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Future Flows Hydrology: an ensemble of daily river flow and monthly groundwater levels for use for climate change impact assessment across Great Britain

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Abstract. The dataset Future Flows Hydrology was developed as part of the project "Future Flows and Groundwater Levels" to provide a consistent set of transient daily river flow and monthly groundwater level projections across England, Wales and Scotland to enable the investigation of the role of climate variability on river flow and groundwater levels nationally and how this may change in the future.

Future Flows Hydrology is derived from Future Flows Climate, a national ensemble projection derived from the Hadley Centre's ensemble projection HadRM3-PPE to provide a consistent set of climate change projections for the whole of Great Britain at both space and time resolutions appropriate for hydrological applications. Three hydrological models and one groundwater level model were used to derive Future Flows Hydrology, with 30 river sites simulated by two hydrological models to enable assessment of hydrological modelling uncertainty in studying the impact of climate change on the hydrology.

Future Flows Hydrology contains an 11-member ensemble of transient projections from January 1951 to December 2098, each associated with a single realisation from a different variant of HadRM3 and a single hydrological model. Daily river flows are provided for 281 river catchments and monthly groundwater levels at 24 boreholes as .csv files containing all 11 ensemble members. When separate simulations are done with two hydrological models, two separate .csv files are provided.

Because of potential biases in the climate–hydrology modelling chain, catchment fact sheets are associated with each ensemble. These contain information on the uncertainty associated with the hydrological modelling when driven using observed climate and Future Flows Climate for a period representative of the reference time slice 1961–1990 as described by key hydrological statistics. Graphs of projected changes for selected hydrological indicators are also provided for the 2050s time slice. Limitations associated with the dataset are provided, along with practical recommendation of use.

Future Flows Hydrology is freely available for non-commercial use under certain licensing conditions. For each study site, catchment averages of daily precipitation and monthly potential evapotranspiration, used to drive the hydrological models, are made available, so that hydrological modelling uncertainty under climate change conditions can be explored further.

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1 Background

Climate change may increase temperatures and change rainfall across England, Wales and Scotland (Murphy et al., 2009). In turn, this may modify patterns of river flow and groundwater recharge, affecting the availability of water and changing the aquatic environment. There have been many studies of the impact of climate change on river flows in different parts of the UK (e.g. Charlton and Arnell, 2011; Diaz-Nieto and Wilby, 2005; Holman, 2006; Kay et al., 2009; Ledbetter et al., 2011; Limbrick et al., 2000; Lopez et al., 2009; Nawaz and Adeloye, 2006; Prudhomme and Davies, 2009; Prudhomme et al., 2010; Wilby and Harris, 2006; Kay and Jones, 2010; Christierson et al., 2012), but coverage is uneven and methods vary. There have been fewer studies of the impacts on groundwater (e.g. Yusoff et al., 2002; Herrera-Pantoja and Hiscock, 2008; Jackson et al., 2011), which again have used a variety of approaches. This means it is very difficult to compare different locations, complicating the identification of appropriate adaptation responses.

The project "Future Flows and Groundwater Levels" was established to provide datasets and products that facilitate the assessment of climate change impact on a range of water-related issues across Great Britain within a nationally consistent framework (http://www.ceh.ac.uk/sci_programmes/Water/FutureFlowsandGroundWaterLevels.html). Future Flows Hydrology is a consistent set of river flow and groundwater level projections for 281 river sites and 24 boreholes across Great Britain to enable the investigation of the role of climate variability on river flow and groundwater levels nationally and how this may change in the future.

At the end of the project, the transient daily (river flow) and monthly (groundwater levels) time series and the climate datasets necessary for their generation were made accessible to the research community so that further impact analyses can be made on a range of specific areas such as fisheries, freshwater ecology, or water availability. The length (around 150 yr) and geographical spread (over Great Britain) of the time series will enable powerful spatio-temporal analysis of the impact of climate change on UK rivers, possible for the first time at such a scale in the UK, thanks to a strict methodological framework which ensures consistency, and hence comparability, of all generated data.

This paper gives an overview of the climate projections used to derive Future Flows Hydrology (Sect. 2), then describes the hydrological models used (Sect. 3) and the study sites (Sect. 4). It concludes by describing the catchment fact sheets that highlight some of the uncertainty of the dataset (Sect. 5), and by describing limitations and making suggestions of use of Future Flows Hydrology (Sect. 6) before concluding on how to access the data.

2 Data: Future Flows Climate

2.1 Description

Future Flows Climate is the set of climate projections used as input to derive Future Flows Hydrology. Its development is described in Prudhomme et al. (2012) with a brief overview provided here. It is an 11-member ensemble of transient climate projections for Great Britain based on HadRM3-PPE-UK, a set of transient climate projections for the UK that were used as part of the derivation of the UKCP09 scenarios (Murphy et al., 2007). HadRM3-PPE-UK was designed to represent parameter uncertainty in climate change projections through a parameter variant experiment and was run under the SRES A1B emissions scenario (Murphy et al., 2009). Detailed information on the model ensemble can be found at http://badc.nerc.ac.uk/data/hadrm3-ppe-uk/.

As HadRM3-PPE time series are provided at a spatial scale too coarse for hydrological application, and because of some biases, systematic differences were identified between its representation of precipitation and temperature and observations. Consequently bias correction and downscaling were applied to both climate variables. Similarly to Piani et al. (2010b), precipitation and temperature were bias-corrected independently. For precipitation, first a bias correction was implemented following the parametric quantile-mapping method described by Piani et al. (2010a) based on the gamma distribution for each ensemble member independently. The time series were then downscaled onto a 1-km grid based on the observed annual precipitation variability within each grid, so that the sub-grid orographic effect was included within the generated 1-km time series. To account for the influence of temperature on the partition between rainfall and snowfall in snow-influenced regions, a simple elevation-dependent snowmelt model was used (Bell and Moore, 1999) to estimate when water is available for runoff. Each of the 11 1-km bias-corrected and downscaled precipitation daily time series were transformed to 1-km "available precipitation" (APr, in mm) 148-yr time series using this method, and using the bias-corrected temperature time series. Potential evapotranspiration (PET) was required as an input to the hydrological models, and so a gridded PET ensemble at 5-km resolution was generated using the HadRM3-PPE climate time series, based on the FAO-56 Penman–Monteith method (Allen et al., 1998) using bias-corrected temperature time series (see Prudhomme et al., 2012).

2.2 Catchment averages

For each study site, catchment (or grid)-averaged time series were derived by superimposing the catchment boundary onto the data grids and calculating area-weighted averages. These time series are daily for available precipitation and monthly for PET. The monthly PET is divided equally through the month to give daily PET similarly to simulations from observed climate (Crooks and Naden, 2007). For the groundwater models average precipitation and PET are determined from weighted averages for an appropriate groundwater catchment identified from groundwater level contour data. The entire time series period ranges from 1950 to 2098.

3 Hydrological models

Three types of hydrological models were used to generate river flow time series for the project:

- Regionalised models (CERF; Griffiths et al., 2006), where a range of catchments (from the whole of Great Britain) are considered together and the best overall set of parameters (sometimes linked to land use and soil characteristics) are defined;
- Catchment models (PDM; Moore, 2007), where the model parameters are fine-tuned to reproduce best the site-gauged flow statistics.
- Hybrid model (CLASSIC; Crooks and Naden, 2007), where a combination of regionalised and calibrated parameters are used.

The R-Groundwater (Jackson, 2012) lumped groundwater model was used to generate groundwater level time series for the project.

The three models used to simulate river flow (CERF, PDM and CLASSIC) employ three different methods of calibration with the emphasis of calibration on different parts of the flow regime. For CERF the emphasis is on water resources as represented by the water balance and low flows, while for PDM and CLASSIC the emphasis is on the upper part of the flow regime and peak flows. The calibration method may affect model performance at different parts of the flow regime.

An individual instance of an R-Groundwater model is calibrated against groundwater levels observed in a single borehole. This is performed through a Monte Carlo process in which model parameters are sampled from a priori defined ranges of plausible values. R-Groundwater models are calibrated against the full range of observed groundwater levels.

The advantage of catchment calibrated models is that they are designed to reproduce best local hydrological processes. For the historic period it is to be expected that a calibrated model should provide a higher level of predictive accuracy than a regionalised model. However, calibrated model parameters are applicable over the local climate range observed within the data used for model calibration and verification of the model performance. In contrast, an advantage of regionalised parameter models is to extend the climate range under which the model parameters are evaluated compared to only using the local climate range; this is particularly important in a warming climate for catchments where evaporation processes might be water limited in the future whereas this has not been the case in the past. Such models can also be used for locations for which there is little or no gauged data or where the data quality is such that it is not suitable for calibration of model parameters.

3.1 CERF

The CERF regionalised rainfall–runoff model (Griffiths et al., 2006) is based around the hydrological response unit (HRU). The structure of CERF is based on two sub-model components; the loss module (based around the FAO56 soil moisture accounting procedure) that generates hydrologically effective precipitation (EP) and the routing module that subsequently routes the EP to the catchment outlet. The HRUs are defined as a function of catchment descriptors for soils, geology, vegetation and topography. Within the routing HRU a probability distributed model of free water in the soil column partitions EP into a slow-flow routing path (groundwater), which is treated as a linear reservoir, and a quick-flow, topographically routed flow path. The model was calibrated across many catchments simultaneously to obtain a best compromise model fit across all catchments with model parameters being a function of catchment descriptors. This combines both model calibration and generalisation in a one step procedure.

3.2 PDM

The Probability Distributed Model (PDM; Moore, 2007) is a lumped rainfall–runoff model with three conceptual stores; a soil moisture store, and fast- and slow-flow stores. The model represents non-linearity in the transformation from rainfall to runoff by using a probability distribution of soil moisture storage. This determines the time-varying proportion of the catchment that contributes to runoff, through either "fast" or "slow" pathways. A simplified version of the full PDM is used to reduce the problem of equifinality and allow use of an automatic calibration routine (Kay et al., 2007). The PDM requires inputs of catchment-average rainfall and potential evaporation (PE), with flow data for calibration.

3.3 CLASSIC

The Climate and Land-use Scenario Simulation In Catchments (CLASSIC) model (Crooks and Naden, 2007) is a catchment model generally used for larger catchments. CLASSIC is a semi-distributed grid-based rainfall–runoff model with three main modules (soil moisture accounting, drainage and channel routing) and with semi-automatic calibration. CLASSIC requires gridded inputs of rainfall and PE, normally at a daily time step, as well as land-use, soil and digital terrain data. A generalised method for determining parameter values from catchment properties makes it suitable for modelling catchments where direct calibration against observed flow is not suitable due to factors such as

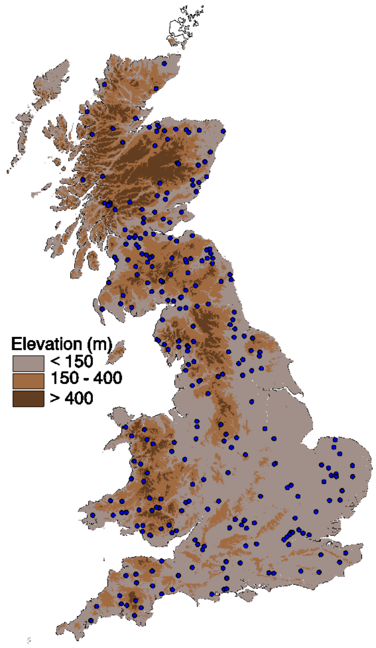

Figure 1. Catchment river outlets where Future Flows Hydrology time series are generated. Copyright ©NERC (CEH) 2012. Contains Ordnance Survey data ©Crown Copyright and Database Right.

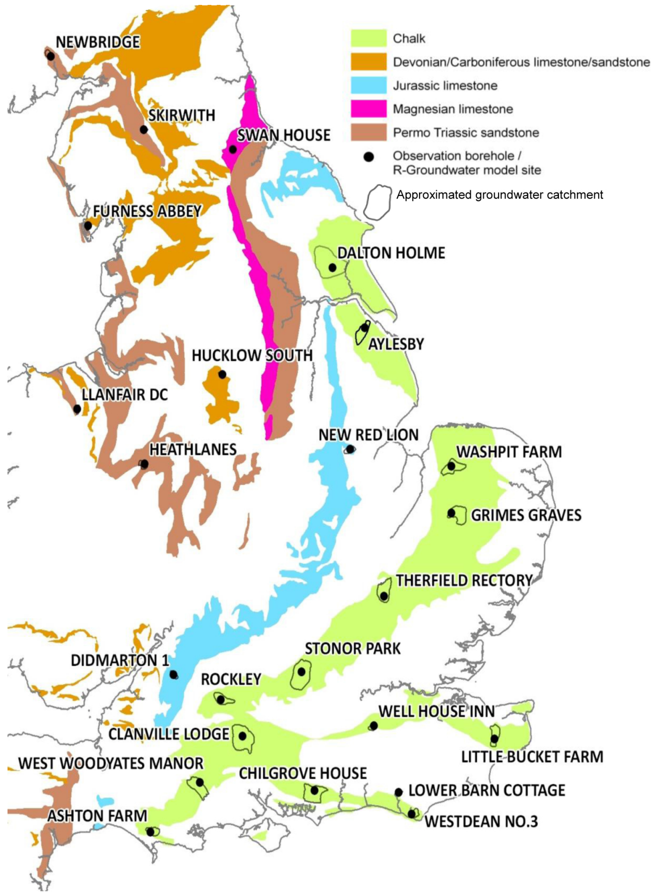

Figure 2. Future Flows Hydrology R-Groundwater model sites. Copyright ©NERC (BGS) 2012. Contains Ordnance Survey data ©Crown Copyright and Database Right.

abstraction and river regulation. The methodology also ensures spatial consistency in flow simulation across the UK.

3.4 R-Groundwater

R-Groundwater (Jackson, 2012) is a lumped catchment groundwater model written in the R programming language and run within the R environment (http://www.r-project.org). It simulates a groundwater level time series at an observation borehole and generates time series of flow through three conceptualised aquifer outlets. These three discharges represent intermittent and perennial discharge to a river, and groundwater flow out of the catchment. The model consists of the following three components: (i) an FAO56 soil moisture balance model producing a time series of potential recharge (soil drainage); (ii) a simple transfer function representing the delay in the time of the arrival of recharge from the base of the soil to the water table; and (iii) a lumped catchment groundwater model based on a simple Darcian representation of flow out of the aquifer outlets.

4 Sites

To capture the range of climate, land use, geological and geographical characteristics found in England, Wales and Scotland, Future Flows Hydrology time series were generated for 281 river catchments (outlets shown in Fig. 1) and 24 boreholes (Fig. 2).

4.1 River flow sites

River flow sites were chosen because they had good records and the hydrological processes could be well reproduced by conceptual hydrological models. Sites were selected in conjunction with the Environment Agency, SEPA and Water Companies. For the river catchments the criteria for selection of catchments and acceptable quality of gauged flow data depends on the model used. For catchments modelled with CERF, the quality of the gauged low flows is of prime importance, which means that all selected catchments must have a natural flow regime. For catchments modelled with PDM, some alteration to low flows is acceptable, but there should be good quality high-flow measurements; while for CLASSIC most catchments being modelled do not have a natural flow record. Some catchments in eastern England have been included where data quality is not as good as other regions to provide a reasonable regional coverage. These factors are reflected in the statistics for evaluation of the historical period.

For selection of catchments modelled with the PDM, a minimum catchment area of around 100 km^2 is imposed.

This is because the modelling for Future Flows is at a daily time step and the purpose of the calibration was simulation of high flows, for which an hourly (or shorter) time step is advisable. For catchments modelled with CERF, small catchments have been included (smallest 2.2 km^2) as timing of high flows is not of importance. Thirty catchments are modelled with two hydrological models. The list of sites with Future Flow Hydrology data is given in the Supplement by hydrometric region.

4.2 Groundwater level sites

The selection of observation boreholes for which their groundwater level time series would be modelled was made in collaboration with Environment Agency of England and Wales regional (and water company) hydrogeological staff. Sites were chosen based on the following criteria:

- They cover the range of major aquifer types across Great Britain (shown in Fig. 2).
- The groundwater level time series is indicative of bulk aquifer storage.
- There is a reasonable length of record, preferably greater than 20 yr.
- Groundwater abstraction impacts are minimal.
- They are not significantly controlled by surface water levels.

These sites are shown in Fig. 2 and listed in the Supplement. Rainfall time series are required to simulate the groundwater level time series at each borehole. These are based on a catchment averaged time series based on approximated groundwater catchments. Groundwater catchments for each observation borehole were estimated from groundwater level contours.

5 Catchment fact sheets

The fact sheets are designed to provide a brief overview on the ability of the river flow or groundwater models to simulate some of the most important components of the water cycle when using observed and modelled climate (see examples in Supplement). This overview is given by sets of statistics (measuring the differences between two time series) and graphs (providing a visual comparison). Detailed information on the meaning of the statistics and graphs is provided in the modelling protocol report (Crooks et al., 2012), which is accessible from the Future Flows and Groundwater Levels web page (http://www.ceh.ac.uk/sci_programmes/Water/FutureFlowsandGroundWaterLevels.html).

One fact sheet is delivered for each site and river flow or groundwater level model combination. If two hydrological models are used to simulate flow at the same site, two catchment fact sheets are provided for this site. Note that different models use different methods of calibration ranging from catchment specific to regionalised parameters, and that the calibration method may affect the statistical measures of model performance.

A catchment fact sheet is divided in three parts. Top front page: general information section with the main physical characteristics of the catchment, its location and the availability of observed flow/groundwater level data. Front: how well the observed flow time series are reproduced by the models when using observed climate, or a measure of the confidence in the model. This is quantified by performance indicators based on an assessment of measures of fit between observed and modelled series fully described in Crooks et al. (2012). Back: how well flow time series are reproduced by the models when using modelled climate, or a measure of the confidence in the climate/hydrological model combination. Both front and back must be looked at to fully understand the factors affecting the Future Flows Hydrology time series. This is very important when the Future Flows Hydrology time series are used to assess climate change impact on a catchment ecosystem. The Future Flows Hydrology flow time series are in $m^3 s^{-1}$. The Future Flows Hydrology groundwater level time series are in metres above Ordnance Datum (m aOD). Example catchment fact sheets are given in the Supplement for one river flow and one groundwater site.

6 Data limitations

Future Flows Hydrology is the product of a long modelling chain, including the modelling of climate variability and potential future evolution under an emission scenario, bias correction and downscaling of precipitation and temperature time series, derivation of potential evapotranspiration time series and the simulation of river flow and groundwater levels. While Future Flows Hydrology has been generated to provide river flow and groundwater level time series as realistically as possible, uncertainty remains (summarised in the catchment fact sheets described above), which will limit its use. We list here some of the most important limitations associated with Future Flows Hydrology and make some recommendations for best practice usage:

- Future Flows Hydrology aims to capture different plausible realisations of 150-yr river flow and groundwater levels under one emissions scenario. The 1951–2012 time slice is not a reconstruction of past hydrology and no past event is expected to be replicated by any ensemble member at the date of their historical occurrence.
- When compared with observations over the pre-2000 reference period, Future Flows Hydrology typically shows the largest departures (but no systematic bias) during dry conditions and in drier regions for surface flow, and an underestimation of groundwater levels,

mainly caused by climate rather than hydrological modelling uncertainty; but no systematic difference in modelling performance can be attributed to any of the surface and groundwater models. It is not recommended to compare Future Flows Hydrology time series directly with observations, or use Future Flows Hydrology time series directly in an impact model prior to checking the extent of differences.

– The signal of change in Future Flows Hydrology is independent of surface and ground water model structure. The national database of Future Flows Hydrology can be compared even if the sites' time series are simulated with different models.

– Future Flows Hydrology contains eleven independent members. No systematic bias is associated with any member. Time series associated with one ensemble member can only be compared with the same ensemble member time series either for a different time slice or different location or model. In order to capture the largest range of variability and signal of change, and to incorporate uncertainty (which all vary seasonally and spatially), it is recommended that all eleven members are considered together rather than a subset of the ensemble.

7 Access

Future Flows Hydrology dataset is associated with a Digital Object Identifier doi:10.5285/f3723162-4fed-4d9d-92c6-dd17412fa37b. This must be referenced fully for every use of the Future Flows Hydrology data as:

> Haxton T., Crooks S., Jackson C. R., Barkwith, A. K. A. P., Kelvin, J., Williamson, J., Mackay, J. D., Wang, L., Davies, H., Young, A., and Prudhomme, C.: Future Flows Hydrology, doi:10.5285/f3723162-4fed-4d9d-92c6-dd17412fa37b, 2012.

All Future Flows Hydrology files are available through the CEH Environmental Informatics Data Centre Gateway under special licensing conditions (https://gateway.ceh.ac.uk/ or http://dx.doi.org/10.5285/bad1514f-119e-44a4-8e1e-442735bb9797). They are also available through the National River Flow Archive (http://www.ceh.ac.uk/data/nrfa/data/search.html?db=nrfa_public&stn=categories:*FUTURE_FLOWS*) and the National Groundwater Level Archive (http://www.bgs.ac.uk/research/groundwater/change/FutureFlows/home.html) where metadata associated with each study site and hydrological observations can be found.

8 Conditions of use

Future Flows Hydrology is available under a licensing condition agreement. For non-commercial use, the products are available free of charge. For commercial use, the data might be made available conditioned on a fee to be agreed with NERC CEH and NERC BGS licensing teams, owners of the IPR of the datasets and products.

Supplementary material related to this article is available online at: http://www.earth-syst-sci-data.net/5/101/2013/essd-5-101-2013-supplement.pdf.

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