




# Risk-based water resources planning in practice: a blueprint for the water industry in England

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## Keywords

climate change; economics; modelling; prioritisation; risk assessment; simulation; water industry; water resources; water supply and demand.

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## Abstract

Resilient water supplies in England need to be secured in the face of challenges of population growth, climate change and environmental sustainability. We propose a blueprint for water resources planning that uses system simulation modelling to estimate the frequency, duration and severity of water shortages at present and in the context of future plans and scenarios. We use multiobjective optimisation tools to explore trade-offs between these risk metrics and cost of alternative plans, and we use sensitivity analysis to identify plans that robustly achieve targets for tolerable risk, alongside other performance objectives. The results of a case study in the Thames basin demonstrate that the proposed methodology is feasible given commonly available data sets and models. The proposed method provides evidence with which to develop water resource management plans that demonstrably balance the risks of water shortages, costs to water users and environmental constraints in an uncertain future.

## Challenges facing the water industry in England

Water companies in England are required to provide safe and wholesome supplies of water. The historic reliability of availability of those supplies, as measured by the security of supply index and reported annually, has been maintained to the levels required by the economic regulator Ofwat (2015a). Severe water shortages, involving widespread water rationing, have not occurred on a wide scale since 1976, although in 1995/96 Yorkshire Water had to truck water across the region when reservoirs in the west ran dry. In April 2012, after two dry winters, water availability in the south and east of England was less than during any historic drought and the situation only recovered thanks to the exceptionally wet summer (Parry *et al.*, 2013).

Looking to the future, increasing pressures on water supplies are foreseen in many parts of the country. Whilst per capita consumption (PCC) of water is declining, demographic change is pushing up overall demand in regions where population growth is strong, notably in the south-east. Water use for non-public water supplies is also evolving, with changing patterns of agricultural water use and new power generation plants replacing obsolete ones. The

impact of climate change on seasonal precipitation and droughts is a significant source of uncertainty, potentially threatening water supplies in future (Watts *et al.*, 2015). There is an evident upward trend in temperature, which will drive up potential evapotranspiration (PE) and hence increase aridity in future (Prudhomme *et al.*, 2012).

It is also recognised that water withdrawals from the environment exceed sustainable limits required to support healthy aquatic ecosystems. About 13% of river water bodies in England are failing to support Good Ecological Status, as defined by the Water Framework Directive, because of over-abstraction and about 42% of groundwater bodies in England are failing Good Groundwater Quantitative Status (Environment Agency, 2013). The Environment Agency's Restoring Sustainable Abstraction (RSA) process is seeking to identify, investigate and solve problems caused by unsustainable abstraction licences. Between 2008 and 2017, the Environment Agency revoked or made changes to 523 licences in England amounting to some 123 ML/day of reductions in licenced abstractions (Defra, 2017). An upper scenario indicates the possibility of more than 2000 ML/day of reductions in licenced abstractions (Water UK, 2016). These reductions, which are necessary to ensure the sustainability of the aquatic

environment and the ecosystem services that it provides, will intensify pressures on the public water supply.

In view of these converging pressures of demand, climate change and unsustainable abstractions, the 2014 Water Act introduced a duty to secure the long-term resilience of water supply systems. Analysis by Water UK (2016) has demonstrated that current levels of resilience are variable between different regions of the country. Some regions have sufficient water resources and infrastructure in place to make water rationing very unlikely in any event. By contrast, other regions would have to impose severe restrictions if there were a prolonged dry spell just slightly longer than seen previously or at a different time of year.

The Water UK study explored a wide range of options for enhancing resilience, promoting a 'triple track' approach that incorporates (i) demand management (including further efforts to reduce leakage from the supply network), (ii) development of new/extended resources and (iii) inter-regional water transfers (Water UK, 2016). A similar combination of interventions was also proposed by the National Infrastructure Commission (2018). Thus, some major investment decisions, together with a plethora of smaller adaptations, are expected to be needed to ensure resilient water supplies in England over the coming years.

Conventional approaches to water resource planning, as the basis for securing investment and the necessary permissions for new infrastructure, have served the England & Wales water industry well since privatisation in 1989. The use of representative estimates of water supply and demand is grounded in the long tradition of engineering hydrology, which simplified the water supply problem to comparing a single value of supply, or yield, with annual demand (Law, 1955). Simple estimates of supply-demand balance will naturally be the starting point for water resources assessment. Testing systems with respect to historic droughts has proved to be an effective way of communicating the severity of conditions that a system is designed to cope with. However, there is general recognition that current methods are no longer adequate given the changes and uncertainties already referred to.

In this paper, we argue that the principles for water resource planning are now in need of fundamental reform if future plans are to transparently and robustly meet the requirement for resilience of the water supply system. Methods to quantify risk and test the resilience of alternative management plans are now well established. In this paper, we set out a blueprint for risk-based water resource planning in England and demonstrate the approach with a simple example for identifying the portfolio and sequence of investments that would deliver a resilient water supply system. We hope that this blueprint will form the basis for a reformed approach to water

resources planning to be adopted in advance of the 2024 regulatory price review, by which time a new set of Water Resources Management Plans (WRMPs) will need to have been developed. This paper is targeted at practitioners with responsibilities for the England's municipal water supplies. However, it will be of interest to a broader global audience interested in practical application of methods to test the resilience of water supply systems and support investment decision making.

The paper is organised as follows. The next section reviews current arrangements for water resources planning in England. Section 'Innovations in planning methodologies and tools' provides a brief summary of the major methodological innovations in water resources planning that have emerged in the last decade and is equivalent to a short literature review. Sections 'Definitions and metrics of resilience and risk' and 'Principles for resilient water resource management planning' describe the conceptual and methodological underpinnings of the risk-based approach. These methods are then applied to the Thames basin in Section 'Example for the Thames basin', where the results of the paper are presented. Section 'Discussion and conclusions' discusses the results and concludes.

## Current arrangements for water resources planning in England

Water companies' WRMPs are expected to conform to the Environment Agency's Water Resources Planning Guideline (WRPG) (Environment Agency, 2016). The 2016 WRPG is simplified and less prescriptive than previous editions, being based on the principles which combine:

- (1) A baseline supply forecast, which includes an assessment of water available for use from current sources. This is based on supplies that can be maintained through a design drought.
- (2) A baseline demand forecast covering water use by people and businesses and leakage. This is based on forecast 'dry year annual average demand', when demand for water is at its highest before water use restrictions are imposed.
- (3) An allowance for uncertainty relating to the supply and demand forecasts. The 2016 WRPG includes a range of possible methods for dealing with uncertainty, including risk-based tools (UKWIR, 2016b) and decision making (UKWIR, 2016a) as well as older deterministic and quasi-probabilistic methods for assessing headroom (UKWIR, 2002b).

The reliability target for water availability is defined in terms of a series of Levels of Service (LoS) which are the target for the maximum frequency with which water com-

panies will impose restrictions including temporary use bans (formerly hosepipe bans), non-essential use bans and severe water rationing. Options for maintaining security of supply into the future and enhancing system resilience are appraised with respect to their cost-effectiveness. The default approach is the least cost Economics of Balancing Supply and Demand (EBS) (UKWIR, 2002a; Padula *et al.*, 2013) method. The plan for delivering both the supply-side and the demand-side investment options to maintain a supply-demand balance across the whole planning period is reported to the Environment Agency and informs a water company's Business Plan submission to Ofwat.

The metric of supply reliability in the current planning arrangements is deployable output (DO) which is the maximum rate at which a system can supply water continuously through a dry period with a known or assumed severity. However, given that the system is continuously varying, the estimated steady-state yield is an abstract quantity that cannot be empirically measured and whose relationship with resilience is ambiguous at best. Estimates of DO are conditional upon the assumed LoS and other assumptions that are not always transparent. Moreover, the use of DO in EBS is misleading because it implies that DO varies linearly and aggregates additively across systems, neither of which are true, in particular in the context of extreme droughts.

The 2016 WRPG is a significant step beyond previous editions, given its explicit acknowledgement of methods for analysing risks and resilience. However, nowhere does the WRPG actually require water companies to report on their level of risk, in terms of their assessment of the likelihood, duration and severity of water shortages, at present or in a range of future scenarios. In view of the duty of resilience, transparent reporting of the risks of water shortages seems to be a reasonable baseline requirement (Hall and Borgomeo, 2013).

## Innovations in planning methodologies and tools

There has been considerable innovation in methodology for water resources management and planning, both in the United Kingdom and around the world. There is a clear divergence between approaches based on bulk water balance calculations (like EBS) and methods based upon system simulation modelling (Matrosov *et al.*, 2013a). Simulation modelling provides the best available approach to analysing risk and testing resilience, because it is possible to accurately test how systems respond to dynamically evolving conditions through time (e.g. multi-year droughts). Simulation modelling also enables exhaustive testing of many combinations of plausible future conditions. We now believe that these methods are sufficiently

mature to form the basis for standard methods for water resources planning.

Meanwhile, there have been major developments in methods for decision making under uncertainty, including robust decision making (Lempert *et al.*, 2003; Dessai and Hulme, 2007), decision scaling (Brown *et al.*, 2012), real options analysis (NERA, 2012; Erfani *et al.*, 2018), dynamic adaptive policy pathways (Haasnoot *et al.*, 2013; Kingsborough *et al.*, 2016; Kingsborough *et al.*, 2017) and info-gap analysis (Matrosov *et al.*, 2013b). Several of these have been piloted by, or in collaboration with, water companies in England and are documented in recent UKWIR reports (UKWIR, 2016a; 2016b). Although the application of these approaches has resulted in a proliferation of jargon, a shared set of principles have emerged from the piloting of these methods:

- (1) extensive testing of the full range of uncertainties to which a system might be exposed, to reveal vulnerabilities and sensitivities;
- (2) identification of solutions that are robust to uncertainties, in the sense that they perform acceptably well under a wide range of plausible future conditions. Robustness may be achieved by the introduction of flexibility (optionality) within plans that are deliberately designed to be adaptive.

Also of relevance has been increasing attention to the multiple objectives and constraints of water resources planning decisions, which it is now possible to explore with multiobjective optimisation routines (Mortazavi *et al.*, 2012; Mortazavi-Naeini *et al.*, 2014; Borgomeo *et al.*, 2016; Giuliani and Castelletti, 2016) and visualise the associated trade-offs between different objectives (Matrosov *et al.*, 2015). Practical application has demonstrated the fragility of solutions that are apparently optimal in the EBS methodology (Matrosov *et al.*, 2013a), whilst there may be only slightly suboptimal solutions that perform much better with respect to other criteria.

## Definitions and metrics of resilience and risk

The Task and Finish Group established by Ofwat in 2015 defined resilience as '*the ability to cope with, and recover from, disruption, and anticipate trends and variability in order to maintain services for people and protect the natural environment now and in the future*'. (Ofwat, 2015b). This definition addresses two timescales over which resilience is of concern:

- (1) in the build up to and during disruptive events, including droughts, during which actions (including those

- in water company drought plans) are adopted to anticipate disruption and enable coping and recovery;
- (2)** on longer timescales to 'anticipate trends and variability' in order to put in place longer term plans to maintain services for people and protect the natural environment now and in the future.

The WRMP process is obviously one of the main mechanisms for ensuring resilience on the second timescale. Repeating the WRMP process every 5 years enables adaptation to new knowledge about trends and variability.

As part of the WRMP process, it is necessary to assess system response to possible droughts (including those that have not been observed, of varying severity, as well as historical droughts), both at present and on a range of different timescales in the future. Thus consideration of system resilience on timescale (1) is essential to delivering resilience on timescale (2). The interaction between these timescales means, for example that a commitment to activating drought plans earlier in a drought (and thus incur more 'false alarms') could reduce the need for possibly costly longer term actions. Our proposed approach involves extensive simulation of possible drought conditions together with drought plans and other responses that would be adopted during those simulated droughts, as the basis for comparing the resilience of alternative plans.

## Principles for resilient water resource management planning

We propose that transparently and cost-effectively planning for the resilience of water resource systems requires:

- (1) Quantification of the risks of harmful outcomes of water shortages**, based on metrics (and accompanying uncertainty bounds) of the frequency, severity and duration of shortages, at present and in future scenarios.
- (2) Testing alternative plans to demonstrate their cost-effectiveness in reducing risk under a range of possible future scenarios**, in order to identify a plan whose costs are demonstrably proportionate to the risks, whilst satisfying other requirements for system performance.

Reporting metrics of risk requires extensive and explicit simulation of hydrological variability, extending well beyond historic droughts to include worse than observed conditions. The methodologies are available to do this either via stochastic streamflow (Borgomeo *et al.*, 2015a; Herman *et al.*, 2016) and groundwater simulation (Mackay *et al.*, 2014), or via regional climate simulations (Guillod *et al.*, 2017) or weather generators (Glenis *et al.*, 2015)

coupled with rainfall-runoff and groundwater models. For spatially extensive systems this will involve consideration of spatial variability in the simulations (Serinaldi, 2009). Other significant sources of uncertainty that need to be included in scenario analysis include uncertainties in population, PCC (for given demand management policies), changed abstraction licences and availability of water from neighbouring water utilities.

Hydrological simulations and demand projections need to be coupled to an efficient water resource system model, of which several exist (Kuczera, 1992; Matrosov *et al.*, 2011), which simulates abstraction arrangements, water allocation and discharges. For risk analysis and optimisation, fast-running 'behavioural' models that exclude some of the details of system operation are more efficient than detailed operational models (Haasnoot *et al.*, 2012). Nonetheless, rules to represent the main elements of drought plans (e.g. restrictions, drought permits and drought orders) need to be simulated in the system model. Where water quality is a potential constraint on abstractions, in particular during droughts, then it can be explicitly included through rainfall-runoff and river water quality simulation (Bussi *et al.*, 2016).

Accompanying uncertainties should be explored:

- (i) probabilistically for those uncertainties for which estimates are available, notably the UKCP09 climate projections and the next generation of UK climate projections;
- (ii) using scenarios for those uncertainties for which likelihoods are hard to estimate e.g. population growth, PCC for given demand management policies, land use change, water availability from neighbouring companies and changes to abstraction licences.

Combining these approaches will yield ranges of probabilities to represent uncertainty in key variables, as illustrated in the next section. Systematic sampling of uncertainties enables sensitivity analysis and isolation of the most influential sources of uncertainty (Pianosi *et al.*, 2016). Combining simulation modelling with probabilistic treatment of uncertainty provides a framework for representation of dynamic (possibly weather-related) changes to demand and for inclusion of other sources of uncertainty, for example outage because of plant failure.

The components set out above can be used to simulate large numbers of future time series of system operation, under given conditions. The frequency, severity and duration of restrictions can be simply counted within these simulations. Stable estimates of the frequency can be obtained by repeated simulation with different realisations of stochastic variability.



This simulation approach provides the basis for testing alternative plans. Preliminary screening of an initial long list will eliminate proposals that are obviously not viable, resulting in a feasible option list which is subject to secondary screening and preliminary studies, which will further eliminate some options, whilst also providing the information on costs, operation rules and reliability that are needed for simulation. Where an option may be implemented at a range of different scales (e.g. leakage reduction programmes) then a cost curve is required to indicate how costs vary with the scale of the programme. Costs need to be articulated in terms of capital and operational expenditure over the planning horizon.

After these two screening stages, the testing of combinations of options in a plan can commence. Given the large number of possible combinations and sequences of options, in all but the simplest of cases it will be necessary to employ optimisation tools like genetic algorithms. Our focus here is upon multiobjective optimisation, as we wish to explore explicitly the trade-off between risk and cost. This trade-off is an inevitable aspect of water resources planning.

A judgement on the level of tolerable risk will be arrived at in the light of exploration of trade-offs between risk and cost. Water companies use four levels to categorise the severity of demand restrictions, with Level 4 (standpipes) being the most severe. An initial target (e.g. a maximum annual probability of 0.005 for Level 3 or Level 4 restrictions) might provide a starting point for exploring this trade-off, but a higher standard could be justified, depending on the consequences and the marginal cost of risk reduction. Exploration of this trade-off should be the subject of deliberation by water companies with their regulators, customers and other stakeholders in order to identify a target level of risk.

There will be a subset of plans that are consistent with the target level of risk at 'near-least-cost' (i.e. their cost is within some small margin of the least cost plan). This near-least-cost set is then subject to further exhaustive scrutiny to explore sensitivities to key uncertainties (e.g. population growth, changed abstraction arrangements). It is possible to use multiobjective optimisation tools to automate that sensitivity analysis, for example by seeking options that minimise the maximum risk over the range of future scenarios (see below). That sensitivity analysis will help to identify a plan that cost-effectively achieves a tolerable level of risk of water shortages, whilst being reasonably robust to future uncertainties.

Reporting should present:

- (1) Baseline analysis of risk of shortages for the present system for a range of future scenarios e.g. climate, population, PCC, etc.

- (2) Results of multiobjective optimisation (trade-off curves between risk and cost over the life of the plan), which inform the identification of the tolerable level of risk.
- (3) Agreed level of risk and the near-least-cost plans that satisfy this target.
- (4) Sensitivity analysis of the near-least-cost plans to identify the preferred plan, which is robust to future uncertainties.
- (5) Metrics of risk for the preferred plan, for a range of future scenarios, illustrating key uncertainties and sensitivities, and explaining how the plan could be adapted if particular scenarios materialise.

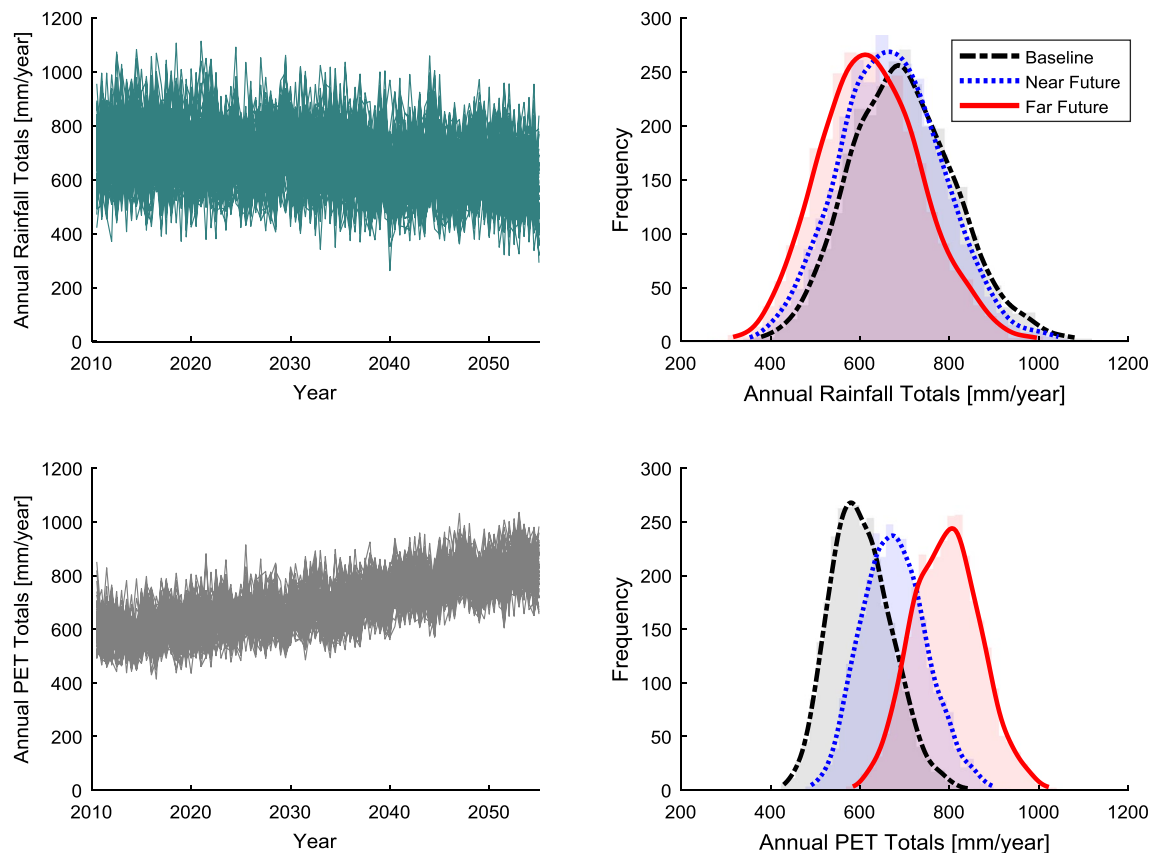
## Example for the Thames basin

To illustrate the concepts and feasibility of the proposed planning approach, we use the example of the Thames basin, including the Swindon and Oxfordshire (SWOX) and London water resource zones, which has an area of 9948 km<sup>2</sup>. The system is supplied primarily by surface water abstraction from the river Thames, directly or via pump storage reservoirs, and by ground-water abstraction from the Chalk Aquifer. Thames Water serves approximately 9 million people in these water resource zones (Thames Water, 2014). Thames Water has recently published its draft Water Resources Management Plan (dWRMP), which employs methods that are consistent with the 2016 WRPG. The example reported here is presented for illustrative purposes and does not in any way supersede anything published in the dWRMP.

## Hydrological simulations

Stochastic hydrological simulations for the Thames basin exist based on (i) the UKCP09 weather generator (Glenis *et al.*, 2015) (ii) stochastic streamflow simulation (Borgomeo *et al.*, 2015a; 2015b) and (iii) new regional climate model runs, which have delivered a large ensemble of spatially coherent synthetic drought simulations (Guillod *et al.*, 2017).

The example presented here is based upon two sets of projections from the new regional climate model runs of weather@home2 (Guillod *et al.*, 2017). The first set, referred to as 'near future', represents climate projections for the period 2020-2050. The second set, called 'far future', represents projections for climate conditions in 2070-2100. Each set of projections contains 100 weather sequences of daily rainfall and PE for the 30-year period. As shown in Fig. 1, outputs from weather@home2 project a significant increase in evapotranspiration across the Thames basin and a minor shift towards lower annual total rainfall.



**Fig. 1.** Total annual Rainfall and PET (Potential Evapotranspiration) times series (left) and frequency distributions (right) spatially averaged over the Thames Basin. Frequency distributions are for three different time slices: baseline (1961–1990), near future (2020–2050) and far future (2070–2100). Generated using data from Guillod et al. (2017). [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

The regional climate model outputs have been propagated through the INCA rainfall-runoff model (Whitehead *et al.*, 1998; Futter *et al.*, 2014). Uncertainties in the parameterization of INCA have been explored by sampling calibrated model parameters (Bussi *et al.*, 2016; 2017). Groundwater yields have been taken from Thames Water's estimates, although enhancements in groundwater modelling should enable more integrated simulation of the sensitivity of groundwater and surface water resources to climatic factors.

### Water resource system simulations

In this example, we use the WATHNET model (Kuczera, 1992; Mortazavi *et al.*, 2012) which is one of several flexible simulation modelling tools that enable large numbers of simulations coupled with multiobjective optimisation. The WATHNET model includes a simplified version of Thames Water's abstractions, storage facilities and discharges, as shown in Fig. 2. The model is driven by naturalised flow simulations at 12 points on

the Thames and is well calibrated against reservoir levels at Farmoor and Datchet (Water UK, 2016), based on an approximation of Thames Water's operation and control rules. In all, the WATHNET model contains 31 nodes. Twenty-five years of simulation on daily basis take approximately 4 min to run on a standard PC. As well as running on a standard PC the model has been implemented on a Linux cluster, which means that the number of simulations that may be run for uncertainty analysis and optimisation is practically without limit. Similarly, low-cost parallel computation could be achieved using cloud computing resources.

### Demand projections

Population growth in London and the Thames basin is one of the main sources of uncertainty for water resources planning in the area. Three population growth scenarios based on projections from Thames Water were adopted alongside four PCC scenarios based on Water UK (2016) (Fig. 3):

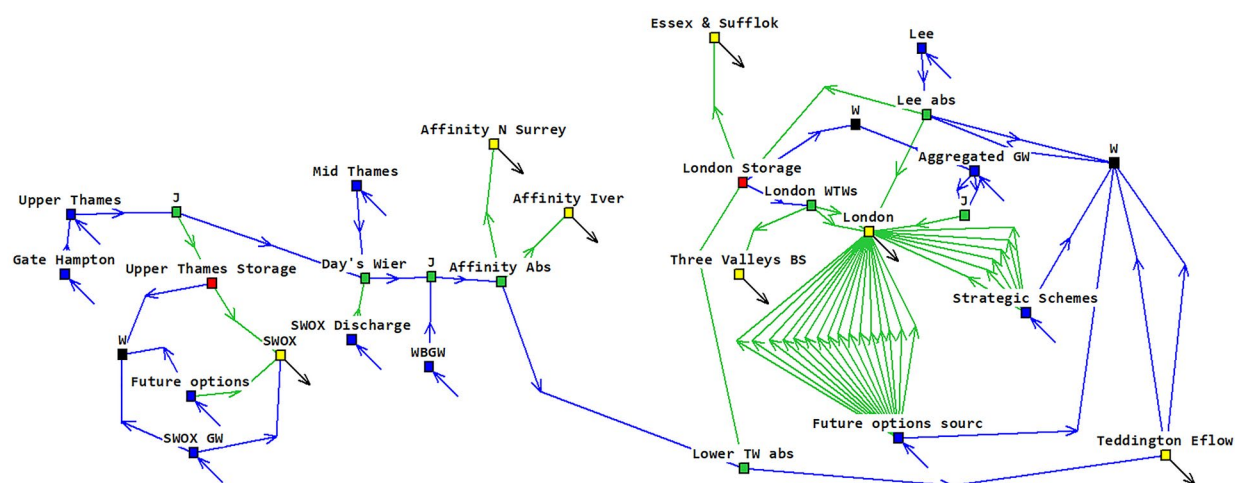


Fig. 2. Schematic representation of the Thames water supply system in the WATHNET platform. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

- (1) **'Business as Usual' (BAU), Upper:** this represents the situation that would occur if water companies continue with their current policies and methods for reducing demand, but the societal and policy support for demand management is low.
- (2) **'Business as Usual' (BAU), Base:** as above, but with a greater degree of societal and policy support. The PCC levels for households without meters under this scenario are shown with a black line in Fig. 3.
- (3) **Extended:** this represents an ambitious extension to demand management, incorporating initiatives such as the use of differential tariffs to help reduce demand.
- (4) **Enhanced:** this represents a 'stepped change' in demand management, incorporating initiatives such as

grey water reuse and much tighter controls on water efficient design for new households.

Seasonal and weather-dependent variations in demand (HR Wallingford, 2012) can be included within the water resource system simulation to represent dynamic (and possibly weather-dependent) changes in demand.

Non-household demand has been scaled by projected GVA for each economic sector. Given the relatively small proportion of non-household demand (about 1%) for public water supply, the effects of changing water intensity in production have not been explored.

### Baseline system risk

In our reporting of the risk of shortages, we focus upon Level 3 and Level 4 restrictions on water use, as these have the most significant impact for people and the economy. Figure 4 present metrics of risk in terms of frequency (Fig. 4, top panel) and duration (Fig. 4, bottom panel) of Level 3 restrictions on water use.

These risk metrics have been calculated with the hydrological and water resource system models described above. Thames Water's system simulations may yield slightly different results. The results are included as examples of the presentation of risk metrics and should not be taken as a definitive analysis of the Thames system.

### Analysis of alternative plans

We consider the supply options included in Thames Water's, 2014 WRMP along with the four levels of PCC illustrated in Fig. 3 (each with associated costs) and a cost curve

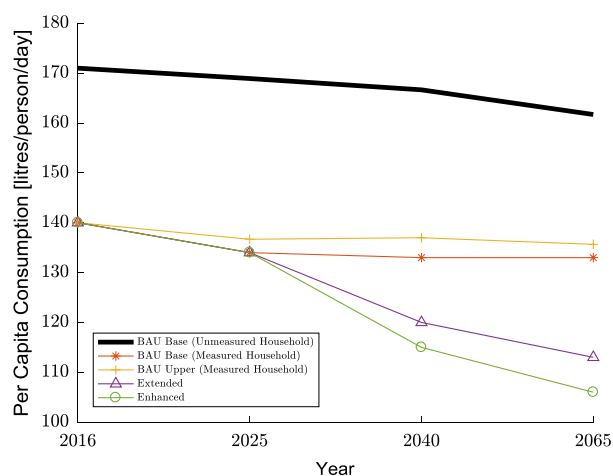
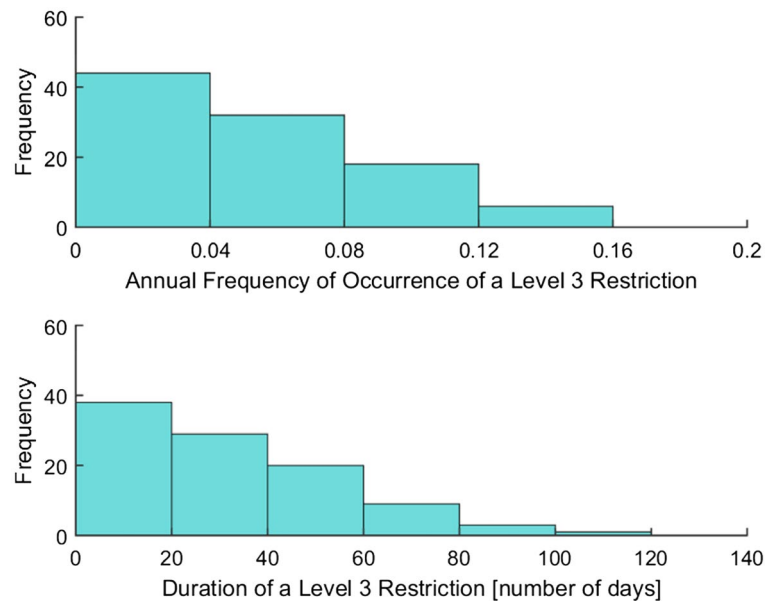


Fig. 3. Per capita consumption projections (litres/person/day) for four demand management scenarios for the London Water Resource Zone (adapted from Water UK, 2016b). [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

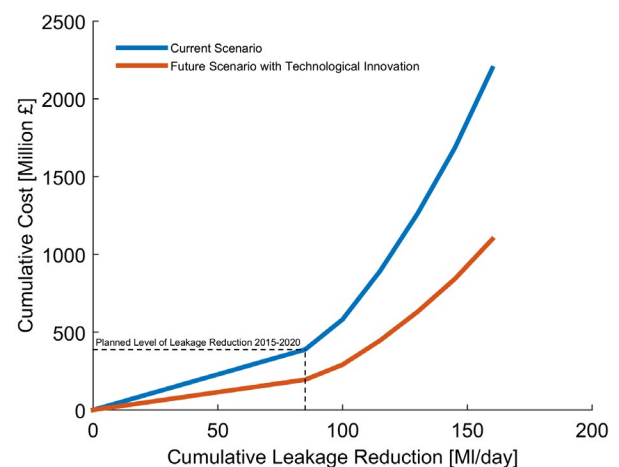


**Fig. 4.** Histogram (top) of the annual frequency of occurrence and (bottom) of the duration of a Level 3 restriction obtained under 100 near-future climate scenarios and a medium growth population scenario. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

for leakage reduction (Fig. 5). To simplify the presentation here, the list of possible supply options was filtered down to the 15 options listed in Table 1 each of which could be implemented in any year of the 25 year plan, subject to an appropriate lead time for planning, design and construction which is shown by the 'earliest start date'.

So far, we have considered the frequency, severity and duration of water shortages as our risk metrics. To simplify the presentation, we wish to condense this into a single risk metric. We have performed this by weighting L3 and L4 restrictions by their economic consequences (estimated to be £6.8 million per day for L3 and £282 million per day for L4) (Lambert, 2015). These estimates are developed on the basis of users' willingness to pay to avoid a day of restriction of a given severity. These estimates need to be treated with caution, as willingness to pay surveys yield a wide range of valuations (Hensher *et al.*, 2006) and have not, as far as we are aware, considered willingness to pay to avoid prolonged restrictions which will not necessarily scale linearly with duration.

Multiobjective optimisation of all of the possible combinations and sequences of plans yields the trade-off curves between risk and discounted TOTEX cost shown in Fig. 6. Figure 6 illustrates the Pareto frontier of all non-dominated solutions, that is plans that cannot be improved upon with respect to one objective (restriction cost) without sacrificing the other objective (total cost of the plan). There are many less cost-effective plans that



**Fig. 5.** Cost curve for leakage reduction for the Thames basin system, showing a variant which includes a future scenario with technological innovation which decreases the costs of leakage reduction. Source: Thames Water (2016a). [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

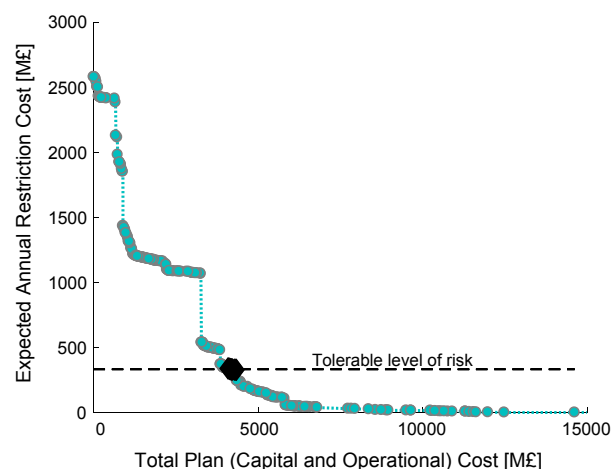
exist to the right of the frontier, but it is impossible to reduce cost (or risk) without incurring higher risk (or cost). The position of this frontier depends upon the assumptions in the modelling. It would be shifted if innovation enabled options to be delivered at lower cost. However, the possibility of innovation and cost reduction does not eliminate the inevitable trade-off between risk and cost – it simply shifts the Pareto frontier.



**Table 1** Short list of supply options considered. Options that are members of the 'near least cost' set of options to meet the target for tolerable risk are shaded

	Solution name	Capacity (ML/day)	Total capex (£k)	Total opex (k£/y)	Earliest start date
1	Base Raw Water Transfer Deerhurst to Cricklade	0,100,300,600	0-47268	0-3128	2027
2	Raw Water Transfer Deerhurst to Radcot	0,100,300,600	0-39972	0-2844	2027
3	Base Raw Water Transfer Lechlade to Culham	300	16899	1264	2027
4	Direct River Abstraction – Teddington to Queen Mother	300	6601	702	2027
5	Desalination South Thamesmead to Coppermills	0,150,300	0-12850	0-832	2023
6	New Reservoir Abingdon 75 Mm <sup>3</sup>	0,24,141	0-44947	0-1527	2032
7	New Reservoir Abingdon 150 Mm <sup>3</sup>	0,20,274,283	0-96875	0-3262	2032
8	New Reservoir Abingdon 75 + 75 Mm <sup>3</sup>	151	55277	1938	2032
9	Desalination North Beckton RO Treatment Plant	150	22275	7091	2024
10	Base Reuse Beckton	0,100,150,200,300	0-39370	0-4307	2022
11	Direct River Abstraction – Three Mills Lock Potable to Service Reservoir	75	1611	4087	2023
12	Direct River Abstraction – Culham Supply	4.5	2257	290	2022
13	Base Reuse Deephams	60	8779	1411	2022
14	Base Raw Water Transfer Draycote	25	0	2534	2027
15	Base Raw Water Transfer Minworth	88	0	6671	2027
16	Base Raw Water Transfer Mythe	15	0	147	2027
17	Direct River Abstraction – Three Mills Lock Potable to Service Reservoir	150	1611	255	2023
18	Desalination South Thamesmead RO Treatment Plant	0,150,300	0-32922	0-13098	2024

Source: Thames Water (2016a).



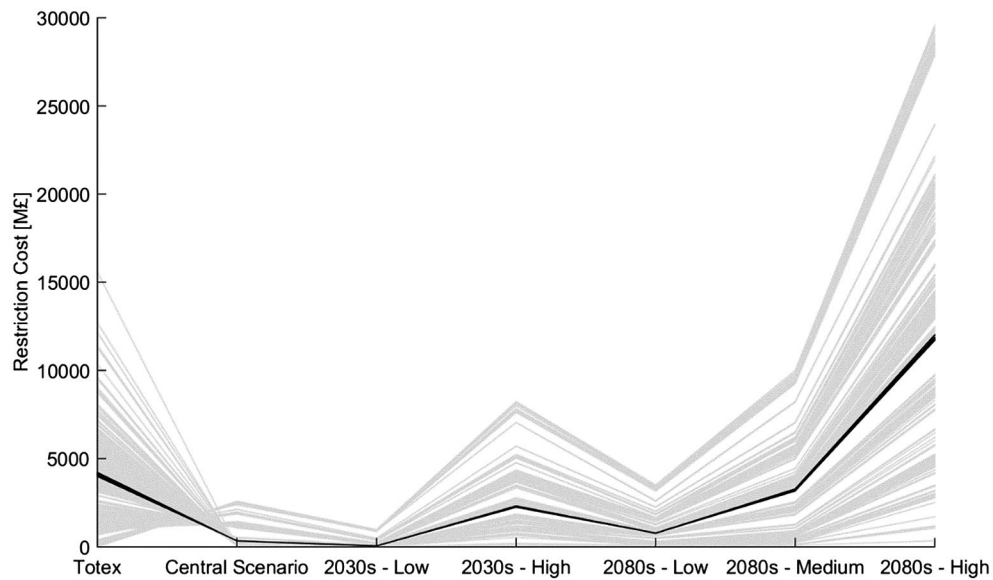
**Fig. 6.** Trade-off between risk (expected annual Level 3 and 4 restriction cost) and cost (discounted TOTEX) for a near-future climate scenario (2030s) and a medium population growth scenario. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

In Fig. 6, we have shown a hypothetical tolerable risk threshold which would be arrived at through deliberation by the water company, their regulators and their customers regarding the tolerability of risk. We have subjected the plans that are near to this tolerable risk threshold (black points in Fig. 6) to further scrutiny to explore their sensitivity to major uncertainties and assumptions. The parallel coordinate plot (Fig. 7) shows

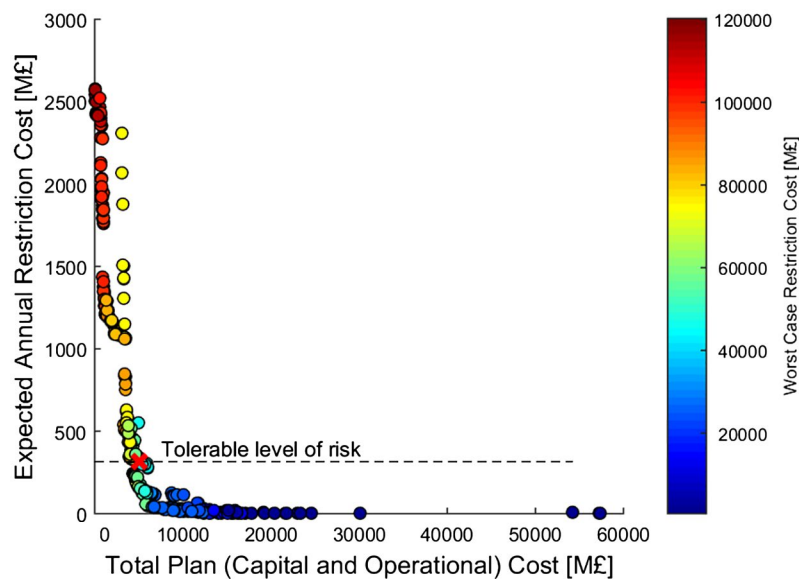
the cost of each plan and its performance (using the same monetised risk metric as previously) in a range of future climate and population scenarios. This approach can be extended to include other variables that are interesting for sensitivity analysis.

Whilst plans that reduce overall risk tend to reduce risk also in the worst-case scenarios, some plans are more effective than others at minimising risk across all scenarios. We have used multiobjective optimisation to seek plans that minimise the worst-case (across all scenarios) risk as well as minimising cost for a given tolerable level of risk in the central scenario (Fig. 8). These plans are as robust as they could be to future uncertainties. There is an inevitable trade-off between cost and robustness, as illustrated by the Pareto frontier in Fig. 9. Figures 8 and 9 illustrate the cost penalty that needs to be incurred to achieve a more robust plan. Scrutiny of this type of plot will help to identify plans that efficiently achieve the tolerable level of risk and are also robust to future uncertainties. One such plan is highlighted in Fig. 8 (red cross in Fig. 8), which Fig. 9 illustrates has close to the lowest worst-case restriction cost, so seems to be a good compromise between cost and robustness.

Figure 10 illustrates the simulated performance of this preferred plan (red cross in Fig. 8), compared to the current system, and its sensitivity with respect to climate change and population growth. Recall however that the



**Fig. 7.** Illustration of the performance of near-least-cost plans evaluated under near-future climate projections and a medium population growth scenario that achieve the tolerable level of risk in Fig. 6. Performance is evaluated as the expected cost of Level 3 and Level 4 restrictions estimated over a combination of climate scenarios (near future 2030s or far future 2080s) and population growth scenarios (low, medium and high).

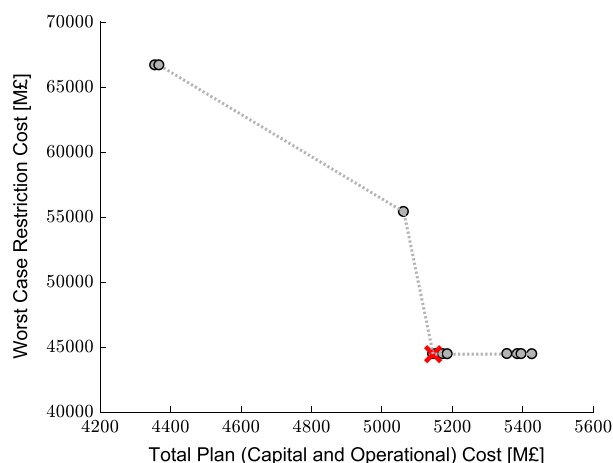


**Fig. 8.** Trade-off between risk (measured as expected annual Level 3 and 4 restriction cost), total plan cost (discounted TOTEX) and robustness (measured as worst-case restriction cost) for Pareto-optimal plans across all scenarios (all possible combinations of climate and population scenarios). [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

plan will be re-evaluated every 5 years, providing the opportunity to adapt it in the light of observed changes and new projections, so in practice the sensitivity to future uncertainties will be reduced through these cycles of adaptation.

## Discussion and conclusions

Public water supplies in England face major challenges. Significant investments and other policy initiatives are being planned to address those challenges. Methods for



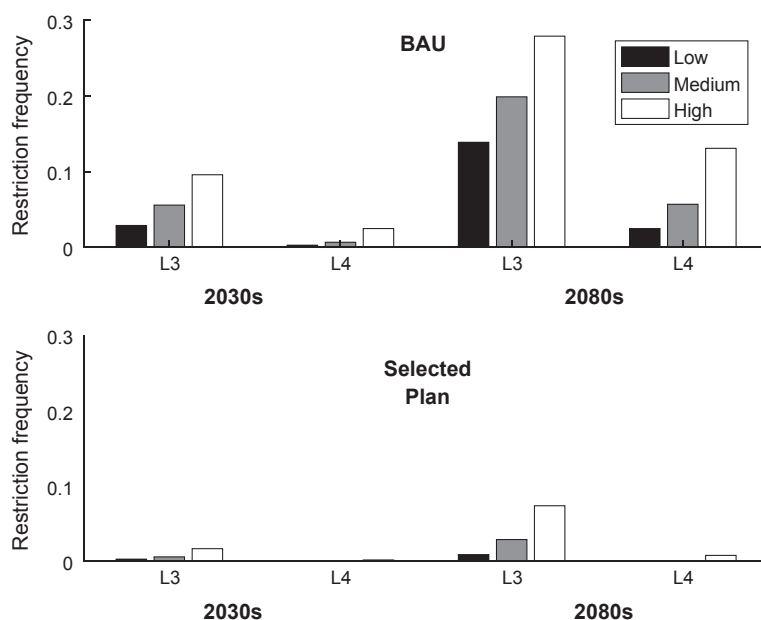
**Fig. 9.** Trade-off between total plan cost (discounted TOTEX) and robustness (measured as worst-case restriction cost) for tolerable level of risk shown in Fig. 8. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

appraisal of water resource management plans have steadily evolved since privatisation of the water industry. The latest version of the Water Resource Planning Guideline requires comprehensive assessment of the effects of uncertainty and scenario analysis to test the robustness of proposed plans. However, water companies are not required to report the level of risk (in terms of the expected frequency, duration, severity and impacts of restrictions on water use) of their plans. Given the

duty of resilience that has been placed on the sector, explicit analysis of risk should become a standard requirement for reporting and comparing alternative plans. After a period of innovation in water resources planning, the time is now ripe for the water industry and its regulators to move to an explicitly risk-based framework for cost-effectively ensuring the resilience of public water supplies.

Identification of preferred plans involves trading off the cost of the plan with the level of risk of water shortages. The tolerable level of risk will require judgement to be made by the water companies and regulators, in view of multiple objectives and the options at their disposal. We have therefore proposed an appraisal methodology that presents the trade-offs between risk and cost, and then for an agreed level of risk scrutinises a small set of near-least-cost plans that achieve that tolerable level of risk. Criteria of robustness to uncertainty and performance with respect to other objectives can also be taken into account to narrow the near-least-cost plans down to the preferred plan.

We have proposed a set of methods that could be realistically implemented by all water companies by the time they prepare their 2024 Water Resource Management Plans. Companies facing particular challenges in the 2019 planning period will already be adopting these approaches for their plans: the latest version of the Water Resource Planning Guideline provides flexibility to do that.



**Fig. 10.** Projected performance (top) under business as usual conditions and (bottom) under the selected plan: annual frequency of Level 3 and Level 4 restrictions including the effects of climate change, for three population growth scenarios (low, medium and high).

The methodology that we have proposed and demonstrated is feasible given widely available models and tools. There are many well-proven approaches to hydrological simulation, water resource system modelling, optimisation and sensitivity analysis. The simulations can be performed quickly and cheaply, even for complex systems, using computer clusters or cloud computing. Visualisation tools enable consistent reporting of risks and transparent evaluation of investment plans. We have provided a concise example to illustrate how the principles might be implemented, but there are many ways of implementing these principles, which water companies will wish to tailor to their own circumstances. The emergence of common hydrological data sets (Prudhomme *et al.*, 2013) and drought simulation libraries (Guillod *et al.*, 2017) provides the basis for consistency between approaches, which is important for regulators who are seeking to compare plans.

We have not sought to explicitly explore trade-offs between the resilience of public water supplies and water requirements for the natural environment. Those trade-offs are for the time being handled via abstraction regulations. If there was better scientific knowledge about the response of aquatic ecosystems to water shortage and other stresses, it would be possible to incorporate ecological status more explicitly into the appraisal of risks and trade-offs. That could open up opportunities for mutually beneficial strategies for joint management of societal and ecosystem resilience to droughts.

We recognise the challenges of communicating probabilistic approaches to non-technical decision makers. For these audiences (who are not the intended readership of this paper), the intuitive notion of a supply-demand balance is a useful starting point, although it is also important to communicate the significance of hydrological variability and the possibility of droughts that are worse than have been previously observed. Simulating system performance in observed droughts is a good way of adding realism to simulation results – even though memories of 1976 are fading. Nonetheless, the trade-off between risk and cost, which is central to our proposals, should be accessible to every decision maker, especially those with financial responsibility on water company boards and in economic regulators.

We emphasise that whilst the methodologies we propose are deliberately intended to enable the exploration of uncertainty, there is a continued need to *reduce* uncertainties, in particular through improved field monitoring, drought response exercises, surveys and validation of models. Drought exercises can help to test assumptions in drought plans. Every drought is an opportunity to verify estimates of flows, groundwater levels, reservoir levels, water consumption and economic

and environmental impacts, and to scrutinise whether the water supply system performed as expected. Universal metering will provide greatly improved information on water consumption and leakage. Continued data acquisition will enhance understanding of variability and trends, which will in turn enable improvements in the simulation models upon which water resources planning increasingly depends.

Finally, we note that we have in this paper focused upon technical approaches to quantify risks and appraise water resource management problems, which is part of the WRMP process. This is a subset of the overall process of integrated water resource management (IWRM) (Hassing *et al.*, 2009), which emphasises ‘the co-ordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems’. The United Kingdom has various policy and regulatory mechanisms in place to achieve the overall goals of IWRM, of which WRMP is just one.

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