METEOROLOGICAL APPLICATIONS
Meteorol. Appl. **21**: 129–140 (2014)
Published online 19 June 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/met.1335

Review

The use of probabilistic weather generator information for climate change adaptation in the UK water sector

C. N. P. Harris,* A. D. Quinn and J. Bridgeman
School of Civil Engineering, University of Birmingham, UK

ABSTRACT: Adapting to climate change in the water sector requires abandoning two crucial assumptions. First, that the climate represented in the instrumental record is representative of the future. Instead, future water resource planning cannot be based on old measurements (or sequences derived from attaching change factors to instrumental data) and it should be recognized that stationarity is no longer viable, and, second, that climate modelling can be expected to give precise and certain predictions of the future. Instead, probabilistic projections of the future that take into account the full range of uncertainty should form the basis of robust climate change adaptation plans.

As a response to the first assumption, it is suggested that stochastic weather generators represent a particularly useful approach to understanding the impacts of future climate change on water resources at a catchment scale, particularly given the recent release of 'science-hidden' tools such as the UKCP09 weather generator. With regards to the second assumption, it is suggested that modelling activity should identify the range of plausible futures to develop probabilities of risk, using those robust decision-making techniques which can gauge the performance of potential adaptation strategies.

The best practice for delivering a replicable and practical hydroclimatological impact assessment for UK water resources at a catchment scale is identified, and an hypothetical example is outlined. It is suggested that although augmenting the resilience of water resources to climate change on a catchment scale is dependent on using the correct modelling tools, the robustness of the method with which that information is used to make adaptation decisions is equally as important.

KEY WORDS statistical downscaling; risk; resilience; water resources; probabilistic decision making; hydroclimatology; uncertainty; water supply and demand

Received 12 September 2011; Revised 6 April 2012; Accepted 30 April 2012

1. Introduction

The need for an overview of the use of stochastic weather generators (hereafter referred to as WGs) for hydroclimatological purposes comes about as a result of recent models displaying increased user-friendliness and 'science-hidden' interfaces (Fowler *et al*., 2007), as well as governmental legislation requiring the assessment of climate change adaptation options leading to an broadened take-up in the water industry. Frequently-used examples of such WGs are the Environment Agency Rainfall and Weather Impacts Generator (EARWIG – Kilsby *et al*., 2007) and the UK Climate Projections 2009 WG (UKCP09WG – Jones *et al*., 2009).

The aims of the present paper are to: (1) review the use of stochastic WGs as a tool for downscaling global climate model (GCM) information for hydroclimatological impacts, with particular focus on the UK, and, (2) discuss how to work with uncertainty when using such tools for water resource management and climate change adaptation. The prose is unique from previous review papers in this area of research in that the focus is on how current WG technology can be used effectively, rather than technical progression (such as Maraun *et al*., 2010), or comparing the merits of different downscaling techniques (such as Fowler *et al*., 2007).

The first section sets the context in which hydroclimatological impact studies in the UK operate, with an overview of our current understanding of climate change impacts on the hydrological system and the resultant stressors on the UK water industry, as well as the need for adaptation. Section 3 is a review of the use of WGs for hydrological impact assessment purposes and the suitability to hydroclimatological studies of the WG approach compared to other downscaling techniques, and introduces a case study illustrating its advantages. Section 4 discusses key factors that must be taken into account when using WG information to assess hydroclimatological impacts and gives an hypothetical case-study illustrating best practice.

2. Climate change impacts on water resources and the need for adaptation tools in the water industry

2.1. Overview of projected hydroclimatological impacts

Within all of the uncertainty involved with climate science it is sometimes easy to forget the certainties; the relentless pursuit of energy by society has altered the composition of the atmosphere

* Correspondence to: C. N. P. Harris, School of Civil Engineering, University of Birmingham, Birmingham B15 2TT, UK.
E-mail: CNH014@bham.ac.uk

and oceans. The associated build-up of greenhouse gases in the lower atmosphere and acidification of the oceans is changing the hitherto relatively stable Earth system within which society has flourished. Temperatures are rising regionally and globally, and will continue to do so, but the regional effect of this change on precipitation is less understood and extremely varied from region to region (Howard *et al*., 2010).

This anthropogenic destabilization of the climate increases the vulnerability of freshwater resources across much of Earth, primarily as a result of societies, infrastructure and agriculture being exposed to climates they were not developed within, built or designed for (Gleick, 2011), with wide-ranging consequences for humanity and ecosystems (Bates *et al*., 2008; Vaze and Sanderson *et al*., 2011; Teng, 2011). There is an observed 7% increase in atmospheric water vapour *per* 1 °C of warming (Trenberth *et al*., 2007), resulting in a shift towards a greater proportion of precipitation falling as rainfall in intense events in the UK (>50 mm day^{-1}) (McGuffie *et al*., 1999; Fowler and Kilsby, 2004; Sun *et al*., 2007; Bates *et al*., 2008).

Trends seen in the UK instrumental dataset indicate an increase in hydrological seasonality, leading to warmer, wetter winters and hotter, drier summers, with greater rainfall intensity overall (Osborn and Maraun, 2008; von Christierson *et al*., 2011). Elevated evaporation rates from land are expected as a result of increased temperatures (Trenberth, 1998, 1999; Meehl *et al*., 2007), leading to more intense drying, heatwaves, wildfires and meteorological droughts (Trenberth, 2009; Dai, 2010). These meteorological changes alter hydrological extremes, increasing the risks of flood and hydrological drought, undermining water security. The threats of increased climate variability and extremes have not been properly appreciated or addressed in many climate change impact studies due to an over-reliance on mean values for temperature and precipitation changes (Trenberth, 2009).

Figure 1 shows a range of different meteorological pressures that climate change will exert on the water industry in the UK in the future, as well as the considerable uncertainty in the extent of those pressures (Murphy *et al*., 2009). However useful such information is for summarizing climate change in the UK, higher-resolution data are needed to inform decision-making at the catchment level.

Preliminary analyses of how these probabilistic climate projections would affect hydrology have shown that average river levels in the 2020s will be reduced in all catchments except a small area of the northwest, and many lowland river basins will be reduced all year round. Significantly higher PET rates increase the difficulty of maintaining supply and environmental standards as the century progresses, especially in the southeast (von Christierson *et al*., 2011).

2.2. Impacts on the water industry

Water infrastructure in the UK has been built over centuries with the assumption that the climate within which it is constructed will remain for its lifetime: this is no longer viable (Gleick, 2011). The water industry has proven to be remarkably resilient to change and pressure in the past, but the immensity (and unpredictability) of the challenge posed by climate change

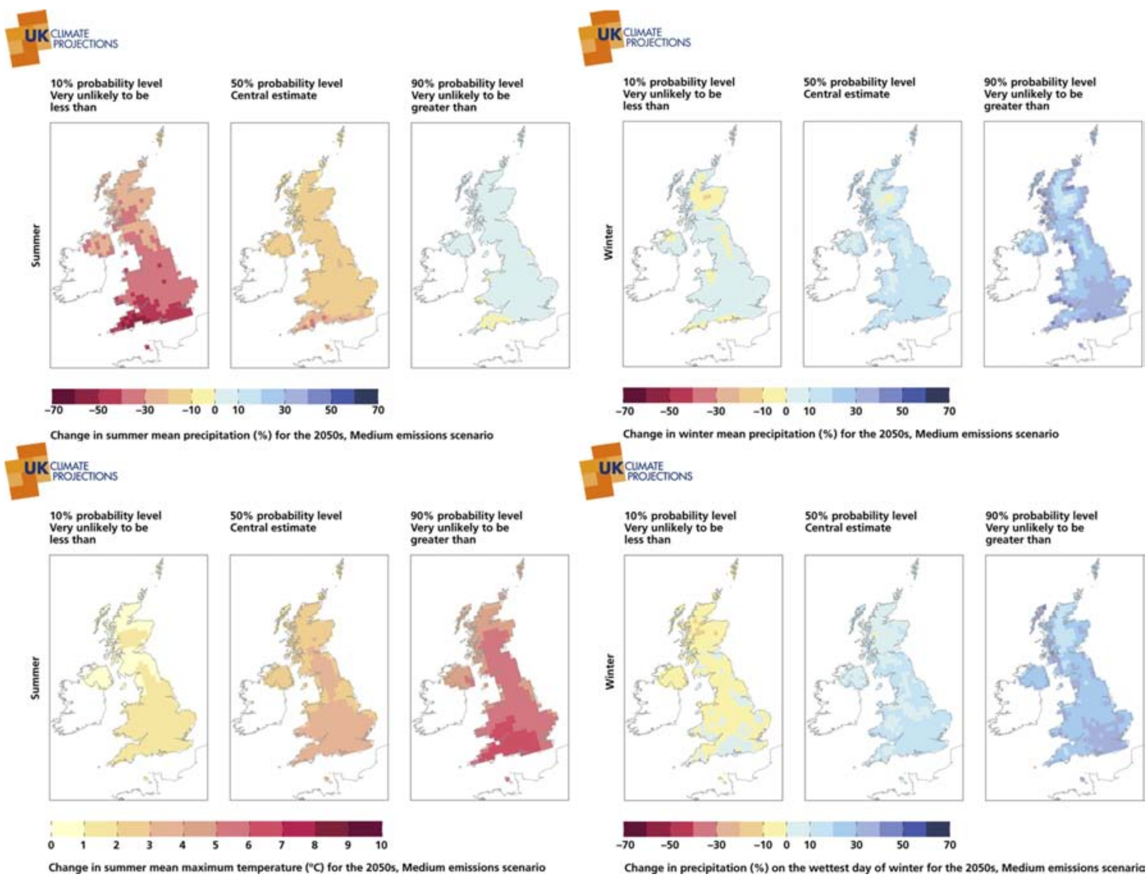

Figure 1. UKCP09 medium emissions scenario projections of precipitation and temperature statistics in the UK for the 2040–2069 period. The range of modelling uncertainty involved and the projected increase in seasonality of precipitation can be seen. (© 2009 UK Climate Projections). This figure is available in colour online at wileyonlinelibrary.com/journal/met

dwarves those that have preceded it. Although climate change impacts in the UK may be less severe than in many other areas of the world, this should not be seen as a vehicle for inaction as large variations in adaptive capacity within the UK exist across regions and socio-economic groups (Smith *et al*., 2001), and it has been shown that the sensitivity of water supply to reduction in flows is high, leading to large increases in risk with relatively small changes in flow (Gleick, 2011). Furthermore, as a leading industry and substantial contributor to greenhouse gas emissions, the UK has an ethical obligation to develop techniques for increasing resilience in water resource systems for distribution to more vulnerable areas of the world through appropriate mechanisms.

Large variations in hydroclimatological change are projected across the UK, with greater drying and peak temperatures in southeast England than elsewhere, and variations in the sensitivity of surface water resources dependent on reservoir size and isolation (Arnell, 1998). The key climate threats to water companies vary spatially, with reduced raw water availability, decreased water quality and inundation of assets crucial to Severn Trent Water, sea level rise important to Anglian Water, and flooding caused by increased storm water overpowering sewer capacity threatening United Utilities, South West Water and other western companies (Anglian Water, 2011; Severn Trent Water Ltd, 2011; South West Water, 2011; United Utilities PLC, 2011). These projected impacts are in line with the expected exacerbation of the meteorological divide in the UK, with southeastern areas susceptible to increased drought frequency and intensity through reduced river flows and prolonged dry days, whilst northwestern areas are at risk of more extreme winter rainfall events, less-reduced or even higher average river flows and associated flooding events (Jones *et al*., 2009; von Christierson *et al*., 2011).

Whatever the key risks to individual water companies, climate change will force the UK water industry as a whole to operate in a more testing environment if levels of service and environmental standards are to be maintained (Water UK, 2008; CIWEM, 2011). At catchment scales, change factor methods (CFMs) for assessing future drought risk based on historical events that underestimate the threat by not taking into account future changes in climate variability (Hall *et al*., 2012) and/or by using short instrumental records, are still used (Milly, *et al*., 2008), thus proliferating complacency towards future impacts. Recent Ofwat research has shown that this complacency towards the threat of climate change to water provision is shared by consumers (Ofwat, 2011) potentially restricting demand-side water savings.

Maintaining continuous water supply constitutes a core objective for UK water companies. Achieving this on a long-term basis requires adapting to climate change, which in turn requires rejecting the assumption that climatic conditions are stationary or that future conditions can be estimated by simply attaching simple flow factors to historical datasets (Milly *et al*., 2008). Therefore, historic hydrological events cannot be considered representative of the future and should only be used as a means of validating simulated climate information.

The process of qualitatively identifying risks is now largely complete across the UK through the Change Adaptation Reports submitted by water companies in 2011. The challenge of effectively quantifying those risks in areas that have been declared vulnerable is now upon the water industry, and with the UKCP09 probabilistic information there are now sufficient tools to achieve it.

2.3. Adaptation to climate change threats

It is becoming increasingly clear that adaptation is necessary if humanity is to manage and overcome the risks posed by climate change successfully (New *et al*., 2011; Smith *et al*., 2011), not least to the water sector (CIWEM, 2011). Adaptation itself covers a broad range of measures and approaches which can vary from 'no-regrets' (both financially and environmentally) and safe to those fraught with risk and open to moral questioning such as large-scale geo-engineering of the atmosphere (Bengtsson, 2006; Brewer, 2008; Hällström, 2008; Schneider, 2008; Bala, 2009; Fox and Chapman, 2011).

On a global scale, mitigation can be considered the best form of adaptation as the reduction of greenhouse emissions carries few negative effects and combats anthropogenic climate change cause rather than dampening the severity of its effects (Rahman *et al*., 2007; Bartlett *et al*., 2009). However, the apparent failures of high profile global climate change frameworks such as the Kyoto Protocol seriously degrade the extent to which this approach can be relied upon, if at all (Prins and Rayner, 2008; Prins *et al*., 2010). This policy failure is acknowledged in recent literature on global-scale impacts of climate change on the hydrological system, which openly discredit the widespread political goals of 2 °C, or 400 ppm of atmospheric carbon dioxide, by looking at the consequences of an Earth with temperatures 4 °C above the pre-industrial 'norm' (Anderson and Bows, 2011; Fung *et al*., 2011; Sanderson *et al*., 2011). Therefore, adaptation in the UK water sector is necessary as a surrogate for failed global and cross-sectoral mitigation attempts.

Adaptation strategies must be developed that are as robust and 'no-regrets' as possible, even given a large range of plausible futures (Dessai *et al*., 2009). Effective management, aided by better tools to make beneficial adaptation decisions, is regarded as more important to increasing water supply resilience than the technologies involved (Howard *et al*., 2010). However, despite vast swathes of literature on the clear need for adaptation in the face of modelled climatic changes over the 21st Century, the extent to which it has been meaningfully carried out in developed nations is surprisingly minimal, with large regional and sectoral variances (Ford *et al*., 2011).

On the other hand, some progress is being made. Requirements made of UK water companies by the Climate Change Act 2008 has led to a total of 19 climate change adaptation reports being carried out in the UK by water companies. These reports assign mostly qualitative determinations of risk to operations, with rudimentary use of UKCP09 information, and little or no use of WG information. The Ofwat Periodic Review in 2009 instructed water companies in England and Wales to include climate change within their estimates of future deployable output, and encouraged the use of probabilistic information from UKCP09 to do so (Arnell, 2011).

The announcement in 2009 that £1.5 billion was to be spent on addressing climate change impacts on the UK water sector by 2015 makes a practical method for successfully using the UKCP09 information essential to water companies looking to attract investment for climate change adaptation measures (Ofwat, 2009; Arnell, 2011). The UKCP09WG represents the ideal tool for further investigation and quantification of risks identified in the Climate Change Assessment Reports.

Whilst accepting the threats and challenges that climate change forces upon the water industry, it is important to remember that climate change makes up only one of a multitude of stressors (collectively termed as 'global change') which must be taken into account when taking stock of future operations (Lehner *et al*., 2006). Population increase in the UK, driven by net migration and reduced mortality, is the core component of elevated water use in the future. Urbanization, household change, altered construction patterns, water cooling for electricity production, agriculture and competing needs such as hydropower lead to different water security challenges from region to region (Birrell *et al*., 2005; Lehner *et al*., 2006). It is therefore important that hydroclimatological impact assessments are synthesized with reports on the future of other pressures, rather than being isolated.

Initial assessments such as von Christierson *et al*. (2011) have shown how to use probabilistic information on nationwide scales, so it is now crucial that the spatial resolution is increased and water companies use the correct techniques in order to increase the resilience of vulnerable water resource systems.

3. The role of stochastic weather generators in downscaling climate information for hydrological impact assessments

This section does not intend to be an exhaustive review of different stochastic WGs and their relative performance, but rather an overview of the use of WGs for hydrological assessment and their performance in relation to other downscaling techniques.

3.1. Downscaling for hydroclimatological assessment

Global-scale modelling endeavours are useful to drive climate change policy and give overviews of large-scale hydrological changes (see Sanderson *et al*., 2011; Todd *et al*., 2011). However, there is a spatial disparity between what GCMs can offer and what water resource managers require to make decisions on water infrastructure and policy (Buytaert *et al*., 2010); therefore downscaling coarse GCM information to a higher spatial resolution is necessary for most hydroclimatological assessments (Varis *et al*., 2004; Hashmi *et al*., 2009). Qian *et al*. (2010) showed that stochastically downscaled information better reproduced extreme hydrological events than data taken directly from GCMs.

There are many different approaches to downscaling coarse resolution GCM information for use in hydrological impact studies, and various review papers have shown the strengths and weaknesses of each (Xu, 1999; Hanssen-Bauer *et al*., 2005; Xu *et al*., 2005; Fowler *et al*., 2007; Maraun *et al*., 2010).

Most hydrological impact assessments require time series of weather variables (chiefly precipitation and potential evapotranspiration (PET)) on a daily time-step (Kilsby *et al*., 2007). The most readily available source of this information is the instrumental record, so hydroclimatological studies have often been based around 'scaling up' previous flood and drought events using average monthly change factors from GCMs (Scibek and Allen, 2006; Leander *et al*., 2007; Boukhris *et al*., 2008) a technique often referred to as the change factor method (CFM – Jackson *et al*., 2011) or an 'implicit' approach (Zhang, 2011). This process does not allow for changes to climatic variability and often uses short instrumental records, leading to underestimations of future hydrological extremes (Semenov and Barrow, 1997; Holman *et al*., 2009; Zhang, 2011).

The CFM assumes that the climate of the past is analogous to the climate of the future (or even present), which in terms of variability and seasonality it is not, as shown by large-scale climate modelling (Solomon *et al*., 2007). An example relevant to the water industry is that using change factors gives an equal number of precipitation occurrence days in the future as the past for no other reason than that was the number in the particular baseline period in the relatively short instrumental record (Diaz-Nieto and Wilby, 2005). The inadequacies of not accounting for climate variability when downscaling for hydrological purposes has long been known (Srikanthan and McMahon, 2001), yet the technique remains in use as a result of its simplicity and inexpensive computational demands (Diaz-Nieto and Wilby, 2005).

The detail and spatial resolution that is suitable when assessing the impact of climate change on water resources will vary from catchment to catchment based on some perceived risk (Todd *et al*., 2011; Hall *et al*., 2012). Greater depth of analysis should be afforded to areas with high proposed investment in adaptation of the water resource system than to those where no investment is planned (Hall *et al*., 2012).

Given the myriad of available climate model downscaling techniques, each with their own particular strengths and limitations, selecting the correct method to use depends on the application (Wilby *et al*., 2009). WGs have particular attributes that render them a distinctly useful approach for detailed assessments of the impacts of climate change on vulnerable water resources at a high spatial resolution (Diaz-Nieto and Wilby, 2005; Kilsby *et al*., 2007). Primary amongst these attributes lies the allowance of changes to climate variability and the creation of potentially endless synthetic sequences of temporally-consistent weather information that permit the projection of meteorological (and thus hydrological) extreme events (Wilks and Wilby, 1999; Hulme *et al*., 2002; Kilsby *et al*., 2007; Jones *et al*., 2009) at a suitable temporal resolution for inputting to biophysical models.

In a study on groundwater recharge under climate change forcings, Holman *et al*. (2009) recommended stochastic modelling is used to assess vulnerable or sensitive groundwater systems, thus enabling improved understanding of future risks of drought severity and persistence as well as high recharge years causing groundwater flooding. However, this level of detail would not always be required: using dynamical downscaling approaches with no assessment of extreme events (such as Cloke *et al*., 2010) would suffice in areas with less risk (Hall *et al*., 2012; Todd *et al*., 2011).

3.2. The stochastic weather generator

WGs are a form of statistical downscaling of coarse climatic data from GCMs, where statistical relationships between large-scale climatic variables and small-scale hydrometeorological variables are searched for. Essentially a collection of stochastic models, WGs create a distribution of plausible estimates of a particular weather climatic parameter (Boukhris *et al*., 2008). The basics of stochastic modelling have long been available (Matalas, 1967; Richardson, 1981), and have spawned a huge array of WGs, notably WGEN (Richardson and White, 1984), LARS-WG (Rackso *et al*., 1991) and CLIMA (Donatelli *et al*., 2005). For a technical review of different stochastic modelling approaches see Wilks and Wilby (1999) and Maraun *et al*. (2010).

WGs have historically been used as a method for infilling missing or erroneous weather records (Wilks and Wilby, 1999), and so are designed to recreate an array of observed weather variables as accurately as possible. The skill of the WG is determined by validating this baseline synthetic weather sequence against the instrumental record (e.g. Min *et al*., 2011).

The basic premise of adapting WGs for future climate projection is the assumption that statistical relationships between climatic parameters in the present (or past) will remain constant in the future. Therefore, it stands to reason that by forcing a WG with the fundamentals of future climates garnered from climate model information, weather sequences typical of future climate scenarios can be produced. The effect of these sequences on hydrology and water resources can then be explored through hydrological models then compared to a baseline, thus constituting a hydroclimatological impact assessment (Wilks, 1992).

WGs enable climate change impact assessments to be conducted at greater resolution in space and time than regional climate models (RCMs) allow, and are particularly relevant to studies in which the sequence of events is important, such as water resource provision (Wilks and Wilby, 1999; Jones *et al*., 2009). Studies comparing the ability to determine climate change impacts on hydrology of statistical downscaling techniques (such as using a WG) with other methods have been carried out. Diaz-Nieto and Wilby (2005) suggested that there is a place in research for both, with the coarser-resolution dynamical downscaling approach used for 'broad-brush' high level assessments of vulnerability (Sun *et al*., 2007; Bates *et al*., 2008; von Christierson *et al*., 2011; Dai, 2010; Todd *et al*., 2011), and statistical downscaling techniques delving deeper to explore detailed impacts deriving from sequencing and persistence of daily events, normally once vulnerable water resources have been identified (Diaz-Nieto and Wilby, 2005).

Combining RCM ensembles with stochastic WGs to create daily weather parameters for future climates has become an increasingly-used method for performing hydroclimatic impact assessments. For example, Herrera-Pantoja and Hiscock (2008) used the CRU WG (Jones and Salmon, 1995) to assess the impact of climate change on groundwater recharge at three sites in the UK, finding significantly increased dry periods leading to a reduction in recharge at each site as the century progresses. Each site presents increased climatic variability in the future, with the dry season found to be particularly affected. They conclude that sites already under groundwater supply pressure will come under increased stress as the century progresses.

Single-site WGs, such as EARWIG, CRU WG and UKCP09WG, are the most commonly used and least complex form of WG and therefore have the advantage of being computationally inexpensive (Semenov, 2008; Wilby *et al*., 2009). Multi-site WGs are more complicated and not part of the suite of tools provided by UKCP09. As a result of this commercial unavailability multi-site WGs are not currently useful for estimation of future deployable outputs in the UK water sector. For a review of multi-site and full-field WGs see Maraun *et al*. (2010).

After Fowler *et al*. (2007) and Bates *et al*. (2008) there has been a move within the hydroclimatic research community towards providing decision-making tools for future planning and management rather than focussing on more in-depth comparison of downscaling methods. At the same time, bespoke single-site future WGs with science-hidden interfaces such as EARWIG (Kilsby *et al*., 2007) and UKCP09WG (Jones *et al*., 2009) have become available, greatly simplifying the process for carrying out a WG-based hydroclimatological impact methodology in the UK and overcoming the issues of low awareness and user-friendliness that held back the take up of WGs (and other forms of statistical downscaling) in the past (Diaz-Nieto and Wilby, 2005; Groves *et al*., 2008).

The process of creating daily future weather sequences using a WG now requires no manual data input, prior knowledge of climate modelling or the need to develop local-scale WGs from scratch as was previously necessary (Varis *et al*., 2004). Such 'science-hidden' tools (Fowler *et al*., 2007) allow non-specialist end users to use the WG approach effectively, facilitating more widespread uptake in industry (e.g. Severn Trent Water Ltd, 2011). This approach does, however, make a WG less flexible: without the ability to take the model apart for further development by third parties, end users can be hamstrung by the omission of a particular variable. In the case of UKCP09WG, a lack of wind speed information reduces its effectiveness in many sectors, particularly railways.

Limitations of WGs remain. UKCP09WG, for example, is inhibited by an inability to produce the most extreme meteorological events, and in particular is not set up to recreate blocking regimes that create heatwaves/droughts and exceptionally cold winters (Jones *et al*., 2009). The February 2011 upgrade of UKCP09WG has substantially reduced the impact of this problem, however extreme high return periods of any given meteorological event should still be treated with caution. Furthermore, the single-station nature of most commercially available WGs creates a problem in that a weather sequence produced at one site will not correspond in time with another station nearby, so an extreme event at station A will not occur on the same day as it does at station B, even if in reality those stations would be subject to the same large-scale weather system (Jones *et al*., 2009). The size of the site can be increased (in the case of UKCP09WG, from 5 km^2 to 10 000 km^2), but this involves spatially-averaging the area, thus reducing accuracy.

These issues, despite reducing the ability to produce realistic projections of future weather sequences, should not deter those in industry from using WGs as the fundamental advantages of the approach over simpler CFMs are substantial. It is important to strike a balance between continually improving the skill and complexity of WGs and actually using them to make real-world decisions.

3.3. Case study: Weir Wood Reservoir

In a direct comparison of WG-based and CFM-based approaches, Harris *et al*. (2009) use an ensemble of RCMs to drive a weather generator (EARWIG) to assess climate change impacts on hydrological multi-seasonal drought events at Weir Wood Reservoir in North Sussex, UK. Drought periods are identified by precipitation totals over three consecutive winter half-years (October to March). Using the weather generator approach, it is found that inflows to the reservoir during future drought events are substantially below levels found in the 102 year instrumental record, and a regular period in the 2080s would constitute extreme multi-seasonal drought today (Figure 2). It is found that the GCM used to drive the weather generator is more important than the emissions scenario used, showing the need for the move towards large ensembles of GCMs or probabilistic information that has been seen in recent years.

A further analysis of the climate change impact on reservoir yields at Weir Wood shows substantially increased pressure on the reservoir in the 2050s and 2080s during drought episodes than in the baseline period (that is, yields for a particular drought rank within a dataset are lower in the future than in the baseline period) (Figure 3). All modelled simulations of the 2050s and 2080s project that yields during equivalent-ranked drought events will be much lower than in the baseline simulation (1960–1990). The yield during the worst drought in

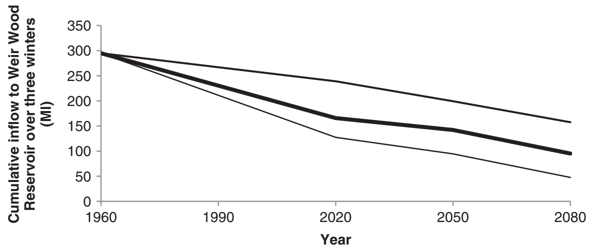

Figure 2. Simulated cumulative inflows at Weir Wood Reservoir over three consecutive winters for the 13th ranked drought periods. Two GCM/RCM combinations and two emissions scenarios (A1FI and A1B) are used. The central line denotes the average of the models, with the upper and lower bounds representing the model range.

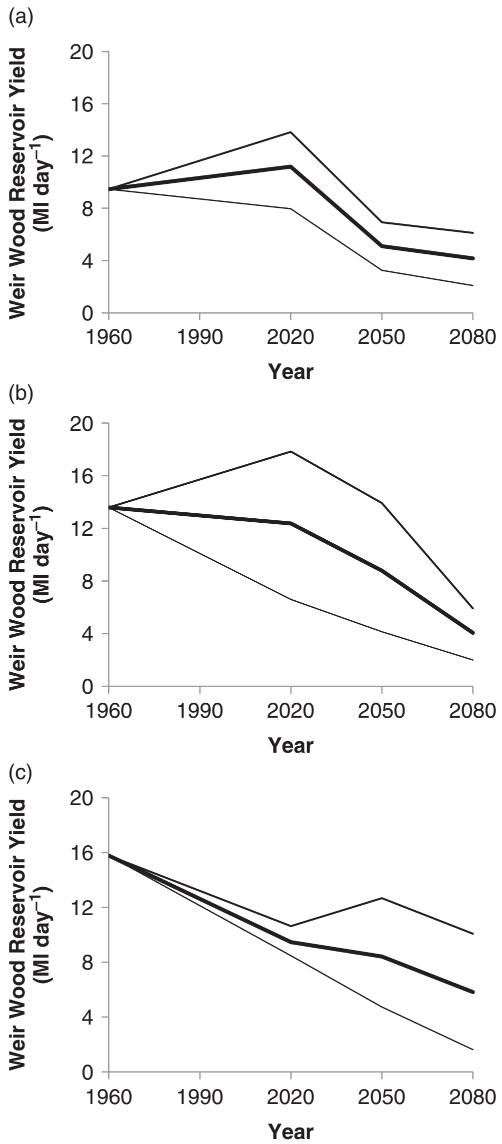

Figure 3. Simulated yields during droughts at Weir Wood Reservoir during the 21st century. (a) 1st ranked 3 winter droughts; (b) 7th ranked 3 winter drought; (c) 13th ranked 3 winter droughts. Ranks were chosen according to their close relation in the baseline simulation with periods in the instrumental record (the baseline simulations shown at 1975 in this figure correspond to the precipitation totals during real drought events in the period 1918–2006). Central lines denote the average of the models, with the outer line showing the range of output.

the instrumental record of 8.9 Ml day^{-1} is surpassed regularly in all scenarios.

With the CFM applied to the instrumental dataset, less severe hydrological drought events in the future are indicated and the sign of change is not always certain (Table 1). This occurs primarily as a result of less substantial PET increases in the future compared to the WG approach, and the inability of the CFM technique to account for changes to climate variability. The number of RCM/GCM combinations used to drive the weather generator or to obtain the change factor values is four, except the 13th ranked simulated droughts, where two combinations were analysed. This represents only a portion of the climate modelling uncertainty, and a larger amount of simulations would be needed to obtain robust statistics against which decision-making could be based. However, the difference between the two approaches in terms future drought severity projection is clear.

Harris *et al*. (2009) show that the WG is able to capture variability and change in droughts in the latter twenty-first century better than the change factor approach. Crucially, the periods of high evapotranspiration within the synthetic dataset that is the stimulus for the major multi-seasonal droughts of the 2080s are not apparent in the perturbed data. The increases in evapotranspiration need to be further investigated to determine exactly why they are occurring at such a greater rate in the WG approach than the perturbation approach. It may be the case that differences in the methods of PET calculation account for some of the disparity.

As this work does not use probabilistic climate information it would be inappropriate for use as the basis of a water resource decision-making process in the sub-catchment. However, the project does show that there is significant scope for underestimation of hydroclimatological impacts in the future when CFM methods are used.

4. Discussion: best practice for assessing climate change impacts on water resources in the UK

4.1. Using information despite uncertainty: the importance of accuracy over precision and robust decision-making

Our ability to quantify the magnitude, pattern and potential impacts of the changes humanity is inflicting on the Earth is of course limited by the fundamental incompleteness of current understanding of the climate system, anthropogenic climate change and climate sensitivity. This epistemic uncertainty manifests itself as disagreement between climate models (Hulme and Dessai, 2004) and is a part of any climate change-based impact assessment.

Selecting the most fit-for-purpose approach (in the case of high resolution catchment-scale water resource adaptation, a WG) and applying it correctly drives down the epistemic uncertainty involved in a study as much as possible. However, the naturally-stochastic nature of the Earth system and the influence of human behaviour means that significant uncertainty will always be involved in a climate change impact study regardless of the quality and relevance of the climate change information provided (Gawith *et al*., 2009). It should be remembered, though, that uncertainty is an inherent part of decision-making in environmental and social phenomena (Dessai *et al*., 2009) and should not be seen as a vehicle for inaction. Rather, the predictions of the future made using modelling approaches should set the boundaries within which decision-making is carried out to find a solution that is deemed to be sufficiently robust (Dessai *et al*., 2009; Pielke, 2009).

Table 1. Changes to total inflow at Weir Wood Reservoir in the 2080s compared to baseline and instrumental conditions.

	1919–1922/1st ranked simulation drought	1970–1973/13th ranked simulation drought
Change factor method	−5.4% (−38.38 to +24.3%)	−1.86% (−28.93 to +21%)
Weather generator method (A1B emission scenario)	−74.47% (−83.05% to −65.7%)	−69.07% (−79.13 to −59.01%)

For the change factor method two notable historical drought events are used as the periods against which rainfall and PET data for the future are derived, with the percentage changes corresponding to inflow to the reservoir during those episodes. In the weather generator approach, simulated drought events of similar scale to those instrumental periods are used as the inflows against which future simulated droughts are compared.

Figure 4. Drought control lines showing a major drought event in 1934 at Tittesworth Reservoir, which acts as the primary drought indicator for the Stoke and Ladderedge drought zones. Water years in which drought capacity falls below these control lines can be used as the basis of defining risk of drought at various severities in the future. Solid line: % capacity of the reservoir. Dashed curve: Tittesworth storage alert line. Dot-dashed curve: Tittesworth apply summer and winter hosepipe ban line. Straight line: Tittesworth emergency level. Straight dotted line: Tittesworth dead water level.

Probabilistic information (such as is provided by the UKCP09WG) can be considered accurate, rather than precise. That is, there is a broad range of plausible futures that should be taken into account, rather than one precise possible future from somewhere on a distribution that may, or may not, be the reality of the future (Dessai *et al*., 2009). Assuming a precise piece of information (such as using a single or small ensemble of GCM projections) is definitely a true representation of the future can lead to maladaptation, as that particular projection may be entirely incorrect. Using a wider distribution of projections (within which, somewhere, is the accurate reality of the future) enables decisions to be made about acceptable risk that leads to increased adaptive capacity (Dessai and Hulme, 2007).

Probabilistic assessments of climate change impacts on water provision can be used to provide the information required for robust decision making (Groves and Lempert, 2007; Dessai *et al*., 2009; Lempert and Groves, 2010), where the performance of different water resource planning strategies is tested against a set of future hydroclimatological and/or socio-economic scenarios across the range of uncertainty. The strategies can then be compared to analyse how well they perform under each scenario, with costs involved to determine the best course of action. This method would allow water resource planners to use the future projections to identify weaknesses in water resource management or adaptation strategies. With that knowledge, sensible decisions on how to augment resilience despite the uncertainties involved can be made (Groves *et al*., 2008). The result: no-regrets decision-making both financially and environmentally.

However, the increase in complexity from single climate change simulations to probabilistic information is a substantial conceptual leap, and requires a change of attitude on the part of water resource policy makers. The ability of the scientific community to communicate this complexity to policy makers successfully, particularly the importance of taking uncertainty into account rather than considering it reason for inaction, is crucial in improving understanding of hydroclimatological impacts and building resilience. Simply throwing the science 'over the wall' without effectively communicating the approach taken will result in an unsustained use of the technology and a reversion to overly simplistic approaches that systematically underestimate potential impacts (Harris *et al.*, 2009; Hall *et al.*, 2012; Sterman, 2011).

The improvement and continual development of our ability to model the global climate system through GCMs is, however, still crucial. GCMs form the backbone of any climate change impact assessment and disagreement amongst global-scale models on the state of the future global climate given a certain alteration of the atmosphere makes up the bulk of uncertainty (Minville *et al.*, 2008; Ducharne *et al.*, 2010; Todd *et al.*, 2011). There is cascading uncertainty from this point on through dynamical downscaling, hydrological modelling, sub-sampling of probabilistic information and emissions scenarios (Groves *et al.*, 2008) that must be dealt with by the research community. Recent studies have shown that the impacts of climate change are relatively insensitive to hydrological parameter uncertainty (Arnell, 2010; Todd *et al.*, 2011) but should not be ignored (Wilby, 2005).

To combat effectively the effect of climate change on water resource vulnerability in the future using WGs, several obstacles and challenges must be addressed in a replicable and uniform manner; a best practice, or framework, must be established (as outlined in Section 4.3).

4.2. Using a risk-based approach

Increasing the effectiveness of UK water resource management into the future requires moving towards a risk-based approach. Following recommendations made by Hall *et al.* (2012), passing a trigger condition that represents a failure to meet a particular Level of Service (LoS) can be deemed a suitable metric of risk. This pre-determined value for each catchment (perhaps expressed as a drought warning curve at a key reservoir) would be representative of a water shortage that means water demand cannot be satisfied. The wide range of futures given by the UKCP09 projections can be transformed into a distribution of probabilities of failure to meet an LoS each year for a particular time-slice in the future.

This results in a statistically robust understanding of the water shortage risks to a supply system in the future, that is, the probability of a particular system 'failing' at a given point in the future. These values can also be compared to a baseline value of water shortage to communicate climate change threat. The determination of an acceptable level of risk is important when analysing the output of such an approach. There would, for example, be little merit in investing in adaptation measures that completely eradicate the possibility of water shortages in the most extreme drought of the driest future scenario. It would stand to reason that the acceptable level of risk for a particular area or subcatchment would remain temporally constant, necessitating a gradual increase in investment to adapt to increasing climate change threats over time.

The selection of water management approaches and adaptation measures should be based on testing the response of various different options against the range of future scenarios. Those adaptation measures that perform statistically well in reducing water shortage risk over the range of uncertainty (by reducing the amount of times a LoS is not met *per* year), whilst remaining cost effective, environmentally sound and within the interests and values of customers and stakeholders would then be deemed suitable for selection (Hall *et al.*, 2012).

It is important not to assume the central area of the UKCP09 distribution to be the most likely course of the future. Instead, equal weighting across the whole range should be given. Failing to do so negates the core advantage of using probabilistic information and represents only a small step forward from the previous approach of using a single mid-value climate change scenario from UKCIP02. However, a sub-sampling approach would need to be used as a large amount of hydrological and water resource modelling will be involved, and processing the full 1000-sequence output from UKCP09WG for each emission scenario and time-slice would be too computationally expensive and time consuming for regular use, restricting uptake. Latin Hypercube Sampling (LHS) (McKay *et al.*, 1979), a stratified sampling approach designed to improve upon straightforward Monte Carlo random sampling, is outlined in Section 4.3 and has been used previously for hydroclimatological assessments by Darch *et al.* (2011) and von Christierson *et al.* (2011), amongst others. A follow-up paper, currently in progress, will assess the optimal process and variable selection for carrying out LHS for hydroclimatological research in the UK.

Should transient WG information (such as that proposed by Burton *et al.* (2010) become available and workable within a UKCP09-like suite, this would represent a step forward from the time-slice approach currently used. However, the lack of transient WG information in the short term does not merit inaction in the immediate future.

4.3. Hypothetical case study

It is suggested that the methodology for a thorough assessment of climate change impact on water resource shortages at a sub-catchment level could include the five phases outlined in this hypothetical case study. The actual tools used could vary (particularly hydrological models, water resource models and, outside of the UK, the weather generator), but the underlying approaches would remain the same. This approach forms the basis of a follow-up paper which assesses the impact of climate change on water resources in the Ladderedge and Stoke drought zones, Staffordshire.

The project is deliberately using tools and software currently in use by water companies to avoid unnecessary expenditure and training acting as barriers to the uptake of the methodology in industry. It should be noted that the first stage in such a study would be to confirm the suitability of such a detailed assessment into future water resources through qualitative assessment (such as the Climate Change Assessment Reports) or lower-resolution probabilistic research (such as von Christierson *et al.*, 2011) There is no need for such high-resolution and probing hydroclimatological impact assessments where coarser studies have shown potential impacts to be negligible.

1. Identification of key drought trigger(s) in the area. Generally, low levels at surface reservoirs constitute the triggers for implementing drought action by a water company. In the UK, a drought warning curve for a reservoir can act as a suitable threshold; water levels below that line can be taken as a 'failure' by the water resource model (Figure 4). The need for a particular demand-saving measure to achieve a given LoS or an inability to supply demand could also be used; as long as the metric remains constant then useful information can be gathered. The term 'failure' in this context does not necessarily mean that the system has failed

to provide water for its demand centres, but that the model has notified that a pre-determined threshold that symbolizes a water shortage situation has been passed.

2. Creation of probabilistic weather generator information. Probabilistic weather generator information is created for the sub-catchment using the UKCP09 user interface. The maximum possible 1000 simulations of 100 years for at least two emissions scenarios should be run for the time horizons required. As a single-point 5 km^2 projection that can be spatially averaged across up to 1000 km^2, it is important to make sure that the area covered is relatively homogeneous. A simple statistical approach to creating pseudo-spatial information for areas with heterogeneous, but related, rainfall profiles is currently in development and will follow in a further paper. Validation of rainfall statistics against instrumental data is crucial: see Kilsby *et al*. (2007) for a typical approach.
3. Sub-sampling. Once the synthetic weather sequences have been shown to reproduce the instrumental data adequately, it is necessary to sub-sample the dataset for each time horizon in order to carry out hydrological modelling. Not doing so results in unworkable computational expense. Latin hypercube sampling has emerged as a useful approach to reducing the amount of projections whilst keeping the range of uncertainty intact: see Darch *et al*. (2011) and von Christierson *et al*. (2011) for example methodologies. A paper assessing different selections of variables for the LHS procedure will follow this one, with the aim of identifying a best practice approach for hydroclimatological research. The amount of sequences that are carried through to hydrological modelling will inevitably be a compromise between scientific thoroughness and practicality in industry, with von Christierson *et al*. (2011) suggesting 20 samples as being suitable.
4. Hydrological modelling. With a suitable number of synthetic daily sequences for future sequences of precipitation and PET prepared (as well as a baseline simulation for comparison), a hydrological model such as Hysim (Manley, 1982) can be used to convert them into flows. The choice of hydrological model will be largely determined by modelling work previously carried out in the region. These daily inflow sequences can then be inputted to a water resource model such as Aquator (Oxford Scientific Software, 2008). The size of water resource model that can be used is spatially restricted by the single-site nature of the weather generator, as using entirely separate weather generator sequences for different areas of the model would create temporally uncorrelated data.
5. Decision-making using probabilistic information. 'Failure' rates, as discussed in phase 1, are determined for each model run, leading to a value of probability of failure *per* unit time. The subsequent range of failure probability constitutes the potential range of the impact of climate change upon the water resource system during the time-slice selected. By incorporating adaptation measures into the water resource model (supply and/or demand-side), their effectiveness can be determined across the range of uncertainty by assessing how each of the simulations respond to a given adaptation strategy in terms of reduction (or otherwise) of failure probability, and how much of the distribution is moved away from a pre-determined unacceptable level of risk. This approach can be used to assess how well an adaptation measure would work across the range of uncertainty, and can therefore be used as a support tool for making no-regrets decisions.

This approach brings up four notable issues. (1) Even with sub-sampling employed, computational costs of modelling will be higher than that to which the water industry is currently used to. Significant numbers of 100 year weather simulations will be put through hydrological and water resource models and then analysed. Clearly, the methodology has the existence (or rapid development) of water resource models as a pre-requisite, limiting its applicability in much of the world. (2) The nature of the dry periods leading to water shortage will not necessarily be known. With the output information being a probability of water shortage *per annum*, and the performance of a particular water management option being measured as a reduction of that value, no information will be given as to why the shortage occurred, or indeed why the water management option succeeds or fails to improve the situation. This more qualitative information would be valuable when targeting adaptation measures, so could be explored as further research. (3) The idea of a particular return period of an extreme event will largely be lost. The output data would not be suitable for describing the possible changes in return periods of extreme events in the future without further exploration. However, it is arguable whether assigning return values in a constantly evolving climate is particularly useful, as the system assumes the climate is constant. It is conceivable that comparing future extreme events in the WG output to historical data as a return period in the twenty century climate would be useful to a water company when communicating climate change to the public or stakeholders. (4) The most extreme drought events, particularly those characterized as multi-seasonal episodes, will not be captured by stochastic weather generators such as UKCP09WG. As a result, an approach for including substantial headroom for such events would be required when assessing future water resource availability.

5. Conclusions

Maintaining continuous water supply in the UK throughout the 21st Century requires acknowledging the threat of climate change, primarily by disassociating stationarity from water resource management. Adaptation to climate change is vital to successfully augmenting the resilience of water provision, and so must be based on sound evidence and take into account the full range of uncertainty associated with any climate change assessment.

Precise projections of the future cannot be expected from climate models given the epistemic and natural stochastic uncertainties involved, yet this should not be seen as a vehicle for inaction in the UK water sector.

WGs represent the most useful approach to hydroclimatological impact assessments due to their high spatial resolution, allowance for climate variability, production of long, temporally consistent weather sequences and daily time-steps. Of the myriad available models, the UKCP09WG has emerged as the favoured tool in the UK water sector due to its production of probabilistic information. Lower-resolution and qualitative studies are, however, essential for identifying areas of vulnerability prior to carrying out such data-intensive research.

A risk-based approach must be taken to water resource management. Given a particular metric of risk for a water supply system (e.g. a failure to meet a particular LoS), the probability of demand not being met by supply can be analysed for various plausible future scenarios. Given acceptable levels of risk, it will be possible to analyse how the probabilities of failure will change over time if no adaptation measures are taken.

The decision-making method used to select water management adaptation options is equally as important as that used to assess the climate change risk. If either of these approaches is not robust, then neither is useful. With this in mind, a form of robust decision-making technique should be used, where the effectiveness of different water management options are analysed across the whole range of uncertainty. It should not be assumed, for example, that any one point across a distribution is likely to be correct; investments that are beneficial across the distribution should be taken up. Instilling this into industry requires a step-change in the approach taken to decision-making on longer-term water resource provision.

Due to our incomplete understanding of our world, our inability to forecast the actions of man, and the stochastic nature of the Earth system, projections of climate change do not, and never will, represent a crystal ball that allows us to see how the future will look. However, by taking a probabilistic approach to assessing the impacts of climate change on the water sector, it is known that somewhere within our distribution the realistic vision of the future exists. By using probabilities of risk and robust decision-making techniques, adaptation options that are as 'no-regrets' as possible can be identified, whilst not making inflexible and potentially maladaptive decisions along the way.

Using probabilistic WG information to assist adaptive decision making in the face of uncertain climate change requires a practical top-to-bottom methodology, from creating the future weather sequences down to selecting the correct adaptation strategies. This eliminates disconnection between science and policy, ensuring stakeholder engagement and making sure that both the correct information is provided to policy makers and that the information is used correctly.

Acknowledgements

The authors would like to acknowledge the assistance of The University of East Anglia, Atkins and Southern Water Systems in completing the work at Weir Wood Reservoir, UK, which is highlighted as a case study in this paper.

List of Acronyms

CFM:	Change Factor Method
EARWIG:	Environment Agency Rainfall and Weather Impacts Generator
GCM:	Global Climate Model
LHS:	Latin Hypercube Sampling
LoS:	Level of Service
PET:	Potential Evapotranspiration
RCM:	Regional Climate Model
UKCIP02:	United Kingdom Climate Projections 2002
UKCP09:	United Kingdom Climate Projections 2009
UKCP09WG:	United Kingdom Climate Projections 2009 Weather Generator
WG:	Weather Generator

References

Anderson K, Bows A. 2011. Beyond 'dangerous' climate change: emission scenarios for a new world. *Phil. Trans. R. Soc.* **369**: 20–44.

Anglian Water. 2011. *Climate Change Adaptation Report: January 2011*. Anglian Water Services Ltd: Huntingdon, Cambridgeshire.

Arnell NW. 1998. Climate change and water resources in Britain. *Clim. Change* **39**: 83–110.

Arnell NW. 2010. The relationship between climate forcing and hydrological response in UK catchments. *Hydrol. Earth Syst. Sci.* **7**: 7633–7667.

Arnell NW. 2011. Incorporating climate change into water resource planning in England and Wales. *J. Am. Water Resour. Assoc.* **47**(3): 541–549.

Bala G. 2009. Problems with geoengineering schemes to combat climate change. *Curr. Sci.* **96**: 41–48.

Bartlett S, Dodman D, Hardoy J, Satterthwaite D, Tacoli C. 2009. Social aspects of climate change in urban areas in low and middle income nations. *Contribution to the World Bank Fifth Urban Research Symposium. Cities and Climate Change: Responding to an Urgent Agenda. Research Cluster 5*. 28–30 June 2009, Marseille, 44p. http://www.urs2009.net/docs/papers/Satterthwaite.pdf

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (eds) 2008. *Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change*. IPCC Secretariat: Geneva; 210 pp.

Bengtsson L. 2006. Geoengineering to confine climate change: is it at all feasible? *Clim. Change* **77**: 229–234.

Birrell B, Rapson V, Smith TF. 2005. *Impact of Demographic Change and Urban Consolidation on Domestic Water Use*, Occassional Paper No.15. Water Service Association of Australia – June 2005, prepared by the Centre for Population and Urban Research, Monash University for Water Services Association of Australia, Melbourne and Sydney.

Boukhris O, Ntegeka V, Willems P, Baguis P, Roulin E, Demarée G. 2008. *Climate Change Impact on Hydrological Extremes Along Rivers and Urban Drainage Systems in Belgium. 1: Literature Review*. Federaal Wetenschapsbeleid: 67 pp.

Brewer PG. 2008. Evaluating a technological fix for climate. *Proc. Natl. Acad. Sci. U.S.A.* **104**(24): 9915–9916.

Burton A, Fowler HJ, Blenkinsop S, Kilsby CG. 2010. Downscaling transient climate change using a Neyman-Scott Rectangular Pulses stochastic rainfall model. *J. Hydrol.* **381**: 18–32.

Buytaert W, Vuille M, Dewulf. A, Urrutia R, Karmalkar A, Célleri R. 2010. Uncertainties in climate change projections and regional downscaling in the tropical Andes: implications for water resources management. *Hydrol. Earth Syst. Sci. Discuss.* **7**: 1821–1848.

von Christierson B, Vidal J-P, Wade SD. 2011. Using UKCP09 probabilistic climate information for UK water resource planning. *J. Hydrol.* **424-425**: 48–67, DOI: 10.1016.j.jhydrol.2011.12.020.

CIWEM. 2011. Policy Position Statement: climate change. http://www.ciwem.org/policy-and-international/policy-position-statements/climate-change.aspx (accessed 7 December 2011).

Cloke HL, Jeffers C, Wetterhall F, Byrne T, Lowe J, Pappenberger F. 2010. Climate change impacts on river flow: projections for the Medway catchment, UK, with UKCP09 and CATCHMOD. *Hydrol. Processes* **24**: 3476–3489.

Dai A. 2010. Drought under global warming: a review. *WIREs Climate Change*. DOI: 10.1002/wcc.81.

Darch G, Arkell B, Tradewell J. 2011. *Water Resource Planning Under Climate Uncertainty in London*. Atkins Report (Reference 5103993/73/DG/035) for the Adaptation Sub-Committee and Thames Water: Atkins.

Dessai S, Hulme M. 2007. Assessing the robustness of adaptation decisions to climate change uncertainties: a cast study on water resources management in the East of England. *Global Environ. Change* **17**: 59–72.

Dessai S, Hulme M, Lempert R, Pielke R Jr. 2009. Climate prediction: a limit to adaptation. In *Adapting to Climate Change: Thresholds, Values, Governance*, Adger N, Lorenzoni I, O'Brien K (eds). Cambridge University Press: Cambridge, UK; 64–78.

Diaz-Nieto J, Wilby RL. 2005. A comparison of statistical downscaling and climate change factor methods: impacts on lowflows in the River Thames, United Kingdom. *Clim. Change* **69**: 245–268.

Donatelli M, Bellochi G, Carlini L, Colauzzi M. 2005. CLIMA: a component-based weather generator. In *MODSIM 2005 International Congress on Modelling and Simulation*, Zerger A, Argent RM (eds). Modelling and Simulation Society of Australia and New Zealand: Melbourne, Australia; 627–633.

Ducharne A, Habets F, Pagé C, Sanquet E, Viennot P, Déqué M, Gascoin S, Hachour A, Marin E, Oudin L, Terray L, Thiéry D. 2010. Climate change impacts on water resources and hydrological extremes in northern France. *XVIII International Conference on Water Resources, CMWR 2010*, Barcelona, Spain.

Ford JD, Berrang-Ford L, Paterson J. 2011. A systematic view of observed climate change adaptation in developed nations. *Clim. Change* **106**: 327–336.

Fowler HJ, Blenkinsop S, Tebaldi C. 2007. Review: linking climate change modelling to impacts studies: recent advance in downscaling techniques for hydrological modelling. *Int. J. Climatology.* **27**: 1547–1578.

Fowler HJ, Kilsby CG. 2004. Future increases in UK water resource drought projected by a regional climate model. *Hydrology: Science and Practice for the 21st Century*. Vol. 1, London, 12–16 July 2004; 15–21.

Fox TA, Chapman L. 2011. Review: engineering geo-engineering. *Meteorol. Appl.* **18**: 1–18.

Fung F, Lopez A, New M. 2011. Water availability in +2 °C and +4 °C worlds. *Phil. Trans. R. Soc.* **369**: 99–116, DOI: 10.1098/rsta.2010.0293.

Gawith M, Street R, Westaway R, Steynor A. 2009. Application of the UKCIP09 climate change scenarios: Reflections and lessons learnt. *Global Environ. Change* **19**: 113–121.

Gleick PH. 2011. Water planning and management under climate change. *J. Contemp. Water Res. Educ.* **112**: 1–5.

Groves DG, Lempert RJ. 2007. A new analytic method for finding policy-relevant scenarios. *Global Environ. Change* **17**: 73–85.

Groves DG, Yates D, Tebaldi C. 2008. Developing and applying uncertain global climate change projections for regional water management planning. *Water Resour. Res.* **44**: 83–106, DOI: 10.1029/2008WR006964.

Hall J, Watts G, Keil M, DeVial L, Street R, Conlan K, O'Connell E, Beven K, Kilsby C. 2012. Towards risk-based water resources planning in England and Wales under a changing climate. *Water Environ.* **26**: 118–129, DOI: 10.1111/j.1747–6593.2011.00271.x.

Hällström N. 2008. What next? Climate change, technology and development. *Development* **51**: 375–381.

Hanssen-Bauer I, Achberger C, Benestad RE, Chen D, Førland EJ. 2005. Statistical downscaling of climate scenarios over Scandinavia. *Clim. Res.* **29**: 255–268.

Harris CNP, Darch G, McSweeney R, Jones PD, Gough M. 2009. Stochastic and perturbation techniques to assess the influence of climate change-induced multi-seasonal drought on water resource vulnerability at Weir Wood Reservoir, North Sussex, UK. *Poster Presentation*, 4 Degrees and Beyond *International Climate Conference, Oxford University*, Oxford, UK, 28–30 September 2009.

Hashmi MZ, Shamseldin AY, Melville BW. 2009. Downscaling of future rainfall extreme events: a weather generator based approach. *18th World IMACS/MDSIM Congress*, 13–17 July 2009, Cairns.

Herrera-Pantoja M, Hiscock KM. 2008. The effects of climate change on potential groundwater recharge in Great Britain. *Hydrol. Processes* **22**: 73–86.

Holman IP, Tascone D, Hess TM. 2009. A comparison of stochastic and deterministic downscaling methods for modelling potential groundwater recharge under climate change in East Anglia, UK: implications for groundwater resource management. *Hydrogeo. J.* **17**: 1629–1641, DOI: 10.1007/s10040-009-0457-8.

Howard G, Charles K, Pond K, Brookshaw A, Hossain R, Bartram J. 2010. Securing 2020 vision for 2030: climate change and ensuring resilience in water and sanitation services. *J. Water Clim. Change* **01. 1**: 2–16.

Hulme M, Dessai S. 2004. Does climate adaptation policy need probabilities? *Climate Policy* **4**: 107–128.

Hulme M, Jenkins GJ, Lu X, Turnpenny JR, Mitchell TD, Jones RG, Lowe J, Murphy JM, Hassell D, Boorman P, McDonald R, Hill S. 2002. *Climate Change Scenarios for the UK: The UKCIP02 Scientific Report*. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia: Norwich.

Jackson CR, Meister R, Prudhomme C. 2011. Modelling the effects of climate change and its uncertainty on UK Chalk groundwater resources from an ensemble of global climate model projections. *J. Hydrol.* **399**: 12–28.

Jones PD, Kilsby CG, Harpham C, Glenis V, Burton A. 2009. *UK Climate Projections Science Report: Projections of Future Daily Climate for the UK From the Weather Generator*. University of Newcastle: UK.

Jones PD, Salmon M. 1995. *Development and Integration of a Stochastic Weather Generator into a Crop Growth Model for European Agriculture*. MARS project, final report to Institute of Remote Sensing Applications, Agricultural Information Systems (ISPRA): UK. Contract No. 5631-93-12, ED ISP GB.

Kilsby CG, Jones PD, Burton A, Ford AC, Fowler HJ, Harpham C, James P, Smith A, Wilby RL. 2007. A daily weather generator for use in climate change studies. *Environ. Modell. Softw.* **22**: 1705–1719.

Leander R, Buishand A, Alders P, De Wit M. 2007. Estimation of extreme floods of the River Meuse using a stochastic weather generator and a rainfall-runoff model. *Hydrol. Sci.* **50**(6): 1089–1102.

Lehner B, Döll P, Alcamo J, Henrichs T, Kaspar F. 2006. Estimating the impact of global change on flood and drought risks in Europe: a continental integrated analysis. *Clim. Change* **75**: 273–299, DOI: 10.1007/s10584-006-6338-4.

Lempert RJ, Groves DG. 2010. Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west. *Technol. Forecast. Soc. Change* **77**: 960–974.

McGuffie K, Henderson-Sellers A, Holbrook N, Kothavala Z, Balachova O, Hoekstra J. 1999. Assessing simulations of daily temperature and precipitation variability with global climate models for present and enhanced greenhouse climates. *Int. J. Clim.* **19**: 1–26.

McKay MD, Beckman RJ, Conover WJ. 1979. A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics* **21**: 249–245.

Manley RE. 1982. HYSIM– a general purpose hydrologic model. Proceedings of the 1978 Pisa Symposium. Pergamon Press: New York, NY.

Maraun D, Wetterhall F, Ireson AM, Chandler RE, Kendon J, Widmann M, Brienen S, Rust HW, Sauter T, Themeßl M, Venema VKC, Chun KP, Goodess CM, Jones RG, Onof C, Vrac M, Thiele-Eich. I. 2010. Precipitation downscaling under climate change: recent developments to bridge the gap between dynamical models and the end user. *Rev. Geophys.* **48**: 1–38.

Matalas NC. 1967. Mathematical assessment of synthetic hydrology. *Water Resour. Res.* **3**: 937–945.

Meehl G, Stocker T, Collins W, Friedlingstein P, Gaye A, Gregory J, Kitoh A, Knutti R, Murphy J, Noda A, Raper S, Watterson I, Weaver A, Zhao Z-C. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Chapter Global Climate Projections*. Cambridge University Press: Cambridge and New York, NY.

Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP, Stouffer RJ. 2008. Stationarity is dead: Whither water management? *Science* **319**: 573–574.

Min YM, Kryjov VN, An KH, Hameed SN, Sohn SJ, Lee WJ, Oh JH. 2011. Evaluation of the weather generator CLIGEN with daily precipitation characteristics in Korea. *Asia-Pacific J. Atmos. Sci.* **47**(3): 255–263.

Minville M, Brissette F. Leconte R. 2008. Uncertainty of the impact of climate change on the hydrology of a Nordic watershed. *J. Hydrol.* **358**: 70–83.

Murphy JM, Sexton DMH, Jenkins GJ, Boorman PM, Booth BBB, Brown CC, Clark RT, Collins M, Harris GR, Kendon EJ, Betts RA, Brown SJ, Howard TP, Humphrey KA, McCarthy MP, McDonald RE, Stephens A, Wallace C, Warren R, Wilby R, Wood RA. 2009. *UK Climate Projections Science Report: Climate Change Projections*. Met Office Hadley Centre: Exeter, UK.

New M, Liverman D, Schroder H, Anderson K. 2011. Four degrees and beyond: the potential for global temperature increase of four degrees and its implications. *Phil. Trans. R. Soc.* **269**: 6–19, DOI: 10.1098/rsta.2010.0303.

Ofwat. 2009. *Future Water and Sewerage Charges 2010–2015: Final Determinations*. Ofwat: Birmingham.

Ofwat. 2011. *Attitudes to Water Servicing in a Changing Climate: Report of Research Findings (Volume 1). Creative Research Prepared for Ofwat*. Ofwat: Birmingham, UK.

Osborn T, Maraun D. 2008. Changing intensity of rainfall over Britain. Climatic Research Unit Information Sheet no. 15.

Oxford Scientific Software. 2008. *A Guide to Aquator, 1. Application, Version 3.0*. Oxford Scientific Software: Oxford.

Pielke R Jr. 2009. Collaeral damage from the death of stationarity. *Gewex,* May 2009; 6–7.

Prins G, Galiana I, Green C, Hulme M, Korhola A, Laird F, Nordhaus T, Pielke R Jr, Rayner S, Sarewitz D, Shellenberger M, Stehr N, Tezuka H. 2010. *The Hartwell Paper: A New Direction for Climate Policy After the Crash of 2009*, Institute for Science, Innovation and Society, University of Oxford, UK; LSE Mackinder Programme.

Prins G, Rayner S. 2008. Time to ditch Kyoto. *Nature* **449**: 973–975.

Qian B, Gameda S, de Jong R, Falloon P, Gornall J. 2010. Comparing scenarios of Canadian daily climate extremes derived using a weather generator. *Clim. Res.* **41**: 131–149.

Rackso P, Szeidl L, Semenov M. 1991. A serial approach to local stochastic weather models. *Ecol. Modell.* **57**: 27–41.

Rahman AA, Alam M, Shafiqul Alam S, Uzzaman MR, Rashid M, Rabbani G. 2007. *UNDP Human Development Report 2007/2008: Background Paper on Risks, Vulnerability and Adaptation in Bangladesh*. Human Development Report Office Occasional Paper. UNDP: New York, NY.

Richardson CW. 1981. Stochastic simulation of daily precipitation, temperature and solar radiation. *Water Resour. Res.* **17**: 182–190.

Richardson CW, White DA. 1984. *WGEN: A Model for Generating Daily Weather Variables*. U.S. Department of Agriculture: Agricultural Research Service: Washington, DC; ARS-8: 83 p.

Sanderson MG, Hemming DL, Betts RA. 2011. Regional temperature and precipitation changes under high end (>4 °c) global warming. *Phil. Trans. R. Soc.* **369**: 85–98.

Schneider SH. 2008. Geoengineering: could we or should we make it work? *Phil. Trans. R. Soc. A.* **366**: 3843–3862.

Scibek J, Allen DM. 2006. Modeled impacts of predicted climate change on recharge and groundwater levels. *Water Resour. Res.* **42**: 18.

Semenov MA. 2008. Simulation of extreme weather events by a stochastic weather generator. *Clim. Res.* **35**: 203–213, DOI: 10.3354/cr00731.

Semenov MA, Barrow EM. 1997. Use of a stochastic weather generator in the development of climate change scenarios. *Clim. Change* **35**: 397–414.

Severn Trent Water Ltd. 2011. *Climate Change Adaptation Report: A Response to the Climate Change Act's Reporting Power*. Severn Trent Water: Coventry.

Smith MS, Horrocks L, Harvey A, Hamilton C. 2011. Rethinking adaptation for a 4 °c world. *Phil. Trans. R. Soc.* **369**: 196–216, DOI: 10.1098/rsta.2010.0277.

Smith JB, Schellnhuber H-J, Mirza MMQ. 2001. Vulnerability to climate change and reasons for concern: a synthesis. In *Climate Change 2001:Impacts, Adaptation, and Vulnerability*, McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS (eds). Press Syndicate of the University of Cambridge: Cambridge, UK; 913–967.

Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL. 2007. *Contribution of Working Group 1 to the Fourth Assessment Report of the International Panel on Climate Change, 2007*. Cambridge University Press: Cambridge, UK, and New York, NY.

South West Water. 2011. *South West Water Climate Change adaptation report-January 2011*. South West Water: Exeter, UK. http://archive.defra.gov.uk/environment/climate/documents/water-comp-adapt-plan/wc-south-west.pdf (accessed 15 January 2012).

Srikanthan R, McMahon TA. 2001. Stochastic generation of annual, monthly and daily climate data: a review. *Hydrol. Earth Syst. Sci.* **5**(4): 653–670.

Sterman JD. 2011. Communicating climate change risks in a skeptical world. *Clim. Change* **108**: 811–826.

Sun Y, Solomon S, Dai A, Portmann RW. 2007. How often will it rain? *J. Clim.* **20**: 4801–4818, DOI: 10.1175/JCLI4263.1.

Todd MC, Taylor RG, Osborn TJ, Kingston DG, Arnell NW, Gosling SN. 2011. Uncertainty in climate change impacts on basin-scale freshwater resources – preface to the special issue: the QUEST-GSI methodology and synthesis of results. *Hydrol. Earth Syst. Sci.* **15**: 1035–1046.

Trenberth KE. 1998. Atmospheric moisture residence times and cycling: implications for rainfall rates and climate change. *Clim. Change* **39**: 667–694.

Trenberth KE. 1999. Atmospheric moisture cycling: role of advection and local evaporation. *J. Clim.* **12**: 1368–1381.

Trenberth KE. 2009. Precipitation in a changing climate- more floods and droughts in the future. *GEWEX News*, 19, 8–10.

Trenberth KE, Smith L, Qian T, Dai A, Fasullo J. 2007. Estimates of the global water budget and its annual cycle using observational and model data. *J. Hydrometeorol.* **8**: 758–769.

United Utilities PLC. 2011. Report on adaptation under the Climate Change Act 2008. http://archive.defra.gov.uk/environment/climate/documents/water-comp-adapt-plan/wc-uuw.pdf (accessed 15 January 2012).

Varis O, Kajander T, Lemmelä R. 2004. Climate and water: from climate models to water resources management and vice versa. *Clim. Change* **66**: 321–344.

Vaze J, Teng J. 2011. Future climate and runoff projections across New South Wales, Australia: results and practical applications. *Hydrol. Processes* **25**: 18–35, DOI: 10.1002/hyp.7812.

Water UK. 2008. How the water industry is adapting to climate change. Water UK briefing December 2008.

Wilby RL. 2005. Uncertainty in water resource model parameter used for climate change impacts assessment. *Hydrol. Processes* **19**: 3201–3219, DOI: 101002/hyp.5819.

Wilby RL, Troni J, Biot Y, Tedd L, Hewitson BC, Smithe DM, Sutton RT. 2009. A review of climate risk information for adaptation and development planning. *Int. J. Climatol.* **29**: 1193–1215.

Wilks DS. 1992. Adapting stochastic weather generation algorithms for climate change studies. *Clim. Change* **22**: 67–84.

Wilks DS, Wilby RL. 1999. The weather generation game: a review of stochastic weather models. *Prog. Phys. Geog.* **23**: 329–357, DOI: 10.1177/030913339902300302.

Xu C. 1999. From GCMs to river flow: a review of downscaling methods and hydrologic modelling approaches. *Prog. Phys. Geog.* **23**: 229–249.

Xu C, Widén E, Halldin S. 2005. Modelling hydrological consequences of climate change-progress and challenges. **22**(6): 789–797.

Zhang XC. 2011. A comparison of explicit and implicit downscaling of GCM output for soil erosion and crop production assessments. *Clim. Change* **84**: 337–363.

