Proceedings of FRIEND-Water 2014, Montpellier, France, October 2014 (IAHS Publ. 363, 2014).

Future Flows: a dataset of climate, river flow and groundwater levels for climate change impact studies in Great Britain

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Abstract Science understanding suggests that anthropogenic greenhouse gas emissions will result in a changed climate that will in turn modify patterns of river flow and groundwater recharge, affecting the availability of water and changing the aquatic environment. While many studies have investigated the impact of climate change on river flows in Great Britain, their coverage is uneven and methods vary, and it is very difficult to compare results from different locations and different sectors and to identify appropriate adaptation responses. Future Flows is a set of nationally consistent projections of climate (1-km gridded daily precipitation and 5-km monthly potential evapotranspiration), river flow (for 282 catchments) and groundwater level (at 24 boreholes) for Great Britain at space and time resolutions for hydrological applications. It is based on the Hadley Centre's 11-member ensemble projections HadRM3-PPE run under the Medium emission scenario SRES A1B. The 11 plausible realisations (all equally likely) of nearly 150 years (from 1951 to 2098), described by Future Flows, enable the role of climate variability on river flow and groundwater levels nationally to be investigated and how this may change in the future. Some climate change uncertainty is accounted for by considering all ensemble members together. In addition to the time series, Future Flows contains information on modelling errors in the river flow and groundwater level projections in the form of catchment fact sheets. These fact sheets contain performance measures for hydrological statistics including monthly flow, flow percentiles and for some catchments flood peaks, and separately the hydro(geo)logical modelling errors from the fuller chain of climate-to-hydrology modelling. This information enables any potential user to have a clear view of the modelling uncertainty before they use the data. Future Flows Climate and Future Flows Hydrology are each associated with a Digital Object Identifier and are available to the research community free of charge for non commercial work.

Key words climate change; hydrology; hydrogeology; uncertainty; emissions scenario

INTRODUCTION

Climate change may increase temperatures and change rainfall across England, Wales and Scotland (Murphy *et al.*, 2009), resulting in changed river flow and groundwater recharge, affecting the availability of water and changing the aquatic environment. Many studies have investigated the impact of climate change on UK river flows (much fewer on UK groundwater) but coverage is uneven and methods vary. Comparing results is hence difficult, complicating the identification of appropriate adaptation responses.

Future Flows Climate and Future Flows Hydrology are an ensemble of climate, river flow and groundwater transient time series derived across Great Britain to facilitate the assessment of climate change impact on a range of water-related issues across Great Britain within a nationally consistent framework. This paper provides a brief overview of the data and methods used. It describes their derivation, condition of use, limitations and data access.

FUTURE FLOWS CLIMATE

Future Flows Climate (FFC) is an 11-member ensemble of transient gridded daily precipitation and monthly potential evapotranspiration projections for Great Britain for the period 1950–2098. It is based on the HadRM3-PPE-UK experiment designed to represent parameter uncertainty in climate change projections and run under the SRES A1B emissions (Murphy *et al.*, 2009). Because HadRM3-PPE time series are provided at a spatial scale too coarse for hydrological application (25-km squares) and because of systematic differences between its representation of precipitation and temperature and observations, bias-correction and downscaling were applied to both climate variables independently, similar to Piani *et al.* (2010b). The temperature time series was bias-corrected and downscaled at 5-km using a linear correction for each ensemble member and month independently, but is not part of FFC.

Precipitation

Daily precipitation was bias-corrected using the parametric quantile-mapping method (Piani *et al.*, 2010a) based on the Gamma distribution for each ensemble member and month independently. The orographic influence on precipitation was captured by scaling the time series according to the observed annual precipitation variability within each grid. Snowmelt processes were accounted for using a simple elevation-dependent snowmelt model (Bell & Moore, 1999) to estimate the partitioning between rain and snowfall and delays due to snow/ice storage.

Potential evapotranspiration

Monthly potential evapotranspiration (PET) was generated on a 5-km grid based on the FAO-56 Penman-Monteith method (Allen *et al.*, 1998) using HadRM3-PPE variables and bias-corrected temperature time series. Vapour pressure was calculated from mean temperature and relative humidity; net radiation was derived from latitude, day of the year (assumed equal to the 15th of the month), cloud cover (with 1-Total cloud lw rad = f cloudiness factor) and vapour pressure (Shuttleworth, 1993).

FUTURE FLOWS HYDROLOGY

Future Flows Hydrology (FFH) is an 11-member ensemble of daily river flows and monthly groundwater levels across Great Britain for the period 1951–2098. It is derived from the FFC.

Surface and groundwater models

Three types of surface/groundwater models were used to generate FFH: (i) a regionalised model (CERF; Griffiths *et al.*, 2006) calibrated to reproduce best observations across many catchments across Great Britain with parameters linked to land use and soil characteristics; (ii) catchment (lumped) models (PDM; Moore, 2007) (R-Groundwater; Jackson, 2012) calibrated to reproduce best local observations; (iii) a hybrid model (CLASSIC; Crooks & Naden, 2007), where a combination of regionalised and locally calibrated parameters are used. Calibration focused on water resource (best simulation of water balance and low flow) for CERF, while for PDM and CLASSIC calibration focused on peak flows. R-Groundwater used a Monte Carlo calibration process to define the best parameter set to reproduce groundwater levels observed in a single borehole. FFH time series are in m^3s^{-1} (flow) and in metres above Ordnance Datum (m aOD) (groundwater level).

Sites

To capture the range of climate, land use, geological and geographical characteristics found in England, Wales and Scotland, FFH time series were generated for 281 river catchments and 24 boreholes (Fig. 1). River flow sites were chosen based on: (i) length of record; (ii) good reproduction of hydrological processes by conceptual hydrological models; (iii) minimum artificial influence (CERF sites) or good quality high flow measurement (PDM sites). Note that some catchments in eastern England have poorer gauged records but were included for better regional coverage. Thirty catchments were modelled with two hydrological models to capture some hydrological modelling uncertainty. Groundwater level sites were chosen based on: (i) good coverage of the major aquifer types (Fig. 1); (ii) groundwater level time series indicative of bulk aquifer storage; (iii) length of record preferably greater than 20 years; (iv) minimal groundwater abstraction impacts; (v) no significant control by surface water levels. FFH sites can be found at http://www.ceh.ac.uk/sci_programmes/water/future%20flows/ffgwlsites.html.

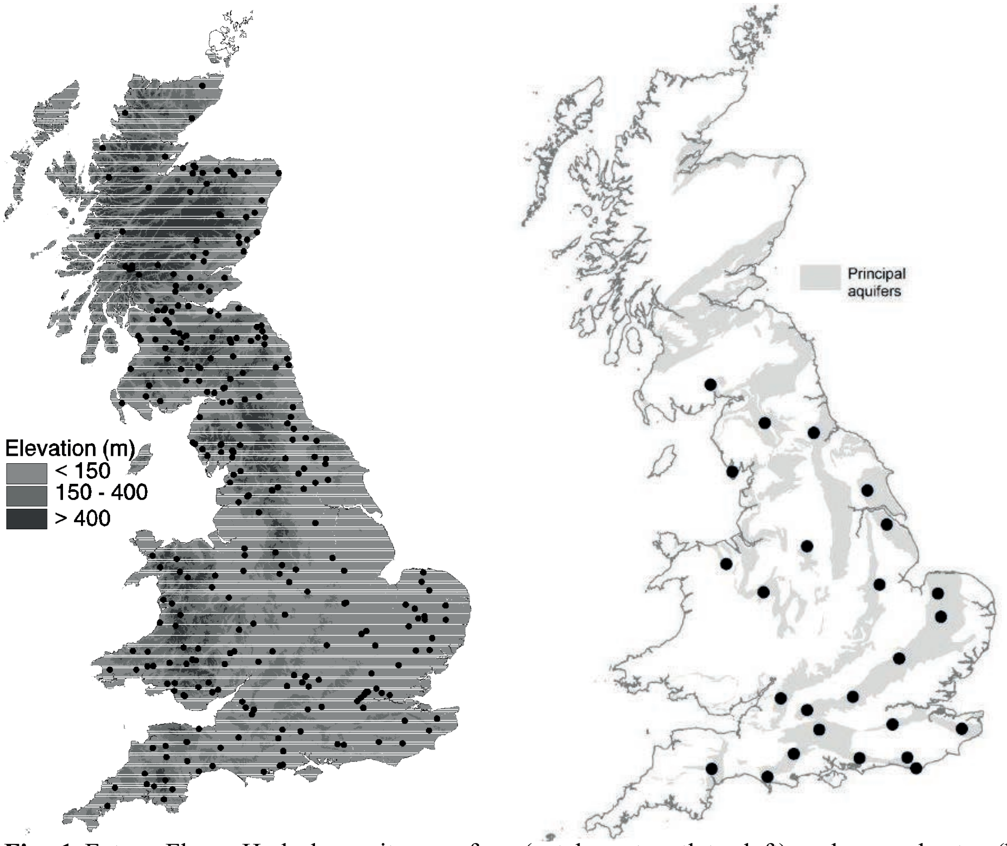

Fig. 1 Future Flows Hydrology sites: surface (catchment outlets; left) and groundwater (boreholes; right). Copyright © NERC (CEH/BGS) 2012. Contains Ordnance Survey data © Crown Copyright and Database Right.

Catchment fact sheets

In addition to the simulated time series, FFH is associated with metadata information summarising key site characteristics (including location and river basin area) and modelling performance in the form of catchment fact sheets. Catchment fact sheets must be studied when FFH time series are used to assess climate change impact on a catchment ecosystem. Performance bands ranging from 1 (good) to 3 (poor) are attributed to a range of metrics described in a modelling protocol (Crooks *et al.*, 2012). The performance indicators are based on measures of fit between observed and modelled series focusing on key parts of the hydrological regime (Crooks *et al.*, 2012): (i) water balance (seasonality, day-to-day variability); (ii) low flows/levels (percentiles Q/L75 & Q/L90); (iii) high flows/levels (percentiles Q/L25 & Q/L5) and flood peaks (RP2 to RP20; only for simulations by PDM and CLASSIC); and (iv) for groundwater levels difference in range level (%). An example of modelling performance assessment is given in Table 1 and Figs 2 and 3 for surface and groundwater simulations, respectively.

DATA LIMITATIONS

Future Flows Climate and Future Flows Hydrology are the product of a long modelling chain, including the modelling of climate variability and potential future evolution under one 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.

Table 1 Modelling performance assessment calculated over the gauged record based on observed available precipitation and MORECS PET (Thompson *et al.*, 1982). Top: surface water for the Llynfi at Coytrahen using CERF for 1971-05 reference; Bottom: groundwater levels at Chilgrove House using R-Groundwater for 1961-05 reference

Surface water		J	F	M	A	M	J	J	A	S	O	N	D
Llynfi at Coytrahen	Bias (%)	–0.1	–4.6	–8.9	–11.4	–6.2	–5.6	1.6	8.3	12.6	5.6	-1.7	-1.7
Model: CERF	Performance band	1	1	1	2	2	1	1	2	2	1	1	1
		Mean Annual			Q90	Q75	Q50	Q25	Q5		Nash Sutcliffe		
	Bias (%)	–1.3			9.9	5.6	–17.4	–9.5	13.9		0.80		
	Performance band	1			1	1	1	1	1		1		
Groundwater		J	F	M	A	M	J	J	A	S	O	N	D
Chilgrove House	Bias (m)	0.51	0.48	0.15	–0.52	–0.08	0.04	0.08	0.19	0.15	0.37	0.13	1.04
Model: R-Groundwater	Performance band	1	1	1	1	1	1	1	1	1	1	1	1
		Mean Annual			L90	L75	L50	L25	L5		Nash Sutcliffe		
	Bias (m)	0.21			0.20	0.45	0.82	0.19	–1.03		0.89		
	Performance band	1			1	1	1	1	1		1		

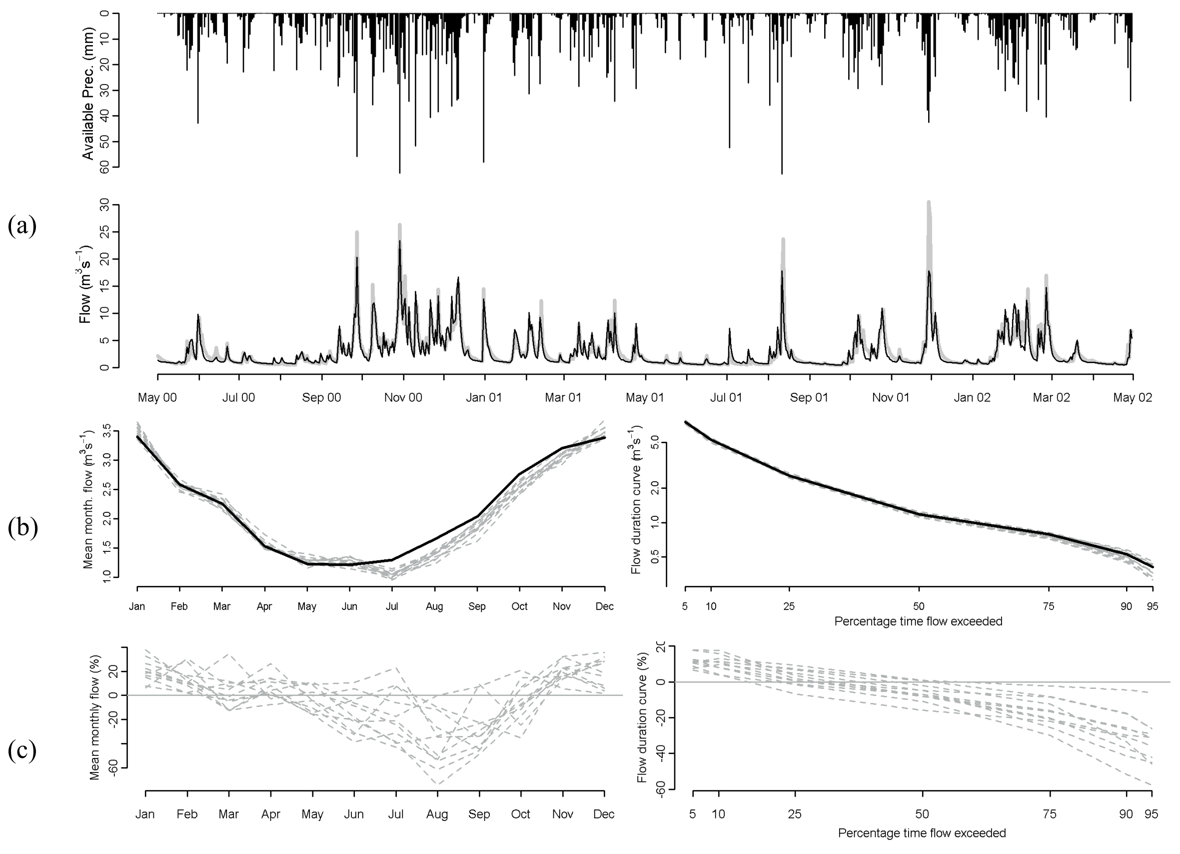

Fig. 2 Assessment of the surface water CERF modelling performance for the Llynfi at Coytrahen for simulations from observed climate (black) and FFC (grey dashed) compared with gauged flows (grey solid): (a) daily hydrographs; (b) mean monthly flow (left) and flow duration curve (right) for 1962–1991; (c) changes in mean monthly flow (left) and flow duration curves (right) between future (2040–2069) and control (1961–1990).

(a)

(b)

(c)

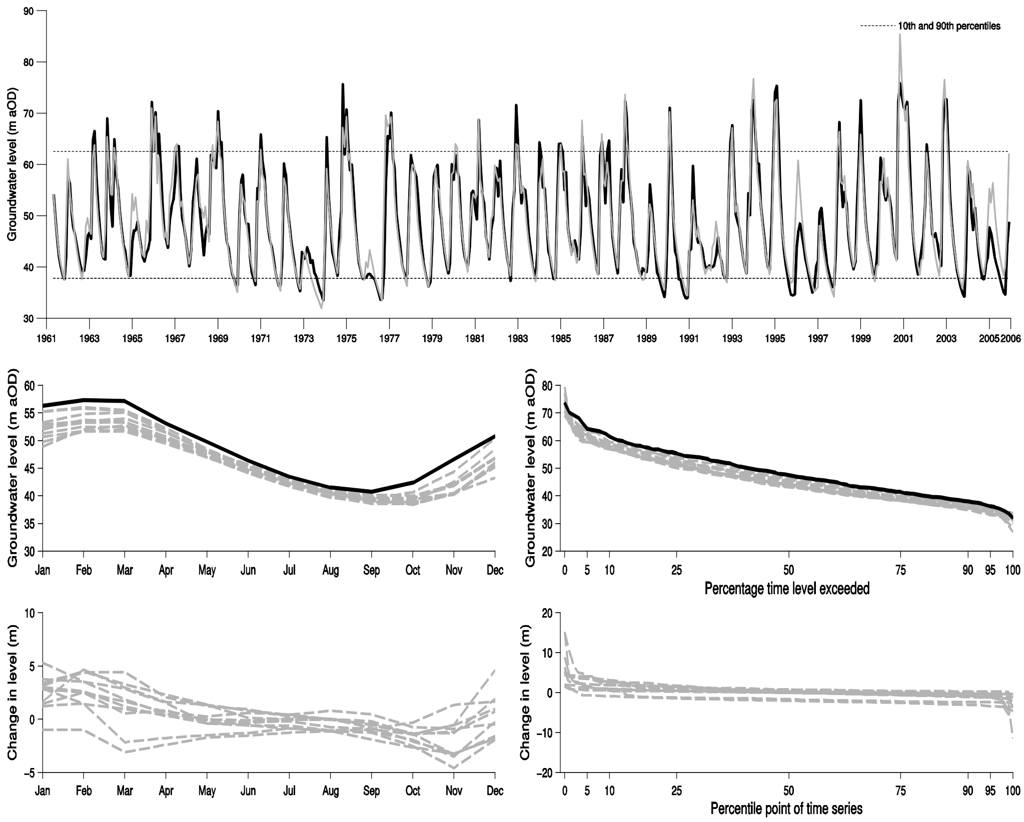

Fig. 3 Assessment of the ground water R-Groundwater modelling performance at Chilgrove House for simulations from observed climate (black) and FFC (grey dashed) compared with gauged levels (grey solid): (a) monthly levels; (b) differences (m) between levels simulated from observed climate and FFC for 1961–2005; (c) changes in mean monthly levels (left) and level duration curves (right) between future (2040–2069) and control (1961–1990).

As a result they contain some uncertainty which will limit their use. Some of the main limitations are given here with some practical recommendations for use.

(i) FFC and FFH are based on HadRM3-PPE experiment under the A1B SRES emission scenarios and hence do not include uncertainty due to emissions scenarios;

(ii) The downscaling and bias correction procedures applied are not physically based and FFC will still contain some discrepancies compared to "real climate";

(iii) All members of FFC and FFH are equally likely plausible realisations of the climate over the 1950–2098 period. They should capture the natural temporal and spatial variability expected in the climate, but do not reproduce historical weather sequences;

(iv) Over the pre-2000 reference period, FFH shows largest differences (but no systematic bias) during dry conditions and in drier regions for surface flow, and an underestimation of groundwater levels; no systematic difference in modelling performance can be attributed to any of the surface and groundwater models. It is not recommended to compare FFH time series directly with observations, or use FFH time series directly in an impact model prior to checking the extent of differences;

(v) The signal of change in FFH is independent of surface and groundwater model structure. The national database of FFH can be compared even if the sites' time series are simulated with different models; and

(vi) FFH contains 11 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 11 members are considered together rather than a subset of the ensemble.

ACCESS

The Future Flows Climate dataset is associated with a digital object identifier doi:10.5285/-bad1514f-119e-44a4-8e1e-442735bb9797. This must be referenced fully for every use of the FFC data as: Prudhomme C., Dadson S., Morris D., Williamson J., Goodsell G., Crooks, S., Boelee L., Davies H., Buys G., and Lafon T.: "Future Flows Climate", doi:10.5285/bad1514f-119e-44a4-8e1e-442735bb9797, 2012. All FFC files are available through the CEH Environmental Informatics Data Centre Gateway under special licensing conditions (https://gateway.ceh.ac.uk/). 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 FFH 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., Prudhomme C., 2012, 'Future Flows Hydrology', http://dx.doi.org/10.5285/f3723162-4fed-4d9d-92c6-dd17412fa37b. All FFH files are available through the CEH Environmental Informatics Data Centre Gateway under special licensing conditions (https://gateway.ceh.ac.uk/) and 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.

CONDITIONS OF USE

FFC and FFH are 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 to a fee to be agreed with NERC CEH and NERC BGS licensing teams, owners of the IPR of the datasets and products.

Acknowledgements FFC and FFH were generated under the partnership project 'Future Flows and Groundwater Levels, SC090016' jointly funded by the Environment Agency of England and Wales, the UK Department for Environment, Food and Rural Affairs, the UK Water Industry Research, the Natural Environment Research Centre (CEH and BGS) and Wallingford HydroSolutions. They are all gratefully acknowledged. Jackson, Barkwith, Mackay and Wang publish with the permission of the Executive Director of the British Geological Survey.

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