68	17, 15
13007	North Esk @ Logie Mill	732	1074	11–929	0.51	15, 18, 17
21008	Teviot @ Ormiston Mill	1110	939	43–611	0.45	19, 6, 15, 24, 17
21009	Tweed @ Norham[1]	4390	955	4–838	0.52	17, 15, 24
22001	Coquet @ Morwick	570	850	5–775	0.44	24, 15
22009	Coquet @ Rothbury	346	905	71–775	0.48	24, 29, 15, 19
23004	South Tyne @ Haydon Bridge	751	1148	59–893	0.34	24, 29, 26
24009	Wear @ Chester le Street[1]	1008	885	6–745	0.46	24, 26
27007	Ure @ Westwick Lock[1]	915	1118	14–710	0.39	24, 26, 29, 6
27021	Don @ Doncaster	1256	799	4–543	0.56	24, 4
28022	Trent @ North Muskham[1]	8231	747	5–634	0.65	24, 21
28066	Cole @ Coleshill	130	722	79–202	0.42	24, 21
28085	Derwent @ St Mary's Bridge	1054	1012	44–634	0.63	4, 24, 15
33019	Thet @ Melford Bridge	316	620	11–71	0.78	1, 24, 5, 18

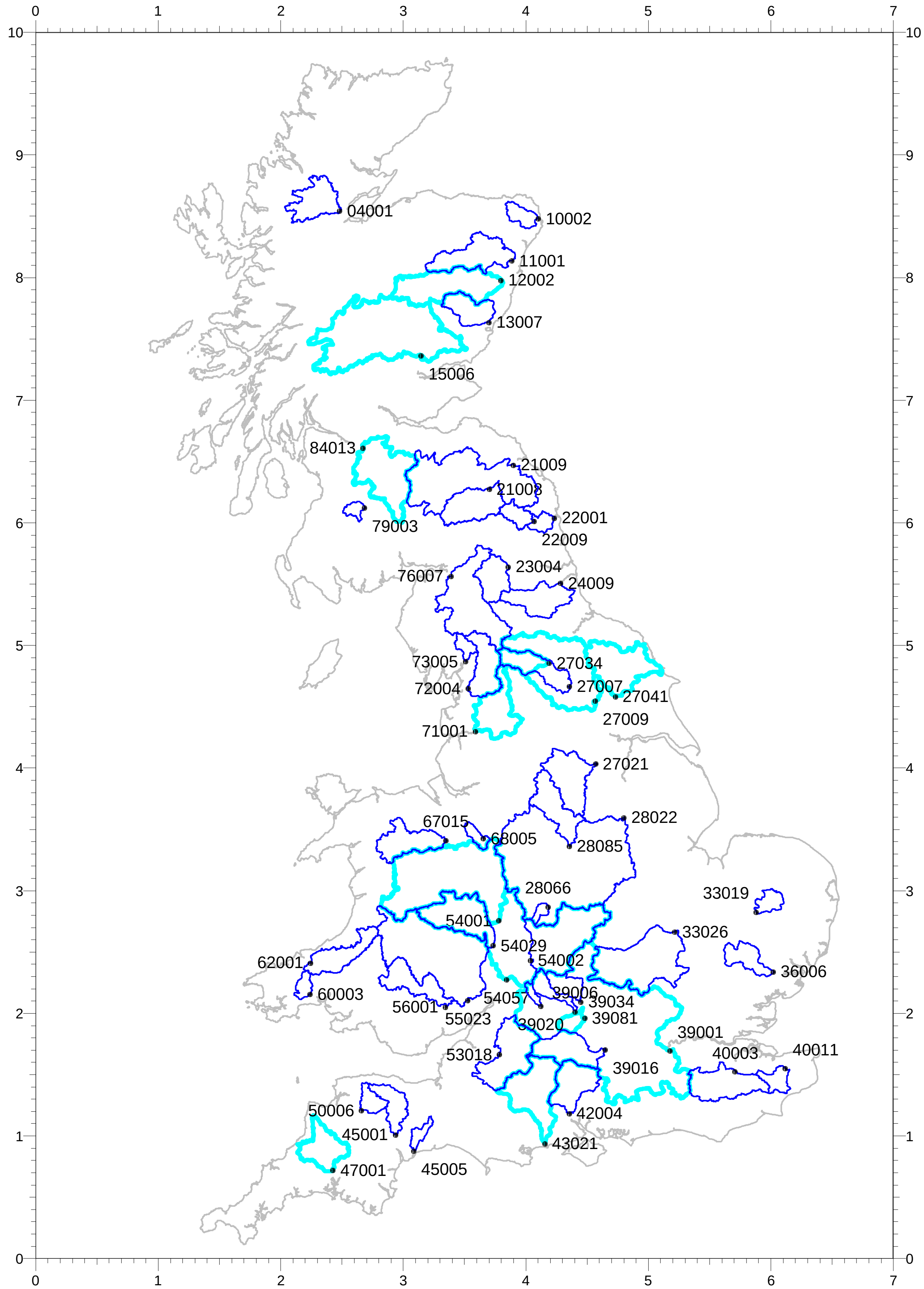
Table 1. *Cont.*

Station Number	River	Area (km^2)	$SAAR_{61–90}$ (mm)	Altitude range (m)	BFI	HOST
33026	Bedford Ouse @ Offord[1]	2570	609	11–247	0.50	21, 23, 25
36006	Stour @ Langham	578	580	6–128	0.52	21, 5
39006	Windrush @ Newbridge	363	743	63–317	0.86	2, 23
39016	Kennet @ Theale[1]	1038	759	43–296	0.88	1, 25, 18
39020	Coln @ Bibury	107	820	101–330	0.93	2, 23
39034	Evenlode @ Cassington Mill[1]	430	691	60–267	0.71	2, 25
40003	Medway @ Teston[1]	1256	744	7–268	0.40	25, 18, 24
40011	Great Stour @ Horton	345	747	13–196	0.69	1, 18, 25, 3
42004	Test @ Broadlands	1040	790	10–296	0.94	1, 6
45001	Exe @ Thorveton	601	1295	26–514	0.50	17
45005	Otter @ Dotton	202	976	15–302	0.53	21, 3, 24
50006	Mole @ Woodleigh	327	1307	48–490	0.47	17, 24
53018	Avon @ Bathford[1]	1552	817	18–304	0.57	2, 25, 23
54002	Avon @ Evesham	2210	654	20–317	0.52	25, 24, 21, 23
54029	Teme @ Knightsford Bridge	1480	818	21–545	0.55	18, 4
55023	Wye @ Redbrook[1]	4010	1011	9–749	0.54	18, 17, 24
56001	Usk @ Chain Bridge	912	1363	23–885	0.50	4, 17, 15, 5, 26
60003	Taf @ Clog-y-Fran	217	1420	9–392	0.55	17
62001	Teifi @ Glan Teifi[1]	894	1382	66–592	0.54	17, 24
67015	Dee @ Manley Hall	1013	1369	25–878	0.54	17, 15, 24, 29
68005	Weaver @ Audlem	207	719	45–221	0.54	24, 18, 5, 10
72004	Lune @ Caton[1]	983	1523	11–734	0.32	29, 24, 26, 15
73005	Kent @ Sedgwick	209	1732	19–812	0.41	17, 29
76007	Eden @ Sheepmount[1]	2286	1183	10–945	0.49	24, 5, 29
79003	Nith @ Hall Bridge	155	1505	173–607	0.27	24, 15, 29

[1] Catchments previously modelled with CLASSIC-catchment; $SAAR_{61–90}$ — standard average annual rainfall for 1961–1990; BFI — baseflow index; HOST — Hydrology of Soil Types [24].

All catchments in the initial selection have been previously modelled with CLASSIC-catchment, and most have an area of at least 1000 km^2, reflecting the fact that CLASSIC-catchment was developed to simulate flows in larger catchments. Two smaller catchments (27034 and 39081) were included to investigate the effect of coarse grid-resolution on simulated flows. The Thames at Kingston (39001) has a naturalised flow record, which has been used for comparison with modelled flow; in all other catchments modelled flow is compared with gauged flow, which may be affected by abstractions, augmentation or regulation. Of the 41 catchments selected for further assessment, 14 had been previously modelled with CLASSIC-catchment. Availability of other medium to large non-modelled catchments with reasonable quality flow data is limited and some were selected knowing that the observed flow data are affected by substantial alterations to flow. A group of 12 smaller catchments (107 km^2 to 570 km^2) was included to test more fully the capability of CLASSIC-GB at a finer spatial scale than that at which CLASSIC-catchment was developed.

Figure 3. Map of Britain showing catchment boundaries and station numbers. Catchments used in initial tests have boundaries in cyan, others in blue. The frame is the GB national grid with numbers at 100 km intervals.



2.5. Model Assessment Methods

Three measures of fit between daily observed flows (Q_d) and simulated flows (q_d) have been used to assess performance of CLASSIC-GB; Nash-Sutcliffe efficiency (NS, Equation (1) [38]), water balance bias (Bias, Equation (2)), and a fit of flow statistics score (derived from monthly mean flows and flow duration curves; mmfd, Equation (3)). The first two of these are frequently used to characterise model performance, while the third is introduced here as a measure of how well the model simulates flow response at seasonal/monthly time scales and across the flow range. Note that over-bars in the equations below indicate overall mean flows, while Q_m (and q_m) indicates mean monthly flows and Q_n (and q_n) indicates daily flows exceeded n% of the time.

$$\mathrm{NS} = 1 - \frac{\sum(Q_d - q_d)^2}{\sum\left(Q_d - \overline{Q}\right)^2} \tag{1}$$

$$\mathrm{Bias} = 100\left(\frac{\overline{q}}{\overline{Q}} - 1\right) \tag{2}$$

$$\begin{gathered}\mathrm{mmfd} = \mathrm{MM} + \mathrm{FD} \\ \mathrm{MM} = \frac{1}{12}\sum_{m=1}^{12} 100\frac{|Q_m - q_m|}{Q_m} \\ \mathrm{FD} = \frac{1}{5}\sum_{n\in\{1,10,25,50,75\}} 100\frac{|Q_n - q_n|}{Q_n}\end{gathered} \tag{3}$$

NS is a dimensionless performance measure which expresses the proportion of variability in observed flows accounted for by the model simulation. A value of 1 indicates an exact fit between observed and modelled flow, a value of 0 that the model is only as good as using the mean flow while a negative value indicates that model simulations are worse than using the mean. NS is sensitive to timing differences of peak flows, which may not be important when just considering whether the model can reproduce the characteristics of the observed flow regime. The Bias (%) indicates how well the balance between rainfall and evaporation agrees with the observed volume of flow over the simulation period. This relates in part to differences between catchment and contributing HMF-GB areas and in part to how well losses from evaporation (adjustment from potential to actual evaporation (AE)) are simulated in the model (as well as measurement errors of all variables). The two component measures within mmfd are derived from percentage differences in mean monthly flow (MM) and flow duration (FD). Here, five points have been used to characterise the fit of the simulated flow duration curve, but more points or a wider range could be included. The two measures have been combined here for convenience of presentation but each provides more specific information than NS or Bias on how well the seasonal soil-moisture cycle (and snowmelt processes where appropriate) are simulated. While the overall Bias can mask considerable variation in water balance at an annual scale, mmfd uses absolute values of percentage differences so that positive and negative values are not cancelled out. For most catchments, apart from the Thames (which has naturalised flow), the Bias and mmfd are also affected by alterations to the natural flow regime.

As well as calculating measures of fit it is also useful to assess the quality of the values [39,40]. Three performance bands (Table 2) have been defined as additional indicators of how well CLASSIC-GB performs (no protocols or procedures for model testing are currently standard hydrological practice [5]).

Table 2. Model performance bands for each performance measure.

Band	NS	Bias (%)	mmfd
1	$NS \geq 0.8$	$-10 \leq Bias \leq 10$	$mmfd \leq 20$
2	$0.6 \leq NS < 0.8$	$-20 \leq Bias < -10$ or $10 < Bias \leq 20$	$20 < mmfd \leq 40$
3	$NS < 0.6$	$Bias < -20$ or $Bias > 20$	$mmfd > 40$

3. Results and Discussion

Initial runs of CLASSIC-GB tested the overall operation of the modelling framework and determined how well the generalised methodology in the runoff-production scheme of CLASSIC-catchment combined with the routing module of HMF-GB. Results are given in Section 3.1. Analysis of these indicated where modifications were required, as described in Section 3.2. The enhanced version was tested on a much larger set of catchments, over a longer time period, with results given in Section 3.3 and discussed in Section 3.4. All testing of CLASSIC-GB used the snowmelt module.

3.1. Initial Results

The runoff setup module in HMF-GB was applied using the same parameter value to catchment property relationships as derived for CLASSIC-catchment, but taking the default parameter values for all areas of HOST classes 1, 2 and 3. CLASSIC-GB was run for four years, 1980–1983, with four grid resolutions—10, 5, 2.5 and 1 km—using 6, 12, 24 and 72 time-steps per day respectively (for compatibility with the grid resolution). Those model parameters that are time-step related, and developed for running at a daily time-step, are adjusted for the time-step length. Results are given in Table 3 for the 13 catchments selected for initial testing, for NS and Bias, and compared with results from CLASSIC-catchment.

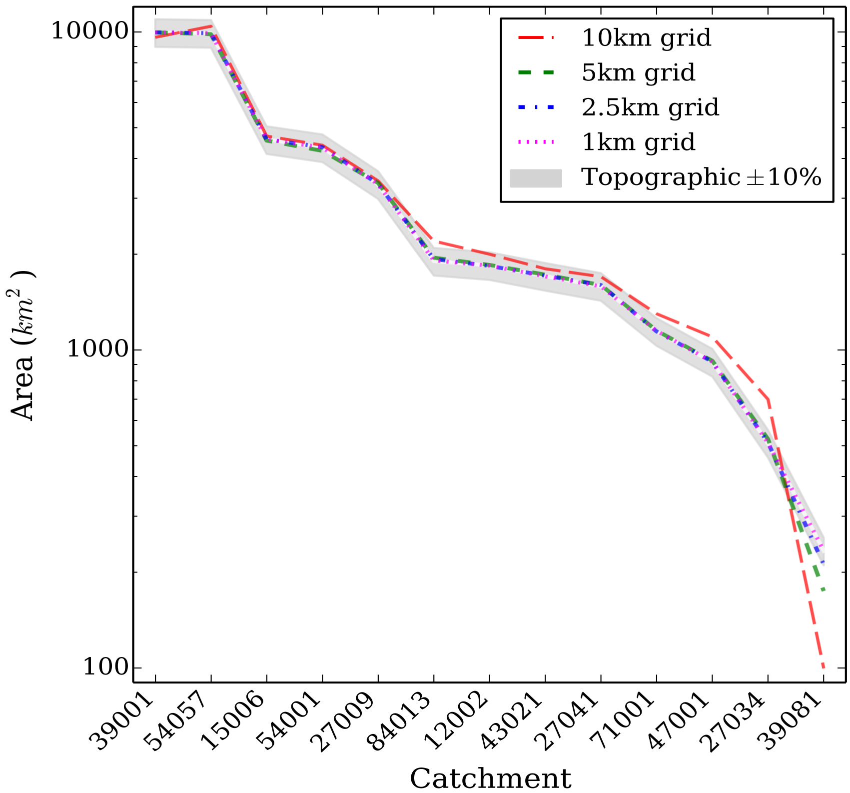
For the smallest catchment (39081) performance improves as the grid size decreases. For the next two smallest catchments (27034 and 47001) there is significant improvement between 10 km and 5 km resolutions but similar performance for the two higher resolutions. For the remaining catchments the best performance is provided by either the 10 or 5 km resolutions, with no improvement in NS by modelling at a higher resolution, though the Bias may be slightly smaller. The high Bias for the smaller catchments is mainly caused by the discrepancy in area between the contributing area defined by the flow paths and the catchment area defined by the topographic boundary. At the 5, 2.5 and 1 km resolutions all Bias values apart from two are within ±10%, indicative of realistic simulation of the water balance, with all NS values greater than 0.60, again apart from two catchments. Contributing areas for the four grid resolutions are compared with the area defined by a high resolution topographic catchment boundary (Figure 4); catchments with an area greater than 2000 km^2 are adequately defined with the 10 km grid while catchments with an area less than 500 km^2 require a 1 km grid.

Table 3. Values of NS and Bias for 13 catchments, with catchments listed in order of increasing catchment area, for four model resolutions from CLASSIC-GB (best value for each catchment in bold) and for CLASSIC-catchment, for 1981–1983 (with 1980 as 1-year warm-up period).

Station Number	10 km		5 km		2.5 km		1 km		CLASSIC-Catchment	
	NS	Bias	NS	Bias	NS	Bias	NS	Bias	NS	Bias
39081	N/A	N/A	0.68	−33.5	0.78	−23.4	**0.80**	**−13.6**	0.79	5.7
27034	0.39	44.5	**0.78**	−5.5	0.72	**1.5**	**0.78**	2.8	0.59	2.8
47001	0.69	32.0	**0.83**	2.3	**0.83**	**−0.4**	0.82	0.6	0.80	0.3
71001	0.71	18.1	**0.79**	2.5	0.70	**0.0**	0.73	0.4	0.64	4.7
27041	**0.74**	−8.2	0.66	−7.1	0.66	**−4.9**	0.65	−5.3	0.93	3.4
43021	**0.68**	**−10.9**	0.63	−15.6	0.63	−16.8	0.60	−17.6	0.89	−10.1
12002	**0.64**	**2.2**	0.63	−6.7	0.57	−3.4	0.55	−3.4	0.74	-2.3
84013	**0.82**	7.1	0.79	**−1.3**	0.79	**−1.3**	0.80	−2.5	0.85	−1.3
27009	0.81	9.5	**0.83**	−4.7	0.76	4.2	0.80	**3.1**	0.92	8.6
54001	0.72	10.7	**0.77**	**−2.2**	0.66	5.8	0.66	4.6	0.90	11.3
15006	**0.50**	−7.7	**0.50**	−9.4	0.48	**−7.5**	0.46	−7.7	0.85	−7.4
54057	0.74	9.7	**0.81**	**−1.5**	0.78	2.8	0.78	2.1	0.85	6.0
39001	**0.84**	−7.4	0.82	**−4.6**	0.81	−5.9	0.81	−5.9	0.96	−0.9
Average*	0.69	8.3	**0.74**	−4.5	0.70	**−2.2**	0.70	−2.4	0.82	1.3

*excluding 39081.

Figure 4. Comparison of contributing area (km^2) for the topographic boundary (used in CLASSIC-catchment) and the four spatial resolutions used in CLASSIC-GB.



Also of interest is how CLASSIC-GB performance for the 13 catchments compares with using CLASSIC-catchment (although datasets used with CLASSIC-catchment are not identical with those in HMF-GB). For most catchments CLASSIC-catchment gives higher NS values than CLASSIC-GB (Table 3), but for the four smallest catchments the position is reversed. Three of these catchments have a high proportion of peat soils (HOST classes 26–29) and/or the fast-responding HOST class 24 for which the smaller grid size (5 km or less in CLASSIC-GB compared with 10 km CLASSIC-catchment) and sub-daily modelling time-step may be an advantage.

3.2. Development of CLASSIC-GB

Catchments where performance is considerably worse using CLASSIC-GB are larger catchments with dominant HOST classes of 15 and 17 (15006, 54001, 54057) and those with a high groundwater component—HOST classes 1, 2 and 3 (27041, 39001, 39081 and 43021). For the first group of catchments visual inspection of modelled and observed hydrographs indicated that the modelled flows were insufficiently attenuated; that is the modelled flows have too high peaks, too fast recession and underestimate low flows. For the second group of catchments differences relate, in part, to use of the same parameter response values for each of the three HOST classes, whereas regional variation was included in CLASSIC-catchment.

Although the routing module in HMF-GB allows parallel surface and sub-surface routing (see Section 2.1), initial CLASSIC-GB runs routed all generated runoff via surface pathways alone (to replicate more closely the channel routing in CLASSIC-catchment, where all runoff is routed together). To investigate whether performance could be improved using the greater attenuation provided by parallel surface and sub-surface routing, CLASSIC-GB was run with runoff split between surface and sub-surface pathways, with all runoff from HOST 1, 2 and 3 and the slow response from other HOST classes taking the sub-surface path. Generally, using sub-surface and return flow makes little difference to generated flows, but using the slower sub-surface wave speeds the hydrograph shape for the three catchments given above (15006, 54001, 54057) is slightly better although the timing of peaks is then often a day late so NS values are considerably lower. The decision was made to preserve the runoff-production scheme as in CLASSIC-catchment as much as possible, so some of the soil-drainage parameter values were reassessed to increase the delay and attenuation in these parameters, with all runoff routed as surface flow. Parameter values were tuned through a combination of visual assessment of daily hydrographs and assessment of measures of fit for ranges of likely parameter values for relevant HOST classes.

To improve the simulation of groundwater flow the regional variation in parameter values of HOST classes 1, 2 and 3, included in CLASSIC-catchment, was introduced into CLASSIC-GB, using a response-time index. The response-time index links a grid with sets of parameters for HOST classes 1, 2 and 3 which are used in the soil-drainage module. Most areas of Britain take default values for the three HOST classes but where there are major aquifers (see the Location Map in [41]) these have been divided into 12 regions allowing for different response-times within the three HOST classes. Each region is used to give a different value to one of the three HOST classes; the other two take the default values. The division is based on sensitivity of water level change to rainfall primarily using groundwater level records (Marsh, personal communication) but also hydrograph recession characteristics for catchments draining significant areas of HOST classes 1, 2 and 3. HOST class 1 (Chalk) is divided into five regions, HOST class 2 (limestone—Jurassic and Magnesian) into four regions and HOST class 3 (soft sandstones—main aquifers are in Permo-Triassic sandstones) into three regions. The other HOST classes use the same soil-drainage parameters for all grids. HOST class 4 is characterised by hard fissured bedrock, including Carboniferous limestone and fissured sandstone. It is therefore quite a diverse group, which combined with water flow through fissures (which may be very variable in size and alignment between catchments) makes it difficult to characterise the drainage response by one set of parameters. Both the spatial heterogeneity and wide geographical distribution mean it is not straightforward to divide HOST 4 into different regions.

Following the two sets of changes described above, NS values are mostly improved; particularly for catchments 15006, 27041, 54001 and 54057. Values for catchments 27034 and 47001 are slightly lower but these are smaller, responsive catchments which perform better with faster routing. Further small changes were made to some of the drainage parameter values so as not to bias the routing too much in favour of larger catchments.

3.3. Final Results

The enhanced version of CLASSIC-GB was assessed on a further 41 catchments, listed in the lower part of Table 1. Results for all 54 catchments, for four grid resolutions and three performance measures, are shown in Figure 5, where the catchments are arranged in order of decreasing catchment area. Results are for a longer time period (1991–2000) than for the initial model runs (1981–1983) but the average pattern of performance is similar between the two time periods, indicating relatively stable simulation of flow characteristics. No results are given for the smaller catchments at 10 km resolution as they are too small to be realistically defined at this resolution. The shaded grey bands in Figure 5 depict three levels of performance (see Table 2); the number of catchments within each band is given at the top of the figure. At least 50% of catchments tested achieve a Band 1 (highest) level of performance, with nearly 90% at least Band 2 level, for NS and Bias. The three catchments with consistently low NS values characterise three situations affecting comparison of observed and simulated flows; impact of water transfer and control of flow for power generation (04001), extensive urban development (28066) and simulation of flow in catchments with disparity in permeability between soils and substrata (33019). A more detailed investigation of the results is given in the following sections.

Examples of observed and simulated (5 km resolution) daily hydrographs for eight catchments are shown in Figure 6. The catchments are selected and arranged (left to right, top to bottom) to show the characteristic hydrograph shapes and flow ranges from different combinations of HOST classes with decreasing baseflow contribution. The slowest response, with recession curves dominating the annual hydrograph, is generated from areas underlain by chalk aquifers (HOST 1), while the fastest response, with little baseflow contribution, is generated from peat soils (HOST 26 to 29). The whole range of different observed runoff regimes is generally well replicated by the simulated flows from CLASSIC-GB.

Figure 5. Values of NS, Bias and mmfd for 54 catchments, listed in order of decreasing catchment area, for four resolutions (10 km—red circles; 5 km—green down-triangles; 2.5 km—blue up-triangles; 1 km—magenta diamonds) for 1991–2000 (with 1990 as 1-year warm-up period). Performance bands are indicated by shading (Band 1—dark grey; Band 2—light grey; Band 3—white; see Table 2) with the number of catchments in each band, at each resolution, presented at the top.

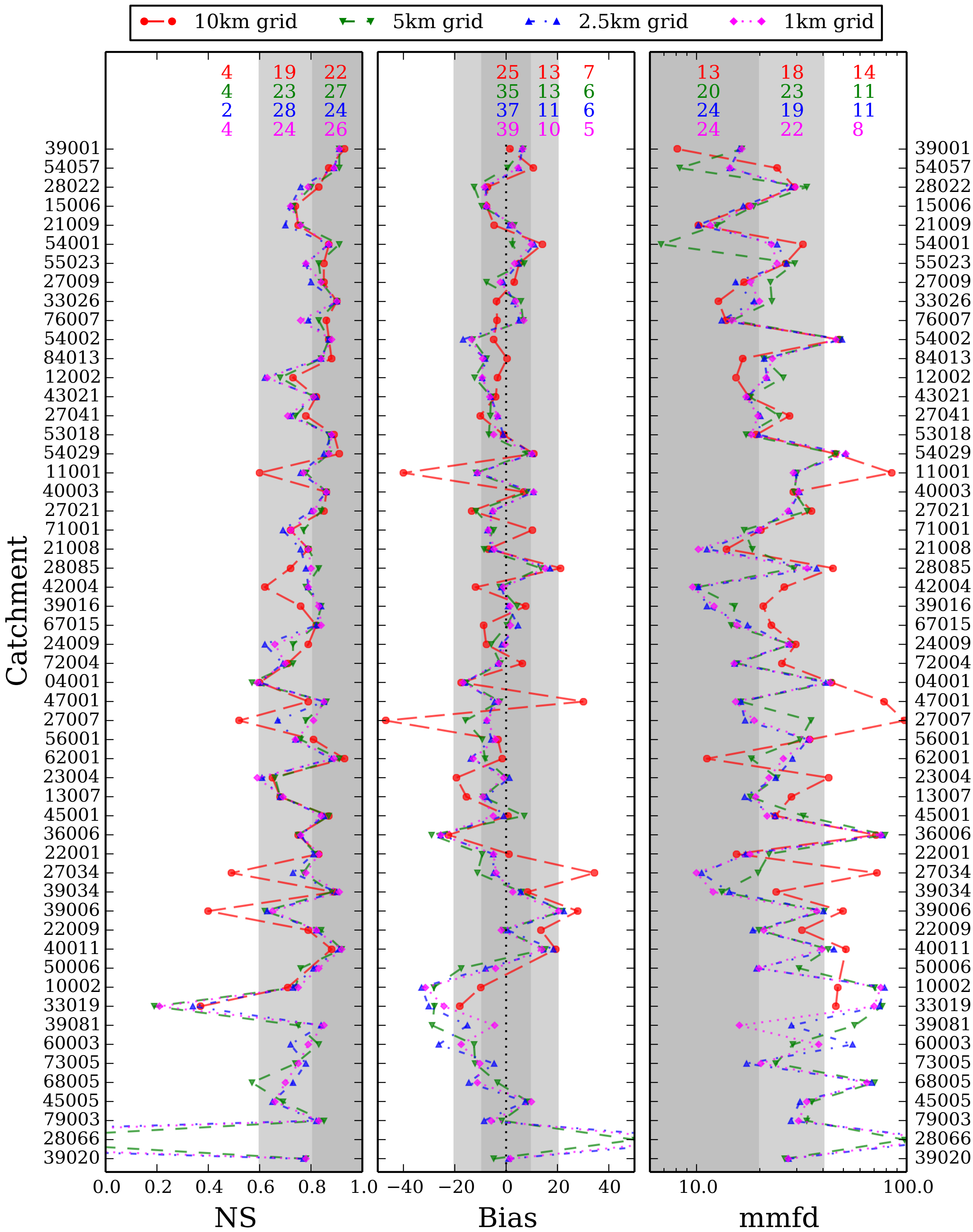
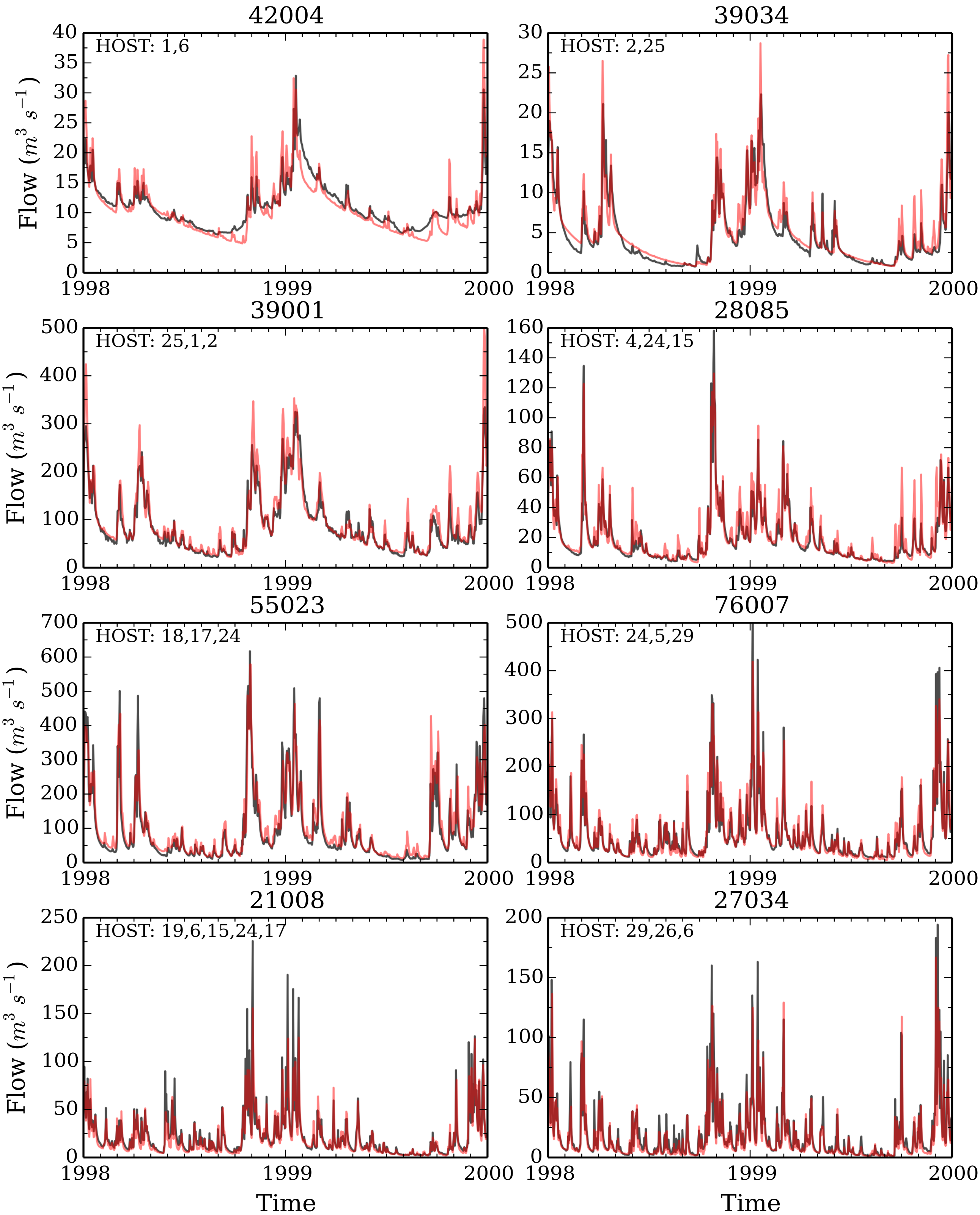


Figure 6. Example observed (black) and simulated (5 km resolution; red) hydrographs for eight catchments for the years 1998–1999. The main HOST classes for each catchment (from Table 1) are given in the top-left of each plot.



3.4. Discussion

The results shown in Figure 5 have been averaged in a number of ways (Table 4) to show the impact of model resolution and to help in understanding how well the generalised parameter methodology for setting up CLASSIC-GB is able to reproduce the observed flow regime. The catchment characteristics used are catchment area, SAAR, BFI and maximum altitude. The average value of the three performance measures for all catchments is given at the top of Table 4 (45 catchments for 10 km resolution, 53 for 5, 2.5 and 1 km resolutions; omitting 28066). Comparing the average values across the resolutions shows that the four NS values are similar, the 10 km resolution provides the lowest average Bias and values of mmfd improve with finer resolution.

Table 4. Average values of the three performance measures, for four resolutions, averaged overall and grouped by catchment area, $SAAR_{61–90}$, BFI and maximum altitude. The best value of each performance measure for each grouping method is highlighted in bold.

	Number of	10 km			5 km			2.5 km			1 km		
	Catchments	**NS**	**Bias**	**mmfd**	**NS**	**Bias**	**mmfd**	**NS**	**Bias**	**mmfd**	**NS**	**Bias**	**mmfd**
Overall		0.77	**−1.3**	33.3	**0.78**	−4.7	28.9	0.77	−3.6	27.7	**0.78**	−3.3	**26.8**
Area (km^2)													
< 350	12	N/A	N/A	N/A	0.72	−9.5	42.7	0.74	−9.4	40.8	0.74	−7.1	37.9
350–999	14	0.71	−1.2	44.0	0.76	−5.5	29.1	0.74	−4.7	26.7	0.76	−5.2	26.3
1000–1999	15	0.78	−3.3	30.2	0.80	−2.8	23.8	0.77	−0.6	23.5	0.78	−0.9	22.9
≥ 2000	12	**0.85**	**0.3**	21.3	0.84	−1.5	**21.2**	0.82	−0.4	**21.2**	0.83	**−0.3**	21.5
$SAAR_{61–90}$ (mm)													
580–749	12	0.77	0.8	36.8	0.75	−4.2	43.9	0.78	−3.6	40.7	0.78	−2.4	38.0
750–949	16	0.79	−3.1	31.4	**0.82**	−5.4	24.7	0.80	−2.8	25.3	0.80	−3.0	25.0
950–1299	12	0.75	−3.2	36.0	0.78	**−0.1**	24.4	0.74	**−0.1**	**21.5**	0.75	−0.5	21.6
≥ 1300	13	0.74	1.7	29.4	0.78	−8.6	24.4	0.75	−7.9	24.5	0.77	−7.1	23.7
BFI													
0.27–0.49	17	0.75	**1.6**	35.9	0.79	−5.5	23.0	0.76	−3.1	**18.9**	0.78	−3.0	19.7
0.50–0.59	20	**0.82**	−3.4	29.6	0.79	−4.4	31.0	0.78	−4.8	32.8	0.79	−4.5	31.4
≥ 0.60	16	0.72	**−1.6**	35.3	0.76	−4.4	32.5	0.76	−2.8	30.8	0.76	−2.3	28.9
Max altitude (m)													
70–299	12	0.76	−2.8	34.5	0.75	−7.2	41.8	0.79	−7.3	39.4	0.77	−6.0	36.7
300–599	13	**0.82**	5.0	33.1	0.81	−1.3	28.1	0.79	−1.2	28.9	0.81	**−0.6**	27.0
600–799	14	0.75	2.1	33.8	0.80	−4.8	24.5	0.76	−2.8	**21.0**	0.79	−2.8	21.4
≥ 800	14	0.76	−7.9	32.1	0.76	−5.7	22.9	0.75	−3.6	23.5	0.75	−4.1	23.7

In terms of catchment area, Table 4 and Figure 5 clearly show that, for all four resolutions, model performance is better for larger catchments and generally improves with finer modelling resolution, though differences from 5 to 1 km are small for NS and Bias. Values of mmfd, though, are lowest at the finer resolutions, for the most part because the catchment area is better defined but also indicating that differences in hydrological processes which occur through the year (with changes in balance between rainfall and evaporation) are being better represented when modelling at a finer resolution. NS and Bias are not as sensitive to differences at the monthly/seasonal scale. For larger catchments (≥2000 km^2) performance is not improved by modelling at lower resolutions than 10 km. While better performance for larger catchment areas is not unexpected, as the setup methodology was developed for such catchments, it also indicates that the range of physical and climatic conditions across large catchments is being well represented through the gridded modelling framework. For smaller catchments, the effect of more detailed hydrological processes than are represented in the model may be evident and the soil-drainage response times and constant routing parameter values may still be slightly biased towards the timing of flow simulation in larger catchments. The noticeably higher Bias and mmfd for small catchments (<350 km^2) also partly reflects percentage differences being accentuated when observed discharge is small and non-natural. In large heterogeneous catchments using generalised parameters is likely to work better as differences in processes and responses across a catchment average out, but in small catchments it is more important to simulate the exact processes taking place, perhaps at a scale which is not represented in CLASSIC. This association between catchment area and model performance of CLASSIC-GB reflects concepts of spatial scale dependency and threshold behaviour [5].

Looking at results grouped by SAAR suggests that, apart from drier catchments (SAAR < 750 mm), average rainfall has little impact on correspondence between observed and simulated flows. The implication of this is that soil-moisture accounting is being realistically modelled, as otherwise performance would relate to average rainfall. In wet catchments evaporation may be a small percentage of rainfall, and how soil-moisture is modelled may not be a determining factor in model performance. However, in catchments where evaporation is water-limited (PE higher than rainfall, [42]) or there is a finer balance between rainfall and evaporation, then the soil-moisture modelling is more critical. (Examples of how different combinations of rainfall and PE affect AE and runoff are given in [42] for three catchments in Britain; 72004—wet/energy-limited, 62001—energy/water-balanced and 39001—dry/water-limited). For drier catchments the average value of mmfd is higher than for the other rainfall bands, which is not evident for NS and Bias, but flow in such catchments is more likely to be affected by substantial water utilisation which results in high percentage differences at low flows. A similar pattern of results is found when altitude is considered; catchments with the lowest maximum altitude (< 300 m) have the lowest performance and, given the geography of Britain, these tend to correspond with the driest catchments. Performance for catchments with the highest altitude is slightly lower than those in the middle bracket (300–799 m) probably reflecting higher uncertainty in climatic data over uplands and modelling of snow-related processes. The average Bias becomes more negative and NS values decrease for the higher altitude groups, though these groups have the best values of mmfd. The results, showing that performance is predominantly independent of SAAR and altitude, are of importance when using the model for climate change studies (or with future climate data) where the balance between rainfall and evaporation in a catchment may change from wet/energy limited to water/energy balanced, for example.

The dominating factor controlling the time-response of flow is soils and substrata, with every catchment having a unique combination and spatial distribution of soil types and underlying substrate. Differences in runoff characteristics for different combinations of HOST classes are illustrated in Figure 6. The heterogeneity cannot be captured in a single characteristic, as noted in [11], but is partly represented by BFI, used as a measure of soil variation. There is little difference in NS and Bias with BFI for all resolutions, but average mmfd is smallest for catchments with low BFI (<0.50) and highest for those with mid-values (0.50–0.59). These results generally show that modelling using individual HOST soil types (and associated sets of parameter values) in the soil-drainage module is able to simulate the range of observed characteristics of rainfall-runoff in different catchments. Permeable catchments, with high values of BFI, can be the most difficult to simulate with generalised parameters (e.g., [12,43]). In CLASSIC-GB, as in CLASSIC-catchment, a number of features are included to specifically allow for differences between response times in permeable and semi-permeable catchments.

A further problem can occur in permeable catchments, notably chalk catchments, which have a permeable substrate with an overlying drift cover. In this case the response is modelled according to the HOST class of the drift soil but the observed flow response may be that of the permeable substrate. Areas where this occurs can be identified by sparse drainage networks typical of permeable regions in catchments with drift soils, normally associated with a denser channel network. In CLASSIC-catchment this problem was allowed for, where relevant, by manual adjustment of areas of appropriate HOST classes in the soil-drainage module. In CLASSIC-GB a generalisation has been included so that where both HOST 1 and 18 are present then the runoff response from the area of HOST 18 is modelled as HOST 1. For all catchments listed in Table 1 where this conjunction occurs the NS values increased. For catchment 39001 the NS value increases from 0.82 to 0.91 (5 km resolution) when both the response-time index and allowance for drift soils are implemented. However, soils other than HOST 18 may have similar impacts, for which it is not appropriate to generalise. This appears to be the case for catchment 33019, which has low performance results for all resolutions. The catchment has a BFI of 0.78 and is entirely underlain by chalk, but has 70% drift cover of which only 14% is HOST 18. Other difficulties in simulating flow in permeable catchments include where the catchment area defined by a topographic boundary differs from that of the groundwater catchment, leading to bias in the water balance. Another HOST class where generalisation may result in poorer performance than expected is HOST 4. This class was noted in Section 3.2 as having a very variable response rate depending on the degree of fissuring and alignment of fissures in the bedrock. Catchment 54029, which has 25% HOST 4, has a Band 1 NS (0.87, 5 km resolution) but relatively poor simulation of mean monthly flow – overestimation of mean daily flows through the summer and underestimation of high flows in the winter resulting in a Band 3 mmfd (46.1, see Figure 5). In this case the response rate is faster than modelled with the default parameter values for HOST 4, whereas these values give good response times for catchment 28085 (Figure 6, 45% HOST 4).

3.5. Additional Analyses

The catchment with the lowest performance values is 28066, which is the second smallest catchment selected, but the main reason for selection was substantial urbanisation (urban extent 40% [36]). Visual inspection of observed and simulated hydrographs for 28066 shows reasonable timing of flow simulation but flows are greatly overestimated. The structure of CLASSIC includes a separate modelling pathway for urban areas (no soil-moisture store, urban drainage parameter), with the area determined from the land cover database using that designated as urban plus a proportion of suburban areas. Assessment of this urban pathway with CLASSIC-catchment for catchments with a range of urban percentages has shown generally good simulation of small summer peaks, the main time when contribution from urban areas is evident. Poor performance for a small urban catchment, therefore, suggests either that the method of modelling runoff from urban areas in CLASSIC is not appropriate for such catchments or that the specific characteristics of this catchment are not well simulated with a generalised approach. Fully allowing for urban land cover involves integration between the land cover and soils databases, which is not currently undertaken; allowance for the urban areas has been achieved by subtracting the urban percentage from the areas of the different soil types in a grid square by area weighting. This method may result in inappropriate simulation of flow response from the remaining soil areas, which will be more apparent in a small catchment. CLASSIC-GB was re-run taking the urban area as just urban without adding any proportion of suburban (all suburban areas modelled as grass), which improves the Bias for 28066 (from 51% to 18%) but still has a negative NS value. However, results for five other catchments with urban extent greater than 4.0% indicate that performance is generally better with the original method of estimating impermeable urban areas. But there clearly may be a difference in how catchments dominated by urban development should be modelled compared with catchments which are predominantly rural but contain scattered areas of urban development. Further modelling for other substantially urbanised catchments is required to determine if it is appropriate to use generalised methods for simulation of flow in such catchments.

Another catchment selected to see how well generalised methods perform where there is substantial alteration to the natural flow is 04001 where 'extensive volumes of surface storage [are] controlled for [Hydro Electric] power generation' [36]. Performance measures are Band 2 or 3 but visual inspection of gauged and simulated hydrographs shows that overall hydrological response is well modelled, while differences between the two flow series indicate when the natural flow is interrupted.

A simple example of how CLASSIC-GB can be used in an investigative way is using two methods for determining sub-daily temperatures in the snowmelt module. One (standard in HMF-GB) uses a sinusoidal variation between daily minimum and maximum temperature while the other uses a constant mean daily temperature (average of minimum and maximum). There was little difference in results between the two methods, but for 46% of the catchments tested a variable temperature gives slightly higher values of NS, for 39% the values are the same and for the remaining 15% a constant temperature gives slightly higher values.

4. Conclusions

The concept and practicality of a hydrological modelling framework (HMF-GB) has been demonstrated through the transfer of the runoff-production scheme from an existing catchment-based model (CLASSIC-catchment) to simulation of river flow at a national scale (CLASSIC-GB). The transfer is possible because of the generalised methodology for setting parameter values from physiographic properties developed for CLASSIC-catchment. The demonstration shows that the HMF could provide a suitable platform for broadening the application of other hydrological model runoff-production schemes.

Although parameter generalisation may generate lower model performance than individual catchment calibration, the assumed stationarity between catchment properties and hydrological processes ensures consistency of simulation between and within catchments and reduces the parameter uncertainty inherent in the calibration of individual catchments for defined time periods. It also allows simulation of flows at ungauged locations or in catchments where direct calibration is not appropriate due to the quality of the flow record. Generalisation can broaden understanding of hydrological processes (and inform model development) by showing where simulated flow responses consistently differ from those in the observed flow record; that is where a generalised approach does not give a good performance. The performance of CLASSIC-GB has been assessed by comparison of simulated flow with observed but the structure of the framework allows for output of intermediate hydrological variables, such as soil-moisture, which could be compared with appropriate field measurements [44]. Such comparison would also contribute to understanding of relationships between physical catchment properties and model representation and parameter values.

The main adjustment required in the transfer between the two versions of CLASSIC was reassessment of some of the soil-drainage parameter values to allow for the change in the routing procedure from catchment-specific routing parameter values to constant values of land and river wave speeds for connecting all flow paths. Results from the enhanced version of CLASSIC-GB show that performance measures, on average, are comparable with those from CLASSIC-catchment, and results from testing over a large group of catchments show that good model performance can be achieved without direct calibration of model parameters. At least 50% of catchments tested achieve a Band 1 level of performance, with nearly 90% a Band 2 level for Nash-Sutcliffe efficiency and water balance bias.

The ability to run CLASSIC at different grid resolutions within HMF-GB demonstrates the effect of averaging hydrological processes. Large catchment areas (>2000 km^2) can be well simulated with a 10 km grid resolution, a 5 km resolution is adequate for catchments larger than 500 km^2, but a finer resolution is required for smaller areas, mainly to ensure that there is a good correspondence between topographic catchment area and contributing grid-square area. However, in small catchments specific attributes of the catchment, such as urbanisation, may not be well represented by generalised methods of setting parameter values at the spatial scale of hydrological processes currently in CLASSIC. Factors such as spatially uniform land and river routing parameter values and use of daily rainfall data, while modelling at a sub-daily time step, may also be implicated in poorer model performance in small catchments.

Integral to the success of the generalisation is the use of the HOST classification system to generate the rainfall-runoff response times of a grid square by cumulating the runoff from each soil type present in the square. A response-time index has been implemented to improve the simulation of flow in areas with permeable substrates, such as chalk and limestone. This has enabled similar levels of model performance to be obtained for all catchment permeabilities, as defined by BFI. Simulation of runoff regimes may be compromised where there is a disparity between response from the substrate, notably chalk, and overlying, but hydrologically connected, drift soils.

HMF-GB provides a valuable platform for easily testing the effect of alternative model formulations, at different spatial resolutions, over the range of climatic and physical properties found nationally and combined in infinite patterns of catchment heterogeneity. Alternative model approaches include, for example, simple differences as in method of calculation of mean daily temperature in the snow module, through variation in the method for calculating soil-moisture, to the changes required to fully implement the HMF routing scheme through use of parallel surface and sub-surface routing. The availability of a range of other databases, in particular a mapping of European soils onto HOST classes [45], potentially widens the scope of the HMF to continental or global application. Currently, the HMF is setup with natural flow paths and simulates natural river flow; additional modules and appropriate databases could allow for water usage and artificial lateral transfer of water between grid boxes (e.g., through pipes and canals). Databases of, for example, climate change scenarios or different land cover enable wide-scale assessment of such impacts on the flow regime. The flexible infrastructure of the framework enables consistent studies, from catchment-based or detailed fine-resolution modelling to less detailed coarse-resolution modelling using very long runs or applying large ensembles.

Acknowledgments

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Author Contributions

The modelling framework concept was developed by Bell, who provided prototype code developed further into HMF-GB by Kay; the HMF datasets were prepared by Davies. The setup and testing of CLASSIC-GB was undertaken by Crooks. The paper was written by Crooks and Kay with comments from Bell and Davies.

Conflict of Interest

The authors declare no conflict of interest.

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