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A simple drought risk analysis procedure to supplement water resources management planning in England and Wales

Sean W. D. Turner [1] & Paul J. Jeffrey [2]

[1]Pacific Northwest National Laboratory, Seattle, WA USA; and [2]Cranfield Water Science Institute, Cranfield University, Cranfield, UK

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Correspondence
Paul J. Jeffrey, Cranfield Water Science Institute, Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK.
Email: p.j.jeffrey@cranfield.ac.uk

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Abstract

The current 'Deployable Output' approach for assessing water resources system performance in England and Wales is a practical, communicable means for assessing the adequacy of a water supply system and determining the relative benefits of proposed system enhancements. A recognised flaw with this approach is that it fails to characterise the severity of potential supply shortfalls, leading to mischaracterisation of risks and benefits associated with alternative candidate investments. Here, we propose a Monte Carlo procedure that could supplement the existing process by exposing the magnitude (% water demand unserved) and duration (number of days) of supply curtailments under a range of drought scenarios. The method is demonstrated using a realistic, stylised water resources system and a discrete number of infrastructure investments. Results demonstrate that vulnerability assessments can expose previously unidentified risks that might radically alter a planner's estimate of the cost-effectiveness of a particular investment.

Introduction

Water companies in England and Wales are responsible for the secure and efficient supply of water to households, businesses, public premises and industry (Water Industry Act of 1991). To fulfil this duty, they must maintain and operate bulk water supply infrastructure that abstracts, stores and transfers water to ensure continuity of supply through severe and prolonged droughts. These water supply systems also need to be continually upgraded to cope with changing conditions, such as increasing demands for water, new abstraction licence conditions and compensatory water release requirements, projected impacts of climate change on the natural availability of water, and changing expectations of customers and other stakeholders. The problem which planners face is that these changes are notoriously difficult to forecast. A water supply system with insufficient capacity may lead to over-frequent restrictions on customer water use (causing some minor inconvenience) or in extreme cases severe supply shortfalls (raising significant human health concerns, as in the recent droughts experienced in Cape Town or Sao Paulo). Moreover, the types of infrastructure project that can address these risks – reservoirs, inter-basin transfers, water reuse schemes, seawater desalination facilities and so on – are expensive and often unpopular, often cast as 'white elephants' when found with the benefit of hindsight to be over-designed (Kielder Reservoir, designed for an industrial boom that never materialised, is the textbook example in the United Kingdom). The water resources planner must somehow strike a balance between levels of investment and water shortage risks, whilst simultaneously satisfying the many and diverse interest groups affected by the decision. It is an unenviable task that demands deep analysis, wide consultation and effective communication and leadership on the part of the water company.

In England and Wales, the water resources planning problem has been formalised through a regulatory process. Each company is obliged to prepare and maintain a Water Resources Management Plan (WRMP) that adheres to detailed planning guidance set out by the Environment Agency (Water Act of 2003). This guidance prescribes a planning methodology that follows traditional 'least cost capacity expansion' principles: forecast supply, forecast demand, buffer against possible error and uncertainty using arbitrary planning margins, and schedule the least-cost combination investments to balance supply and demand over a 25-year horizon. The metric of supply, termed Deployable Output (DO), is computed as the maximum flow of water that can be supplied without interruption under a repeat of the drought of record. This approach suffers a well-known flaw. It fails to adequately expose the implications of alternative designs on the frequency, duration and severity of possible supply failures (Klemeš *et al*., 1981; Turner *et al*., 2014). A wide range of new planning frameworks that would overcome this issue have already been described. These include risk-based approaches (Hall *et al*., 2012; 2019; Hall and Borgomeo, 2013; Borgomeo *et al*., 2018) as well as multi-objective robust decision analytic frameworks (Herman *et al*., 2015). Indeed, this has been a fast moving field of academic endeavour over recent years with significant advances in adaptive planning tools which enable flexibility in modifying engineering projects in the context of least-cost water supply investment scheduling. For example, Real Options Analysis has been deployed using multistage stochastic mathematical programming (Erfani *et al*., 2018), an approach which has influenced wider assessments of flexible investment strategies for the water sector under climate change uncertainty (Fletcher *et al*., 2019). Other work has explored ways of improving the robustness of engineered water resources systems under different levels of risk, thereby allowing an explicit trade-off between incremental increases in robustness and investment costs for a given level of risk (Borgomeo *et al*., 2018). Similarly, the use of using metamodels for the optimisation of robust investment planning under deep uncertainty has been proposed (Beh *et al*., 2017).

Yet the sector has been reluctant to adopt many of these tools. Interview research suggests that planners believe the trade-offs these analyses expose are often too complex to communicate to customers and that the implied workload is impractical given the company's limited time and budget for planning activities (Turner and Jeffrey, 2015). Rather than overhauling a planning process that is popular and well understood in the industry, a more palatable way to advance risk assessment might be to develop simple, supplemental techniques for exposing vulnerabilities concealed by traditional supply-demand assessments.

Here, we propose a very simple analysis of water supply shortfall risk that may supplement the current approach by exposing previously unrecognised vulnerabilities. Our analysis relies on some of the classic yet often neglected tools of water system analysis, namely system stress testing using Monte Carlo simulation of the water supply system (Fiering, 1997) and complementary risk analysis considering both the magnitude and duration of simulated water supply shortfall events (Hashimoto *et al*., 1982). We apply the approach to a realistic, stylised water resources system to explore how this more in-depth analysis of risk might affect a planner's estimation of cost-effectiveness of alternative system investments.

Method

Our test bed for this analysis is a stylised version of a water resources system located in northwest England. The system comprises three distinct but weakly connected supply areas. Water is abstracted from a combination of small storage reservoirs (approximately 90 day critical period on the 50-year drought), streams and boreholes to supply 55 mL/d (annual average) to around 150,000 people. The catchments are relatively wet (annual rainfall ~ 1800 mm) and are characterised by steep rocky terrain and a corresponding flashy hydrological regime. The rivers and lakes that provide and store water in the zone are protected under various environmental designations, meaning the incumbent water provider has very few options for expanding capacity. For the purpose of this study, we impose hypothetical abstraction limits and minimum compensatory flow release constraints in order to replicate conditions similar to those experienced by water providers facing increasingly stringent environmental regulation.

We use a model of the resource system developed in Aquator (Oxford Scientific Software, 2008), which includes the major bulk supply assets as well as various operating rules, including time limited abstraction licences, compensation flow arrangements based on reservoir levels and binary rules for switching on new resources (Fig. 1). Aquator simulates the allocation of water within the system using an optimiser that minimises the operational cost (defined through marginal costs of use for each component in the model) when water is plentiful. A breach of any reservoir control curve switches the optimiser mode to maximise resource state, which implies use of more expensive resources. Specifically, this system drafts water from boreholes and transfers (which augment rather than fully satisfy water demands) when storages begin to draw down during dry conditions. The control curves are defined based on past operational decisions in the system.

We model six realistic, contrasting options for enhancing the system. These are: (a) Do nothing; (b) A new river abstraction to Supply Area 1; (c) Remote groundwater schemes feeding Supply Area 3, plus a new pipeline to support Supply Area 1 from Supply Area 3; (d) An increase in the transfer capacity between Supply Area 2 and Supply Area 1; (e) A re-opening of an abandoned groundwater source in Supply Area 3 plus new pipeline between Supply Area 3 and Supply Area 1; and (f) A re-zoning of demands in Supply Area 1 so that they are fed from a large neighbouring resource system via inter-basin transfer. These options and the associated costs are based loosely on actual interventions and costs proposed in a prior WRMP.

The aim of the experiment is to compare the performance of each enhancement option using conventional capacity expansion planning and then, with the proposed supplementary risk assessment informed by Monte Carlo simulation. The capacity expansion approach follows existing industry guidelines (EA, 2012): Deployable Output is computed as the highest demand that the system can consistently supply under a repeat of historical weather conditions, subject to a set of modelled constraints and assuming an industry standard 30-day reserve storage

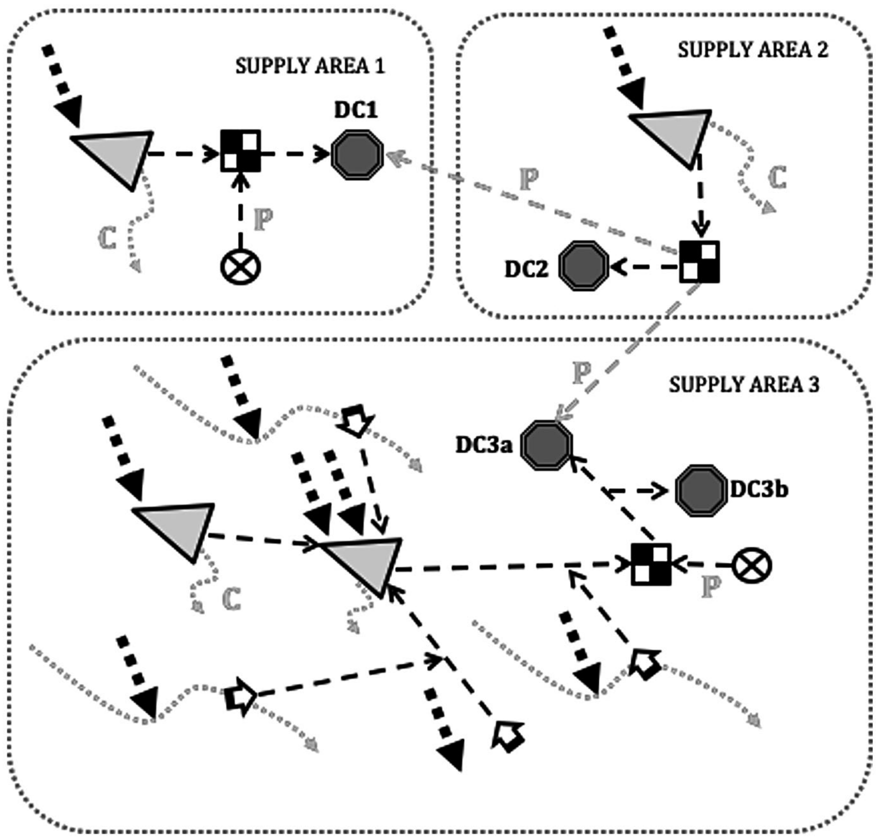

Fig. 1. Resource system schematic showing reservoirs, inflow sequences (large perforated arrows), river reaches, linkages, abstractions, boreholes, treatment works and demand centres (DCs). C denotes compensatory flow requirements on river reaches. P denotes pumped pipelines.

margin in the reservoirs. This is then compared against forecasted demand to identify supply-demand deficit.

The supplemental risk analysis requires that the system is stress tested under a range of plausible future scenarios. This is performed by Monte Carlo simulation. Here, we represent uncertainty in demand forecasts, asset constraints and catchment characteristics by sampling from the probability distributions (water companies already prepare descriptions of these uncertainties to inform 'headroom' analysis, so developing these inputs would impose little additional computational or labour burden). The most important uncertainty is the inflow, which ought to encompass a range of plausible drought conditions. This may be achieved using a stochastic technique (e.g. Borgomeo *et al*., 2015) to create replicate samples of reservoir inflow time series that preserve the statistical properties and spatiotemporal correlation of the observed inflow records. Here, we instead rely on a pre-existing precipitation and potential evapotranspiration data derived from an 11 member, one square-km gridded daily weather time series from the FF-HadRM3-PPE regional climate model (Prudhomme *et al*., 2012). These spatially correlated weather time series are transformed to reservoir inflows using rainfall runoff models calibrated for each of the nine flow sites within the system. Since the reservoirs in this system reliably refill each winter, over-year behaviour is unimportant. We can, therefore, build the Monte Carlo analysis from multiple year-long simulations, each using randomly sampled inflow years and with future demands sampled from a probability distribution. Similar to the approach adopted in a recent risk analysis of an electricity supply system (Turner *et al*., 2019), we characterise risk using the simulated supply shortfalls recorded across 3000 1-year simulations. A vulnerability matrix that characterises each shortfall according to its severity (% of demand unserved) and duration (days) is used to visualise results (Fig. 2).

To understand how this type of risk-based understanding might influence the system design, we attach arbitrary consequence severity scores to each banded square of the vulnerability surface. The scores reflect the common assumption that consequence forms a non-linear relationship with both shortfall magnitude and duration (e.g. Draper and Lund, 2004; Turner *et al*., 2017). The consequence severity scores were used to derive two metrics of risk. Our first metric is a relative risk score ('RRS') that quantifies risk in each demand centre by combining probabilities

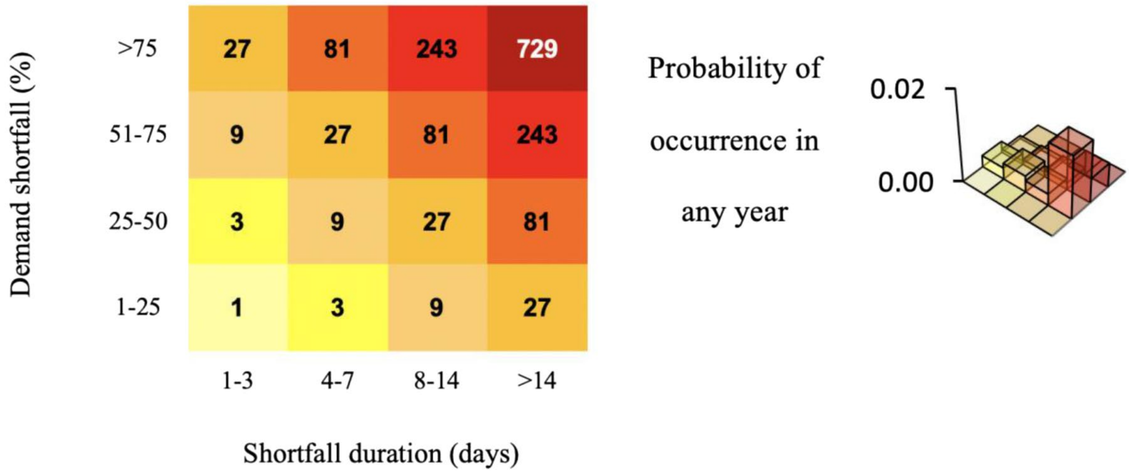

Fig. 2. Subjective scoring for relative risks and example vulnerability surface based on event probability of occurrence. [Colour figure can be viewed at wileyonlinelibrary.com]

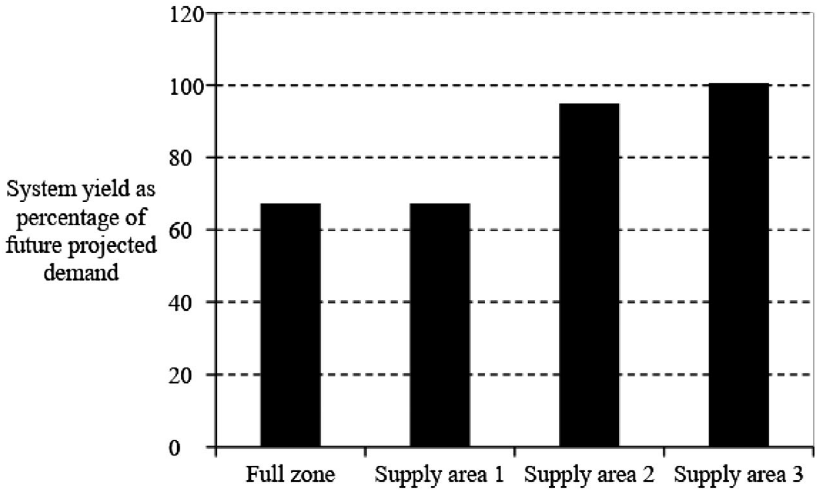

Fig. 3. System yield for full zone and separate supply areas.

from the stochastic analysis with consequences assigned by the subjective impact scores [Eq. (2)]. The second uses these scores to create an overall risk score for each option by combining RRSs and weighting them by average demand for each demand centre (thereby accounting for population affected by shortfall). We term this the demand-weighted risk score (DWRS).

$$\text{RRS} = \sum (\text{Probability} \times \text{Arbitrary impact}) \tag{1}$$

$$\text{DWRS} = \sum (\text{Average annual demand} \times \text{RRS}) \,/\text{Total demand} \tag{2}$$

Average incremental costs (£ capital expenditure per unit risk reduced) are computed for each option (based on the DWRS and compared against average incremental costs derived from deterministic system yield assessments (£ capital expenditure per unit increase in DO).

Results

Figure 3 shows the yield (or Deployable Output) for the full test zone and separately for each of the supply areas. The yield for the full zone is constrained by the yield at Supply Area 1; Supply Area 2 and Supply Area 3 are deemed healthy in comparison (though Supply Area 2 suffers a minor deficit under the hypothetical conditions imposed). These results provide a baseline against which to test the outputs of our exploratory stress testing analysis.

The vulnerability surfaces derived by Monte Carlo simulation draw an entirely different picture of risk under

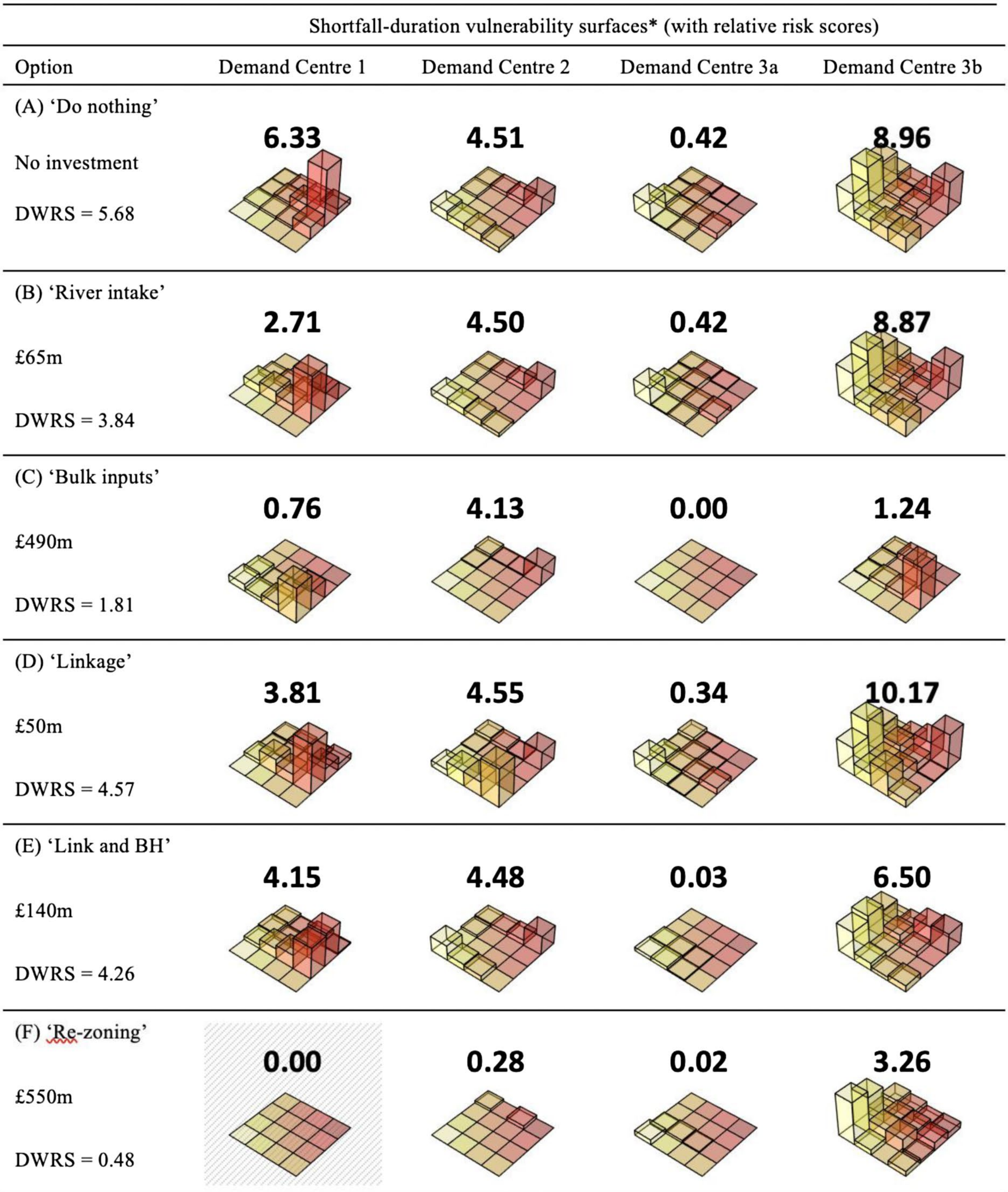

Fig. 4. Subjective scoring for relative risks and example vulnerability surface based on event probability of occurrence. [Colour figure can be viewed at wileyonlinelibrary.com]

'do-nothing'. While the above system yield analysis emphasises significant supply-demand deficit in supply area 1 alone, the vulnerability surfaces identify clear vulnerability in supply areas 2 and 3 as well as supply area 1 (Fig. 4). Closer inspection of the simulations reveals the reason for these discrepancies; low-probability high-consequence risks are simply not explored through simulations of the short (50-year) historic sequence. In particular, we find that the conventional analysis overlooks the fact that, whilst unlikely to suffer failure, Supply Area 2 is vulnerable because it relies on a single resource and cannot be augmented from elsewhere in the zone. Demand Centre 3b is vulnerable to significant shortfall in years that contain two separate small droughts, which deplete the annual licence in the borehole in that area leaving it vulnerable should the reservoirs become depleted. The historical record does not feature these inflow patterns and thus overlooks the risks.

The various proposed interventions have varying success in tempering the risks identified under ‘Do Nothing’ (Fig. 4). We find that the most expensive interventions (‘Bulk inputs’ and ‘Re-zoning’) are the only options that effectively address vulnerability in supply area 3, while only the ‘Re-zoning’ addresses vulnerability in Supply Area 2. One relatively inexpensive option (‘Linkage’) offers only marginal decreases in risk score for Supply Areas 1 and 2, yet actually exacerbates risk in Supply Area 3, which has to now compete with Supply Area 1 for water made available for transfer from Supply Area 2. This is perhaps the most alarming result offered by our analysis, because the ‘Linkage’ option is one that is determined to be effective in closing the supply-demand imbalance almost entirely when analysed with the DO approach.

The marked differences in the results of yield analysis and Monte Carlo stress testing bear out when the cost effectiveness of the options is compared. The more nuanced risk assessment demotes the ‘linkage’ option from most cost effective to second most cost effective (it remains prominent due to its very low cost) (Fig. 5). The ‘river intake’ option emerges as the most cost-effective, while the ‘bulk inputs’ option is found to be the least cost effective – a consequence of failure to deal with the risks in supply area 2. This an important result because it shows that a stress test of the system might help planners rule out expensive, ineffective measures. Conversely, the relatively cheap ‘Link and Borehole’ option (which, incidentally has a low environmental impact) is shown to be quite effective in reducing system vulnerability in both Supply Areas 1 and 3, even though it is found to be the least cost-effective means of increasing DO.

Discussion and conclusions

(1) This is a modest but revealing contribution to the growing literature base on public water supply drought risk analysis, relying on the deployment of two well understood analysis techniques to offer a low-investment approach for water resource and asset investment planners. The results show that the simple process of simulating more streamflow data through the model and exploring shortfall severity and duration identifies additional risks that would otherwise be overlooked in a standard DO analysis. This understanding would influence the planner’s understanding of relative cost-effectiveness across alternative investment options – as demonstrated by our simple case study. The approach also helps highlight and expose elements of the system responsible for vulnerability. It could, therefore, function as a tool for formulating options in addition to one for comparing the effectiveness of those options for reducing supply shortfall risk.

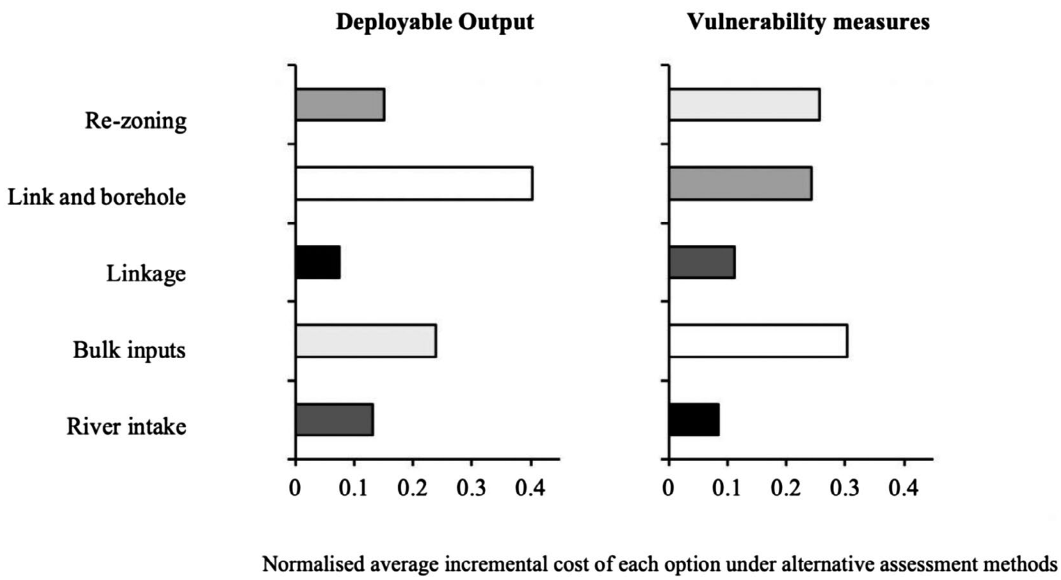

Fig. 5. Relative cost effectiveness of each option and comparison of alternative assessment methods (shading becomes darker with increasing cost effectiveness).

(2) The granularity of the vulnerability surfaces is interesting because, across 3000 years of simulated inflows, one might expect smoother surfaces with decreasing probability as event duration increases. Instead we find, for instance, that Demand Centre 2 exhibits higher risk for long-duration events than short duration events. The result reflects the fact that the inflow sequences contain only a small sample of drought events that cause shortfalls. It so happens that the damaging drought contained within the sequences exceeded 14 days' duration. Shortfall magnitude is a different matter: if the reservoir in Supply Area 2 were to fail (by storage depletion) then Demand Centre 2 would immediately suffer 100% shortfall (assuming no new water entering the system) because this population cannot draft water from other sources. Additional inflow data would, therefore, smooth these profiles along the event duration axis (with decreasing probability as duration increases), but maintain coarseness along the event magnitude axis. In order to obtain a fuller picture of vulnerability, the analyst might have to stress the system under an even broader spectrum of possible droughts than assessed here. The tools for generating a large enough inflow sample analysis are readily available.

(3) The vulnerability scores and resulting cost-effectiveness measures presented in this work are subject to nontrivial uncertainty and subjectivity. Our analysis relies on an 11-member regional climate model ensemble; a multi-model ensemble would create different risk surface shapes. Perhaps an exploration of more unlikely but plausible extremes would have identified new system vulnerabilities. Then, there is the difficult question of whether climate projections are indeed able to produce the types of drought that may occur warming patterns. How can we adequately assess risk if we lack knowledge of likelihood and severity of the future droughts? Furthermore, the risk-scores applied to varying levels of shortfall magnitude and duration are subjective. A critic might argue that these scores could be adjusted to achieve any desired result. Given these limitations and analytical problems, we must reflect on the value of the study for practical resource planning. We would suggest that the key advantage of this analysis is in the identification of previously unrecognised vulnerabilities rather than the quantification of their occurrence frequencies/magnitudes or their implied costs. The point is not to determine the best option analytically. Rather it is to reveal to the planner what might have been overlooked previously. Which parts of the system are vulnerable? Why does one option appear to address those vulnerabilities better than another? How might the supply system be exposed to drought risk if option X is selected and can those additional risks be addressed by some other means? If the knowledge delivered by a thorough stress test helps the planner to address any one of these questions more effectively, then the relatively small investment in the additional analysis would be seem trivial in comparison to the benefits delivered.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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