Products and datasets

Science Report/Project Note – SC090016/PN8

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Executive summary

The project 'Future Flows and Groundwater Levels' was set-up to provide datasets and products facilitating the assessment of climate change impact on a range of water-related issues across Great Britain within a nationally consistent framework.

Based on the ensemble runs from the Hadley Centre regional climate model HadRM3-PPE, underpinning the UKCP09 scenarios, the following datasets and products have been generated:

- **Future Flows Climate (FF-HadRM3-PPE)**: 11-member ensemble of 1-km gridded climate time series (available precipitation and potential evapotranspiration) derived for Great Britain from the HadRM3-PPE, the MetOffice Hadley Centre's Regional Climate Model ensemble output underlying the UKCP09 products;
- **Future Flows Hydrology (FF-HydMod-CatID)**: 11-member ensemble of daily river flow and monthly groundwater level time series for 282 river sites and 24 boreholes derived from Future Flows Climate using specific hydrological/groundwater level models (HydMod);
- 11-member ensemble of precipitation and potential evapotranspiration daily catchment average time series for 282 river sites and 24 boreholes derived from Future Flows Climate;
- National maps (or 'snap shots') of changes in river flow statistics (including mean monthly flows and low flow statistics) for most large rivers of Great Britain;
- Regional maps (or 'snap shots') of changes in groundwater level and river flow statistics for one region;
- Briefing notes for decision-makers on how to use these results.

All those datasets and products are made available through dedicated web pages. Their use is restricted under a licensing condition agreement. Non-commercial use is free; commercial use might be possible conditioned to a fee to be agreed with CEH or BGS licensing team, owner of the IPR of the datasets and products.

This report briefly explains the content of each dataset and product and how to access them.

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Section I Background

I. 1 Future flows and groundwater levels project

Climate change will increase temperatures and change rainfall across England, Wales and Scotland. In turn, this will 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, but coverage is uneven and methods vary. This means that it is very difficult to compare between different locations, which means that it is hard to identify appropriate adaptation responses.

The project 'Future flows and groundwater levels' aimed to develop two main products:

- national maps (or 'snap shots') of changes in river flow statistics (including mean monthly flows and low flow statistics) for most large rivers of Great Britain;
- daily time series of flows from 1951 to 2098 at 282 river sites and 40 boreholes across Great Britain so that the range of possible changes in both river flow and groundwater levels in the next 100 years can be examined.

These two products provide complementary assessment of the possible impact of climate on river flows in Great Britain, and the transient river flows and groundwater levels do:

- enable to investigate the evolution of the time series over time without having to interpolate linearly between fixed time periods;
- provide multiple realisations of historic climate and flows, hence allowing a better understanding of climate variability and its impact.

I. 2 Data sets

At the end of the project, the transient daily time series and the datasets necessary for their calculations were made accessible to the whole research community so that further impact analyses can be made on a range of specific areas such as fishery, freshwater ecology, water availability etc… The length (around 150 years) 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, for the first time possible at such a scale in the UK thanks to a strict methodological framework which ensures consistency, and hence comparability, of all generated data.

Specifically, the following datasets and products are made available:

- **Future Flows Climate (FF-HadRM3-PPE)**: 11-member ensemble of 1-km gridded climate time series (available precipitation and potential evapotranspiration) derived for Great Britain from the HadRM3-PPE, the MetOffice Hadley Centre's Regional Climate Model ensemble output underlying the UKCP09 products;
- **Future Flows Hydrology (FF-HydMod-CatID)**: 11-member ensemble of daily river flow and monthly groundwater levels time series for 282 river sites and 24 boreholes derived from Future Flows Climate using specific hydrological/groundwater level models (HydMod);
- 11-member ensemble of precipitation and potential evapotranspiration daily catchment average time series for 282 river sites and 24 boreholes derived from Future Flows Climate;

- National maps (or ‘snap shots’) of changes in river flow statistics (including mean monthly flows and low flow statistics) for most large rivers of Great Britain;
- Regional maps (or ‘snap shots’) of changes in groundwater level and river flow statistics for one region;
- Briefing notes for decision-makers on how to use these results.

I. 3 Conditions of use

All the products will be made available via dedicated websites under licensing condition agreement. For non-commercial use, the products will be available free of charge. For commercial use, the data might be made available conditioned to a fee to be agreed with CEH licensing team, owner of the IPR of the datasets and products.

The license terms and conditions will have to be agreed prior to the time of data download. It can be found at the CEH Gateway, National River Flow Archive and British Geological Survey websites.

Section II Future Flows Climate: Ensemble gridded climate time series

II. 1 Background

The HadRM3-PPE time series are provided at a 25-km grid spatial resolution and daily time temporal resolution. However, brief analyses of precipitation and temperature time series for the historical (pre-2000) period showed systematic differences with observations. This is a common feature in regional climate model outputs, mainly because their coarse spatial resolution does not allow for the small scale (temporal and spatial) atmospheric processes to be adequately reproduced. Because this can have an implication when used to model river flow and groundwater levels, the HadRM3-PPE daily outputs were modified using a statistical technique so that their statistical properties match that of the observations, for the same periods. In addition, a spatial downscaling was applied, to incorporate the spatial heterogeneity observed in precipitation within each 25-km grid square.

II. 2 Description of Future Flows Climate

Future Flows Climate is the ensemble gridded climate data of the Future Flow and Groundwater Level project; its acronym is FF-HadRM3-PPE. It covers England, Wales and Scotland. The dataset has been developed within the project using a consistent approach nationally, hence enabling comparison of results across a range of scales and geographical regions.

Future Flows Climate is derived from the eleven members of HadRM3-PPE ensemble simulations of the climate, based on the SRES emission scenarios A1B. The downscaling and bias correction procedures applied to the HadRM3-PPE were considered necessary to provide a product that is appropriate for hydrological and groundwater level simulations. However, the techniques used are not physically-based, and Future Flows Climate will still contain some discrepancies compared to ‘real climate’.

Future Flows Climate time series range from 1951 to 2098 and are provided at a 1-km grid resolution, which is a resolution necessary for most hydrological applications. They consist in 11 different plausible realisation of the climate over this period under the A1B emission scenario. This means that they are designed to capture the natural temporal and spatial variability expected in the climate as well as possible, but they do not reproduce historical weather sequences. In other words, none of the Future Flows Climate time series of precipitation or temperature are expected to provide, for the period 1975-1976, the same weather sequence as observed in 1975-1976. However, within the longer period of 1951-2000, it is expected the main day-to-day patterns characteristic of the climate of Great Britain resemble that observed in any point. For example, it is expected that short duration intense precipitation patterns (characteristics of a convective system) are generated for grids in southern regions, while precipitation events of long duration but relatively small daily intensity (typical of frontal systems) are generated for areas in the west of the country.

The dataset is provided as NetCDF files, which is a standard format used for large gridded time series.

II. 2. 1. Temperature

HadRM3-PPE daily temperature time series were spatial downscaled and bias-corrected based on a 5-km daily temperature time series (the UKCP09 gridded observation data sets, (Perry et al., 2009)). A linear transfer function was applied to the HadRM3-PPE temperature time series at the 5-km resolution of the observation.

This time series is an intermediate product not directly used in the modelling of transient river flow and groundwater levels time series. It is not made publically available.

II. 2. 2. **Available precipitation**

With temperature rising, the partition of precipitation between rainfall and snowfall in snow-influenced regions (such as for example Scotland and some parts of northern England and Wales) is likely to differ from that observed historically. However, the role of precipitation in the hydrological processes and runoff generation is very different when it falls as rain or as snow, because water contained in snow (and ice or snow-pack) is locked for a certain period and thus not available for any of the hydrological processes during this period, and in particular for runoff generation. With a warming of the climate, snow-driven delay is likely to play a smaller role, potentially modifying river flow seasonal pattern.

Spatial downscaling and bias correction was first performed on HadRM3-PPE precipitation time series. The procedure uses a 25-km average observed daily precipitation matching the resolution of HadRM3-PPE aggregated from the 1-km daily observed precipitation time series (Keller, Young et al. 2006) to establish a transfer function for each month and each 25-km grid of the averaged observational data; the transfer function aims to minimise the difference between the observed and simulated daily pattern at that grid. When applied to the HadRM3-PPE daily time series, this transfer function generates a new 25-km bias-corrected gridded daily time series where most of the statistical properties (and in particular the first three moments of daily rainfall) are similar to the observed for the same historical period. The time series is then further downscaled at a 1-km based on the observed annual precipitation variability within each grid, so that the sub-grid orographic effect can be included within the generated 1-km time series;

Snow-melt processes are accounted for by using a simple elevation-dependant snow-melt model (Bell and Moore 1999) to estimate when water is available for runoff. The 1-km bias-corrected and downscaled 11 precipitation daily time series are transformed in 1-km ‘available precipitation’ (APr) time series using this method, and using the bias-corrected temperature time series. The available precipitation time series are used as input of all the models used to generate the transient daily river flow and groundwater levels products.

Because of the volume of data describing FF-HadRM3-PPE-APr, the time series were saved in different netCDF files to increase the speed of download, copy, reading and manipulations. APr datasets (corresponding to the total daily available precipitation expressed in mm) from each 11 ensemble member are saved separately and for 30-year period. File names contain the name of the ensemble member consistently with the Hadley Centre’s notations and the time period. A total of 11*5 = 55 files describe the entire APr dataset, of 18.5Gb each. The entire time series period ranges from 1950 to 2098.

II. 2. 3. **Potential Evapotranspiration**

Evapotranspiration is an important element of the hydrological processes as it represents the main loss of water from precipitation to runoff. In hydrological and hydrogeological models, potential evapotranspiration is used as input to generate river flow and groundwater levels.

To insure as much consistency as possible within the project, potential evapotranspiration at 5-km resolution was generated using HadRM3-PPE climate time series, based on the FAO-56 Penman Montieth method at a monthly time scale (Allen, Pereira et al. 1998). For temperature the downscaled and bias-corrected time series downscaled are used instead of the HadRM3-PPE temperature as they are a more realistic representation of temperature. The FF-HadRM3-PPE-PE files are at a 1-km resolution for consistency with the APr time series spatial resolution.

Because of the volume of data describing FF-HadRM3-PPE-PE, the time series were saved in different netCDF files to increase the speed of download, copy, reading and manipulations. PE datasets (corresponding to the total monthly expressed in mm) from each 11 ensemble member are saved separately and for 30-year period. File names contain the name of the ensemble member consistently with the Hadley Centre's notations and the time period. A total of 11*5 = 55 files describe the entire PE dataset, of 1.25 Gb each. The entire time series period ranges from 1950 to 2098.

II. 3 Access and acknowledgement

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 Future Flows Climate data as:

Prudhomme C., Dadson S., Morris D., Williamson J., Goodsell G., Crooks, S., Boelee L., Davies H., Buys G., Lafon T., 2012, 'Future Flows Climate', http://dx.doi.org/10.5285/bad1514f-119e-44a4-8e1e-442735bb9797

Future Flows Climate sets of files (55 for APr, 55 for PE) 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).

Section III Ensemble catchment average climate time series

III. 1 Background

The hydrological and groundwater level models are conceptual representations of the hydrological processes within a catchment. Two types of models have been used: lumped models, which consider the catchment as a unique entity; and (semi-)distributed models, which consider the catchment as a set of different entities. In both cases, the spatial resolution at which the processes are modelled is usually coarser than 1-km. As the models need input data at the same resolution they work at (i.e. the whole catchment, or a part of the catchment), average time series at that resolution need to be calculated.

For each 282 river sites and 24 boreholes modelled in the project, APr and PE average time series are used as input of the hydrological and groundwater level models. These time series are made available when a lumped model is used so that users can undertake their own modelling on those catchments. This could help to explore, for example, uncertainty in hydrological and groundwater modelling in the context of climatic change. For catchments modelled using a gridded model, no climate time series is provided as they are specific to the model used. However, relevant information can be extracted from the Future Flows Climate data.

III. 2 Description

III. 2. 1. Catchments simulated by PDM, CERF or BGS lumped groundwater models

PDM, CERF and BGS lumped groundwater model consider the catchment as a whole, and require input data averaged over the whole catchment: FF-HadRM3-CatID.

For a given catchment, this consists of an ensemble of 11 time series (each associated with a different ensemble member); for each day, the time series are calculated as the arithmetic average of Future Flows Climate of that day for all grid cells contained within the catchment boundary.

The datasets are provided as two .csv files, one file for APr and one file for PE, each containing catchment average time series for the 11 ensemble members. They range from 1951 to 2098.

III. 2. 2. Catchments simulated by CLASSIC and ZOOM models

CLASSIC and ZOOM are (semi-)distributed models which consider the catchment as a set of different homogeneous areas; for both models, the areas are grid-squares; the size of the grid-squares depend on the catchment and on the model. These models hence require input data averaged over each of the grids describing the catchment, very specific to the model used, and corresponding to a very large amount of gridded data. For those reasons no climate dataset is provided; however, relevant climate information for the catchments can be extracted by the user directly from Future Flows Climate at the resolution required.

III. 3 Access

The catchment climate average time series time series are only available for the study catchments modelled using a lumped model and at the resolution of the hydrological or

groundwater level model. They are accessible through the Future Flows and Groundwater Levels pages of the National River Flow Archive (http://www.ceh.ac.uk/data/nrfa/index.html) and the British Geology Survey (www.bgs.ac.uk) webpages under special licensing conditions.

Section IV Future Flows Hydrology: ensemble river flow and groundwater levels time series

IV. 1 Description of Future Flows Hydrology

Future Flows Hydrology is an ensemble of daily river flow and monthly groundwater level time series simulations based on Future Flows Climate data; its acronym is FF-HydMod-CatID. These time series are available for 282 river sites and 40 boreholes and range from 1951 to 2098 (to allow for a warming period of the hydrological models).

For each study site, Future Flows Hydrology consists of an ensemble of 11 time series (each associated with a different ensemble member).

The datasets are provided, for each site, as one .csv containing simulated time series for each 11 ensemble member. Where two hydrological models were used to simulate river flow at the same site, two files are produced.

IV. 2 Access and acknowledgement

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., Prudhomme C., 2012, 'Future Flows Hydrology', http://dx.doi.org/10.5285/f3723162-4fed-4d9d-92c6-dd17412fa37b

Future Flows Hydrology time series are only available for the study catchments. They are accessible through the CEH Gateway (https://gateway.ceh.ac.uk/), the Future Flows and Groundwater Levels pages of the National River Flow Archive (http://www.ceh.ac.uk/data/nrfa/index.html) and the British Geology Survey (www.bgs.ac.uk) webpages under special licensing conditions.

Section V National maps of changes in river flow statistics

V. 1 Description

This product consists of 11 sets of river network maps for Great Britain corresponding to scenarios of changes in river flow statistics by the 2050 for each of the 11 members of the Future Flows Climate projections. Each set consists of mapped changes in mean flow, monthly mean flow for each month of the year and the flows corresponding to the Q95, Q70 and Q10 flow exceedence percentiles.

The river maps have been derived by the application of the CERF generalised rainfall runoff models to over 1,000 catchments across Great Britain with the incremental catchment area between modelled points in the network being in the order of 200km^2 or less. The maps present scenarios of changes in river flow statistics by the 2050s design horizon. These were derived using a change factor methodology, where monthly changes between 2040-2069 and 1961-1990 where calculated for each of the Future Flows Climate ensemble members for precipitation and potential evapotranspiration; the observed historical rainfall and potential evapotranspiration time series where then scaled according to these change factors, and CERF run using these 11 possible realisations of the 2050s future climate. Each river flow indicator (monthly flow and exceedence percentiles) obtained with each of the 11 runs where then compared with those obtained when river flow was simulated using the observed historical rainfall and potential evapotranspiration time series (also called baseline).

The catchment level changes in the flow statistics were then assigned to the river reaches that occur uniquely within each catchment.

V. 2 Access

Maps of changes in river flow indicators for Great Britain derived from HadRM3-PPE-CERF are available through the Future Flows and Groundwater Levels as .png files for each of the flow statistics (http://www.ceh.ac.uk/sci_programmes/Water/Future%20Flows/FFRiverFlowChanges-2050s.html).

Section VI Regional maps of changes in groundwater level and river flow statistics

VI. 1 Background

The regional groundwater model of the Chalk aquifer of the Marlborough and Berkshire Downs and south-west Chilterns (MABSWEC) has been used to simulate changes in groundwater levels across this regional Chalk aquifer system. Gridded data are provided for changes in mean March, June, September and December levels for each 11 Future Flows Climate projections and for six 30-year time-slices during the 21st century.

VI. 2 Description

This product consists of set of ASCII grids (asc files) of changes in mean monthly groundwater level for each of the 11 Future Flows Climate projections. Changes from the baseline (1961-1990) are calculated for March, June, September and December for the following six 30-year time-slices:

- 2030s (2021-2050)
- 2040s (2031-2060)
- 2050s (2041-2070)
- 2060s (2051-2080)
- 2070s (2061-2090)
- 2080s (2071-2098)

The data set therefore consists of 264 .asc files (11 RCMs $\times$ 4 months $\times$ 6 time-slices)

VI. 3 Access

Maps of changes in groundwater level across the MABSWEC region derived from HadRM3-PPE-MABSWEC are available through the British Geology Survey website website as .png files for each of the statistics.

Gridded values of changes in groundwater level across the MABSWEC region, based on the FF-HadRM3-PPE climate projections, are available through the Future Flows and Groundwater Levels website as ASCII grid (.asc) files (http://www.bgs.ac.uk/research/groundwater/change/FutureFlows/regionalModel.html).

Section VII Briefing notes

VII. 1 Description

Briefing notes will be prepared to ease the interpretation and use of the products. They are designed for scientists, water managers and policy makers, and written for a non-scientific readership. They provide brief over-view of methodology, advice on interpretation of results, and recommendation for use of the datasets and products.

VII. 2 Access

Briefing notes will be provided with each of the data sets in zipped packages. They will also be made available through the project website http://www.ceh.ac.uk/sci_programmes/Water/Future%20Flows/FFGWLReportsandPublications.html.

Section VIII References

Allen, R. G., L. S. Pereira, et al. (1998). FAO irrigation and drainage paper 56 - Crop evapotranspiration - Guidelines for computing crop water requirements. Rome, Food and Agriculture Organisation of the United Nations**:** 300.

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