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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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Abstract

Water resources managers are required to develop comprehensive water resource plans based on severely uncertain information of the effects of climate change on local hydrology and future socio-economic changes to localised demand. In England and Wales, current water resource planning methodologies include a headroom estimation process separate from water resources simulation modelling. This process quantifies uncertainty based on only one point of an assumed range of deviations from the expected climate and projected demand 25 years into the future. The research presented herein addresses this problem by developing an integrated the Water Resources Planning Robustness Assessment (WRP-RA) method based on Information-Gap Decision Theory (IGDT) to quantitatively assess the robustness of various supply side and demand side management options over a broad range of plausible futures. Findings show that beyond the uncertainty range explored with the headroom method, a preference reversal can occur, i.e. some management strategies that underperform at lower uncertainties, outperform at higher levels of uncertainty. Also, some management strategies that perform relatively well within the headroom range of uncertainty, fail just beyond this range.

Additionally, this thesis demonstrates that when 50% or more of the population adopts demand side management in the form of efficiency related measures and/or innovative options such as rainwater collection and/or greywater reuse, the robustness of a management strategy can be greatly improved as can its ability to recover after a drought episode. The use of Multi-Criteria Decision Analysis shifts the focus away from reservoir expansion options and large-scale river abstractions that perform best in regards to water availability, to strategies that include innovative demand side management actions of rainwater collection and greywater reuse as well efficiency measures along with more traditional supply-side schemes. Therefore, this thesis illustrates how the WRP-RA can offer a comprehensive picture of the relative robustness of management strategies to more extreme supply/demand futures. The knowledge of which options and collections of options perform better in response to higher demands and lower supplies offers insight into more secure long term investment strategies.

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Abbreviations

AISC	Average Incremental Social Cost
BAU	Business As Usual
BAWSCA	Bay Area Water Supply and Conservation Organisation
DD	Drought Deficit
DO	Deployable Output
DSM	Demand Side Management
DYAA	Dry Year Annual Average
DYCP	Dry Year Critical Peak
EBSD	Economics of Balancing Supply and Demand
GAMS	Generic Algebraic Modelling Software
IGDT	Info-Gap Decision Theory
LoS	Level of Service
MCDA	Multi-Criteria Decision Analysis
MDO	Minimum Deployable Output
MILP	Mixed Integer Linear Programming
MOO	Multi-Objective Optimisation
NAO	North American Oscillation
NPV	Net Present Value
NYAA	Normal Year Annual Average
PDF	Probability Distribution Function
PR	Public Review; e.g. PR09 or PR14
RDM	Robust Decision Making
RRM	Reservoir Risk Measure
RR	Reservoir Ratio
SMD	Safety Margin Deficit
SSA	Strategic Supply Area
TE 2100	Thames Estuary 2100
THR	Target Headroom
UKCP09	UK Climate Projections 2009
WAFU	Water Available for Use
WRMP	Water Resources Management Plan
WRP-RA	Water Resources Planning Robustness Assessment
WTP	Willingness to Pay

1 Introduction

1.1 Motivation

This thesis introduces a new water resources planning robustness assessment (WRP-RA) method based on the application of Info-Gap decision theory (IGDT) to evaluate management strategies in the context of a severely uncertain future. The awareness of climate change necessitates the development of adaptation and mitigation policy by all levels of government and resource management agencies and companies. This call for action places these groups in a difficult situation. They are expected to generate responsive and proactive policy often at the local level without an accurate understanding of how climate change will influence their region or resources. In effect, people responsible for policy development need to develop management strategies, "…that will work reasonably well no matter what the future holds" (Lempert and Schlesinger 2000).

The scientific community bears responsibility to generate findings and results that answer the needs of decision-makers (McNie 2007), and many are asking for more accurate information with which to plan future management using a traditional decision-making approach. Accurate information is required because traditional deterministic decision-making approaches require some certainty and are not designed to handle addressing severe uncertainty required by topics such as resilience and robustness. Wrestling with this demand for appropriate data to inform climate change affected policy has led many researchers to highlight the "cascade of uncertainties" (Jones 2000) in translating global climate change into local impacts (Arnell 1998, Jones 2000, Hall 2003, Wilby 2005, New 2007, Wilby 2010, Dessai 2009). In response, there is also a growing body of research that acknowledges the difficult context of decision-making under severe uncertainty and is developing new approaches to sample the uncertain space and explore the robustness of management options to a variety of futures (Lempert 2000, Lempert 2006, Stainforth 2007, Prudhome 2010, Hine 2010, Hall 2010, and Lempert 2010).

Info-Gap Decision Theory is a theoretical approach that addresses the issue of uncertainty within the decision-making context (Ben-Haim 2001, Regan 2005, McCarthy 2007, Hine 2010, Hall 2010), as is the model with other robust decision-making techniques (Lempert 2000, Lempert 2006, Stainforth 2007, Prudhome 2010, Hall 2010). The exploration of sources of uncertainty related to climate change in water resources planning has led to an evaluation of the complete decision-making process and revealed that not only climate change and its local hydrological impacts are subject to uncertainty; future demands are also uncertain. To extend the lack of certainty further, the current and future actions of decision-makers are also uncertain (Arnell 1998, Lempert 2010). In spite of this emerging uncertainty, the inertia governing the water resources decision-making, management and regulatory processes struggles to evolve from traditional deterministic plans with definitive management actions. The ability to adapt to climate change necessitates the ability to adapt within the management context (Lempert 2010, Ranger 2010) so that high cost financial commitments can wait until necessity requires them and also so that water managers are not only ready to respond as future conditions change, but also have the legal flexibility to do so.

This thesis uses Info-Gap Decision Theory as a technique to compare the robustness of various management choices in terms of their ability to respond to uncertain future water supply and demand conditions. On a practical, methodological level, this thesis describes a robustness assessment method (WRP-RA) that can be reproduced within the existing work-flows of water management companies. Resource management agencies not only need new methods to evaluate their strategic operations; they also need to be able to easily integrate them within the structure of existing information and planning systems.

1.2 Research question

In an effort to investigate options for long-term water management in response to an increasingly uncertain future, the research question this thesis addresses is: Does an Info-Gap Decision Theory (IGDT) based water resources planning methodology offer a pragmatic approach to plan for a severely uncertain future; and in this regard, support the design of an robust management plan?

The term pragmatic is used because it is important for a method to be easily applicable so it can benefit the water industry. A robust management plan is referred to because any investment in infrastructure should be evaluated based on its ability to perform adequately under severe uncertainty. It may be some time before the robustness is needed, but water resources managers should devise strategies that are able to respond to future uncertainties.

1.3 Aim and objectives

The aim of this research was to develop a WRP-RA methodology to aid long-term water resources planning under increasing uncertainty. Three case studies were explored to validate and demonstrate the usefulness of this methodology. The first case study demonstrates how the WRP-RA can be applied with a simplified simulation model in a simple water resources network. The second two case studies compare the benefits of the WRP-RA with two selection routines of the Current method of the Economics of Balancing Supply and Demand (EBSD); a traditional UK water resources planning method. The following three objectives were defined to focus research towards this aim.

Objective 1. Develop a WRP-RA methodology to evaluate the robustness of water resources management strategies over ranges of severe uncertainty.

Satisfying this objective:

- Requires the development of new risk-based performance metrics; the Reservoir Risk Measure, Drought Deficit and Safety Margin Deficit. These metrics are introduced in Section 3.3.2 and demonstrated in Section 4.2.
- Includes an exploration of innovative demand management options including rainwater harvesting and greywater reuse, also introduced in Section 3.3.2 and demonstrated in Section 4.2.
- Is supported by the use of Multi-Criteria Decision Analysis (MCDA) to expand management strategy evaluation beyond just water deficit and cost. This technique is described in Section 3.3.6 and demonstrated in Section 4.2.

Objective 2. Expand the WRP-RA methodology to a simulation model of a Strategic Supply Area (SSA) composed of multiple sources, demand nodes, treatment works and a piped network.

Satisfying this objective requires the translation of techniques developed to serve Objective 1 into a larger network simulation environment. This approach is described in Section 3.3 and demonstrated in Section 4.3, where the benefits of the WRP-RA are compared with the EBSD Current AISC selection method for water resources planning, in a simulation context.

Objective 3. Implement the WRP-RA methodology with an optimisation model to explore the relative performance of different management strategies as the supply / demand deficit worsens.

Satisfying this objective requires a different application of the technical approach (used in Objectives 1 and 2) to frame the uncertainty for parameters that define the supply / demand settings of the optimisation model. It also requires and interpretation of other performance metrics of the optimisation model (i.e. the amount of demand reduction that must be invoked in order for the modelling calculations to become feasible). This approach is described in Section 3.3 and demonstrated in Section 4.4, where the benefits of the WRP-RA are compared with the EBSD Current approach for water resources planning in an optimisation context based on the LP/IP selection method.

1.4 Methodology

This thesis introduces the WRP-RA as an effective means to understand the implications of severe uncertainty in water resources planning and identify robust management strategies. The application of this WRP-RA is demonstrated in case studies based in England and its relative benefits are compared with existing planning methodologies used in England and Wales (Environment Agency 2008, 2013). The source of severe uncertainty in this context is fundamentally epistemic as due to non-stationarity, it is unknown how the effects of climate change will materialise and it can be considered equally unknown how the patterns of human migration and water use will manifest. This central epistemic uncertainty makes it impractical to continue the application of previous decision-making methods that rely upon sound understandings of aleatoric uncertainties in water resources planning. Severe uncertainty is a distribution of outcomes that cannot be characterised from known distribution patterns or may exhibit unpredictable behaviour in its tail ends (Ben-Haim 2001). A robust management strategy is one that performs satisfactorily well over a wide range of futures (Ben-Haim 2001). In order to understand the added value of this new WRP-RA method, methodologies and results of case studies are compared with the EBSD AISC and LP/IP selection methods in Sections 3 and 4 respectively (Environment Agency 2008). The EBSD AISC approach identifies a least-cost management strategy by comparing the unit cost of water for different, supply-side, demand-side or network improvement options and then schedules these options to create a portfolio that satisfies future water deficit in the most economic manner. The unit cost of water is calculated based on the Average Incremental Social Cost (AISC), explained in Section 3.2.3, where the performance criteria of the EBSD methods are also defined. The EBSD LP/IP approach uses optimisation routines to select and schedule a least-cost portfolio of options.

IGDT does not offer a method to select and schedule a portfolio of water management options. It only offers a means to compare the relative robustness of portfolios by testing the performance of management strategies, over an unbounded range of uncertainty. In this thesis small deviations from the expected outcome are referred to as conditions under lower uncertainty and larger deviations are referred to as those experienced under higher uncertainties. The case studies in this research rely on the two EBSD Current selection methods to develop a portfolio of options that define a management strategy. The EBSD and IGDT methods to characterise and quantify uncertainty are then compared. The EBSD Current method uses the headroom estimation method to quantify uncertainty. The seminal EBSD methodology paper (UKWIR 2002) also introduces advanced methods to quantify uncertainty, referred to as EBSD Advanced in this paper. The Advanced method is similar in approach to AISC and LP/IP approaches, except for the handling of uncertainty. The authors of the seminal EBSD paper were also aware that there could be better methods to characterise and quantify uncertainty (UKWIR 2002). In this paper, reference is made to stochastic analysis as a component of EBSD Advanced as a means to address uncertainty. Reference is also made to Blue Skies Modelling to suggest there may be other equally helpful techniques to address uncertainty in water resources planning. This thesis proposes that an IGDT based WRP-RA is one of these Blue Sky techniques and offers an alternative to stochastic analysis.

This thesis includes a comparison of methods to understand the benefit an IGDT based WRP-RA as opposed to the Current EBSD AISC and LP/IP selection methods and their use of the headroom estimation method. Section 3.2 describes the methodological steps taken with the AISC approach, using a simulation model, and the LP/IP approach using an optimisation model. Section 3.3 introduces the application of the WRP-RA in a simulation and optimisation environment.

1.5 Thesis structure

Section 2 Literature Review	Describes the water resources planning context in England and Wales including current and evolving practice with a focus on dealing with uncertainty. Discusses the technical means to accomplish water resources planning, introduces Info-Gap Decision Theory and describes other potential methods to enhance traditional planning practices and take account of severe uncertainty.
Section 3 Methodology	Describes the proposed WRP-RA method and how to apply it in different settings and describes traditional EBSD methods as a means to compare the added benefit of the IGDT-based method.
Section 4 Case Studies	Describes three applications of the WRP-RA and compares results obtained with traditional EBSD methods with those obtained using the IGDT-based approach.
Section 5 Summary and Conclusion	Summarises the results of the case studies as a means to clarify the utility of the WRP-RA method. Discusses the contribution of this research and future research that can build upon these findings.

2 Literature review

2.1 The International challenge of water balance uncertainty

Dealing with severe uncertainty when planning for a long-term secure supply of water is a challenge that many countries grapple with (Gleick 2000, Mayer and Muñoz-Hernandez 2009, Arnell 2009, Langsdale 2007). This thesis focuses on the UK context because the three case studies are based in the UK. A short summary of water resources planning conditions and practices in Israel, Australia, United States and Canada is provided below to highlight the momentum towards the use of new methods to understand the implications of severe uncertainty, and as such indicate the generic and global utility of an IGDT-based WRP-RA methodology.

Worldwide, the future demand for water and availability of supply are the critical components that govern long-term water resources planning. Regulations evolve to balance the needs of the environment with the demands of society and to ensure fair competition in commercial ventures that capture, treat and distribute water. Whether water management investment decisions rest with commercial companies, governments or a combination of these; all water resources planners must devise plans that ensure an adequate supply of water into the future with enough foresight to be able to implement needed schemes in time to avoid unnecessary scarcities and hardship. A long view to the future is a merit of sustainable planning (Loucks 2000, Gleeson et al. 2012) but the longer the view into the future, the more uncertain the future looks.

- In Israel, a branch of their central government, the Israeli Water Authority develops a Water Master Plan to 2050 as an indication of future trends and develops a detailed strategy to guide investment for the short term. For the more uncertain longer term, a probabilistic analysis of future trends informs the likelihood of supply / demand shortfalls (Israel Water Authority 2012).
- In Australia, local service providers adhere to state defined regulations that satisfy the federally defined National Water Initiative (NWI). Regional implementation of the NWI differs in detail but is similar in intent. Water planning involves long-term strategies of 30-50 years and shorter term investment plans of 5-10 years. In the development of the South East Queensland strategy, the historical record was used to generate 1000 replicates of data, each representing more than 100 years of inflow data – a

form of synthetic flow series for Supply Demand Balance (SDB) assessments (Queensland Water Commission 2012). The State of Victoria requires the exploration of a range of future climate scenarios to avoid “surprises” and also requires using a “no regrets” approach to identify approaches that work under a variety of planning scenarios (State Government of Victoria 2011). Melbourne accomplished this direction in detail to explore a range of supply and demand settings in terms of water resources availability and potential urban conditions (Mortazavi et al. 2013). The long-term strategies for Melbourne developed in this analysis are adaptive in that they provide the foresight and information to know when to defer or bring forward actions.

- In the western state of California, the Bay Area Water Supply and Conservation Agency (BAWSCA) develops a long-term 30 year strategy that investigates normal year, dry-year and multiple-dry year conditions (BAWSCA 2012). Also in California, the RAND Corporation piloted their Robust Decision Making method and introduced the concept of deep uncertainty to the Inland Empire Utilities when they explored the vulnerability of management strategies to an extended variety of plausible future conditions (Lempert, 2006). Denver Water and the Metropolitan Water District provide two more examples of water authorities that feel the need to delve deeper into uncertainty with robust decision making techniques (Means et. al. 2010).
- In British Columbia, Canada, 10 years ago, researchers began the process of encouraging citizens and water resources managers to consider the effects of climate change on the sustainability of their water supply and use by embedding themselves in community-based participatory planning exercises (Tansey 2004; Turner 2004; Langsdale 2007). These initial explorations have developed into a growing community of practice (Baltutis et al. 2012).

In all these instances, regulators and water resources managers are investigating an expanded view of the future that includes an increase in the range of uncertainty to be explored. When regulators and managers look to a more challenging future they are forced to consider innovation and new ways of managing water including rainwater harvesting and greywater reuse. The prospect of a water challenged future drives the innovation and managers and regulators are forced to take bold new steps and invest considerable sums to ensure water security. A better understanding of the ability of their potential management strategies to perform well over increasing uncertainty (i.e. their robustness), will offer more clarity in the decision making context and more comfort in any investment decisions.

The IGDT-based WRP-RA methodology offers a full view of the performance of management strategies throughout deficit situations up till the point of failure.

2.2 UK Regulatory context

The purpose of water resources planning is to ensure that there is enough supply to meet future demand and that no household, business or the environment suffers hardship from a lack of water. As such, water resources planning is based on the potential for the worst situation to occur and guidelines in England and Wales require that companies plan to meet dry year consumption patterns to an appropriate Level of Service (LoS), in weather conditions akin to the worst drought on record (Environment Agency 2008, 2013). Dry year consumption patterns are higher than those in a normal year. Levels of Service are designed to accommodate some reduction in service under extreme situations so a customer of a water company would be asked to forego hosepipe use at some point during the summer and/or autumn once every 20 years if there was a drought and may also be asked to forego the use of water for any non-essential use for up to 3 or 4 months once every 40 years if the drought was extreme (South West Water 2009).

Every five years, the government of England and Wales update the water resources planning guidelines. These guidelines dictate what is included in a water company's 25 year Water Resources Management Plan (WRMP) and the range of methods to be employed (Environment Agency 2012). These guidelines detail techniques to evaluate the capacity of a company to meet future demands and also how to quantify a portfolio of new options to satisfy the supply/demand deficit, including headroom uncertainty, with a least-cost management strategy. A company must present a 25 year plan to its customers and gain approval that the plan achieves a desired level of service based on a customer's Willingness to Pay (WTP). The derivation of this WTP value is determined in a fairly structured conversation between a water company and its customers, observed by the watchful eye of the financial regulator, Ofwat. Historically, the prime objective of water resources planning has been to identify the least-cost plan so customers are not expected to pay more than they have to. The least-cost imperative was in full effect for the 2009 Public Review (PR09), during which Water Resources Management Plans for 2010 till 2035 were consulted upon. In Public Review 2014 (PR14) a shift in approach started as some companies began to present best-value plans that cost more, but offer some form of added benefit – usually described as resilience (Thames Water 2014, Southern Water 2014, Sutton East Surrey Water, 2014).

At present, the term resilience is an all-encompassing phrase in Water Resources planning in England and Wales. The transition towards new water resources planning methodologies requires additional evidence to inform robust and resilient decisions and additional engagement to develop a common understanding and promote consensus-based decisions. This thesis considers robustness as a further investigation of headroom, which is a safety of margin that address uncertainty around supply and demand figures, and resilience as a further investigation of outage, which investigates how distribution networks can safeguard against or recover from interruptions to service. Assessments that look at robustness and resilience help define linkages between the Water Resources and Drought Management Plans. This thesis explores issues related to robustness in terms of the ability to withstand water deficit situations brought on by diminishing supply and increasing demand. This thesis also makes reference to opportuneness which is an aspect of IGDT that can inform resilience planning.

Based on Environment Agency research evidencing future challenges for water resources in England and Wales in the Case for Change document (Environment Agency, 2012), Defra introduced the concept of Resilience with the Water White Paper (HM Government, 2011). The Duty to Resilience has been confirmed with Royal Assent of the Water Act (HM Government, 2014). Resilience can mean many things, such as resilience to floods and water quality issues or the ability to recover after a water main has burst, but the pre-eminent issue for most water companies (South West Water 2010, WRSE workshops 2015) is resilience to drought – referred to as robustness in this thesis. Many companies talk about the dreaded three-dry winters (South West Water 2010, WRSE workshops 2015). For example, if the 2012 spring rains did not arrive in London for a few more days there may have been standpipes in the street. Up to PR09 water companies limited the evaluation of their robustness to drought to information found in the historical record. In PR14, Southern Water extended the historical record with a stochastic foray into the EBSD Advanced approach to gain a deeper understanding of their water supply situation in the context of longer return periods (Southern Water, 2014). Most other companies remained focussed on analysis that relied on the historical record. There may be anecdotal examples of droughts with longer duration. Indeed there is reference to such a drought in the diary of Kew Gardens, but in most parts of the UK the hydrological record does not go far enough back. In many parts of Cornwall, the location of two of the case studies in this thesis, the records only go back to 1930's. The application of IGDT to address uncertainty in water resources planning is specifically designed to deal with extremes in lack of supply when these extremes are coupled with an extreme increase in demand, and offers a method to test robustness to such extremes where there is an information gap such as a limited historical record of hydrological conditions.

There is some uncertainty as to what level of drought should be used as a design drought for planning purposes. Many water companies choose different design droughts and some companies do not have adequate historical river flow and groundwater records to be able to plan accurately for the worst drought on record and are left to plan for the worst drought they have evidence for. In addition, the uncertainty of droughts increases with the unknown influence of climate change. Likewise, it is hard to obtain an accurate assessment of future demand due to population growth and how people and businesses will use water in more extreme water scarce situations.

This thesis explores a novel, technical approach based on IGDT to understand the impact of severe uncertainty on a WRMP and proposes the WRP-RA as a means to understand the robustness of management strategies to uncertainty as a key element of decision making. With IGDT, it is not critical to be accurate with uncertainty. Moreover, the important element is to consider a wider range of uncertainty; i.e. from the range of values with low uncertainty, closer to the expected outcome, to the range of values with higher uncertainty, at the tails of the probability distribution. This thesis also offers a method to present more than one plan to customers to provide a better appreciation of the best-value as compared with one least-cost plan. The ability to communicate the relative robustness of plans is important, as successful adaptation occurs when decision-making is accompanied by shared learning (Adger et al. 2005), and the water resources planning process is governed by the willingness of water company customers to pay for investments that will provide a more secure future.

2.2.1 Current practice – Economics of Balancing Supply and Demand

The WRMP guidelines offer companies three technical approaches to balance supply and demand economically; the aforementioned EBSD Current, Advanced and Blue Skies Modelling. At present, uncertainty is addressed in the first two of these methods with the headroom estimation method and with the addition of stochastics for the EBSD Advanced approach. The headroom estimation method does not address severe uncertainty under climate change, just the mean projections, and with the new direction from parliament to satisfy a duty to resilience, current practice needs to evolve to accommodate more uncertainty. This thesis proposes that a preferred management strategy is not fully evaluated until its robustness to future uncertainty is compared with other strategies that also perform adequately well – whether these strategies are least-cost or not. The full value of a management strategy is not known until its performance is evaluated over a wide range of plausible futures. It is important to note that a robust management strategy that can handle severe uncertainty of future conditions need not be implemented in its entirety within the next 25 years – the standard planning horizon for Water Resources Management Plans. The value of a robust strategy is that it has components that can satisfy more extreme futures and is therefore ready to provide additional security as and when needed.

2.2.2 Sources of Uncertainty in Water Resources Management

The practice of water resources planning has always recognised variable weather patterns and their accompanying change in hydrology and influence on dry season water demand. Previously these factors could be considered in terms of probabilities of return; a 1:40 year drought or a 1:10 winter storm, for example. However, since climate change has begun to show its effects on weather patterns and as a result, influenced a ‘more than normal’ change in local hydrology, the previously thought ‘normal’ frequency of events can no longer be taken for granted (Milly 2008, Kiang 2011). The accumulated knowledge of seasonal and yearly hydrological changes as expressed in probability distributions is a helpful background but an uncertain guide for the future.

In England and Wales, water resources management requires looking to the future for at least 25 years (Environment Agency 2008). Most water companies rely on stream gauge information to assess their available supply in terms of inflow from streams or rivers and recharge rates for groundwater aquifers to assess the pump-able yield for which they have abstraction rights. The effect of climate change necessitates a re-evaluation of historical data and a method to simulate future river flows and recharge rates, etc. as perturbed by new weather regimes. There is a cascade of modelled information to consider before a future value for daily inflow or groundwater yield can be ascertained (Jones 2000, New et al. 2007, Ranger et al. 2010, Wilby and Dessai 2010). The effects of future emission scenarios drive future global weather patterns represented by different Global Climate Models (GCMs); GCMs are downscaled by Regional Climate Models (RCMs); from RCM variables the effects on local hydrology are assessed by a variety of impact models. Each of these steps and the final assessment of different adaptive policy responses to address these impacts contain associated uncertainties (Wilby 2010). The current practice within the water industry in England and Wales to optimise under a set of expected circumstances is no longer adequate to plan for a variable future (Hall et al. 2011).

The assignment of probabilities to climate change projections may offer a view of the future that is more approachable for probabilistic risk analysis and more easily interpreted through the lens of risk management (cf. McIntyre et al. 2003). This probabilistic presentation can easily become a misrepresentation, as these probability distributions are heavily influenced by choice of GCM (New et al. 2007) and the post-processing techniques employed to downscale to the local level (New et al. 2007, Lopez et al. 2006). There are also more subtle uncertain influences arising from the emission scenarios and impact model parameters (Wilby and Harris 2006, Dessai and Hulme 2007). To some extent the bias of GCM choice can be addressed by taking an ensemble approach (Lopez et al. 2009, Manning et al. 2009), but a proper representation of the probability of impacts can only be achieved by a thorough end-to-end analysis (New et al. 2007), and an understanding of the downscaling techniques used, specific to the impact that needs to be explored (Lopez et al. 2006). The UK Climate Projections 2009 (UKCP09, Murphy et al. 2009) provide a probabilistic range of expected climate futures, but their applicability to water resources planning is still being explored and debated (e.g., UKWIR 2009, Darch et al. 2011, Arnell 2011, HM Government 2012, WRMP 2024).

The future supply of water is not the only aspect of water resources planning in question. Future demand is also difficult to predict. The call for sustainability, new building requirements and more efficient water use, has motivated water companies to develop different initiatives to lessen consumption, but how much less water are people willing and able to live with? The success of different demand management initiatives is still in question (Arnell 1998, Arnell and Delaney 2006; Environment Agency 2001 and 2004). For example, in the South West Water (SW Water) Water Resources Plan 2009, the cumulative range of uncertainty that results from all the uncertainties related to demand including demand-side meters, demand forecast, the effect of climate change on demand and the effect of demand side management is almost double the range attributed to an aggregation of the uncertainties associated with the supply side parameters (South West Water 2009).

The uncertainties associated with water resources planning are varied and complex, and could be severe; and as such, require a deeper evaluation.

2.2.3 Characterising and Quantifying Uncertainty with the EBSD Approach

Current long term water resources planning in the UK defines the expected future as the water supply generated with the mean climate change projections coupled with the mean increase in demand (Environment Agency 2008). A Water Available for Use (WAFU), which is Deployable Output (DO) minus Outages (time periods when the system cannot supply water) and Losses (losses due to treatment works needs and other non-leakage and non-demand relates water use), is calculated by an evaluation of how much water a system could deliver to meet a certain Level of Service. For example, if the level of service to be met is to require a hosepipe ban less than once every 20 years, then the conditions of an historic dry climate year or sequence of years perturbed by mean climate change coupled with a future demand regime would need to be met by a management plan that would allow for a hosepipe ban only once in 20 years. In order to accommodate uncertainty, a safety factor for headroom is added. Headroom is calculated based on the likelihood that the uncertain parameters which feed into the water resources model will appear as expected or as some other value from their probable distribution.

This headroom value is added to projected demand and the management plan is revised to satisfy the balance between supply and a combination of demand plus headroom.

The current water resources planning context provides one view of the future that summarises the relationship between WAFU, demand, and headroom based on the management option that is chosen. As an example, Figure 1 illustrates the results of the management option for 15% Increase in Efficiency in the relationship between WAFU, demand and target headroom.

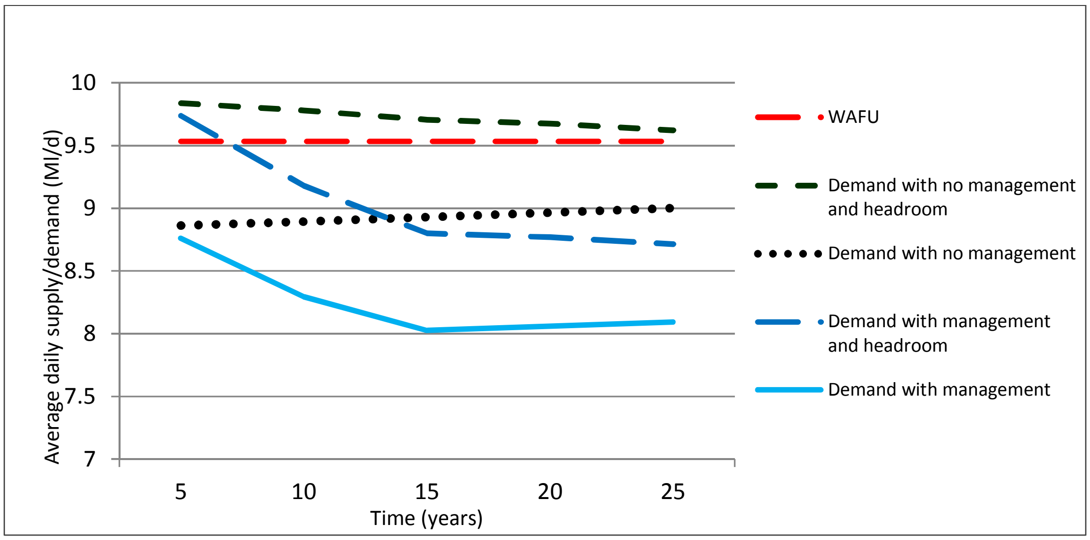


Figure 1. Example of supply/demand balance over a 25 year planning horizon for 15% water use efficiency reductions for 75% of residential use and 100% of commercial and industrial use.

There are challenges with the EBSD headroom approach for evaluating uncertainty in terms of analytical process and probabilistic methods. First, a level of service is decided upon often as a precursor to planning, rather than as a result of a system's ability to achieve such service based on an analysis of future conditions, and the ability to pay for the management actions required. Second, the headroom value is calculated independent of the water resources simulation. Third, the generation of a headroom value includes the assignment of probability distributions to each of the uncertain parameters and the combination of the standard deviations and means of these individual PDFs into a combined PDF for all uncertain parameters. Fourth, a Monte Carlo simulation of this combined distribution is completed, and an assumed, pre-specified percentile of this distribution is used as an overall headroom value. Finally, this obtained headroom value is then added to the demand forecast to formalise a safety margin. This final step often initiates further manual adjustments in the management strategy. This selection routine does not account for severe uncertainty.

Severe uncertainty is a distribution of outcomes that cannot be characterized from known distribution patterns or may exhibit unpredictable behaviour in its tail ends (Ben-Haim 2001). When dealing with severe uncertainty, such as that from climate change and variable socio-economic circumstances, it is challenging to (a) choose an accurate probability distribution for each parameter separately and especially for all parameters combined and (b) choose an appropriate percentile value from this combined distribution to represent headroom. It is also a complicated analytical sequence to quantify future conditions in a separate analytical process. The recombination of projected demand and headroom and re-evaluation of the ability of management options to achieve a certain LoS for both is a complex process. Management adjustments may be needed to accommodate demand plus headroom and these adjustments may change WAFU and/or demand. A change in WAFU and/or demand can influence headroom values since the calculation of headroom is intrinsically related to WAFU and demand. The inter-relationship of these processes can create an iterative analytical back and forth problem that is unfeasible to bring to conclusion. In addition, the measurement values that this planning process is based on, WAFU and headroom, are not directly observable, and although they are derived from reservoir levels, some measurement of the frequency of low reservoir levels based on the range of possible supply/demand combinations would offer a less complicated and easier to monitor assessment of a management plan's ability to handle uncertainty (cf. Hall et al. 2011).

In summary, a limited range of uncertainty is explored with headroom and the current process includes a separate analysis for:

1. current and projected conditions to understand the need for water
2. headroom associated with these projections
3. the amount of Deployable Output (DO) that schemes can provide
4. a reassessment of these schemes as part of the water resources network to understand network constraints and clarify the available LoS
5. a selection and scheduling of management portfolios based on DO
6. a revision of headroom to properly account for a combined management strategy

This thesis recognises all these needs and suggests that 2 through 6 inclusive could all be handled together in an iterative simulation of the water resources network that investigates a variety of future states to dynamically explore uncertainty in situ. The LoS and design drought would be inherent in these simulations and represented post-analysis to quantify the ability of a management strategy to provide a LoS depending on supply/demand conditions instead of a LoS being defined pre-analysis as a means to guide the choice of options that make up a management strategy. The fact remains that water companies perform these simulations anyway in order to evaluate points 1 and 4. Instead of abstracting the results from these simulations to a separate headroom estimation method, the characterisation and quantification of uncertainty could all be addressed in real time as part of system simulations currently performed to evaluate constraints and performance of a management strategy in the determination of a LoS.

The implementation of these simulations in a WRP-RA would require additional iterations to test the ability of a system to withstand a variety of challenging supply/demand futures (i.e. its robustness). Although this thesis does not look at resilience in detail, an assessment of a system's ability to recover is possible with an interpretation of the IGDT opportuneness curves. In some respects, it is very hard to predict what challenges a system will be faced with and the characteristics of these challenges. The import part is how robust and resilient a system is to a range of challenges. A system can be tested without knowing the exact detail of these challenges. We will never know the exact detail of a challenge. The headroom methodology focusses on the detail of the challenge. The IGDT based WRP-RA focuses on the effect more than the detail of the challenge and provides insight into a system's robustness to a range of futures instead of its ability to respond to one accurately portrayed version of the future. Section 3.3.1 introduces new metrics with which to measure a management strategy's ability to perform robustly to a wide range of futures.

2.2.4 Evolving practice

The document referred to as WR27, presents a forward look at evolving the Water Resources Planning Tools (UKWIR, 2012) and states that in many cases the current headroom approach is not adequate and that some situations require a further exploration of non-headroom uncertainties to evaluate: (1) supply forecast variation such as uncertain bulk transfer agreements and (2) demand forecast variation such as different potential demand forecasts, for example. A repeated running of scenarios is recommended as a form of sensitivity analysis to understand the relative impact of different non-headroom uncertainties and as a result the ability of a management strategy to handle a range of uncertainties. The WR27 report also states that the use of yearly planning variables in the EBSD methodology don't provide an adequate and realistic guide to the impact of future uncertainties on the frequency, duration and intensity of future water scarcity. Time series analysis of system performance under different management strategies is recommended to offer a more accurate and descriptive view of performance. Finally, emphasis is placed on presenting a best-value plan, reflecting the trend in research direction (Matrosov, Padula and Harou 2013) as opposed to a least-cost plan so that customers have an appreciation of how much extra security they can have for their investment with one management strategy as compared with another.

The Water Act (HM Government 2014) legislates a duty to provide resilience. Defra has provided the policy direction and given the duty to Ofwat. The Environment Agency promotes a new approach to water management that remedies the current gap between Water resources Management Plans and Drought Plans (Hepworth 2015). The water companies are also interested in linking these two plans with their 5-year Business Plans to ensure a fully integrated approach to planning and to explore new methods to justify investment for adding additional security in their water resources plans (WRSE 2015). There will need to be strong evidence to support the case for additional investment beyond a least-cost strategy (WRSE 2015). This justification will need to include the exploration of a wider range of futures (Turner, Marlow et al. 2014, and Borgomeo et al. 2014). All these approaches and recent research in adaptation planning under climate change uncertainty (Hoang 2013) speak to the need for a way to quantify more extreme situations and compare the ability of different management strategies to handle such situations in order to ascertain which strategy is the most nimble in dealing with future extremes (Turner, Blackwell et al. 2014, Degaris, pers. comm. 2014). At the same time there is general concern of approaching paralysis by analysis (South West Water planning staff, pers. comm. 2015, Turner and Jeffery 2015). A thorough approach is needed and one that is simple to execute is beneficial as it has more chance of being incorporated into the water company work flows. The IGDT-based WRP-RA satisfies both of these requirements.

There are some pioneers in the industry testing different approaches to address these issues. Three examples are provided below.

- Southern Water has published a Resilience Paper (Southern Water, 2014) that presents water conditions resulting from extreme drought events. This modelling uses the North Atlantic Oscillation (NAO) to perturb historic climatic time series and extend climate influences for a thousand years and then uses stochastic techniques to generate weather conditions that simulate different drought conditions for extreme return periods up to 1:500. These weather conditions are translated into river and groundwater flow series that represent supply available for different return periods. The Southern Water stochastic approach provides a yield analysis of available DO with an ever dwindling supply of water as introduced for different return periods. Traditional EBSD methods are still employed to develop a management strategy with these new DO values, but the stochastics replace the need for headroom.
- The Water Resources East Anglia (WREA) group has, with the help of Prof. Julien Harou's research consortium, expanded upon the use of a multi-criteria genetic algorithm (Hadka 2015), first tested with simplified portion of a Thames Water network (Matrosov 2011), to identify portfolios that offer a balance of benefits in terms of their reliability, cost, environmental protection and other factors in response to a variety of supply and demand forecasts. The WREA project is one attempt to approach the 3 dimensional complexity of water resources planning; 1D – the combination of options that makes up the portfolio, 2D – the scheduling of these options over a 25 year, or longer, planning horizon and 3D – the ability of these portfolios to perform over ever increasing uncertainty. It is extremely hard to tackle all these dimensions in one analysis routine, even with an incredible fast simulation model such as IRAS (Matrosov 2011).
- The Environment Agency, with the help of CH2M, has used the WRSE EBSD LP/IP Optimisation model to identify management strategies for droughts of different return periods. This work, termed the 'EA Drought

Pilot' project uses reasoned approximations to reduce available DO for the different drought return periods. This approach is not as detailed in its creation of water supply yield data as Southern Water's stochastic approach. The 'EA Drought Pilot' runs are based on reductions in existing supply and the yield of options in combination with the implementation of demand reductions as defined by LoS and additional emergency supplies of water available with drought permits and drought orders. This analysis was repeated for different supply return periods and different planning settings that attempted to standardise an approach to Levels of Service and the quantification of a Design Drought for all companies in the south east of England. The Environment Agency 'EA Drought Pilot' result in a least cost management strategy for each and every scenario of which there are 27.

The important point to draw from this Section is that the research and discussion of needing to explore more uncertainty in the UK in different ways than headroom estimation is now translating into practice and there is room for a number of different approaches at varying levels of sophistication. Most companies would like to test management strategies against an ever-dwindling supply and increasing demand, but some will not have the time or resources to do this. All companies would benefit from technical direction. However, it is hard to know in advance the myriad of issues that may crop up to put a system at risk, or what combination of supply and demand issues leads to a drop in a Level of Service. As suggested with the new concept of a middle-state of resilience (Butler 2015), an exact description of the settings that cause a disruption in service is not necessary. Moreover, the important part is to concentrate on knowing where a system is vulnerable and what actions make a system robust to a wide variety of such vulnerabilities. The WRP-RA can achieve a 'middle-state' robustness assessment with little extra investment in resources.

2.3 Simulation and optimisation

The mathematical modelling of water resources planning is achieved through simulation and optimisation routines supported by a variety of software programs and platforms (Mayer and Muñoz-Hernandez 2009). The three core dimensions to long-term water resources planning, as already stated, are:

1. Which portfolio of options should be included in a management strategy to satisfy a supply/demand deficit?
2. At what point in the future will each of the individual options need to be implemented?
3. How will this management strategy cope with uncertainty?

Approaching all three of these dimensions within one simulation, optimisation or analysis approach is difficult to achieve in terms of mathematical formulation and computing power – even with the power of super computers. In most cases the approach is broken down into at least two separate modelling exercises with methods to integrate the results. The selection routines of the EBSD methodology approaches dimensions 1 and 2. Dimension 3 - uncertainty is handled with the headroom estimation method.

The advanced techniques referenced in Section 2.2.4 also breaks down the modelling requirements into separate steps. It would only be realistic to explore all 3 dimensions at the same time for a simple system because although the supply/demand balance equation is simple, the characterisation of the system and situation is not.

Table 1 lists analysis methods based on planning needs and context; i.e. whether modelling is needed for operational reasons or long-term planning. Most water companies have network modelling software that helps them plan the detailed operations required to move water around the system. Either this model or a more generalised representation of this model is used to assist with long-term planning needs, such as the yearly planning averages required for EBSD modelling. The point of this table is to highlight the mechanics of decision-making as approached by water companies in England and Wales and in so doing expose the relative merits of different approaches to address uncertainty.

Table 1. Water resources planning context, needs and analysis method

Planning context	Planning needs	Analysis methods
Operational	Calculate S/D water balance of network	Rule-based Simulation or Optimisation
	Optimise use of existing network	Optimisation
Long-term planning	Perform DO analysis to develop yearly planning average	Simulation, optimisation or rule-based, spreadsheets and curve-fitting techniques
	Select new schemes	Expert judgement - EBSD Current - AISC approach
		Optimisation - EBSD Current - (Linear Programming) with yearly averages
		Optimisation - (Genetic Algorithm) with daily/weekly simulation
	Schedule new schemes	Expert judgement - EBSD Current - AISC approach based on analysis of Supply Demand Deficit
		Optimisation - EBSD Current - (Linear Programming) with yearly averages
		Real Options
	Characterise and Quantify Uncertainty (climate change, risk and resilience)	Headroom
		Stochastic
		Robust Decision Making
		Info-Gap

It is taken for granted that some form of simulation model is used to understand the constraints of a water resources network and the behaviour of this network under different supply/demand settings. Currently in UK water resources planning, a combination of DO assessment and LoS analysis methodologies are used to derive yearly planning averages for dry year average, critical peak and minimum DO amounts, which inform the selection and scheduling of options with the two EBSD methods (Environment Agency 2008, 2013). These analyses most often use a simulation model, but the yearly planning averages can be derived by other means.

This thesis focuses an investigation on the last 4 rows of Table 1 – the methods used to characterise and quantify uncertainty. Below is a short summary of the relevance of some of the new methodologies referenced throughout the table.

- The use of Real Options in the scheduling of management strategies enhances an appreciation of how to implement adaptive strategies over the long-term without spending too much too soon and also without losing future flexibility (NERA 2013). Inherent in the use of Real Options is the need to understand the behaviour of management strategies under more extreme conditions and therefore, new approaches to understand the implications of deeper uncertainty are required to use Real Options to its full potential.
- The use of a Multi-Criteria Genetic Algorithm offers a means to derive multiple potential management strategies that balance the performance of more than one metric (Hurford et al. 2014). The result is a multi-dimensional Pareto surface that offers decision-makers a large selection of possible strategies that balance water resources planning needs such as reliability, cost, environmental protection and other factors. This technique can include scheduling and uncertainty, but adding these two dimensions to the existing objective of selecting a balanced combination of options greatly increases the complexity of the calculations. Although the results of a MCDA genetic algorithm expose a great deal of information on management strategy performance, with so

many strategies to choose from, there is more effort needed to help decision-makers hone-in on the best value strategy.

- The use of stochastic modelling to develop a range of different supply values for different return periods, as employed by Southern Water (Southern Water 2014), coupled with different scenarios to address a range of demand forecasts offers a replacement for the headroom estimation method and is an understandable next step as it extends the probabilistic principles that define the headroom approach.
- Info-Gap Decision Theory (IGDT) and Robust Decision Making (RDM) take a different tact than headroom estimation or stochastics and navigate the ranges of uncertainty without probabilistic preference to an assigned distribution. IGDT continues this exploration of uncertainty without bounds until a system fails. RDM explores uncertainty within defined ranges to identify vulnerabilities. Both IGDT and RDM leverage the benefits of an accurate network model and explore the ramifications of uncertainty within the simulation environment instead of using an external analysis routine. (This thesis demonstrates in Section 4.4 that IGDT can also be applied in conjunction with optimisation modelling.)

The next sections of the literature review describe these analytical methods in more detail and discuss how they contribute to water resources planning under severe uncertainty.

2.4 Info-Gap Decision Theory

Info-Gap Decision Theory provides an approach to compare the ability of different management options to satisfy system performance criteria over an unbounded range of uncertainty and has been used for decision support in many fields from engineering to conservation science (Ben-Haim 2001, Regan et al. 2005, McCarthy and Lindenmayer 2007) with one previous application related to water resources, (Hipel and Ben-Haim 1999) and one to flood risk (Hine and Hall 2010). The prospect of dealing with severe uncertainty forces preference away from what is optimum for a defined set of circumstance (to optimise) towards what is good enough over a wide range of possible circumstances (to satisfice). The simplicity of being reliant only on the central tendency of parameters to begin an assessment that addresses uncertainty is advantageous. An investigation of climate change sensitivity in terms of future temperature change (Hall et al. 2007), and an expert elicitation of the probability of tipping points occurring for different temperature rise profiles (Krieger et al. 2009), both reveal general agreement with central tendencies but show a wide spectrum of opinions in the associated ranges.

IGDT offers the ability to evaluate management decisions continuously at many points in the calculation sequence as uncertain parameters increase outwards from their central tendency in an unbounded fashion. There is no requirement to take a position on how wide a range of variation should be considered. Figure 2 graphically depicts the unbounded nature of an IGDT assessment of a system equation with two uncertain parameters (u^1 and u^2). The potential result of this system equation deviates from its expected result (represented by "ct") that would arise from the central tendency of both parameters, by an uncertain amount (represented by α), dependent on how much each parameter deviates from its expected value. Although this figure uses a simple example with two parameters, an Info-Gap characterisation of uncertainty behaves similarly with multiple parameters.

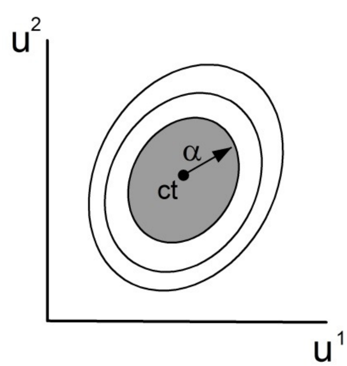


Figure 2. An Info-Gap exploration of uncertainty (Hine and Hall 2010)

Although the uncertain space is unbounded, Info-Gap takes a targeted approach to explore this space. The Robust Decision Making approach (Lempert and Groves 2010, Matrosov, Wood and Harou 2013) considers multiple possible futures within defined boundaries, but the mathematical arrangements of Info-Gap organises the trends of all uncertain variables (no matter how many), to either increase or decrease simultaneously in two trajectories to explore robustness and opportuneness. An exploration of robustness expands uncertainty in the direction that pushes the system in question most quickly towards failure (in basic terms for water resources management, if demand increases and/or supply decreases). An exploration of opportuneness expands uncertainty in the direction that pushes the system in question most quickly towards windfall success (in basic terms for water resources management, if demand decreases and/or supply increases).

As an example, risk of water shortage is the performance criteria used in Equation 1 to evaluate the robustness of water management options. A robust water management option has a risk of water shortage (*R*) that is as large as possible, but still less than or equal to a critical risk value as defined by a promised level of service (r_c). South West Water's promised level of service is that there will be a hosepipe ban not more often than once in twenty years. The most robust ($\hat{\alpha}$) option (*q*) is one that protects water supplies at the same level of risk as all the other options at the highest level of uncertainty (α). To quantify uncertainty and evaluate robustness, each one of the supply and demand parameters (*u)* changes unfavourably with increasing uncertainty (α).

$$\hat{\alpha}(q, r_c) = \max\left\{\alpha : \max_{u \in U(\alpha, \tilde{u})} R(q,u) \le r_c\right\} \quad (1)$$

The performance criteria used to evaluate opportuneness is slightly different because the risk of water shortage quickly disappears as all uncertain parameters trend towards favourable conditions. Therefore, the extent of a safety margin before a risk of shortage would occur is used as the performance criteria to evaluate opportuneness with Equation 2. This safety margin is defined as the volume of water between the operational management curve (which signifies the optimum reservoir volume at different times of the year), and the drought management curve (which signifies the minimum acceptable reservoir volume at different times of the year). Over the course of a year, this safety margin can be in deficit (R) by a large amount but must be less than or equal to a minimum volume of water (r_w) which defines the minimum opportuneness criteria. The most opportune ($\hat{\beta}$) option (q) is one that offers the same safety margin (R) as other management options at the lowest level of uncertainty (α). To quantify uncertainty and evaluate higher levels of opportuneness, each one of the supply and demand parameters (u) changes favourably with increasing uncertainty (α).

$$\hat{\beta}(q, r_w) = \min\left\{ \alpha : \max_{u \in U(\alpha, \tilde{u})} R(q, u) \leq r_w \right\} \qquad (2)$$

Graphs of robustness and opportuneness are used to compare the performance of water management options as one or more parameters trend away from their central tendency into the range of uncertainty.

Info-Gap Decision Theory offers a method to characterise uncertainty that works in conjunction with the simulations of a water resources model as part of an integrated dynamic analysis. There is no need to predefine levels of service and iteratively evaluate a WAFU value that satisfies these levels of service with headroom depending on the management option that is explored. Within an IGDT-based dynamic modelling framework, the assessment of how each management option deals with uncertainty occurs through successive runs of the water resources simulation model as parameter values stray from their central tendency into greater levels of uncertainty.

2.5 Other methods to explore severely uncertain futures in the context of water resources planning

Info-Gap Decision Theory is one of a few new and innovative analytic methods that help decision-makers understand the impact of severe uncertainty, (as future uncertainty is much more uncertain than it used to be), and develop pragmatic and proactive management strategies to make their systems more secure in the face of higher uncertainties. Each method addresses some aspects of planning with uncertainty, but not one method offers a comprehensive solution for all issues. This section introduces each method and Table 2 summarises their benefits and drawbacks in order to place the use of IGDT in the context of other techniques.

2.5.1 Stochastic development of available yield

As used by Southern Water in the development of their Resilience Paper, this is the first use of stochastic modelling to support the development of long-term water resources planning in England and Wales since it was suggested in the original EBSD paper (UKWIR 2002). Southern Water's approach investigates uncertainty stochastically to define the return period of different drought events in order to put in context the limited water availability for different extreme events (Southern Water 2014). These values can then be incorporated into different planning scenarios and coupled with different demand settings to explore different futures and a systems ability to cope.

This approach is like putting one foot in the water. It expands the traditional EBSD approach and the treatment of uncertainty into more severe futures with the conceptually intuitive concept of a return period for water supply only. In the Southern Water application, demand is addressed with different scenarios and not stochastics. This is a useful application as stochastic modelling of supply and demand in tandem would be challenging in terms of required computing and also technical application. A better appreciation of the risk-based conditions of water resources management can be gathered with stochastic modelling of both supply and demand (Mortazavi et al. 2012).

Stochastic modelling still assumes some form of a distribution of potential future states, as such it is important to stretch the range to much larger extremes, i.e. 1000 years as was considered in Southern Water's analysis. In the UK, gathering enough information to accurately portray more extreme return periods is challenging given the limitations of UKCIP09. It is also important to include consideration of potential nuances related to climate change as looking backwards for an extended period may not be an accurate guide to extremes of the future (Turner et al, 2014 and Harris et al 2013).

In comparison with IGDT:

Taken to the full extent of its possibilities, stochastic modelling could be considered similar to IGDT as they both attempt to explore a myriad of potential future states and management performance related to these states. Albeit, a full exploration of many uncertain factors with stochastic modelling is a challenging endeavour. In guiding principles, these two techniques are quite different in that stochastic modelling still assumes some distribution for uncertainty, whilst IGDT does not.

Stochastic modelling may be conceptually an easier transition to a deeper evaluation of uncertainty because of its probabilistic nature, but without an evaluation of the full extents of severe uncertainty as can be accomplished with IGDT, the performance of management strategies up till failure is unknown. Additionally, because the derivation of extreme return periods requires an extensive amount of data that is hard to gather from UKCIP09 (Turner et al, 2014) and stochastic calculations require advanced computer computational power, it is a challenging endeavour to achieve a complete stochastic evaluation.

2.5.2 Scenario exploration

Extended scenario exploration is promoted in WR27 (UKWIR 2012) as a means to incorporate non-headroom uncertainties and has been adopted in PR14 as a means to promote best-value versus least-cost plans. This method is conceptually familiar to decision makers and is helpful for public engagement as scenarios can be accompanied by an understandable narrative. Scenarios are a good means to compare baseline activity, or Business As Usual (BAU) with some conceivable future states and management responses, but with a scenario-based approach it is hard to provide a full view of potential futures as quickly and efficiently as can be accomplished with scenario neutral methods (Prudhomme et al. 2010).

In comparison with IGDT:

Scenario exploration offers a few different views of the future and specific management responses to these future states, whilst IGDT compares the ability of a few management strategies to perform in the context of multiple plausible futures that test a system's robustness and indicate its opportuneness. IGDT could be an add-on to scenario evaluation as a post-process to compare the relative robustness of management responses designed to address specific scenarios. This approach is described in Section 4.4.

2.5.3 Robust Decision Making

The process of Robust Decision Making (RDM) offers a thorough assessment of the ability of management options to respond to any plausible future within a defined range of uncertainty (Lempert 2000, Lempert 2006, Hall 2010, Lempert 2010, Matrosov 2011, Matrosov, Wood and Harou 2013). RDM is a process that involves 6 strategic analytical steps (Lempert 2006). These steps are:

1. Define all the boundaries of a range of plausible futures and create a portfolio of management options.
2. Through computer simulation run all possible combinations within these boundaries.
3. Assess the parameters that expose vulnerable management responses.
4. Develop options to strengthen against vulnerabilities.
5. Characterise trade-offs to guide the decision of options.
6. Characterise deep uncertainty and potential responses for decision-makers.

The RDM approach continues to evolve in order to respond to the needs of decision-makers. In a similar fashion to Real Options, the RDM analysis has helped decision-makers become more comfortable with the concept of adaptive planning (Lempert and Groves 2010).

The prospect of preparing for an extreme future, that is possible but seems improbable, and preparing for it with financial commitments and operational changes can seem daunting. The benefit of knowing which management options can handle an extreme future and knowing at what point in time operational changes need to be invoked is immensely valuable. The ability to define adaptive measures for future decision-makers to evoke if necessary is both an action of fiscal responsibility and a robust preparation for an uncertain future.

In the early stages of its development, the valuable information contained in the RDM process and results was too complicated to communicate to analysts and decision-makers. Co-development of RDM analysis through successive workshops has helped bridge this communication challenge (Lempert 2010). In this era of acknowledging an uncertain future and accepting the responsibility to plan sustainably and proactively, the ability to communicate the influence of uncertainty on strategic decisions is critical.

In comparison with IGDT:

RDM and IGDT are very similar in that both techniques question the validity of probabilistic techniques in the case of deep (RDM phrasing) or severe (IGDT phrasing) uncertainties. It is hard to argue with this point. In a sense, when evaluating the potential impact of future states that could occur at the tail end of distributions, what is the relevance of a distribution? These non-probabilistic approaches are not apocalyptic. They are merely suggesting that there is much to be gained from exploring the robustness of management strategies, especially when large investments are at stake. This far-reaching knowledge provides essential information for adaptation.

Neither method helps select the portfolio of options that makes up a management strategy. RDM explores a larger combination of futures as it evaluates performance against any combination of uncertainty, whilst IGDT explores wider range of future along two paths, when all uncertainties trend for the worst (robustness) and when all uncertainties trend for the better (opportuneness). It could be said that RDM is not limited to the Info-Gap requirement of defining a tight system with parameters that increase or decrease favourable or not; and instead RDM freely explores a variety of combinations. It also could be said that the two trends that IGDT considers (robustness and opportuneness) define the edges of all possible futures and there is no need to understand the noise in between. Furthermore, although RDM explores a larger combination of possible futures, there is no specific aspect to explore the IGDT concept of opportuneness (windfall opportunity when uncertainty trends in a beneficial direction) – and therefore with RDM, it is not easy to identify the aspects of management strategies that offer a quicker recovery.

In a sense, both methods provide similar information and RDM focusses on identifying vulnerabilities and policy responses to these vulnerabilities, whereas the main concern of Info-Gap is to compare the relative performance of complete plans. These two methods can provide complementary information (Matrosov, Wood and Harou 2013).

2.5.4 Multi-Objective Optimisation with a Genetic Algorithm

Multi-Objective Optimisation (MOO) is a very attractive method as it gives the decision-makers and stakeholders access to all the important metrics that define a best-value management strategy (Maier et al. 2014). Instead of pre-filtering options to consider and carefully compiling one or a few proposed management plans, multi-objective optimisation presents all possible plans based on desired performance for important metrics. This a posteriori decision making is optimum as decisions that limit candidate strategies before modelling can result in some of the best Pareto front candidates not being identified (Herman et al. 2015). In addition, potential best-value strategies are not just presented with a two-dimensional Pareto front that balances two competing objectives such as cost and water security, they are presented with many dimensions to understand a fuller picture of how each management strategy performs in respect to each objective. With this approach, a multi-dimensional Pareto surface offers information on cost, water security, environmental impact, carbon emissions, energy use, etc. Perhaps the most attractive aspect of this method is that it does all the work in selecting a balanced optimum portfolio of options. Once the network is designed and the options are characterised properly, the genetic algorithm can proceed to find the best compromise between many competing objectives and will also report on all runner-up options. A decision-maker need only dig into the details of a few management strategies to confirm the means to achieve their desired end is appropriate. This analytical process can leave the impression that all possible strategies are considered.

In comparison with IGDT:

IGDT and MOO are two techniques that cover two different parts of the 3 dimensions of long-term water resources planning. Although it is possible for MOO to also accommodate scheduling and robust uncertainty analysis, these two elements can require a lot of extra computing power in the context of long term water resources planning. Approaches to address these aspects in this sector are still underway (Hadka and Reed 2015 and Deb and Gupta 2006), and in other applications of multi-objective optimisation (Odan et al. 2015).

2.5.5 Real Options

Real Options is a technical method used to plan when to implement options over the long-term so as not to spend more than is needed at any one point in time and also to retain future flexibility to be able to respond should the future require more intense intervention (Zhang and Babovic 2012, Woodward et al. 2014). Real Options is based on a probabilistic appreciation of the likelihood of future events occurring and the value of investing in options that retain future flexibility vs. options that remove such flexibility (UKWIR 2012, NERA 2013).

In comparison with IGDT:

Real Options helps plan when to shift tact in a management strategy whilst still being prepared for future changes. IGDT provides the information of when different strategies perform better than others at increasing levels of uncertainty. These methods could complement each other. IGDT could provide the information on management strategy performance at different states of uncertainty as input data for Real Options. Ironically, a non-probabilistic method could inform a probabilistic one.

To make a Real Options approach valuable a longer look into the future than 25 years is necessary. A growing consensus in the water resources planning community is that 80 years is a more informative planning horizon when considering robustness and resilience. (WRMP 2024, WRSE interviews).

As a summary note, there could be a ‘Dream Team’ of analysis techniques that combines the top performers. In this combined approach, MOO takes care of selecting a collection of potential management strategies, an optimisation-based IGDT takes cares of comparing their relative robustness over increasing uncertainty and Real Options is used to plan the adaptation pathways. This combination would provide a very thorough and very robust decision making process.

Table 2. Benefits and drawbacks of different methods to approach uncertainty for decision-making

Method	Benefits	Drawbacks
Info-Gap Decision Theory	• Requires minimal extra preparation, can be implemented with most simulation and optimisation software. • Explores an unbounded range of uncertainty until system failure. • Gives an indication of the relative robustness and opportuneness of management strategies.	• Does not help with the selection or scheduling of options. • Can be hard to explain as it is a non-probabilistic approach and is conceptually challenging for people to understand and integrate with other related decision-making approaches.
Stochastic modelling	• Dynamically assesses a comprehensive range of values. • Can represent various states of an extreme situation in terms of return periods. • Easy integration of results into a risk-based approach suited to probabilistic methods.	• Scheduling different elements is technically challenging. • Hard to represent the performance at the tail end of distributions, especially when two or more uncertain factors occur at the same time both at the extreme end of a distribution.
Scenario exploration	• Easily explainable future conditions and management responses for decision-makers and the public. • Analysis can be focussed, detailed and fully developed.	• The number of scenarios that can be explained and understood in terms of their relevance is limited. • May not include some future states that could occur. • Can be hard to compare strategies developed for many futures and many different responses to these futures.
Robust Decision Making	• Open characterisation can represent any future state. • Exposes vulnerabilities as a primary aspect of the process. • Easily accompanies the planning process. • Iterative nature fosters learning of the system and different ways to approach uncertainty.	• Does not help create management strategies in the first place, it informs the revision of strategies based on their vulnerability to future uncertainties. • It is intensive in the computing power and time required to set-up an analysis and as such is not an easy undertaking.

Method	Benefits	Drawbacks
Multi-Objective Optimisation with a Genetic Algorithm	• Metrics are calculated for all possible management strategies in a balanced optimal way. • The background details of candidate management strategies are available.	• May not include scheduling or an easily definable approach to uncertainty depending on the complexity of the system. • May require reformulating a water resources network for a software that can handle the intense computing.
Real Options	• Decision process includes accounting for the ability to adapt. • Investment decisions are considered long-term and not short-sighted. • The process of preparing information results in a deeper understanding of the system.	• Does not necessarily help with the characterisation or quantification of future uncertainty, it focuses on developing an adaptive action plan that responds to a conceptualisation of future uncertainty. • Relies heavily on probabilistic techniques and as such risks not exploring activity at the tail ends of distributions.

2.6 Summary of literature review

This literature review has provided 5 key insights to guide the development of the WRP-RA.

- In the UK and Internationally water resources planners are looking for means to analyse, evaluate and understand the implications of more severe uncertainty than they have previously explored. (Turner, Marlow et al 2014, Means et al 2010)
    - The WRP-RA tests an unbounded range of uncertainty.
- In the UK, the headroom estimation method somewhat conceals the uncertainty and includes an elaborate and disconnected analysis cycle.
    - The WRP-RA is designed to expose uncertainties and explore them dynamically in situ as part of the system modelling process.
- Although there are choices of methods to characterise more severe uncertainties, many can be considered technically challenging to implement.
    - Using IGDT offers an approach to understand the relative robustness of management strategies with little additional effort.
- Always in the back of a water resources manager's mind is the question, "What if it's a really bad drought?" Up till present, in the UK, the question has been how will my water supply system perform when faced with a 3rd dry winter? If that question is answered, the next might be, "Just how robust is my system?"
    - IGDT tests a management strategy until failure.
- In order to benefit water resources planning broadly, a new robustness assessment method should be applicable within simulation and optimisation modelling.
    - The WRP-RA is applied in both the simulation and optimisation environments.
- The end result of water resources planning is to be able to portray the issues to decision-makers, stakeholders and the public, in a convincing manner that shows the value of investing in increased robustness and/or resilience.
    - The results of the WRP-RA are presented in a 'best-value' approach as suggested in WR27 (UKWIR 2012).

3 Methodology

3.1 Overview

This section describes the technical steps required to perform a WRP-RA and how the WRP-RA approach is compared with current UK water resources planning methods to show its relative value in this decision-making context. The methodology is described in a generic sense and can be applied in other water resources planning contexts, globally. The value of using IGDT as part of this method is in comparing the relative performance of management strategies to assess which one performs better in terms of robustness (ability to withstand uncertainty that tests the system), or opportuneness (ability for improved performance from uncertainty that benefits the system), as uncertainty increases progressively from the expected conditions to the tails of the distributions that characterise future supply/demand settings.

In order to appreciate any additional benefit the WRP-RA provides when compared with existing UK water resources planning practices, the WRP-RA method is compared with two variations of the current industry standard EBSD Modelling as described in Section 2.2.1. These two variations include the AISC selection method, whereby a least-cost plan is selection by choosing options with the lowest Average Incremental and Social Costs (AISC) and LP/IP selection method whereby a least cost plan is selected with an optimisation routine. Two different models were used to compare these EBSD selection processes with the WRP-RA.

1. A bespoke MATLAB simulation model was developed specifically for this research for in order to replicate a typical network simulation model and to explore the AISC selection method. This thesis uses two variations of the bespoke MATLAB simulation model in Case Study 1 (described in Section 4.2) and in Case Study 2 (described in Section 4.3).
2. A bespoke Generic Algebraic Modelling System (GAMS) optimisation model was used to replicate optimisation modelling and explore the LP/IP selection method. This thesis uses one version of the bespoke GAMS model in Case Study 3 (described in Section 4.4).

Other models and analysis methods were used for different aspects of long-term planning. @Risk software was used to replicate the headroom estimation method commonly used by water companies. Additional analysis methods and post-processing of simulation and optimisation results to present candidate best-value and robust strategies were completed in Excel 2010.

In order to respond to the current evolution of water resources planning guidelines in England and Wales, a method to identify a best-value plan is demonstrated for each of the two EBSD methods and the WRP-RA. The best-value presentation of results is a side benefit of the WRP-RA method. The primary benefit of the IGDT-based robustness assessment method, is its ability to compare the relative performance of management strategies over increasing uncertainty and its potential to reveal preference reversals. A preference reversal occurs when a management strategy performs worse than other strategies in response to expected conditions and performs better at wider deviations from the expected. In order to aid decision-making in water resources planning which requires many considerations, a number of performance metrics are weighted and combined in a MCDA evaluation to compare the relative robustness of portfolios with regards to a range of management concerns.

As a summary of the analytical and modelling work completed for this thesis, Table 3 builds on Table 1 and again lists analysis methods based on planning needs and context. It additionally indicates which methods and approaches are used in this thesis. As part of general practice, water companies in England and Wales use some form of operational simulation modelling to plan the movement of water around their system on a daily and/or weekly time step. This model is commonly run on a deterministic basis and infrequently run in optimisation mode. This simulation model is also often used to inform long-term planning; firstly to help with the development of yearly water supply planning averages (referred to as Deployable Output (DO) in the UK), as explained in Section 3.2.1, and secondly to test the performance of different management strategies against different supply/demand settings to develop management strategies that satisfy their Level of Service (LoS).

Table 3. Water resources planning context, analysis methods and aspects addressed in this thesis

Planning context	Planning needs	Analysis methods	Thesis approach
Operational	Calculate S/D water balance of network	Simulation	MATLAB custom programmed routine (daily time steps).
	Optimise use of existing network	Optimisation or Rule-based	Rule-based MATLAB routine to supply water locally first, then backfill with other supplies (daily time steps).
Long-term planning	Select new schemes	EBSD Current - AISC approach	Priority based on AISC volumetric cost of water (yearly time steps).
		EBSD Current – LP/IP Optimisation	GAMS Mixed Integer Linear Programming (MILP) Least-Cost optimisation based on financial, environmental and social and carbon costs associated with Capex, Fopex and Vopex.
	Schedule new schemes	EBSD Current - AISC approach	Implement lowest cost schemes first based on expert judgement (yearly time steps).
		EBSD Current - LP/IP Optimisation	Optimise the implementation and utilisation of schemes to satisfy the supply/demand deficit at the least cost based on modelling results (yearly time steps).
	Characterise and Quantify Uncertainty (climate change, risk and resilience)	Headroom	Monte Carlo evaluation of a combined uncertainty of input values to calculate a value to add to demand that must also be satisfied as part of the supply/demand deficit.
		Info-Gap Decision Theory (IGDT)	Simulation testing of strategy performance over different supply/demand settings: successively challenging for robustness and successively favourable for opportuneness.
	Select management strategy	EBSD Modelling	As above with the addition of a best-value assessment.
		WRP-RA	Using IGDT, MCDA and a best-value approach and to select a comprehensively robust strategy.

3.2 Select a Least-cost Management Strategy with EBSD Current methodology

The major steps of the EBSD Current water resources planning methodology are shown in Figure 3.

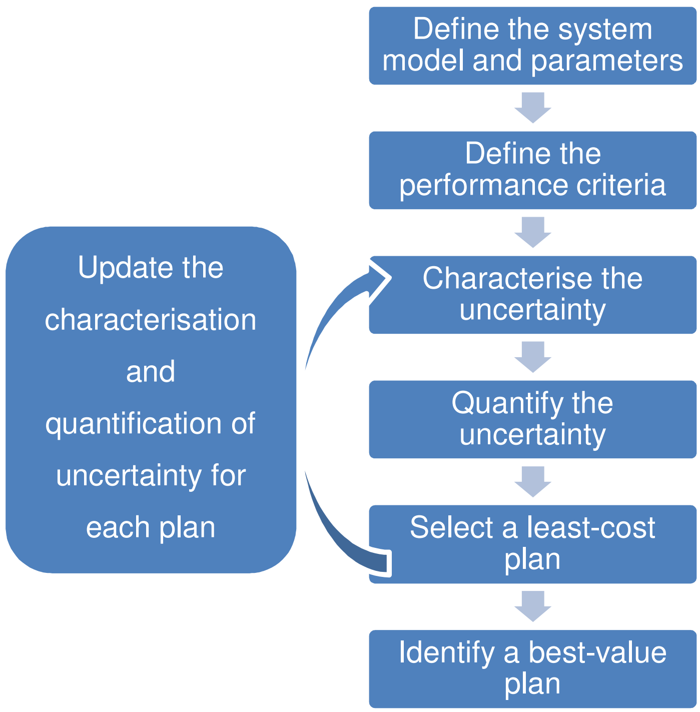


Figure 3. Major steps of the EBSD Current water resources planning methodology

3.2.1 Define the system model and parameters

In order to perform EBSD Modelling with the current method, a set of parameters derived as yearly planning averages must be developed to quantify the demand that must be met, the current and potential supply of water and any associated uncertainties. Below is a description of the EBSD parameters needed to calculate the supply/demand balance as stated in Equation 3 (UKWIR, 2012).

$$Supply\ Demand\ Balance = Supply - Demand + Target\ Headroom\ (THR);$$

where Supply = Water Available For Use (WAFU) = Deployable Output (DO)– Outage – Loss (3)

Target Headroom (THR)

Target Headroom is the composite value that includes all the uncertainties related to the supply demand balance equation. The derivation of headroom is discussed in more detail in Section 3.2.2. The aim of this thesis is to propose the WRP-RA as an alternate method to characterise and evaluation uncertainties related to the supply demand balance equation. The WRP-RA method enables an exploration of management strategy response to severe uncertainty. As such, a thorough understanding and re-enactment of the existing headroom estimation approach is a helpful point of comparison.

Deployable Output for options (DO)

Deployable Output is the amount of water that can be made available to a water resources system given a series of constraints that include: hydrological yield, abstraction rules, reservoir control rules, pumping plant capacities, raw and treated water mains capacities and water treatment works capacities. The quantification of existing DO available within a system is explained in the LoS section below.

Outage

Outage refers to planned or unplanned disruptions of service that could be related to such factors as water lost due to a burst pipe or poor water quality. Outage assessments are conducted completely independently from headroom assessments. As the goal of this thesis is to explore uncertainty related to water scarcity and not network disruptions, an outage assessment was not reproduced.

Process Loss

Process loss refers to non-leakage loss in the system before water arrives at its final destination; e.g. water used in treatment works that is therefore not able to contribute to satisfying demand.

Water Available for Use (WAFU)

The Water Available for Use is defined as the Deployable Output of a system minus Outage and Process Loss.

Level of Service, Design Drought and Deployable Output of a water resources network

The development of yearly planning averages is guided by a company's choice of LoS and Design Drought. A LoS is a company's commitment to its customers to provide water without restriction except under drought conditions that occur at a low probability. For example, South West Water promises to invoke a hosepipe ban no more than once every 20 years, giving a 5% reduction in demands for no longer than 6 months. A Design Drought is the driest drought on record. For example, South West Water plans its Levels of Service in relation to the 1975-78 drought as this is the driest drought on the record available to them and therefore the most challenging for their water resources system. A company arrives at a Deployable Output figure by simulating the water resources system through a drought period to see the total amount of water that can be delivered within its defined LoS. For example, with a 5% reduction in demand.

Cost

The cost to implement an option is the main determinant (apart from water security) of EBSD results as the purpose of EBSD Modelling is to find a least-cost plan to satisfy the supply demand deficit.

For the AISC selection method, every type of option, whether supply-side, demand management or network upgrade, is assessed in detail to arrive at an Average Incremental Social Cost (AISC) in Net Present Value. The AISC is a volumetric cost calculated by dividing the total cost to implement an option by the total amount of water available over its asset life. All options can be evaluated based on the same asset life or different depending on the characteristics of the option.

Volumetric costs and any costs that represent the social and environmental benefits or costs of an option are also included in the calculation of an AISC value. This value is then used to compare the relative cost of each option. It is possible to compare the actual amount of water utilised for one option or a portfolio of options with the full capacity available; i.e. a reservoir could provide a capacity of 10 Ml/d, while only 5 Ml/d is used.

For the LP/IP selection method, nine different cost values are assigned to every option. Three types of costs; Capital (Capex), fixed operating (Fopex) and volumetric (Vopex) were assigned to each of 3 categories; Financial, Environmental and Social and Carbon. Capex and Fopex costs are assigned as annuities and discounted each year the option was used. Vopex costs are calculated based on the amount of water used and not the total capacity available. These costs are also discounted each year the option is used.

Costs related to the existing network are handled differently for each EBSD selection method:

- For the AISC selection method, costs associated with the treatment and distribution of water within the existing network and costs related to implementing new options are included.
- For the LP/IP selection method, a marginal cost is assigned to any surplus water that exists. This cost for existing surplus DO is included to facilitate the identification of any options that could provide water at a rate less expensive than the current cost.

3.2.2 Characterise the uncertainty

There is a defined approach to headroom estimation that lists a number of supply-side and demand-side uncertainties (

Table 4) that influence the accuracy of the supply/demand balance of Equation 3. Water companies choose which uncertainties are significant for their water resources system and how to characterise each uncertainty based on guidance from industry literature (UKWIR, 2002). Each individual uncertainty is assigned a probability distribution along with its defining characteristics; e.g. Normal distribution with a standard deviation of 4 Ml/d. Justification is provided as to why a particular distribution is chosen. Once each individual distribution is defined, they are all combined to generate an overall representation of uncertainty. This combined uncertainty is then sampled with Monte Carlo and a percentile value is chosen for each year of the 25 planning horizon to arrive at a time series of volumetric headroom values in Ml/d that are then added to demand as part of the supply/demand balance equation.

Table 4. Components of headroom uncertainty from UKWIR, “An Improved Methodology for Assessing Headroom”, Report Ref No 02/WR/13/2, 2002

Supply related	
S1	Vulnerable surface water licences
S2	Vulnerable groundwater licences
S3	Time limited licences
S4	Bulk imports
S5	Gradual pollution causing a reduction in abstraction
S6	Accuracy of supply-side data
S8	Uncertainty of impact of climate change on source yield
S9	Uncertain output from new resource developments
Demand related	
D1	Accuracy of sub-component data
D2	Demand forecast variation
D3	Uncertainty of impact of climate change on demand
D4	Uncertain outcome from demand management measures

The application of the headroom estimation method for this research is described in more detail in Section 3.2.4.

3.2.3 Define the performance criteria

Cost is the main performance criterion that dictates the merit of an EBSD solution with both the EBSD Current selection methods. Before the programme development stage where a least-cost combination of options is selected and scheduled, the options appraisal process filters options based on a number of criteria in order to minimise risk, and identify the most viable and acceptable solutions. Environmental concerns are addressed with a Strategic Environmental Assessment and other specialised assessments as needed. Environmental and social issues are also included in the final selection and scheduling process via the assignment of environmental and social costs.

3.2.4 Quantify the uncertainty

A water resources model simulates the mass balance of a reservoir(s) and daily inflows from other supply sources based on a sequence of historic inflow data to explore hydrologic variability over a 25-year planning horizon. During the 25-year planning horizon domestic, agricultural and commercial /industrial demand can increase or decrease depending on circumstance. Management interventions occur at specified times over the 25-year planning horizon and adoption rates for demand side management options gradually increase over time.

To quantify uncertainty with headroom estimation in this thesis for the AISC selection method, supply and demand values are assessed every 5 years for each management strategy. A probability distribution, as defined in Table 5, is assigned to each uncertain parameter that affects supply and demand in exactly the same way it was assigned by South West Water in their PR09 WRMP. All of these individual distributions are combined together in @Risk software and sampled with Monte Carlo for 5000 simulations to derive a combined distribution profile (Figure 4). A percentile from this combined distribution is chosen, as described in the distribution column of Table 5 to derive a resulting total value for the overall combined headroom for a particular time step and management strategy. A linear trend between these headroom values at 5 year intervals is calculated and included in the supply/demand balance equation.

Table 5. Parameters evaluated for uncertainty with headroom estimation (range and distribution are based on the South West Water WRMP, the percentile range is specific to this thesis and values are calculated) (South West Water 2009).

Headroom component	Description	Range	Distribution	Percentile range	Values (Ml/d)
S8	Changes in yield from Climate change	Historic inflows perturbed by wet to mean and mean to dry climate change scenarios	Triangular	80 to 87.5 over the planning horizon.	Mean = 163.224 Wet = 168.121 Dry = 158.3273
S6/2	Supply meter accuracy	+/- 2.5%	Normal		Mean = 163.224 SD = 4.08
S6/4	Changes in yield from Catchment changes due to Climate Change	+/- 10%	Normal		Mean = 163.224 SD = 8.16
D2	Changes in population, commercial/industrial and agricultural use	+/-10%	Normal		Mean = 150.11 Loss = 159.12 Gain = 141.11
D3	Changes in demand due to climate change	+/- 1.4%	Triangular		Mean = 150.11 Loss = 150.37 Gain = 149.86
D1	Demand meter accuracy	+/- 2.5%	Normal		Mean = 150.11 SD = 1.84
S9/E	Potential gain or loss in demand reductions related to the number of homes to adopt efficiency measures	+10% (gain) or -20% (loss) of expected number	Triangular		Mean = 150.11 Loss = 151.89 Gain = 149.52
S9/RG	Potential gain or loss in demand reductions related to the number of homes to adopt rainwater harvesting and/or greywater reuse	+10% (gain) or -20% (loss) of expected number	Triangular		Mean = 150.11 Loss = 151.35 Gain = 149.70

The values used in Equation 4 (UKWIR (Headroom) 2002) that represents the combined uncertainty distribution for Monte Carlo assessment of headroom uncertainty as defined in @Risk can be found in Table 5.

$$\textit{Headroom Uncertainty} = S8+S6/2+S6/4+D2+D3+D1+S9/E+S9/RG \qquad (4)$$

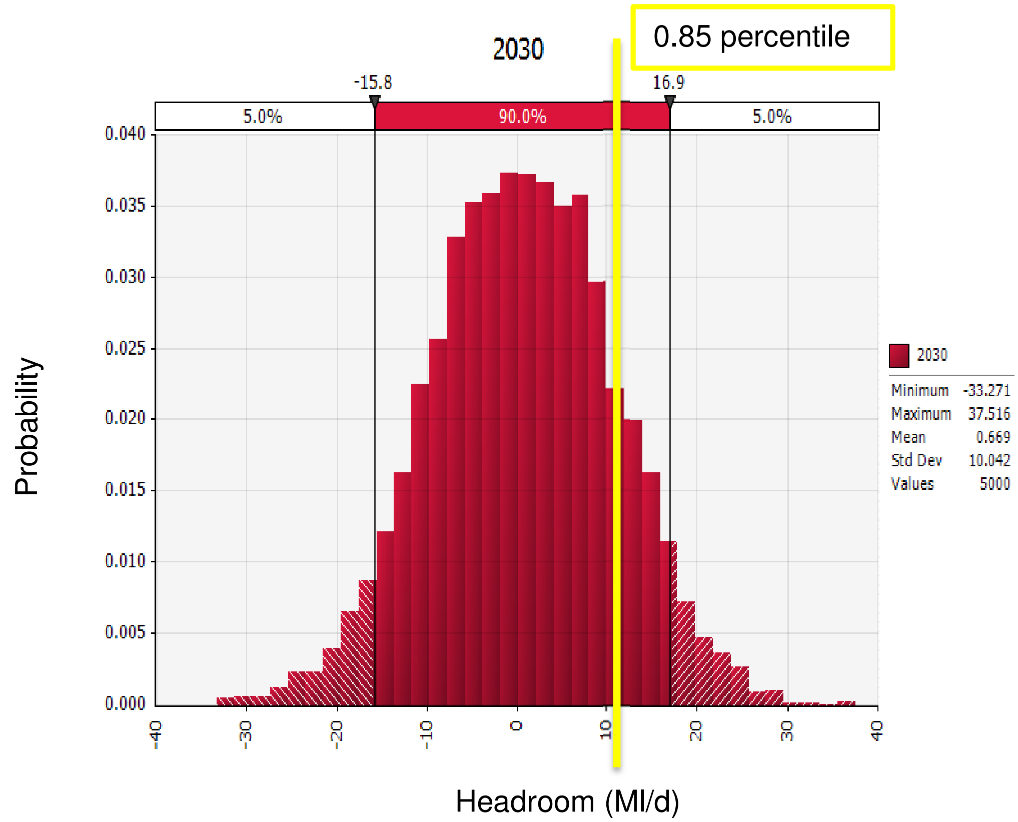


Figure 4. Plot of combined uncertainty distribution (from @Risk) for all parameters listed in Table 5

As evident in Figure 4, the potential range of uncertainties in not fully explored with the headroom estimation method. The expected value is often between 5-10% of WAFU – 7.5% is a comfortable range expected by regulators at the time of PR09 (Whiter, pers. comm. 2010). The chosen headroom of the 85th percentile in this example is depicted in Figure 4 with a thick yellow line. Table 6 contains all the characteristics of the distribution and identifies the headroom value as 11.12 Ml/d which is less than 7.5% of DO (7.5% of DO is 12.25 Ml/d). A quick review of Figure 4 shows shifting the representative percentile for headroom further along this tail to the 95th percentile or further would greatly affect the supply/demand balance. The possibility for future conditions that may render real the values at the end of these distribution tails is one reason to delve deeper and explore the ramifications of severe uncertainty.

Table 6. Characteristics of a combined headroom distribution

Chosen percentile	Headroom Value	Percentile	Value
0.85	11.122	0.01	-23.403
		0.05	-15.849
		0.1	-12.102
Distribution characteristics		0.15	-9.768
Minimum	-33.271	0.2	-7.779
Maximum	37.516	0.25	-6.194
Mean	0.669	0.3	-4.854
Mode	1.047	0.35	-3.46
Median	0.686	0.4	-1.996
Std Dev	10.042	0.45	-0.636
Skewness	-0.0377	0.5	0.686
Kurtosis	2.9117	0.55	2.038
Values	5000	0.6	3.425
Errors	0	0.65	4.809
Filtered	0	0.7	6.215
Left X	-15.8	0.75	7.555
Left P	0.05	0.8	9.235
Right X	16.9	0.85	11.122
Right P	0.95	0.9	13.659
Dif. X	32.739	0.95	16.89
Dif. P	0.9	0.99	23.733

For the LP/IP selection method, Target Headroom values were included as part of the input data.

3.2.5 Select a least-cost management strategy

As portrayed in Table 1 of Section 2.3, there are a few approaches available to select and schedule a portfolio of options. Within the existing EBSD methodology, there are four levels of increasing complexity that can be used: (1) EBSD Current using Average Incremental and Social Cost and expert judgement or an LP/IP optimisation routine with a static Headroom value; (2)

EBSD Intermediate, again with either selection method, and a further Monte Carlo evaluation of supply/demand futures to ascertain if the Target Level of Service (LoS) is viable, followed by an iterative adjustment of the Headroom value until the Target LoS is viable; (3) EBSD Advanced using the exact same process as EBSD Intermediate with a goal of ascertaining if customers are willing to pay for the Target LoS instead of ascertaining if the Target LoS is viable or not; and (4) Blue Skies Modelling which uses a fully stochastic evaluation to optimise a LoS whether the optimisation has a goal of meeting a Target LoS or a goal of an appropriate amount of investment to avoid a target frequency of failure. As stated in Section 2.1, the industry is progressing a range of methods to compliment and/or replace EBSD Advanced. The WRP-RA offers a new way to approach uncertainty, which could be considered an interpretation of an EBSD Blue Skies Modelling approach.

Select a portfolio with EBSD Current AISC

To select a least-cost portfolio with the EBSD Current method using the calculated AISC value (Section 3.2.1) as each option has a relative cost, a company decides when to implement the most cost-effective options that rectify the supply-demand deficit over a 25 year planning period, guided by expert judgement. The EBSD Current AISC approach is suited for small water supply systems with a small number of options to choose from. Companies may also present a preferred plan that differs from the least-cost plan for any variety of reasons. Industry practice is shifting towards other methods to evaluate cost that support more informative discussions as part of public consultation and include the presentation of a choice of management strategies in a best-value context (UKWIR 2012, WRSE 2015).

Select a portfolio with EBSD Current LP/IP Optimisation

To select a least-cost portfolio with the EBSD Current LP/IP selection routine, a company prepares information for an optimisation model to select and schedule an optimised portfolio of options that satisfy the supply/demand balance. The EBSD LP/IP selection routine is a more appropriate method for larger companies that have many options to choose from.

The EBSD optimisation problem is formulated as a mixed integer linear programming (MILP) optimisation problem. A single objective is used to minimise discounted capital, operational (both fixed and variable), environmental and social costs. Firstly, the model ensures that a positive SDB is possible and invokes demand reduction if there is not enough supply. Secondly, to select an optimum portfolio of options, the model makes two kinds of decisions:

- The extent of annual use in Ml/d of supply schemes and transfer schemes to move water between zones (for both existing and optional schemes) with the inclusion or not of demand management schemes; and
- The start year for investment decisions on optional schemes (source, transfer and demand management).

The model identifies the minimum cost solution for four simultaneous water demand scenarios: dry year annual average (DYAA), dry year critical period (DYCP), normal year annual average (NYAA), and minimum deployable output (MDO). Not all companies use MDO in their planning and so an approach has been developed for WRSE to accommodate modelling of MDO e.g. through use of DYAA. The model is constrained to ensure balanced supply and demand for all four annual scenarios. A least cost strategy is optimised by finding the minimum combination of capital (Capex), fixed operating (Fopex) and variable operating (Vopex) costs for water delivered in each of the annual scenarios.

3.2.6 Identify a best-value management strategy

As introduced in Section 2.2.4, there is a trend in water resources planning to understand and communicate the merits of a range of management strategies in an attempt to find the best-value. Traditionally, industry practice has focussed on identifying the least-cost plan. For example, PR09 was clearly dominated by a least-cost directive. In PR14, Thames Water, Southern Water and Sutton and East Surrey Water (Thames Water 2014, Southern Water 2014, Sutton and East Surrey Water 2014) presented compelling evidence of better value plans to ask their customers to invest in more than just the least-cost. Because of this least-cost planning legacy and Ofwat's duty to protect water company customers from higher bills, companies will need to justify why a management strategy different from the least-cost one is worthy of the additional investment. Industry papers (UKWIR 2012) suggest the best-value matrix is an evolution of

Willingness to Pay and can be conceptualised as a plot of additional headroom vs. the cost to achieve it. The reasoning is that all stakeholders (customers, regulators and the companies themselves) can easily see the extra cost related with extra security afforded when more headroom is available. Of course there will need to be other explanations of what that headroom provides, but in essence, extra headroom provides a more secure Level of Service.

This thesis presents two versions of a best-value plot to indicate additional water security and the related cost of investment to achieve additional security:

1. For the EBSD Current AISC selection method additional water security is represented by surplus water available at the end of the planning horizon. The related cost is the total cost to implement each management strategy.
2. For the EBSD Current LP/IP selection method additional water security is represented by the avoidance of forced demand reduction whereby the optimisation model reduces demand when there is not enough water available from additional supply options, demand management options or transfers. The related cost is the total cost to implement each management strategy.

3.3 Select a Robust Management Strategy with the WRP-RA

The major steps of the Water Resources Planning Robustness Assessment methodology are shown in Figure 5.

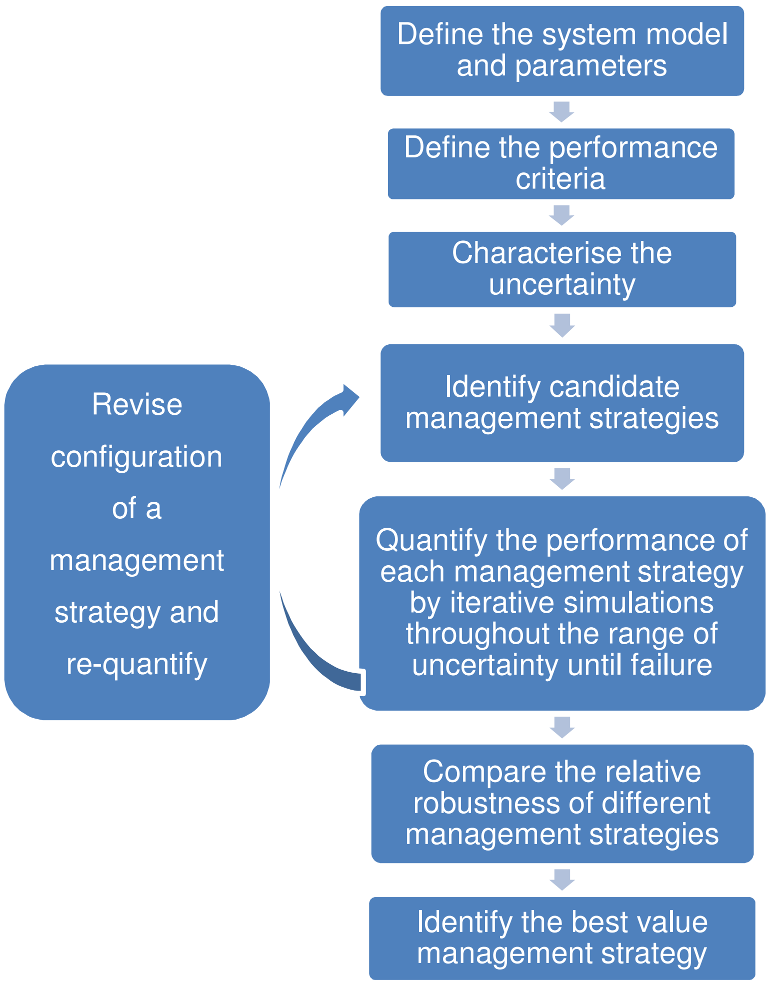


Figure 5. Major steps of the Water Resources Planning Robustness Assessment methodology

3.3.1 Define the system model and parameters

Two different types of system models were evaluated with the WRP-RA for this research.

(1) A simulation model based on a mass balance calculation shown in Equation 5; storage equals the minimum of reservoir capacity or reservoir volume, plus inflow, minus the environmental flow and minus the demand. The Simplified version simulates a simple system with one river fed reservoir, one demand node and the potential for additional supply

from the regional network. The SSA version simulates the behaviour of a larger water resources network – a Strategic Supply Area.

$$storage_t = \min\{reservoir_{capacity}, \max(0, reservoir_t + \mathrm{inflow}_t - envflow_t - demand_t)\} \tag{5}$$

(2) An optimisation model based on two central least-cost objective functions, Equations 6 and 7, and previously constructed by Padula et al., 2013, where the model satisfies the mass balance for 4 different annual supply demand scenarios (set *SCEN*) simultaneously for each time step based on different weightings ($tscen_{scen}$), at nodes (*SUPPLYN*) based on the availability of additional water transferred via links (*LINKS*). The below equations are an indication of how the model optimises. The model calculates the capital costs and fixed operation costs once and then calculates the volumetric costs (*Vopex*) for each of the 4 scenarios based on their individual SDB. This thesis focusses on the results of this model rather than its formulation. A detailed description of the model formulation can be found in (Padula et al., 2013).

$$vopexs_{i,t} = \frac{\sum_{scen \in SCEN} tscen_{scen} \times svar_i \times Sut_{i,t,scen}}{\sum_{scen \in SCEN} tscen_{scen}} \quad \forall i \in SUPPLYN, t \in T \tag{6}$$

$$vopexl_{i,j,t} = \frac{\sum_{scen \in SCEN} tscen_{scen} \times lvar_{i,j} \times Qut_{i,j,t,scen}}{\sum_{scen \in SCEN} tscen_{scen}} \quad \forall (i,j) \in LINKS, t \in T \tag{7}$$

The Simplified simulation model satisfies the demand from one demand centre by drawing water as needed from the local reservoir and regional imports for backup supplies when the local system is over-challenged. The Simplified simulation model is the basis for Case Study 1 described in Section 4.2.

The SSA simulation model addresses the mass balance on a daily time step for a number of reservoirs based on available inflows and a prioritisation of river abstraction versus reservoir use depending on the season. This model distributes water to a variety of demand nodes constrained by pipe and water treatment works capacities. The model attempts to satisfy demand first by local supplies and then backup from a further supplies still within the SSA. The SSA simulation model does not prioritise any activity based on cost. It accepts the settings of a management strategy and seeks to satisfy the supply demand balance on a priority basis, given network constraints, satisfying demands locally as much as possible before seeking additional water from elsewhere in the network. The SSA simulation model is the basis for Case Study 2 described in Section 4.3. (Routing issues that accompany a daily time step are not considered a hindrance in the application of the model in the case study for this thesis. The long spine main to the southern tip of Cornwall involves a time lag of a day, but due demand being satisfied locally first, the time lag does not come into play in a material sense.)

The optimisation model works on yearly averages of available water for four different annual scenarios (normal year, dry year, critical peak and minimum deployable output) and has no carry over storage component. It seeks to satisfy the supply demand balance at each time step constrained by the pipe capacity of water transfers between zones and any particular constraints that accompany new options. It chooses from which source to derive water based on cost. The Optimisation model is the basis for Case Study 3 described in Section 4.4.

In terms of parameters, each model has a different set of inputs to quantify supply, demand and constraints.

- The simulation model is more detailed by its nature and includes additional information such as abstraction rules to guide when to take water from rivers or reservoirs to remain licence compliant, control rules to govern reservoir behaviour and a more detailed characterisation of demand which invokes a simulation of micro-component use while the model is running.
- The optimisation model works with generalised datasets that provide yearly averages abstracted from other simulation models and analyses.

The mass balance achieved is similar for each model in that each model attempts to solve a water deficit and reports back if it cannot. There are two stages of failure to satisfy the mass balance in both models; the first during which some demand is not met and reported back and the second in which there is a system failure because either a reservoir has run dry in the case of the simulation model, or no demand can be satisfied in one or more of the demand centres in the optimisation model. These failure states are described in more detail in Section 3.2.5 and their use in water resources planning in terms of Level of Service is discussed in Section 3.2.1.

Costs

In the Simplified simulation model there is no consideration of capital (Capex) or fixed (Fopex) operating costs. All costs are based on variable (Vopex) operating costs needed to treat and move the water. This approach is used in order to evaluate any savings associated with domestic demand-side management including reduction in water use, domestic rainwater harvesting and greywater reuse as compared with treatment and pumping costs within the distribution network. Costs evaluated at the household level include sewage treatment to indicate any cost benefit associated with domestic water reuse which lessens the amount of sewage.

In the SSA simulation model, Fopex and Vopex of operating the existing network and additional Capex, Fopex and Vopex related to option implementation are included to be able to compare the cost of water available with the existing network configuration as compared with the cost of water from new options. Capex, Fopex and Vopex associated with domestic rainwater and greywater systems are also included to be comparable with larger options as implemented in the distribution network.

In the Optimisation model, a marginal variable Vopex is assigned to any surplus water available within the existing network configuration to compare the cost of existing surplus water as compared with the cost of water from new options Capex, Fopex and Vopex related to option implementation.

In the Simplified simulation model, Vopex includes financial and carbon related costs. In both the SSA simulation and the optimisation models, Capex, Fopex and Vopex include financial, environmental and social and carbon related costs.

In order to accommodate a fair comparison between the WRP-RA method using the SSA simulation model and the EBSD Current AISC approach, AISC option costs were developed using the SSA simulation model (Section 3.2.1). The application of costs with the SSA simulation model as part of the WRP-RA method differs from the EBSD Current use of AISC in two ways:

- Volumetric costs were calculated in the SSA simulation model at each treatment work or pumping station based on energy and carbon costs related to the flow of water instead of being considered as part of the option itself. This method to handle volumetric costs means that by default, the ability of a new option to provide water at less cost than existing supplies is addressed. Furthermore, there can be other savings related to how an inflow of new water changes the flow of water throughout the whole network that are unknown unless costs are calculated where they occur.
- Capex and Fopex costs were included in the SSA simulation model as annuities and discounted each year the option was utilised. Carbon cost was calculated based on the amount of carbon emitted and the projected carbon cost for that year. This method is felt to be more realistic in terms of expenditure as cost is only accounted for when it is incurred as a result of using an option. Because this model is a simulation model and not an optimisation model driven by a least-cost objective and because the selection and timing of schemes is provided to the model, there is no bias to option selection because of a large Capex annuity compared with a smaller Capex annuity.

3.3.2 Characterise the uncertainty

The range of uncertainty for each parameter and the direction in terms of increase or decrease in value that pushes the system towards failure is already defined in the EBSD characterisation of headroom. The main difference in the characterisation of this uncertain space with the WRP-RA is that an IGDT approach starts at the central tendency estimate and continues to evaluate an unbounded range of values until system failure, while the EBSD headroom estimation process selects one value associated with a level of confidence from an assigned probability distribution to represent an expected uncertainty. The choice of an appropriate level of confidence and type of probability distribution is based on experience and established practice. However, the evaluation of uncertainty is restrained to the limits defined by these choices. Table 7 lists all the parameters evaluated for uncertainty with the simplified and SSA simulation models: 3 related to supply, 5 related to demand and 1 related to cost for energy. Table 8 lists all the parameters evaluated for uncertainty with the optimisation model. The parameters in the grey shaded rows are explored in an unbounded fashion until the system fails. All other parameters are explored up to the edge of the uncertainty range defined by the EBSD headroom estimation process.

Table 7. Parameters evaluated for uncertainty with the Simplified and SSA simulation model

Mathematical Abbreviation	Description	Range	Info-Gap Central Estimate
$S_{cc(dry)}$ $S_{cc(wet)}$	Changes in yield from Climate change	Historic inflows perturbed by wet to mean and mean to dry climate change scenarios	Historic inflows perturbed by mean climate change scenario
S_{meter}	Supply meter accuracy	+/- 2.5%	As historically registered by inflow meters
$S_{catchment}$	Changes in yield from Catchment changes due to Climate Change	+/- 10%	As historically registered by inflow meters
D_{growth}	Changes in population, commercial/industrial and agricultural use	+/-10%	Expected 10% increase in domestic demand, decrease in commercial and industrial demand and no increase in agricultural demand
D_{cc}	Changes in demand due to climate change	+/- 1.4%	Same as current demand pattern
D_{meter}	Demand meter accuracy	+/- 2.5%	As registered by demand meters
$D_{eff(gain)}$; $D_{eff(loss)}$ applied to $D_{reduce(eff)}$	Potential gain or loss in demand reductions related to the number of homes to adopt efficiency measures	+10% (gain) or -20% (loss) of expected number	Adoption rates as defined by management options
$D_{inn(gain)}$; $D_{inn(loss)}$ applied to $D_{reduce(inn)}$	Potential gain or loss in demand reductions related to the number of homes to adopt rainwater harvesting and/or greywater reuse	+10% (gain) or -20% (loss) of expected number	Adoption rates as defined by management options
Cost	Potential magnitude of increase in cost for electricity	A further 100% increase or 50% decrease of what is expected	Increase of 50% by the end of the 25 year planning horizon

Table 8. Parameters evaluated for uncertainty with the optimisation model

Mathematical Abbreviation	Description	Range	Info-Gap Central Estimate
$S_{cc(dry)}$ $S_{cc(wet)}$	Changes in yield from Climate change	A linear decrease of up to 5% at the beginning of the planning horizon and 50% at the end	Projected supply (Deployable Output) without headroom
D_{growth}	Changes in population, commercial/industrial and agricultural use	A linear increase of up to 5% at the beginning of the planning horizon and 25% at the end	Projected demand (Distribution Input) without headroom

3.3.3 Define the performance criteria

For an application of the WRP-RA with a simulation model, this thesis defines a reservoir risk measure (RRM) as an insightful and easily monitored metric to quantify the risk of water shortage and compare the robustness of management options (Figure 6). In the literature, recent water resource planning metrics focus on Reliability as represented by a probability of failure to meet a defined Level of Service (Hall et al 2012; Matrosov et al 2013; Turner et al 2013 and Mortazavi et al 2012). Hashimoto (1982) presented a fuller concept of performance that includes measures for Resilience and Vulnerability in addition to a measure for Reliability.

The metrics introduced as part of the WRP-RA build on Hashimoto's comprehensive approach and offer a novel method to monitor management strategy success with insight into the overall performance of the water distribution system; which is the basis of the ability of a system to satisfy demand. The modelling process also evaluates the ability of a system to meet a particular Level of Service, but the performance metrics introduced below reflect the Reliability, Resilience and Vulnerability of the water distribution system as a priority and then the repercussions of this system performance are evaluated on their ability to meet demand at a certain Level of Service. The reason for this differentiation is that it is often better to ensure system Reliability and Resilience and guard against its Vulnerability by reducing the Level of Service a system provides. This situation is why water companies rely upon demand reduction measures as part of any drought episode to extend the ability of a system to provide an adequate amount of water. In a similar sense, Yarra Valley Water in Australia found that by initiating the use of a desalination plant much earlier during a drought episode, they were able to improve the reliability of their reservoir (Gough, pers. comms, 2015). These new performance metrics capture both the benefit of operational choices, (e.g. reservoir control rules), and the ability of a management strategy to improve the performance of a water resources network as an system that provides an adequate supply of water, more importantly than a system that provides an optimum level of service.

- The Reservoir Risk Measure and Drought Deficit (described below) provide metrics that characterise system performance relative to reservoir control curves and as such provide valuable performance information in advance of any LoS failure. These two metrics identify Reliability based on the number of times the reservoir volume falls below the drought curve and they identify Vulnerability based on the extent of the volume of water that is lacking below this curve during any sequence of time during any year.
- The Reservoir Ratio (described below) offers a single value to gauge a reservoir volume status against the reservoir control rules. The magnitude of this value provides an indication of vulnerability for planning scenarios and an informed warning sign to alert operational staff of when to act quickly during the occurrence of a drought.
- The Safety Margin Deficit (described below) provides a metric to identify system resilience based on its ability to recover after a dry period.

The RRM is measured in two ways:

- For the Simplified simulation model, the RRM is calculated as the product of the probability of the reservoir storage level (S_t) falling below a point on a drought management curve (D_{CCt}), (i.e. the number of days below this curve divided by the total number of days of the planning horizon for each iteration of increasing uncertainty), and the average volume (Ml) of water deficit below this curve, (i.e. average as calculated over of one iteration of increasing uncertainty, with each iteration being the result of one 25 year simulation run). This water deficit is referred to as a drought deficit (DD) in this thesis.

- For the SSA simulation model, the RRM was replaced by the DD as the total amount of water deficit below the drought management curve, measured in Ml, for each iteration of a 25 year simulation run. Two additional metrics were added to indicate the likelihood of different Level of Service reductions; the number of days with a greater than a 5% reduction in service, and the number of days with a greater than a 10% reduction in service.

A drought management curve indicates minimum acceptable reservoir volumes (i.e. levels) for different times of the year. If a reservoir volume falls below a point on this curve, then some management action may be necessary to safeguard supplies. A reservoir ratio (RR) as defined in Equation 8 was created to evaluate this relationship.

$$RR = \frac{S_t - Dcc_t}{Dcc_t} \tag{8}$$

If RR > 0, the reservoir level is above the drought management curve; if RR = 0, the reservoir level is the same as the drought management curve; if -1 < RR < 0, the reservoir level is less than the drought management curve and if RR = -1, the reservoir is empty. The influence of uncertainty on the RR is quantified in a similar fashion as for the mass balance of the water resources simulation. The RR is calculated for each stepwise exploration into the uncertain space as characterised by the IGDT approach. The RR value changes in response to changing reservoir storage levels.

Operational failure occurs when the reservoir is empty (RR = -1) and management decisions are guided by the frequency, duration and magnitude of water shortages when -1 < RR < 0 in order that RR never equals -1. If the reservoir levels stay below a point on the drought management curve for a 60 days, some form of water use restriction will be invoked. A reoccurring prolonged negative RR value would result in failure from a customer's viewpoint if it precipitated a hosepipe ban more often than the promised level of service, (i.e. once every 20 years). If the RR value remained negative for a further 90 days, a request for emergency water abstraction or relaxation of environmental requirements could be made in order to satisfy human needs at the detriment of resident wildlife and the local ecosystem. The DD provides more information than the RR to guide how soon a water use restriction should be put into place and how long it should last because the magnitude of the deficit is taken into account. In the simplified simulation model, the RRM provides a comprehensive indicator with which to compare management plans because it combines the quantification of how often a restriction may occur in the future with the magnitude of such a restriction. In the SSA simulation model, the DD replaced the RRM as it is indicative of the overall magnitude of drought events and as such offers a comprehensive measure that addresses the inter-related aspects of frequency and duration. The consequence of droughts is measured in terms of the amount of demand reduction required to survive the drought using the two new metrics added for the SSA simulation model; number of days where (1) greater than a 5% and (2) greater than a 10% reduction in service occurred.

This thesis defines a safety margin deficit (SMD) and a yearly minimum reservoir level, as two comprehensive metrics to compare the opportuneness of management options. The safety margin is defined as the volume of water between the operational management curve, which signifies the optimum reservoir volume at different times of the year, and the drought management curve, which signifies the minimum acceptable reservoir volume at different times of the year.

The reservoir ratio, the drought deficit and the safety margin deficit are all depicted in Figure 6.

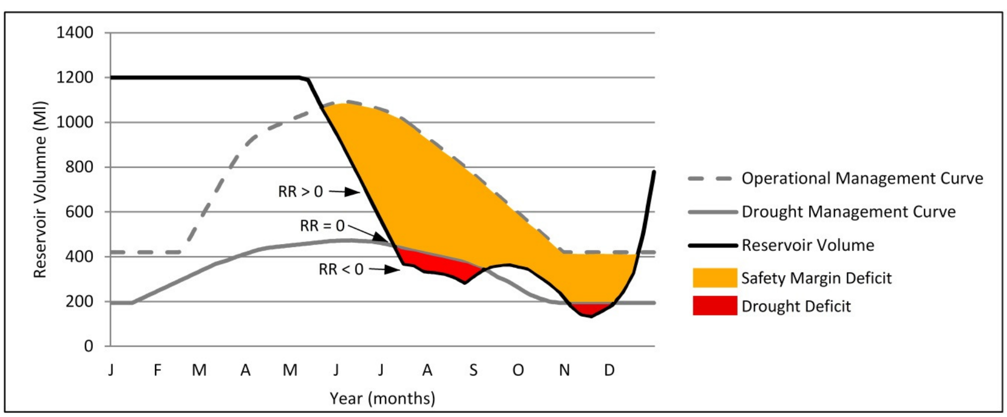


Figure 6. Relationship of reservoir level, operational and drought management curve showing derivation of reservoir ratio (RR), safety margin deficit (SMD) and drought deficit (DD).

Other metrics are tracked as part of the MCDA analysis and described in Section 3.3.6. Environmental impact is measured by the amount of post-reservoir stream flow and yearly minimum reservoir level. Local self-sufficiency is measured by the amount of additional water requested from the regional system. Cost is measured as the sum of energy costs for the movement and treatment of water in the distribution network and in the household rainwater collection and greywater reuse systems and the cost to implement new options. The costs customers must pay for the water they receive from the larger system is also included to identify any savings related to customers supplying their own water based on rainwater collection and/or greywater reuse. Carbon emissions are calculated based on the emissions related to the movement and treatment of water in the distribution network and in domestic rainwater and greywater systems.

For an application of the WRP-RA with an optimisation model, this thesis uses three variations of demand reduction (percent average, percent maximum and total) to quantify the relative robustness of management. Cost is used as a performance metric to identify the price of added robustness. An evaluation of demand reduction from three perspectives provides helpful information. The total demand reduction indicates the overall deficit situation. The percent maximum demand reduction indicates critical zones and critical supply demand conditions that may need additional emergency response. The percent average demand reduction indicates which zones on average incur more deficit and could benefit from the added security of additional transfers from those zones that don't experience deficit issues.

3.3.4 Identify a best-value management strategy

In order to compare the benefits of IGDT-based WRP-RA with evolving EBSD methods that include a best-value representation, a method to identify best-value strategies with added robustness qualities was developed. The evolving EBSD approach includes a trade-off curve to compare the benefits of providing additional headroom vs. the costs involved (UKWIR, 2012). The WRP-RA approach to best-value is similar in principle to an EBSD approach in that it compares the relative cost incurred to provide extra water security. The added benefit of WRP-RA approach is that is explores water security and related cost for more extreme future uncertainties and as such provides a more complete picture of the security that is being invested in. With an expanded view of potential futures, a decision can be made in terms of how much people are willing to pay for extra security with a clear idea of the limit of this security, particularly because the WRP-RA explores the ability of a management strategy to perform up until failure. Indeed, there may be surprises in that some management strategies may be less expensive and still offer a higher surplus of water. A WRP-RA approach to best-value follows and supports the motivation for this thesis, in that it assesses the best value a management strategy can provide at the extremities of its usefulness (i.e. just before it fails).

The WRP-RA approach to best-value offers two insights, whereas the EBSD best-value approach offers one. The single insight common to both is the understanding of cost associated with varying levels water security. The additional insight available with the WRP-RA is full knowledge of a management strategy's potential to provide water security under increasingly extreme futures and the relative cost of this robustness. Increasingly extreme futures are explored by running a model for multiple iterations and incrementally changing the supply / demand settings for each iteration to incrementally characterise a more extreme version of the future in a stepwise fashion.

An application of the best-value method using WRP-RA in the simulation context, uses the cost associated with the last successful iteration of a planning horizon for each management strategy and plots this against the total number of days that strategy can provide water without a reduction in service over all the planning horizon iterations. An application of the WRP-RA best value method in the optimisation context, plots the cost of the last successful iteration of a planning horizon against percent maximum demand reduction and total demand reduction. In the application of the WRP-RA, each subsequent iteration tests the system towards failure. Using the total number of days (or percent maximum demand and total demand reduction) over all iterations instead of the performance over the last successful iteration is important because some management strategies may fail after a short number of iterations and some after further iterations. The strategy that fails after a short number iterations may perform better than the strategy that fails after more iterations before failure. Using the total number of days of unrestricted use over all iterations shows the relative strength of a lower performing and longer lasting strategy when compared with a higher performing strategy that fails early on.

If all the management strategies perform without failure for the same number of iterative explorations into greater uncertainty, then the cost associated with the last successful iteration can be plotted against the metrics also for the last iteration instead of overall iterations. Using just the last iteration as a basis for comparison is valid in this instance because all strategies fail at the same iteration. The interesting aspect is how well each strategy performs in the extreme situation.

The WRP-RA approach to best-value using IGDT offers an extended appreciation of the most critical aspects of water planning addressed routinely with EBSD methods – cost and water security. As discussed in the development of the Reservoir Risk Measure, an appreciation of water deficits is complex and requires addressing issues related to frequency, duration, magnitude and then related consequences. Likewise, as conditions become more demanding and harder for a system to perform to an expected Level of Service, other aspects of water resources planning may also be compromised, such as the environment. Other resulting effects will also change, such as carbon emissions. The customer/company relationship that governs the adoption of long-term plans in England and Wales is another important consideration and social acceptance, or promotability is often mentioned by water companies (WRSE, 2015) as one of the key issues standing in the way of implementing certain options. With this in mind, the WRP-RA method also includes Multi-Criteria Decision Analysis, discussed in detail in Section 3.3.6, to provide a comprehensive view of each management strategy performs in respect to a broader range of factors to aid decision making.

3.3.5 Quantify the uncertainty

The Simplified and SSA simulation models simulate the mass balance of a reservoir(s) based on a sequence of historic inflow data to explore hydrologic variability over a 25-year planning horizon. During the 25-year planning horizon domestic, agricultural and commercial /industrial demand can increase or decrease depending on circumstance. Management interventions occur at specified times over the 25-year planning horizon and adoption rates for demand side management options gradually increase over time.

To quantify uncertainty in the simulation models, the 25-year planning horizon is repeated multiple times; once for the baseline values of the uncertain parameters and then multiple times for further iterations to incrementally sample the range of uncertainty associated with each uncertain parameter. An exploration of uncertainty is continued beyond the expected uncertain range for the 4 parameters shaded grey in Table 7 until the operational failure of an empty reservoir occurs.

The optimisation model optimises a least-cost combination and schedule of supply and demand options and transfers to satisfy the mass balance for all Water Resource Zones (WRZ) over a 25-year planning horizon. During the 25-year planning horizon domestic, agricultural and commercial /industrial demand can increase or decrease depending on circumstance. The model chooses when to initiate options and how much water to use from each option. The savings associated with demand side management options gradually increases over time.

To quantify uncertainty in the optimisation model, demand is incrementally increased and supply is incrementally decreased until the supply / demand deficit cannot be rectified in one or more zones even with a reduction in demand. This situation creates a model infeasibility and indicates failure of the system.

In both the simulation and optimisation models, a summary of how each management strategy performs over each step into increasing uncertainty provides the data to generate the robustness and opportuneness curves.

Equations 9, 10 and 11 define the evaluation of the uncertain space around supply (S), demand (D) and cost (C) respectively for the simulation models and Equations 12 and 13 define the evaluation of the uncertain space around supply (S), demand (D) respectively for the optimisation model. In each equation the real value for supply (S), demand (D) or cost (C) lies somewhere in between the nominal value minus or plus the associated incremental changes in parameter values at varying levels of uncertainty level as represented by an increasing α.

$$U_S(\alpha,\tilde{S}) = \{\ \tilde{S} - \alpha * (\tilde{S}_{cc(dry)} + \tilde{S}_{meter} + \tilde{S}_{catchment}) \le S \le \tilde{S} + \alpha * (\tilde{S}_{cc(wet)} + \tilde{S}_{meter} + \tilde{S}_{catchment})\ \} \tag{9}$$

$$\begin{aligned} U_D(\alpha,\tilde{D}) = \\ \{\ (1+\alpha * \tilde{D}_{growth}) * (\tilde{D} + \alpha * (\tilde{D}_{cc} + \tilde{D}_{meter})) + \\ \underbrace{\alpha * \tilde{D}_{eff(loss)} * \tilde{D}_{reduce(eff)}}_{<expected\_adoption\_rate} + \underbrace{\alpha * \tilde{D}_{inn(loss)} * \tilde{D}_{reduce(inn)}}_{<expected\_adoption\_rate} \ge D \ge \\ (1-\alpha * \tilde{D}_{growth}) * (\tilde{D} - \alpha * (\tilde{D}_{cc} + \tilde{D}_{meter}) - \\ \underbrace{\alpha * \tilde{D}_{eff(gain)} * \tilde{D}_{reduce(eff)}}_{>expected\_adoption\_rate} - \underbrace{\alpha * \tilde{D}_{inn(gain)} * \tilde{D}_{reduce(inn)}}_{>expected\_adoption\_rate}\ \} \end{aligned} \tag{10}$$

$$U_C(\alpha,\tilde{C}) = \{\ \tilde{C} - \alpha * (\tilde{Cost}) \le C \le \tilde{C} + \alpha * (\tilde{C}ost)\ \} \tag{11}$$

$$U_S(\alpha,\tilde{S}) = \{\ \tilde{S} - \alpha * (\tilde{S}_{\text{decrease}}) \le S \le \tilde{S} + \alpha * (\tilde{S}_{increase})\ \} \tag{12}$$

$$U_D(\alpha,\tilde{D}) = \{\ (1+\alpha * \tilde{D}_{growth}) \ge D \ge (1-\alpha * \tilde{D}_{growth})\ \} \tag{13}$$

3.3.6 Identify robust management strategies using MCDA

IGDT evaluates how a strategy performs in comparison with others over increasing uncertainty. The most robust strategy is the one that delivers the same performance, (equal or better than the critical reward criteria), as other strategies as uncertainty increases in an unfavourable direction. The most opportune strategy is the one that delivers the same performance, (equal or better than the minimum windfall reward criteria), as other strategies as uncertainty increases in a favourable direction. Robustness curves are generated by plotting a change in the performance metric (e.g. water availability or cost) on the x-axis against stepwise increases in uncertainty plotted on the y-axis. Opportuneness curves are generated by plotting a change in the performance metric (e.g. SMD or yearly minimum reservoir values) on the x-axis against stepwise increases in uncertainty plotted on the y-axis. In this research additional robustness curves are generated for other metrics related specifically to security of supply (e.g. percent demand reduction or the number of days during which customers have to reduce their consumption), or other aspects of planning such as cost and carbon emissions.

These other robustness curves were generated because the decision of which water management option or portfolio of options is preferred, entails more than an assessment of water availability. Cost is important (cf. HM Treasury 2011). Environmental impacts and the production of carbon emissions also need to be addressed. In the Simplified simulation model, the draw on regional supplies is an important consideration, mainly because if weather is dry for one reservoir in a system, chances are the other reservoirs are experiencing less inflow as well and overall system resilience may depend on highly self-sufficient localised systems. Social acceptance is necessary to get a proposed management option accepted. The impact of social acceptance was explored in the SSA simulation model. To account for all these criteria holistically, a few important metrics are combined and evaluated with a MCDA approach. The WRP-RA approach allows for an individual evaluation of performance robustness for each of the multiple criteria.

A compromise programming MCDA method (US Army Corps 2010, Jansenn 2001, Kiker et al. 2005, and DCLG 2009) is used to combine the results for multiple criteria over multiple-steps of increasing uncertainty. This thesis aggregates an overall ranking of multiple criteria to explore the effects of various weightings. A basic MCDA calculation (Equation 14) is used to offer maximum transparency to the weighting and resulting performance criteria (Steele et al. 2009), and because the decision-making approach is not designed to find an optimal solution, but to offer a comparable distance to the ideal solution. A scale factor of p=2 is used to weight criteria proportional to their magnitude. The weighting factor for the criteria receiving the weighting factor is 3 times the weighting factor of the remaining criteria.

$$\textit{Distance(j)} = \sum \left\{ w(i)^p \times \left(\frac{f(i^*) - f(i)}{f(i^*) - f(i^-)} \right)^p \right\}^{1/p} \tag{14}$$

The variables used in Equation 14 are $w(i)$ for the weight of each criteria, $f(i^*)$ for the optimal value, $f(i^-)$ for the least optimal value, $f(i)$ for the criteria being evaluated and p for the scaling factor,(US Army Corps 2010). In this thesis, the minimum value is the optimal value and the maximum value is the least optimal value. The metric for environmental impact is inverted in order that the previously optimum maximum value for post reservoir streamflow or yearly minimum reservoir volume is portrayed as an optimum minimum value in similar fashion to all the other metrics. MCDA criteria evaluated with the WRP-RA method include those that indicate the risk of water shortage, environmental impacts, cost implications and carbon emissions and are listed in more detail in the description of each case study.

3.4 Summary of Methodology

The EBSD headroom estimation methodology offers a methodology to calculate an acceptable amount of water to act as a safety margin relative to each component of supply and demand. As such, the proportion of headroom is directly related to the amount of supply needed to provide a promised Level of Service and is also directly related to the amount of demand that must be met. The WRP-RA quantifies the Level of Service possible with different management strategies over increasing uncertainty. There is a strong similarity in the method used to determine the ability of a management strategy to deliver a certain LoS as part of the EBSD methods and the application of the proposed WRP-RA.

As described in Section 3.2.1, the derivation of the water resources network constrained yearly planning variables for WAFU and DO, (including a system-wide assessment of the potential LoS), is achieved by repeatedly simulating the water resources network and requesting increasing amounts of demand until the system fails to provide water in accordance with the defined LoS. This iterative simulation till failure is repeated for each management strategy to understand the additional DO available throughout the system as constrained firstly by hydrology, secondly by abstraction licences and finally by the network. The ascertained values for supply side DO along with the DO for any demand management measures are then used as defining values to guide the headroom estimation method in which a probability distribution type (e.g. normal or triangular) and its characteristics are assigned for the uncertain components of supply and demand.

The application of the IGDT-based WRP-RA also requires iterative simulations of a network model whilst incrementally increasing uncertain parameters to evaluate how much uncertainty the system can handle before failure. One of the metrics that defines failure could be the Level of Service; i.e. a more robust management strategy would deliver the proposed LoS over a wider range of uncertainty than a less robust management strategy. In effect, the WRP-RA method is almost accomplished already by the water companies in their LoS assessments as required for the EBSD method. To fully apply the WRP-RA, they would need to also decrease supply whilst increasing demand and arrange their water resources simulation models to collect more helpful metrics such as the RRM or DD. Water companies are limited in the depth to which they explore supply/demand uncertainty in their system-wide network analysis by the definition of LoS and they are limited in their exploration of uncertainty, in general, by the definition of headroom. It is intuitive and hard to resist the urge to continue the exploration of a management strategy's ability to satisfy increasing demand. In fact, South West Water routinely continues the exploration of increasing demand beyond the bounds of their Level of Service till failure in order to understand the relative long-term merit of different strategies. This exploration is akin to a 'back of the envelope' application of IGDT.

The main differences between the currently applied headroom estimation process and a full application of the IGDT-based WRP-RA method are:

- The system wide LoS evaluation process only increases demand whereas the WRP-RA increases demand and reduces supply.
- The characterisation of uncertainty with the headroom estimation method is achieved by separate analysis and the assignment of probability distributions whereas the WRP-RA assesses the ability of management strategies to perform under increasing uncertainty in situ.
- Most importantly, the current characterisation and quantification of uncertainty with headroom enforces arbitrary assumptions about the

likelihood of future extremes and cuts short a full assessment of system performance over increasing amounts of uncertainty until failure.

- Additional insight can be gained by evaluating the performance of management strategies at higher ranges of uncertainty which are currently not evaluating with the existing methodologies.

The ramifications of these methodological differences are demonstrated in the following three case studies.

4 Case Studies

4.1 Overview

Three case studies are included in order to show the flexibility of the WRP-RA method and its ease of implementation and also because there are at least three or more settings in water resources planning that could benefit from the WRP-RA. Each case study reveals unique insights gained from exploring the performance of management strategies over increasing uncertainty and as such provides a fuller picture of how the WRP-RA offers a more comprehensive view with which to assess different management strategies.

- Case Study 1 is a representative simple system and the prototype implementation that first tested the mechanics of using IGDT as part of a WRP-RA and used a simplified initial version of the bespoke MATLAB simulation model.
- Case Study 2 is an implementation of the WRP-RA method with a regional simulation model and an opportunity to compare the WRP-RA with the EBSD Current AISC selection method. To complete Case Study 2, the simplified initial version of the bespoke MATLAB simulation model was evolved in order to have flexibility in trying out different ways to use IGDT, to configure the simulation to quantify multiple metrics and to track the performance at every point of the system to identify points of failure that may be harder to expose with standard water resources simulation software such as Miser, Aquator or WEAP.
- Case Study 3 is an implementation of the WRP-RA method with a bespoke GAMS optimisation model and an opportunity to compare the WRP-RA with the EBSD Current LP/IP selection method. There is less flexibility to include custom defined metrics due to the style of EBSD optimisation. Also, the WRSE optimisation model is designed to define different management strategies to address different supply/demand settings which posed a challenge to implementation of the WRP-RA as the WRP-RA is designed to compare the relative performance of already defined management strategies in response to the same set of increasingly demanding supply/demand characteristics.

4.2 Case Study 1 – Drift Reservoir

The purpose of Case Study 1 was to develop the WRP-RA method to explore severe uncertainty in water resources planning and achieve the three points of Objective 1:

- Develop new performance metrics
- Implement innovative demand management options
- Include Multi-Criteria Decision Analysis

4.2.1 Motivation

In 2009, research in water resources planning in England and Wales promoted a move towards a risk-based approach in quantifying the impacts of climate change and other uncertainties on water supply and distribution systems. During this research trend the performance of water supply and distribution systems has been quantified by a few different metrics: the fraction of simulation runs that fail to meet demand (Lopez et al. 2009); the probability of failing to meet a Level of Service (Hall et al. 2011); supply reliability and storage susceptibility (Matrosov, Woods and Harou 2013); and a composite indication of engineering robustness that includes reliability, storage susceptibility and resilience (Matrosov, Padula and Harou 2013). Since 2013 two branches have emerged to measure performance; one that continues with a single risk-based metric of the probability of failing to meet a level of service (Borgomeo et al. 2015, Turner et al. 2014) and a second to evaluate performance based on multiple criteria (Mortazavi et al 2013, Matrosov et al 2015). The research conducted for this thesis focusses primarily on the development of metrics that reveal the robustness of a water distribution network and secondarily the ability of the distribution system to provide a certain Level of Service. The reason for this approach is that when dealing with severe uncertainty and the need to develop a robust water resource management strategy, the longevity of adequate performance can be sustained further if the optimum Level of Service is compromised. If the optimisation and focus of measuring performance is directed predominantly on providing a certain Level of Service; it is hard to distinguish between management strategies that perform adequately well in terms of the LoS under expected conditions and more robustly in response to more severe uncertainties; and those strategies that deliver an optimal LoS under expected conditions but may not respond well in response to more severe uncertainties. The results of Case Studies 1, 2 and 3 all show that the most robust management strategy may not be able to meet the Level of Service to the highest standard, but will be able to deliver water to an adequate level over a wider range of uncertainty.

As this research is testing the boundaries of water resource system performance under severe uncertainty, the introduction of more ambitious demand management actions was included to evaluate the benefit of utilising different water sources via rainwater harvesting and water reuse via domestic greywater recycling. These demand management actions have been required in Australia to survive their extended drought, and are actions that have been shown to provide a significant amount of domestic consumption (Ward et al. 2010, Chiu et al. 2009), and improve the reliability and resilience of a water distribution network (Ghisi et al. 2007, Basupi et al. 2014).

The MCDA approach of this research recognises the value of developing a strategy that performs well for a few significant criteria and balances the performance trade-off in terms of cost, environmental impact and service reliability (Mortazavi et al 2013, Matrosov et al 2015). Due to the nature of the WRP-RA which offers a non-optimised approach of evaluating system performance over an unbounded range of uncertainty, a MCDA approach that facilitates weighting and evaluates performance at lower and higher uncertainties is used to render transparent the relative benefit of different strategies in regards to a few significant criteria.

4.2.2 Description

This study uses a simple semi-real water resources system based on the Drift reservoir and Penzance demand node, located in southwest Cornwall, UK as shown in Figure 7. The reservoir has a 1200 Megalitre (Ml) capacity which satisfies roughly 89% of the local demand. The remaining 11% is supplied from other regional supplies located within the Strategic Supply Area (SSA) which encompasses approximately the county of Cornwall. Demand is roughly 70% residential, 20% commercial/industrial and 10% agricultural. If the required demand is greater than the local abstraction limits of 10.91 Megalitres per day (Ml/d), the remaining demand is sourced from regional supply. There is an additional 0.5 Ml/d supplied by the regional system if the Drift reservoir falls below its operational curve and an additional 2.0 Ml/d supplied by the regional system if the Drift reservoir falls below its drought management curve. This curve defines the optimal reservoir volume to preserve a full Level of Service for the time of year based on historic weather patterns. Due to gardening needs and an influx of tourists, summer demands can be as much as 35% higher than winter demands, all at a time when summer flows are low. Although, it may be more common for environmental requirements to vary between summer and winter, in the Drift catchment there is a required base environmental flow of 1.36 Ml/d at all times throughout the year.

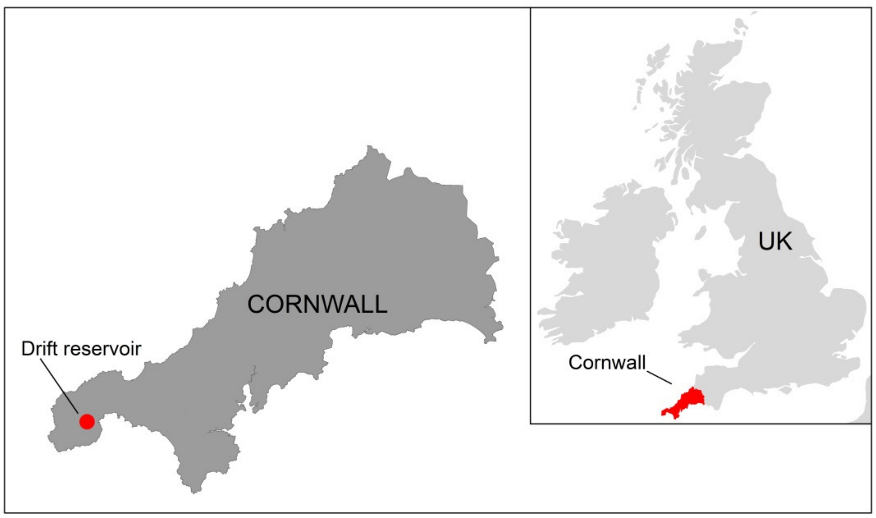


Figure 7. Simple network study area location

The daily time step water resources model used in this research is constructed in MATLAB. Look-up tables hold time series values to serve the parameter needs of the water reservoir mass balance Equation 5. These parameters include: daily inflow and rainfall values over a 25 year period from 1962 to 1986 inclusive, average weekly demand factors that show an increase in use during the summer months and a slight reduction in the winter, and UKWIR climate change flow factors to quantify the effects of climate change on future river flows. These flow factor values are sourced from SW Water and guided by the final UKWIR CL04 Method 1 methodology of December 2008 (UKWIR 2009). In the MATLAB code are baseline values for per capita demand, population in terms of the number of houses, commercial and industrial combined demand, and agricultural demand. Growth factors for each of these three demand components project an expected increase of 10% in population, a drop of 10% in commercial and industrial demand and an increase of 5% in agricultural demand.

Uncertainty sources

As mentioned in Section 3.2.2, uncertainty is explored for 3 supply-side parameters, 5 demand-side parameters and cost (Table 7*)*. With the EBSD headroom estimation approach most of these parameters are assigned a probability distribution based on a percent variation from the expected value. With normal distributions the range of variation is centred on zero and the percent deviation equates roughly to two standard deviations. With triangular distributions the mean value is the expected forecast and the best and worst cases are either percent deviations or defined values as is the case with the uncertainty of climate change impact on source yield. The climate change impact parameter is considered a triangular distribution guided by values predicted for the wet, mid and dry scenario inflows. Other parameters include: accuracy of supply-side meters (normal distribution with 5% variation), climate change impact on catchment process (normal distribution with 10% variation), accuracy of demand-side meters (normal distribution with 2.5% variation), demand forecast variation (triangular distribution with 10% variation), impact of climate change on demand (triangular distribution centred on a 1.4% increase with a range of 20% variation either side of this increase), and adoption of efficiency measure (triangular distribution with a potential increase in adoption rate of 10% and drop in adoption rate of 20%).

The WRP-RA method uses the same central tendency values as the headroom approach, (for example, inflow values associated the climate change mid scenario or the expected population growth), but instead of selecting a percentile value from each parameter's assumed distribution as with the headroom approach, the IGDT calculation sequence samples the full range of this uncertainty and beyond for the 4 parameters shaded in grey in Table 7 until the system fails.

Water resources management options

This case study explores the relative performance of 81 different management options: 8 different supply side options, 9 different efficiency related options, 60 different domestic rainwater and greywater options and 4 different combination strategies. Such a large number of options are explored to assess the extent of intervention needed to achieve significant management results. For instance, is an increase in reservoir volumes from 1200 Ml to 1400 Ml enough or is 1600Ml or 1800Ml needed? Would efficiency reductions of 10% in 50% of households suffice or would the reductions need to be 15% in 75% of households to make an impact, and how many homes would need to incorporate greywater and/or rainwater use to help the overall system achieve a positive supply/demand balance?

The range of 81 options explored includes:

1. Increase reservoir volume from 1200 Ml to 1400 Ml, 1600 Ml or 1800 Ml at the end of the third periodic review of the planning horizon, on the 15th year (4 options).
    - Reservoir expansion was included as an option as practitioners in the water industry talk about reservoirs as robust supply options.
2. Immediate increase of transfers from regional system when reservoir falls below operating curve from 1 Ml/d to 1.5, 2 and 2.5 Ml/d (3 options).
    - Transfers were included as options as they are promoted by regulators and used by water companies as an environmentally friendly and regionally strategic option for additional supply.
3. Immediate increase of water treatment capabilities from 11 Ml/d to 13 Ml/d and increase yearly abstraction limit to allow for an increase in abstraction of 1.364 Ml/d (1 option).
    - An increase in treatment was considered as this is a common water company technique to increase network capacity (i.e. South West Water personal communication and tactics used by WRSE water companies).
4. An increase in water use efficiency reductions of 5%, 7.5%, 10%, 12.5% and 15% for a third of residential homes. Efficiency reductions of 15% were also modelled for 50%, 66%, 75% and 90% of residential homes. Efficiency reductions start gradually and make their maximum impact by the midpoint of the planning horizon, before the 15th year. Efficiency

reductions include commercial and industrial use with the assumption that reductions would be achieved with all commercial and industrial operations (9 options).

- Water use efficiency reductions were considered as the UK government promotes a sustainable level of consumption (HM Government, 2011).

5. Domestic rainwater collection for (R1) toilets only, (R2) toilets and outside use, (R3) with the addition of clothes washers and (R4) with the addition of bathing water for 33%, 50%, 66%, 75% and 90% of residential homes. The adoption of rainwater collection practices increases incrementally with a third of all adoptees starting the practice in the first 5 years, followed by two-thirds in the next 5 years and the final third before the 15th year. The assumed cistern size ranged initially from 500 - 7500 litres. Final simulations concentrated on cistern sizes of 2400l as this size showed significant gains for each rainwater use scenario. The assumed roof size is 50 m^2. It is important to have a rainwater cistern at least as large as 2400l to show significant reductions in water demand from the mains (25 options).

    - Domestic rainwater collection was considered as it is an innovative demand side solution used elsewhere in the world in water scarce regions.

6. Domestic greywater use for (G1) toilets only, (G2) toilets and outside use for 33%, 50%, 66%, 75% and 90% of residential homes. The adoption of domestic greywater practices increases incrementally with a third of all adoptees starting the practice in the first 5 years, followed by two-thirds in the next 5 years and the final third before the 15th year. For higher adoption rates of 50-90%, the increases during each 5 year period are proportionately higher (10 options).

    - Domestic greywater use was considered as it is an innovative demand side solution used elsewhere in the world in water scarce regions.

7. Rainwater collection for bathing and clothes washing and greywater for toilets and outside use (R/G) for 33%, 50%, 66%, 75% and 90% of residential homes. The adoption of combined greywater use and rainwater collection increases incrementally with a third of all adoptees starting the practice in the first 5 years, followed by two-thirds in the next 5 years and the final third before the 15th year (25 options).

    - Combined rainwater harvesting and greywater use were considered to understand the maximum savings afforded with these techniques.

8. Other management option combinations include: greywater use for toilets with a 50% adoption rate and an additional 1Ml regional transfer; increased efficiency with a 50% adoption rate and an additional 1Ml regional transfer; greywater for toilets and increased efficiency each with a 50% adoption rate; and rainwater for bathing and clothes washing, greywater for toilets and outside use and increased efficiency – each with an adoption rate of 1/3 of all homes. These combination strategies follow a similar pattern to the individual interventions of slowly ramping up adoption rates over a 15 year period (4 options).

    - Combination strategies were considered to explore integrated innovative demand side management techniques.

4.2.3 Results and discussion

As mentioned Section 3.3.2, the WRP-RA method characterises the uncertainty of input parameters into a water resources model. The quantification of uncertainty requires repeated simulations of the model as uncertain parameters stray from their central tendency through the uncertainty range of each uncertain parameter 10% of this range at a time, and beyond for 4 parameters; climate change effect on (1) source yield, (2) catchment change and (3) domestic demand and (4) growth in terms of population, commercial/industrial and agricultural activity. A summary of how each metric performs during each of these simulation steps into increasing uncertainty provides the base data to generate the robustness and opportuneness curves.

Figure 8 shows the robustness curves for a selection of the management strategies (

Table 9) explored in terms of their performance relative to the reservoir risk measurement (RRM) as described in Section 3.3.3. This figure shows that valuable information can be gathered from the performance of management options beyond the range of uncertainty explored with the EBSD headroom estimation method (depicted by the blue dashed box). This blue dashed box shows the range of performance values that result from an interplay of the parameter values found in the probabilistic range between confidence levels 75% and 85%. At the edge of this confidence level range, three strategies fail; two options with rainwater collection only and the efficiency only option. Many other strategies fail before level 10 of increasing uncertainty on the y-axis, which marks the edge of the uncertainty range as defined in the EBSD approach (Table 7); reservoir expansion of 200Ml, an increase in regional transfer of 1Ml, greywater only adopted by 50% of homes, rainwater and greywater reuse adopted by 50% of homes and the combined demand side management option of rainwater, grey water and efficiency at an adoption rate of 33% of homes each. Only the combinations of increased efficiency or greywater reuse in 50% of homes plus additional regional transfer, rainwater and greywater reuse adopted by 75% of homes and the reservoir expansion of 300 Ml or 400Ml are robust enough to make it past level 10 of increasing uncertainty.

Table 9. Summary of management strategies evaluated with the WRP-RA

Management Strategy ID	Management Strategy Description
M1	15% reduction in water use for 50% of users
M2	15% reduction in water use for 50% of users and a 1 Ml/d regional transfer
M3	Greywater toilet for 50% of users
M4	Greywater toilet for 50% of users and a 1 Ml/d regional transfer
M5	Greywater toilet and 15% reduction in water use for 50% of users
M6	Greywater for toilet and outside use in 50% of homes
M7	Rainwater and greywater in 50% of homes
M8	Rainwater and greywater in 75% of homes
M9	Rainwater, greywater and 15% reduction in water in 33% of homes
M10	Reservoir increase of 200 Ml
M11	Reservoir increase of 300 Ml
M12	Reservoir increase of 400 Ml
M13	Rainwater for toilet and clothes in 50% of homes
M14	Rainwater for toilet, clothes and bath in 50% of homes
M15	Increase in regional transfer by 1 Ml/d
M16	Increase in treatment and abstraction
BAU	No intervention

Just before level 10, there is preference reversal between the reservoir expansion of 200 Ml and rainwater and greywater combined option with 75% adoption rate. This preference reversal is manifested as a crossing of the corresponding robustness curves: solid purple for reservoir expansion and dash -blue for rainwater/greywater. At lower values of the RRM (below approx. 60 Ml), the rainwater and greywater combined option is more robust, but beyond this RRM value, the reservoir expansion of 200 Ml is more robust (for a short period), meaning it can provide the same level of performance at higher levels of uncertainty. The reservoir expansion of 200 Ml option trends in a direction to be more robust than the efficiency and greywater options with additional regional transfer, but fails before it can. In the long term, preference returns for the rainwater and greywater combined option with 75% adoption rate as it proves more robust than the reservoir expansion of 200 Ml option. The robustness curves show that a substantial increase in reservoir volume is needed for a significantly robust option. It is interesting to note that the efficiency and greywater options with additional regional transfer are the most robust demand side management (DSM) option while they last, but at approximately level 12 and 14 respectively both these options fail. Although the rainwater and greywater combined option with 75% adoption rate is less robust than these two DSM options at lower levels of uncertainty, it is more robust in the long term because it eludes failure until uncertainty level 14. Evaluating the robustness of management options past the range assessed with the EBSD headroom approach provides more information to differentiate the value of different strategies and options. Within the dashed blue line box, most options perform reasonably well. Which options fail first is only revealed outside of this box at wider deviations from the expected outcome.

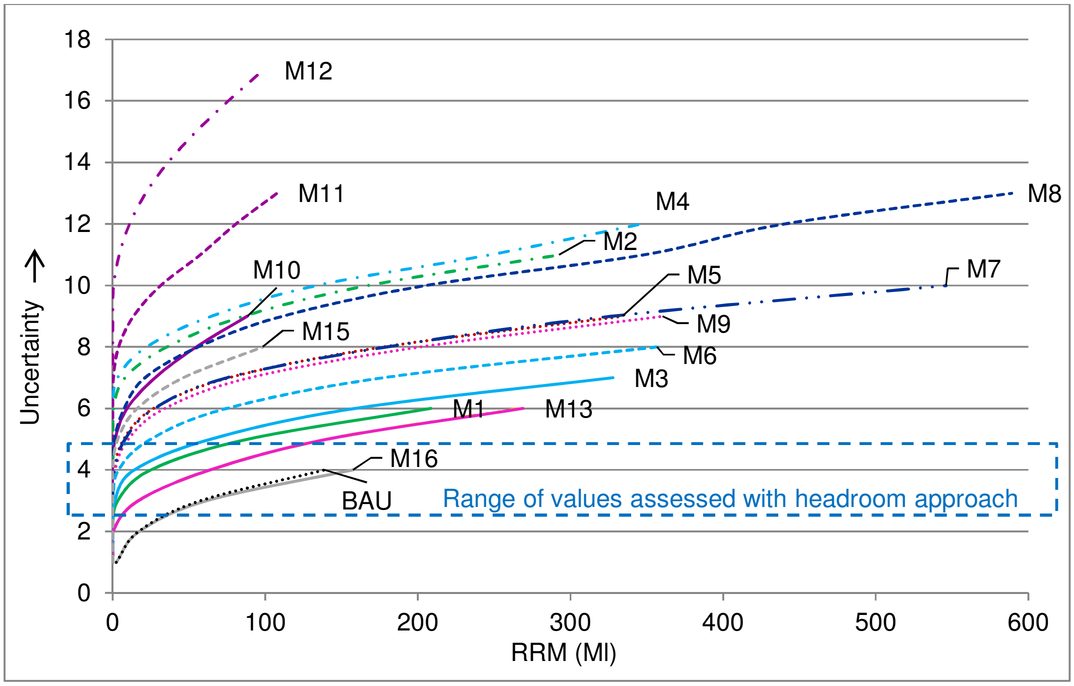


Figure 8. Robustness of different management strategies as assessed by a reservoir risk measure (RRM); the product of the probability of the reservoir falling below the drought management curve and the average volume (Ml) of water deficit below this curve.

Figure 9 shows the opportuneness curves for a selection of the management strategies (

Table 9) explored in terms of their relative success based on the safety margin deficit (SMD). The management options that are successful enough to survive failure beyond level 6 of increasing uncertainty (the extent of the range of uncertainty evaluated as part of the EBSD headroom estimation), are included in these opportuneness curves to see if their performance under auspicious conditions provides further insight on their merit. This graph shows that the reservoir expansion options are the quickest to lessen the SMD, followed by the combined demand side management option of greywater use for toilets and increased efficiency each in 50% of homes. At lower efficiencies, a close third and fourth to lessen the SMD are the demand side management options of greywater for toilets and increased efficiency both with additional regional water transfer. At higher efficiencies however, these two options are outperformed by the rainwater and greywater combinations at 75% and 50% adoption rates, respectively. These preference reversals highlight the fact that rainwater harvesting lessens the demand for water from reservoirs, and contributes to a quicker return to a positive water balance with a greater safety margin.

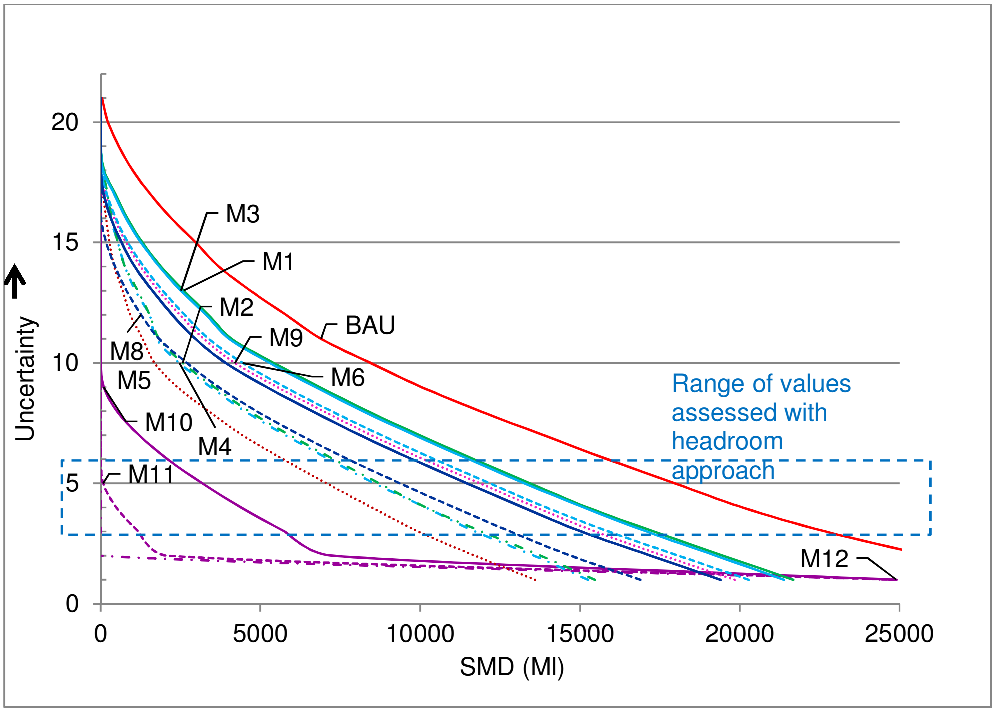


Figure 9. Opportuneness of different management strategies as assessed by safety margin deficit (SMD)

Figure 10 shows the probability that the reservoir level will fall below the drought control curve for 13 of the best performing management options and the no intervention option for comparison. The probability curves show erratic behaviour with the probability increasing and decreasing with increasing uncertainty due to the fact that reservoir levels can move up and down in relation to points on the drought management curve more than once each year. This behaviour creates a mess of crossing lines. The use of the RRM in Figure 8 creates cleaner plots and shows a consistent trend for the security of a reservoir because it takes into account the combination of frequency and magnitude in an overall measure. The RRM as a performance indicator offers a much clearer view of the relative merit of management options.

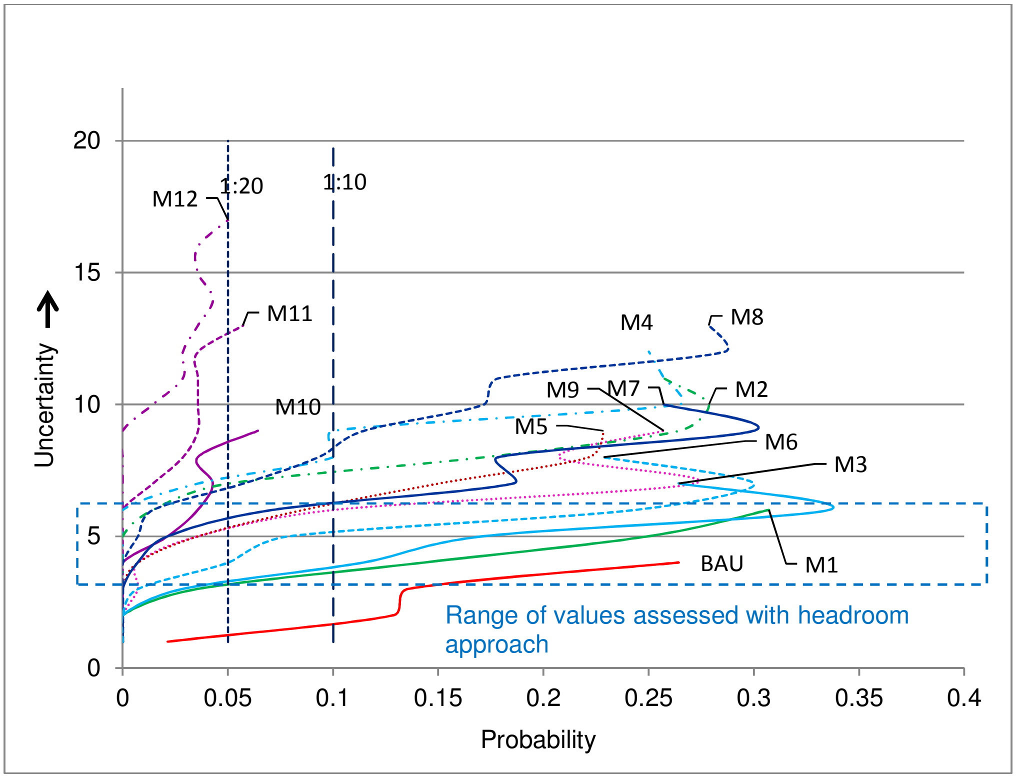


Figure 10. Probability that reservoir levels will fall below the drought control curve.

The only options that ensure a reservoir volume will not drop below a point on a drought management curve more than once in 20 years (termed below as the 'once in 20 years test') are the reservoir expansion options. A willingness to endure the reservoir volume dropping below a point on the drought management curve more often, up to once in 10 years (termed below the 'once in 10 years test'), allows for the consideration of a variety of other management options. Taking into account the fact that the probability of an occurrence is not as important as its magnitude, the robustness curves based on the RRM show that many DSM options that pass the 'once in 10 years test' but not the 'once in 20 years test' perform relatively well. In fact, three of these DSM options avoid operational failure at much higher levels of uncertainty than the reservoir expansion option of 200Ml, which passes the 'once in 20 years test'.

Table 10 lists the ranking of management options as a result of an MCDA performance evaluation based on different weightings for each of the following six criteria:

1. Risk of water shortage. Evaluated as a combination of robustness with the reservoir risk measure and opportuneness with the safety margin deficit.
2. Environmental impact. Based on the total yearly amount of outflow from the reservoir. This study considers the environmental flow and any other outflow whether it is flow through or spillage as contributing to the total outflow from the reservoir.
3. Local self-sufficiency. Based on the additional amount of water requested from the larger regional water system
4. Cost. Based on the (1) operating costs to treat and move the water, (2) individual consumer costs for those who opted for the demand side management (DSM) actions when those management options exist and standard costs when there are no DSM management actions and (3) the total consumer cost for all residential water. An emphasis is placed on residential water use because most of the DSM options are focussed on residential use and in this case study the commercial/industrial use is a small component of total system demand. Customer costs include sewage treatment based on figures originating from SW Water [10]. The pricing is adjusted to create a tiered tariff that increases costs 10% for water use above 130l per capita consumption (pcc) and another 10% for use above 150l pcc. This tiered tariff approach is created for the sake of research and does not originate from South West Water. Costs for system operations are sourced from average yearly cost per unit data from SW Water. Costs for rainwater and greywater processing originate from the Urban Water Optioneering Tool (UWOT) (Makropoulos et al. 2008) model technical library and from the University of Exeter's rainwater harvesting installation at the Innovation Centre (Ward 2010). Energy and Carbon conversion factors are sourced from SW Water's Water resources Plan (SW Water 2009), UWOT and the University of Exeter's rainwater harvesting installation.
5. Carbon footprint. Calculated from emissions in the generation of electricity related to the treatment and movement of water. The emission conversion factor is reduced over the chronological running of the model in a linear fashion to incorporate the national grid's stated climate change goals to reduce grid emissions 45% by 2020 and 80% by 2050.

6. Social acceptability. To include social acceptability, each management option is assigned a value between 1 and 10. Reservoir expansion is considered less acceptable (assigned a value of 8), efficiency options are considered more acceptable (assigned a value of 3), innovative options such as rainwater harvesting and greywater use are considered to be in between these two (assigned a value of 5), and combination options are assigned a value of 4.

For simplicity's sake, the rankings for each criteria grouping are presented for only two levels of low and high uncertainty instead of a ranking for each of the 20 steps of increasing robustness. Low uncertainty refers to level 5 of increasing uncertainty in Figures 8, 9 and 10 and is the same range of uncertainty as-is used to generate the headroom value in the EBSD headroom estimation approach. High uncertainty refers to level 10 of increasing uncertainty in the same figures and is the range of uncertainty associated with the outer boundary of the uncertainty range as defined in the EBSD headroom estimation approach. A rank of 1 indicates a management option that performs the best. An overall rank is provided to indicate the comprehensive robustness of a management strategy. If a management strategy fails to rank in the top 10 for lower uncertainty, it is assigned a value of 11 and if it fails in terms of a system failure before reaching the level of higher uncertainty it is assigned a value of 21. The total is a sum of all the rankings for a strategy. The lower the score, the more robust the management strategy and the overall rank is assigned accordingly.

Table 10. Multi-Criteria Decision Analysis performance evaluation with different weightings for the Drift Reservoir. The far right column of the table provides a key to the colour coding that is designed to help easy identification of which type of management intervention performed well over the most criteria and also where preference reversal occurred at higher percentiles that might not have been noticed within the percentile range assessed with the current headroom calculation.

Management strategy	Equal weighting		Emphasis on Water Availability		Emphasis on Environment		Emphasis on Local self-sufficiency		Emphasis on Cost		Emphasis on Carbon		Emphasis on Social Acceptability		Total	Overall Rank
	Uncertainty															
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High		
M1 - 15% reduction in water use for 50% of users	9	21	11	21	8	2	8	21	7	4	11	21	5	21	170	8
M2 - 15% reduction in water use for 50% of users and a 1 Ml/d regional transfer	6	2	7	2	6	21	11	2	9	3	11	4	4	4	92	2
M3 - Greywater toilet for 50% of users	8	21	11	21	9	21	6	21	6	21	10	21	9	21	206	11
M4 - Greywater toilet for 50% of users and a 1 Ml/d regional transfer	7	3	6	3	7	3	11	3	8	21	9	21	8	1	111	5

Management strategy	Equal weighting		Emphasis on Water Availability		Emphasis on Environment		Emphasis on Local self-sufficiency		Emphasis on Cost		Emphasis on Carbon		Emphasis on Social Acceptability		Total	Overall Rank
	Uncertainty															
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High		
M5 - Greywater toilet and 15% reduction in water use for 50% of users	1	21	1	21	3	21	3	21	3	2	11	21	2	21	152	6
M6 - Greywater for toilet and outside use in 50% of homes	5	21	10	21	5	21	5	21	5	21	11	21	7	21	195	10
M7 - Rainwater and greywater in 50% of homes	4	21	9	21	4	21	4	21	4	21	8	21	3	21	183	9
M8 - Rainwater and greywater in 75% of homes	3	1	5	1	2	1	2	1	1	1	11	3	6	2	40	1
M9 - Rainwater, greywater and 15% reduction in water in 33% of homes	2	21	8	21	1	21	1	21	2	21	1	21	1	21	163	7
M10 - Reservoir increase of 200 Ml	11	21	4	21	11	21	11	21	11	21	7	21	11	21	213	12

Management strategy	Equal weighting		Emphasis on Water Availability		Emphasis on Environment		Emphasis on Local self-sufficiency		Emphasis on Cost		Emphasis on Carbon		Emphasis on Social Acceptability		Total	Overall Rank
	Uncertainty															
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High		
M11 - Reservoir increase of 300 Ml	11	5	3	5	10	5	9	5	11	21	6	5	5	5	96	3
M12 - Reservoir increase of 400 Ml	10	4	2	4	10	4	10	4	10	21	5	2	10	3	99	4

At lower uncertainties the top ranked four options are the same with some change in order for all weightings except emphasis on water availability, carbon and social acceptability. These top four DSM options; Rainwater, greywater and efficiency in 33% of homes, Greywater toilet and 15% reduction in water use for 50% of users, Rainwater and greywater in 75% of homes and Rainwater and greywater in 50% of homes perform well because they offer a balance of benefits that satisfy a wide range of criteria and the DSM measures have high adoption rates. Most of these DSM dominant strategies are outperformed in the water availability weighting at lower uncertainties because the reservoir expansion strategies perform so well in terms of robustness and opportuneness for water availability. Management strategies that include efficiency rise in the rankings to the top four with the carbon and social acceptability weightings because efficiency limits the amount of carbon created during the treatment and distribution of water and because efficiency is classified as one of the most socially acceptable options. The reservoir expansion strategies rank low in all cases except for low and high uncertainty for water availability because the ability of these options to alleviate a risk of water shortage is not significant enough to counteract lower performance in other criteria.

Only five management options succeed at higher uncertainties. The preference for including efficiency measures at lower uncertainties with the Rainwater, greywater and efficiency in 33% of homes, Greywater toilet and 15% reduction in water use for 50% of users strategies is replaced by a preference for increased supply with additional regional transfers and significantly high adoption rates with the rainwater and greywater use occurring each in 75% of homes. At higher uncertainties the need for more water exerts such a significant influence to overbalance the carbon and socially acceptable weightings. For these weightings, one would expect the 15% reduction in water use for 50% of users and a 1 Ml/d regional transfer strategy to rate high because increased efficiency means decreased carbon use and efficiency is also more socially acceptable. However, the top three ranked options at higher uncertainties for the carbon and socially acceptable weightings outperform the efficiency option with regional transfer because, on balance, they either supply more water or reduce water use more effectively at higher uncertainties.

It is interesting to note that the combined volume of all the cisterns in any management strategy that includes rainwater collection ranges from 14Ml to 18Ml at the beginning and end of the planning horizon for adoption rates in 50% of homes; and 31Ml to 40Ml for adoption rates in 75% of homes. This volume is significantly smaller than the volumes that are added to the reservoir in the reservoir expansion options. The reason such a small volume can have such a large impact is because use over the year lessens the requirement for more water from the reservoir, thus making it easier to keep reservoir levels higher. Also, the frequent use of a small-scale system means there is little chance of wasted spill over water. Whereas with a reservoir, there is lots of water that spills over without ever contributing to the system's needs, unless of course there is a large enough reservoir, like the one expanded by 400 Ml, with enough space to keep more of this water for the summer season.

4.2.4 Summary

The application of the WRP-RA in Case Study 1:

- Demonstrates that the new metrics of a Reservoir Risk Measure and Safety Margin Deficit offer a comprehensive way to compare the performance of management strategies in a simulation setting. The RRM creates an overall view of frequency and duration to indicate the magnitude of impact avoided by different management strategies. The robustness curves show that some options perform relatively well over a longer period, Rainwater and Greywater at 75% adoption while some perform better but for a smaller range of uncertainties, Reservoir increase of 200 Ml. The opportuneness curves also show the merit of the Rainwater and Greywater at 75% adoption strategy as it reduces the SMD to zero quicker than all other options except for the reservoir expansion options.
- Shows interesting results in the expanded evaluations of the performance of management strategies over increasing uncertainty beyond the range of values commonly explored with a traditional headroom approach. For example:
    - Innovative options such as rainwater catchment and greywater reuse can provide benefits, but need to be implemented on a large scale.
    - Water efficiency also needs to be implemented on a large scale for real benefits to accrue.
    - IGDT robustness curves show that an increase in reservoir size must be significantly large to provide measurable robustness.
- Helps contribute to a broader understanding of the consequences associated with different management choice through the implementation of MCDA. The MCDA includes various weightings for different decision preferences and makes

the impacts of decisions on aspects such as the environment, carbon and other social issues more transparent.

4.2.5 Limitations

There are two significant limitations in the application of the WRP-RA for Case Study 1.

- A full range of hydrological variation was not investigated. The WRP-RA approach further tests the worst case situation by increasing the climate change flow factors from mid to dry effects, but does not explore a range plausible hydrological time series that could occur and result in a variation of different drought episodes.
- Other than the identification of the range of uncertainty explored with the headroom estimation method, a narrative to explain the severity of each level of increasing uncertainty as represented in the robustness curves was not provided. Although the relative robustness is apparent based on the trajectory of the robustness curves, without a narrative, it is harder to understand the supply/demand settings that each strategy is responding to over the unbounded range of uncertainty.

4.3 Case Study 2 – Colliford Strategic Supply Area

The purpose of Case Study 2 was to achieve Objective 2:

- Identify additional benefits of the WRP-RA when compared with the UK approach for water resources planning, EBSD Current, in a simulation context.

Achieving this objective required applying the WRP-RA to an expanded pipe network composed of multiple sources, demand nodes and treatment works that is governed by a variety of abstraction rules and reservoir control curves.

The AISC selection method was explored instead of the LP/IP optimisation selection method because at the time the research was conducted South West Water used the AISC selection method and a proper like for like comparison required the use of the same selection methods.

4.3.1 Motivation

In order to evaluate the WRP-RA approach and test the performance criteria in a meaningful sense, Case Study 2 was developed at the scale of a Strategic Supply Area and the WRP-RA was compared with the Current EBSD methodology that dominates water resources planning in England and Wales. Case study investigations have been performed for smaller components of other Strategic Supply Areas in England and Wales in order to propose new methodologies that test the performance of systems over more extreme supply demand settings than have been planned for in PR09 and PR14 (Lopez et al. 2009, Matrosov, Woods and Harou 2013, Matrosov, Padula and Harou 2013, Borgomeo et al. 2015, Turner et al. 2014). These studies have discussed the benefits of new methodologies in comparison with the EBSD approach, but have not directly compared the results of the new methodologies with those of the EBSD approach to clarify the main differences and advantages of new methods. Case Study 2 provides a direct comparison of the WRP-RA and the EBSD Current with the AISC selection method in order to clarify the main advantages and additional insight that can be garnered with a deeper investigation of uncertainty to compare management strategy performance.

4.3.2 Description

Similar to Case Study 1, Case Study 2 uses a semi-real water resources system, this time based on the Colliford Strategic Supply Area (SSA) that encompasses the whole of Cornwall, UK (Figure 11). The Colliford SSA is mostly self-sufficient with minimal import and export to the neighbouring Roadford SSA. Colliford SSA is comprised of abstraction from 6 rivers and 6 reservoirs, delivery to 19 demand nodes, water treated from 9 water treatment works (WTW) most of which contain pumps and 5 other significant pumping sites.

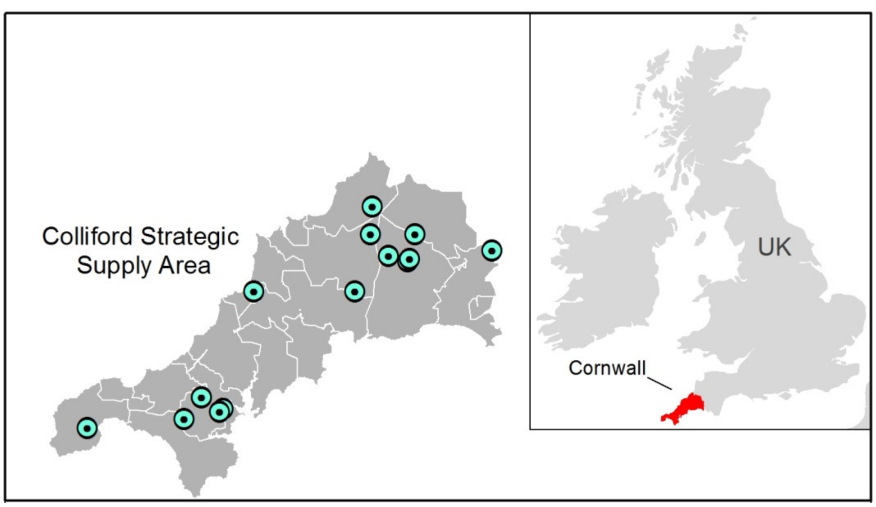


Figure 11. Colliford SSA Study area with boundaries of Water in Supply demand area boundaries and point location of abstraction points for rivers and reservoirs

The simulation model used in this study was also composed in MATLAB. The model is configured to follow a calculation sequence with built-in redundancy. It supplies water on request from the 19 demand nodes within the capacity of water treatment works, the pipe network, allowances of abstraction licenses and ability of reservoirs and rivers to supply the demand requested. Figure 12 is a rendition of the schematic for the Colliford SSA as represented in MISER water resources software. Figure 13 is a higher resolution version of part of this network showing the additional highlighted numbers which indicate significant pipe constraints (Ml/d) in the network. If a water treatment works, abstraction license or abstraction source cannot meet a demand, a request for the unmet portion of the demand is passed on to be satisfied by further supply points in the SSA network. The arrows in

Figure 14 illustrates the backup supply for each part of the network. The final backup source of water is the Colliford Reservoir. The current network can transfer water from this reservoir to all, except 3 demand nodes of the SSA. This connectivity is significantly aided by a long spine main that stretches to the south western most tip of Cornwall. This prioritised delivery of water (demand satisfied by local supply first, supported by backup from other points of system supply) is very close to how South West Water plans its delivery of water as evidenced in the calibration results listed in Table 11.

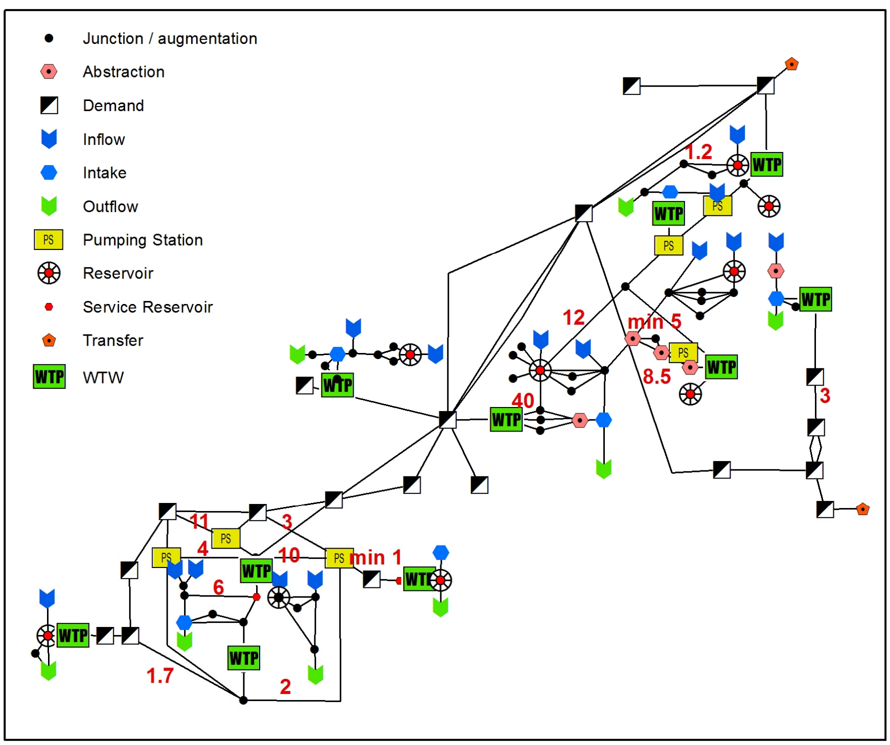


Figure 12. Schematic of Colliford Strategic Supply Area from Miser software (pipe constraints in red text)

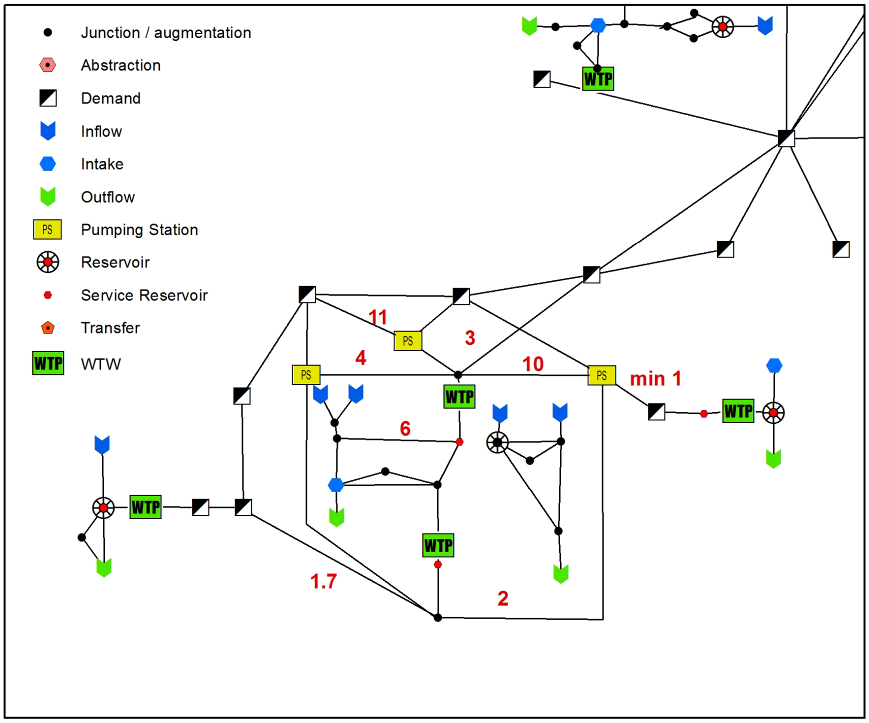


Figure 13. Higher resolution of southern Cornwall part of the SSA

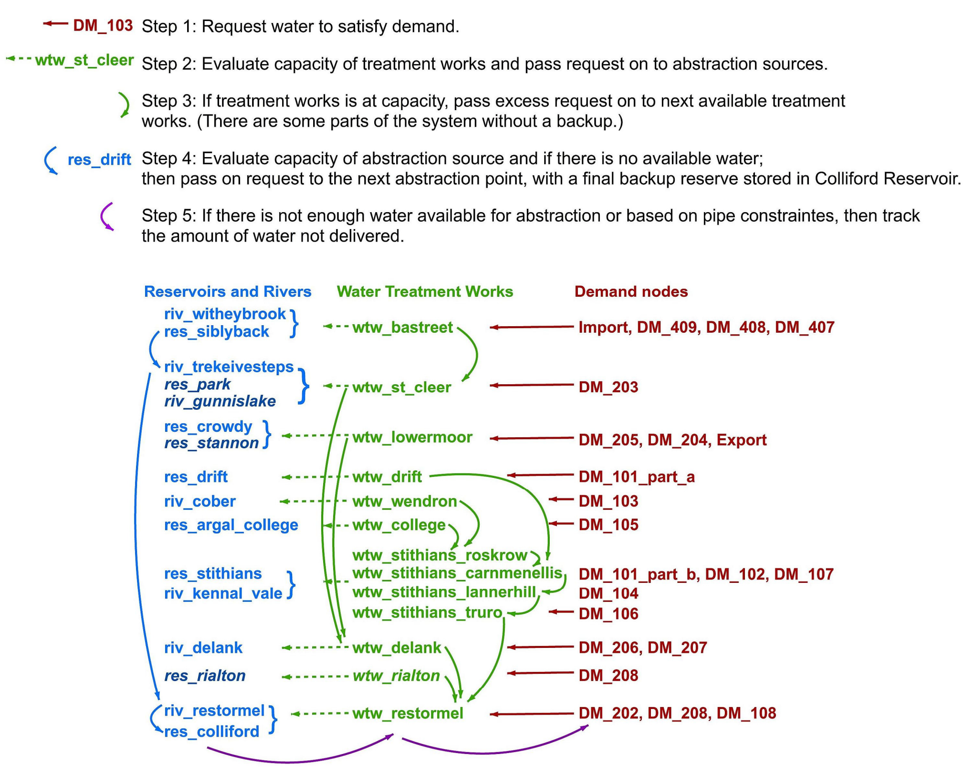


Figure 14. Prioritised delivery of water in the MATLAB SSA Network model

The behaviour of reservoirs in the MATLAB simulation model follows drought management curves defined by South West Water to maintain an optimal operational reservoir volume for the time of year based on historic weather patterns. These control curves also include the reservoir levels that trigger the pumping of significant amounts of water; such as incremental increases in the transfer of water from Colliford Reservoir to St. Cleer treatment works and winter pumping from the Restormel River to replenish Colliford Reservoir. In the SSA simulation model, if some of the smaller reservoirs fall below a point on their drought management curves, then less water is delivered from these reservoirs and more is sourced from Colliford Reservoir. Colliford is the largest reservoir in the system, acts as a strategic backup supply and defines the ability of the SSA to survive long term droughts. The system fails when Colliford reservoir runs out of water. The Restormel water treatment works similarly plays a significant role in the robustness of the system mostly due to its large capacity (at present 100 Ml/d) and its strategic location beside the Fowey River which provides a river abstraction when flows are high enough and acts as a conduit for backup supply originating from the Colliford reservoir. Many of the management strategies explored in this case study leverage the interplay between Colliford Reservoir and Restormel water treatment works and some enhancement of their strategic offerings. As evident in the pattern of the green water treatment works backup flow lines in Figure 14, almost all demand centres of the system can be 'backed-up' by water originating in the Colliford reservoir and passing through the Restormel water treatment works.

There are 3 demand nodes in the SSA that can fail to deliver the amount of water required because they either have pipe connections with limited capacity or are isolated without backup supply from the larger system and have limiting constraints of local treatment works or available supply.

Demand in the system as a whole is roughly 40% residential, 32% commercial/industrial and 13% agricultural and varies for each demand node. Due to gardening needs and an influx of tourists, summer demands can be as much as 35% higher than winter demands, all at a time when summer flows are low. Each abstraction point is governed by a license that preserves a certain amount of flow for environmental needs.

The daily time step SSA simulation model used in this research is constructed in MATLAB is based on the functioning of the simplified simulation model (Section 4.2).

The main advancements of the simplified model are the addition of more demand centres, water treatment works, river intakes and reservoirs along the accommodation of pipe constraints and complex abstraction rules. A daily time step was used for better comparison with the South West Water MISER model.

To reiterate the sources of information for the model, as stated in Section 4.2.2 that describes the Drift reservoir model, look-up tables hold time series values to serve the parameter needs of the water reservoir mass balance Equation 5. These parameters include: daily inflow and rainfall values over a 25 year period from 1962 to 1986 inclusive, average weekly demand factors that show an increase in use during the summer months and a slight reduction in the winter, and UKWIR climate change flow factors to quantify the effects of climate change on future river flows. These flow factor values are sourced from SW Water and guided by the final UKWIR Methodology of 2011 (UKWIR 2011). The MATLAB code contains baseline values for per capita demand, population in terms of the number of houses, commercial and industrial combined demand, and agricultural demand. Growth factors for each of these three demand components project an expected increase of 7% in population, a short-term drop of 10% in commercial and industrial demand (which recovers over the planning horizon) and an increase of 5% in agricultural demand.

Constraints within the model

Abstraction from reservoirs and rivers is controlled by daily and yearly maximum abstraction amounts and the capacity of the system to deliver a certain amount of water to a demand node is constrained by water treatment works and pipe capacities.

Calibration check of the Colliford SSA Network Model

To provide confidence that the MATLAB simulation model behaved as expected and offered a fair representation of the Colliford SSA, a calibration check was performed during which simulations were run for the design drought years (1975-1979) using the same input data as used in the SW Water MISER model. The amount of water abstracted from each reservoir in the Colliford SSA was totalled for the simulation period (Table 11) to ensure each model used river abstraction and reservoir abstraction in approximately the same manner. This check also confirmed by proxy that the handling of environmental flow defined in the abstraction licenses were approached similarly in each model. The MISER model employs a similar tactic to the MATLAB model to maximise the amount of river abstraction when possible in order to preserve reservoir levels for critical dry periods.

Table 11. Comparison of water abstracted from reservoirs during model calibration check

Reservoir	SW Water MISER model	MATLAB model	Relative difference
Argal/College	404,103	430,385	6.50%
Colliford	12,529,868	12,574,061	0.35%
Crowdy	482,632	492,457	2.04%
Drift	287,247	301,310	4.90%
Siblyback	1,216,194	1,224,461	0.68%
Stithians	2,789,576	2,863,023	2.63%
Total	17,709,620	17,885,697	0.99%

Time series of reservoir storage levels were also compared to evaluate the consistency of how the two models performed over the 5 years in daily time steps (Figure 15). Some variation is evident in the reservoir levels as in the total water abstracted (Table 101). The MATLAB model relies on water abstracted from reservoirs more than the MISER model. This variation is considered to be due to how each model maximises the benefit from river abstraction. Each model is guided by abstraction coefficients as to when to abstract a larger portion of water from a river over the course of a year to maximise the abstraction benefit. Establishing a method to maximise this benefit is necessary because often the daily maximum is larger than the yearly maximum divided by the number of days in a year. South West Water has a set of weekly abstraction coefficient values to guide river abstraction optimally within the MISER model. A custom set was developed for the MATLAB model in order to explore reasoning and rationale behind when to maximise abstraction. The deviation is not considered of material concern and is expected when a research version of a model is created from scratch as compared with a software company that has devoted many years of development to a model.

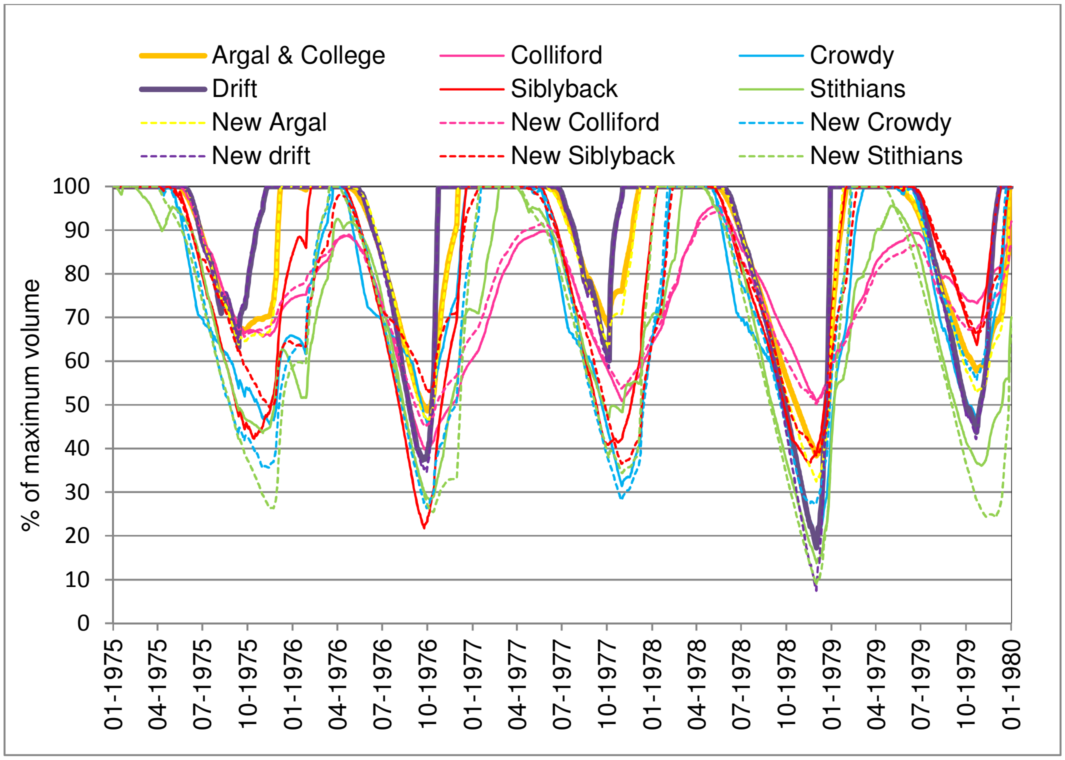


Figure 15. Comparison simulated reservoir storages during calibration check - New denotes MATLAB model results

Uncertainty sources

For the Colliford SSA, uncertainty is explored in two different ways; with headroom estimation for the EBSD Current AISC approach as described in Section 3.2 and using the WRP-RA as described in Section 3.3. Table 12 is a compiled version of Table 5 and Table 7, and includes details of how uncertainty related to the 3 supply-side parameters, 5 demand-side parameters and cost is accounted for in the EBSD and WRP-RA approaches.

Table 12.Parameters evaluated for uncertainty. Headroom estimation values are taken from a percentile of an assigned distribution. For IGDT, The parameters in the grey shaded rows are explored in an unbounded fashion until the system fails and all other parameters expand up to the edge of the range defined by the EBSD headroom estimation process.

Mathematical Abbreviation	Description	Range	Headroom estimation value	Info-Gap Central Estimate
Scc(dry) Scc(wet)	Changes in yield from Climate change	Historic inflows perturbed by wet to mean and mean to dry climate change scenarios	Percentile of triangular distribution increasing from 80 to 87.5 over the planning horizon.	Historic inflows perturbed by mean climate change scenario.
Smeter	Supply meter accuracy	+/- 2.5%	Percentile of normal distribution increasing from 80 to 87.5 over the planning horizon.	As historically registered by inflow meters
Scatchment	Changes in yield from Catchment changes due to Climate Change	+/- 10%	Percentile of normal distribution increasing from 80 to 87.5 over the planning horizon.	As historically registered by inflow meters
Dgrowth	Changes in population, commercial/industrial and agricultural use	+/-10%	Percentile of normal distribution increasing from 80 to 87.5 over the planning horizon.	Expected 10% increase in domestic demand, decrease in commercial and industrial demand and no increase in agricultural demand
Dcc	Changes in demand due to climate change	+/- 1.4%	Percentile of triangular distribution increasing from 80 to 87.5 over the planning horizon.	Same as current demand pattern

Mathematical Abbreviation	Description	Range	Headroom estimation value	Info-Gap Central Estimate
Dmeter	Demand meter accuracy	+/- 2.5%	Percentile of normal distribution increasing from 80 to 87.5 over the planning horizon.	As registered by demand meters
Deff(gain); Deff(loss)				
applied to Dreduce(eff)	Potential gain or loss in demand reductions related to the number of homes to adopt efficiency measures	+10% (gain) or -20% (loss) of expected number	Percentile of triangular distribution increasing from 80 to 87.5 over the planning horizon.	Adoption rates as defined by management options
Dinn(gain); Dinn(loss)				
applied to Dreduce(inn)	Potential gain or loss in demand reductions related to the number of homes to adopt rainwater harvesting and/or greywater reuse	+10% (gain) or -20% (loss) of expected number	Percentile of triangular distribution increasing from 80 to 87.5 over the planning horizon.	Adoption rates as defined by management options
Cost	Potential magnitude of increase in cost for electricity	A further 100% increase or 50% decrease of what is expected	Not included.	Increase of 50% by the end of the 25 year planning horizon

Water resources management strategies

This case study explores 14 different management strategies that alleviate the supply/demand deficit (Table 13) in accordance with the PR14 WRMP guidelines (Environment Agency, 2008). These strategies were developed with traditional EBSD planning procedures as described in Section 3.2. First, a forecast supply demand balance including target headroom was developed based on yearly planning values. Second, portfolios of options were combined with different start dates to satisfy the supply demand deficit in the most cost-effective manner. The expectation is for water companies to promote the least-cost strategy or a strategy close in cost if there are some other significant constraints that make the least-cost strategy less feasible to implement (UKWIR 2002). This case study considers all the possible option combinations, (composed from the feasible options list in South West Water's 2010 WRMP and including two innovative demand management options based on learnings from the simplified simulation model), that could satisfy the supply demand balance over the 25 year planning horizon, regardless of cost.

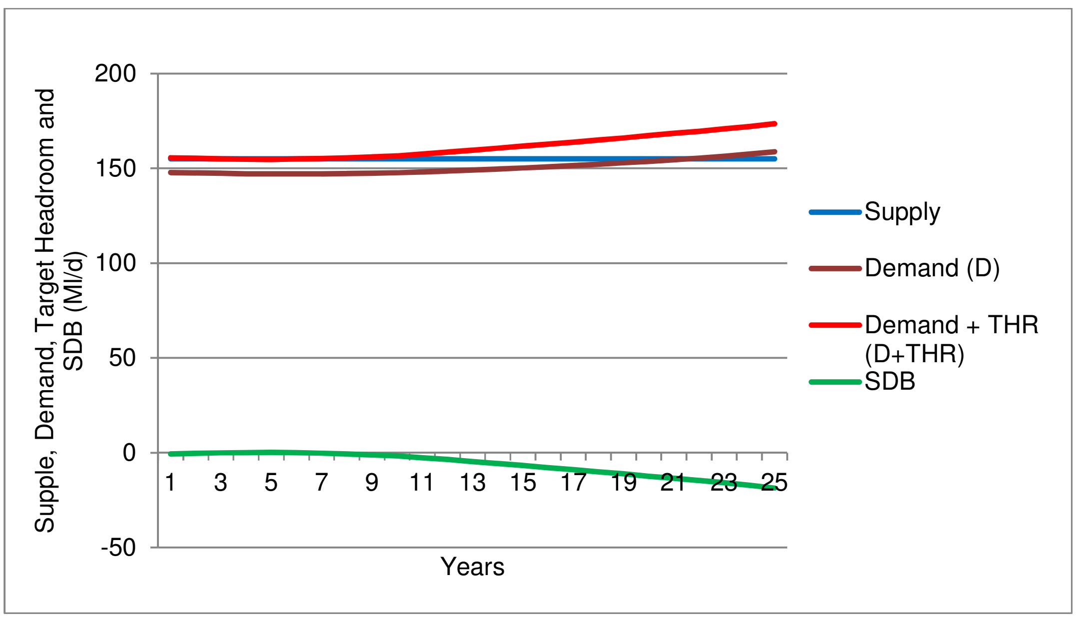


Figure 16. SSA 25 year forecast supply demand balance (SDB)

The options used as building blocks to make the 14 management strategies are listed below along with the shorthand names used in the legend of subsequent figures. The text in brackets refers to the type of option. i.e. [WTW] stands for water treatment works upgrade, [I] stands for inflow, [DM] stands for demand management and [R] stands for reservoir. In the creation of strategies, options were first chosen with a goal of supplying the least amount of water needed for any one year and at the same time, stalling the implementation of options until necessary. After the least cost combinations were chosen, then other possible combinations were developed if they could also satisfy the supply/demand deficit, and again stalling the implementation of options until necessary in order to defer capital investment.

1. Increase the capacity of the Restormel water treatment works – Rest [WTW].
2. Increase the maximum daily abstraction amount from the Fowey River at the Restormel intake – Rest [I].
3. Include Park and Stannon Lakes, historic clay mining pits, as supply reservoirs in the system – Park [R].
4. Reinstate the Rialton water treatment works to include Rialton river inflow and Porth reservoir as part of the network – Rialton [I].
5. Introduce a pipe to import water from the Gunnislake River which is part of the Roadford SSA, treat this water with spare capacity at the St. Cleer water treatment works and store and make it available to the spine main that extends to the south western tip of Cornwall – Gunnislake [I].
6. Introduce a pipe to bring water from the Camel River to the Restormel water treatment works intake and thus supplement the water available from the Fowey River and also allow more water to be pumped to the Colliford River for winter storage – this scheme runs from October till March – Camel [R].
7. Promote an increase in efficiency of 10% for 50% of residential homes and commercial businesses. Reductions related to water use efficiencies start gradually with a third of all benefits showing 2 years before the savings is needed, followed by the second third a year later and the final third during the year the savings is needed – Eff [DM].
8. Rainwater collection for bathing and clothes washing and greywater for toilets and outside use (R/G) for 25% of residential homes. This combination strategy follows a similar pattern to the efficiency interventions of slowly ramping up over the 2 years previous to when the savings is required –RG [DM].
9. Rainwater collection for bathing and clothes washing, greywater for toilets and outside use and increased efficiency – each with an adoption rate of 1/3 of all homes. These combination strategies follow a similar

pattern to the individual interventions of slowly ramping up over the 2 years previous to when the savings is required – Trio [DM].

Table 13. Management strategies developed with EBSD Current AISC approach

Management strategy	Start year | 1st Option		Start year | 2nd Option		Start year | 3rd Option	
M1	1	Camel [I]	12	Rest [WTW]	n/a	
M2	1	Park [R]	15	Eff [DM]	18	Rest [WTW]
M3	1	Park [R]	12	RG[DM]	17	Rest [WTW]
M4	1	Park [R]	12	Trio[DM]	17	Rest [WTW]
M5	1	Park [R]	14	Rest [I]	n/a	
M6	1	Park [R]	14	Rialton [I]	23	Rest [WTW]
M7	1	Park [R]	15	Rialton [I]	22	RG[DM]
M8	1	Park [R]	15	Rialton [I]	22	Trio[DM]
M9	1	Gunnislake [I]	9	Rest [WTW]	21	Park [R]
M10	1	Gunnislake [I]	9	Rest [WTW]	21	Trio[DM]
M11	1	Camel [I]	12	Park [R]	17	Rest [WTW]
M12	1	Camel [I]	12	Rialton [I]	21	Rest [WTW]
M13	1	Gunnislake [I]	9	Camel [I]	12	Rest [WTW]
M14	1	Gunnislake [I]	9	Rialton [I]	16	Rest [WTW]

Deployable Output for the options

The quantification of the DO that an option can provide to a system is different for supply and demand management (DM) options.

In the MATLAB SSA Model the benefit of DM options for efficiency was quantified based on the percent reductions for residential and commercial customers as proposed in the South West Water's PR09 WRMP. The benefit of greywater and rainwater options was quantified by the reduction either would provide based on a micro-component analysis of domestic use.

The DO available for supply side options in the MATLAB SSA Model is constrained by a number of factors.

- Hydrological yield
    - All supply side options in the Colliford system are based on river abstraction and the potential yield is dependent on historic inflows (or perturbations to these inflows). A daily time series of inflows was supplied by South West Water and this time series was perturbed by UKWIR climate change flow factors and further

adjusted to explore the outer edges of uncertainty for application of the IGDT-based WRP-RA method.

- Licensed abstraction quantities and constraints
    - The choice of when to abstract different amounts of water from a river and reservoir can have an impact on the available DO especially when the daily maximum abstraction is more than is less than the yearly maximum abstraction divided by 365. This thesis explored a few approaches all that tried to maximise abstraction from rivers in the winter and from reservoirs in the summer.
- Reservoir control rules
    - Further constraints on optimising the use of this yield are impacted by the reservoir control rules that govern the operation of reservoirs again. These reservoir control rules were provided by South West Water.
- Pumping plant capacities
    - Pumping plant capacities are included in the MATLAB model as provided by South West Water.
- Raw and treated water mains capacities
    - Constraints on the pipe network are included as shown in Figure 12 and Figure 13.
- Treatment works capacities
    - Treatment works capacities are included in the MATLAB model as provided by South West Water.

Since all constraints on supply side DO are included in the input data or in the model formulation, the only aspect of evaluating the available DO available for future management strategies is to run repeated simulations of the MATLAB model until a Level of Service rule is broken.

Outage is a temporary interruption and is commonly included in EBSD modelling as a Ml/D value. Process Losses are loss related to treatment works and other non-leakage issues. Leakage is considered a component of demand. The outage figures as presented in the PR14 WRMP for the Colliford SSA were used for the EBSD Current method employed in Case Study 2. Process losses are included as part of the water treatment works in the MATLAB custom model.

For Case Study 1, yearly averages were not required as this study focussed purely on daily simulation to develop the WRP-RA method and it did not compare results with any EBSD method. For Case Study 2, DO available for individual schemes are available from South West Water's 2010 WRMP, but in order to properly compare EBSD and WRP-RA results, yearly average DO used in this research was recreated with the MATLAB SSA simulation model.

The Environment Agency promotes the creation of flow time sequences (by various methods) that stretch further in the past than currently available to assist with the creation of DO based on Design Droughts from an extended historic time sequence. South West Water maintains these approaches are not appropriate in their context as the weather patterns in Devon and Cornwall (Cornwall in particular) are so variable in nature that the only valuable flow data comes from actual flow records (South West Water planning staff, pers. comms., 2010)

To mimic South West Water's Levels of Service, a value for the baseline WAFU of the Colliford SSA and additional DO available from future options was calculated in the MATLAB model based on the ability of the Colliford network to deliver water as long as a 5% reduction did not occur with a higher probability than 0.05. Ironically, although South West Water assesses its DO values from its design drought period, 1975 and 1979, the MATLAB custom model failed routinely in 1984. This lag time of failure beyond the design drought is explained by the nature of the Colliford Reservoir and catchment. It can take up to 5 years to recharge the Colliford reservoir and if the subsequent years after a drought happen to be dry, the ability of the system to recover is hindered.

This lag time for failure beyond the dry year period is an additional learning resulting from the development of a custom model, the application of network modelling in a slightly different manner to the routine practice of South West Water and the exploration of greater ranges of uncertainty. Simulation runs should extend beyond the design drought for at least 5 years because the Colliford reservoir can take 5 years to recharge and any further extreme dry years during that critical 5 years could push the system into failure.

Average Incremental and Social Costs for the options

The AISC approach used by South West Water assumes a consistent asset life of 60 years for every option (South West Water 2009)

AISC costs were assigned for each option independently (Table 14) based on the procedure followed by South West Water (Section 3.2.1) and updated with the Deployable Output figures derived with the MATLAB SSA Model. The costing of the innovative Greywater reuse and Rainwater Collection demand management options includes the assumption that the homeowner would pay half the cost as the use of these systems would help them be more self-sufficient with their water use and also save money on their water bills over the long term. It's thought to be reasonable that SW Water would pay for the other half of the installation cost as the support of these innovative Demand Management options is an extension of their existing support and financial investment towards Water Use Efficiency and the results of this modelling show that these innovative options offer more savings than standard Water Use Efficiency measures.

Table 14. Average Incremental and Social Cost of Options

Option	Cost (pence/m^3)
Park[R]	0.0
Rest[I]	0.0
Rest[WTW]	8.9
Eff[DM]	17.8
Camel[I]	24.9
RG[DM]	56.7
Rialton[I]	33.8
Gunnislake[I]	37.8
Trio[DM]	68.7

Headroom estimation

As described in Section 3.2.1, Headroom values were developed using the same assignment of distribution and ranges as used by SW Water in their PR14 WRMP and the same software, @Risk. The only difference in application for this thesis is the percentile values of the combined uncertainty distribution from which the values were chosen from. Figure 17 shows that South West Water chose a headroom value based on the 85th percentile at that start of the planning horizon and reduced this to the 75th percentile at the end. As a result the headroom value varies a minimal amount (1 Ml/d on either side) around a central value of 10 Ml/d.

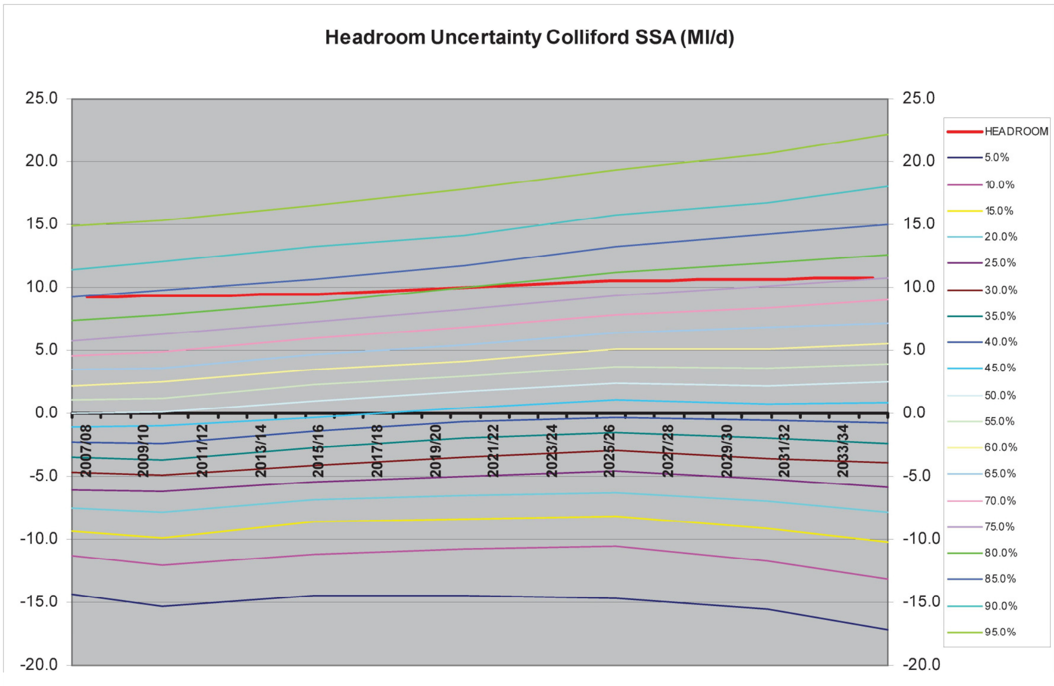


Figure 17. Value range for Headroom uncertainty as chosen by South West Water (South West Water 2000)

A more conservative approach is used in the MATLAB SSA Model (Figure 18) by showing more confidence at the start of the planning horizon with the choice of the 80th percentile and less confidence at the end of 25 years with the choice of the 87.5th percentile. A sensitivity test was completed to see the effect of using headroom values ranging from 9 to 11 Ml/d as used by SW Water as compared with the wider range of 7.5 to 17.5 Ml/d used with the MATLAB model. With a lower headroom value as derived from a lower percentile range, in 12 out of 14 portfolios, the only difference was that the implementation of the 2nd and 3rd options could be delayed by anywhere from 1 to 4 years. In one portfolio, the 2nd and 3rd option would need to be implemented earlier in the planning horizon and in the remaining portfolio; there was no change in the start date for 2nd and 3rd options.

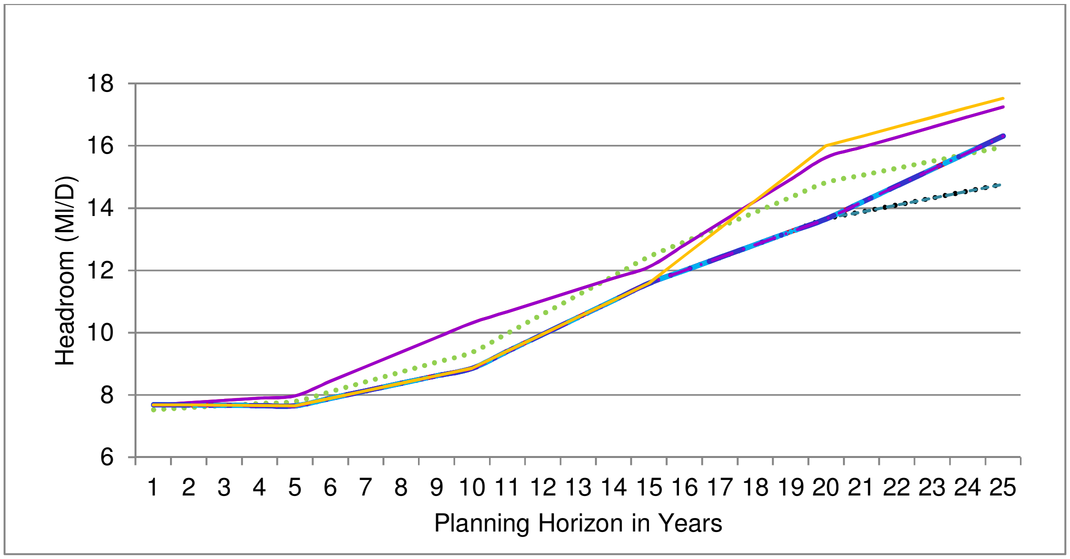


Figure 18. Value range for headroom uncertainty used in the MATLAB model

4.3.3 Results and discussion

Figure 19 shows the Supply Demand Balance (SDB) of the three least-cost management strategies. Solid lines indicate the SDB before the management strategy is put in place and the dashed lines indicate the SDB after the management strategy is invoked. The strategies achieve a positive SDB either through an increase in supply or a reduction in demand or a combination of both. A few strategies show a small deficit (Appendix A); M4 in the last year, M7 and M8 in the last two years and M12 in year 20. These deviations are accepted as they are either small in nature and/or only impact the last few years of the planning horizon.

The pie-charts in Figure 19 show a breakdown of the total cost for the portfolio into the amount of spend for water utilised to satisfy the supply/demand balance and the amount of spend for water that is unutilised – i.e. the remaining cost to create the full capacity. These costs are calculated by multiplying the AISC value by the amount of water used from the options over the course of the planning horizon and the amount of excess water.

Figure 19. Supply demand balance and spend profile of the three least-cost management strategies identified with the EBSD Current method – M5, M2 and M6 in order of increasing cost.

A common practice with the EBSD Current approach is to complete enough analysis to be able to choose one least cost portfolio (as was the case with South West Water's PR09 plan). Ofwat would require substantial justification for any WRMP that included a management strategy with a portfolio of options more expensive than the least cost. As can be seen in Figure 20, M5 is the least cost. There may be some case made to choose M2 as the cost for M2 is not substantially higher, but M2 wouldn't be a better choice as Figure 21 shows it has less surplus water at the end of the planning horizon. There would need to be substantial justification made to choose M6 as the cost to implement M6 is almost triple the cost for M5. M6 would be a better choice as it does have more surplus water than M5 at the end of the planning horizon.

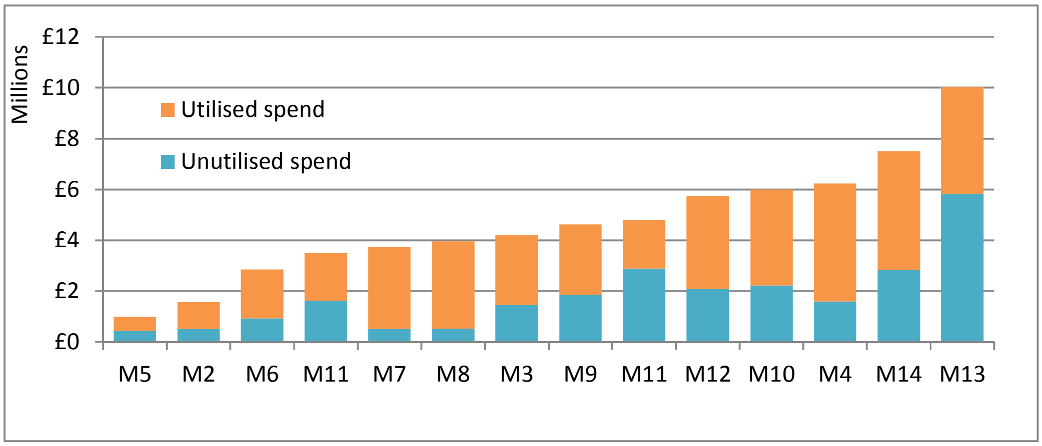


Figure 20. Total cost of management strategies over the planning horizon based on AISC approach

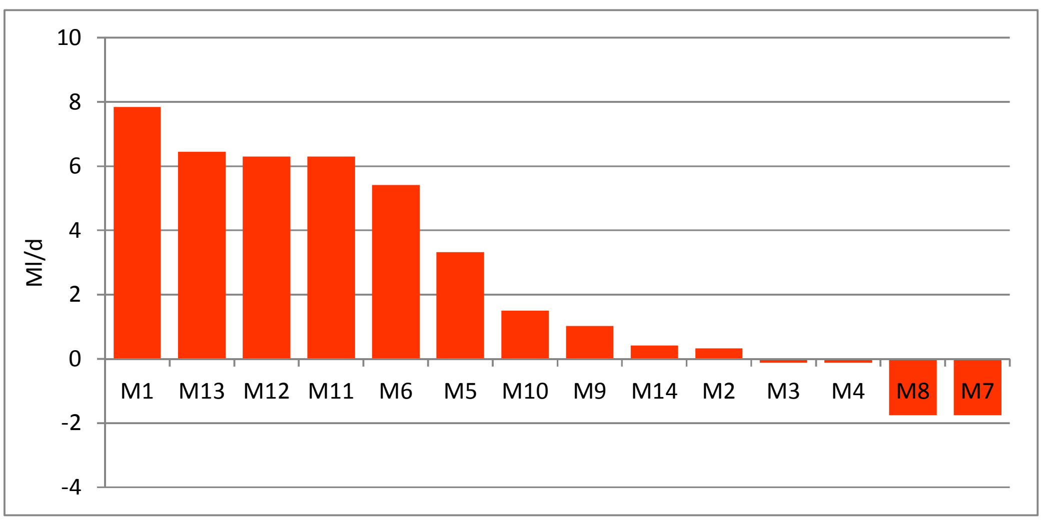


Figure 21. Supply/demand balance at end of the planning horizon

At the time the South West Water PR09 WRMP was completed, the concept of a best-value plan was not fully mature. Some companies such as Thames

Water (Thames Water, 2014) have included the concept in their PR14 plans. At present, more companies are considering a best-value approach, lead in part by the recommendations of the UKWIR Water Resources Planning Tools 2012 documents (UKWIR, 2012). Figure 22 offers a view of one best-value approach that could be accomplished without much further effort than is employed for EBSD modelling. This plot shows the amount of surplus possible with each portfolio compared with the cost to implement the portfolio. The least cost M5 is in the relative centre of this plot and as such is considered of fairly good value. An argument could be made that the surplus afforded by strategy M6 provides so much more value as to make the extra spend worthwhile. M11 offers a little more surplus and only costs a little more. How is it possible to know how much more investment is worth it? How much better is M6 than M5 and M11 than M6? More information is needed to inform this decision.

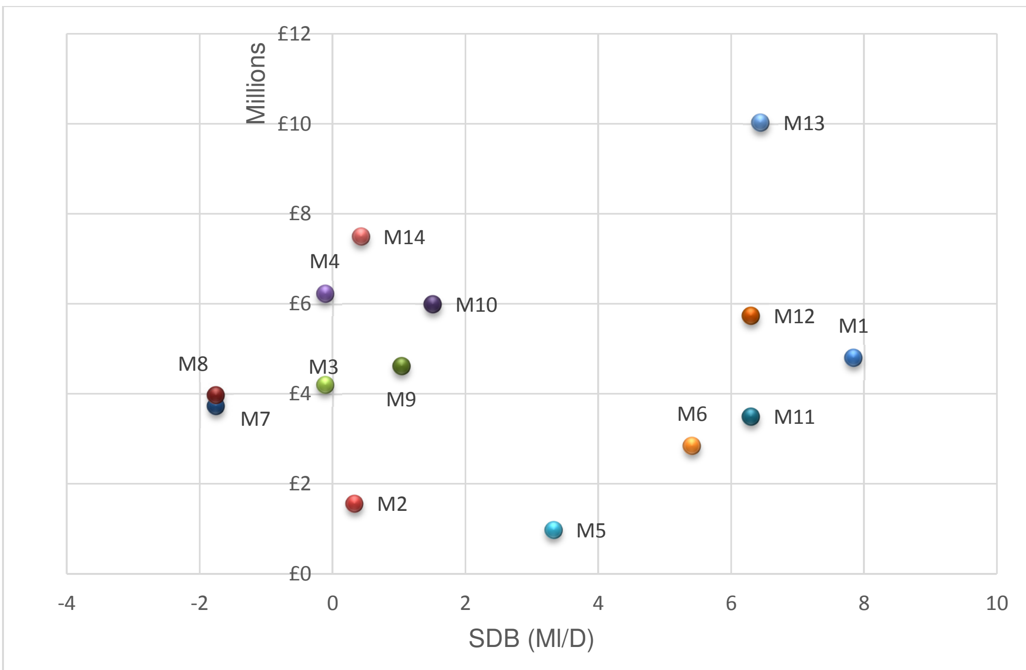
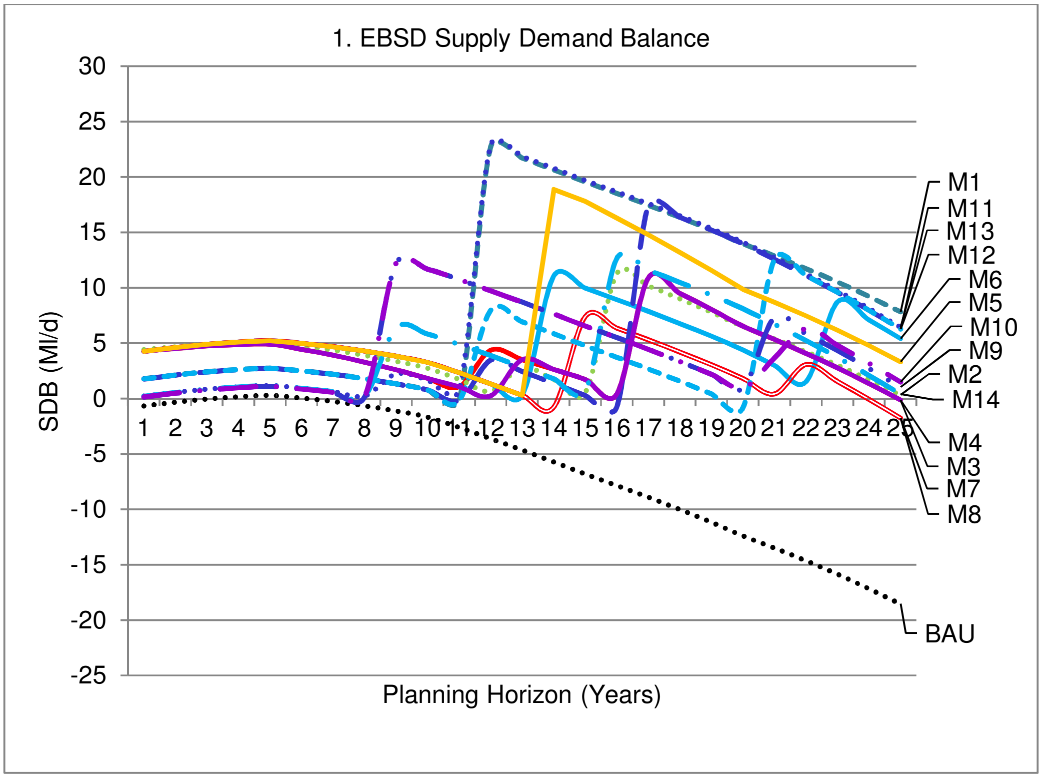


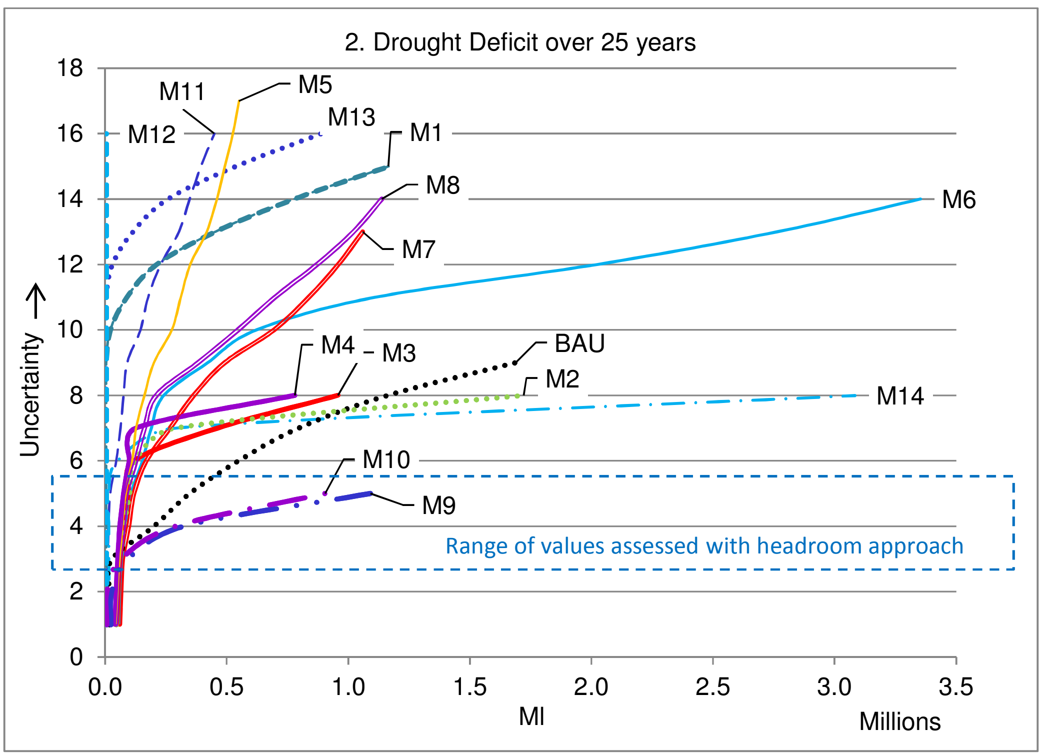
Figure 22. Best value portfolio based on cost and supply demand balance at the end of the planning horizon

The limited nature of the EBSD approach, in the standard approach for PR09 with only one scenario completed, and in general, with only one view of future uncertainty, makes it hard to justify additional expenditure. There simply isn't enough evidence.

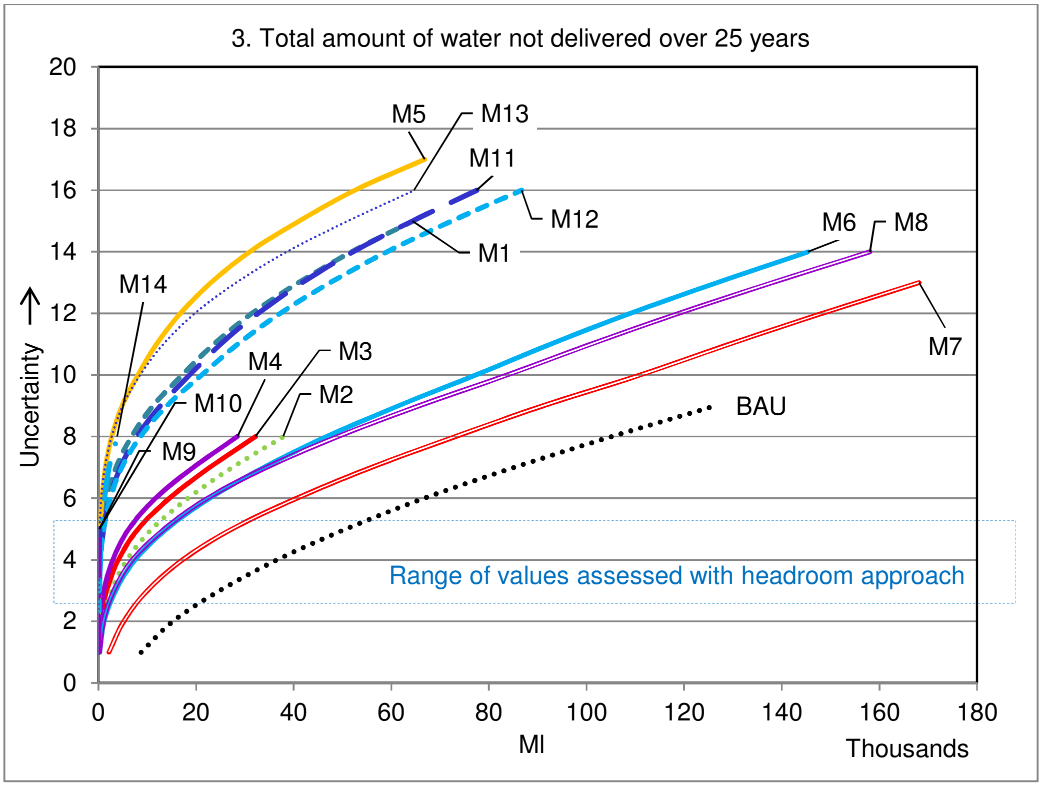
The IGDT-based WRP-RA method offers a more complete picture of how management strategies perform over a wider range of future uncertainty, enables the relative comparison of strategies as uncertainty increases and also tracks different metrics to gauge performance in more than one aspect. An appreciation of how a system performs under increasing uncertainty is important as can be seen when comparing Plot 1 with Plots 2 through 7 in Figure 23. Plot 1 shows the supply demand balance over 25 years with the EBSD Current methodology. Uncertainty is included in this plot with headroom as an additional component of demand. Plots 2-7 show the performance of the system based on different metrics over increasingly demanding futures until the system fails. By coincidence, M5, the EBSD least-cost strategy is also one of the most robust portfolios as it performs as well or better than all of the other portfolios over increasing uncertainty. It's important to note that in Figure 21 and Figure 22, M5 performs 5th best and in Plot 1 of Figure 23, M5 is the most robust strategy because it performs without failure to the highest level of uncertainty, albeit at lower performance than four other strategies at lower uncertainties, M12, M11, M13 and M1 and two other strategies at higher uncertainties, M12 and M11. M5 becomes third place after a preference reversal with M1 at uncertainty level 13 and M13 at uncertainty level 15. Beyond these levels and at higher uncertainties M5 performs better. The EBSD Current method is not able to portray M5 as the most robust option, because the EBSD method is limited in its exploration of uncertainty.

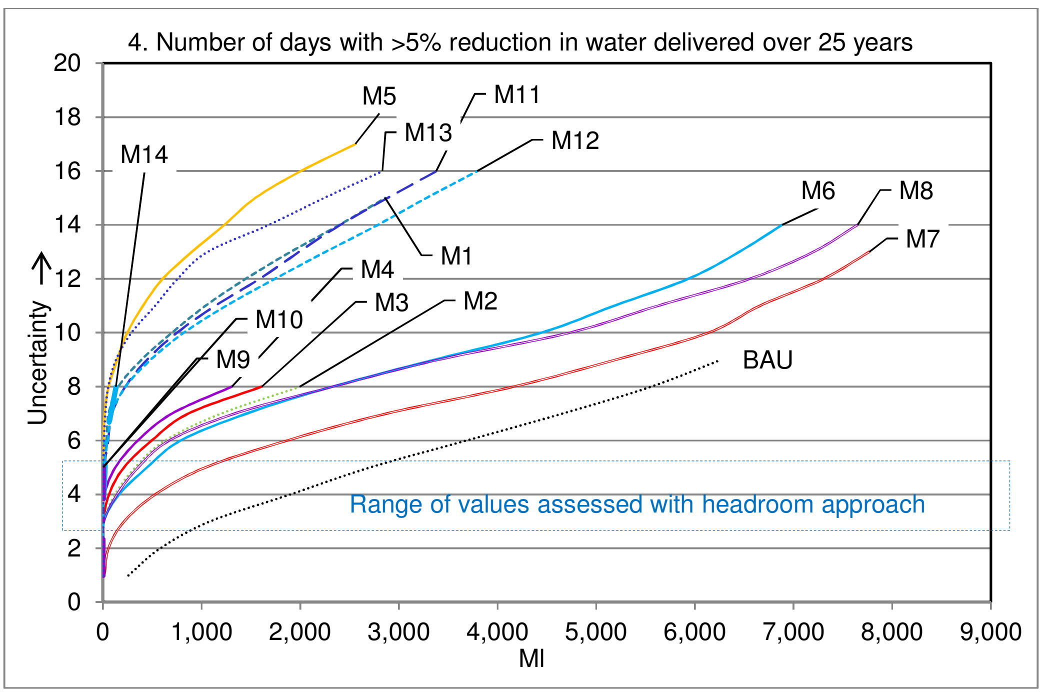


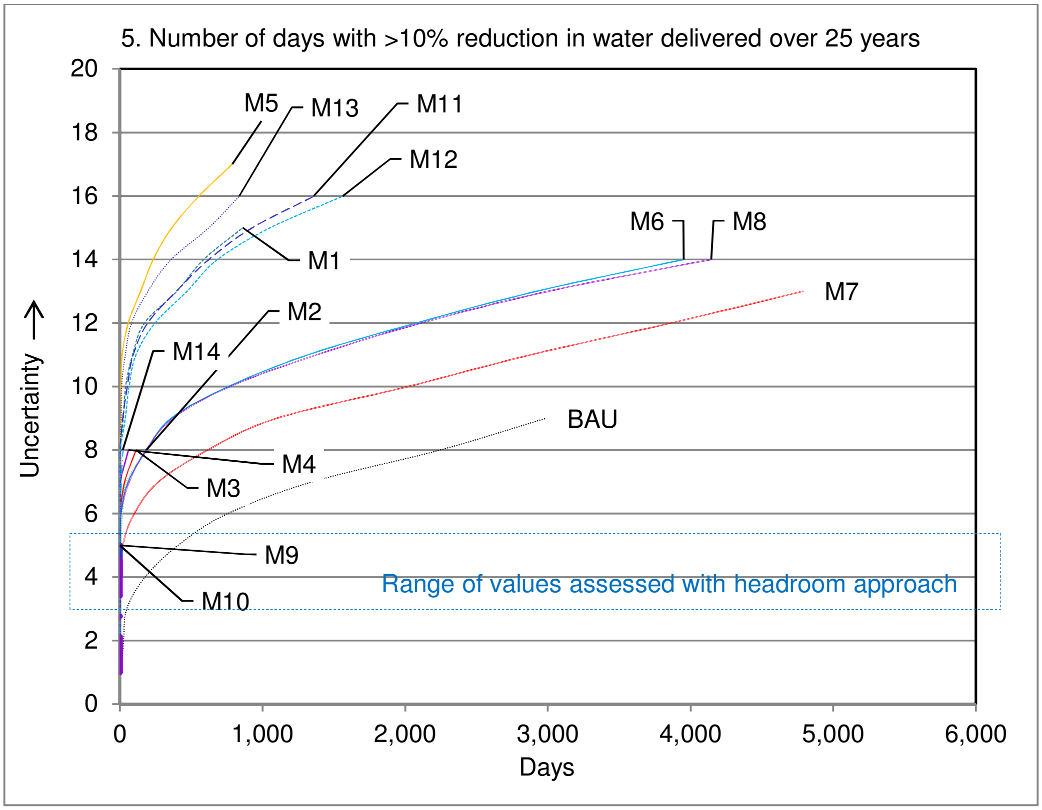
1. EBSD Supply Demand Balance
SDB (Ml/d)
Planning Horizon (Years)
M1
M11
M13
M12
M6
M5
M10
M9
M2
M14
M4
M3
M7
M8
BAU

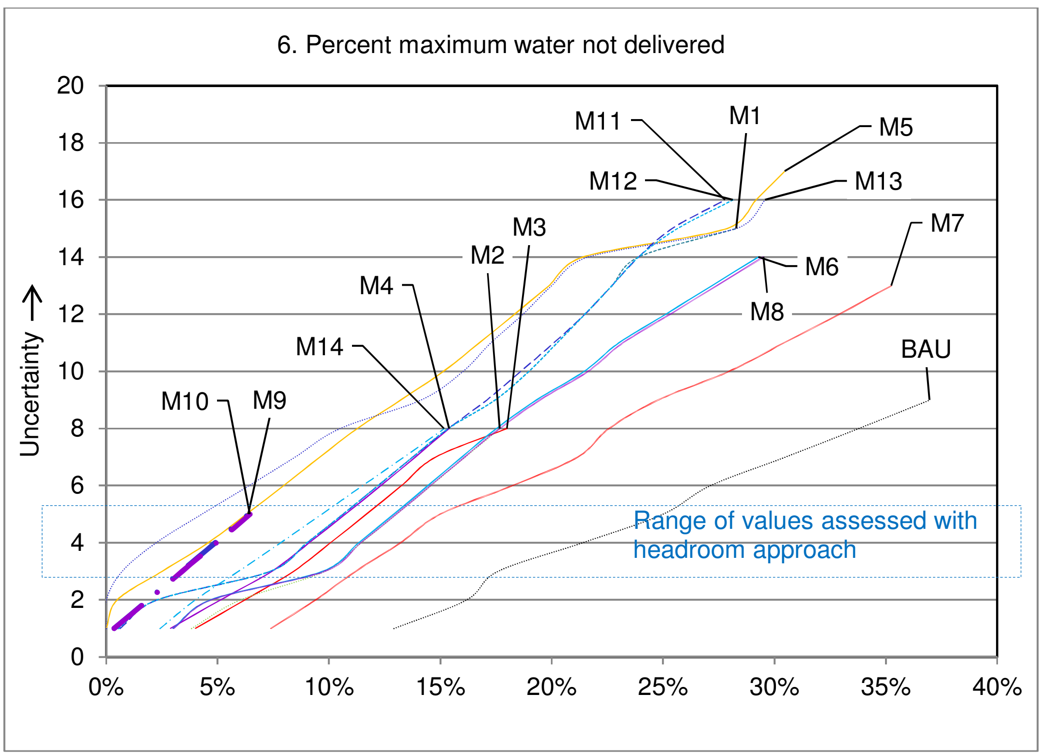


2. Drought Deficit over 25 years
Uncertainty
Ml
Millions
M11
M5
M13
M12
M1
M8
M6
M7
M4
M3
BAU
M2
M14
M10
M9
Range of values assessed with headroom approach


3. Total amount of water not delivered over 25 years
Uncertainty
Ml
Thousands
M5
M13
M11
M12
M1
M6
M8
M7
M14
M4
M3
M2
M10
M9
BAU
Range of values assessed with headroom approach
0
2
4
6
8
10
12
14
16
18
20
0
20
40
60
80
100
120
140
160
180


4. Number of days with >5% reduction in water delivered over 25 years
Uncertainty
Ml
M5
M11
M13
M12
M14
M1
M6
M8
M7
M4
M3
M2
M10
M9
BAU
Range of values assessed with headroom approach
0
2
4
6
8
10
12
14
16
18
20
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000


5. Number of days with >10% reduction in water delivered over 25 years
Uncertainty
Days
M5
M13
M11
M12
M1
M6
M8
M7
M2
M14
M4
M3
BAU
M9
M10
Range of values assessed with headroom approach
0
2
4
6
8
10
12
14
16
18
20
0
1,000
2,000
3,000
4,000
5,000
6,000


6. Percent maximum water not delivered
Uncertainty
M11
M1
M5
M12
M13
M3
M2
M6
M7
M4
M8
M14
BAU
M10
M9
Range of values assessed with headroom approach
0
2
4
6
8
10
12
14
16
18
20
0%
5%
10%
15%
20%
25%
30%
35%
40%

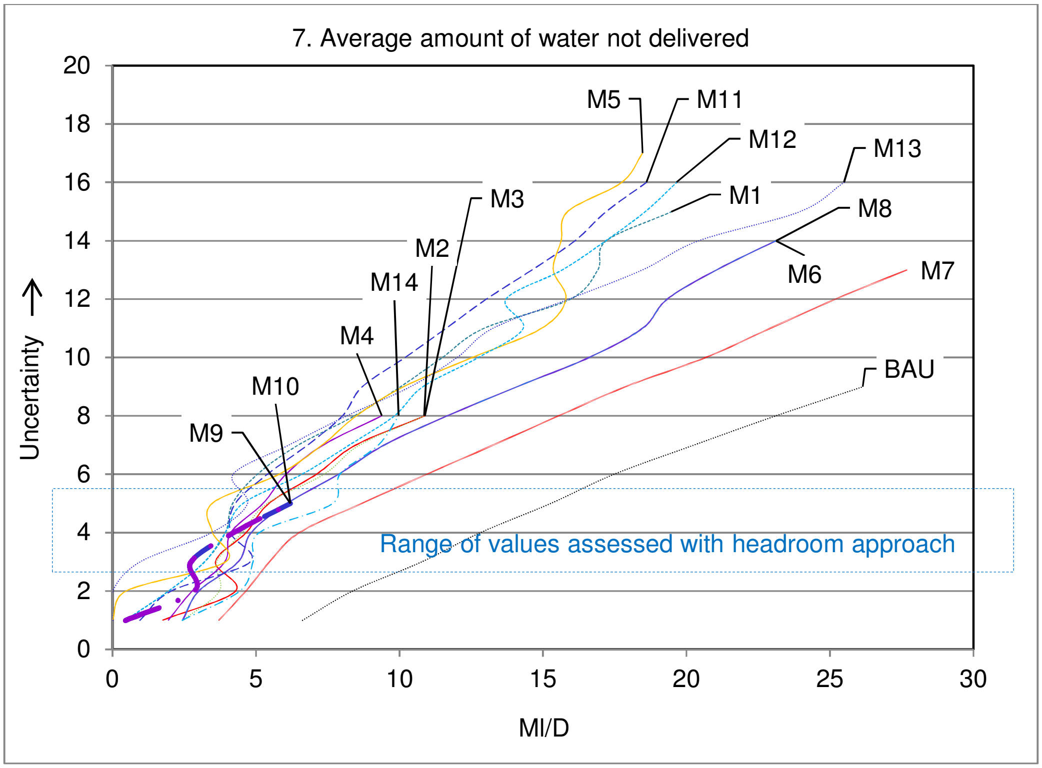


Figure 23. WRP-RA Performance metrics for the MATLAB SSA Model – Plots 1-7

There are four important aspects revealed in Plots 2-7 of Figure 23 when comparing the Drought Deficit (DD) with the other water scarcity metrics. The DD is based on the total amount of deficit below the drought management curves of all the reservoirs in the Colliford SSA. The DD is a comprehensive Risk Measure as it quantifies magnitude (including frequency and duration) of water scarcity events in terms of how they affect the water supply system. The DD is also an indicator of when a company would need to shift gears and consider drought planning measures and is therefore an indicator of significant importance. The other metrics are all related to demand and the ability to deliver water to a promised Level of Service. In essence, the DD is a signal of the overall water security of the Strategic Supply Area depending and the other metrics are indicators of how much reduction in service customers may endure. In the grand scheme of things, the water security of the SSA is the most important as it provides long term continuity of service regardless of periodic reductions.

1. Strategies M7 and M8 show an increased performance with the DD in comparison with M6 which most often performs the same or better than

M8 in all the other plots. Strategies M7 and M8 include innovative demand side measures (M7 – rainwater and greywater use in 25% of domestic properties and M8 – rainwater, greywater and efficiency in 33% of domestic properties). The extra demand side measures associated with M8 produces a marked improvement. The fact that both of these portfolios perform well with the DD metric indicates that DSM schemes help maintain reservoir levels.

2. Related to the benefit of these innovative DSM options, M3 and M4 (M3 – includes rainwater and greywater use in 25% of domestic properties and M4 – includes rainwater, greywater and efficiency in 33% of domestic properties) consistently perform better than M2 which includes efficiency measures in 50% of properties. The enhanced performance of innovative options reveals that there are marked benefits to using water differently instead of, or in addition to, using less of it.
3. Strategies M9, M10 and M14 show some strange behaviour. With the DD metric, all these portfolios perform worse than No Intervention, which is the current management strategy with no new options. With the other water scarcity metrics, all these strategies perform better than most of the other portfolios, but fail sooner than any of the others. This behaviour is related to the Gunnislake inflow option. This option provides a helpful supply of water to the SSA Network at lower uncertainties in a location and timing that lessens the need to rely on the Colliford Reservoir and the Restormel treatment works. At higher uncertainties however, the Gunnislake River does not provide enough flow to supply the water when needed. These management strategies were designed to use the Gunnislake inflow early in the planning horizon because with the headroom estimation method, they provided enough water; but when there is less or no water early in the planning horizon at higher uncertainties, this deficit early in the planning horizon initiates a snowball of negative effects, such that later in the planning horizon the strategy can no longer perform adequately. The reason that No Intervention performs better than these Gunnislake portfolios is that No Intervention consistently delivers less water than needed and therefore conserves water in the reservoirs. The Gunnislake portfolios satisfy water demands at further extremities of the SSA system in a way that the No Intervention

could not and at the same time, makes it possible to increase a drawdown of the Colliford reservoir to satisfy other demands close to the reservoir. This behaviour explains why the strategies that include the Gunnislake option initially show almost no reduction in service, but fail at higher levels of uncertainty. In this case the high Level of Service at the lowest levels of uncertainty comes at a price. The beneficial aspects of the Gunnislake inflow can be fully realised when combined with other options that balance its failings, as can be seen with M13 when it is combined with the Camel inflow.

4. Strategy M12 offers a reverse example of the behaviour of the Gunnislake strategies which performed the best in respect to water scarcity metrics and worst in respect to the DD metric. M12 performs best with the DD metric, in fact with this management strategy, there is never a reservoir that goes below the drought management curve before it fails. M12 performs, on average, 4th best with the other water scarcity metrics. This result again prompts the question which is more important; maintaining the overall water security of the SSA as indicated by strong performance with the DD or ensuring customers rarely go without water as indicated by strong performance with the other water scarcity measures? There is another interesting aspect of the system behaviour based on the DD metric when governed by strategy M12. With this strategy the system performed perfectly and then failed all of a sudden. With this situation there is little ability for advanced warning.

As described in Section 3.2.1 and Section 3.3.1, costs are accounted for differently in the EBSD Current and the WRP-RA method. The EBSD method includes costs only for new options based on a separate AISC methodology that calculates a unit volumetric rate for each option. The WRP-RA method includes the volumetric costs related to treating and distributing all water, whether these costs arise from new options or existing sources. The WRP-RA method also includes the Capex and Fopex costs associated with new options as annuities that start when an option is initiated and are charged each subsequent year with a discount factor applied. Capex and Fopex costs are broken down into the 3 categories of financial, environmental and social and carbon costs. The WRP-

RA costs were derived based on a consistent 60 year asset life to be comparable with the EBSD AISC derived costs.

As the WRP-RA method explores a wide range of futures, each with a different and increasing uncertainty, (compared with the EBSD method that explores one future with one characterisation of uncertainty via headroom estimation), and management strategies fail at different levels of uncertainty, the last iteration in which a strategy succeeds is chosen as the reference point for cost comparison. Figure 24 shows that with the WRP-RA method, the strategies dominated by the Gunnislake inflow are the least expensive and those dominated by the Camel inflow are the most expensive. The higher costs are partly due to the fact that these Camel inflow dominated strategies continue to perform at higher levels of uncertainty when there is increased demand; and therefore, are treating and distributing more water. Additionally, the timing of when an option is initiated is influential. With the WRP-RA costing method, M5 is no longer the least cost because the costs of treating and distributing the water within the existing network configuration are included in the cost evaluation, and they weren't included with the EBSD Current approach. With the WRP-RA method, M5 is close to the middle in terms of cost. The WRP-RA method shows that the introduction of a few new options can result in a less expensive delivery of water than No Intervention.

In terms of identifying a best-value strategy, the total number of uninterrupted days of service was chosen as the definitive metric for the WRP-RA method to replace the SDB at the end of the planning horizon as was used with the EBSD method. This service metric indicates not only a portfolio's ability to withstand increasing uncertainty for more and more demanding futures, it also conveys to what Level of Service this was possible. As shown in Figure 25, the performance of management strategies fall into a few main categories. Firstly, M5 is the most robust strategy (which is not indicated with the EBSD Current method). The next most robust set of strategies are those dominated by the Camel inflow, followed by those including innovative DSM schemes, followed by the No Intervention strategy and the more modest strategies that sought to merely address the supply/demand balance to the minimum standard and least-cost as required by EBSD. Finally, the least robust strategies are those dominated by the Gunnislake inflow. These results show that more significant investments need to be pursued to achieve a higher level of robustness.

In comparing these WRP-RA results with the EBSD method, there are 4 important points to note.

1. Most strikingly, the EBSD method shows M7 and M8 as having a negative SDB at the end of the planning horizon, whilst the WRP-RA method places these strategies in the middle range of robustness. This result shows that a dynamic appreciation of the effects of uncertainty in the context of network simulation offers more informative and sometimes unexpected results. These results may be hard to realise via the disjointed EBSD methods that combine four different static analysis techniques (DO, Level of Service, headroom and the scheduling methodology) to look at one version of the future and one version of uncertainty.
2. M5 is shown to be more robust than all other strategies with the WRP-RA method, as opposed to the EBSD method which identified M5 in the middle of the other strategies in terms of performance.
3. One similarity is that both the EBSD and the WRP-RA methods indicate the Camel inflow dominated options perform better.
4. With the EBSD Current method there is no easy way to compare the costs associated with future options with No Intervention; and as such, there is no easy way to identify the cases where a more robust system could be put in place at a cost savings.

The WRP-RA method shows a general trend in best-value strategies with higher cost related to more robustness as seen in Figure 26. This plot also conveys that similar robustness can be achieved for a wide variety of costs. In particular, M3 and M14 both achieve just below 80,000 days of uninterrupted service before system failure and M14 costs £10 Million less than M3. Similarly, M13 achieves a much more robust performance of just over 140,000 days of uninterrupted service with only a very small increase in cost compared with M14. Although M5 may be the most robust, M13 is the best-value as it is fairly close in robustness to M5 for much less expense.

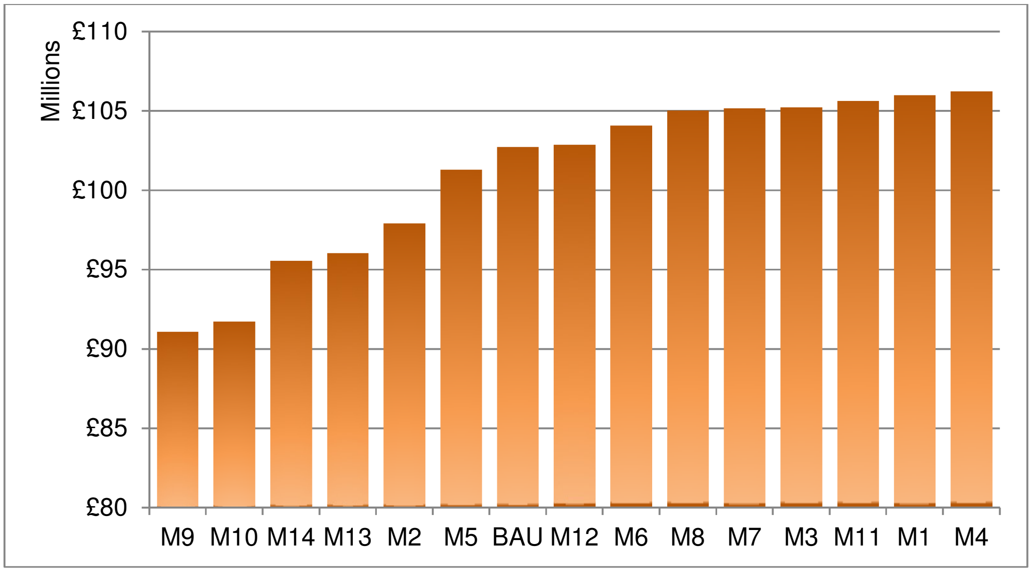


Figure 24. Total cost of portfolios based on the WRP-RA approach during the last successful implementation for a complete planning horizon

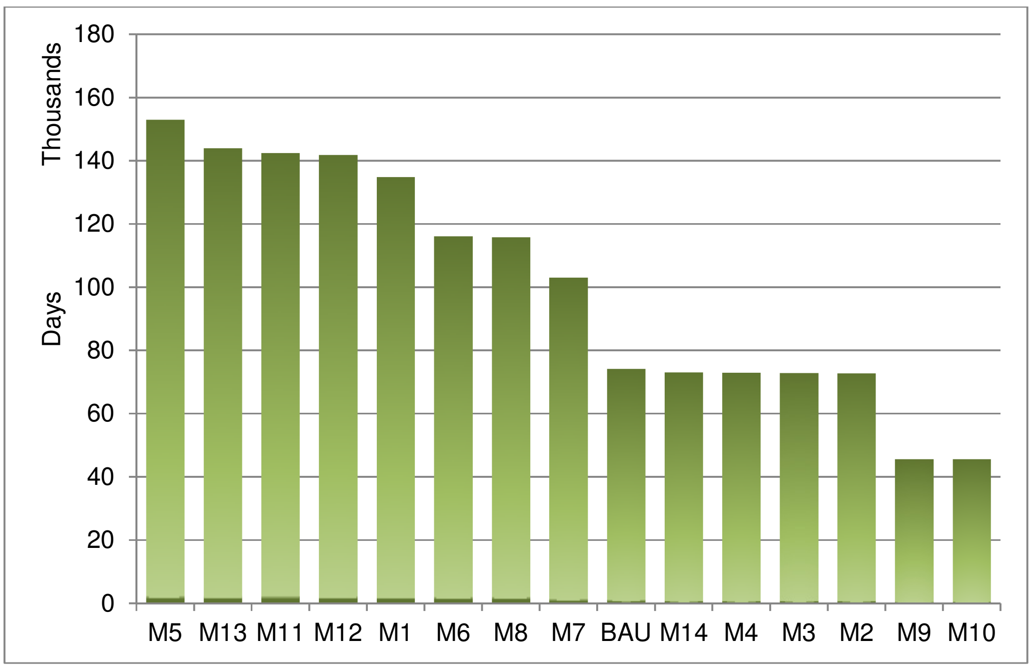


Figure 25. The number of days of uninterrupted service over all the future iterations of a planning horizon

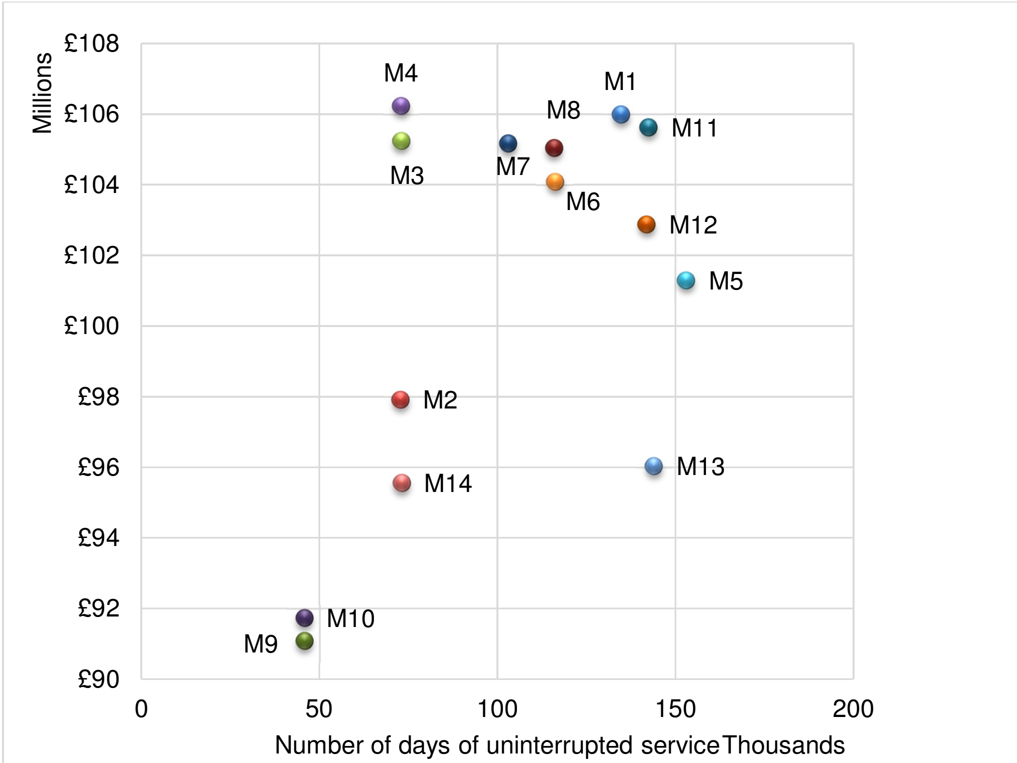
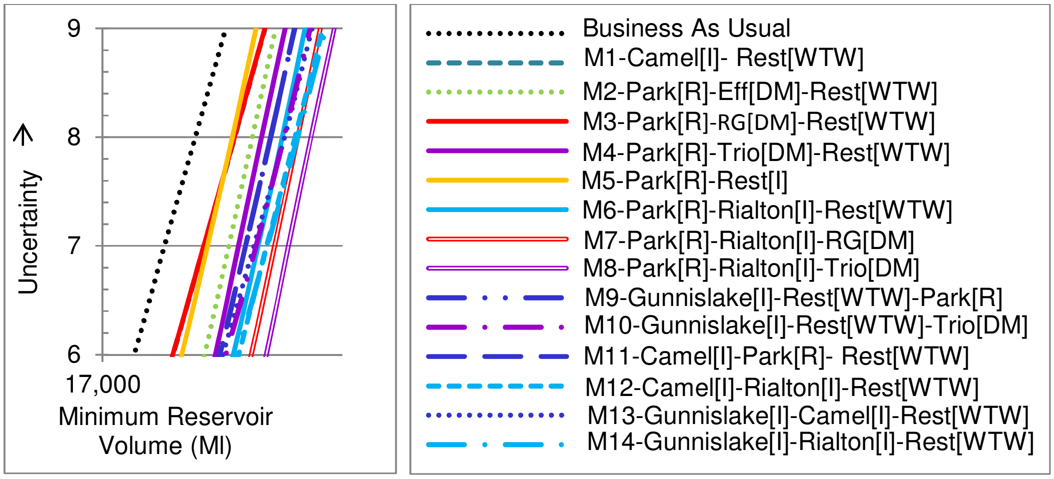


Figure 26. Best value portfolio based on number of days of uninterrupted service over all the future iterations of a planning horizon before system failure

The inclusion of opportuneness as part of IGDT method helps evaluate resilience because it provides an indication of how quickly a system can return to a less vulnerable operating state. The minimum level of the Colliford Reservoir was used for the opportuneness measure for this SSA because this reservoir is the significant backup source for the whole SSA and also a point of vulnerability as it can take 5 years or longer to recharge to its normal volume. Figure 27 portrays opportuneness in combination with robustness for the Colliford minimum reservoir level with relative robustness on the left and the relative opportuneness on the right. The more robust management strategies are those that retain the same or higher reservoir level at higher uncertainties. The more opportune strategies are those that recover to a higher reservoir volume at lower uncertainties.

Figure 27 shows that all strategies are more opportune than Business As Usual. M7 and M8, which include innovative DSM, are two of the most opportune portfolios as they quickly recover reservoir levels at lower levels of uncertainty. M10, M13 and M14 also show an enhanced trajectory towards reservoir recovery which indicates the benefit of the Gunnislake Inflow to ease reliance on the Colliford Reservoir and help it recover its operating levels, when river flows are beneficial.



Inset for Figure 27

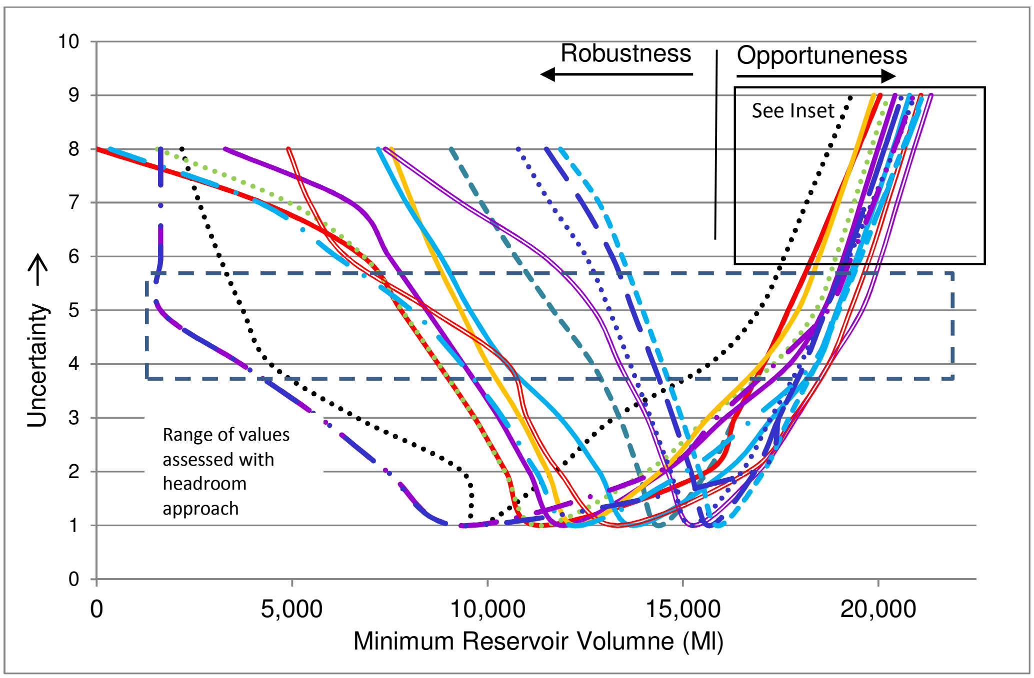


Figure 27. Opportuneness and robustness for Colliford minimum reservoir level

The three other metrics included in the WRP-RA method, Carbon, Cost and Social Acceptability, show little variation, (or none in the case of Social Acceptability), over the trend towards increasing uncertainty. The upwards trend in robustness curves for carbon (Figure 28) and cost (Figure 29) after iteration 10 can be attributed to less and less water being delivered as the water resources network is more and more challenged and has trouble providing a full Level of Service. The upwards motion in the Cost graph before iteration 10 that occurs with DSM-based strategies show the benefit of DSM, in particular because the model applies these DSM options over a percentage of the population such that associated demand reduction matches the pace of population increase. In this application DSM can lessen the impact of extremes.

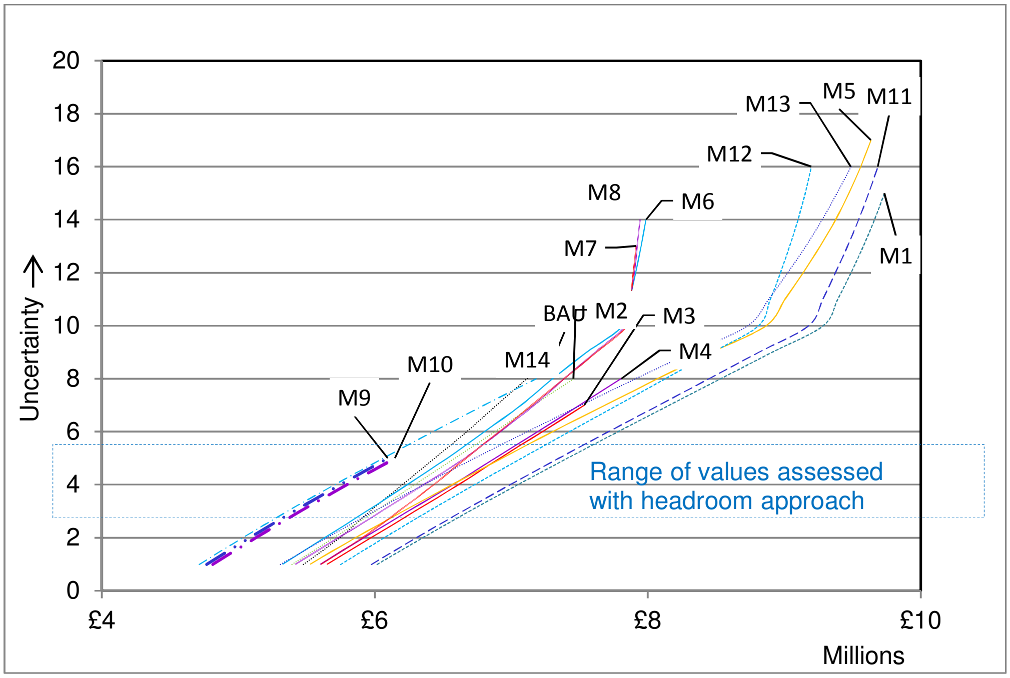


Figure 28. Carbon robustness curves for Colliford SSA management strategies

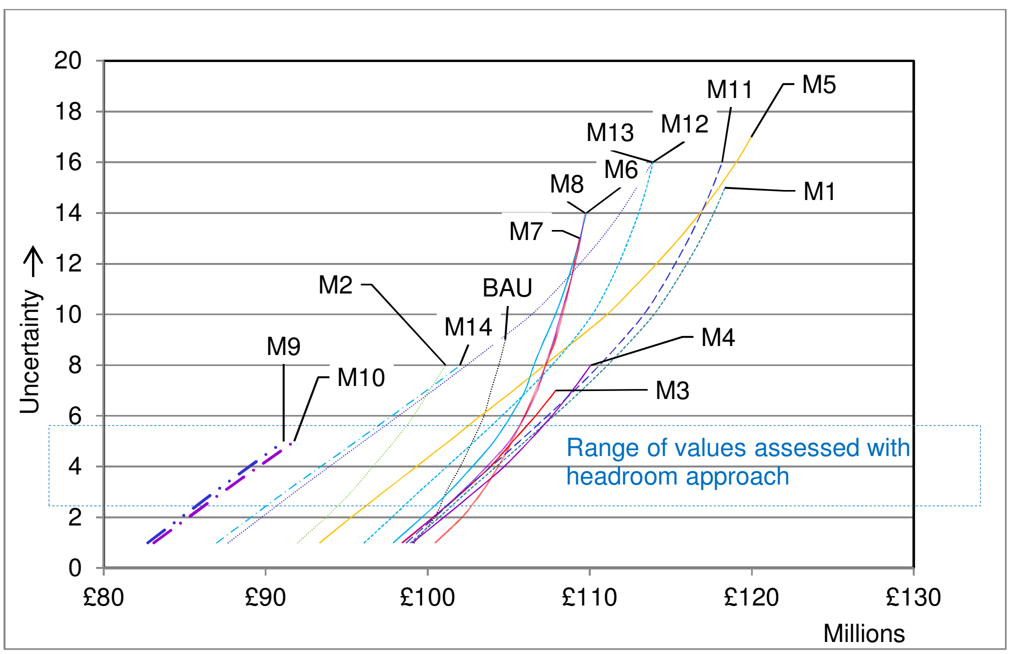


Figure 29. Cost robustness curves for Colliford SSA management strategies

As stated in Section 3.3.6, other factors, such as environmental aspects, carbon emissions and social acceptability (Figure 30) need to be considered when selecting the most appropriate management strategy. To accommodate a balanced understanding of a broader range of factors in the decision making process, a MCDA is included with the WRP-RA method.

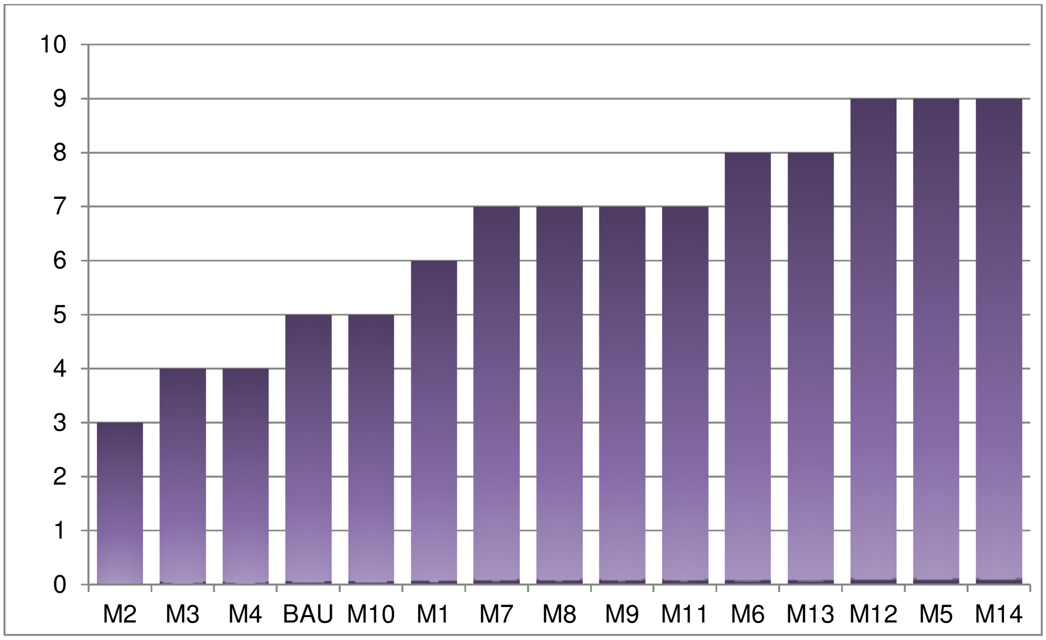


Figure 30. Relative social acceptability for Colliford SSA management strategies

The five criteria evaluated with MCDA for Case Study 2 are:

1. Risk of water shortage. Evaluated as a combination of robustness with the Drought Deficit (DD), opportuneness with the minimum reservoir level and a few other factors indicative of the ability of a management strategy to deliver a promised level of service including; the number of days service drops by 5% and 10% as well as average and total amounts of water not delivered.

2. Environmental impact. Based on the yearly minimum reservoir level. If the significant reservoir level is in jeopardy, the next two options a company has to source additional water is by invoking demand reductions and then applying for drought permits to take further water from the environment.

3. Cost. Based on the (1) operating costs to treat and move the water, (2) costs to implement new options.

4. Carbon footprint. Calculated from emissions in the generation of electricity related to the treatment and movement of water. The emission conversion factor is reduced over the chronological running of the model in a linear fashion to incorporate the national grid's

stated climate change goals to reduce grid emissions 45% by 2020 and 80% by 2050.

5. Social acceptability. To include social acceptability, each management option is assigned a value between 1 and 10, with 10 being least acceptable. Reservoir expansion is considered less acceptable (assigned a value of 8), additional river abstraction is more acceptable for some rivers with no identified fish habitat issues (assigned a value of 7), but for other rivers with fish habitat issues even less acceptable than reservoir expansion (assigned a value of 9). Efficiency options are considered more acceptable (assigned a value of 3), innovative options such as rainwater harvesting and greywater use are considered to be slightly less acceptable than efficiency as some effort is required (assigned a value of 4). The addition of efficiency and/or innovative demand management lessens the impact of reservoir expansion or river abstraction by a value of 1.

Table 15 shows the performance of different management strategies based on different weightings. The MCDA shows a consistent preference for 5 strategies with very little deviation in priority at higher uncertainties. The most striking result is that these strategies are not consistently represented as part of the top 5 priorities at lower uncertainties.

An overall rank is provided to indicate the comprehensive robustness of a management strategy. If a management strategy fails to rank in the top 10 for lower uncertainty, it is assigned a value of 11 and if it fails in terms of a system failure before reaching the level of higher uncertainty it is assigned a value of 21. The total is a sum of all the rankings for a strategy. The lower the score, the more robust the management strategy and the overall rank is assigned accordingly.

Table 15. Multi-Criteria Decision Analysis performance evaluation with different weightings for SSA Network

Management strategy	Equal weighting		Emphasis on Water Availability		Emphasis on Environment		Emphasis on Cost		Emphasis on Carbon		Emphasis on Social Acceptability		Total	Cumulative Rank
	Uncertainty													
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High		
BAU	11	21	11	21	11	21	11	21	11	21	5	21	186	14
M1	11	8	3	8	5	8	11	8	11	8	6	8	95	7
M2	11	21	11	21	4	21	5	21	5	21	1	9	151	9
M3	7	21	7	21	11	21	7	21	11	21	3	10	161	11
M4	6	21	6	21	11	21	11	21	9	21	2	21	171	13
M5	9	6	11	6	11	6	6	6	11	6	11	6	95	7
M6	10	1	10	1	8	1	9	1	11	1	11	1	65	3
M7	11	3	11	3	9	3	11	4	7	3	9	3	77	4
M8	8	2	9	2	6	2	10	3	6	2	7	2	59	2
M9	4	21	11	21	2	21	2	21	2	21	10	21	157	10
M10	1	21	1	21	1	21	1	21	1	21	4	21	135	8
M11	11	7	4	7	7	7	11	7	11	7	8	7	94	6
M12	11	5	5	5	11	5	8	5	11	5	11	5	87	5
M13	5	4	2	4	3	4	3	2	8	4	11	4	54	1
M14	3	21	11	21	10	21	4	21	3	21	11	21	168	12

M1-Camel[I]- Rest[WTW]	M6-Park[R]-Rialton[I]-Rest[WTW]	M11-Camel[I]-Park[R]- Rest[WTW]
M2-Park[R]-Eff[DM]-Rest[WTW]	M7-Park[R]-Rialton[I]-RG[DM]	M12-Camel[I]-Rialton[I]-Rest[WTW]
M3-Park[R]-RG[DM]-Rest[WTW]	M8-Park[R]-Rialton[I]-Trio[DM]	M13-Gunnislake[I]-Camel[I]-Rest[WTW]
M4-Park[R]-Trio[DM]-Rest[WTW]	M9-Gunnislake[I]-Rest[WTW]-Park[R]	M14-Gunnislake[I]-Rialton[I]-Rest[WTW]
M5-Park[R]-Rest[I]	M10-Gunnislake[I]-Rest[WTW]-Trio[DM]	

Looking back at the individual components of the MCDA, it's understandable that M13 ranks higher than M12 as it is much less expensive and more socially acceptable than M12 and performs at a similar level of robustness for all measures except the DD. It's also understandable that M6 ranks in between M8 and M7 as M6 performs better (but very close to M8) on carbon and cost and most other measures except for DD in which both M7 and M8 outperform M6. M8 also outperforms M6 with opportuneness. The fact that M8 outranks M7 also makes sense at it is more ambitious with demand management. However, it is less rationale that all of M6, M7, M8, M11, M12 and M13 all rank higher than M5 (tied at 7th with M1) which is the most robust in that it can perform for one more level of uncertainty than all others (albeit at a slightly lesser performance than M1, M11, M12 and M13). M5 outperforms all other strategies for most of the other water scarcity metrics. The main reason M5 ranks lower is due to social acceptability. The social acceptability is slanted this way because many companies find it difficult to convince the public to accept a scheme that has perceived environmental impacts. Thames Water continues to explore the benefits of Abingdon Reservoir, but local stakeholders hold firm in their stance to petition against this option, even though there are no regulatory issues with this scheme.

4.3.4 Summary

There are two points to cover in this summary; firstly to reflect on the application of the WRP-RA for Case Study 1, and secondly to review the different results from the EBSD Current and WRP-RA methods.

In comparison with Case Study 1:

- The advancement of the MATLAB simulation model shows good comparison with the MISER simulation model which confirms appropriate model construction and indicates successful calibration.
- There are similar message with innovative DSM schemes in both models in that extensive implementation is required to offer comparable water savings to other supply side schemes and there are significant benefits with broader implementation, one of which is the extra help these DSM measures offer when recovering from a drought situation as exemplified by the opportuneness curves.

- There are also similar messages with the MCDA approach in that weighting of performance criteria provides a transparent view of the relative performance of different management strategies in regards to these criteria.

In comparing the EBSD Current and WRP-RA method:

- The EBSD best-value plot is informative, but not conclusive as we still do not know how various management strategies perform at higher levels of uncertainty. The EBSD method presents us with a choice of 3 management strategies that offer a reasonable amount of surplus supply; M5 (3.3 Ml/d), M6 (5.4 Ml/d) and M11 (6.3 Ml/d), each with associated costs increasingly higher in a similar trajectory to their increasingly higher availability of surplus water. The costs for these strategies are in the middle of the spectrum, so choosing one of them would constitute additional investment above the least-cost solution. With the prospect of investing more for additional water security, it is hard to let go of wondering, how much better is M11 than M6 and in turn M6 than M5 over the long term? Answering this question requires a deeper understanding of performance. After implementing a best-value assessment with the WRP-RA, we know that M5 is actually the most robust and can provide an uninterrupted level of service for 32% more days than M6 up till the point of failure. M6 in turn offers uninterrupted service for 23% more days than M11. The additional insight of the best-value plot with WRP-RA indicates that a different preference in strategies should ensue when investing in robustness for the longer-term.
- The EBSD Current lack of insight into deeper uncertainties based on the limited headroom estimation method portrayed different results to the WRP-RA method. In particular:
    - The Gunnislake dominated options M9, M10 and M14, fail early with the WRP-RA, whereas they show no sign of deficit with the EBSD method.
    - The innovative DSM dominated options, M7 and M8, show a negative surplus with the EBSD method, but with the WRP-RA , prove to be fairly robust and rank 4th and 2^{nd,} respectively with MCDA.

    - M5 performed moderately well with the EBSD method and proved to be one of the most robust methods over many of the performance criteria. As stated previously, it received a median score due to its poor social acceptability as it involved additional abstraction in a river that supports sensitive fish habitat. In reality, the environmental assessments show no issues and no threats with additional abstraction, but the perception remains. This point reinforces the need for methods that test a systems robustness in order to provide information that helps sway negative public perception of larger schemes such as reservoirs, additional river abstraction or other new and innovative approaches such as water reuse. If the public comprehends the value of robustness it may help them approach these types of schemes from a more objective perspective.
- The WRP-RA method also introduces the concept of opportuneness (how a system behaves if uncertainty trends in a favourable direction; i.e. wider deviations from the expected future that increase the supply/demand balance) and provides a glimpse of which management strategies would help a system recover quicker than others. This concept is not included in the EBSD Current methodology.

4.3.5 Limitations

There are two significant limitations in the application of the WRP-RA for Case Study 2.

- Due to the nature of the Colliford Water Resource Zone and the use of EBSD Current method, only a small numbers of schemes were available to develop candidate management strategies in order to compare their relative robustness. The use of an optimisation selection method may have developed more and/or different management strategies. This small number of strategies was enough to show additional insight gained with the WRP-RA method as opposed to the EBSD Current approach. Also, the small number of management strategies is representative of the EBSD Current approach and therefore this Case Study offers a valid comparison with this method.

- The robustness of candidate management strategies was compared by incrementally increasing demand and decreasing supply at the same time. The relative performance of strategies could be different in response to a larger deviation in either demand or supply.

4.4 Case Study 3 - WRSE

The purpose of Case Study 3 was to test the ability of the WRP-RA to explore severe uncertainty in a different modelling context than Case Studies 1 and 2. The reason to apply the WRP-RA in this regional setting was to test Objective 3:

- Tailor the WRP-RA methodology for use with an optimisation model.

Achieving this objective requires a simplification of the technical approach to address the core aspects of exploring severe uncertainty. This application requires the framing of a comparable analytic space from which to understand the relative robustness of a variety of management strategies that were chosen as optimum portfolios for different supply, demand and planning scenarios.

4.4.1 Motivation

Case study 2 provides a direct comparison between the WRP-RA methodology and the EBSD Current approach with the AISC selection method, which is a valid approach for smaller water resource systems with a limited number of options and management strategy configurations to choose from. For Strategic Supply Areas that are larger, or for regional studies that include a much larger number of options and potential management strategy configurations, an LP/IP selection method is more appropriate.

The computational needs of robust optimisation are challenging due to the multiplicity of decision variables that are introduced when considering a wider range of uncertainty, and until the advent of evolutionary algorithms, the only way to achieve optimisation was to limit the number of decision variables with hard constraints (Mortazavi et al. 2012). The development of evolutionary algorithms has enabled the investigation of robust optimisation for multiple criteria (Deb 2001, Deb and Gupta 2006). The ability to use these evolutionary algorithms and conduct a robust optimisation evaluation of management strategies can be a complex endeavour and require specialist simulation programs and genetic algorithm orchestration (Matrosov et al. 2015).

The WRP-RA is proposed as a valid and informative method to evaluate the performance of different management strategies using the optimisation environment that already exists as part of the EBSD LP/IP selection method. The existing EBSD LP/IP selection method can be used to select candidate management strategies for a range of more demanding futures. Candidate strategies can also be devised based on other rationale such as testing the robustness of a certain collection of options or evaluating the performance of new operating procedures, or other reasons. These candidate strategies can then be tested with the WRP-RA to identify which strategy is more robust. In this sense the WRP-RA achieves similar performs results to an evolutionary algorithm approach as it samples performance over a range of uncertainty and generates multi-metrics with which to compare management strategy performance. As such, WRP-RA method offers a valid approach to compare the robustness of management strategies in the optimisation environment.

4.4.2 Introduction

During the process of regional EBSD modelling for Water Resources in the South East, there was much discussion by all members of the WRSE Group about what future scenarios to explore with the WRSE model (Padula et al 2013). The model, based on the EBSD Current methodology, produces one least-cost management strategy for each future scenario. During the modelling of draft company plans for PR14, many requests were put forward by water companies for particular scenarios above and beyond the ten base case scenarios that had been agreed upon by the Group. This trend to request new scenarios also included the Environment Agency sponsoring an additional set of ‘Drought Pilot Runs’ to see how the existing collection of options coped with more extreme drought events that result in a loss of Deployable Output for each Water Resource Zone (WRZ) and future options. Each new scenario run created a new management strategy that was the least-cost portfolio to address that future state: but with approximately 110 scenarios (including a set of 17 sensitivity analysis runs), it was difficult to come up with one regional strategy and equally difficult to know the relative merit of each of the resulting 110 management strategies.

This case study demonstrates that the WRP-RA offers a method to compare the relative robustness of management strategies chosen for different future settings. In order to achieve this comparison, the WRSE optimisation model is provided only the options that were chosen to serve the needs of the original scenario run and no other options from the feasible list. The optimisation model can now only choose when to initiate options and how much water to use from each option, instead of being able to also choose additional options. In a sense this approach is a precursor to an adaptive management strategy which would require having the foresight of which set of options is most robust and being prepared to implement the options, but only when necessary.

4.4.3 Description

The Water Resources in the South East (WRSE) Group (the Group) was convened to explore opportunities for existing and new water resources to be shared in the most efficient and effective way, whilst maintaining security of supply, protecting the environment and minimising costs to customers.

The core members of the WRSE group include six water companies that supply customers in the south east (namely Portsmouth Water, Sutton and East Surrey Water, South East Water, Southern Water, Thames Water and Affinity Water). Other organisations that also have input into the work of the Group include the Environment Agency, Ofwat, the Drinking Water Inspectorate (DWI), Department for Environment, Food and Rural Affairs (Defra) and the Consumer Council for Water.

The WRSE model is a regional least-cost options selection model built using the GAMS software by Prof. Julien Harou’s research group. It follows the EBSD Current methodology to solve the SDB for 34 water resources zones (WRZs) (Figure 31) managed by the WRSE Group. The model was intended to deliver results that underpin a regional water resources strategy which will contain a range of strategic options. Each water company provided information required by the model to represent their supply demand settings and feasible options.

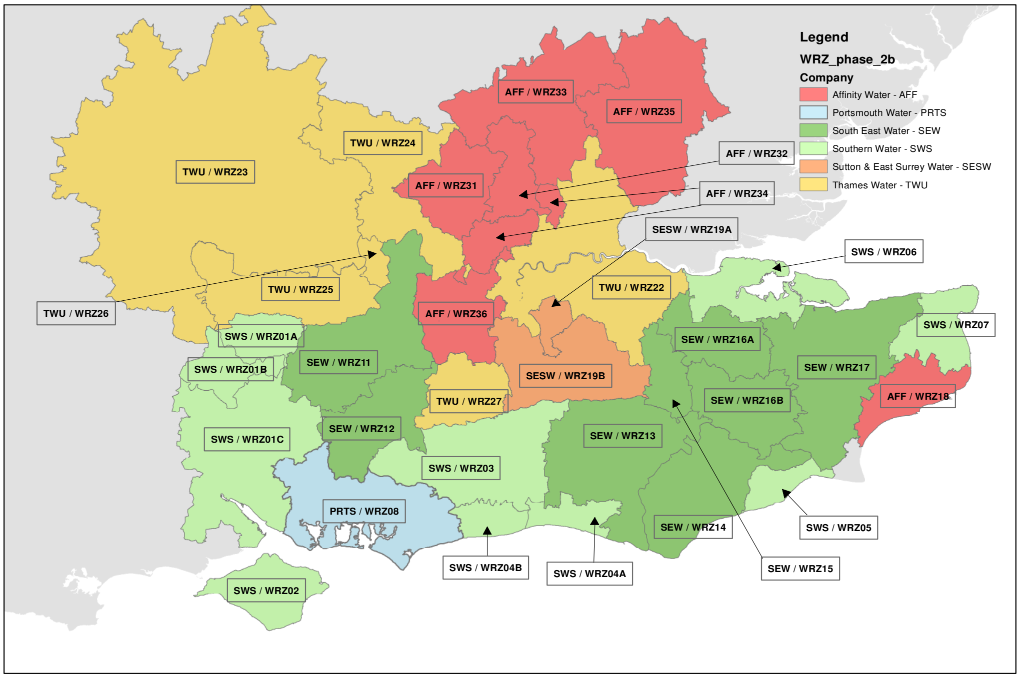
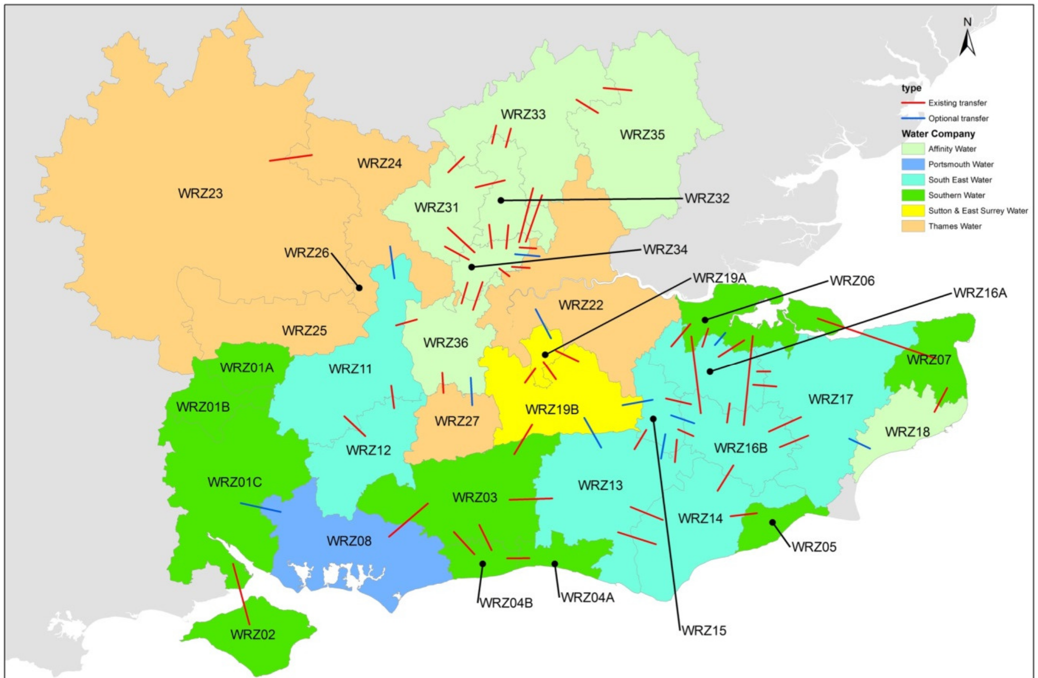


Figure 31. Map showing the location of Water resources Zones of the Water Resources in the South East Group

Design of the Strategic Regional Network (SRN)

The WRSE model is designed to consider the projected supply/demand settings for each of the 34 Water resources Zones surrounding and including London (Figure 32) and then optimise a set of new supply, transfer and demand management options to satisfy future supply/demand deficit. There is a central node in each zone that holds values for the existing supply (Deployable Output), demand (Distribution Input), associated Target Headroom, Losses, Outage and any Sustainability reductions. The regional model has a network structure. Currently 34 WRZs include supply and demand management options within their WRZ. 'Source-junction nodes' are used to represent supply schemes that can be shared between more than one WRZ. Transfers are constructed as links between WRZs and source-junction-nodes.



Schematic representation of the existing and optional transfers selected during entire planning period (2015-2040)

Figure 32. Map of the WRSE region including some existing transfers between zones

The WRSE model is an optimisation model which is solved in two steps with each step occurring once every year. The first step is to ensure that demand at each WRZ, for each year throughout the planning horizon, can be adequately met by existing supply and transfers and future demand management, source and transfer options. The second step of the model is to activate options and allocate water to meet those demands at the least capital and operational costs.

During the first step, if demand cannot be fully met in some years, then demand reductions will be initiated in order to make the mathematical problem feasible. After demand reductions have been implemented until there is no deficit, the model will proceed to step 2 and satisfy the deficit in each zone by selecting the least-cost supply of water from the options available.

Constraints within the model

The model has been developed and formulated to include a number of constraints, summarised as follows:

- The Mass Balance Constraint ensures a balance of supply and demand at all points of the system for all time steps.

- Capacity Constraints ensure that water derived from all options is less than the maximum offered.
- Ratchet constraints can be used to ensure that once an option is selected its use is continued at the same or higher amount.
- Start date constraints ensure that no option can be utilised before it is available.
- Mutually exclusive constraints allow a choice of only one options from a set of options.
- Mutually dependent constraints ensure that if additional options are required to implement an option, they will also be selected when the dependent option is selected.
- Continuity or ‘irreversibility’ constraints maintain the activation of an option.
- Prerequisite constraints with the AND condition ensure that if a larger scheme requires some a sequence of options to be implemented, they are implemented in the correct sequence. The OR condition enables a choice of options for any step in the sequence. The lag time condition enables a delay in implementation of any one option in the sequence.

Water resources management options

The WRSE model explores the implementation of a variety of option types as listed in Table 16. Particular scenarios that have been used to test the WRP-RA method for the region are listed in Table 17 with an explanation of why in the last column titled ‘Reason for inclusion’.

Table 16. Options available in the WRSE model

Option category	Option type	Description
Demand management	• Leakage reduction • Water efficiency • Metering	Demand management options have user-defined annual water saving profiles which start from their first year of selection by the model. The selected start year may be set to be a fixed year, which is always the earliest start year for metering options, or may be a flexible start year, which is selected by the model to be after the input earliest start year.
Network improvements	• Water Treatment Works • Network Improvements	Network improvement options increase the capacity of the network and free up previously unavailable water.
Source (supply)	• Reservoir • New Surface Water • Existing Surface Water • New Groundwater • Existing Groundwater • Conjunctive Use Schemes • Effluent Reuse • Aquifer Storage and Recovery	Source options include extra capacity available from additional exploitation of existing source options and new capacity from new scheme development.
Transfer	• Existing transfers • Intra-company transfers • Inter-company transfers • Transfers in from outside the region	Transfer options increase the interconnectivity of the region and can bring additional water into the region from other external sources.

Table 17. Scenario runs conducted with the WRSE EBSD model

WRSE Scenario ID	Scenario description	Reason for inclusion
A (A - Ph2)	Base case	Base for comparison
B2	Scenario A + Linear *increase* of DI by 1% in 2015 to 2.5% increase at the end of planning period.	Option set chosen to meet challenge of increased demand.
B3	Scenario A + Linear decrease in DO (baseline DO - baseline SR) by 1% in 2015 to 10% reduction at the end of planning period.	Option set chosen to meet challenge of decreased supply.
B4	Scenario A + Further Sustainability Reductions set on a zone by zone basis.	Option set chosen to meet second challenge of decreased supply related to SR specifics
G2	Ratchet constraints 'off' for future transfers.	To test if ratchet constraints limit ability for system to respond. (requires model setting change)
I1	Bough Beech WTW upgrade forced *with* Havant Thicket reservoir forced at their earliest start dates.	To understand any benefit of early introduction.
I4	Restrict amount of Reuse selected to TWUL (Limit re-use options to TWUL), with forced strategic transfer into TWUL.	Explore value of transfer vs. reservoir (requires forcing for a certain date)
I5	Restrict amount of Reuse selected to TWUL (Limit re-use options to TWUL), with forced UTR instead of forced strategic transfer.	Explore value of reservoir vs. transfer (requires forcing for a certain date)
J1	Set sustainability reductions to PR09 levels.	Can an option set chosen for less demanding SR values succeed?
J4	No new transfers; but allow model to still select existing transfers as options when optimal	Test longevity of success without new transfers.
J5	Delay all effluent reuse to 2025.	Does later initiation of effluent reuse prohibit more robustness?
J8	Full metering across region, applying uniform date for completion and a consistent set of assumptions across companies.	Does full and consistent metering offer a better chance for robustness?

WRSE Scenario ID	Scenario description	Reason for inclusion
J9	Proxy for resilience: using the DO reduction scenario, include reduced costs for identified resilient options.	Does resilience cost in option selection make a large difference?
K1	Non RO (Reverse Osmosis) options de-activated.	Yes, as requested by Steve Tuck to see impact.
K5	No EXDO costs assigned.	Does the inclusion of ExDO costs make a significant difference to option selection?
K13	Further Affinity changes to DO, THR and inclusion/exclusion of specific options	Considered final most accurate version of the network and options.
K14	Altered asset life for desalination options	Does the potential for lower annuities and as such more desalination plants produce a more robust option set?
Phase 3 Run1	All feasible options from draft WRMPs	To explore benefit of feasible options part of final draft plans.
Phase 3 Run2a (A - Ph3)	Only the preferred options with their preferred start dates as the earliest start date	To explore performance with only the preferred options
Phase 3 Run2b	All feasible options with the preferred options assigned their preferred start dates as the earliest start date	Compare the difference of performance with preferred start dates.
Phase 3 Run2a RMS	Phase 3 Run 2a with new alignment to explore a reconfiguration of the River Medway Scheme	Evaluate the benefit of a new alignment for the River Medway Scheme.
s7	Adjustments to supply to signify a 1:200 year return period drought event	Investigate the robustness of an option portfolio chosen for a 1:200 year return period.
s8	Adjustments to supply to signify a 1:500 year return period drought event	Investigate the robustness of an option portfolio chosen for a 1:500 year return period.

Application of the WRP-RA

The mechanics of applying the WRP-RA is a deeper investigation of uncertainty similar in intent to two scenarios already investigated by the WRSE Group. Scenario B2 explores a future of increasing demand and scenario B3 explores a future of decreasing supply. These two factors of the supply/demand equation were not explored in combination (which is exactly the intent of IGDT) during any of the WRSE scenarios.

Following the intent of EBSD Advanced and Blue Sky approaches (UKWIR 2002) to address uncertainty in other ways than headroom, an application of the WRP-RA for this strategic regional network removed headroom values as a parameter and instead applied:

- A linear increase in DI of scenario B2 by 2.5% increments at the end of the planning horizon and 0.5% at the beginning so the final run will be an increase trending from 5% to 25%, and
- A linear decrease in DO of scenario B3 by 5% increments at the end of the planning horizon and 0.5% at the beginning so the final run will be a decrease trending from 5% to 50%

In these WRP-RA model runs, the WRSE model is provided with the final set of options selected by the model to satisfy the SDB of the original scenario run. By testing each management strategy against the same set of increasingly challenging supply/demand settings, it is possible to compare the relative robustness of each management strategy based on its performance in regards to cost and demand reduction.

The goal of Case Study 3 is to test the ability of a portfolio of options to respond to future extreme conditions of which it is unknown when they will occur and as such it is also unknown when each option would be needed. This mirrors the experience of water companies in that they are fairly certain what they need to invest in for the next 5 years, somewhat certain about the next 10 and less certain beyond 10 years (WRSE 2015). This is why water companies want to work towards a Real Options type of approach so they can plan potential pathways for investment and figure out when to introduce certain options or option types.

This variance in timing and extent of use offers a view of overall robustness and performance of a collection of options. The indication of when different options are selected after their earliest start date helps a company know when they need to be prepared to use an option.

In the iterative implementation of the WRP-RA, supply was reduced and demand increased until the model became infeasible. The amount of demand reduction forced by the model acts as an associated measure of performance to indicate total demand reduction as a regional metric, maximum demand reduction in any one zone to indicate the extent of localised imbalances and average demand reduction overall all zones as a measure of general performance across the region.

Overall, the portfolios of options which defined a management strategy performed relative well in that there were not overly frequent infeasible models. All portfolios failed at the same level of supply/demand imbalance, although they performed and costed differently along this path. The performance in terms of required demand reduction and relative cost offers the ability to distinguish which portfolio could be the best value.

4.4.4 Results and discussion

The objectives of this case study are to demonstrate; firstly, a method to use the WRP-RA with an optimisation model and secondly, the additional insight the WRP-RA method provides over and above the EBSD Current method. The WRSE modelling presents a unique situation of multiple management strategies all responding to a different future. A similar situation will likely occur again, as water companies in England and Wales evaluate their resilience to different risks and uncertainties. As experienced with the WRSE project, once there are multiple management strategies available, there can be confusion as to the relative merit of each strategy. The WRP-RA offers the ability to compare the relative robustness of each strategy.

Figure 33 shows the cost for each management strategy derived with the WRSE model to achieve the SDB for each specific scenario settings. The strategies shaded in light amber were not carried forward for a full analysis as they did not perform as robustly as the those shaded in dark amber. It is important to note that at this stage, with a wide range of costs, the cost to achieve a positive SDB did not necessarily dictate the robustness of that strategy. Mangement strategies for B2, B3, B4, s7 and s8 are the only strategies that are derived from scenario settings that characterise a more challenging future. All the other strategies were selected for a future similar to the Base Case and their differences were based predominantly on different model configurations to favour a few options as opposed to other options, or other differences in the implementation of options such as the removal of ratchet constraints on transfers as was the situation explored for sceario G2 . In fact, the strategies selected as part of Phase 3 modelling denoted with a '-Ph3' were selected to meet the needs of a less extreme future than any of the other scenarios, except for the aforementioned B2, B3, B4, s7 and s8.

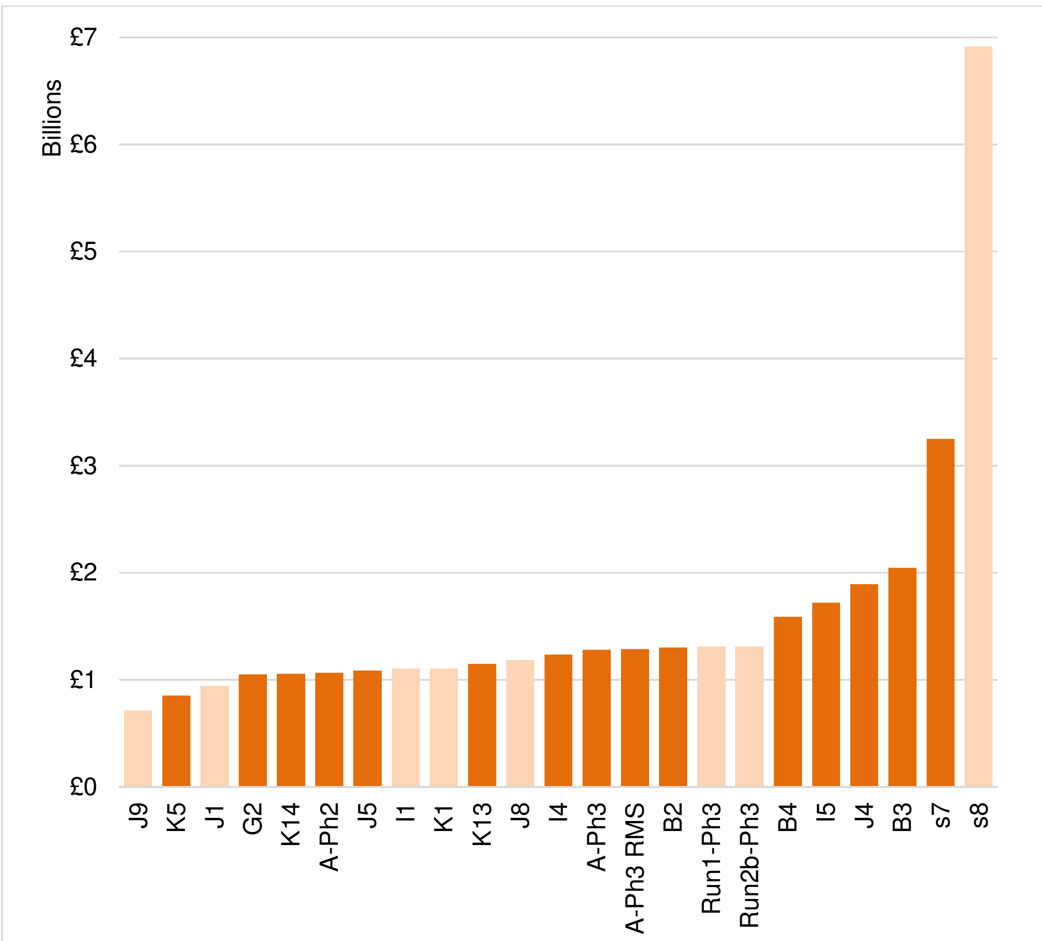


Figure 33. Total cost for each portfolio based on EBSD Current LP/IP optimised results

The fact that different portfolios can achieve a satisfactory SDB for approximately the same cost confirms suspicions within the WRSE group of the ‘shallow-bowl’ effect. This effect is the result of a large number of options that have relatively the same cost and when combined in different ways can satisfy the SDB within relatively the same total cost. This effect has been noted in other investigations of the EBSD Modelling (Padula and Harou, 2014), and offers further motivation to explore the relative robustness of management strategies so that a more definitive differentiation can be made to inform investment choice.

The application of the WRP-RA method to this set of strategies offers a more informative perspective on their relative merit. Figure 34 shows a wide range of results in terms of the percent maximum demand reduction necessary to get remedy the supply/demand deficit over increasing uncertainty. This plot also shows some performance changes past the range of uncertainty assessed with headroom as highlighted by the dashed blue line box. There are two strategies that are clear leaders; B3 – with scenario settings based on a linear decrease in supply to 10% reduction at the end of planning period, and s7 – one of the resilience runs with scenario settings to replicate a drought with a 1:200 return period. B4 – with scenario settings that include increased sustainability reductions is the third most robust for this metric. All the other strategies group together at the higher levels of uncertainty and show a wider range of performance just below and within the headroom range of uncertainty. A – Ph3 and A – Ph3 RMS show increasingly better performance towards the upper ranges of uncertainty. These results are fortunate as these Ph3 runs represent two variations of the company final plans; and when compared with the draft plans (A – Ph2 shown as a dotted black line), they indicate a more robust final strategy. The unique behaviour of s8 can be explained by the fact that scenario settings for this ‘Drought Pilot Run’ included additional demand reductions to replicate enforced water restrictions for a 1:500 drought event. As such, the portfolio of options for s8 is at a disadvantage at lower uncertainties when it relies upon the additional demand reductions (that aren’t present in the runs for this case study). At higher uncertainties when other management strategies are attempting to cope with extensive demand reductions, it performs fairly well because it has a larger collection of options to choose from. The management strategy for s8 was compiled by the optimisation model in extreme situations of water scarcity in both the baseline DO settings and the options available, and because of this pervasive scarcity, the optimisation model needed to select a larger number of options than normal.

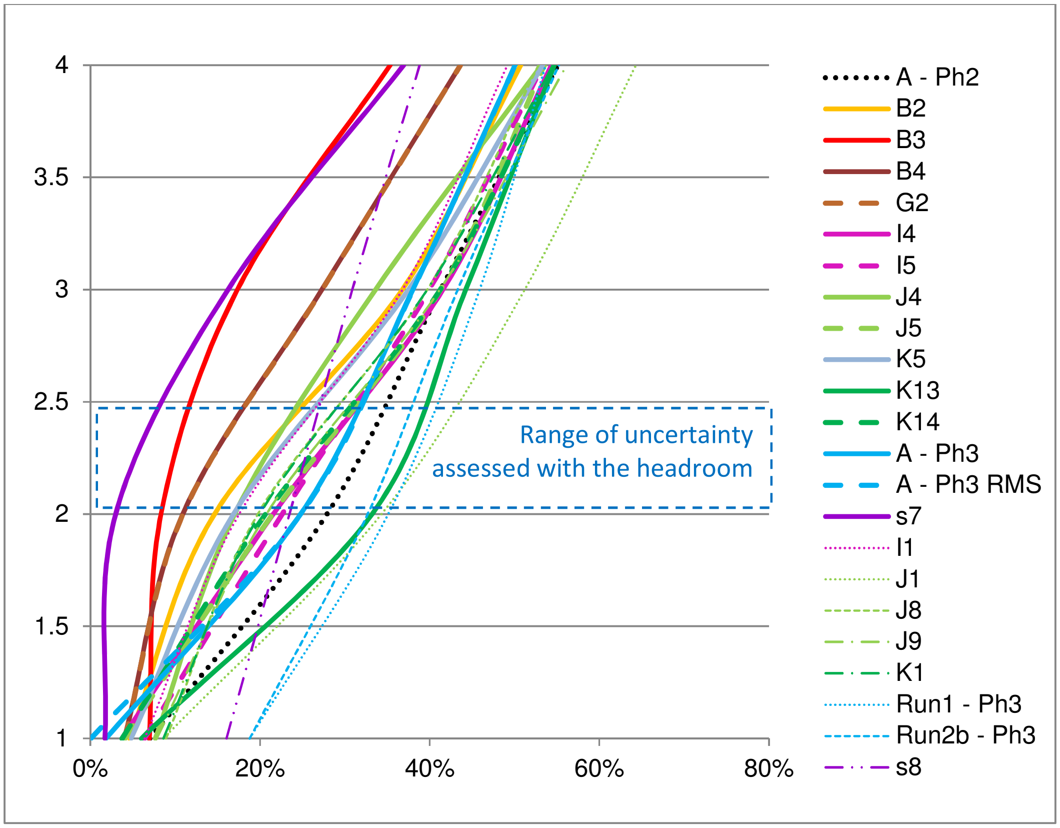


Figure 34. Percent maximum demand reduction for all WRSE runs

The best performing of the management strategies, those with thicker lines in were brought forward for additional analysis and evaluation, with results displayed in Figure 35. I1 performs better than I4 and I5 in terms of percent maximum demand reduction and equally well in terms of percent average reduction and cost, but it does not perform as well when looking at total demand reduction so was not carried forward for further analysis. After discussions with the Portsmouth water company representatives who are promoting the Havant Thicket reservoir that is a major component of I1, it would be worthwhile to consider including this strategy as one of the robust candidates in future analyses. This conversation happened after final results were generated, so I1 is not included in further analysis for this case study.

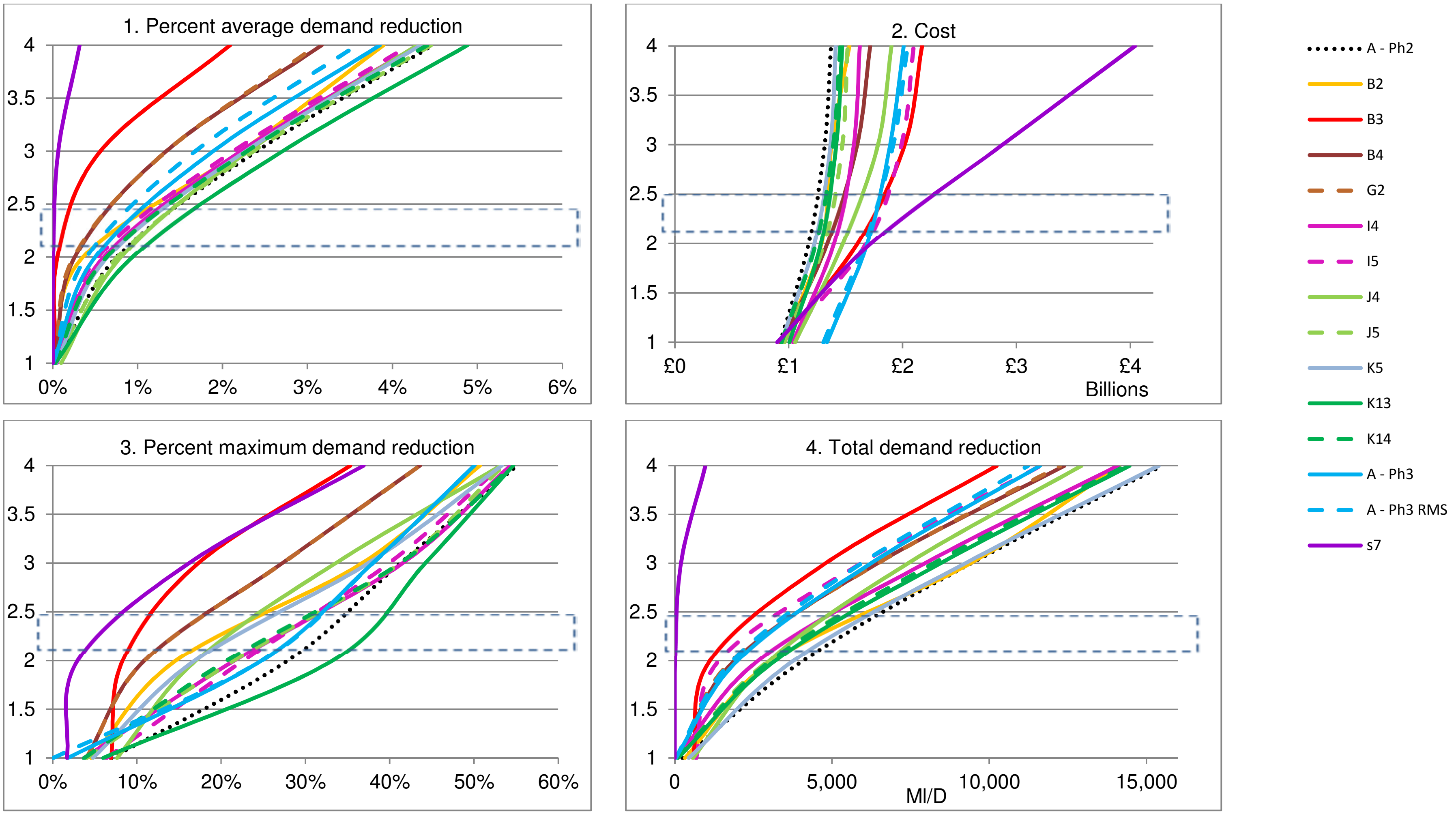


Figure 35. IGDT Performance metrics for the WRSE model – Plots 1-4

There are four important aspects revealed in Plots 1-4 of Figure 35.

1. You get what you pay for – most often, but not always. Strategies s7 and B3 perform consistently the best in that respective order, except for percent maximum demand reduction (Plot 3), where B3 outperforms at the highest level of uncertainty. These two strategies also cost the most in the same order as their relative performance. S7 costs much more at higher levels of uncertainty. The next best performing strategies are B4 and G2, which perform equally well for all metrics and the two A-Ph3 strategies which perform similar, with the RMS variation performing better with respect to percent average demand reduction and total demand reduction (Plots 1 and 4). I5 performs to the same level as the two A-Ph3 strategies when total demand reduction is concerned, but worse in the other water scarcity metrics and it costs more than either of the two A-Ph3 strategies. B4 and G2 perform better than the two A-Ph3 strategies in both percent average and maximum demand reduction (Plots 1 and 3) and just slightly worse in total demand reduction (Plot 4), and these two cost significantly less than the two A-Ph3 strategies. In the case of B4 and G2, you can get more and pay less.
2. There is a significant performance reversal that could initiate a preference reversal in Plot 3. In an assessment of the performance of portfolios in the range of uncertainty used for headroom, the two A-Ph3 scenarios are not preferable as they perform 3rd to last at this stage of uncertainty. However, looking towards higher uncertainties, these two scenarios perform 5th best and this shift in ranks does make these portfolios much more preferable. This reversal indicates the value of evaluating strategy performance at increasing levels of uncertainty.
3. The robust performance of B3, B4 and s7 is understandable as these strategies were selected to address more extreme scenario settings. The scenario settings that motivated these strategies can be summed up respectively as; steadily decreasing supply over all WRZs (B3), decreasing supply in those zones with Sustainability Reductions (B4), and a 1:200 year drought event (s7).
4. The success of G2, which is tied for 3rd place, is interesting in that the only significant difference of this management strategy is that the ratchet constraint

is turned off for all future transfers such that the model can start and stop transfers at will instead of maintaining an existing transfer and only being able to increase its use in the future. This result extolls the value of flexibility and preparedness. The ability to turn transfers on and off when needed is an efficient use of resources and having transfers available to use when needed provides additional robustness.

5. Perhaps the most time relevant result from these plots is gathered from the performance of the two A-Ph3 strategies, in particular when viewing their cost in relation to the other portfolios at lower and higher uncertainties. In an era when water resources planning is shifting from least-cost to best-value, these strategies are signature selling points. They are by far the most expensive portfolios at lower uncertainties, but prove to be of greater value (in terms of performance over all uncertainties) than many of the other strategies. These two management strategies also end up being less expensive than a few of the high performing portfolios at the higher ranges of uncertainty.

Keeping in mind the new emphasis in water resources planning in England and Wales for best-value strategies (UKWIR 2012) and in order to emulate the best-value plots developed in Case Study 2, best-value plots were also generated for these WRSE management strategies. The building blocks for a best-value perspective include the total cost incurred before system failure (Figure 36) and two views of performance; percent maximum demand reduction to indicate the maximum reduction required for any one zone (Figure 37) and total demand reduction to indicate the overall reduction required for the region (Figure 38). In these charts, at the higher levels of uncertainty a regular set of strategies vies for best performance. **Error! Reference source not found.** shows a rank preference for these strategies for two different metrics; total demand reduction and percent maximum demand reduction.

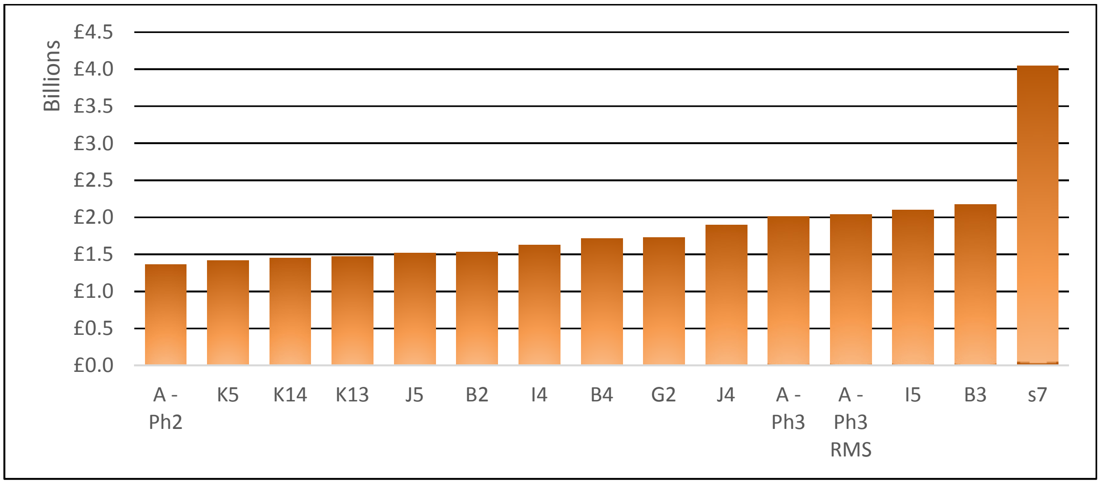


Figure 36. Total cost of portfolios based on IGDT approach during the last successful implementation for a complete planning horizon

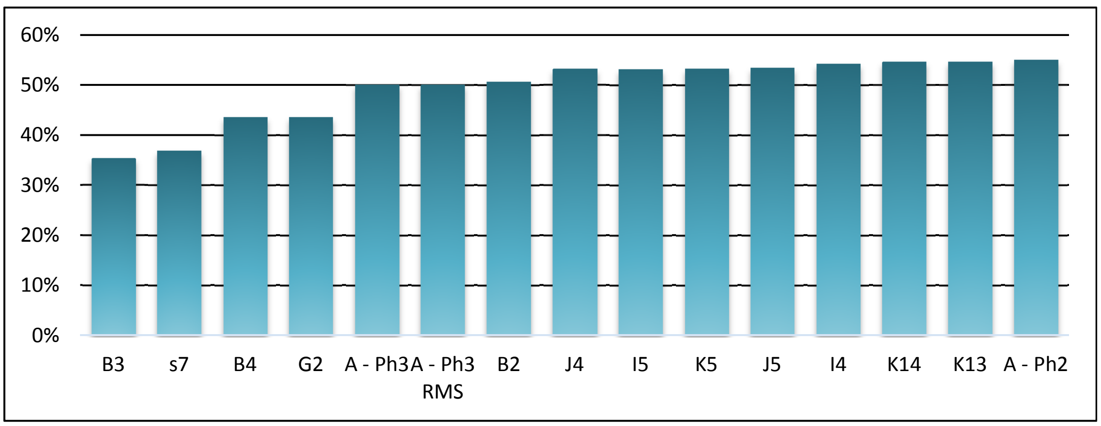


Figure 37. Percent maximum demand reduction of portfolios during the last successful implementation of a complete planning horizon

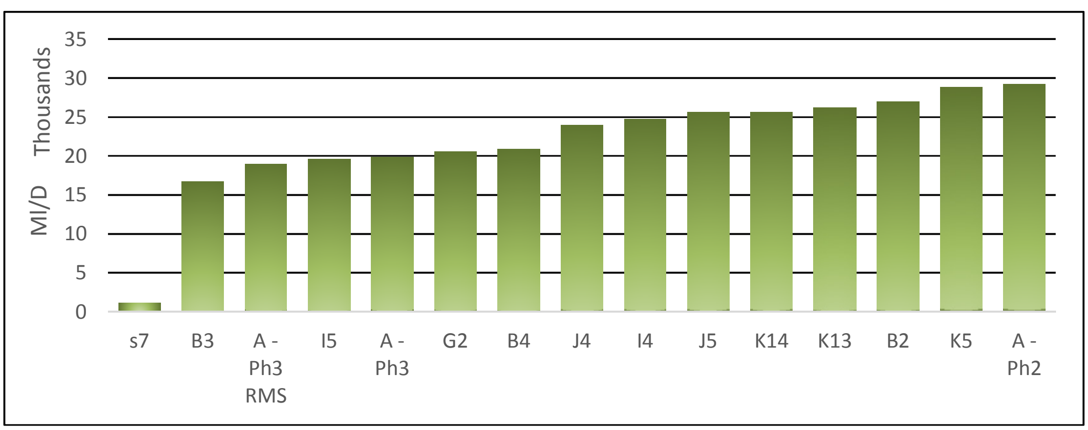


Figure 38. Total demand reduction of portfolios during the last successful implementation of a complete planning horizon

A more comprehensive and informative view of portfolio performance is shown in the best-value plots, Figure 39 and Figure 40. In each plot, there are 3 distinct groupings in terms of robust performance as listed in Table 18.

Table 18. Best-value robustness groupings of WRSE portfolios

Best-value robustness groupings of WRSE portfolios		
Performance	Percent maximum	Total
High	S7, B3	S7
Medium	B4, G2, A-Ph3 RMS, A-Ph3, B2	B3, A-Ph3 RMS, I5, B4, G2, A-Ph3,
Low	I5, J4, J5, I4, K5, I4, K13, K14, A-Ph2	B2, J4, J5, I4, K5, I4, K13, K14, A-Ph2

An evaluation of these results in respect to cost, shows that for little extra expense to implement the B3 scenario, there is a lot more value in terms of performance.

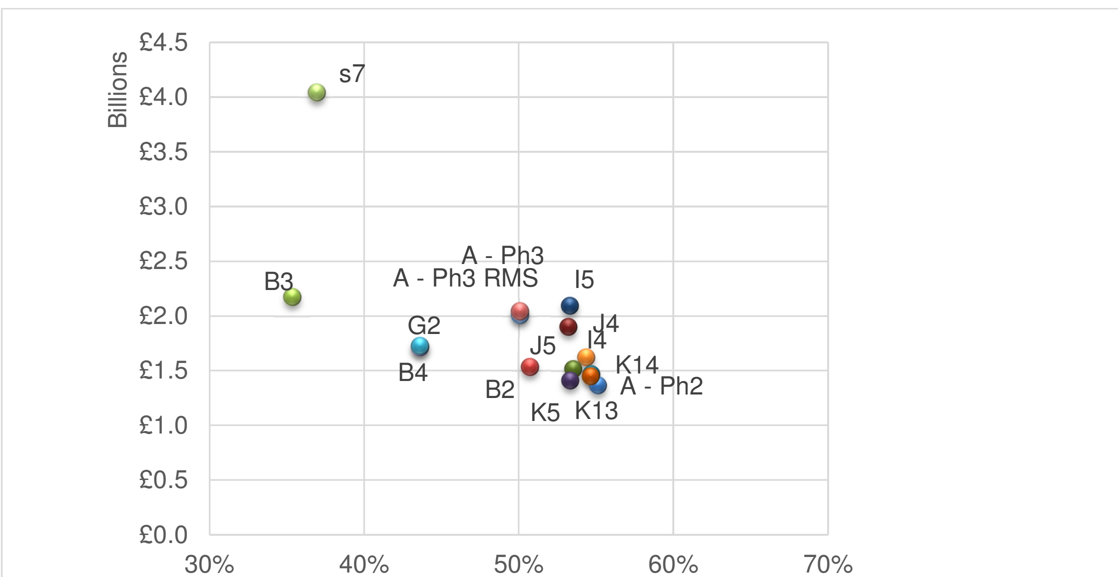


Figure 39. Best-value WRSE portfolio in terms of percent maximum demand reduction

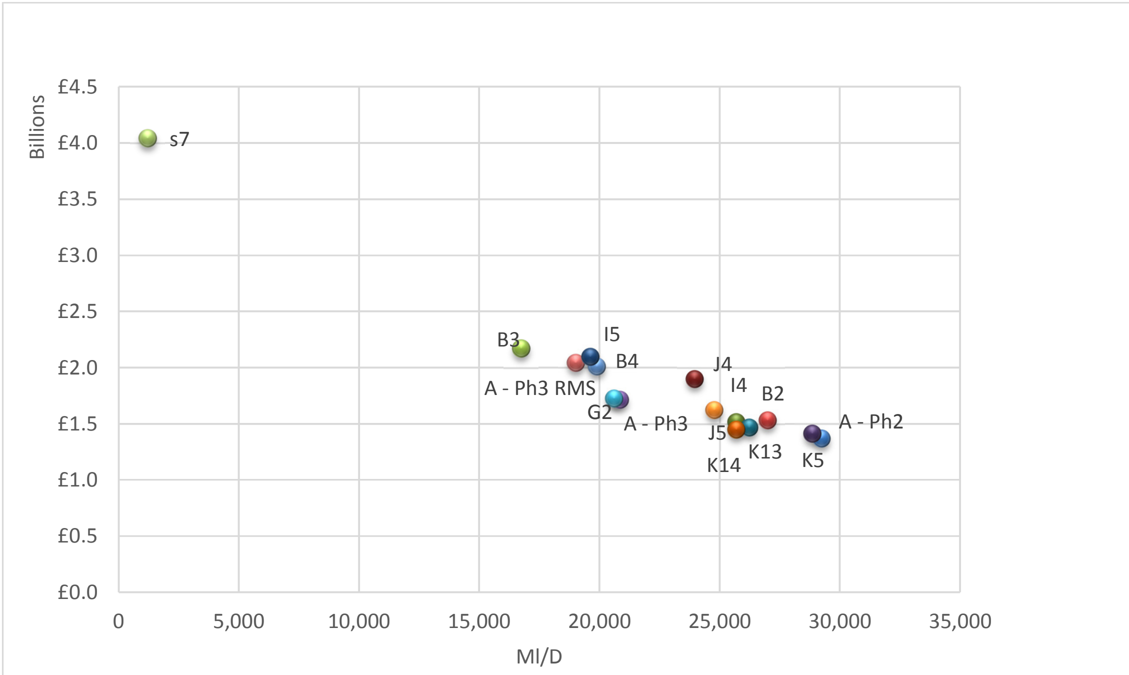


Figure 40. Best-value WRSE portfolio in terms of total demand reduction

As stated at the introduction to the MCDA analysis for Case Studies 1 and 2, other factors need to be considered when selecting the most appropriate management strategy such as Environmental aspects, carbon emissions and social acceptability. These aspects are evaluated during the options appraisal stage of EBSD Modelling and included as costs within the WRSE GAMS optimisation model. There was no attempt to bring these other criteria into the decision making process for a second time. An MCDA analysis was still conducted to accommodate a balanced understanding of how each management strategy performance relative to three demand reduction metrics and cost.

The four criteria evaluated with MCDA for Case Study 3 are:

1. <u>Percent average demand reduction.</u> For each time step of the planning horizon, the total demand reduction is divided by the total demand to arrive at an average percent reduction in demand for that year. The highest average percent reduction that occurred over the whole planning horizon is used as an indicator of performance.

2. <u>Percent maximum demand reduction</u>. For each time step of the planning horizon, the percent demand reduction in any one Water resources Zone is tracked. The highest percent reduction that occurred in any one zone over the whole planning horizon is used as an indicator of performance.

3. <u>Total demand reduction</u>. For each time step of the planning horizon, the total demand reduction in Ml/d is tracked. This yearly total is summed for the whole planning horizon and used as an indicator of performance.

Table 19 shows the performance of different portfolios based on different weightings. An overall rank is provided to indicate the comprehensive robustness of a management strategy. If a management strategy fails to rank in the top 10 for lower uncertainty, it is assigned a value of 11 and if it fails in terms of a system failure before reaching the level of higher uncertainty it is assigned a value of 21. The total is a sum of all the rankings for a strategy. The lower the score, the more robust the management strategy and the overall rank is assigned accordingly.

The MCDA analysis shows a consistent preference for 4 portfolios with very little deviation in priority at higher uncertainties except when considering total demand reduction and cost. These 4 portfolios also perform best at lower uncertainties as well except again for some deviation when considering equal weighting, total demand reduction and cost. Although B3 appears the strongest candidate, an evaluation of cost makes G2 a close second. The two A-Ph3 portfolios and B4 appear to be good secondary candidates as well.

When looking at cost and robustness it’s valuable to keep in mind the performance at lower uncertainties as well as higher uncertainties, because in all likelihood robustness may not be needed in the next few years. If possible it would be fiscally better to find a portfolio that is affordable at lower uncertainties and continues to be affordable and adequate at higher uncertainties. In this respect G2, appears to be a portfolio that offers strong performance at lower and higher uncertainties for a median price.

Table 19. Multi-Criteria Decision Analysis performance evaluation with different weightings for Case Study 3 - WRSE

Management strategy	Equal weighting		Emphasis on Percent Average Demand Reduction		Emphasis on Percent Maximum Demand Reduction		Emphasis on Total Demand Reduction		Emphasis on Cost		Total	Overall Rank
	Uncertainty											
	Low	High	Low	High	Low	High	Low	High	Low	High		
B3	3	1	1	1	2	1	2	2	5	1	19	1
S7	5	2	2	2	1	2	1	1	10	4	30	2
G2	1	3	3	3	3	3	4	6	1	3	30	2
B4	2	4	4	4	4	4	5	7	2	2	38	3
A 11 Ph3 RMS	10	5	6	5	11	5	6	3	11	6	68	4
A 11 Ph3	11	6	7	6	11	6	7	4	11	5	74	5
I5	11	8	8	8	11	8	3	5	11	21	94	6
J4	11	9	11	9	7	8	10	8	7	9	139	10
J5	9	21	11		9	21	9	21	8	10	119	8
I4	7	10	9	10	10	21	8	10	9	21	115	7
K5	8	21	11	21	11	10	11	21	4	8	126	9
K14	11	21	10	21	8	21	11	21	11	21	156	11

The fact that the same cost approach was used for an application of the EBSD and WRP-RA methods with the WRSE model provides the ability to compare the resulting costs from each application. Figure 41 compares these costs to highlight an incremental cost of robustness as a management strategy copes with more and more uncertainty. The light green bars represent the initial investment required to implement a 25-year plan that satisfies the EBSD Current methodology and the dark green bars represent the additional cost incurred with each strategy if it was required to respond to the most challenging future of the WRP-RA in which the strategies did not fail (i.e. uncertainty level 4 in the robustness plots). The difference in costs could be considered the incremental cost of robustness as a company invests further to respond to a more extreme future. Contingent on the robustness provided by each strategy, a low starting cost and low final cost are desired. Likewise, a large difference in costs is also advantageous as this would indicate that significant investment can be avoided until necessary. Of the top six ranked strategies in the MCDA (B3, s7, G2, B4 and the two A-Ph3 strategies – s7 and G2 are tied for 2nd place), G2 proves the most economical and the two A-Ph3 strategies are not far behind. To be fully prepared, any additional options included in either B3 or s7, could be considered as reserves.

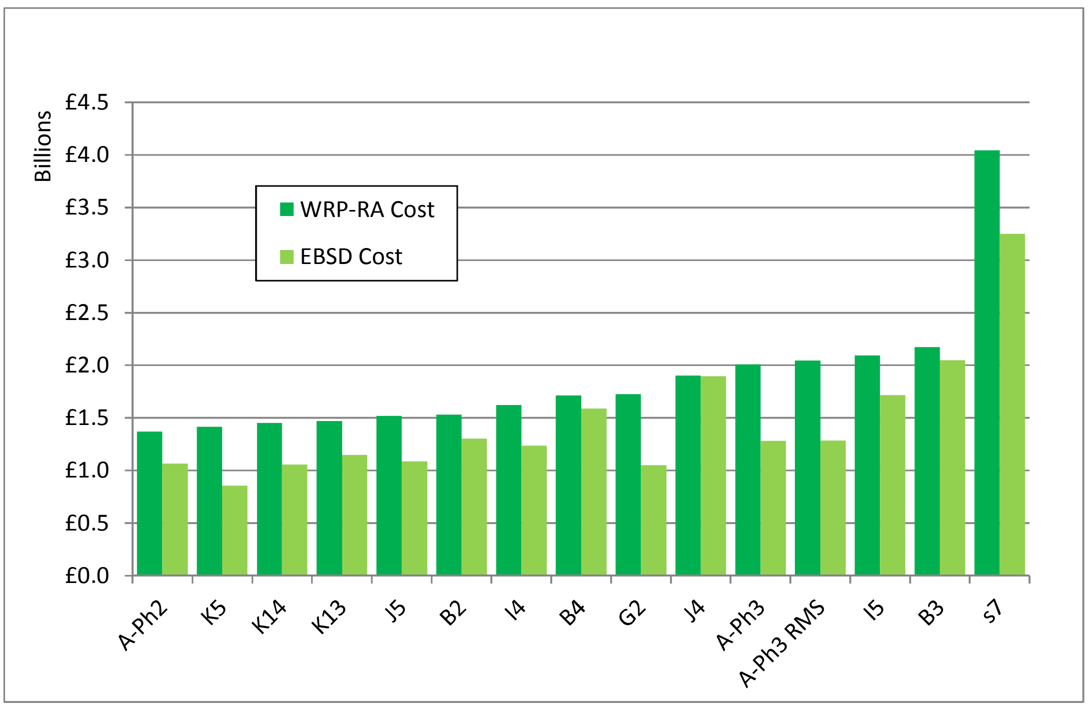


Figure 41. The incremental cost of robustness: a comparison of the initial cost to implement a management strategy for 25 years with the EBSD method and the cost of the final year of successful performance before failure with the WRP-RA method

4.4.5 Summary

The application of IGDT with a strategic regional network has demonstrated some benefits of the WRP-RA method:

- The WRP-RA confirms an intuitive sense that the most robust management strategies were formulated in response to more demanding futures; i.e. s7 in response to a 1:200 year drought and B3 in response to reduced DO.
- The WRP-RA offers insight into the real costs of robustness and this case study demonstrates that cost does not directly translate into robustness. G2 is a relatively inexpensive management strategy and ranks in the top 3 for all measures of robustness except total demand reduction in which it ranks 4th.G2 offers more robustness at less cost than other strategies.
- The implementation of the WRP-RA offers the ability to compare strategies over the same set of supply / demand settings and helps with a relative assessment of different management choices. This comparison shows that water companies have a good sense of their systems as the reformulation of the draft plans (A-Ph2) into final plans (A-Ph3 and A-Ph3 RMS) shows marked improvement. This improvement may be due to the fact that many companies already employ more advanced analysis techniques than EBSD to plan their strategy.
- The WRP-RA offers value with a simplistic application to accompanying an optimisation routine that selects different management strategies for different future scenarios. This case study demonstrates a method to compare the relative robustness of management strategies. In the context of the WRSE model, this approach highlights some robust peaks in a shallow bowl of strategies. The results clearly show six strategies (B3, s7, G2, B4 and the two A-Ph3 strategies) as more robust than the others.
- The WRP-RA offers a means to compare the relative cost of additional robustness as exemplified in Figure 41. This representation helps decision-makers know which collection of options are most cost-effective to satisfy needs of expected future and also the potential costs required to satisfy needs under more challenging conditions.

4.4.6 Limitations

There are two significant limitations in the application of the WRP-RA for Case Study 3.

- The planning horizon evaluated was the standard 25 year planning period that water companies plan for in the development of their Water Resource Management Plans. A comparison of the relative robustness of management strategies makes more sense over a longer planning horizon as the uncertainty of future conditions increases further into the future.
- The implementation of management strategies change as they respond to increasingly larger supply/demand deficits by either initiating schemes sooner and/or adding additional schemes. An identification of what changes in supply and/or demand (or ‘trigger points’) necessitate additional investment is not provided. A description of these ‘trigger points’ would help water resource planners monitor supply demand settings to be ready to respond appropriately.
- The relative robustness of candidate strategies was completed without identification of which schemes help a strategy perform better in response to more extreme supply/demand settings; i.e. the options that are relied upon at higher levels of uncertainty as compared with the options used for the expected future. The knowledge of which schemes increase future robustness can inform an adaptive approach to implementation in that the ability to implement the most robust options must be safeguarded. This information can inform critical infrastructure decisions as supply/demand conditions worsen.

5 Summary and conclusion

5.1 Summary of work

The results of this research show that the WRP-RA methodology offers a broader understanding of how different management strategies perform over a wider range of plausible futures than is explored with the traditional EBSD headroom estimation process used in England and Wales. IGDT enables the exploration of uncertainty in an unbounded fashion economically by marking the outer edges of system performance with robustness and opportuneness curves. As such, IGDT offers a pragmatic approach to understand the relative performance of management strategies for a severely uncertain future; and in this regard, it provides significant information to help design a management plan that is most secure in response to an uncertain future. This information is important as decision-makers will be more comfortable with investment decisions if they know the full capabilities of the strategies they invest in.

The WRP-RA utilises the capabilities of IGDT to benefit water resources planning in a number of ways as summarised below.

The identification of preference reversals

The use of IGDT within a WRP-RA reveals information not accessible at the lower uncertainties explored with the EBSD 'headroom range of uncertainty'. In both Case Studies 1 and 2 there are management strategies that fail just beyond this 'headroom range of uncertainty'. In Case Study 2, strategies dominated by the Gunnislake option perform relative well when assessed with the EBSD method, but fail at the higher level of the 'headroom range of uncertainty' when assessed with the WRP-RA method. The WRP-RA demonstrates that the failings of strategies that rely heavily on the Gunnislake options can be greatly improved with the addition of the Camel inflow and an upgrade to the Restormel treatment works. This combination of options forms strategy M13 which makes a very robust strategy and receives the top overall rank with the WRP-RA MCDA.

The application of the WRP-RA in Case Studies 1 and 2 also demonstrates the benefits of including innovative DSM such as rainwater collection and greywater reuse as part of a robust strategy. The application of EBSD Current in Case Study 2 portrayed innovative DSM dominated strategies as having supply/demand deficits at the end of the planning horizon. A dynamic and integrated assessment of these strategies with the WRP-RA method showed that not only do these techniques help make a strategy more robust to withstand increasing demands and decreasing supplies, they also help a water resources system recover quickly. This type of information can help guide investment for resilience.

These preference reversals and previously unknown behaviour of management strategies at higher uncertainties are important to consider because a management strategy focused on robust decision-making is less likely to be constrained by epistemological limits and therefore more likely to succeed than a strategy focused on optimal decision-making predicated on the predictive accuracy of climate models (Dessai et al. 2009). In essence, it is impossible to know the full potential of a management strategy until its ability to cope with extreme futures is assessed up until point of failure.

A fully informed best-value assessment

A best-value comparison that evaluates performance at higher uncertainties reveals a best-value management strategy for the long term over more demanding supply/demand situations than are currently explored with EBSD techniques. In Case Study 2, strategy M5 offers median performance when evaluated with the EBSD method, but when the performance of this strategy is explored over a wider range of uncertainty, it proves to be one of the most robust strategies. The inclusion of social acceptability ratings as part of the MCDA, however, places M5 much lower in the ratings. A poorer social acceptability rating was assigned to this strategy as there are fish habitat spawning areas in certain parts of the river to be accounted for when increasing the daily maximum abstraction. This poorer rating was assigned purely as in indication of the power of perception that this strategy has negative environmental impacts. All the environmental assessments have been completed for this scheme and report no concerns. When planning for robustness and resilience with the prospect of a severely uncertain future, it is advantageous to not pre-filter any options that don't appear promotable until a full understanding of their performance potential is known. Many companies forego investigating options in more depth if they think they will be hard to promote (WRSE 2015). Pragmatically, the discussion of social acceptability of options should occur after the full potential of an option to perform under more extreme situations is fully understood. Highlighting the additional and economical robustness a questionable scheme would further inform the debate as part of a public consultation.

Insight into the incremental cost of robustness

In Case Study 3, the benefits of the G2 management strategy would likely be overlooked without the implementation of the WRP-RA. The only management tactic employed in G2 is the ability for transfers to stop and start instead of being forced to continue in full use at the same or greater capacity once initiated. When first evaluated as part of a series of Public Review 14 (PR 14) modelling sensitivity runs, G2 was just another sensitivity run that offered some interesting information but could not be differentiated from other sensitivity runs for two reasons:

1. The performance of G2 was hard to compare with other management strategies because each strategy was derived to address different supply demand settings.
2. G2, along with many other strategies only explored a limited range of uncertainty. The only strategies that explored supply/demand settings resulting from an exploration of greater uncertainty were B3 and B4 of the PR14 modelling and s7 and s8 of the Environment Agency 'Drought Pilot Runs'. It is hard to fully differentiate the relative performance of strategies until they are tested in response to a consistent set of supply/demand settings that characterise an increasingly wider range of uncertainty with the WRP-RA.

Over most of the WRP-RA, G2 was closely tied with B4 in all metrics including total cost. The only aspect that distinguishes G2 as the overall best candidate is the fact that it is less expensive than B4 under expected supply/demand settings and the resulting ability to delay additional investment until necessary makes G2 a more attractive strategy.

A broad perspective approachable to decision-makers

The inclusion of MCDA enables the assessment of each management strategy over multiple metrics in order to highlight differently weighted performance results that might influence management choices. In both the Case Studies 1 and 2, a balanced assessment of the performance of management options over a range of criteria identified the ability of innovative demand management to lessen the draw on reservoirs at all times. Less draw on reservoirs makes it easier to keep their levels high and less dependence on reservoirs when new rains come also helps speed their recovery to a beneficial operating volume. A broader view of performance is important because when responding to climate change, there is a danger of maladaptation if not all metrics or water resources issues are taken into account. (Barnett and O'Neill 2009).

The benefits possible through robust decision making approaches such as IGDT are only realised if the results can be communicated effectively and inspire new contemplation by decision-makers and water managers. The proposed WRP-RA method includes a best-value and MCDA view of robustness specifically because water resources planners are interested in these representations to help decision-making for PR19 (WRSE 2015, and personal communication). The process of robust decision making is new and can be considered complicated and hard to communicate (Lempert and Groves, 2006). "Decision-making in management of the aquatic environment is, more often than not, a complex, discursive, multi-player process." (Hall, 2003) The inclusion of a best-value and MCDA view as part of the WRP-RA introduces robust decision making in a manner planners and decision-makers are used to and interested in using to make robust policy development is a more approachable endeavour.

A pragmatic approach to understanding the implications of severe uncertainty

The implementation of the WRP-RA in the planning context of England and Wales can be accomplished by simply expanding the derivation of network constrained DO and LoS. As discussed in Section 3.4, the LoS assessment for a water resources system requires an incremental increase of demand to evaluate the maximum DO any management strategy can provide. This DO value is then fed into the headroom estimation process, which is not necessary. A robust evaluation of performance can be accomplished as part of the derivation of DO and LoS via repeated simulations that incrementally explore greater and greater uncertainty within the simulation environment. Expanding the DO derivation within the hydrological, licence and network constraints via an unbounded IGDT assessment (as was completed with the WRP-RA) until failure provides a full view of future performance.

The use of concepts such as LoS and return periods are helpful for engagement purposes. Customers can comprehend how often they should expect to reduce their consumption in the event of infrequent drought periods. At the same time, basing water resources modelling and planning to a pre-defined LoS can lead to a fragmented approach in which different assumptions and approaches are hidden and inconsistent. For example; each of the 6 water companies in the south east offers a different LoS and base their design drought on different historical droughts. They then state different amounts of DO that are available for themselves and for the region based on these intrinsic assumptions. The uncertainty surrounding future droughts and the effects of climate change, (along with other uncertainties including demand) are hidden within a headroom value. It would be more informative to expose all these uncertainties and test the relative ability of different management strategies to respond to these uncertainties as part of simulation runs. The resulting information from these simulation runs would let customers know what LoS (and the related cost) each management strategy could provide over a trajectory of increasing uncertainty. The iterative exploration of management strategy performance in simulation over an unbounded range of uncertainty is the basis of the WRP-RA.

The current move in water resources planning in the UK towards resilient best-value approaches provides the opportunity to inform and engage water customers, regulators and stakeholders with a deeper appreciation of performance at different levels of uncertainty trending towards severe uncertainty. With this information, the full value of investment is available and the decision becomes more a matter of which LoS customers would like to pay for than which plan they would support to achieve their traditional LoS. Additionally, by describing the effects of climate change as part of iterative explorations into uncertainty, customers would gain a better understanding of how climate change is affecting the predictability of water resources and this greater understanding may help them be more willing to reduce their water use more frequently instead of preferring to maintain their historic LoS. The results of Case Study 2 showed that management strategies can better protect the overall water security of the SSA with more frequent demand reductions.

5.2 Contributions of work

This Water Resources Planning Robustness Assessment method based on Info-Gap Decision Theory offers the technical platform to address some of the proposed improvements to the current water resources planning process as noted by Hall et al. (2011); and this research has helped expand the debate and investigation in a few significant areas.

- A risk-based approach is enabled in two ways:
    - o The WRP-RA tracks the overall water security of a regional water supply system in terms of observable and operational measures such as the reservoir ratio (RR), the reservoir risk measure (RRM), the drought deficit (DD) and the safety margin deficit (SMD). These metrics characterise the security of a water resources system in terms of the frequency, duration and magnitude of scarcity conditions depending on the management strategy that is in place.
    - o The WRP-RA directly evaluates the Levels of Service possible with different strategies as a result of supply/demand conditions, instead of as a precursor to strategy development. The WRP-RA quantifies the demand reduction associated with a management strategy during simulation runs and compares the reduction with that required for other strategies over an unbounded range of increasing uncertainty. This use of the concept of LoS is a direct measure of consequence related to the frequency, duration and magnitude of water scarcity a is more informative and transparent than using LoS it as a guiding parameter that presupposes an acceptable LoS to plan for, and as such, limits the exploration of what the real LoS could be under different conditions.
- The limitations and often misleading results of the headroom estimation process have been exposed by comparing EBSD Current AISC and LP/IP selected results with WRP-RA results derived from a greater exploration of uncertainty than is achieved with EBSD. This further exploration of uncertainty expands on the direction promoted in the UKWIR WR 27 report (UKWIR, 2012) to address non-headroom uncertainties with scenarios and to post-validate EBSD results with time series analysis. The range of uncertainty explored is the important consideration. Instead of evaluating system performance up to an imposed percentile of an imposed distribution as practiced with headroom, evaluating strategies over the full range of uncertainty until failure with the WRP-RA provides greater understanding of the long term performance of management strategies.
- The application of the WRP-RA demonstrates that the integration of uncertainty analysis within the water resources system simulation process removes the need for

headroom as suggested by other research (Hall et al., 2011) and as tested in application by Southern Water with their stochastic assessment of DO.

- The WRP-RA offers a pragmatic approach to planning with severe uncertainty and takes a different tact on responding to the question, 'How extreme a future should we plan for?' The WRP-RA employs the IGDT principle that testing to the point of failure provides a complete picture of performance. This pragmatic approach is similar to the concept of middle-state resilience (Butler, 2015) which implies we may never know all the impacts a system will be placed under, but we can test how resilient a system is to a number of physical pressures/stressors which are a condensed version of the range of impacts from a large number of unimaginable future conditions. The WRP-RA methodology echoes the middle-state resilience sentiment that the preciseness of uncertainty is not the priority, but rather the range explored.
- The WRP-RA shows the importance of the concept of preference reversals in that as uncertainty increases some poor performing strategies at lower levels perform better at higher levels of uncertainty as evidenced in plot 2 of Figure 23, Section 4.3.2, where management strategy M5 performs worse than M1 and M13 at lower uncertainties, but performs more robustly at higher uncertainties.
- With this research, the value of innovative demand management has again been shown to contribute to a robust management strategy over increasing uncertainty These DSM approaches are valuable as they lessen the draw on reservoirs, speed recovery of a system and lessen the need for pipe capacity expansion (Basupi et al. 2014).
- The WRP-RA responds to one failing of current decision making in that currently investments are made based on an incomplete picture of possible futures. Case Study 2 shows that many of the plans considered least-cost with headroom, were not best value at higher uncertainties. Without a full understanding of whole system performance under severe uncertainty, this information would not be known. Through an examination of how portfolios perform over increasing uncertainty, there is a better appreciation of the robustness available for the investment made. The best value plots identify the most economical robust strategies as M13 for Case Study 2 and G2 for Case Study 3.

- The WRP-RA enhances the concept of a ‘best-value’ plan because it helps select a best value plan based on robustness over a wider range of futures. Knowing the amount of surplus water, as portrayed with the headroom version of a best-value plan (UKWIR, 2012), is not as valuable as knowing how well a Level of Service can be protected with a strategy up until the point of failure, as portrayed with the WRP-RA version of a best-value plan.
- The WRP-RA method identifies a management strategy’s ability to recover from a supply/demand deficit situation with the inclusion of IGDT opportuneness curves. Through an understanding of how quickly the SMD value decreases (Fig. 9, Section 4.2.2) or how quickly the yearly minimum reservoir level increases (Fig. 27, Section 4.3.2) when situations turn favourable, the speed of system recovery can be ascertained. This aspect of analysis is significant and unique to the IGDT technique and WRP-RA methodology.
- The use of MCDA provides an opportunity to more comprehensively and systematically assess the benefits of each management strategy on the whole with results for more than one factor at different levels of uncertainty. It is important to consider investment decisions based on more factors than least cost (Harou, 2015) and MCDA offers this perspective.
- This research has also shown that the consideration of elements to include in the MCDA is influential. The low performance of strategy M5 in Case Study 2 shows the danger of pre-supposing social acceptability as this portfolio ranked low mainly due to its perceived social acceptability score. A deeper investigation of robustness provides a more informed view of the long-term value of options and management strategies. As such, a consideration of social acceptability is best left till the performance results are fully known.

5.3 Future research

The implementation aspect of understanding the robustness of various management strategies to severe uncertainty is to develop an adaptive management plan that includes an identification of when and under what circumstances different options will be necessary. The following would help develop this knowledge.

- To address the first limitation of Case Study 1 in section 4.2.4, explore the application of a WRP-RA with drought sequencing as well as the intensification explored in this research to understand if different timings and durations of drought episodes test the robustness of management strategies in a different ways.
- To address the second limitation of Case Study 1 in section 4.2.4, develop a method to describe different levels of increasing uncertainty with some narrative; e.g. an uncertainty level of 7 corresponds to the supply / demand setting of a climate change high emissions scenario in 2050 coupled with a 20% increase in population and no demand reduction.
- To address the first limitation of Case Study 2 in section 4.3.4, use a multi-objective optimisation approach to select a broader range of candidate strategies and then apply a WRP-RA evaluation to see if more insight can be gained on the relative merit of any of these strategies.
- To address the second limitation of Case Study 2 in section 4.3.4, complete further sensitivity testing to evaluate which strategies perform better to demand uncertainty vs. supply uncertainty and include this information in an adaptive strategy along with significant benchmarks for monitoring shifts in demand and/or supply.
- To address the first limitation of Case Study 3 in section 4.4.5, lengthen the planning horizon so adaptive planning can occur in a more suitable context as severe uncertainty will likely manifest over a longer horizon than 25 years. Many recent conversations (WRMP 2024, WRSE workshops, 2015) are suggesting at least 80 years is a more helpful planning horizon.
- To address the second limitation of Case Study 3 in section 4.4.5, establish a systematic way to define trigger points with enough foresight to implement options as needed (or be ready to respond) when things do get worse. In this regard it will be necessary to rephrase the concept of return periods and to

develop new methods of communication to refer to extreme events as return periods are less valid in the context of climate change. In the face of non-stationarity, yesterday's 1:50 year event could be tomorrow's 1:10 year event.

- To address the third limitation of Case Study 3 in section 4.4.5, develop an adaptive and flexible method (such as Real Options) to schedule the options that belong to a robust management strategy using the metrics collected with the WRP-RA, and others as needed.

Glossary

Adapt, adaptive, adaptation	The flexibility to change a management strategy when required by a change in drivers/conditions.
Average Incremental Social Cost (AISC)	The total cost of a water management option divided by the total amount of water made available with the option.
Aquator	A water resources network simulation software commonly used by water companies in the UK.
ASR	Aquifer storage and recovery. A scheme by which water can be transferred (usually by pumping) into an aquifer during times of high water availability (in particular winter) to enhance the groundwater storage available in dry weather.
Business As Usual (BAU)	A management strategy with no new interventions.
Baseline forecast	A demand forecast which reflects a company's current demand management policy but which should assume the swiftest possible achievement of the current agreed target for leakage during the forecast duration, as well as implementation of the company water efficiency plan, irrespective of any supply surplus.
BAWSCA	Bay Area Water Supply and Conservation Organisation
Best value	The UK Government expects water companies to plan provision of reliable, sustainable supplies at best value to customers while protecting the environment. See the Guiding Principles document of the national water resources planning guideline (Environment Agency et al, 2012)
Carbon costs	The calculated cost associated with the carbon construction and operation of a scheme/transfer. For further guidance see Her Majesty's Treasury (HMT) guidance for the cost of carbon (Shadow Price of Carbon or SPC), and the water resources planning guideline (Environment Agency et al, 2012).

Climate change	The UK climate is expected to change. The impacts on future deployable output and water demand have been estimated using the results from UKCP09 (see below).
Defra	Department for Environment, Food and Rural Affairs
Demand management or Demand Side Management	The implementation of policies or measures which serve to control or influence the consumption or waste of water (this definition can be applied at any point along the chain of supply).
Drought Deficit (DD)	The amount of water missing from the reservoir below the drought management curve.
Deployable output (DO)	The output of a commissioned source or group of sources or of bulk supply as constrained by: environment; Licence, if applicable; Pumping plant and/or well/aquifer properties; raw water mains and/or aquifers; transfer and/or output main; treatment; water quality.
Dry year annual average (DYAA) unrestricted daily demand	The level of demand, which is just equal to the maximum annual average, which can be met at any time during the year without the introduction of demand restrictions. This should be based on a continuation of current demand management policies. The dry year demand should be expressed as the total demand in the year divided by the number of days in the year.
Dry year critical period (DYCP)	The time in a dry year when demand is greatest, often taken to be the peak week.
EBSD	Economics of Balancing Supply and Demand
Environmental and social costs	Environmental impacts can be valued in monetary terms so that they can be added to, or subtracted from other items with monetary value such as capital and operating costs. A number of techniques exist for estimating the value that society has placed on the environment. These are summarised in The economics of balancing supply and demand (Environment Agency and UKWIR, 2002), which

	also recognises that not all factors can be given a monetary value.
GAMS	Generic Algebraic Modelling Software
Greywater	Water from showers and laundry can be treated in the home for reuse to flush toilets or for outside in the garden.
GW	Groundwater sources
IGDT	Info-Gap Decision Theory
Leakage control	May include mains replacement, reduction in supply pipe leakage, pressure reduction and/or improved find and fix policies. A set of leakage control programmes have been specified as demand management options for the modelling.
Level of Service (LoS)	A commitment by a water company to ask for demand use reductions no more than 1 in x years and for no longer than x number of monks.
MCDA	Multi-Criteria Decision Analysis
Meter programme	Properties, which are to be metered according to a specified metering policy. A set of metering programmes have been specified as demand management options for the modelling.
Method	A technical approach to accomplish an analysis.
Metrics	An attribute a corresponding value with which to monitor performance.
Minimum Deployable Output (MDO)	The level of demand, which normally occurs during late summer/early autumn, when river flows are at their minimum and groundwater levels are at their lowest prior to the onset of the winter recharge period.
MILP	Mixed Integer Linear Programming
Miser	A water resources network simulation software commonly used by water companies in the UK.
Model	A mathematical representation of a water resources system.

Megalitres (Ml/d)	Million litres per day
MOO	Multi-Objective Optimisation
NAO	North American Oscillation
Net Present Value	The value of future expenditure with discount factors to convey the money saved by differing implementation.
Network	A collection of nodes and links that compromise a water resources network
Normal Year Annual Average (NYAA) daily demand	Average daily demand in normal weather conditions
Ofwat	The Water Services Regulation Authority
Option	A scheme that can be used in the future to supply water or reduce demand or improve the network configuration and distribution.
Outage	A temporary loss of deployable output resulting from non-availability of water supply assets.
Pcc	Per capita consumption.
PDF	Probability Distribution Function
Performance criteria	Values tracked with a simulation or optimisation model that indicate the ability of a portfolio of options to satisfy the needs of the system.
Planning Horizon	The number of years over which planning to satisfy the supply/demand balance is calculated.
Portfolio	A collection of options chosen for a long term management plan.
Process losses	Water losses involved in producing treated water, before input into the water distribution system.
Public Review (PR)	A once every 5 years public consultation about WRMPs; e.g. PR09 or PR14
Rainwater harvesting/collection	The collection of water for use with bathing and washing, toilet flushing or outdoor use.

Reservoir Ratio (RR)	A ratio of the reservoir storage minus the drought control curve and this difference divided by the drought control curve.
Reservoir Risk Measure (RRM)	The product of the probability of a reservoir falling below the drought management and the average amount of water missing from the reservoir when compared with the drought management curve.
Resilient	The ability to withstand a recover from future extremes.
Resource zone (RZ, WRZ)	The largest possible zone in which all resources, including external transfers, can be shared and hence the zone in which all customers experience the same risk of supply failure from a resource shortfall.
Risk	A measure of the probability and magnitude of an event and the consequences of its occurrence.
RMS	River Medway Scheme, which includes the major existing sources River Medway, Bewl Reservoir and Darwell Reservoir. Phase 3 runs were carried out with existing or more flexible operating rules for the RMS.
Robust Decision Making (RDM)	A planned process to compare the ability of management strategies to perform satisfactorily over a wide range of plausible futures.
Robust/ Robustness	The ability to perform satisfactorily over a wide range of plausible futures.
Safety Margin Deficit (SMD)	The amount of water not in the reservoir between the operational management curve and the drought management curve.
Scheme	Synonymous with Option – i.e. An option that can be used in the future to supply water or reduce demand or improve the network configuration and distribution.

Security of supply	The confidence with which a company's target levels of service (frequency of demand restrictions etc.) can be reached. Target headroom assessment involves choosing a level of risk which the company accepts that it can manage, which normally increases during the planning period. Supply is considered secure if resources are sufficient to meet demand plus target headroom.
Strategic Supply Area (SSA)	An area within a water company's jurisdiction which is designed to be mostly self-reliant for water and in which all demand nodes should receive a similar level of service in different hydrological conditions.
Supply-demand balance	The difference between water available for use (including imported water) and demand at any given point in time. Sometimes this is interpreted with target headroom added to demand.
Sustainability reduction	Reductions in deployable output due to changes in abstraction licences required by the Environment Agency to meet statutory and/or environmental requirements.
Target headroom (THR)	An allowance for uncertainty in forecasts supplies and demands. It is defined as the threshold of minimum acceptable headroom, which would trigger the need for water management options to increase water available for use or decrease demand.
Tariffs	Charging for metered water supply at different rates, e.g. a higher rate after a threshold amount (rising block tariff), or a higher rate in summer (seasonal tariff).
Thames Estuary 2100 (TE 2100)	Adaptive management plan for the Thame estuary
Total leakage	The sum of losses from the distribution network (assets owned by the water company) and underground supply pipe losses (pipes owned by customers).
UKCP09	UK Climate Projections 2009, as published by Defra (2009)

Unrestricted demand	The demand for water when there are no restrictions in place (this definition can be applied at any point along the chain of supply).
Water Available for Use (WAFU)	Deployable Output minus Outage and Loss
Water efficiency	Water efficiency initiatives designed to help or support consumers to conserve water.
Water resources management plans (WRMP)	Water undertakers have a statutory duty to prepare and maintain a water resources plan (also known as water resources management plans) under new sections of the Water Industry Act 1991, brought in by the Water Act of 2003. New plans are prepared at least every five years and the next are due to be published in 2014.
Water resources planning guideline (WRPG)	The water resources planning guideline (Environment Agency et al, 2012) provides a framework for water companies to follow in developing and presenting their water resources plans. It helps water companies show how they intend to maintain the balance between demand for water and their supply. It sets out good practice behind the composition of a plan, the approaches to developing a plan and the information that a plan should contain.
Water resources zone (WRZ)	See resource zone
WEAP	A water resources network simulation software commonly used Internationally in developing countries and by researchers.

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