Scenarios of future water availability in the UK

Simpson, J.M. [1,2], Ives, M.C.[1]

1. University of Oxford, Environmental Change Institute 2. Centre for Ecology & Hydrology

Background

As part of its work on the National Infrastructure Assessment (NIA) the National Infrastructure Commission (NIC) has been developing scenarios to help understand how the UK's future infrastructure requirements could change in response to different scenarios or drivers of future change. These scenarios are based on available empirical evidence about past trends, and on quantitative and qualitative forecasts of changes in the economy, population and demography, climate, and technology. Quantitative modelling of 'baseline' outcomes in these scenarios, and of packages of policy proposals in the most relevant scenarios, will allow an assessment of the robustness of policy options to future uncertainty.

The scenarios are assessed using the national infrastructure system model (NISMOD), which was developed by the UK Infrastructure Transitions Research Consortium (ITRC), as well as models used by Government departments for the water, waste, transport, and energy sectors.

The results from the scenario analyses are intended to provide evidence on the potential challenges for each of the infrastructure sectors (energy, transport, water and waste) through identifying the likely scale of future infrastructure demands and to support the development of infrastructure recommendations that are robust to future uncertainty.

In the case of water supply, the principal sources of future change in the UK are anticipated to be socio-economic growth, climate change, and increasing environmental restrictions. Climate change is projected to alter the distribution of rainfall and evaporation (Prudhomme et al., 2012b), which will alter the available quantities of water for public supply (Prudhomme et al., 2013, Arnell, 2004, Hannaford and Buys, 2012). For instance, the Department for Environment, Food and Rural Affairs (Defra), in their UK Climate Change Risk Assessment anticipates a decline of 10% to 45% in deployable output of water by 2050 under a medium emissions scenario (Defra, 2012).

The impact of climate change on environmental water quantity in Great Britain has been studied extensively (Arnell et al., 2015). Recent work by Prudhomme et al. (2013), resulting in the Future Flows Hydrology dataset, produced 11 scenarios for river time series from 1951 to 2098 for 282 sites across the UK. Future Flows Hydrology (FFH) has since become an accepted methodology for climate change impact assessments conducted by water companies (Environment Agency et al., 2012). As with earlier projections of climate change, the anticipated spread of future hydrological conditions projected by the FFH scenarios is broad (Prudhomme et al., 2013) and attaching probability to each scenario is not straightforward (Rougier, 2007, Brown and Wilby, 2012).

As part of the ITRC's analysis of the UK's future infrastructure requirements a process was developed for applying the 11 Future Flow Hydrology (FFH) scenarios to the NISMOD water model (also known as GBWIM) (Hall et al., 2016). This methodology is described below along with the extension of this same methodology to the development of an additional 22 scenarios based on the new low and high emissions Future Flow scenarios produced by HR Wallingford.

The additional CCRA2 low and high emissions scenarios

In 2015, HR Wallingford released their "CCRA2: Updated projections for water availability in the UK"[1]. As part of the 2nd Climate Change Risk Assessment project (CCRA2), HR Wallingford provided new FFH datasets for the low and high global emissions outputs of the Hadley Centre Global Circulation Model (GCM). To incorporate these new FFH scenarios into their modelling for the NIA, the NIC requested that the same methodology that was used to produce the original 11 climate scenarios for NISMOD be used to incorporate these additional 22 scenarios into NISMOD.

In the Surface water projections (2.3.1.) section of HR Wallingford (2015) it explains the approach used by HR Wallingford to generate the additional FFH scenarios. In short, the larger UKCP09 set of model runs that includes high and low global emissions scenarios were employed to generate a new set of future river flow projections called 09-Hydrology that "translate the existing FFH dataset to Low and High emissions scenarios". In the associated documentation HR Wallingford provide details of the Quantile-quantile mapping procedure employed to generate these additional datasets.

Essentially, HR Wallingford has supplied 22 additional hydrological datasets in a similar format to the original 11 FFH datasets. The original 11 FFH datasets are based on the medium emissions scenario of the HadCM3 model and represent 11 different stochastic outcomes of that medium emissions scenario. The 22 additional CCRA scenarios are versions of these original 11 FFH datasets that are adjusted to encapsulate the differences between the medium emission model outputs and the low and high emissions model outputs. They therefore capture a larger range of the uncertainty in the future water flows that may result from alternative emission levels. As higher emissions are expected to generally lead to lower rainfall in the UK a general rule is that the low and high emissions datasets should provide scenarios of higher and lower water availability, respectively, than the original median FFH datasets.

NISMOD-LP Baseline Water Supply Modelling

The ITRC, led by the University of Oxford, has developed a new system-of-systems modelling capability for analysis, design and planning of interdependent infrastructure systems at a national scale. Much of this research has been encoded into the National Infrastructure System Model (NISMOD) family of models. NISMOD-LP (NISMOD Long-term Performance) simulates the capacity of infrastructure systems (energy, transport, digital communications, water, and waste) and the changing demands for those services in a range of different future scenarios. The model is purposefully designed to test and optimise the performance of alternative investments and policies for infrastructure provision into the future. Each sector model is reasonably complex with each model also integrated and co-ordinated through a system-of-systems framework through linkages between the models introduced via cross-sectoral demand for services.

[1] HR WALLINGFORD 2015. CCRA2: Updated projections for water availability for the UK. Final Report. Wallingford, UK: HR Wallingford. https://www.theccc.org.uk/publication/climate-change-risk-assessment-ii-updated-projections-for-water-availability-for-the-uk/

The water supply model for NISMOD-LP (Simpson et al., 2016, Ives et al., 2017) is a high level national water resources model based on existing regional water resource management arrangements in Britain. The model tracks the water balance, and availability of water for supply, at the scale of Water Resource Zones (WRZ), aggregating estimates of surface and groundwater availability in each WRZ, and simulates the effect of investment in storage, transfer, reuse and desalination supply infrastructure, as well as changes in water use and leakage.

In order to assess future resources from a supply/demand perspective in the NISMOD-LP system, the baseline supply projections contained in any FFH dataset must be converted into supply quantities available for future abstraction under a range of strategies for investment in water supply infrastructure. These supply quantities or 'yields' are defined as the deployable outputs, or long term maximum water available for abstraction, within each WRZ.

Where groundwater is used for all or part of an abstraction, the current groundwater deployable output is used in all current and future scenarios of available groundwater yields Y_G. River and reservoir sources are modelled in more detail.

For each WRZ a representative river gauge from the FFH set was identified. Modelled time series and sub-catchment areas were accessed from the National River Flow Archive[2]. Using recent WRMPs, information from water company drought plans, internet research and interviews with water company staff, a database of water supply assets was developed. For WRZ with multiple river abstraction points, a composite representative river abstraction sub-catchment was created by summing the total non-nested abstraction sub-catchment areas, such that

$$A(r_I) = A\left(\bigcup_{i \in I} G(i)\right)$$

where $A(r)$ is the sub-catchment area of composite river abstraction r, based on the set of river abstractions I, with $G(i)$ being the geometry of the sub-catchment of river abstraction i. The ratio of this to the sub-catchment modelled in the Future Flows dataset was used as a multiplier for the modelled Future Flows time series,

$$Q(r_I) = \frac{A(r_I)}{A(o)} \times Q(o)$$

in which $Q(r_I)$ is the flow time series for the composite river set r_I, and $A(o)$ is the area of the sub-catchment for the representative modelled Future Flow time series $Q(o)$.

If a WRZ features river intakes or reservoir storage the total catchment sizes for each of these are also derived from a Digital Elevation Model (DEM) and flows are extrapolated on the basis of the ratio of catchment sizes to identify future scenarios of total flow passing river intakes and total flow available to reservoirs.

[2] http://www.ceh.ac.uk/data/nrfa/

Reservoir sub-catchments were derived using a digital terrain model acquired from EDINA Digimap DEM[3] at 50m horizontal resolution. Similar to the development of a representative abstraction for each WRZ, a representative reservoir was identified using the total reservoir capacity

$$C(R_J) = \sum_{j \in J} C(j)$$

where $C(R_J)$ is the storage of the composite reservoir R_J which represents the set of all reservoirs in the WRZ J, and the sum of the non-nested reservoir sub-catchment areas,

$$A(R_J) = A\left(\bigcup_{j \in J} G(j)\right)$$

giving the flow time series for a composite reservoir as

$$Q(R_J) = \frac{A(R_J)}{A(o)} \times Q(o)$$

with sub-catchments again using information on modelled flows under climate change to represent reservoir inflows. Where reservoirs are offline, reservoir intake sub-catchment areas are included in the total of WRZ reservoir sub-catchment areas.

Acceptable return periods of future shortage are identified from the drought plan for each WRZ outlined in the WRMP, which is then used to identify the maximum yield from each WRZ which will not violate these rules. During shortages, per capita demand is assumed to be reduced by a percentage based on estimates in WRMPs, allowing us to calculate the maximum amount of deployable output that can be abstracted without incurring a breach of level 1, level of service restrictions (which equates to around a 1 in 10 year drought). River abstraction yields are thus determined with consideration given to licenced minimum residual flows and maximum abstractions. The initial value for river yield Y_r is set as

$$Y_r = P(Q_r - m_r, l_r)$$

in which m_r is the minimum residual flow and l_r is the licenced maximum abstraction for river r. P is a function relating to the desired return period of the yield. This is used in a similar capacity to 'dry year' terms in water planning, except in this case the return period of the dry condition is set in line with the return period of the minimum acceptable period p set out in the water company drought plan for the shortest return period drought event. Here, $P(Q)$ is based on the series of annual minima $(q_1, q_2, q_3, \dots, q_n)$ of the time series Q; $P(Q)$ is the $\frac{n}{p}$th smallest value of this series.

A similar equation is used to identify licenced reservoir input abstractions, which can be represented as

[3] http://digimap.edina.ac.uk/

$$Q_{in,R} = \min(Q_R - m_R, l_R)$$

Here, $Q_{in,R}$ is used as a vector input to the reservoir storage. Due to the filtering effect of reservoir storage, reservoir yields are calculated using an iterative numerical approach. Stored water S in the composite reservoir at time t is calculated as

$$S_t = \begin{cases} C_R, & if\ S_{t-1} + Q_{in,R} - Y_R > C_R; \\ 0, & if\ S_{t-1} + Q_{in,R} - Y_R < 0\ ; \\ S_{t-1} + Q_{in,R} - Y_R, & otherwise \end{cases}$$

At the first time step $(t = 1)$ the reservoir storage is set to equal to the current reservoir capacity as a starting point. The yield for the composite reservoir, Y_R, is then identified iteratively as presented in Figure 1.

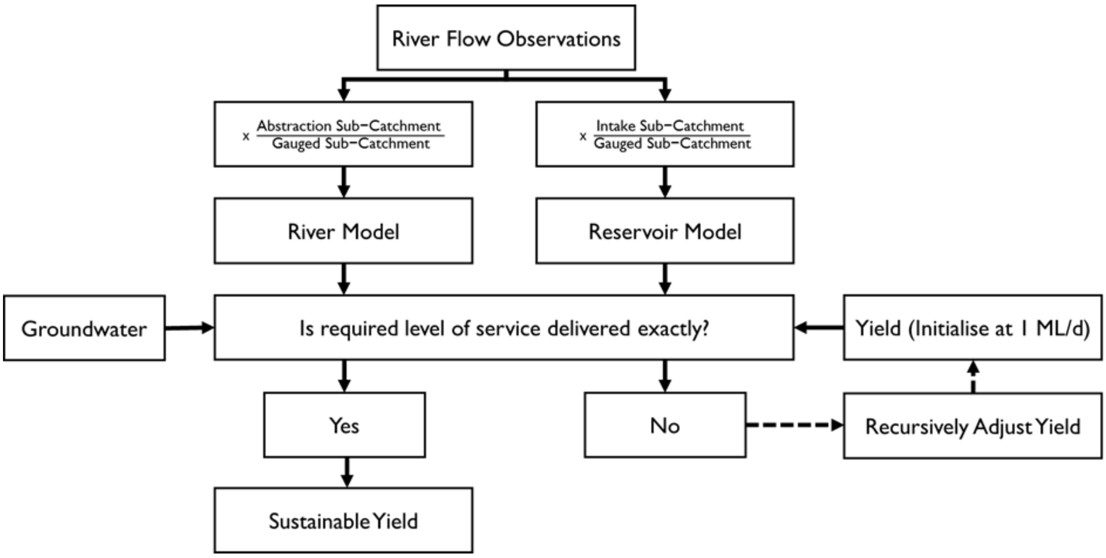

Figure 1: A stylised representation of the logic used to convert the river flows from the 11 Future Flow climate scenario data sets to sustainable yields for each WRZ

Values for monthly minimum acceptable storages are identified for the composite reservoir from those given for the largest reservoir in the WRZ of the water company's drought plan. These are scaled proportionally to the capacity of the composite reservoir. In line with the drought plans, the water system can be considered to have failed if these minima are exceeded on average more regularly than the return period. Violations of these thresholds are considered on an annual basis, so more than one violation per year is considered a single violation in that year. The maximum acceptable value for Y_R is identified as the maximum value of Y_R which does not fail this criterion. As the relationship between Y_R and S is monotonic, Y_R is increased from 1 megalitre per day (MLD) by 1 MLD per iteration until failure is observed.

Total possible yield from a WRZ is then identified as

$$Y = Y_G + Y_r + Y_R + Y_{misc}$$

where Y_{misc} represents alternative sources such as desalination and spring supplies currently in use.

A simple form of transient yield under climate change is provided by dividing Future Flows Hydrology series into three sections (1951-2014, 2015-2049 and 2050-2098), using these to identify available water for the central year in each case and interpolating linearly between these points, as set out by Prudhomme et al. (2012a). Thus, for each WRZ, eleven time series of available supply, indicative of plausible climate change futures, are identified at each annual time step of the model run. The hydrology and water supply module receives information on river flows within the WRZ from the Future Flows Hydrology dataset and provides 11 scenarios of river flows from 1960 to 2100 at a single point within the WRZ. The additional 11 low and 11 high emission scenarios are produced using the method but applied to the alternative low and high FFH datasets supplied by the CCRA2 project.

The likelihood of the Low emissions scenarios

One point of note regarding the 22 new emission scenarios is that although it is difficult to assign a probability to each scenario within a single FFH dataset (Rougier, 2007, Brown and Wilby, 2012) this is not necessarily the case regarding the 3 collections of 11 datasets. In particular, we argue here that the low emissions scenarios are inherently less likely than the medium and high scenarios.

The FFH "low emissions" scenarios are based on the IPCC B1 storyline[4] which produces the lowest cumulative emissions (as shown in Figure 4 of (IPCC, 2000)) and which results in the lowest representative concentration pathway - RCP2.6. The RCP2.6 emission and concentration pathway is a representative of mitigation scenarios aiming to limit the increase of global mean temperature to 2°C (van Vuuren et al., 2011). Krey & Riahi (2009) discuss whether we can assign a probability to the possibility of global temperatures staying below a 2°C global mean temperature increase. The problem with assigning probabilities to such scenarios is that you have two key sources of uncertainty, (1) the GCM models and their ability to correctly predict the impact of GHG emissions on 'radiative forcings' i.e. global temperatures (see (Meinshausen et al., 2009)); and (2) what the human race does to limit GHG emissions over this century. Most research has more to say about the former, but each of the IPCC "Representative Concentration Pathways (RCPs)"[5] also includes important assumptions (storylines) about the latter.

In the storyline associated with B1 they assume a lot of profound changes in the global economy that result in global annual GHG emissions peaking sometime between 2010 and 2020, with emissions declining substantially thereafter. The B1 storyline was developed over fifteen years ago and despite the recent Paris Agreement, unfortunately, not much has happened in terms of changes to the global economy on the ground that will limit emissions. There has been some progress – the UK is doing better than most countries – but it's not happening globally on the scale required by B1. As promulgated in the abstract to Krey (2009) "whether or not such low targets can be achieved in the long-term depends on a number of assumptions about, for instance, technological change and the willingness of countries to immediately join a post-Kyoto agreement to limit anthropogenic climate change."

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[4] http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=94

[5] https://en.wikipedia.org/wiki/Representative_Concentration_Pathways

In short, achieving the RCP2.6 pathway now will require huge changes in infrastructure systems in the current decade, in energy systems in particular (including decommissioning perfectly functioning fossil fuel power stations), which is becoming increasingly unlikely given that it is now 2017 and no such solutions are being suggested.

Many of the current optimistic scenarios that eventually keep global average temperature rise below 2°C predict an "overshoot" (Rogelj et al., 2015), which means that we likely exceed this target but then manage to eventually reduce the GHGs in the atmosphere ("negative emissions") by capturing and storing more than we release. To this effect all of the RCP2.6 models assume large amounts of bio-energy with carbon capture and storage (BECCS) as a proxy for such low carbon and negative emissions energy production. Unfortunately, according to Smith and Torn (Smith and Torn, 2013), BECCS have serious problems to overcome as a solution if it is to be done at scale – including limits on land use, nitrogen requirements and impacts on global food systems. Alternative negative emissions technologies are available, such as direct air capture, however these alternatives are considered more expensive than BECCS (Fuss et al., 2013, Kriegler et al., 2013).

As pointed out in Krey (2009) the "second-best scenarios" which involve the Chinese government and Brazil dragging their feet, so-to-speak, on emissions reductions will not limit emissions below the 2°C target. These second-best scenarios could be considered more likely in the light of China's pledge to peak its emissions by 2030, and the pledges from the Nationally Determined Contributions (NDCs) of all the countries that have ratified the Paris Agreement, amounting to changes that are not expected to meet the 2 degrees target – more likely 3.2 degrees (Yann Robiou du et al., 2016). Furthermore, the U.S. which is still the biggest emitter of GHG in the world, has taken a new direction under the Trump administration with recent cuts to virtually all Federal funding for climate change research and pledges to increase employment in coal and other fossil fuel producing industries.

Additional sources of future flow uncertainty

One final point worth considering is that the low and high scenarios of the Hadley model (HadCM3) are not the only possible source of climate change uncertainty. There are more GCM models outputs than those produced by Hadley. The Brazilians, for instance, have used the Hadley Center Global Environment Model version 2 (HadGEM2-ES) and Model for Interdisciplinary Research On Climate version 5 (MIROC5) to generate their future climate change scenarios (Almagro et al., 2017) in order to capture the model structure uncertainty represented by the different GCM models. The Hadley model would be the best for UK (as it is calibrated more specifically for the UK/EU area) but it is not unreasonable to argue that other GCM models could also be used to provide different estimated flows for the UK and thus alternative representations of possible futures. The IPCC generally provide the results from the entire ensemble of these GCMs in their analyses, which produces a much larger band of uncertainty than any single model.

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