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Comparison of info-gap and robust optimisation methods for integrated water resource management under severe uncertainty

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Abstract

This paper evaluates two established decision making methods and analyses their performance and suitability within an Integrated Water Resource Management (IWRM) problem. The methods under comparison are Info-Gap decision theory (IG) and Robust Optimisation (RO), with particular regard to two key issues: (a) a local vs global measure of water supply robustness and (b) a pre-specified vs optimisation method of generating intervention strategies. Solutions are compared with plans proposed from current industry practice especially in regard to employing a longer planning horizon. The results reveal the impact of using alternative methodologies and analysis parameters on the final intervention strategies selected.

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Keywords: Water resources planning, decision making methods, climate change uncertainity, robust optimisation, info-gap decision theory

1. Introduction

Water management regulatory frameworks differ around the world but in many countries similar plans are developed under the auspices of Integrated Water Resources Management (IWRM) programmes. For instance, water utilities in the UK are required to produce Water Resource Management Plans (WRMPs) every five years that outline their long-term strategies for maintaining a secure water supply to meet anticipated demand levels. These

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plans justify any new demand management or water supply infrastructure needed and validate management decisions [1]. Similar IWRM planning is fostered around the world as recommended by the Global Water Partnership (GWP) with the vision of a water secure world [2], including increasing regard given to sustainable water planning and policy in developing countries [3]. Modern day IWRM planning is a multi-objective problem where decision makers are required to develop strategic adaptive plans to maximise the security of water supplies to future uncertainties, whilst minimising costs, resources usage, energy requirements and environmental impact [4].

Substantial anthropogenic change of the Earth's climate is leading to a large potential range of possible futures that could threaten the reliability of vital regional water supplies. This, combined with increased urbanisation and rapidly growing regional populations is putting pressures on existing water resources infrastructure [4]. Water companies and utilities worldwide are now under pressure to modernise their management frameworks and approaches to decision making in order to identify more sustainable and cost-effective water management adaptations that are reliable in the face of future uncertainties.

The current approach within the UK, as stated in the Environment Agency's (EAs) Water Resources Planning Guideline for England and Wales [1] and the Economics of Balancing Supply and Demand (EBSD) [5], is to produce a "best estimate" of future deployable output (or system yield), then using climate change projections and regional population forecasts, the aim is to deliver an acceptable (i.e. target) level of service for the least cost given the projected changes in supply and demand. This produces a single best estimate of the future supply-demand balance over time and encourages a "predict and provide" type approach to WRM over a single projected future or pathway [6]. However, the current EBSD approach does not explicitly explore the full range of possible futures and incorporates uncertainties using "target headroom" as a buffer between a theoretical planning deficit and a physically realised water supply deficit. Consequently it does not safe-guard against the more extreme projected scenarios; such as severe changes in individual supply source availability at peak demand periods [1] or highly unexpected events (the so called black swans) [7]. It does not encourage the most robust or flexible strategies to be derived, but instead satisfies a single projected supply-demand balance over a short timescale of 25 years.

Extensive international research is being carried out to test and evaluate a wide range of prospective Decision Making Methods (DMMs) that demonstrate notable potential in handling severe uncertainties in regard to IWRM adaptive planning. This paper evaluates two established decision making methods and analyses their performance and suitability within an IWRM problem. The methods under assessment are Info-Gap decision theory (IG) [8] and Robust Optimisation (RO) [9]. These methods have been studied in the context of IWRM [10–12] however the following two key issues have not previously been addressed: (a) a local vs global measure of water supply robustness for the selection of intervention strategies and (b) a pre-specified vs optimisation generated intervention strategies. We also compare the method's solutions with the current EBSD derived solutions and compare the impact of utilising a longer planning horizon in the decision process.

First the general IWRM problem is described followed by the concepts of resilience, robustness, strategies and costs before giving a brief description of the two decision making methods under review. The quantitative case study is then outlined followed by results and discussion exploring the performance of each method and evaluating the concepts of robustness and resilience in comparison with current industry procedures.

2. Methodology

2.1. IWRM problem definition

The IWRM problem is defined here as the long-term water resources planning problem of supply meeting future demand. The aim is to, for a given planning horizon, determine the best intervention strategy (i.e. set of interventions scheduled across the horizon) that are required to upgrade the existing regional WRM system that will maximise the robustness of future water supply whilst minimising the total cost of interventions required. Robustness of water supply (see definition below) is evaluated across a range of, pre-defined supply and demand scenarios which are used to represent uncertain future climate change and population demographics. The above problem is solved by using the two different decision making methods, each with its specific implementation. The results obtained by using the different decision making methods are compared after all solutions are re-evaluated using the definitions of resilience, robustness and costs outlined below.

2.2. Resilience, robustness and costs of intervention strategies

The term resilience is a concept under considerable discussion in recent IWRM research [13,14]. It is often defined as the speed at which a system can recover from failure [15] or a system's ability to "gracefully degrade and subsequently recover from" a failure event [16]. Here we define a failure event, based on levels of service, as the point at which the system requires a water restriction to be put in place, due to the system approaching a point of water deficit (or shortage), and we define resilience as the time taken for the system to enter, and recover from, a failure event. We set the desired resilience level as the total duration (in months) a system is allowed to be under restriction, based on customer agreement.

Robustness of a long-term water supply is defined here as the fraction (i.e. percentage) of future scenarios of supply and demand that result in an acceptable system performance. For example, if 80 out of 100 future scenarios are deemed to have been met then the robustness of the water supply is 80%. The acceptable performance is defined as the desired resilience level being maintained for the full duration of pre-specified long-term planning horizon.

Different intervention strategies can be produced for a region by employing different combinations of new potential water resource (i.e. individual intervention) options arranged over a strategic planning horizon. The total costs of strategies in the form of Net Present Values (NPVs) are derived using a standard discount equation applied to both the estimated capital (£M) and operation costs (£M/yr) over the planning horizon.

2.3. Decision making methods – Method 1. Info-Gap decision theory (IG)

Info-Gap (IG) decision theory is a non-probabilistic decision theory that seeks to maximise robustness to failure, or opportunity for windfall success, under deep (or "severe") uncertainty [8]. This addresses two contrasting consequences of uncertainty, the threat of failure and the possibility of unimagined success [17]. IG favours robustness of satisficing in its approach to decision making. A strategy of satisficing robustness can be described as one that will satisfy the minimum performance requirements (performing adequately rather than optimally) over a wide range of potential scenarios even under future conditions that deviate from the best estimate [8,18]. IG evaluates the robustness of an intervention strategy as the maximum radius of localised uncertainty that can be negotiated while maintaining these specified performance requirements. Fig. 1 [19] gives a diagrammatic representation of the unbounded assessment of Info-Gap from a "most likely" scenario ($\tilde{u}$), exploring two uncertain parameters ($U1$ and $U2$) in staged expansions (α), until an unacceptable level of system performance is reached (r_c), known as the critical reward level. Opportuneness is also displayed, calculated as the shortest distance of uncertainty traversed to reach a highly desirable outcome (r_w), known as the windfall reward level.

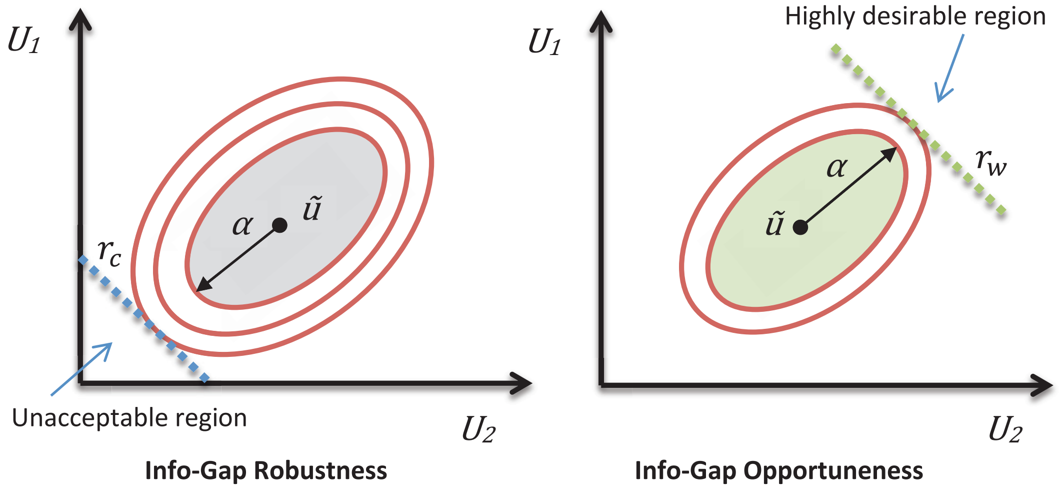

Fig. 1. Info-Gap Robustness and Opportuneness

2.4. Decision making methods – Method 2. Robust Optimisation (RO)

Robust Optimisation (RO) involves the application of appropriate optimisation algorithms to solve problems in which a specific measure of robustness is sought against uncertainty [9]. Optimisation can be defined as trying to find the best solution among a set of possible alternatives without violating certain constraints [20]. It is mostly employed to identify a single best estimate solution to a singular or multi-objective problem [21]. However, under severe uncertainty, this optimum solution may be vulnerable to conditions which are outside of the range of conditions examined in the optimisation, hence this predictive approach cannot be used for decision making under severe uncertainty, since often a theoretically "optimum" solution does not exist [22]. RO can overcome this difficulty by finding the best solutions as global Pareto-optimal robust solutions across the full horizon of uncertainty [23], leaving trade-offs among the various objectives out of the optimisation process and in the hands of the final decision maker [24,25]. A detailed review of different aspects of optimisation within the IWRM context was conducted by Maier et al. [26]. A wide range of optimisation techniques are available for RO including: Genetic Algorithms, Particle Swarm Optimisation, Ant Colony Optimisation, Linear Programing Techniques or combined process approaches such as Many-Objective Visual Analytics or Many-Objective Robust Decision Making (MORDM).

2.5. IWRM simulation model

A dynamic water resource network model has been developed that simulates, using a monthly time step, the supply and demand balance of a regional water supply system over a pre-established time horizon. Different future scenarios and intervention strategies can be input to the system, analysing the performance of each system combination via system resilience results.

3. Case study

This case study aims to quantitatively compare the contrasting mechanisms and outputs of Info-Gap and Robust Optimisation on a real world IWRM case study in the UK. The applicability of using the Future Flow climate change projections in water resource adaptation planning was also assessed and the above DMM results compared with those derived from current industry practice.

3.1. Case study description and objective

IG and RO are applied to a case study resembling the Bristol Water Resource Zone (BWRZ). This region is now regarded by the Environment Agency as a 'high water stress area' [27] due to pressure on local water resources from projected rising populations and increased climate variability. The existing water resources and their abstraction priority order are listed in Table 1. The aim of the IWRM problem analysed here is to, for a given long-term planning horizon, determine the best intervention strategy(ies) to upgrade the existing regional WRM system that will maximise the robustness of future water supply whilst minimising the total cost of interventions required.

Table 1. BWRZ existing water sources and abstraction priority ordering [27]

Resource Abstraction Priority	Resource Description	Minimum Deployable Output (MDO) In Ml/d	Projected to be affected by climate change?
1	Sharpness canal	207	No
2	Groundwater sources	40	No
3	Mendip reservoirs	Highly variable	Yes - significantly
4	Chew Magna abstraction to reservoirs	Highly variable	Yes - significantly
5	River Axe abstraction to reservoirs	Highly variable	Yes - significantly

The Bristol Water (BW) company water resources plan is based upon the operation of the Company area as a single resource zone. This means that all water resources (river, groundwater and reservoirs) within the company area are capable of being shared throughout the zone at all times of the year [27]. In this way, no part of the zone is solely dependent upon the yield of a single water source. This has been the approach adopted in previous BW WRMPs and agreed as appropriate for the current 2014/15 plan with the Environment Agency [27]. The primary river and groundwater sources are considered reliable and sustainable over the full planning period; hence, there are three aspects to the reservoir system to be modelled when projecting climate scenarios. These are: the Mendip catchment region (direct reservoir inflows); the river Axe at Cheddar and the lake at Chew Magna.

3.2. Supply and demand Scenarios

In this analysis we test the application of using Future Flow scenarios [28] to generate future flow projections for the region's major contributing rivers, lakes and reservoirs. The Future Flows project utilises the latest projections from the UK Climate Impact Programme (UKCIP) including the UKCP09 probabilistic climate projections from the Met Office Hadley Centre. They provide 11 plausible realisations (all assumed equally likely) of the river flows at various river gauging stations across England, Wales and Scotland and account for the impact of climate change to 2100 under a Medium emission scenario. The gauging site at Midford Brook was used to generate flow/inflow projections for all the regional rivers, lakes and reservoir sources. This is a 147.4 km^2 catchment area adjacent to the Mendip region. To obtain future scenarios for the three water sources, monthly flow factors have been calculated for the Midford Brook data. Flow factors describe the percentage change in monthly average river flows from 1961-1990 with those of 30 year segments of Future Flow data. These flow factors are then used to credibly perturb the historic flow data at each of the three sites. To allow for different natural variability the 11 Future Flow scenarios and historic base case flows are resampled [29] in seasonal blocks to form 331 discrete future supply scenarios. It should be noted that the supply scenarios are from a different source and of longer duration than those used by Bristol Water in their EBSD methodology and have been used directly as transient sequences to plan intervention strategies, as opposed to the EBSD method which assumes a linear interpolation of supply availability from baseline to the 2030s.

Demand Scenarios for the Bristol Water region have been produced using the ONS population projections [30]. They consist of 3 scenarios of low to high population growth used to perturb historic demand values, which are then made subject to 2 alternative headroom additions based on the BW 90 and 100% risk and uncertainty calculations [27]. This formed 6 discrete scenarios of demand.

3.3. Resilience of water system and robustness of water supply

As detailed in the methodology the resilience of each intervention strategy under a discrete future scenario of supply and demand is calculated as the total duration (in months) that the system is under a restriction due to low storage levels in the systems reservoirs. The current BW WRMP desired level of service (following customer consultation) is to implement temporary use bans no more than 1 in every 15 years [27]. Hence over a 50 year planning horizon we deem the system as acceptable if it maintains a resilience level of <4 months over the planning horizon and must never reach a magnitude that would induce a water shortage. The robustness of the water system is then calculated as the percentage (%) of discrete future scenarios under which the system performs acceptably.

3.4. Intervention strategies

An investigation into potential new water supply resources was carried out using data surveys for the Bristol Water region [27]. This created a list of potential intervention options (Table 2), from which different intervention strategies can be formed by implementing combinations of the new supply options, arranged over a 50 year strategic planning horizon (2015-2064). The total costs of strategies are calculated in the form of Net Present Values (NPVs) using an annual discount rate of 4.5% [27]. The options C4, D1, D4, D6 and R4 feature in the BW WRMP 2014 as planned interventions for 2015. Hence, for this investigation we have assumed that these interventions will be put in place from the start of the planning horizon and included them in all intervention strategy assessments.

Table 2. Intervention options available for the Bristol Water region [27]

Option Code	Intervention Option	Capital Cost (£M)	Opex Cost (£M/year)	Scheme Yield (Ml/d)
	OPTIONS TO REDUCE WATER CONSUMPTION			
C1	Smart metering rollout	11.45	0.06	2.6
C2	Compulsory metering of domestic customers	32.32	2.40	8
C3	Selective metering of domestic customers (high users - large gardens etc.)	5.98	0.32	3.2
C4	Selective change of ownership metering domestic customers	32.45	1.45	11.6
C5	Business water use audits	0.00	0.30	1
C6	Household water efficiency programme (partnering social housing)	0.00	0.42	0.4
	OPTIONS TO REDUCE WATER LOSSES			
D1	Pressure reduction	2.47	0.01	2.8
D2	Mains Infrastructure replacement	78.47	0.00	2.2
D3	Communication Pipe replacement	36.24	0.00	3.4
D4	Communication Pipe and subsidised Supply Pipe replacement	3.51	0.00	2.2
D5	Leakstop enhanced	1.75	0.00	0.2
D6	Active leakage control increase	0.00	0.91	4.4
D7	Zonally targeted infrastructure renewal	165.08	0.06	13.4
	OPTIONS TO PROVIDE ADDITIONAL WATER RESOURCES			
R1	Minor sources yield improvement	14.68	0.32	1.8
R2	City docks to Barrow transfer scheme	179.42	1.87	30
R3	Desalination plant and distribution transfer	179.42	1.87	30
R4	Cheddar second reservoir	99.67	0.16	16.3
R5	Purton reservoir and transfer scheme	288.57	4.30	25
R6	Pumped refill of Chew Valley reservoir from river Avon	153.81	3.40	25
R7	Upgrade of disused southern sources	8.30	0.30	2.4
R8	Effluent re-use for commercial and industrial customers	165.75	1.91	20
R9	Avonmouth WWTW direct effluent re-use	185.85	2.07	20
R10	Severn Springs bulk transfer	100.94	0.89	15
R11	Reduction of bulk transfer agreements	0.00	0.30	4
R12	Bulk supply from: (Wessex Water Bridgewater)	26.37	2.31	10
R13	Bulk supply from: (Vyrnwy via Severn and Sharpness)	151.95	4.29	25
R14	Huntspill Axbridge transfer (traded licence)	10.23	0.14	3
R15	Honeyhurst well pumped transfer to Cheddar	5.11	0.01	2.4
R16	Gurney Slade well development	10.70	0.26	1.5
R17	Holes Ash springs re-development	10.22	0.02	0.8
R18	Chew Stoke Stream reservoir	54.81	0.17	8

3.5. Info-Gap decision theory application

An area-based robustness pathway method to map the uncertainty region of potential supply and demand scenarios via IG decision theory is used here. This method is introduced in order to directly utilise the discrete Future Flow scenario projections within the IG analysis and aims to combat the issues of expanding out over a range of scenario projections that are extremely variable and not monotonically increasing, i.e. where a function of distance (α) between discrete projections cannot easily be established. This calculates the expanding horizon of uncertainty as an area rather than as a function of distance and the robustness level is calculated as a sum of all successful (α') deviations (total no. of local scenarios satisfied). In order to run the IG analysis we must first order the supply and demand scenarios into a range of severity. This is derived by running all the scenario combinations on the current water system set-up and then ordering the scenarios by average resilience results.

The IG analysis expands outward in a theoretically unbounded assessment; however, the analysis is constrained by the range of scenario projections available. Therefore we can re-define the IG robustness of a strategy as a percentage over the whole range of considered uncertainty. We test a range of pre-specified intervention strategies and derive a Pareto front of results to examine trade-offs between robustness and cost. These are both uncommon steps in the IG process but it allows us to compare the different DMM results more easily.

The starting point ($\tilde{u}$) in the IG robustness analysis has been selected as the median severity scenarios of supply and demand. Opportunity functions are not explored in depth in this paper due to issues of space.

3.6. Robust Optimisation application

For the application of the RO method to this IWRM problem we select the optimisation algorithm NSGAII, as its high performance and capabilities in handling multi-objective problems is well documented [31,32]. We set the objective functions as a minimisation of cost and maximisation of robustness. The decision variables are the intervention strategies formed from a pool of intervention options (Table 2). A range of population and generation sizes were tested with the aim of identifying the Pareto set of results for robustness vs NPV of total cost, where all non-dominated strategy results are discovered.

4. Results

For each decision making method the 331 supply and 6 demand scenarios (i.e. a total of 1986 possible scenario combinations) were modelled with the intervention strategies, which are assessed in accordance to objective functions subject to each method's individual constraints. This led to the identification of Pareto sets for both decision making methods, trading-off the robustness of water supply and cost of intervention strategies (Fig. 2). The IG Pareto front was formed artificially by running the IG analysis multiple times, whereas the RO Pareto front was formed by default in the GA optimisation process.

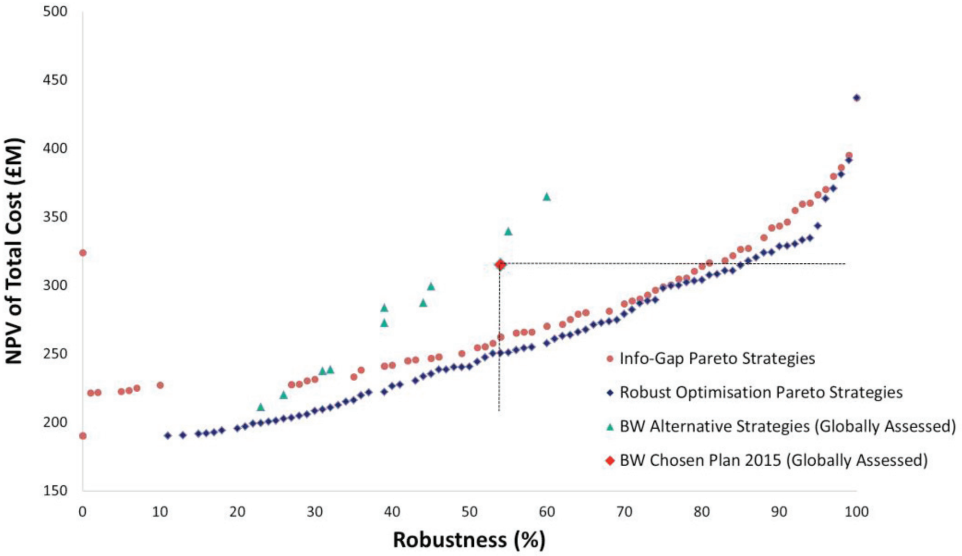

Fig. 2. Pareto strategies identified by the IG and RO methods, including BW WRMP 2015 proposed strategies

Fig. 2 also displays the robustness and NPV of total cost of BW's proposed plan for 2015-39 [27] (as well as BW's alternative optimised intervention strategies) calculated globally using our dynamic simulation model and resilience thresholds.

As it can be seen from Fig. 2, the RO method produces the lower costing strategy recommendations than the IG method for the equivalent robustness level across the majority of robustness levels. This is due to the RO directly optimising for robustness and cost, i.e. seeking to identify the Pareto optimal front, as opposed to the IG method's pre-specified strategy assessment which can leave potentially optimal solutions un-identified. IG's examination of the uncertainty region from a local point outwards also leads to more stringent resilience requirements than those placed on global robustness. The Pareto fronts converge above 95% robustness, marked as the point at which the differences in the constraints of local and global robustness become negligible. There is a widening cost gap between Pareto strategies around 90% robustness, resulting from a group of strategy combinations discovered by the RO process that were not included in the pre-specified list analysed by the IG method. The larger gaps in Pareto coverage of robustness for the IG method is due to the occasional large increase in resilience required for an individual scenario when they are ordered by a severity index that is not monotonically increasing. This highlights the difficulty in ordering discrete scenarios into a range of severity and presents a potential weakness in the IG method in application to IWRM.

The BW 2015 proposed plan is indicted as being only 54% robust to our range of future scenarios and considerably less cost-effective than the IG and RO Pareto strategies. However, we expected to see a reduced level of overall robustness due to the greater range of uncertainty now under assessment, the use of transient supply sequences, and the expansion to a longer planning horizon (50 years), as well using differing DMM's and a robustness concept not implemented by BW. Despite these differences a comparison allows us to analyse the effect of varying these characteristics.

From Fig. 2 we select an IG and RO Pareto strategy of similar robustness to the BW 2015 proposed plan (vertical line on Fig.2) and an IG and RO Pareto strategy of similar total NPV to the BW proposed plan (horizontal line on Fig.2). Fig. 3 displays the additional water resource (in Ml/m) added to the water system over the 50 year planning horizon by the intervention options selected. The main differences identified from this evaluation is the RO and IG Pareto strategies replacement of multiple smaller interventions with one or two larger ones later in the planning horizon in order to reduce overall costs in the long-term but still ensure high levels of system robustness.

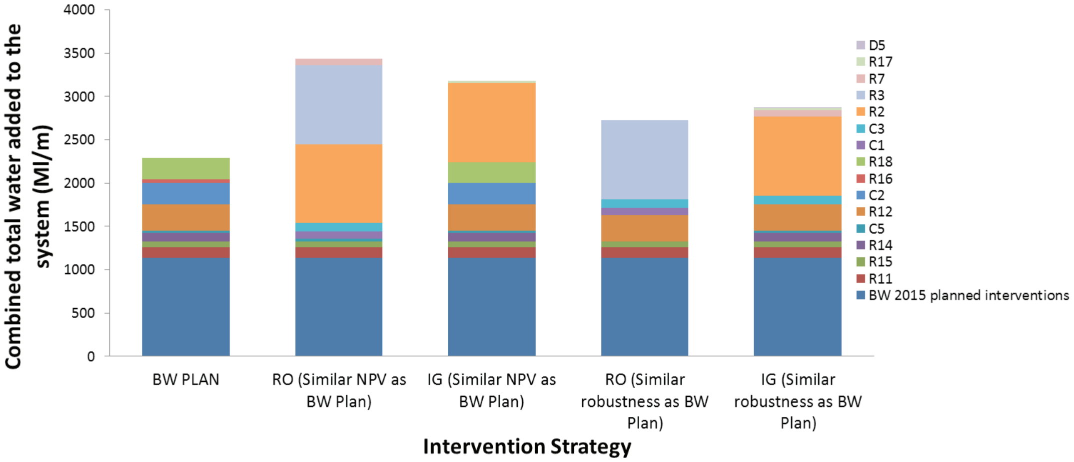

Fig. 3. Intervention option components of selected strategies (for approx. robustness level of 54% and NPV's of £314M)

Fig.4. presents the intervention options sequenced over time for the BW proposed plan and the RO/IG Pareto strategies of similar NPV. Despite the far greater volume of water supply added by the DMM selected Pareto strategies, all strategies are projected to result in the same NPV over the full planning horizon due to the method of discounting costs, which can greatly reduce the high price of larger intervention options if moved to later in the planning horizon. However, this could impact on the overall system robustness, especially to uncertainties outside of those considered in this investigation. This illustrates the potential influence of varying the length of the planning horizon and the importance of selecting an appropriate discount rate.

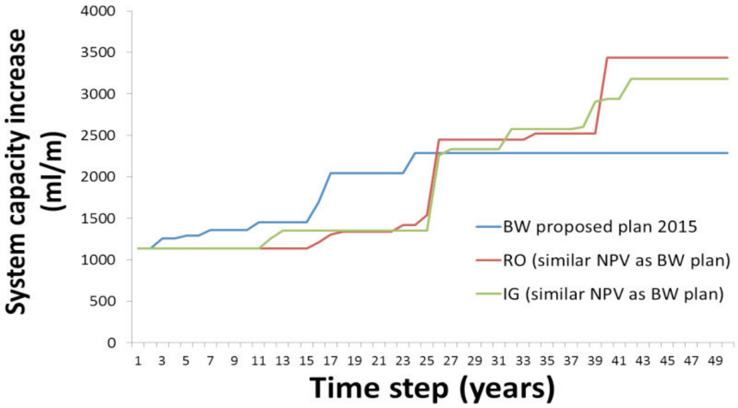

Fig. 4. Intervention option sequencing over time (for BW and RO/IG Pareto strategies of similar NPV)

Fig. 5 explores resilience graphs for the 3 strategies featured in Fig. 4 as well as a strategy of no adaptation (no interventions applied), under discrete scenarios selected from the 50th, 75th and 95th percentile of the supply and demand scenario combination severity range.

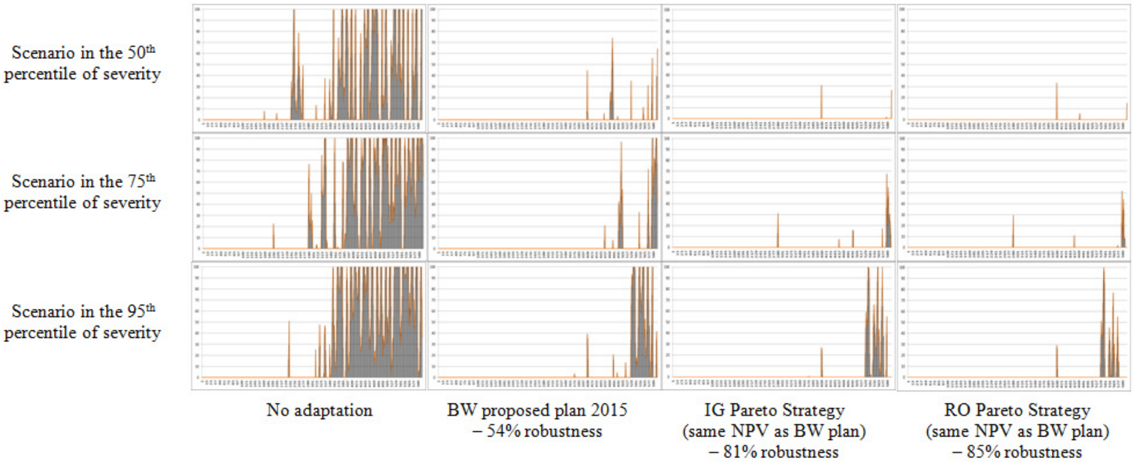

Fig. 5. Resilience graphs for selected intervention strategies (with y--axis of normalised volumes of deficits and x-axis of time)

The normalised peaks on the graphs indicate when the volume of water in the system in a month has fallen to a level that initiates a restriction order (temporary use ban) to be put in place (values listed by BW [27]). The height of the peaks indicates the magnitude of the deficits up to a water shortage (100%). The peaks must not reach 100% and must not occur too frequently (surpass the set resilience metric). The height of the peak and its resulting time to reduce back to a 'secure' level is the resilience of the strategy to a discrete scenario. Analysing these graphs allow us to see the decreasing resilience of the current system ("No adaptation") over the planning horizon and demonstrates the need for new intervention options from the middle of the planning horizon onwards.

5. Conclusions

Based on the case study results obtained, the following main conclusions can be drawn regarding the IG and RO method comparisons:

1. Both decision methods produced a varied range of strategy formations for matching robustness levels. This demonstrates the sensitivity of the decision methodology on the strategy selection process, especially when dealing with a large pool or intervention options. Testing of a range of decision methods is recommended in order to explore the full definition of system robustness.
2. RO provided the simpler computational set-up, can automatically generate complex intervention strategies and identifies the trade-offs between conflicting objectives without users having to specify pre-defined intervention strategies. However, it is more computationally demanding due to its iterative process and its need to evaluate every scenario in a global assessment (which can limit the number of intervention options and objectives considered). Conversely, it generally produced the more cost effective solutions.
3. IG can tailor local robustness around the most likely scenarios which offer an alternative assessment to otherwise global or linear forms of analysis. However, difficulties exist in the IG methodology when ordering discrete scenarios of supply and demand into a severity range when they are not monotonically increasing and in identifying an appropriate starting point. The former issue could be alleviated by alternatively incorporating relevant uncertainty variables. Pre-specifying the strategies also limited the range of final solutions derived however IG could be combined with optimisation to improve this.
4. In comparison with the BW 2015 proposed WRM plans we conclude that quantifying the robustness explicitly (as opposed to indirectly, via headroom and level of service failure) and using this and costs as drivers to identify solutions, is likely to result in more robust and less costly plans when compared to a more conventional approach used currently in the UK engineering practice. In addition, it can be observed that the selection of planning horizon length influences the range and timing of intervention options selected.

These differences highlight how the current industry standard for water supply system adaptation planning could benefit by applying a wider range of decision methodologies and assessment tools as well as a more encompassing investigation into potential future uncertainties.

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