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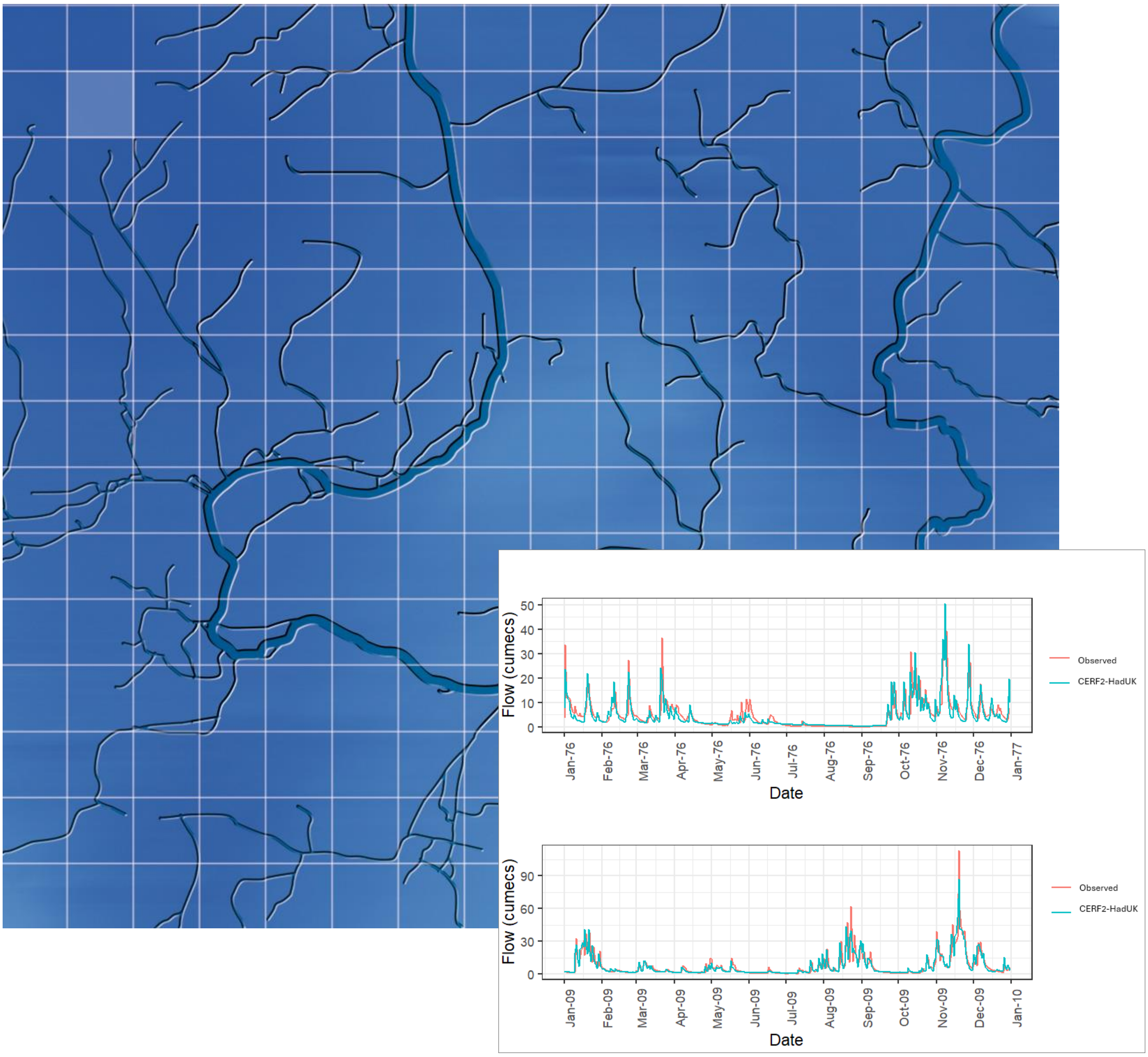
Development of the CERF2-HadUK rainfall-runoff model



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Document issue details

WHS8516

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1	28/03/2024	Draft	Tracey Haxton (*Technical Director*)	Jude Jeans (*Technical Director*)
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For and on behalf of Wallingford HydroSolutions Ltd.

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Contents

1 Executive summary

Qube is a web-based water resource model that can be used to estimate natural and influenced flow durations curves (FDCs) and time series for ungauged sites throughout the UK and Ireland.

Within an ungauged catchment, a natural FDC can be estimated based on the catchment characteristics (runoff and soil properties) within the catchment. Qube can also be used to estimate daily flow time series in ungauged catchments through the use of the generalised Continuous Estimation of River Flows (CERF)[1] rainfall-runoff model. CERF is used to produce a daily time series of flow percentiles for ~11,000 TSEP (time series of exceedence probabilities) catchments within Great Britain (GB). In application, Qube selects the most similar TSEP catchment, based on distance and catchment characteristics to the ungauged location, and scales the time series to the FDC; this ensures that the time series and FDCs within Qube are internally consistent.

In the past few years, a number of UK wide gridded datasets have been produced by the Met Office (MO) and UK Centre for Ecology and Hydrology (UKCEH). The MO have developed the HadUK observed meteorological datasets (Hollis et. al., 2018), which UKCEH have subsequently used to produce potential evaporation (PE, PET and PETI) datasets[2] . The MO UKCP18 climate change, RCP8.5 pathway datasets have also been downscaled and biased corrected by UKCEH as part of the eFLaG[3,4] project to produce 1km gridded time series of precipitation and PE datasets.

The CERF rainfall-runoff model has been redeveloped, hereafter referred to as CERF2-HadUK, using the HadUK precipitation dataset and UKCEH PETI dataset using gauged flow data from 472 gauges. A number of measures of fit were used to assess the model performance taking into account the temporal variability of flows, the annual and seasonal bias and the ability to reflect the FDC at these gauges. CERF2-HadUK has then been run for the TSEP catchments across GB using the historical meteorological forcing datasets. This allows the estimation of time series flow data to be estimated at ungauged catchments throughout GB within Qube. The ongoing commitment by the MO and UKCEH to regularly update these datasets means that time series data within Qube can be regularly updated in the future.

This report details the redevelopment of the CERF model based on the HadUK and UKCEH meteorological forcing datasets and presents results for the 472 development gauging stations.

[1] Griffiths, J., Keller, V., Morris, D., Young, A.R. 2008. Continuous estimation of River Flows (CERF). Environment Agency. SC030240
[2] https://catalogue.ceh.ac.uk/documents/9275ab7e-6e93-42bc-8e72-59c98d409deb
[3] https://www.ceh.ac.uk/our-science/projects/eflag-enhanced-future-flows-and-groundwater
[4] Hannaford, J., Mackay, J. D., Ascott, M., Bell, V. A., Chitson, T., Cole, S., Counsell. D., Mason Durant, M., Jackson, C. R., Kay, A. L., Lane, R. A., Mansour, M., Moore, R., Parry, S., Rudd, A. C, Simpson, M., Facer-Childs, K., Turner, S., Wallbank, J., R., Wells, S., Wilcox, A. 2023, The enhanced future Flows and Groundwater dataset: development and evaluation of nationally consistent hydrological projections based on UKCP18. Earth Syst. Sci. Data, 15, 2391–2415, https://doi.org/10.5194/essd-15-2391-2023, 2023

2 Introduction

This science report provides a summary of the redevelopment of the Continuous Estimation of River Flows (CERF)[5] rainfall-runoff model. This includes updates to the CERF structure and a recalibration using Met Office (MO) observed daily gridded HadUK precipitation datasets and potential evaporation (PE) datasets developed by UKCEH, as well as updated land cover from the UKCEH Land Cover Map (LCM)[6]. The resulting CERF structure and calibration will be referred to as CERF2-HadUK.

Qube provides daily flow time series in ungauged catchments through the use of the generalised CERF daily rainfall-runoff model. CERF uses precipitation and potential evaporation (PE) datasets to produce a time series of flow percentiles at ~11,000 TSEP (time series exceedance percentile) catchments within Great Britain (GB). In application, Qube selects the most similar TSEP catchment to the ungauged location and scales the time series to the natural FDC; this ensures that the time series and FDCs within Qube are internally consistent.

There is a need for many users to be able to estimate recent flow time series in Qube; this includes GB regulators (SEPA, NRW and the EA) as well as water companies and the wider hydrological community. The ability to estimate recent time series has been limited by the timely availability of gridded meteorological forcing datasets.

PE can be calculated using different formulations hence may be referred to using different acronyms, for example PET and PETI, which provide some indication of the form used. The datasets readily available at the time of the Qube original development (2016-2019) were the UKCEH GEAR[7] 1km rainfall dataset and the UKCEH CHESS PET[8] 1km dataset. Note that the UKCEH CHESS PETI dataset, which includes an interception component for grass, and is generally found to improve the estimation of evaporation within hydrological models, was not available at the time. At the time of the CERF2-HadUK redevelopment in 2023, the GEAR dataset was available to 2019 and this specific CHESS PET dataset to 2017.

More recently, the MO have developed the HadUK meteorological dataset[9], held by CEDA (Centre for Environmental Data Analysis), the national data centre for atmospheric and earth observation research. The dataset is developed from a number of funding streams with the purpose 'to facilitate monitoring of UK climate and research into climate change, impacts and adaptation' and is updated on an annual basis. The HadUK dataset is available at a 1km resolution and covers a range of meteorological variables, including rainfall and other variables required to estimate the PE, and is widely used throughout the hydrological community. UKCEH have developed a HadUK PE dataset[10] held by the EIDC (Environmental Information Centre).

The CERF parameterisation is sensitive to the specific formulations used to produce the PE. In the past it has been calibrated to both MORECS and MOSES formulations which have been widely used throughout the water resource community. It is therefore necessary to calibrate CERF to the HadUK

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[5] Griffiths, J., Keller, V., Morris, D., Young, A.R. 2008. Continuous estimation of River Flows (CERF). Environment Agency. SC030240

[6] https://www.ceh.ac.uk/data/ukceh-land-cover-maps

[7] Tanguy, M.; Dixon, H.; Prosdocimi, I.; Morris, D.G.; Keller, V.D.J. (2021). Gridded estimates of daily and monthly areal rainfall for the United Kingdom (1890-2019) [CEH-GEAR]. NERC EDS Environmental Information Data Centre. https://doi.org/10.5285/dbf13dd5-90cd-457a-a986-f2f9dd97e93c

[8] Robinson, E.L.; Blyth, E.M.; Clark, D.B.; Comyn-Platt, E.; Rudd, A.C. (2020). Climate hydrology and ecology research support system potential evapotranspiration dataset for Great Britain (1961-2017) [CHESS-PE]. NERC Environmental Information Data Centre. https://doi.org/10.5285/9116e565-2c0a-455b-9c68-558fdd9179ad

[9] Hollis, D.; McCarthy, M.; Kendon, M.; Legg, T.; Simpson, I. (2018): HadUK-Grid gridded and regional average climate observations for the UK

[10] https://catalogue.ceh.ac.uk/documents/9275ab7e-6e93-42bc-8e72-59c98d409deb

precipitation and newly developed PETI dataset. In addition, the land cover dataset which underpins the CERF model has been updated and updates to the CERF model structure have also been implemented.

The historical modelling outputs using the HadUK datasets will replace the present flow exceedance time series datasets used within Qube. It is anticipated that this will be updated regularly.

This science report provides details on the development of the CERF2-HadUK rainfall-runoff model. Section 3 presents an overview of the CERF model structure and Section 0 provides details of the main datasets used. The development process is then described in Section 5, followed by the results, discussion and conclusions in Sections 6 and 7.

3 The CERF rainfall-runoff model

3.1 Introduction to CERF

CERF is a generalised semi-distributed daily rainfall-runoff model. The inputs to the model are time series of precipitation and PE which, combined with a number of spatial datasets (digital terrain model (DTM), soils and land cover) are used to produce a time series of simulated river flows. The model is generalised such that it can be run for any topographically defined catchment in GB without recourse to gauged or observed data.

CERF requires both meteorological and spatial datasets as summarised within Table 1. For further details on the specific datasets used within the project see section 4.2.

Table 1. The datasets required for CERF.

Dataset	Specific Dataset	Type	Resolution (temporal or spatial)	Description	Use case
Precipitation	HadUK	Meteorological	Daily, 1km grid	Catchment average daily precipitation	Meteorological forcing data
Potential evaporation	HadUK-PE	Meteorological	Daily, 1km grid	Catchment average daily potential evaporation	Meteorological forcing data
Digital Terrain Model	UKCEH IHDTM	Spatial	50m	Topography	Used to determine catchment boundaries and as part of quick flow routing.
Soils based on HOST	HOST	Spatial	1km	1km dominant soils. 29 main classes.	Used within the loss and routing module.
Vegetation based on Land cover	LCM2015	Spatial	1km	1km dominant land cover/ vegetation. 7 main classes.	Used as part of the loss model.

The rainfall-runoff processes within CERF are broken down into two main components: a loss module, and a routing module, as presented within Figure 1. The loss module is made up of interception and soil moisture losses and produces hydrologically effective precipitation (EP). The routing module splits the EP into quick flow and slow components and routes this through the catchment. The loss module is described in more detail in section 3.2 and the routing module is described in section 3.3.

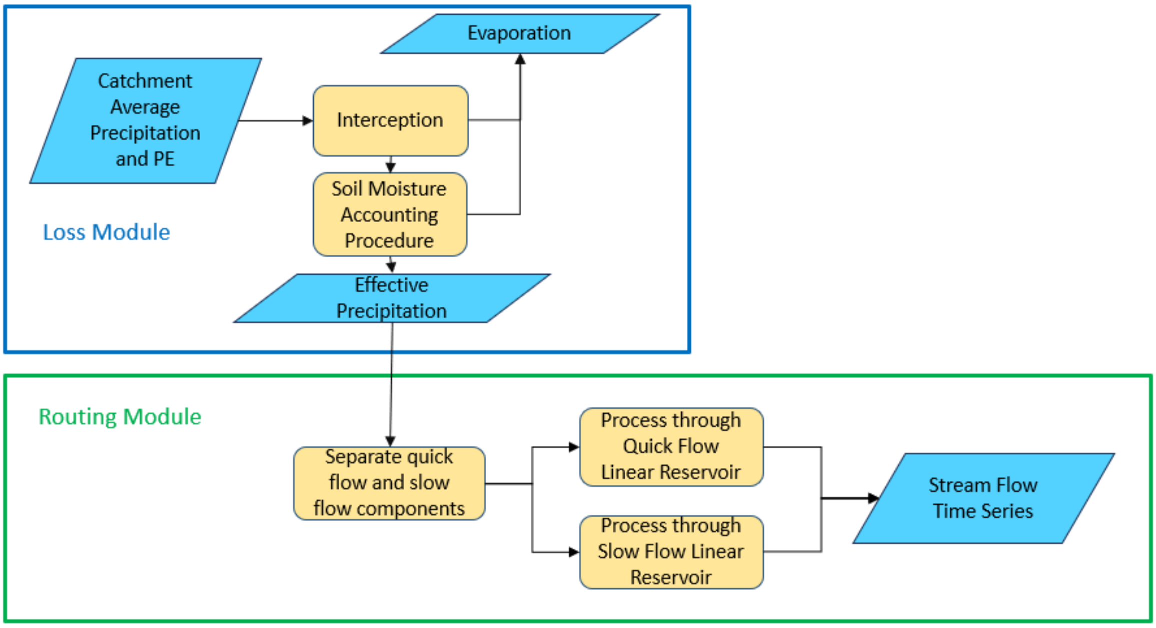

Figure 1. The CERF structure illustrating the loss module and the routing module.

The basic model building block within CERF is a Hydrological Response Unit (HRU), which is applied to all parts of a catchment where the hydrological response is similar. A HRU is defined by the catchment descriptors, using a combination of the 29 soil classes and the 7 vegetation classes to yield a large number of potential combinations (203). In practice, the number of actual combinations is significantly less as some vegetation/soil class combinations do not occur. The individual cells within the HRUs represented within the catchment are amalgamated to form HRUs with a fractional extent that is not necessarily contiguous within the catchment.

The number of HRU used within a particular catchment depends on the complexity of the catchment. For example, a small catchment with very similar soils, geology and vegetation will only have a few HRUs, whilst a large, diverse catchment will have many, see Figure 2 for an example catchment. The model parameters for each of the modules are fixed for each individual HRU and as CERF is a generalised model, these do not vary between catchments.

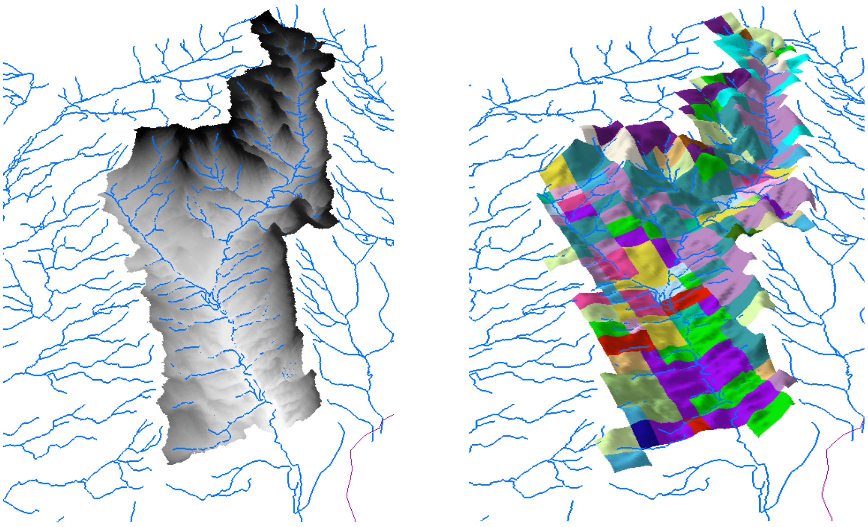

Figure 2. An example catchment showing the digital terrain model and HRUs (vegetation and soil combinations).

3.2 The loss module

The basic model structure for the loss module consists of an interception sub-module and a soil moisture accounting procedure sub-module; a treatment of transpiration losses based on the FAO56 procedures for determining crop water requirements, Allen et al.,1998[11].

3.2.1 Interception sub-module

Interception can vary greatly depending on a large number of variables, e.g. meteorological (precipitation type and intensity), the structure of the leaf area and density of the canopy. The interception model adapted in the CERF model is based upon the daily interception model proposed by Calder (1986)[12]. This model has been tested through observation on a number of vegetation types in the UK (Hall and Harding, 1993[13] and Harding et al., 1992[14]).

Considering vegetation class j, covering a fraction of the catchment, A_j, the intercepted depth of precipitation on day i is given by:

$$I_{ji} = A_{ji} * \gamma_{ji} * \left(1 - e^{-\delta P_i}\right) \tag{1}$$

where:

I_{ji} = the interception depth within day i from vegetation class, j (mm);

γ_j = maximum daily interception loss for vegetation class, j (mm);

[11] Allen, R.G., Pereira, L.S., Raes, R. and Smith, M. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements. Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations, Rome, 300 p.

[12] Calder, I.R. 1986. The influence of land use on water yield in upland areas of the UK. Journal of Hydrology, 88 : 201-211.

[13] Hall, R.L. and Harding, R. 1993. The water use of the Balquhidder catchments : a processes approach. Journal of Hydrology, 145 : 285-314.

[14] Harding, R., Hall, R.L., Neal, C., Roberts, J.M., Rosier, P.T.W., and Kinniburgh, D.G. 1992. Hydrological impacts of broadleaf woodlands : implications for water use and water quality. Project report 115/03/ST. National Rivers Authority, Bristol. 135 pp.

δ = scaling constant for vegetation type (mm^{-1});

P_i = precipitation depth within day i (mm).

Interception losses may be adequately modelled (i.e. within experimental error) by re-parameterising the above equation as a one-parameter model. This parameter, 'maximum daily interception loss' (γ), is intrinsically related to vegetation type. A scaling constant (δ), is used to set the precipitation depth at which maximum interception loss is reached.

The final interception model is based on that within a generalised rainfall-runoff model by Young 2006[15]. An additional interception store, equal to maximum interception depth, is included within the model to ensure continuity is maintained between time steps. The conceptual structure is presented in Figure 3.

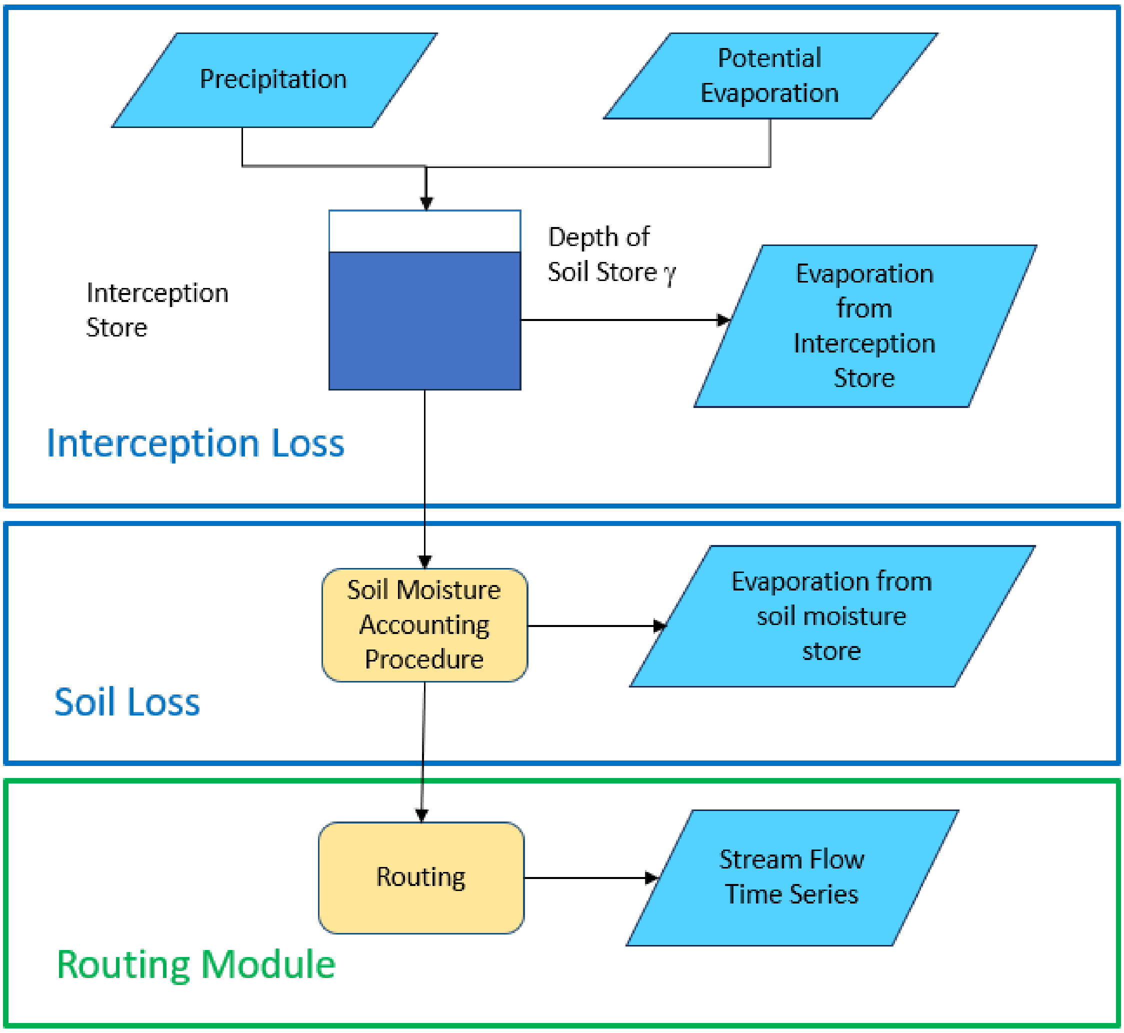

Figure 3. The interception sub-module within CERF.

[15] Young A.R. 2006. Stream flow simulation within UK ungauged catchments using a daily rainfall-runoff model. Journal of Hydrology, 320, 1-2, pp 155-172.

3.2.2 Soil moisture accounting procedure sub-module

The soil moisture accounting procedure sub-module, presented in Figure 4, describes vegetation as a function of maximum root depth, Z_r, and 'moisture depletion fraction', p, for a range of vegetation and soil types.

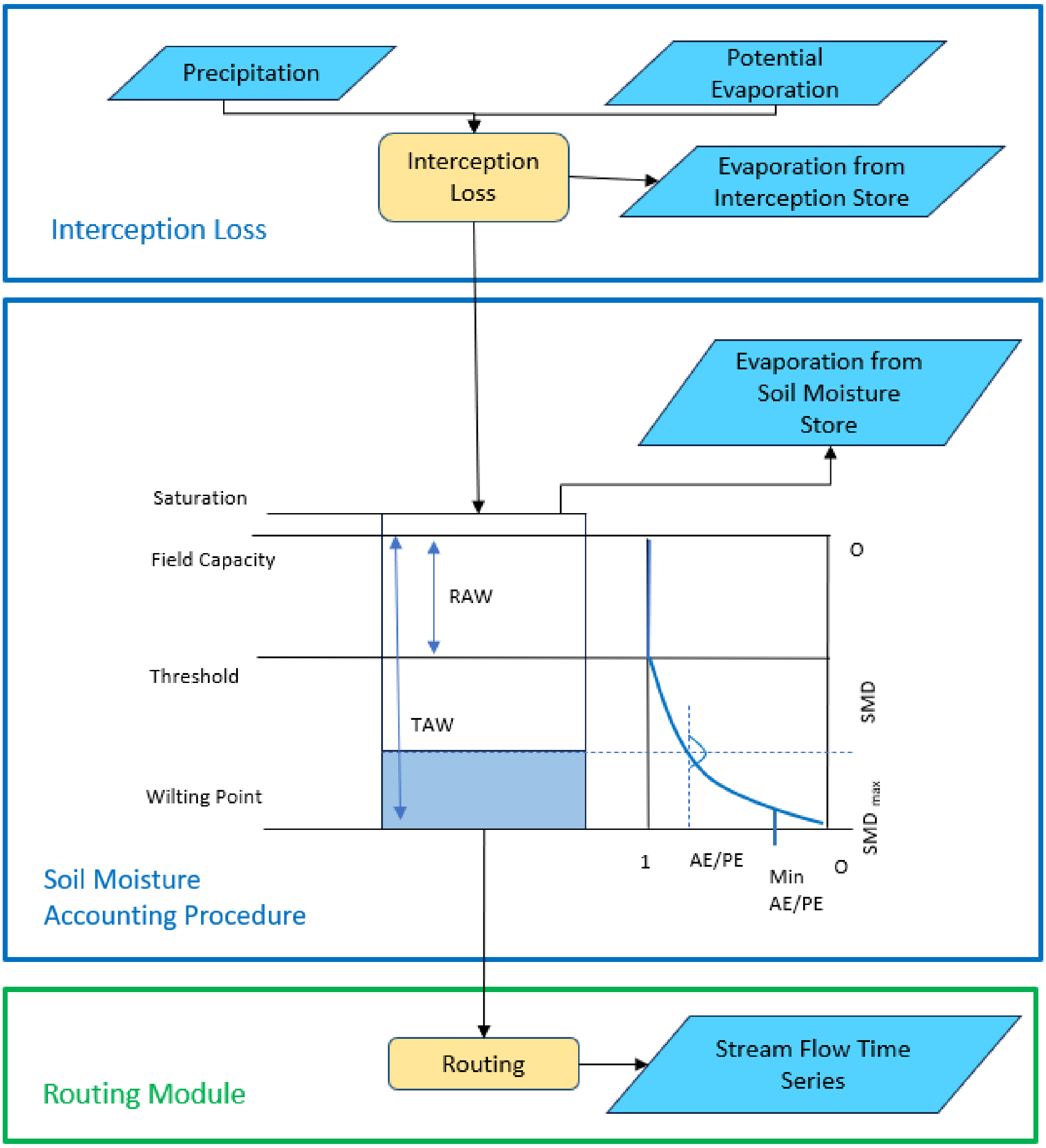

Figure 4. The soil moisture accounting procedure sub-module within CERF.

The Total Available Water (TAW) is the amount of water available to plants after a soil has drained to its field capacity. It is defined as the product of Z_r and the difference between field capacity (FC) and wilting point (WP), both properties of the soil class:

$$TAW = Z_r * (FC - WP) \tag{2}$$

As moisture content within the soil column decreases, vegetation will find it more difficult to extract moisture from the soil matrix. Plants freely transpire until the Soil Moisture Deficit (SMD) exceeds the threshold defined as Readily Available Water (RAW). The value of RAW is related to TAW by a vegetation defined depletion factor (p), which is comparable to the 'rooting constant' described by Penman (1949)[16]:

$$RAW = p * TAW \tag{3}$$

Beyond the RAW threshold, the plants become increasingly stressed and evaporation reduces below the potential rate in proportion to the depth of threshold exceedance.

Effective precipitation (EP) is generated by the original module when the SMD within the module is zero.

The output from the loss module within a catchment is an EP and actual evaporation (AE) time-series for each HRU within the catchment.

3.2.3 Update of the soil moisture accounting procedure sub-module

Within the soil moisture accounting procedure, effective precipitation is only generated when the soil moisture deficit is zero, this means that unless the HRU is fully saturated, no runoff will be generated. A bypass function was previously introduced where, for specific HRUs, a percentage of runoff 'bypassed' the loss module allowing runoff even when SMDs are present.

This concept of a bypass has been extended in CERF2-HadUK by using a probability distribution of store depths with the maximum storage depth being equal to TAW and a minimum value of zero (a depth of zero is equivalent to the previous representation of bypass). Thus, it is the distribution of soil store depths that contribute to the maximum soil moisture capacity at saturation. The use of probability distributed soils stores is described by Moore et al. 2007[17]. Modelling the storage within an HRU in this way enables saturated runoff, or effective precipitation, to be generated prior to full catchment saturation being reached.

A pareto distribution of store depths is used, as illustrated in Figure 5, which has three parameters; the minimum storage depth (zero), the maximum storage depth (TAW) and the shape parameter (b). As part of the calibration process, different values of 'b' were tested in a number of catchments. An optimum value of 0.5 is used, see Appendix 1 for more details.

[16] Penman, H.L. 1948. Natural Evapotranspiration from open water, bare soil, and grass, Royal Society of London Proceedings, Series A, 193: 120-145.
[17] Moore, R. J. 2007. The PDM rainfall-runoff model, Hydrol. Earth Syst. Sci., 11, 483–499, https://doi.org/10.5194/hess-11-483-2007.

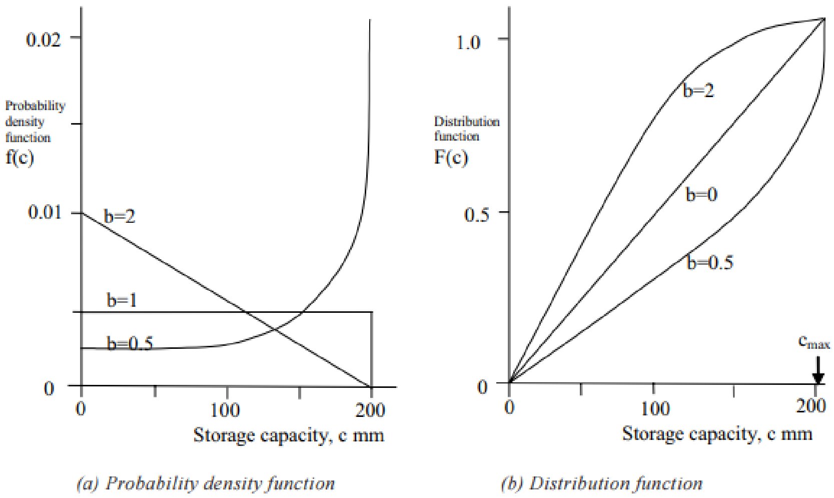

Figure 5. The pareto distribution after Moore, 2007.

There was also a desire to be able to capture the way in which the runoff responds following a drought period. For example, in the 1976 drought, it was recognised that the SMDs could reach the limit of TAW for longer periods (depending on soils, geology and geographic location). Following precipitation, within CERF, the SMDs were quickly replenished and runoff commenced more quickly than indicated by the observed data.

It is hypothesised that greater soil moisture deficits can build up during drought periods, compared to those found in 'normal' years. This could be addressed in the model by increasing the depth for which soil moisture deficits can build up within a particular catchment, i.e. increasing TAW. However, doing so would adversely affect the water balance within more typical years.

To allow deficits to build up in years with prolonged periods of low rainfall, without adversely impacting more typical years, a minimum actual evaporation/potential evaporation ratio (AE/PE) has been introduced. This means that additional soil moisture deficits can build up beyond the threshold, but these deficits are only reached in extreme years.

The rate at which the AE/PE decreases to the 0 once below RAW is maintained, but this decreases to a minimum level at which it remains, e.g. SMDs are allowed to exceed TAW. The minimum AE/PE was calibrated and set to a value of 0.3. See Appendix 1 for further details.

3.2.4 Parameterisation of the loss model

The parameterisation of the loss module is based on both the vegetation and soils class. The parameters required are presented in Table 2, which are required for each HRU.

Table 2. Loss Model Parameters.

Sub-module	Spatial data used for classification	Parameter name	Unit	Description
Interception	Land cover - vegetation	γ	mm	The maximum depth of water that can be held by vegetation.
Soil Moisture Accounting Procedure	Land cover – vegetation	Zr	mm	Maximum rooting depth
Soil Moisture Accounting Procedure	Land cover - vegetation	p		Depletion Factor
Soil Moisture Accounting Procedure	HOST - soils	FC	mm	Field Capacity
Soil Moisture Accounting Procedure	HOST - soils	WP	mm	Wilting Point

For the interception sub-module, the parameterisation is largely based on results from UK studies. which includes parameter values for Coniferous (Calder, 1986[18]) and Broadleaf (Harding et al., 1992[19] ; Calder et al. in Roberts et. al, 2001[20],Roberts et al., 1998[21]) woodlands.

For the soil moisture accounting procedure sub-module, the parameterisation of FC (Field Capacity) and WP (Wilting Point) within the original development of CERF was defined for each soil class based on the average percentages of sand, silts and clays in each HOST class from the UK National Soil Resource Institute's SEISMIC (Spatial Environmental Information System for Monitoring the Impact of Chemicals) dataset. The Zr (maximum rooting depth) and p (depletion factor) are defined for each vegetation class and are free parameters which were calibrated within the original CERF project.

3.3 The routing module

The routing module routes the effective precipitation (EP) timeseries to the catchment outlet via a semi-distributed routing scheme. In the UK, the dominant influence on the routing of water through the land surface is hydrogeology and its impact through soils and topography.

The overall CERF structure with the different aspects of routing highlighted is presented in Figure 6.

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[18] Calder, I.R. 1986b. A stochastic model of rainfall interception. Journal of Hydrology, 89 : 65-71.
[19] Harding, R., Hall, R.L., Neal, C., Roberts, J.M., Rosier, P.T.W., and Kinniburgh, D.G. 1992. Hydrological impacts of broadleaf woodlands : implications for water use and water quality. Project report 115/03/ST. National Rivers Authority, Bristol. 135 pp.
[20] Roberts, J.M., Rosier, P.T.W. and Smith, D.M. 2001. Effetcs of Afforestation on Chalk Groundwater Resources - Summary of Final Report to the Depatment of the Environment Transport and the Regions, CEH Wallingford.
[21] Roberts, J.M., Rosier, P.T.W. and Kirby, C. 1998. Broadleaf woodlands. The implications for water quantity and quality. Environment Agency R&D Publication no.5, Bristol, pp50.

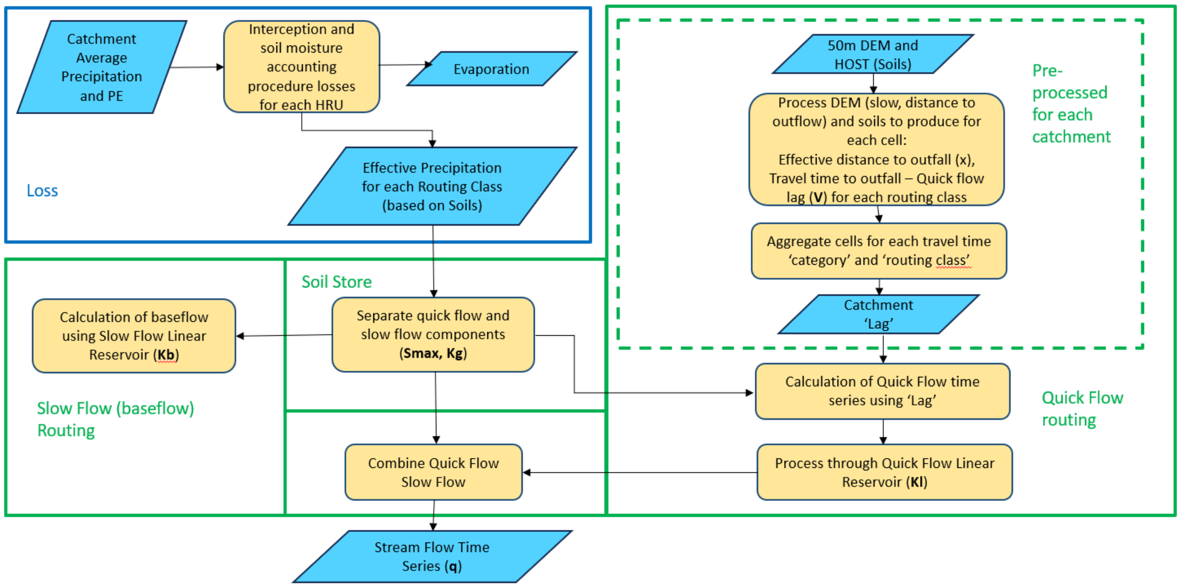

Figure 6. Flowchart of CERF semi-distributed model structure, highlighting the routing module.

In the routing structure, the EP enters a probability distributed soil store, based upon a uniform distribution, that conceptually represents the catchment variation in soil storage capacity between field capacity and saturation. Runoff from the store is passed through a quick flow reservoir with a time constant (Kl) whilst drainage, proportional to the storage content of the store, is passed through a slow flow (baseflow) reservoir with time constant (Kb). The sum of the resultant surface and base flow from the routing reservoirs is the simulated streamflow (q).

3.3.2 The free water soil column store

The water within the soil moisture accounting module is bound within the soil matrix and cannot move, it is the water available to fund evaporation and water in excess of this bound potential forms effective precipitation, as described.

The effective precipitation is free to drain under gravity to the slow flow routing module. The free water soil store is modelled as a uniformly probability soil store with a fully saturated storage capacity of Smax. The uniformly distributed soil store depths that contribute to this storage depth range from a minimum depth of zero to a maximum storage depth of Smax/2. Drainage within a time step is proportional to the fraction the storage depth represents of the saturated storage depth, and lateral runoff to the quick flow routing path is generated from the fraction of the soil that is saturated within the time step, see Moore et al 2007[22].

The functioning of the store is controlled by two calibrated parameters; the saturated storage capacity, Smax, and the drainage coefficient of proportionality, Kg. This module is applied as a semi-distributed model at the grid cell dimension (1km^2) of the HOST soil dataset used within CERF.

[22] Moore, R. J. 2007. The PDM rainfall-runoff model, Hydrol. Earth Syst. Sci., 11, 483–499, https://doi.org/10.5194/hess-11-483-2007

3.3.3 Quick flow routing

Quick flow runoff is generated at the grid cell level by the partition of effective precipitation into quick and slow flow components. The quick flow runoff is topographically routed to the catchment outlet using a scheme loosely based on that within TopModel[23]. The transit time for runoff to route across a cell is a function of the gradient across the cell and the velocity at which water will move downslope through the soils within the cell. To route the quick flow component of effective precipitation, the spatial and hydrological characteristics of each grid cell must be represented. These include:

- Cell slope [m/m] (β)
- Velocity at which the surface flow runoff will travel across cells, the transfer velocity [km/hr] (V)
- Distance to catchment outflow via drainage network [km] (x)

The IHDTM drainage direction grid coupled with the elevation grid (Morris and Flavin, 1992[24]) was used to define both the distance from any cell to the catchment outflow point and the individual cell slopes along the drainage path. 1km^2 resolution grids of x/β were then created for each cell within each catchment. These were used within the optimisation process to calculate the time taken for quick-flow to reach to outflow when routed through different combinations of soil types. Total travel time (σ) for each cell then, is calculated as a function of the distance and slope to the catchment outlet (x/β) and the hydrological properties of downstream cells such that, as presented in Equation 4:

$$\sigma = \sum_{i=1}^{N} \frac{\Delta x_i}{\bar{\beta} V_{Sh}} = \sum_{i=1}^{N} \frac{x_i - x_{i+1}}{2\bar{\beta} V_{Sh(i)}} + \frac{x_i - x_{i+1}}{2\bar{\beta} V_{Sh(i+1)}} \qquad (4)$$

where σ = travel time to outfall

$\bar{\beta}$ = average slope between cell i and cell (i+1)

x_i = actual distance between cell (i) and downstream cell (i+1)

$V_{Sh(i)}$ = soil type specific transfer velocity parameter of cell i

N = number of cell increments in the pathway to outfall point

Equation 4 was executed within every 1km^2 cell within each catchment. For run-time purposes the travel times found for a given soil type were divided into 100 'class-σ' subdivision of equal length. The resulting 1km^2 resolution 'travel time' catchment grids were then used to estimate the amount of u_s that will arrive at the catchment outfall each time-step such that, for each time-step (Equation 5):

$$\sum_{n=1}^{N} \sum_{m=1}^{29} \sigma_n u_{sm} \qquad (5)$$

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[23] Beven, K. J., Kirkby, M. J., Freer, J. E., and Lamb, R.: A history of TOPMODEL, Hydrol. Earth Syst. Sci., 25, 527–549, https://doi.org/10.5194/hess-25-527-2021, 2021

[24] Morris, D. and Flavin, R.W. 1990. A Digital Terrain Model for Hydrology, 4th International Symposium on Spatial Data Handling, July 23-27, Zurich.

where u_{sm} = Surface flow proportion of effective precipitation in any time-step on HOST soil type m

m = HOST soil class

n = number of 'class- σ' subdivision up to a maximum total N = 100.

V is the soil type transfer velocity and parameterisation is required for each routing class (aggregated HOST classes).

The quick flow for each HRU is then routed through a linear reservoir, defined by parameter Kl, which is based on the HOST soil class for the HRU.

3.3.4 Baseflow routing reservoirs

Drainage to baseflow is routed through a set of Hortonian routing reservoirs (Horton,1938[25]). representing different substrate geologies that may be within the catchment. These are defined based on the substrate geology classification within HOST soil classes and grouping these together. The actual number of reservoirs in application will be determined by the substrate geology classes present, each with a fractional area extent summing to one across the catchment. The final base flow for the catchment is the sum of the outflows from each of the storage reservoirs with each weighted by it's corresponding fractional extent.

The basic form for a storage based reservoir defining the outflow at a point in time, q(t) is given by Equation 6.

$$q(t) = \frac{1}{k} s(t)^n \tag{6}$$

where: s(t) = the volume of water in storage at time, t;

k = a constant (with units of time);

n = the order of the reservoir.

The order could be linear (n=1), or non linear, usually, quadratic (n=2) or cubic (n=3). The non-linear reservoirs have a higher initial recession rate than the linear reservoir, but in the tail of the recessions the rates are fairly similar. In rainfall-runoff modelling, it is common practice to choose an appropriate value of n, and to optimise k to avoid the problem of covariance between k and n. As the focus of CERF is modelling at a daily time step, modelling the lower parts of recession curve accurately the choice of configuration is not critical thus a linear reservoir was selected for computation ease and runtimes.

The explicit formulation of Equation 6 neglects that, within a time step, the instantaneous value of s is dependent on the function of the outflow, q. Combining Equation 6 with the continuity equation we obtain Equation 7.

$$\frac{dS}{dt} = u - q \tag{7}$$

in which u is the inflow over the time period yields for a linear reservoir, Equation 8.

[25] Horton, R.E., 1938. The interpretation and application of runoff plat experiments with reference to soil erosion problems. Proc. Soil Sci. Soc. Am. 3, 340–349

$$\frac{dq}{dt} = \frac{1}{k}(u - q) \tag{8}$$

Rearranging 3 and integrating over the time period (t,t+Δt) gives the explicit recursive solution for q as Equation 9.

$$Q_{(t+\Delta t)} = e^{-\frac{\Delta t}{k}} * q_t + u\left(1 - e^{-\frac{\Delta t}{k}}\right) \tag{9}$$

The k parameters for the baseflow reservoirs are identified through calibration.

3.3.5 Parameterisation of the routing model

Routing parameterisation is based on HOST soil classes. Each of the HOST soil classes are attributed to 10 distinct routing classes that behave similarly, based on the descriptions of the HOST soil classes and analysis of results during calibration.

The parameters for the routing model are summarised in Table 3. This table also lists units where applicable. For convenience the units for Kl and Kb were set as hours.

The simulated flow has units of length per unit time and thus to obtain streamflow the simulated time-series is rescaled by the catchment area, with appropriate changes in units to yield a flow in cumecs.

Table 3. Routing Model Parameters.

Sub-module	Parameter name	Parameter	Unit	Description
Distributed soil store	Smax	Smax	mm	The maximum storage capacity
Distributed soil store	Drainage Coefficient	Kg	hour	Drainage time constant
Quick flow routing	Surface Velocity	V	Km/Hr	Surface Velocity
Quick flow routing	Quick Time Constant	Kl	hour	The time constant for the quick flow linear reservoir.
Slow Flow, Linear Reservoir	Slow Time Constant	Kb	hour	The time constant for the base flow linear reservoir

4 Datasets

As discussed previously, CERF requires a number of datasets. These include forcing data; the meteorological datasets (precipitation and PE), as well as spatial datasets (HOST, Land cover and the DTM).

For the purpose of calibration, gauged river flow data is also required.

4.1 Meteorological forcing datasets

There are two forcing datasets required to run CERF: precipitation and potential evaporation.

The Met Office HadUK-Grid[26] dataset has been used for the precipitation dataset. HadUK-Grid is a collection of gridded climate variables derived from the network of UK land surface observations and interpolated to a 1km resolution to provide a complete and consistent coverage. HadUK spans a period from 1836 to present day, with the start time dependent on the variable and temporal resolution. Daily, monthly, seasonal, and annual timescales, as well as long term averages are available. The HadUK-Grid Gridded Climate Observations on a 1km grid over the UK, v1.1.0.0 (1836-2021)[27] daily data has been used within CERF2-HadUK. Data was downloaded from the CEDA archive from January 1955 to December 2021.

The UKCEH Hydro-PE HadUK-Grid[28] has been used for the potential evaporation dataset. This dataset utilises HadUK-Grid meteorological variables, such as air temperature, daily precipitation, monthly mean water vapour pressure, monthly mean sea level pressure, monthly total sunshine hours and monthly mean wind speed, to compute daily total potential evapotranspiration (PET) and daily total potential evapotranspiration with interception correction (PETI). The PET was calculated using the Penman-Monteith equation parameterised for a well-watered grass surface with the PETI including a correction added for interception by a grass canopy on days with non-zero precipitation. The dataset has a 1km resolution over the UK and covers the period between January 1969 to December 2021. For the project, the daily PETI dataset from January 1969 to December 2021 was downloaded from the EIDC archive.

4.2 Spatial datasets

CERF requires a soils dataset and a vegetation dataset, as well as a Digital Terrain Model (DTM) to describe elevation.

To model soil, the UKCEH Hydrology of Soil Types (HOST)[29] dataset has been used. HOST is a hydrologically based classification of the soils of the UK available for each 1km square both as percentage breakdown and dominant class.

The original development of CERF used the UKCEH Land Cover Map 2000[30] to represent the spatial variation in landcover or vegetation. For this update the UKCEH Land Cover Map 2015 (LCM2015)[31] 1km dominant land cover raster has been used. This dataset reports the class with the highest

[26] https://www.metoffice.gov.uk/research/climate/maps-and-data/data/haduk-grid/haduk-grid
[27] https://catalogue.ceda.ac.uk/uuid/bbca3267dc7d4219af484976734c9527
[28] https://catalogue.ceh.ac.uk/documents/9275ab7e-6e93-42bc-8e72-59c98d409deb
[29] https://catalogue.ceh.ac.uk/documents/296fb1e8-3912-48d3-9d22-2a300aabefc3
[30] Smith, G.M., Fuller, R.M., Sanderson, J.M., Hill, R.A. and Thompson, A.G. 2001. Land Cover Map 2000:a parcel-based approach from satellite images, Proceedings of the RSPS meeting in Uncertainty and Remote Sensing and GIS, p689-702.
[31] Rowland, C.S.; Morton, R.D.; Carrasco, L.; McShane, G.; O'Neil, A.W.; Wood, C.M. (2017). Land Cover Map 2015 (1km dominant target class, GB). NERC Environmental Information Data Centre. https://doi.org/10.5285/c4035f3d-d93e-4d63-a8f3-b00096f597f5

percentage cover for each pixel using 10 aggregate classes. These classes have been further aggregated to the hydrologically relevant classes specified within CERF (Table 4).

Table 4. LCM2015 aggregate classes to CERF Vegetation description

LCM Aggregate Class	LCM Aggregate Class number	CERF Vegetation description
Broadleaf woodland	1	Deciduous
Coniferous woodland	2	Coniferous
Arable	3	Arable
Improved grassland	4	Grass
Semi-natural grassland	5	Grass
Mountain, heath, bog	6	Upland
Saltwater	7	Water
Freshwater	8	Water
Coastal	9	Water
Built-up areas and gardens	10	Urban

The UKCEH Integrated Hydrological Digital Terrain Model[32] (IHDTM), 50m resolution, has been used to provide the topographic input to the quick flow routing module, as previously described.

4.3 Gauged river flow dataset

The NRFA daily gauged flow records are used for calibration purposes. The daily flow records up to the end of September 2021 were downloaded from the NRFA website for 1498 gauging stations. Where NRFA meta data or descriptors are referred to the information was either obtained from the individual NRFA gauging station pages (e.g https://nrfa.ceh.ac.uk/data/station/info/7004) or downloaded from the NRFA using the R RNRFA library[33].

The initial gauged dataset used to develop the model was the 'Region Of Influence' dataset utilised within the ROI method for the estimation of the FDC within Qube. This dataset represents gauged catchments which are:

- At least 6 years in length.
- Natural (taking into account artificial influence and urbanisation).
- Good hydrometric quality (HQ), at low flows in particular.
- Limited ephemerality within the river flow record such that this does not impact on the FDC. Ephemerality is when there can be zero flows within the flow record for proportions of the year, usually within summer months.

Additional catchments were added through analysis of stations in the UK benchmark dataset[34] and detailed assessment of those which were dominated by coniferous or deciduous land cover to increase representation.

Gauged catchments were subsequently removed, or used for limited parts of the study, from the initial dataset where there were:

[32] https://www.ceh.ac.uk/data/integrated-hydrological-digital-terrain-model
[33] https://cran.r-project.org/web/packages/rnrfa/index.html
[34] Harrigan, S, Hannaford, J, Muchan, K, Marsh, T. J., 2018, Designation and trend analysis of the updated UK Benchmark Network of river flow stations: the UKBN2 dataset. Hydrology Research 1 April 2018; 49 (2): 552–567. doi: https://doi.org/10.2166/nh.2017.058

- Water balance errors within the catchments generally caused through the incorrect estimation of the contributing catchment (assumed within CERF to be the topographic area). These were identified where the NRFA note that the contributing catchment area is very different to the topographic catchment. These catchments were removed from the dataset.
- Discrepancies in the temporal timing of flows due to snowmelt within the catchments; an issue as the precipitation dataset used does not incorporate snowmelt. Catchments which were identified as being impacted by snowmelt were not used for all parts of the development process. For example, they might be used whilst assessing the overall water balance but not for seasonal water balance, nor the daily time series fits. For completeness these gauging stations are included in the statistics presented.
- Large impacts on flows due to urbanisation. Catchments with the dominant land cover class of 'Urban', or those that had an URBEXT2000 greater than 0.15 (these criteria identify the same stations) were removed from the statistics presented as the model is conditioned to produce 'natural' estimates and uses underlying soils for routing.
- Significant anthropogenic impacts on the flow regime or poor hydrometry; identified through catchment meta data readily available from the NRFA.

There are 472 stations in the final development and assessment dataset. The location of the NRFA daily gauging station dataset and the development dataset used are presented in Figure 7. Details of the development stations are provided in Appendix 2.

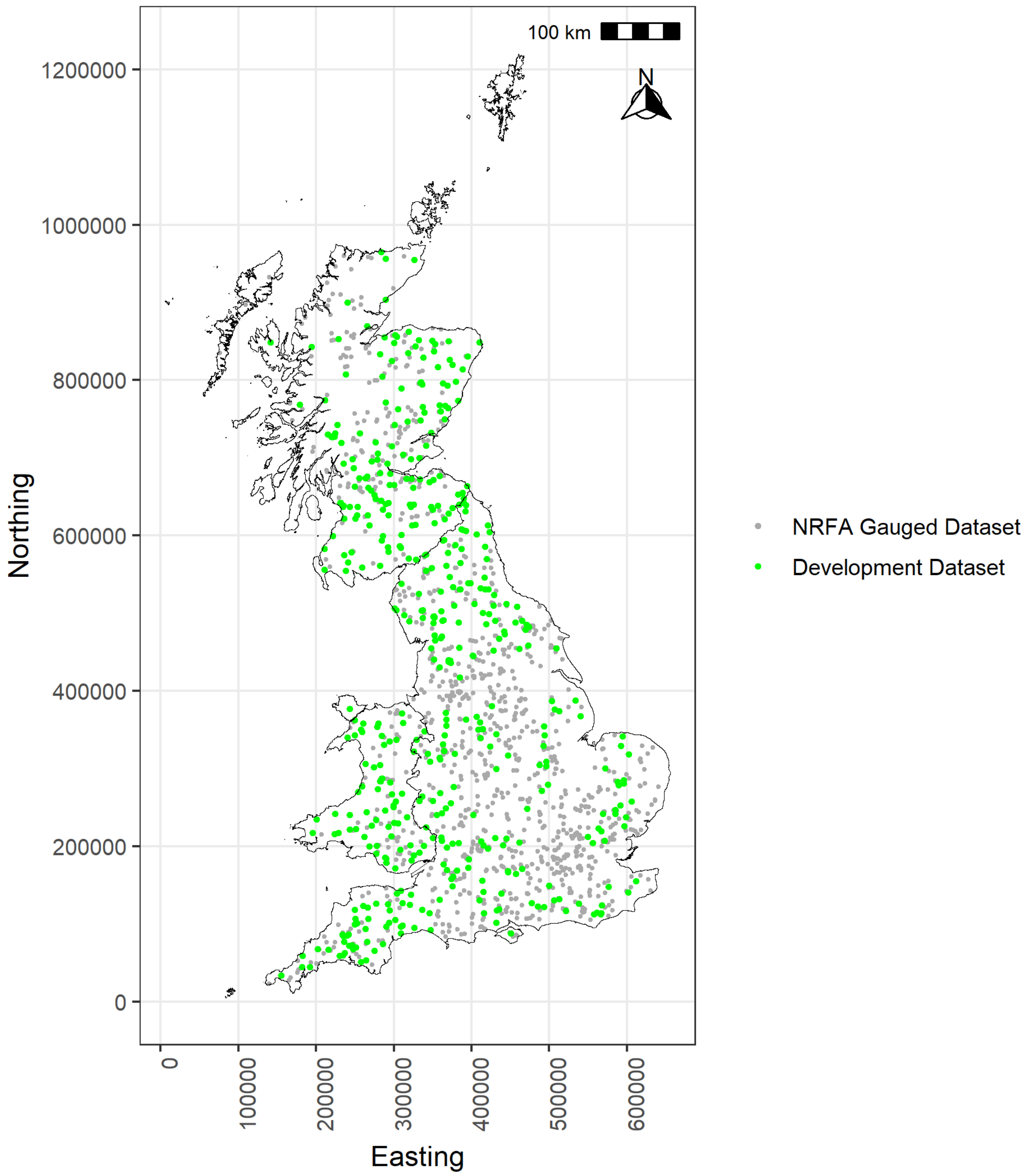

Figure 7. Location of NRFA gauging stations and those used in the CERF development.

Histograms of different catchment descriptors for these gauging stations are presented in Figure 8. The histograms provide an indication of the variability of catchments within the development dataset in comparison with the NRFA daily gauging station dataset, which although inherently biased itself, gives an indication of how well the variability of descriptors across the UK are captured. Note that for consistency the descriptors presented are those as stated by the NRFA, which may be different to those used in the development project. Not all gauging stations have all variables assigned hence the histograms only present those with the relevant information.

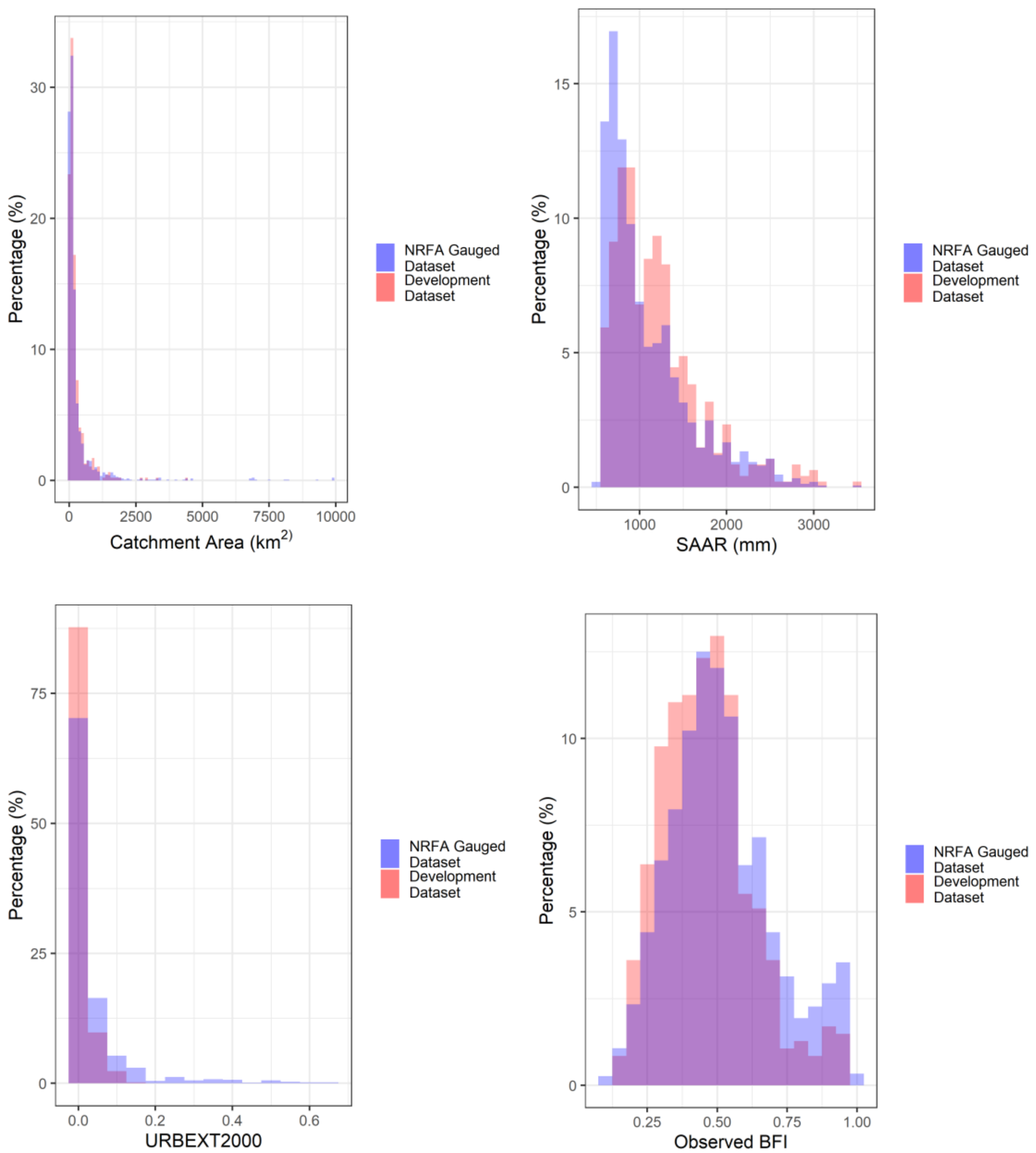

Figure 8. Histograms of descriptors within the development dataset.

Figure 9 presents the dominant landcover for each of the two datasets using both LCM 2007, as cited within the NRFA dataset, and the LCM 2015 classes that are used within the project dataset.

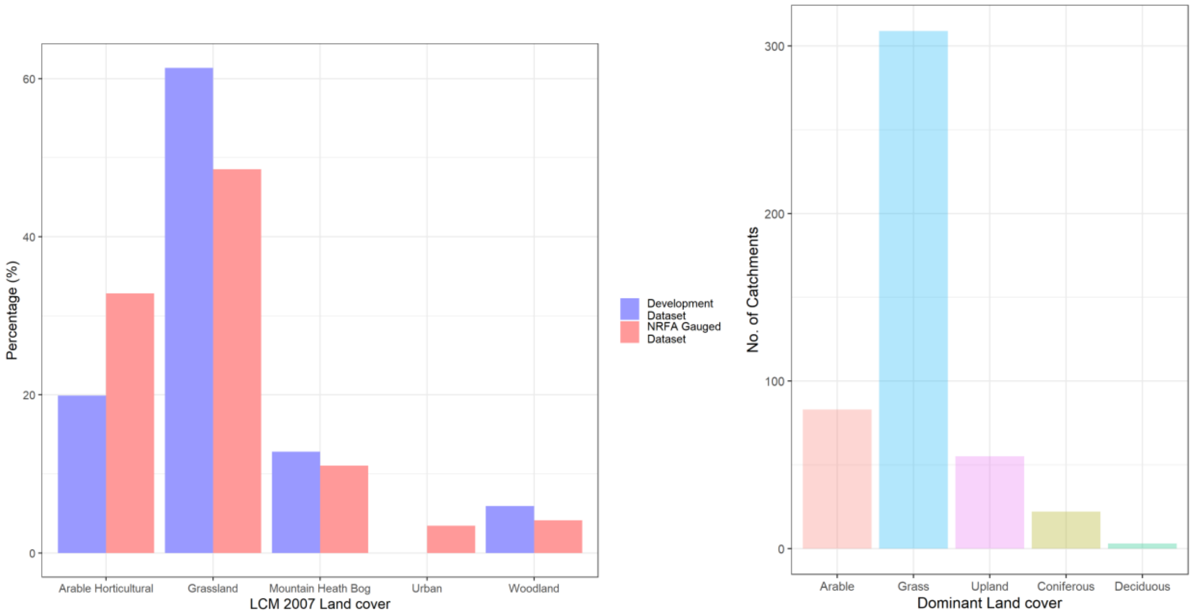

Figure 9. Land cover for each of the two datasets. (Left: LCM 2007 data from the NRFA. Right: LCM 2015 dominant land cover classes within the development dataset)

The spatial distribution of the gauging stations is fairly uniform across GB. It can be seen that the density of stations in the South and East is lower than elsewhere. The development dataset also has a greater proportion of higher standardised average annual rainfall (SAAR), and lower base flow index (BFI) catchments.

With respect to land cover the proportion of each land cover types within the development dataset is similar to the NRFA gauged data. As within the whole NRFA gauged dataset, there is a dominance of grass catchments with few forested catchments. There is a good correlation between the identified LCM2007 and the LCM2015 land cover categories.

4.4 Gauged catchment boundaries

Catchment boundaries are used in the derivation of catchment average meteorological datasets (precipitation and PE), extraction of catchment descriptors (soils and land cover) and in the topographic quick flow routing.

These boundaries were generated in Qube using the IHDTM for all gauged river catchments (1498) which had daily gauged flow data. In general, except where anomalies were identified, the NRFA IHDTM coordinates were used to derive these boundaries.

5 CERF2-HadUK development process

CERF consists of two modules; the loss module largely impacts the annual and seasonal water balance, whilst the routing module impacts the timing and response of the catchment to precipitation events. The parameters for the two modules are associated with soil (based on HOST) and/or vegetation classes (based on land cover), as well as the IHDTM, and these result in a potentially large number of parameters to be calibrated.

In the original development of CERF, the model was calibrated to all catchments, but also a subset of catchments leaving the remainder for evaluation. The differences in model outcomes were marginally different for most catchments in the evaluation dataset for each approach but, with some catchment types poorly represented in the UK gauged network, it was found to be preferable to optimise the model over all catchments and measurement records. The more catchments there are in the development dataset, the more information there is to calibrate the model against, thus enabling a more sophisticated, identifiable deterministic model structure to be used. Similarly, using more catchments reduces the potential to bias model parameter sets by compensating for systematic error in the forcing data/water balance assumption for any one catchment.

For development of CERF2-HadUK, a baseline set of parameters was available from which to start the calibration process. In this case the CERF MORECS parameter set is used as the MORECS formulation is more closely related to PETI, than MOSES.

Given that this is a generalised model scheme (rather than calibration to one catchment), the diversity of UK catchments and the fact that the starting point is an existing parameterisation, it was considered beneficial to maximise the calibration dataset by both the number of gauges used and the period of record by using all available appropriate data for calibration.

A number of specific measures of fit were used to compare model outputs to observed/gauged data, detailed in section 5.1. Extensive visual inspection of observed and modelled hydrographs was also completed.

5.1 Measures of fit

A number of statistical measures of fit were used as part of model development which are presented in Table 5.

Spearman rank has been included in the assessment, as the ranking of the flows are used as part of the donor process to generate the Qube daily flow times series for any catchment.

Table 5. Measures of fit used to assess the modelled flows against observed flow records. Note that a suffix Obs refers to the observed gauged flow and sim, the simulated or modelled flow.

Measure of fit	Equation	Focus
Nash Sutcliffe Efficiency (NSE)	$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{obs} - Q_{sim})^2}{\sum_{i=1}^{n}(Q_{obs} - \overline{Q_{obs}})^2}$	High flows
NSE of log flows	$NSE_{log} = 1 - \frac{\sum_{i=1}^{n}\left(ln(Q_{obs}) - ln(Q_{sim})\right)^2}{\sum_{i=1}^{n}\left(ln(Q_{obs}) - \overline{ln(Q_{obs})}\right)^2}$	Low Flows
Kling Gupta (Classic, after Gupta 2009[35])	$KG = 1 - ED$ $ED = \sqrt{(r-1)^2 + (a-1)^2 + (b-1)^2}$ $a == \frac{\overline{Q_{sim}}}{\overline{Q_{obs}}} \quad b = \frac{\sigma_{sim}}{\sigma_{obs}}$ *Where: r is the pearson coefficient* *σ is the standard deviation*	General time Series Fit
Spearman Rank	$SR = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}}$ where x are the Q_{obs} ranks and y are the Q_{sim} ranks.	Correlation of ranked flows.
Annual Percent Bias (Absolute Percent Bias also used)	$Percent\ BIAS = \left[\frac{\sum(Q_{obs} - Q_{sim})}{\sum Q_{obs}}\right] \times 100$	Overall Water balance
Seasonal percent bias of mean flow (Summer, Winter)	As above, selecting seasonal flows. Summer = Jun-Jul-Aug Winter = Dec-Jan-Feb	Seasonal Water balance
Percent Bias at Flow percentiles (Q95, Q30, Q10) Absolute Percent Bias is also calculated for Q95	$Percent\ BIAS\ Q_x = \left[\frac{Q_{x\ obs} - Q_{x\ sim}}{Q_{x\ obs}}\right] \times 100$	Specific flow statistics. Range from low to high flows.

[35] Gupta, H. V., Kling, H., Yilmaz, K. K., & Martinez, G. F. (2009). Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. Journal of hydrology, 377(1-2), 80-91. doi:10.1016/j.jhydrol.2009.08.003. ISSN 0022-1694

6 Results and discussion

This section presents the results of the redevelopment process. The median value of the measures of fit are presented for the CERF2-HadUK model as well as for the coincident CERF 2019 and G2G gauging stations. The distributions of the measures of fit are then presented as box and spatial plots followed by a discussion of the results.

Table 6 presents the medians of the objective measures of fit used to assess the performance of the model (detailed in Table 5) across all development gauged catchments. For comparison with previous versions of CERF, the median of the measures of fit for the coincident gauges of the development dataset, and that held for CERF 2019 (the current model outputs used within Qube) are presented. G2G is a generalised model, as is CERF, hence the performance of the coincident gauging stations are also presented for CERF2-HadUK are presented alongside estimates of the G2G statistics, as presented within Hannaford et al., 2023[36].

Box plots of the measures of fit for the CERF2-HadUK development dataset are presented in Figure 10. Figure 11 presents the NSE and percentage bias at both mean flow and Q95 for the coincident gauging stations from CERF2-HadUK and CERF 2019.

[36] Hannaford, J., Mackay, J. D., Ascott, M., Bell, V. A., Chitson, T., Cole, S., Counsell. D., Mason Durant, M., Jackson, C. R., Kay, A. L., Lane, R. A., Mansour, M., Moore, R., Parry, S., Rudd, A. C, Simpson, M., Facer-Childs, K., Turner, S., Wallbank, J., R., Wells, S., Wilcox, A. 2023, The enhanced future Flows and Groundwater dataset: development and evaluation of nationally consistent hydrological projections based on UKCP18. Earth Syst. Sci. Data, 15, 2391–2415, https://doi.org/10.5194/essd-15-2391-2023, 2023

Table 6. Median values of the measures of fit (Table 5) for the development dataset, and coincident gauging stations with other datasets; the CERF 2019 model (using GEAR and CHESS meteorological data) and the G2G dataset used in eFLaG.

Measure of Fit	CERF2-HadUK	CERF2-HadUK (common with CERF 2019 dataset)	CERF 2019 (common with CERF2-HadUK dataset)	CERF2-HadUK (common with G2G dataset)	G2G presented in eFLaG*
Number of gauges	472	427	427	186	
NSE	0.68	0.68	0.68	0.70	~0.72
ln NSE	0.73	0.74	0.75	0.73	~0.73
Kling Gupta	0.76	0.76	0.76	0.77	~0.77
Spearman Rank	0.91	0.91	0.92	0.90	
Annual Percent Bias (%)	-2.28	-2.28	4.99	-2.34	
Annual Absolute Percent Bias (%)	7.50	7.58	6.95	8.97	~8
Summer Percent Bias (%)	-0.96	-1.06	2.01	-3.89	
Winter Percent Bias (%)	-0.90	-0.64	5.64	0.41	
Q10 Percent Bias (%)	2.91	3.31	13.58	4.68	
Q30 Percent Bias (%)	-6.20	-6.56	3.11	-6.27	
Q95 Percent Bias (%)	22.89	23.52	16.98	13.85	
Q95 Absolute Percent Bias (%)	42.35	41.95	37.38	35.74	~48

**Estimates of the median measures of fit are based on Hannaford et al., 2023.*

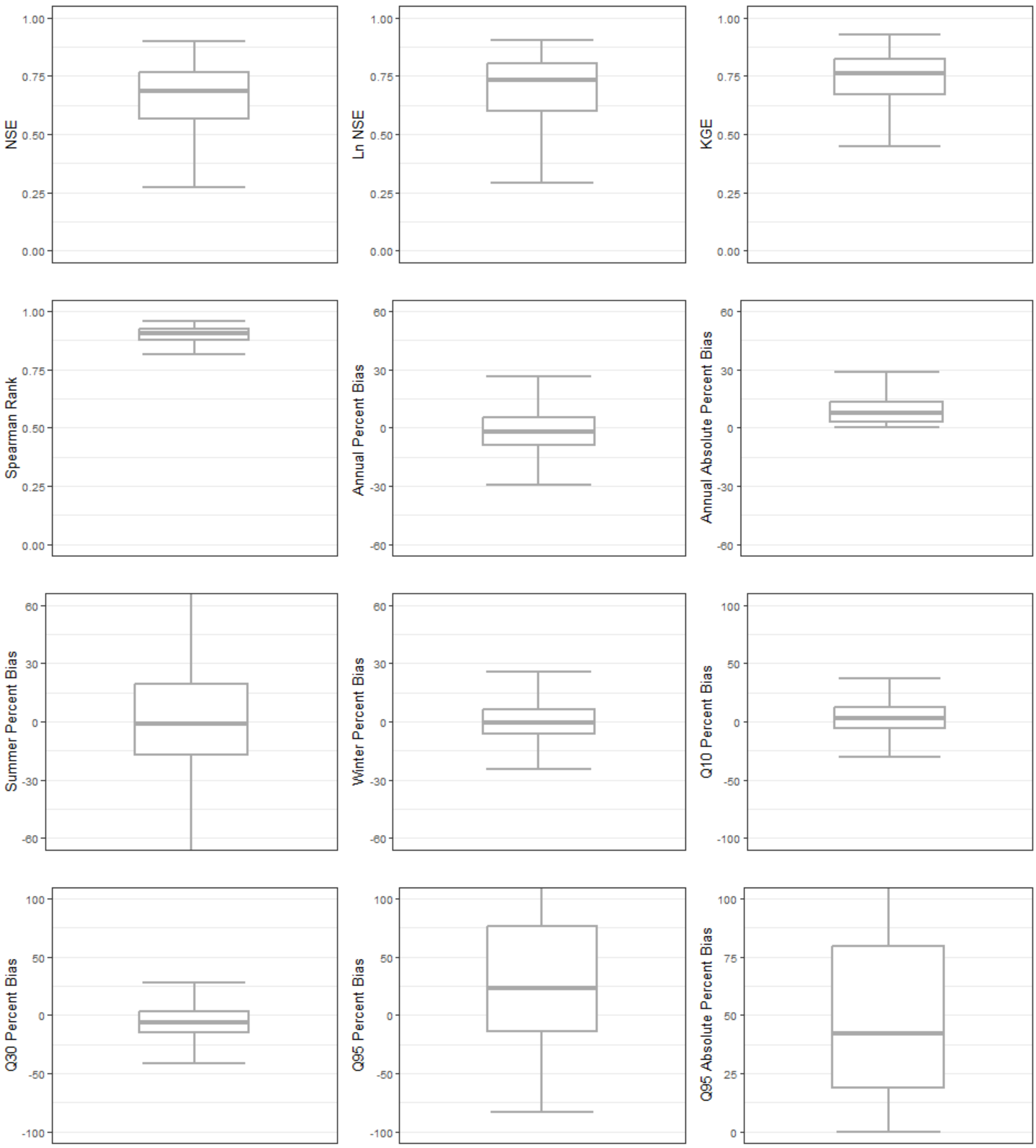

Figure 10. Box plots of the measures of fit for the CERF2-HadUK development dataset.

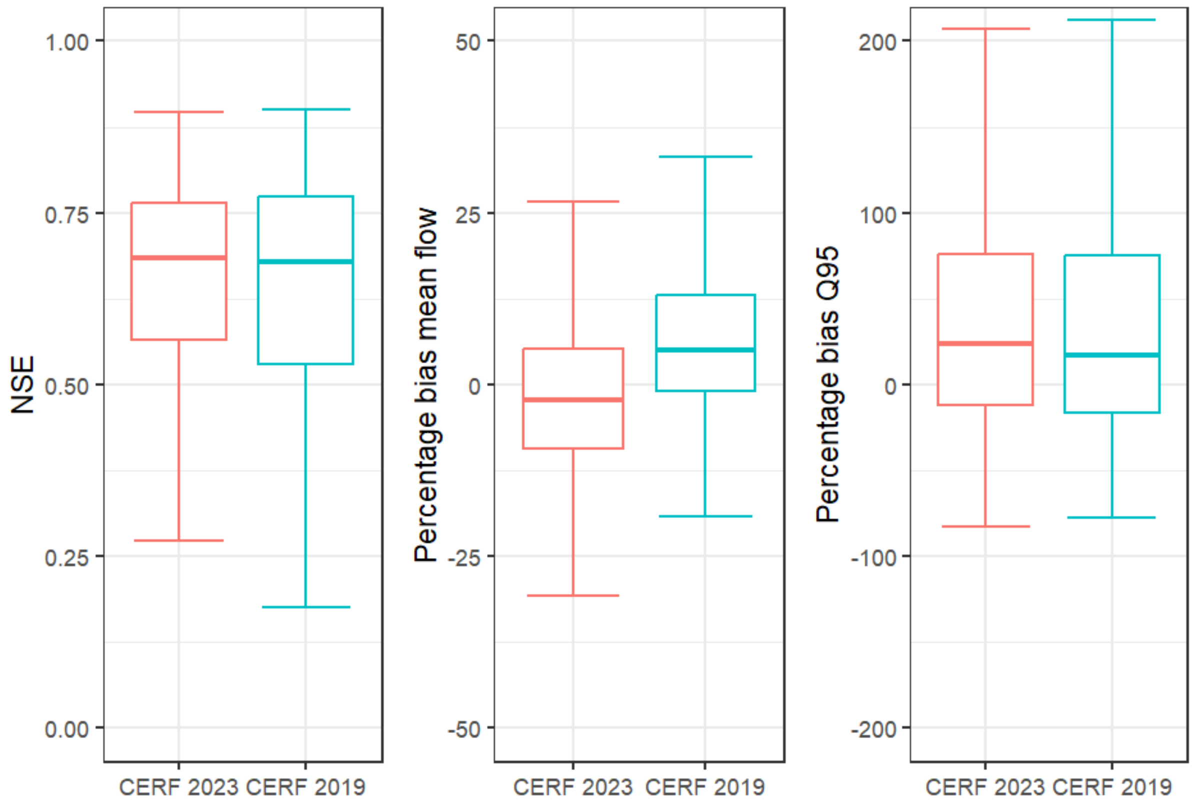

Figure 11. Box plots of the NSE and Percentage Bias at mean flow and Q95 for the coincident gauging stations in the CERF2-HadUK and CERF 2019 datasets. Table 6 illustrates that, in general, all datasets and methods/models perform similarly. There is no one method or dataset that outperforms all others, for all measures of fit. This illustrates the value of using multiple measures of fit, and that the measures of fit should be appropriate for the purpose for which the model is to be used.

The results for the G2G subset of gauges are presented here for comparison of, where appropriate, the same measures of fit presented in Hannaford et al., 2023[37] and this illustrates that the two models perform, broadly, similarly; the CERF2-HadUK model appears to better estimate the low flows (Q95). The variability of results for different models and subsets of gauging stations illustrates that comparison of model performances using externally reported measures of fit should be undertaken with care as, even where measures of fit are exactly the same, results can be sensitive to the selection of gauging stations (and, in addition, other possible differences such as the period of record).

The box plots in Figure 10 illustrate the variability of each measure of fit for the CERF2-HadUK model for the development dataset. These indicate that the overall fit for most gauging stations is

[37] Hannaford, J., Mackay, J. D., Ascott, M., Bell, V. A., Chitson, T., Cole, S., Counsell. D., Mason Durant, M., Jackson, C. R., Kay, A. L., Lane, R. A., Mansour, M., Moore, R., Parry, S., Rudd, A. C, Simpson, M., Facer-Childs, K., Turner, S., Wallbank, J., R., Wells, S., Wilcox, A. 2023, The enhanced future Flows and Groundwater dataset: development and evaluation of nationally consistent hydrological projections based on UKCP18. Earth Syst. Sci. Data, 15, 2391–2415, https://doi.org/10.5194/essd-15-2391-2023, 2023

satisfactory (NSE, ln NSE, Kling Gupta and Spearman Rank) with the Spearman rank being less sensitive (lower variability) than other measures of fit where the scale of the discharge values are of more importance.

As expected, there is greater variability in the Summer Percent Bias than the Annual and Winter Percent Bias. This is due to winter flows being dominated by the response to precipitation, whereas the runoff generation processes in summer are complicated by the build-up of soil moisture deficits. In addition, summer mean flows are likely to be smaller than annual or winter mean flows, so a smaller absolute difference in flows will be reflected by a larger percentage. This is also true for the high and low flow percentiles, where the Q10 percentage bias variability is smaller than the Q95 percentage bias, with the latter being more challenging to represent as well as being, in general, a far smaller value from which the percentage change is calculated.

The value of examining the variability alongside the median values is illustrated in Figure 11 where the NSE and Percent Bias for the mean flow and Q95 are presented for the coincident gauging stations of CERF2-HadUK and CERF 2019. Whilst the median NSE values are similar, the variability of the NSE for the CERF2-HadUK model is reduced. In addition, the variability of the percentage bias at mean flow is similar, although shifted, between the two models. For the Q95 Percent Bias, the median for the CERF 2019 model is slightly lower, although the variabilities are very similar.

The spatial distribution of the NSE and Annual Percent Bias is presented in Figure 12 and Figure 13.

Figure 12 illustrates that there is a slight general west/east and north/south divide with wetter and more impermeable catchments (where the runoff processes are easier to capture) generally showing improved NSE values. Lower values, in areas such as the Cairngorms in Scotland, illustrate the impact that snowmelt (which is not included in the current forcing datasets) can have on the NSE. For many of these catchments there will be a low NSE during spring, where snowmelt will impact on the timing of events.

Figure 13 illustrates that, in general, there is no significant trend relating to bias. There is a slight tendency for mean flows to be underestimated within higher rainfall catchments, to the west and north.

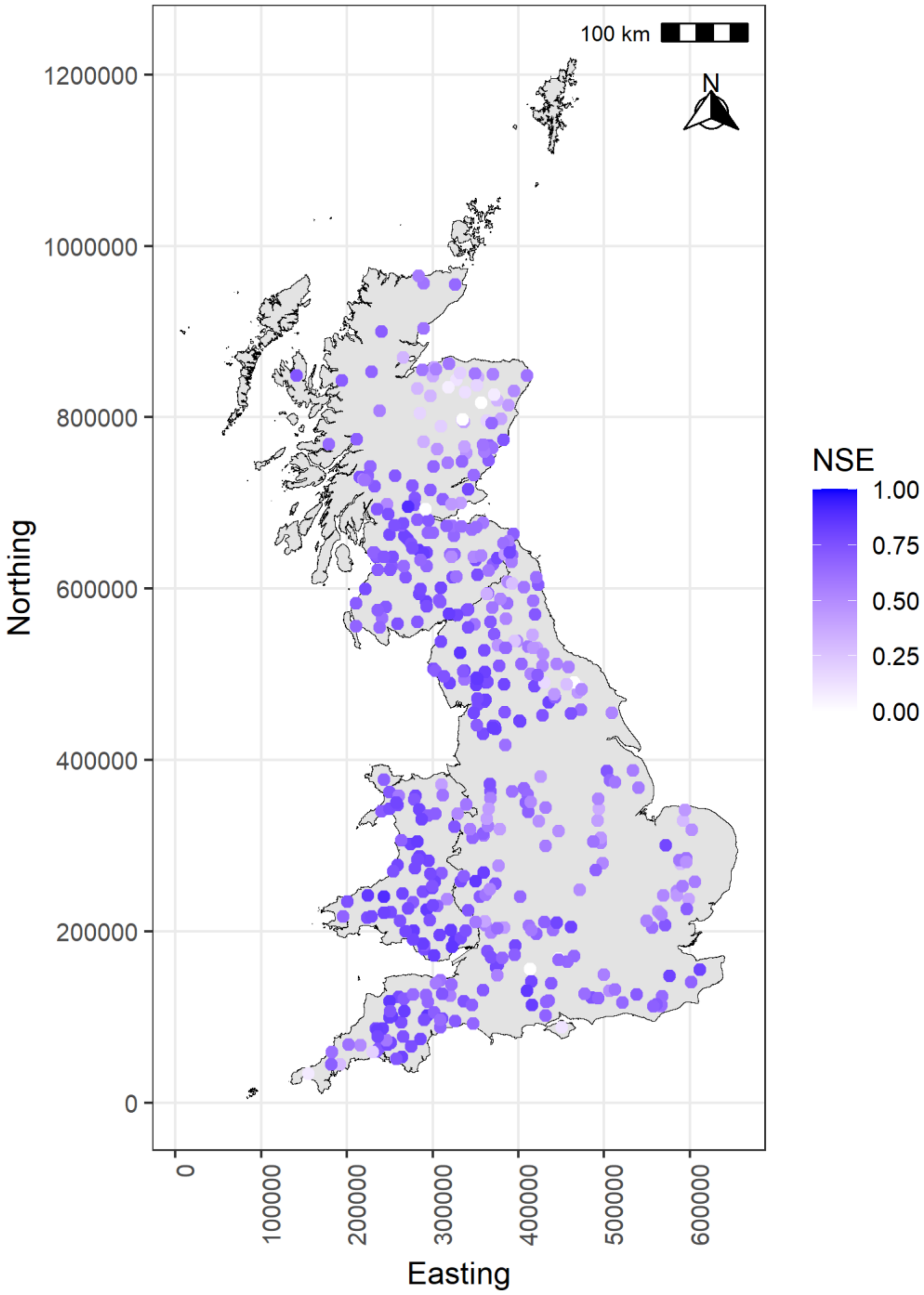

Figure 12. Spatial distribution of the NSE for the CERF2-HadUK development dataset.

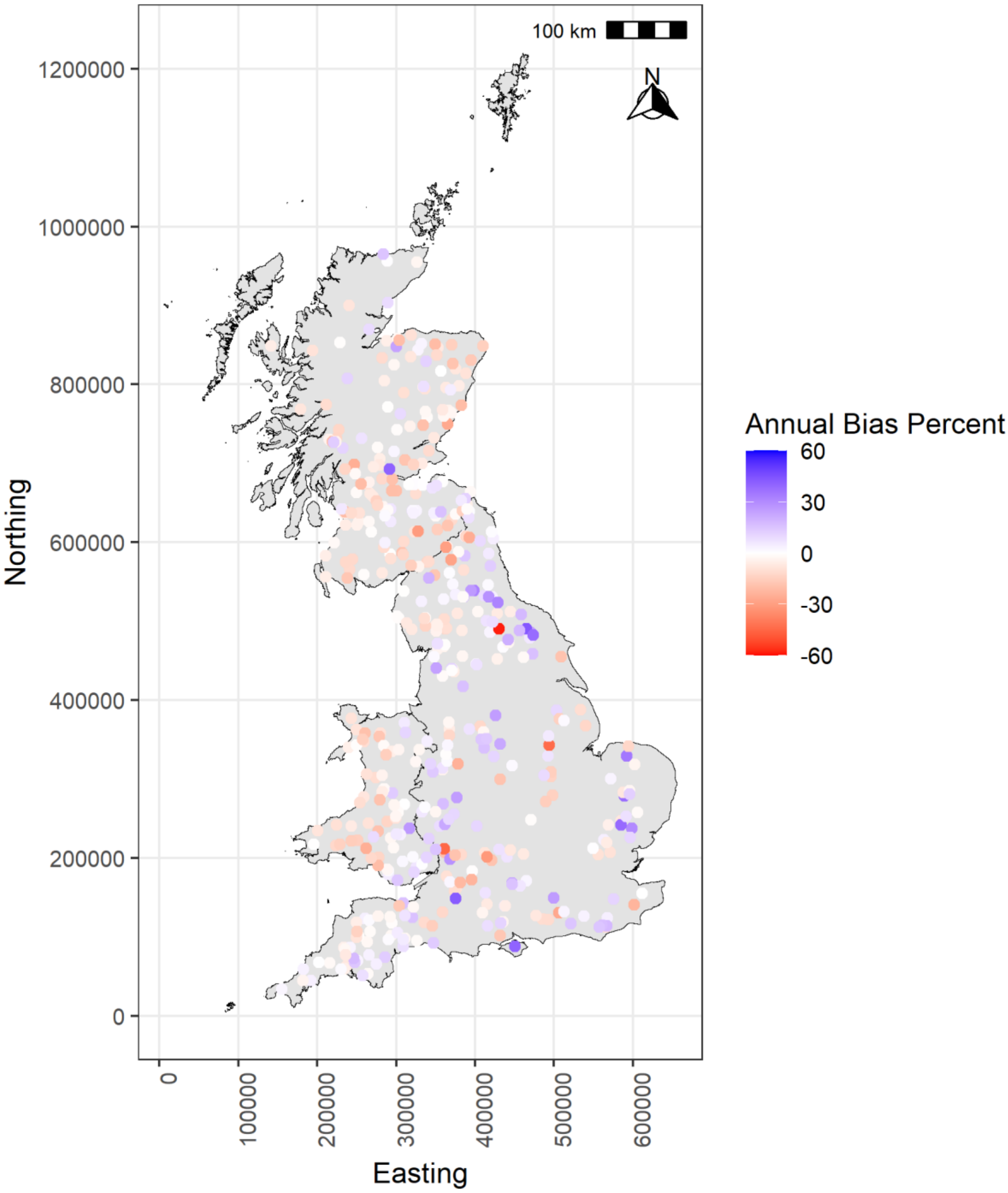

Figure 13. Spatial distribution of the Annual Bias for the CERF2-HadUK development dataset.

7 Conclusion

The CERF daily rainfall-runoff model has been developed using the HadUK precipitation and UKCEH derived PETI datasets, which are scheduled to be updated frequently, to produce the CERF2-HadUK model. The performance of the model for 472 gauges throughout GB is good, and similar to other generalised models for GB.

The model has been run for the period 1955 – 2021 for all Qube TSEP catchments (~11,000) within GB to enable daily flow time series to be generated in Qube for any ungauged catchment for this period.

The development of the generalised model allows the subsequent use of Met Office UKCP18 climate change forcing data and the UKCEH eFLaG dataset to be modelled throughout GB, as described in the "Development of climate change adjusted flow statistics in Qube" report.

8 Acknowledgements

We thank the members of the project board at the EA, NRW and SEPA for their invaluable advice and insight throughout the project.