

eFLaG: enhanced Future FLOws and Groundwater. A national dataset of hydrological projections based on UKCP18

Supporting Information Document

OVERVIEW

Enhanced Future Flows and Groundwater (eFLaG) is a dataset of nationally consistent hydrological (river flow, groundwater level and groundwater recharge) projections for the UK, based on the latest UK Climate Projections (UKCP18; Murphy et al. 2019). The eFLaG projections span from 1981 to 2080 and an accompanying observation-driven dataset provides river flow and groundwater level/recharge simulations for 1962 (1963 for river flow) to 2018 respectively.

eFLaG was established through a partnership project funded by the Met Office led component of the Strategic Priorities Fund Climate Resilience Programme under contract P107493 (CR19_4 UK Climate Resilience). The dataset was created by the project partners: UK Centre for Ecology & Hydrology (UKCEH), British Geological Survey (BGS) and HR Wallingford.

The project workflow is illustrated in Figure 1. eFLaG is driven by the UKCP18 dataset, specifically the 'Regional' 12km projections, to which a bias correction is applied. The UKCP18 projections are applied to a set of river flow and groundwater simulation models for a set of locations across the UK: specifically, 200 catchments, 54 boreholes and 558 groundwater bodies (see eFLaG_Station_Metadata.xlsx for site listing and associated metadata; Figure 2 for Site Location Map).

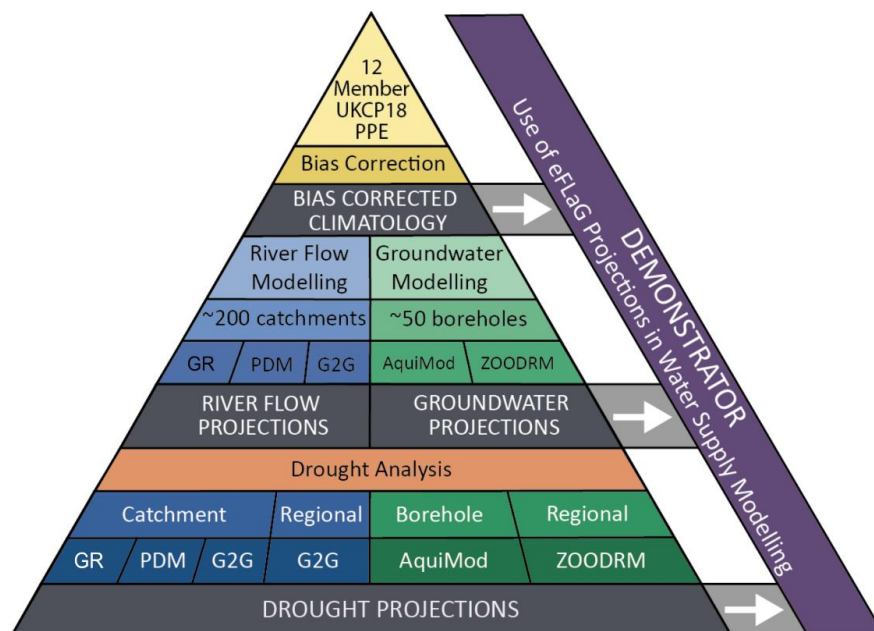


Figure 1 Project workflow illustrating the stages used to create the eFLaG dataset

CATCHMENT SELECTION

For river flows, a metadata database was assembled of all National River Flow Archive (NRFA; <https://nrfa.ceh.ac.uk>) gauging stations in the UK. Metadata compiled included membership of key national strategic networks (e.g. near-natural Benchmark (UKBN2; Harrigan et al. 2018a)) and previous studies/datasets (e.g. an overlap with the original Future Flows and Groundwater Levels catchments (FFGWL; Haxton et al. 2012) and recent modelling endeavours through the [Drought and Water Scarcity Programme](#) projects; 'Historic Droughts', 'IMPETUS' and 'MaRIUS'). Selection focuses on data and hydrometric quality, with longer record lengths prioritised. Catchment representativeness was considered, ensuring the eFLaG sites represented UK hydrological and geographical variability. The selection also considered water industry relevance, which was achieved by asking stakeholders at an eFLaG workshop for a view on site selection.

For groundwater levels, a set of 54 boreholes were selected from the BGS National Groundwater Level Archive (NGLA; <https://www2.bgs.ac.uk/groundwater/datainfo/levels/ngla.html>) which cover the principal aquifers of the UK. The selection was made to ensure coverage of the most important aquifers in the UK. They were also chosen for their high-quality historical record whereby all boreholes are monitored regularly (at least monthly) and are not significantly affected by abstractions and have observation records that are at least 10 years in length. A number of boreholes were also identified as strategically important for long-term drought risk assessment and to support the water resources planning through consultation with stakeholders at the eFLaG workshop.

Groundwater recharge simulations have been aggregated spatially over 588 groundwater bodies covering England¹, Wales² and Scotland (O'Dochartaigh et al. 2015). These groundwater bodies are physically justifiable as they reflect known hydrogeological characteristics including groundwater recharge and groundwater flow regimes so that each catchment represents a distinct body of groundwater that can reasonably be considered in isolation neighbouring catchments. They were also created for the implementation of the Water Framework Directive. Groundwater body shapefiles are available at the links in the footnotes for England and Wales and included in the eFLaG dataset for Scotland.

¹ <https://data.gov.uk/dataset/2a74cf2e-560a-4408-a762-cad0e06c9d3f/wfd-groundwater-bodies-cycle-2>

² <http://lle.gov.wales/catalogue/item/WaterFrameworkDirectiveWFDGroundwaterBodiesCycle2?lang=en>

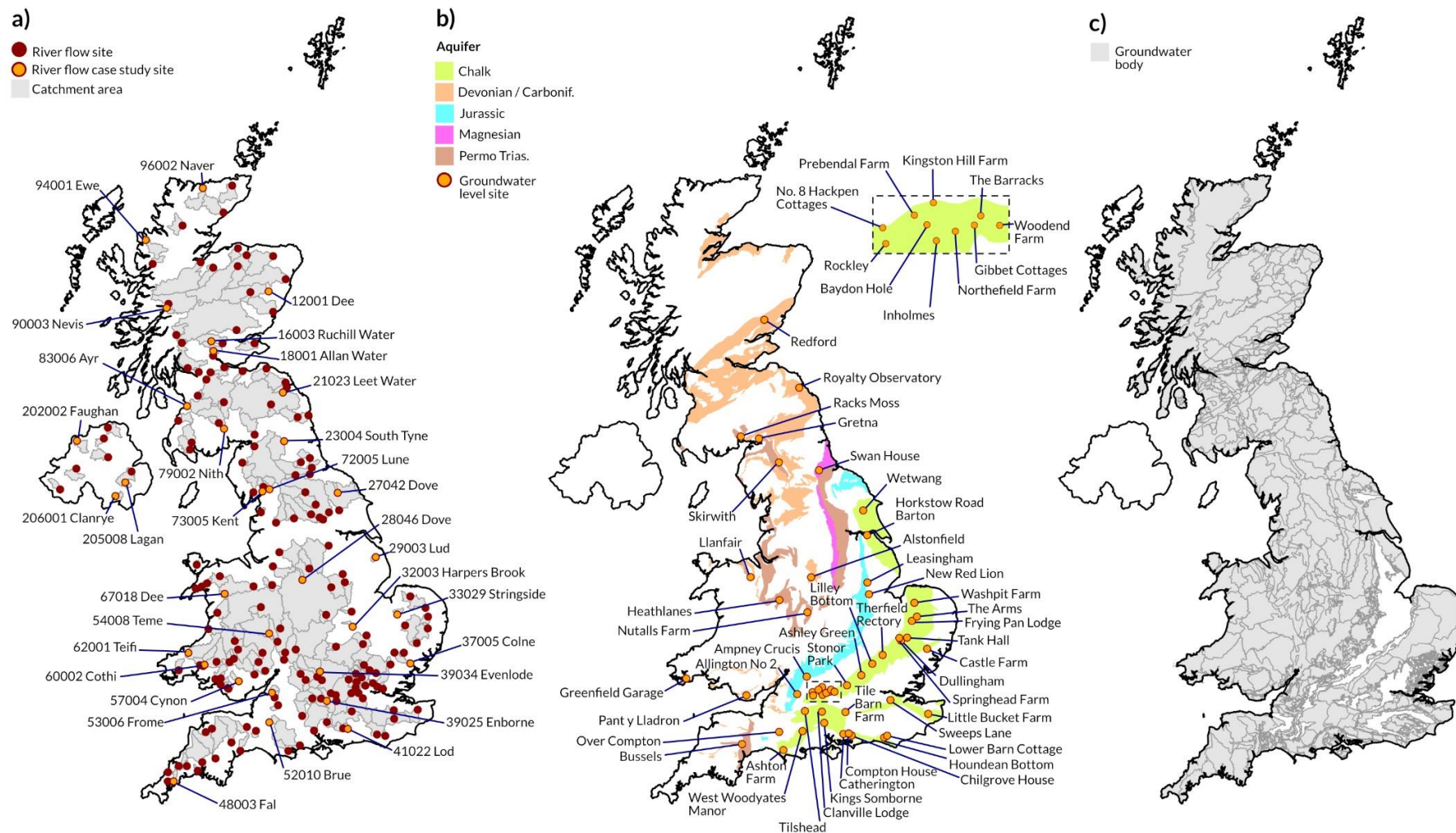


Figure 2 a) Map of the 200 eFLaG river flow sites and their catchment areas - highlighting those used as Case Study sites; b) Map of 54 eFLaG boreholes and principal UK Aquifers including The Chalk, Devonian and Carboniferous aquifers (Devonian/Carbonif.), Jurassic limestones (Jurassic), Magnesian limestones (Magnesian) and Permo-Triassic sandstones (Permo Trias.); c) Map of 558 groundwater bodies.

DATA GENERATION METHODS

Creation of an enhanced Future Flow and Groundwater (eFLaG) dataset is underpinned by river and groundwater models used to transform rainfall and potential evaporation (PE) to river flow, soil moisture, groundwater levels and recharge. The approach builds on that employed under FFGWL (Prudhomme et al. 2013) whilst exploiting developments in hydrological modelling for droughts since that time.

UKCP Data Processing and Bias Correction

eFLaG uses the UKCP18 Regional projections created by the Met Office (Murphy et al. 2019). They were created using perturbed-parameter runs of the Hadley Centre global climate model (GCM) and regional climate models (HadGEM3-GC3.05 and HadREM3-GA705 respectively). These provide a set of 12 high-resolution (12km) spatially-consistent climate projections over the UK, covering the period December 1980 to November 2080.

The UKCP18 RCM output was processed to provide both the 1km gridded and catchment-average time-series of precipitation and PE required for hydrological and groundwater modelling.

The 1km gridded time-series of precipitation and PE were then used to produce the time-series of catchment-averages required for each of the eFLaG catchments. The catchment average values were derived using the standard UK National River Flow Archive approach for catchment average rainfalls, as described in NRFA (2021).

Hydrological and groundwater model ensemble

eFLaG uses three hydrological models (GR4J/GR6J, PDM and G2G), one groundwater level model (AquiMod) and one groundwater recharge model (ZOODRM). All of these models are used to provide 'at site' simulations at the catchment or borehole scale.

G2G

The Grid-to-Grid (G2G) hydrological model is an established area-wide distributed model that has been used to investigate the spatial coherence and variability of floods and droughts at catchment, regional and national scales. Model output typically consists of natural river flows at both gauged and ungauged locations, and can be provided as both time-series for specific locations or 1km× 1km grids. The G2G model has been used for climate impacts modelling of floods (Bell et al. 2009, 2012), low flows (Kay et al. 2018) and droughts (Rudd et al. 2019) and is used operationally for flood forecasting (Cole and Moore, 2009; Moore et al. 2006). All outputs are reported in units of cubic metres per second (abbreviated to m^3s^{-1} and sometimes also referred to as 'cumecs').

GR4J/GR6J

GR4J (Génie Rural à 4 paramètres Journalier) is a simple daily lumped conceptual model with only four free parameters. GR4J has been used for hydro-climate change research across the globe, and has demonstrated good performance in a diverse set of catchments in the UK. The model has been applied in the UK for operational seasonal forecasting, as well as for long-term drought reconstructions nationwide (Harrigan et al. 2018b, Smith et al. 2019).

GR6J (Génie Rural à 6 paramètres Journalier) (Pushpalatha et al. 2011) is a six parameter variant of the GR modelling suite that was developed to improve low flow simulation and groundwater exchange.

Recently, GR6J has increasingly been applied in UK water resources applications (e.g. Anglian Water Drought Plan). A .csv file of calibrated model parameters is provided as part of eFLaG_dataset.zip. All outputs are reported in units of cubic metres per second (abbreviated to m^3s^{-1} and sometimes also referred to as 'cumecs').

PDM

The Probability Distributed Model or PDM (Moore, 2007; UKCEH, 2021) is a simple, very widely used lumped rainfall-runoff model that can be configured to a variety of catchment flow regimes. PDM may be thought of as a toolkit of model components representing a range of runoff production and flow routing behaviours, and with a choice of time-step. A .csv file of calibrated model parameters is provided as part of eFLaG_dataset.zip, or, alternatively, PDM input files of those parameters may be requested from ForecastModelSupport@ceh.ac.uk. All outputs are reported in units of cubic metres per second (abbreviated to m^3s^{-1} and sometimes also referred to as 'cumecs').

AquiMod

AquiMod is a lumped conceptual groundwater model that links simplified equations of soil drainage, unsaturated zone flow and saturated groundwater flow to simulate daily groundwater level time-series at a specified borehole (Mackay et al. 2014). It has a flexible model structure that can be optimised to different hydrogeological settings. The model has been applied for historical reconstruction of groundwater levels (Jackson et al. 2016), groundwater level forecasting (Mackay et al. 2015), and regional groundwater flood mapping (Upton et al. 2011). AquiMod is also used operationally to deliver groundwater flood forecasts. All outputs are reported in units of metres Above Ordnance Datum (mAOD) and represent the simulated groundwater level at the borehole.

ZOODRM

ZOODRM is a distributed recharge calculation model originally developed to estimate recharge values to drive groundwater simulators (Mansour and Hughes, 2004). It is applied over the British Mainland using a $2\text{km} \times 2\text{km}$ square grid. The FAO Drainage and Irrigation Paper 56 (FAO, 1988) approach, modified by Griffiths et al. (2006), is used to calculate potential recharge. This method removes actual evaporation and soil moisture deficit from rainfall and calculates potential recharge as a fraction of the excess water using a runoff coefficient value. The model has been used in the past to assess changes in 21st century seasonal recharge across river basin districts and groundwater bodies in the UK based on the FFGWL climate change projections (Hughes et al. 2021). All outputs are reported in units of mm per day and represent an average of potential groundwater recharge over the modelled area of the groundwater body.

QUALITY CONTROL

Sources of quality-controlled, long-term data for model calibration and evaluation were the national standard repositories for hydrological data:

- River flows: UK National River Flow Archive (<https://nrfa.ceh.ac.uk/>)
- Groundwater levels: UK National Groundwater Level Archive (<https://www2.bgs.ac.uk/groundwater/datainfo/levels/ngla.html>)

For all of the models, evaluation was undertaken in two stages, which is standard practice for appraising a model for simulation of climate change impacts:

1. Evaluation when driven with baseline observed climate data
2. Evaluation when driven with baseline climate model data.

A full assessment of the validation metrics can be found in Hannaford et al. (in prep).

Step 1 involves the assessment of the performance of model simulations driven by observed climate data (the simobs runs) against observations of river flow and groundwater. Within eFLaG, a range of

different metrics were used to assess different facets of performance: particularly low flow metrics but also some that evaluated performance across different parts of the flow regime. Table 1 describes the range of metrics used for evaluation, based on the NERC Drought and Water Scarcity (DWS) Programme (AboutDrought, 2021) including an inter-comparison of a range of widely-used models.

Table 1. Model calibration and evaluation metrics used in eFLaG.

Evaluation Metric	Equation	Focus
Nash-Sutcliffe Efficiency (R^2 Efficiency)	$NSE = 1 - \frac{\sum_{i=1}^n (Q_i - q_i)^2}{\sum_{i=1}^n (Q_i - \bar{Q})^2}$ <p>Q_i and q_i are observed and modelled flow for day i of a n day record. \bar{Q} is the mean observed flow.</p>	High Flows
Nash-Sutcliffe Efficiency log flows	$NSE_{log} = 1 - \frac{\sum_{i=1}^n (\log(Q_i) - \log(q_i))^2}{\sum_{i=1}^n (\log(Q_i) - \log(\bar{Q}))^2}$	Low Flows
Nash-Sutcliffe Efficiency square root flows	$NSE_{sqrt} = 1 - \frac{\sum_{i=1}^n (\sqrt{Q_i} - \sqrt{q_i})^2}{\sum_{i=1}^n (\sqrt{Q_i} - \sqrt{\bar{Q}})^2}$	Average Flows
Modified Kling Gupta Efficiency [square root flows]	$KGE'_{sqrt} = 1 - \sqrt{(r - 1)^2 + (\beta - 1)^2 + (\gamma - 1)^2}$ <p>where r is the correlation coefficient, β is the bias ratio $\frac{\mu_{\sqrt{q}}}{\mu_{\sqrt{Q}}}$, and γ is the variability ratio $\frac{CV_{\sqrt{q}}}{CV_{\sqrt{Q}}}$ or $\frac{\sigma_{\sqrt{q}/\mu_{\sqrt{q}}}}{\sigma_{\sqrt{Q}/\mu_{\sqrt{Q}}}}$</p> <p>$\mu$, σ and CV are the mean, standard deviation and coefficient of variation of flow (here of the square root of modelled and observed flows as indicated by the suffix)</p>	Generalised
Absolute Percent Bias	$absPBIAS = \left \frac{\sum (q_i - Q_i)}{\sum Q_i} \right 100$	Water Balance
Mean Absolute Percent Error	$MAPE = \left(\frac{1}{n} \sum_{i=1}^n \left \frac{Q_i - q_i}{Q_i} \right \right) 100$	Systematic
Absolute Percent Error in Q95	$Q95_{APE} = \left \frac{Q95 - q95}{Q95} \right 100$	Low Flows
Low Flow Volume	$LFV = 100 \frac{\sum_{p=70}^{95} (\sqrt{q_p} - \sqrt{Q_p})}{\sum_{p=70}^{95} (\sqrt{Q_p})}$ <p>Here q_p and Q_p are the modelled and observed flow p percentiles</p>	Low Flows

**Absolute Percent Error in the Mean Annual
Minimum on a 30-day moving average**

$$MAM30_{APE} = \left| \frac{QMAM30 - qMAM30}{QMAM30} \right| 100$$

where $QMAM30 = \frac{1}{n} \sum_{j=1}^n \min_j \left(\frac{Q_{j,i-29} + Q_{j,i-28} + Q_{j,i-27} \dots Q_{j,i-1} + Q_{j,i}}{30} \right)$ Low Flows

Here $Q_{j,i}$ is observed flow for day i of hydrological year j for a record of n years

*1/100th of the mean observed flow was added to both modelled and observed flow values during evaluation in order to avoid errors and biases due to very small and zero flows.

Step 2 looks at the performance of the simobs and simrcm runs over the common baseline period. This assessment cannot use performance metrics based on time-series, as climate models are not expected to reproduce the sequencing of events seen over the historical period (Kay et al. 2015). Instead, the comparison is done using flow duration curves and low flow frequency curves: thus, comparing the statistical characteristics of the flows rather than their day-to-day equivalence (Kay et al. 2015, 2018).

DATA STRUCTURE

The data are stored as .csv files in the folder structure shown in Figure 3. In total there are 3304 files: one for each variable, model and catchment/borehole combination. They can be broadly split into two groups of files (Table 2), simobs and simrcm, as follows.

simobs

For the meteorological data, the simobs files contain date-indexed, observation-driven simulations (sim) data for precipitation with snowmelt and potential evaporation. For river flows and groundwater levels the simobs files contain date-indexed, observation-driven simulations (sim) and associated observations (obs) if they exist.

simrcm

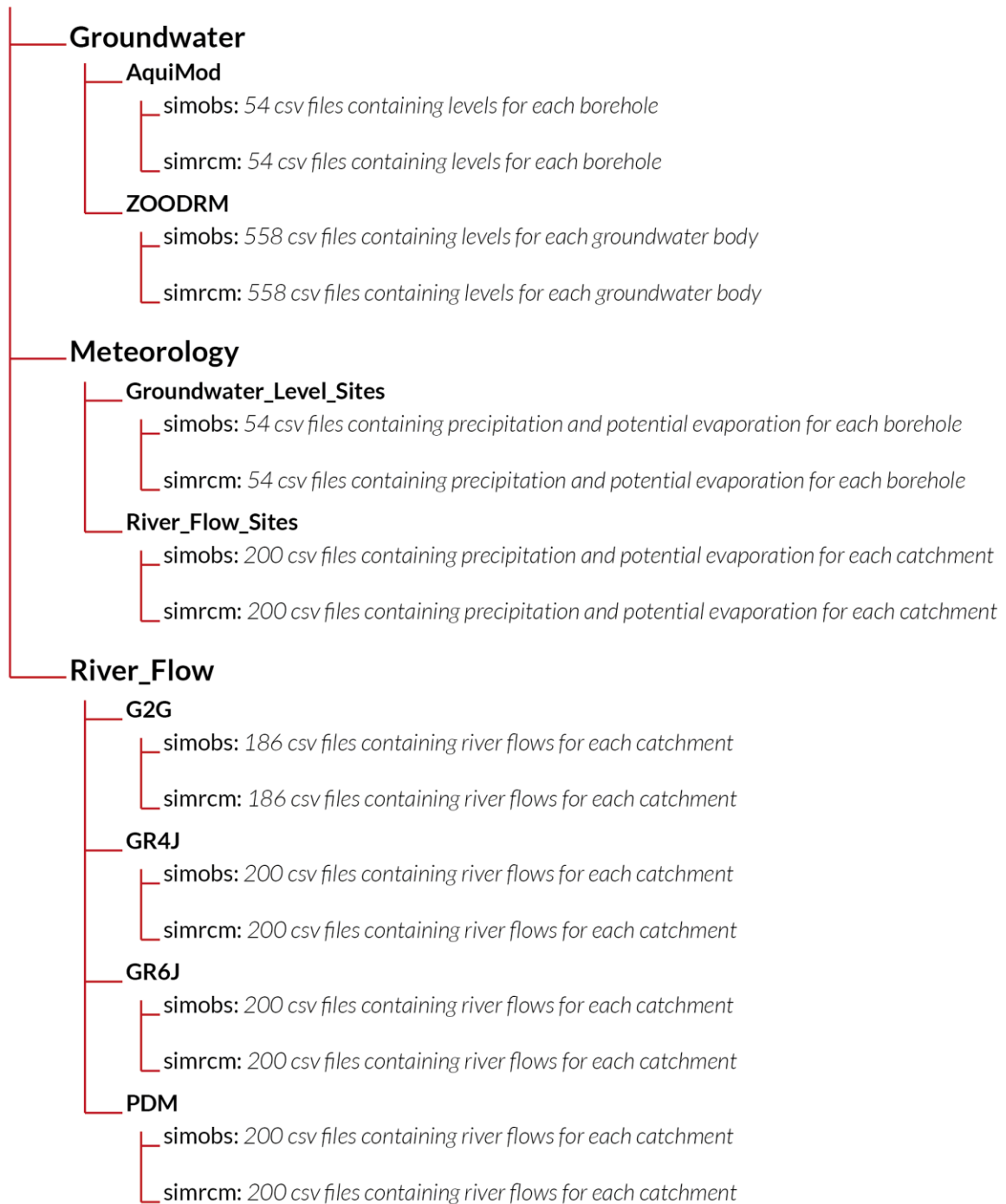
For the meteorological data, the simrcm files contain date-indexed, RCM-driven simulations for the twelve RCMs used in eFLaG for both precipitation with snowmelt and potential evaporation. For river flows and groundwater levels the simrcm files contain date-indexed, RCM-driven simulations for the twelve RCMs used in eFLaG.

Table 2. eFLaG dataset structure information

	Data	Name of file	Years available
simobs	Daily meteorology (precipwsnow (mm d ⁻¹) + PET (mm d ⁻¹))	<i>ukcp18_simobs_nrfa-station-number/borehole-name.csv</i>	Jan 1961 – Dec 2018
	Daily river flow (m ³ s ⁻¹)	<i>modelname_simobs_nrfa-station-number.csv</i>	Jan 1963 – Dec 2018
	Daily groundwater levels (m AOD)	<i>AquiMod_simobs_borehole-name.csv</i>	Jan 1962 – Dec 2018
	Daily groundwater recharge (mm d ⁻¹)	<i>zoodrm_simobs_groundwater-body-name.csv</i>	Jan 1962 – Dec 2018
simrcm	Daily meteorology (precipwsnow (mm d ⁻¹) + PE mm d ⁻¹)	<i>ukcp18_simobs_nrfa-station-number.csv</i>	Dec 1980 – Nov 2080
	Daily river flow (m ³ s ⁻¹)	<i>modelname_simrcm_nrfa-station-number.csv</i>	Dec 1982 – Nov 2080
	Daily groundwater levels (m AOD)	<i>AquiMod_simrcm_borehole-name.csv</i>	Jan 1982 – Nov 2080
	Daily groundwater recharge (mm d ⁻¹)	<i>zoodrm_simrcm_groundwater-body-name.csv</i>	Jan 1981 – Nov 2080

where *modelname* is G2G, PDM, GR4J, GR6J. NRFA station numbers and borehole names are given in the eFLaG_Station_Metadata.xlsx workbook.

eFLaG_Dataset.zip



27 directories, 3304 files

Figure 3 Visualisation of eFLaG dataset folder structure

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