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# Towards risk-based water resources planning in England and Wales under a changing climate

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## Abstract

The publication of the UKCP09 climate change projections for the United Kingdom provides the opportunity for more rigorous inclusion of climate change uncertainty in water resources planning. We set out how the current approach to incorporating climate change and other uncertainties in water resources planning may be updated to incorporate the UKCP09 projections. In an uncertain future, the frequency with which customers will experience water shortages cannot be predicted for sure, so a water company cannot predict definitely whether it will or will not fulfil its Level of Service commitments. We therefore go on to propose that the probability of failing to meet Level of Service (for given populations of customers) provides an appropriate metric of risk, which conveniently summarises the uncertainties associated with supply and demand, including climate change uncertainties. We sketch out how this risk metric can be calculated based upon simulation modelling of the water resource system.

## Introduction

Management of water resources has always been a problem of decision making under uncertainty. The sustainable management of water resources requires a long-term perspective. Yet looking to the future reveals a host of major uncertainties, with respect to pressures from climate change, demographic change, land-use changes and other socio-economic drivers (ONS 2008; Water UK 2008; CLG 2009; Environment Agency 2010). In parts of the United Kingdom that are already susceptible to summer water stress, such as the South and South East, these pressures are likely to be significant (Environment Agency 2009). As a result, decision makers need to review how best to assess the impacts of change upon water resources, along with associated measures of uncertainty, and incorporate these assessments in sustainable water resources management.

Every 5 years, water companies in England and Wales, in consultation with the Environment Agency, produce Water Resources Management Plans (WRMPs) where they lay out the actions they will take in order to maintain security of water supply over the next 25 years or more. These WRMPs form an important part of the water companies' business plan submission to Ofwat (the Water Services Regulation Authority for England and Wales) for the 5-yearly Periodic Review (PR) of water prices. Adaptation to climate change is increasingly featuring in the water companies' investment plans. In the 2009 Periodic Review (PR09) water companies proposed more than £1.5 billion in investments to adapt their water resource systems to climate change. However, because the analysis justifying these investments predated the UKCP09 projections, Ofwat requested that these adaptation investments be re-evaluated using the new projections. Ofwat has a mechanism in place which allows companies to re-open the price determination in this area before the next formal price review, if justified using UKCP09 (Ofwat 2009).

The next PR will be published in November 2014, when Ofwat will set price limits for the 5 years from 2015 to 2020. Investment planning for this next review, which is now underway, will need to incorporate the UKCP09 projections within a rational risk-based framework. In the following section, we critically review the current arrangements for WRMP, with a particular emphasis upon the effects on water resources planning of climate change and other uncertainties. We go on to explore the implications of the UKCP09 projections and propose how they may be fitted within the existing framework for WRMP. However, the probabilistic nature

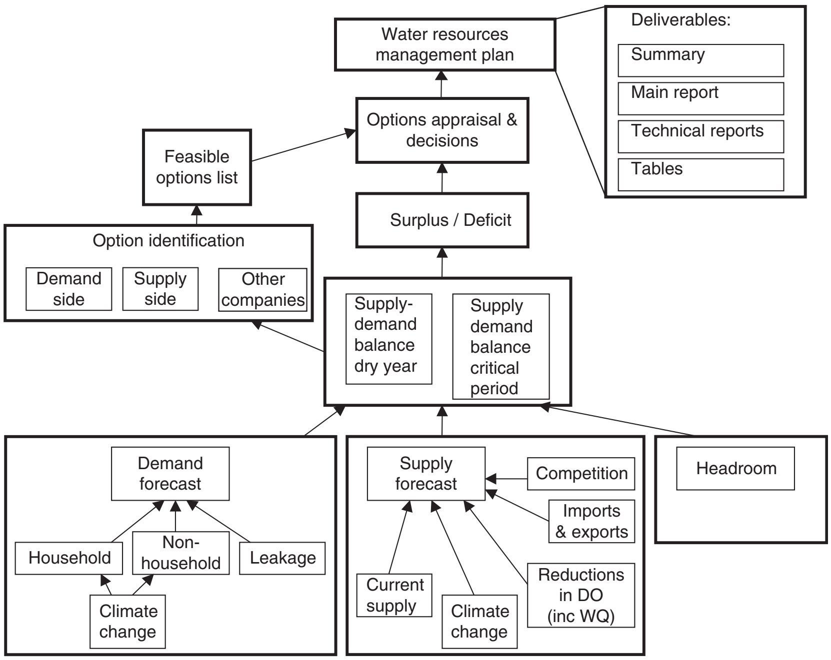


**Fig. 1.** Components of a water resources management plan, from Environment Agency (2008).

of the UKCP09 projections draws attention to the potential for a more complete risk-based approach to evaluation of options for water resources management, which would supersede current UK procedures. While it is not possible to fully elucidate such an approach within the scope of one paper, we set out principles for how water resources management planning can be put on a more rational risk-based footing and sketch out a potential implementation which is based upon simulation modelling.

In setting out the principles here we recognise that there are many uncertainty factors besides climate change that will also affect the supply–demand balance over future decades. These could include changes to the way that water abstraction is controlled to protect the environment, changes in population and water consumption, and changes in catchment hydrology as a result of land-use change. In principle, these can be accommodated within the structure described, either by inclusion in probability distributions or through a scenario-based planning approach.

## Current arrangements for water resources management planning in England and Wales

Water companies' WRMPs are expected to conform to the Environment Agency's Water Resources Planning Guideline (WRPG) (Environment Agency 2008), which builds on a long tradition of engineering hydrology in simplifying the water supply problem to compare a single value of supply, or yield (Law 1955), with annual demand (Fig. 1). The deterministic comparison between supply and demand is conceptually simple and easy to explain, which is advantageous given that water company plans have to be published and are subject to public consultation.

In its simplest definition yield, or deployable output (DO), is the maximum rate at which a system can supply water continuously through a dry period with a known or assumed severity. This implies that, in a more severe drought, this yield cannot be guaranteed, so short-term measures, such as restrictions on water use, may be needed to maintain adequate supplies. Since the 1998 systematic review of water company yields (Environment Agency 1998) and the subsequent first set of water resources plans for the 1999 Periodic Review (Environment Agency 1999), DO has been defined as the volume of water that could be supplied through a repeat of the worst droughts of the 20th century, taking into account the water company's policy on water-use restrictions.

Defining DO with reference to historic droughts has practical advantages but also presents some problems. From a policy perspective, it is useful to be able to explain that water companies aim to supply water through the worst drought in living memory without serious restrictions on water use. Using a real drought also allows simplified approaches to hydrological modelling: in many places, long gauged flow records exist, and it is often possible to use these to extend shorter records for adjacent catchments. On the other hand, while droughts tend to exhibit a high degree of spatial coherence (Hannaford *et al*. 2011), the severity of a given drought varies between different catchments [see, e.g., Doornkamp *et al*. (1980) for an examination of the variability of the 1976 drought]. In practice this means that the standards to which water companies are planning are not necessarily consistent or objectively communicated. A further problem with this approach is that it suggests that the worst drought of the 20th century represents a reasonable bound on drought severity. In fact, we know that, in the 19th century, there were much longer droughts than in the 20th century (Marsh *et al*. 2007). Using historic droughts also implies that the climate and catchments are not subject to change: it assumes that a drought of the 1920s or 1930s is as likely to occur today with the same hydrological response. However, catchments evolve, altering hydrological response (Ivanović & Freer 2009), and climatic stationarity can no longer be assumed (Milly *et al*. 2008).

The WRPG also introduces a theoretical 'dry year', in which demand that is typical for dry conditions is satisfied fully, unconstrained by drought restrictions, so is denoted as $D_{DYA}$ (dry year annual average unrestricted daily demand) and available supply is the long-term yield. Analysis proceeds with the conservative assumption that demand every year in the future is the $D_{DYA}$, with demographic and climate changes (as they effect demand) superimposed, to allow any possible deficits to be identified in the year they first occur.

The target for water availability is defined in terms of a series of Levels of Service (LoS) which state the maximum frequency with which water companies will impose restrictions including hosepipe bans, nonessential use bans and severe water rationing. In this paper, for reasons that will become clear below, we think of an LoS as being a target for the maximum annual probability of a shortage of given severity, so an example of an LoS might be 'an annual probability of hosepipe bans no greater than 0.05'.

Uncertainty in the WRMP is incorporated via a 'headroom' allowance, which is 'a buffer between supply and demand designed to cater for specified uncertainties' (Environment Agency, 2008). Thus, the 'available headroom', $H_A$, in a resource zone is defined as the difference between the water available for use (WAFU) [which is deployable output (DO) including raw-water imports, less raw water exports, less outage] and the $D_{DYA}$. The various constructs mentioned above are brought together in the WRMP process that is illustrated in Fig. 1.

UKWIR (2002) sets out a methodology for analysing headroom, which identifies nine supply-related and four demand-related sources of uncertainty (Table 1), though S1–S3 have now been excluded from assessments and S7 is included in assessment of outage. UKWIR (2002) recommends that these uncertainties be represented as probability distributions. The probability density functions (pdfs) for uncertainty in supply and demand, $f_S(q)$ and $f_D(q)$ respectively (where $q$ is a supply or demand variable expressed in terms of Ml per day), are taken as the sums of all their different constituent sources of uncertainty, which are computed using Monte Carlo simulation, taking account of the correlation between the different uncertainties.

**Table 1** Sources of uncertainty in water supply/demand identified by UKWIR (2002)

| Supply side uncertainties | Demand side uncertainties |
|---|---|
| S1 Vulnerable surface water licences | D1 Accuracy of subcomponent data |
| S2 Vulnerable groundwater licences | D2 Demand forecast variation |
| S3 Time-limited licences | D3 Uncertainty of impact of climate change on demand |
| S4 Bulk imports | D4 Uncertain outcome from demand management measures |
| S5 Gradual pollution of sources (causing a reduction in abstraction) | |
| S6 Accuracy of supply-side data | |
| S7 Single source dominance | |
| S8 Uncertainty of impact of climate change on source yields | |
| S9 Uncertain output from new resource developments | |

Supply and demand are not independent because both supply and demand may be influenced by the same processes (e.g. climate change). Statistical dependence can be dealt with by computing the distribution of the demand *given* supply, $f_{D|S}(q)$. The pdf of available headroom, $f(h)$, which is the difference between the distribution of supply and the distribution of demand given supply, is computed as the convolution of the two pdfs:

$$f(h) = \int_0^{q_{\max}} f_s(q-h) f_{D|S}(q) \mathrm{d}q, \qquad (1)$$

where $q_{\max}$ is the upper bound on the support for the distribution functions $f_S(q)$ and $f_{D|S}(q)$. The headroom methodology standardises the distributions of supply and demand by their mean values $\mu_S$ and $\mu_D$, respectively, so the headroom uncertainty pdf $f_u(h)$ is given by:

$$f_u(h) = f(h - \mu_S + \mu_D). \qquad (2)$$

The 'target headroom', $h_T(P)$ is a deterministic quantity that the water company seeks to provide for in its WRMP. It is back-calculated from Eq. (2), by identifying an acceptable probability, $P$, (the 'Level of Risk' or LoR) at which the distribution $f(h)$ may become negative:

$$h_T(P) = -F_u^{-1}(P), \qquad (3)$$

where $F_u^{-1}(P)$ is the inverse cumulative distribution function of $f_u(h)$ [Eq. (2)] at probability $P$. The headroom calculation is repeated for every year of the planning period to identify how and when a range of management options is expected to yield a surplus or deficit compared with the target headroom.

## Climate change

Water companies in England and Wales were asked to consider climate change in their 1999 WRMPs. Subsequent planning rounds have developed this, and in 2007 water companies were directed by Ministers (in the Water Resources Management Plan Direction 2007) to explain how forecasts of supply and demand consider climate change.

### Climate change and supply

For assessments of DO, the WRPG recommends scaling historic rainfall and evaporation sequences to represent future climate. This is a change factor approach to downscaling global climate model (GCM) data, also known as a 'delta change' or 'perturbation' method (Fowler *et al.* 2007). The change factor method is simplified because it retains the structure of the historic record. Droughts change in severity but still occur at the same times in the record and for almost the same duration, though the precise start and end may be altered because of changes in the magnitude of rainfall and evaporation. Preserving the structure of the historical climate record is both helpful and problematic. It is beneficial because it allows direct comparison of water availability before and after climate change, allowing water companies to explain the impact of climate change on their system. However, it is also questionable because there is no reason to expect that future droughts will be scaled versions of past droughts.

UKWIR (2006) provided monthly change factors for rainfall and evaporation and also monthly river flow factors for 70 catchments, obtained from six GCMs. The mean changes estimated across the six models formed a 'Mid' scenario of future climate, while changes at plus one and minus one standard deviations from the mean were described as 'Wet' and 'Dry' scenarios, respectively. The flow factors corresponding to these scenarios are used to scale the observed time series, which can then be used to calculate the corresponding DO. UKWIR (2006) then recommends use of a triangular pdf for S8 (defined by the 'Mid', 'Wet' and 'Dry' points) in the headroom calculation.

### Climate change and demand

Relatively little attention has been paid to the impact of climate change on the demand for water in England and Wales. This is at least partly because there is no unified theory or model that identifies the drivers of demand, though a large number of possible factors have been identified. Herrington (1996) explored several ways of thinking about the impact of climate change on demand, including gathering demand information from other parts of the world with similar economic and social characteristics and warmer climates. Downing *et al.* (2003) built on a scenario approach to demand forecasting (Environment Agency 2001a, b), adjusting specific microcomponents of demand to reflect changes in use as a result of higher temperatures. For example, the frequency of garden watering and showering or bathing may be expected to increase in a warmer climate. On the other hand, demand can be less in wet or dull weather years, though these reductions in demand can in due course 'bounce back' to the underlying trend.

The WRPG recommends the use of the results from Downing *et al.* (2003). In practice, this adds a few percent to total mains water demand by the 2020s or 2030s. Other factors are expected to change demand much more, at least in the next two decades: for example, further reductions in leakage will help to conserve water and the introduction of water metering may lead to water savings of 10–15% (Environment Agency 2009).

### The UKCP09 climate change projections

In June 2009, the latest climate change projections for the United Kingdom (UKCP09) were launched. The projections are based upon a large 'perturbed physics' ensemble of the Met Office Hadley Centre's HadCM3 GCM, dynamically downscaled to a $25 \times 25$ km grid using the HadRM regional climate model. The climate projections are available for the period 2010–2099, using seven overlapping 30-year time slices that move forwards in decade steps (i.e. 2010–2039, 2020–2049, etc. until 2070–2099). An innovative methodology for assessment of uncertainty was developed (Murphy *et al.* 2007), so the results are reported at different probability levels, for example 10% (very unlikely to be less than), 50% (central estimate), 90% (very unlikely to be greater than). These probabilities reflect the relative strength of the evidence that supports a projected outcome. The ranges for projected precipitation change can be large even in the 2020s (see, e.g. Fig. 2).

The UKCP09 projections are presented as being conditional upon three different emissions scenarios (identified as High, Medium and Low). No information is provided about the relative likelihood of these emissions scenarios, as future emissions will be determined by human decisions. In principle this presents difficulties for incorporating these scenarios into WRMP, but in practice there is not

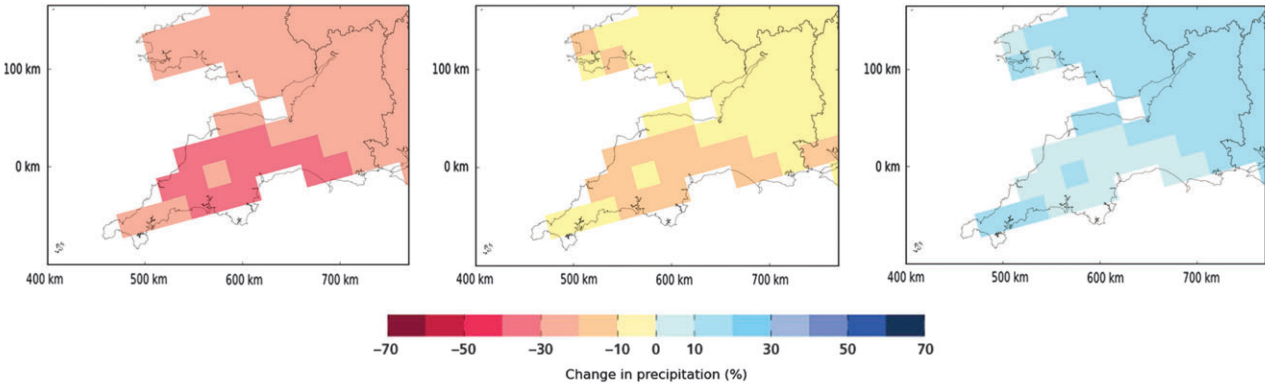


**Fig. 2.** UKCP09 projected changes in mean summer rainfall for southwest England for the 2020s (medium emissions scenario).

a significant difference between projections based upon different emissions scenarios up to the 2030s.

The UKCP09 projections are accompanied by a weather generator (WG) which simulates time series of local (5 km scale) future daily precipitation, temperature, PE and other weather variables based on the UKCP09 projections. The WG uses well-established stochastic simulation methods for daily weather variables (Kilsby *et al*. 2007), calibrated from observations. Changes between the reference period (1961–1990) and future decades are extracted from the UKCP09 probabilistic projections and factored into the WG, so that it can be used to simulate future climates for specified decades, yet is grounded in observed climatology. The WG can be used to simulate very long series of weather events which are representative of the selected time slice, so facilitates more extensive sampling of climate variability than is possible by applying change factors to observed series [the approach adopted in UKWIR (2006)]. Even for the reference period, some of these simulated series may be expected to have droughts that are more severe than in the observed record. In UKCP09 a large number of WG parameterisations (up to 10 000) can be generated – this large 'ensemble' allows one to extensively explore the climate model uncertainties encapsulated by UKCP09.

The combination of probabilistic quantification of climate model uncertainty with stochastic simulation WG technology makes UKCP09 internationally groundbreaking. However, there are still limitations, the most significant from a WRMP perspective being:

**1.** While the WG reproduced the statistics of the control period well, there are remaining issues with how well climate models (and thus UKCP09) can robustly project future precipitation variability and extremes, including prolonged hot dry spells.

**2.** The WG effectively reproduces daily and monthly variation in climate variables. The variance in annual rainfall totals has also been shown to be reproduced well. Year-to-year patterns are independent, so persistent multiyear droughts occur no more frequently than would be expected under the assumption of independent annual totals. UK rainfall series do not exhibit significant 'long memory', but a more variable climate may bring with it increased risk of persistent multiyear droughts which would be very significant for the water industry, so the possibility of long memory processes (which may, for example, be associated with large-scale climate oscillations) merits attention.

**3.** The UKCP09 WG simulates stationary series that are representative of 30-year time slices. Ideally, adaptive management strategies need to be tested with respect to how they perform in a changing (nonstationary) climate, which requires transient climate scenarios (i.e. scenarios that simulate how climate is expected to change as one goes through the 21st century) of the type generated by Burton *et al*. (2010).

**4.** The UKCP09 WG produces weather series for individual locations (5 km × 5 km grid squares), while for water resources purposes, spatially coherent precipitation variables are required over whole catchments, and also for groups of catchments in cases where interbasin transfers are significant. The UKCP09 WG Guidance (Jones *et al*. 2009) is cautious about the use of the WG for provision of rainfall series for whole catchments. However, for water resource planning purposes, where aggregate rainfall (e.g. monthly) is of most relevance, the effect of spatial variation in precipitation over the subcatchments may not be significant.

## Incorporating the UKCP09 projections in the existing WRMP framework

The headroom framework outlined above is probabilistic so can accommodate probability distributions derived from UKCP09. In this section we set out how this may be achieved. While the existing approach is probabilistic, for reasons we will explain in the next section, it is not explicitly risk-based, nor is it well suited to appraisal of adaptive management strategies. Therefore in the next section we set out the case for a risk-based alternative method that goes beyond the existing headroom methodology.

The framework set out in Fig. 1 and Eq. (2) involves separating out mean estimates of the impacts of climate change on supply and demand from the associated uncertainty (which is incorporated within the headroom calculation). The approach proposed here therefore proceeds by constructing a probability distribution of climate change impacts on supply and demand and then separating this into a mean and a pdf with zero mean. Projected changes in supply may be obtained by a number of methods using the UKCP09 projections. Here we describe an approach based upon the WG, the attraction being that the WG enables extensive sampling of natural variability in weather conditions, providing a well-developed route for generating statistical estimates of drought frequency in present and future climate.

There are two levels of uncertainty that the UKCP09 WG can be used to explore:

*U1: Natural variability*: The WG generates synthetic time series of weather variables (including precipitation, temperature and PE). In calculating supply, series of precipitation and PE need to be input to rainfall-runoff models (and/or groundwater models where appropriate) in order to give flow (and groundwater level) series that can be input into the water companies' water resource models in order to generate corresponding predictions of DO for different water resource management options. Temperature series from the same WG run can be used to estimate changes in demand, thus dealing conveniently with the correlation between supply and demand. Long simulations (of several hundreds of years) representative of the reference (1961–1990) and future time slices (2020s and 2030s) can be used to extensively explore natural variability in weather conditions that may be (statistically) expected in present and future climates.

*U2: Climate change uncertainty*: For future climates, the WG analysis of U1 can be repeated for different sets of change factors from UKCP09, enabling exploration of the range of uncertainty associated with projected climate changes. This second layer of uncertainty is referred to as 'epistemic uncertainty' as the distribution of change factors represents the range of uncertainty associated with our lack of knowledge about the behaviour of future climates. Thus U2 will generate a distribution of estimates of DO.

Suppose that the three distributions of DO illustrated in Fig. 3 are written as $F_{\text{baseline}}$, $F_{\text{2020s}}$ and $F_{\text{2030s}}$. The mean climate effect on supply in the 2020s is $\mu_{\text{2020s}} - \mu_{\text{baseline}}$. A smooth curve may be fitted through $\mu_{\text{baseline}}$, $\mu_{\text{2020s}}$ and $\mu_{\text{2030s}}$ to enable construction of a time trend of mean DO, similarly through the quantiles of $F_{\text{baseline}}$, $F_{\text{2020s}}$ and $F_{\text{2030s}}$ to enable construction of climate change uncertainties for each intervening year, which can then be input as S8 (Table 1) in the headroom calculation.

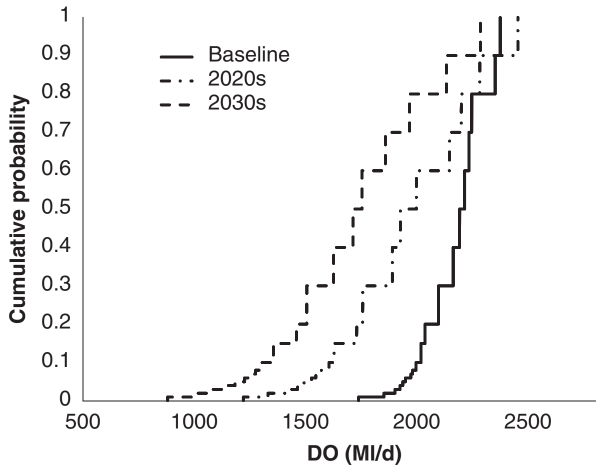


**Fig. 3.** Typical cumulative probability distribution of DO for the baseline, 2020s and 2030s using a sample of UKCP09 probabilistic outputs.

An inevitable consequence of UKCP09 is that water companies will have to do more simulations using their water resource models than they are accustomed to. Judicious sampling of natural variability (U1) and epistemic uncertainties (U2) can ensure that the number of simulations is still manageable. Note, for example, that in Fig. 3 more cases have been sampled at the lower tail of the distribution of DO, so that the probability estimates are more accurate in the circumstances that are most relevant to the WRMP. As the simulations are independent of one another it is straightforward to deploy them on distributed or cloud computing facilities (Harvey & Hall 2010).

## A risk-based approach to water resources management planning in England and Wales

### The need for a risk-based approach

The approach to WRMP set out in Fig. 1 is essential deterministic, but has embedded within it frequency-based definitions of LoS and a probabilistic approach to dealing with uncertainty via headroom. Nonetheless, the WRMPs that emerge from this analysis cannot be described as risk based: a risk-based approach would make explicit the probabilities of a range of observables outcomes (e.g. water shortages of different severity), at present and in future, for a range of different management options. The focus upon abstract supply metrics

(DO) rather than observable outcomes (the frequency with which customers experience, or are predicted to experience water shortages) makes it difficult objectively to weigh up the risks and costs associated with alternative strategies for water resources management. It also makes it more difficult post-implementation to monitor and evaluate the effectiveness of adaptation investments.

The use of the term 'Level of Risk' (LoR) suggests that the current approach is risk based, but LoR is defined on a scale of headroom uncertainty (Ml/d), so has no direct interpretation in terms of the probability that a given LoS will or will not be achieved. The probability that the available headroom is less than zero approximates to the probability that the LoS will not be achieved (though the use of the dry year annual average daily demand means that even this approximation is biased), but any other quantiles of headroom uncertainty cannot be directly interpreted in terms of the frequency with which customers are expected to experience water shortages.

While the probabilistic headroom methodology explores a number of sources of epistemic uncertainty, natural variability (reflected, e.g. in the occurrence of wet and dry years) is only incorporated by testing the observed series (e.g. of flows, precipitation, etc.). Of course this observed record forms the basis for our understanding of natural variability, but just testing observed series is very limiting in terms of the severity, sequencing and spatial extent of droughts. Yet these extreme events largely determine the risk of shortages to which water customers are exposed, now and in the future, so merit careful statistical analysis (Tallaksen & van Lanen 2004), including proper treatment of the associated statistical parameter and model uncertainties (Coles 2001).

It is clear from Fig. 1 that the WRPG separates forecasting of supply and demand from analysis of uncertainty in those quantities. Thus, for example, in allowing for the impact of climate change on the supply–demand balance, the mean climate change effect is included in the supply and demand forecasts while the variance on that climate change projection is included in the headroom calculation. This makes it rather difficult to trace the effect of individual drivers (such as climate change) and to identify the most appropriate adaptation responses. It has also raised the question of how the mean value is selected for the supply and demand calculation (in the absence of uncertainty). For example, $D_{\mathrm{DYA}}$ is taken as the demand forecasting, which may be a reasonable conservative assumption, but the $D_{\mathrm{DYA}}$ is not for an average year, so it does not represent the mean of the distribution of demand uncertainty.

The explicit representation of uncertainty in UKCP09 acts as a stimulus to re-evaluate the representation of uncertainty in WRMP. In particular, Ofwat in its final determination of price limits for 2010–2015 has required water companies who want to propose further investment in adapting to climate change before the next price review to produce 'reasonable, risk-based, analysis consistent with the range of projected outcomes reflected in the application of a suitable analytical tool to UKCP09'. As the climate change signal grows compared with natural climate variability, it is becoming increasingly necessary to improve the assessment of the impact of climate change on water resources, and make demonstrably proportionate adaptation decisions. Any new approach to climate change in WRMP must concentrate on the main purpose of the water resources planning regime – to make sure that water companies are taking timely and appropriate steps to maintaining security of supply in the face of all pressures. In doing this, attention must be paid to developing methods that improve adaptation to climate change. Where uncertainties are large, it pays to build in flexibility and modify strategies as new information materialises, through a process of 'adaptive management'. Analysis of phenomena that evolve through time, be they deliberate (like adaptive management strategies) or largely outside the control of decision makers (such as the 'bounce back' phenomenon mentioned above) requires an approach that simulates the evolution of future sequences of events through time. Of course these events are uncertain, so simulation involves dealing with multiple time series of alternative futures and tracking their performance with respect to relevant metrics (e.g. cost and frequency of shortages) through time. Adaptive management cannot be properly analysed using existing approaches that are based upon a series of annual 'snap shots' of the balance between supply and demand for each year individually, without tracking specific (uncertain) sequences of events.

From the above discussion we conclude that the existing framework for water resources planning is not fully fit for purpose because (1) it is not genuinely risk-based; (2) its reliance upon observed series means that natural variability is not adequately explored; (3) it separates mean values from uncertainty, making the sources of future change and uncertainty difficult to attribute; and (4) it is not well suited to testing and evaluation of adaptive management strategies.

## Principles of a risk-based approach

A risk-based approach is one that explicitly considers the probability and consequences of harmful events, in this case water shortages for people or the environment. We do not dwell here upon quantification of the consequences of water shortages, but take it that these are proportionate to the severity of shortage and the number and vulnerability of water consumers effected, among other factors. First we set out some guiding principles for water resources planning in a changing climate, before sketching out a potential implementation in practice.

**1.** The depth of analysis should be in proportion to the severity of risks of water shortage and the scale of potential investment in adaptation of the water resource system. Where risks (at present and in a changed climate) are small and no major investments are planned, then simplified approaches are justifiable. Our emphasis here is on situations where it is necessary to appraise major investment decisions.

**2.** Analysis of water supply should take full account of the current and future requirements for sustainable flows to support Good Ecological Status and other environmental safeguards. These requirements may change in a changing climate (Environment Agency 2009).

**3.** Analysis should focus upon prediction of the frequency of water shortages and other observable events that are directly related to customers. These events of relevance to customers are typically triggered by physical (and observable) thresholds within the water supply system (e.g. reservoir levels) being passed. A focus upon observable events is in contrast to current emphasis upon DO, which is not a directly observable quantity. Predicted frequencies of water shortages and other observable events that are directly related to customers can be compared with LoS, which are the target probabilities of water shortages that a water company seeks to ensure will not be exceeded [see also (7) and (8)].

**4.** The variability in hydrological conditions that may result in water shortages should be extensively explored using statistical analysis. This may be achieved through simulation of events (and sequences of events) of a range of different durations, spatial extents and severities. The probability of events more extreme than in the observed record should be estimated (along with accompanying uncertainties) and their consequences analysed.

**5.** The evolution through time of a range of possible futures should be explored. Within this simulation framework, water resource management options can be defined as adaptive strategies, where the occurrence of particular events triggers an investment or other management actions. In order to estimate the probabilities of relevant quantities (e.g. water shortages) in any particular year, it is necessary to do multiple simulations of sequences of years and aggregate the results for each year in the simulation.

**6.** Uncertainty analysis should be an integral aspect of the water resources calculation rather than being separated from the central estimates of uncertain quantities. Thus the water resources planning calculation should, through and through, be an uncertainty analysis. For climate uncertainties, a quantification already exists in UKCP09. For hydrological model uncertainties this may involve calibration/validation exercises in order to generate probability distributions for hydrological predictions of catchment runoff/supply. Uncertainty is dealt with by repeating the simulations in (5) for different samples of uncertain quantities (i.e. demand assumptions or climate change factors) (Lopez *et al*. 2009).

**7.** The key output is a distribution of the probability of shortages (corresponding to the trigger conditions for various LoS), in each year of the planning period. In other words, we recognise that, because of uncertainty, we cannot precisely predict the probability of shortages, but we can estimate a distribution of probabilities and use that to calculate the probability of failing to meet a range of LoS.

**8.** The probability of failing to meet a LoS (to a given number of customers) is an objective measure of the risk of water shortage. Investment by the water company is justified on the basis of reducing this probability of not meeting a LoS. Determining a tolerable probability of not meeting a LoS involves weighing up (in the broadest sense) adaptation costs with the consequences of water shortages, taking into account the interest of customers and shareholders, alongside externalities including the environment's need for water. There is a direct trade-off between the LoS and the probability of not achieving it: the higher the LoS (i.e. the lower the target probability of water shortages) the higher will be the risk of not achieving the LoS, all other things being equal. Thus determining the tolerable probability of not meeting a LoS needs to take place in tandem with the process of setting the LoS.

**9.** Even though uncertainty analysis is a central principle [see (6), above], responsible analysis will include careful sensitivity analysis to explore the implications of plausible variations in distributions and other assumptions (including interannual autocorrelation) and seek to identify water resources management options that are as far as possible robust to these residual uncertainties, in that the options perform acceptably well over the range of uncertainty (Dessai & Hulme 2006; Hall 2007; Manning *et al*. 2009).

The WRPG and other aspects of the regulatory regime are already based upon several of these principles (e.g. proportionality), but in other respects these principles imply a significant development of existing practice, most notably in the treatment of uncertainty and risk.

The flow diagram in Fig. 4 provides an overview of a simulation strategy for calculating the risk of water shortages in a changing climate. The approach involves multiple simulations of future series of rainfall, temperature, flow, groundwater levels and water supply for the years today to 2050. Each simulation is a different possible sequence of natural variability in rainfall and other weather conditions (U1), which evolves through time due to the changing climate change signal. This use of 'transient' WG simulations actually involves some extensions beyond UKCP09, though methods to do so have been developed (Burton *et al*. 2010) and are now being adapted to UKCP09. Simulation of the water resource management system predicts observable quantities (e.g. flows, reservoir levels and groundwater levels). If and when the value of these quantities trigger restrictions on water use (at various levels of severity), then this is reflected in the subsequent demand. The output from each simulation is a record of the relevant observable quantities of the water resource system and the timing and severity of any water shortages. Repeating this process for different simulated weather series enables an estimate of the probability of water shortages (at various levels of severity $L_i$), $P_t(L_i)$, in each year $t$ of the simulation to be built up. More simulations will enable more stable estimates of these probabilities to be obtained. Note that $P_t(L_i)$ will change from year to year due, for example, to the effects of changing demand, climate change and investment in new resources. We expect that changes in climate and demand will lead to relatively smooth changes in $P_t(L_i)$ between one year and the next, whereas commissioning of new resources may lead to step changes. For each year of the simulation $P_t(L_i)$, extracted from the simulations for year $t$, can be compared with the corresponding LoS, Si, to see whether, according to those simulations, the LoS will or will not be met.

As Fig. 4 illustrates, the process described in the previous paragraph needs to be repeated in order to test the effect of uncertainties (U2) in the assumptions that go into each simulation. Thus we generate multiple estimates of $P_t(L_i)$, so that the distribution of these multiple estimates reflects the uncertainty that previously has appeared in the headroom calculation. Figure 5 is an example of a histogram of estimates of $P_t(L_i)$ extracted from a simulation exercise of this type. It shows how in most of the results $P_t(L_i)$ is less than $S_i$, so in these cases the LoS is predicted as being met, while in a few cases it is not. The probability of not achieving a given LoS in year $t$ is our proposed measure of the risk of water shortages in that year. As illustrated in Fig. 4, if equally weighted

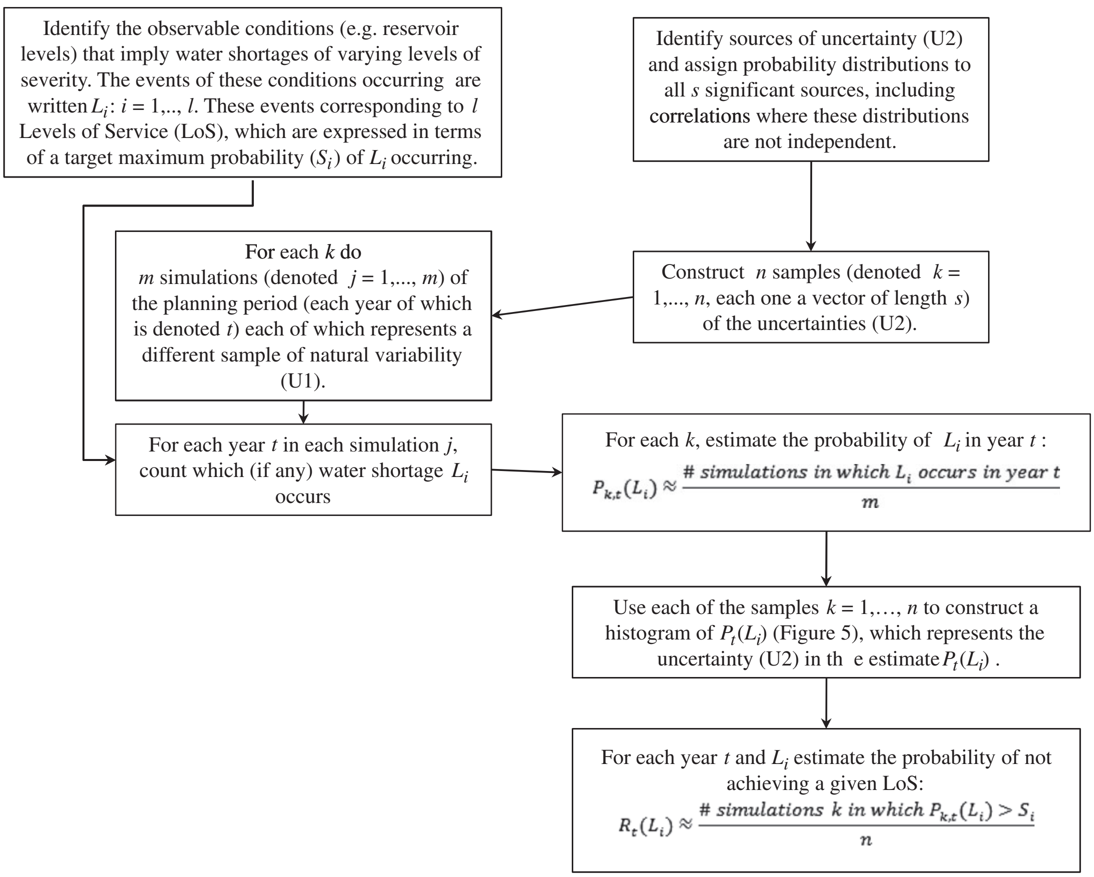


**Fig. 4.** Overview of a simulation strategy for estimating the risk of water shortages in a changing climate.

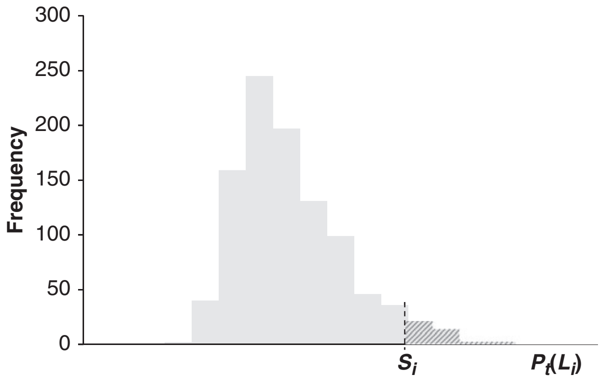


**Fig. 5.** Histogram of simulated probabilities $P_t(L_i)$ of water shortages of severity $L_i$ being imposed in year $t$.

Monte Carlo samples are used, this measure of risk can simply be estimated as the proportion of the total number of simulations that fail to meet the level of service. More formally, if $F_{P_t(L_i)}$ is the cumulative distribution function of $P_t(L_i)$ (which may be estimated empirically from the data shown in Fig. 5), then we define the risk, $R_t(L_i)$, in year $t$ associated with LoS $S_i$ as:

$$R_t(L_i) = 1 - F_{P_t(L_i)}(S_i). \quad (4)$$

If $R_t(L_i)$ is intolerably high then it will be necessary to propose water resource management options that cost-effectively reduce the risk. These options can be implemented in the water resources simulation and thus compared in terms of effectiveness in reducing $R_t(L_i)$. Identification of preferred options should be supported by sensitivity analysis of the robustness of the choice of options to major assumptions in the analysis.

## Conclusions

**(1)** In this paper we have set out how the current framework for WRMP in England and Wales may be updated to incorporate UKCP09 probabilistic projections. However, the emergence of UKCP09 has also provided a stimulus for a more fundamental re-evaluation of WRMP in England and Wales and an opportunity to recast it on a more transparent risk-based footing. While in this paper we have set out a number of reasons why the WRMP framework cannot be considered to be fully risk based, we have not sought to analyse the history for why this is the case, other than as far as has been necessary to explain the current approach to calculating headroom and analysing the impacts of climate change. The existing WRMP framework benefits from its simplicity and back-compatibility with deterministic approaches to balancing supply and demand that have existed in the water industry for more than half a century. However, as with other fields where deterministic approaches have been superseded by risk-based methods (such as in flood risk management and earthquake engineering), the risk-based approach ultimately offers a more rigorous approach to dealing with uncertainty and forms the basis for more efficient and transparent resource allocation and regulatory decisions. Moreover, a move towards a probabilistic simulation approach also provides more opportunity for statistical validation against observations, as the basis of the approach is the simulation of sequences of rainfall, flows, etc. and their observable consequences (e.g. water shortages of specified severity), rather than being focused upon generation of probability distributions of abstract quantities (such as DO) that are hard to validate.

**(2)** We have set out essential principles of a workable methodology: (1) the depth of analysis should be in proportion to the risks of water shortage and magnitude of proposed investment; (2) analysis should take full account of the current and future requirements for sustainable quantities of water for the environment; (3) analysis should focus upon prediction of the frequency of water shortages and other observable events that are directly related to customers; (4) variability in hydrological conditions that may result in water shortages should be extensively explored using statistical analysis and simulation; (5) analysis should be based upon simulation of sequences of events through time; (6) uncertainty analysis should be an integral aspect of the water resources calculation; (7) the key output of the uncertainty analysis is a distribution of the annual probability of water shortages (whose severity corresponds to the trigger conditions for various LoS); (8) these probabilities of failing to meet a LoS (to a given number of customers) is an objective measure of the risk of water shortage; and (9) the sensitivity of decisions to plausible variations in distributions and other assumptions should be scrutinised in order to identify options that are as far as possible robust to significant residual uncertainties. In particular, in relation to the ninth principle, we recognise that the probabilistic quantification of uncertainty in UKCP09 does not embrace all sources of climate uncertainty and is subject to a range of methodological assumptions, as is the case with other sources of uncertainty in water resources planning. However, far from undermining the risk-based approach presented here, the presence of significant residual uncertainty further underlines the need for a decision framework that can be used to evaluate sensitivity to assumptions and residual uncertainties and that can accommodate further quantification of uncertainties when it becomes available.

**(3)** In a short paper, it has not been possible to set out in algorithmic detail how a risk-based approach can be implemented. A worked example will be the subject of a subsequent paper. However, we have sketched a possible simulation approach that implements the risk-based principles. An inevitable consequence of this simulation approach is that water companies will have to do more modelling of their water resource system than they are accustomed to. The computation expense can be reduced through the adoption of efficient sampling strategies and using models that are appropriate for long-term strategic analysis. Extensive simulation studies will not be justifiable where the risks are small and the scale of future investment in water resources is negligible. However, English and Welsh water companies proposed at least £1.5 billion of investment in balancing supply and demand in response to climate change in their submissions to PR09 so adaptation decisions on this scale easily justify a modicum of analytical effort.

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