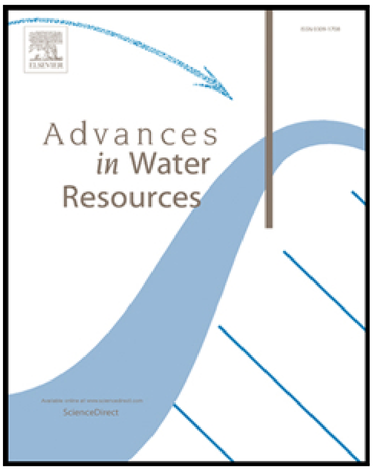

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Highlights

- New metrics for assessing resilience of long-term water supply/demand balance under uncertainty are proposed addressing different aspects of water deficits including duration, magnitude, frequency and volume of these events.

- Metrics are tested, validated and demonstrated on a real Bristol Water supply system.
- The key finding is that, unlike in current practice so far, multiple metrics covering different aspects of resilience should be used simultaneously for water resources management under uncertainty.

Resilience-based performance metrics for water resources management under uncertainty

TOM ROACH (1, 2), ZORAN KAPELAN (1), RALPH LEDBETTER (2)

(1): University of Exeter, College of Engineering, Mathematics and Physical Sciences, Harrison Building, North Park Road, Exeter EX4 4QF, UK
(2): HR Wallingford, Howbery Business Park, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BA, UK
Corresponding author: T Roach (Email: Tom.Roach@atkinsglobal.com)

Abstract

This paper aims to develop new, resilience type metrics for long-term water resources management under uncertain climate change and population growth. Resilience is defined here as the ability of a water resources management system to 'bounce back', i.e. absorb and then recover from a water deficit event, restoring the normal system operation. Ten alternative metrics are proposed and analysed addressing a range of different resilience aspects including duration, magnitude, frequency and volume of related water deficit events. The metrics were analysed on a real-world case study of the Bristol Water supply system in the UK and compared with current practice. The analyses included an examination of metrics' sensitivity and correlation, as well as a detailed examination into the behaviour of metrics during water deficit periods. The results obtained suggest that multiple metrics which cover different aspects of resilience should be used simultaneously when assessing the resilience of a water resources management system, leading to a more complete understanding of resilience compared with current practice approaches. It was also observed that calculating the total duration of a water deficit period provided a clearer and more consistent indication of system performance compared to splitting the deficit periods into the time to reach and time to recover from the worst deficit events.

Key Words

Resilience; climate change adaptation; water resources management; water supply; performance metrics; reliability

1 Introduction

Multiple modern decision-making methodologies are currently being trialled for application to water resources management (WRM) adaptation planning under deep uncertainty; however, the output results from these 'adaptation investigations' can be highly dependent on the performance metrics employed. Terms such as 'robustness' or 'flexibility' are typically used to define the performance or 'pliability' of a water system or adaptation strategy across a broad range of future conditions or scenarios (Groves et al., 2008; Maier et al., 2016; Matrosov et al., 2013; Moody and Brown, 2013; Smit et al., 2000); however, it is the performance metrics (or criteria/indicators) that will define the performance of a water system to a single future scenario or set of conditions. Despite the widening range of decision-making approaches under development, the outputs from these methods are highly dependent on how the water resource system performance itself is evaluated. For example, how to define the assessment metrics applied to quantify the performance of a water system to a given future scenario and how this performance can vary over the range of potential futures/uncertainties. It's within these more practical engineering features that a wider knowledge gap is often over looked.

The more well-known performance metrics often cited within WRM literature are those of Hashimoto et al. (1982) who were among the first to propose the use of the terms; reliability, vulnerability and resilience for water resource system performance evaluation. These performance criteria, in general, refer to how likely a system is to fail (its reliability), how severe the consequences of failure might be (its vulnerability) and how quickly it can bounce back, which is the recovery from a failure (its resilience). The term resilience has gathered particular traction in recent studies, with the general agreement that 'resilience' as a concept for WRM, should go beyond its original 'Hashimoto' definition. Walker and Salt (2006) are advocates for the idea of 'resilience thinking', which ventures beyond the concepts of optimization to believed 'knowns' but instead fosters the capacity to look at social-ecological systems as a whole and incorporate diverse approaches to increase resilience to both expected and unexpected disturbances. This resilience thinking was applied in Seekell et al. (2017) as an indicator-based analysis to compare the sustainability of global food systems. It was found that very few countries performed high or low for all indicators, emphasizing the complexity of system dynamics and the varied information provided by different metrics.

Resilience has been previously defined in both an ecological and engineering sense by Holling (1996), who describes the more engineering aspects of resilience as ones of efficiency, constancy and predictability, and the more ecological ones as persistence, change and unpredictability. A combined appreciation of both aspects was recommended to improve overall resilient system design. Carpenter et al. (2005; 2001) furthered the social-ecological understanding of resilience by defining it as the magnitude of disturbance that can be tolerated before a system moves to a different region of state space controlled by a different set of processes; however, they registered the difficulties in measuring the thresholds or boundaries between states in a complex system dynamic and concluded the need for improved surrogate metrics to bridge the gap between resilience theory and applied resilience.

Lansey (2012) defined the resilience of a water distribution system as its ability to “gracefully degrade and subsequently recover from” a failure event. Walker et al. (2004) discussed resilience under the original Holling (1986) definition, as the ability/capacity of a system to return to an equilibrium or steady-state after a disturbance, to absorb shocks but still maintain function, structure, identity and feedbacks. An in-depth review of resilience concepts, in the context of socio-ecological systems, was conducted by Folke (2006) who discussed the policies of adaptive capacity and transformability to better inform on system resilience. A detailed review of cross sector resilience measures was also conducted by Hosseini et al. (2016) and Angeler and Allen (2016). Davidson et al. (2016) furthered the idea of resilience thinking by presenting a range of original definitions and typologies of resilience interpretations, concluding that we must ‘be open to alternative traditions and interpretations if it (resilience) is to become a theoretically and operationally powerful paradigm’.

Several examples of resilience being used as a quantified performance metric/criterion in water management include Matrosov et al. (2012) and Paton et al. (2014) who calculated resilience as the average duration of time a system is under a temporary restriction. Fowler et al. (2003) calculated it as a fraction of the total future time a system is under an unsatisfactory state. Loucks (1997) calculated it as the probability of a system recovering once it enters an unsatisfactory state. Jung (2013) calculated it as a function of system failure severity and recovery time. Butler et al. (2016) defines it in terms of minimising both the magnitude and duration of level of service failures over a systems design life. Yazdani et al. (2011) characterised resilience as a more complex combined metric of four infrastructural qualities of robustness, redundancy, resourcefulness and rapidity. Linkov et al. (2014) recommended breaking the resilience management of systems down into an analysis of the time to absorb and then recover from adverse conditions via an assessment into the 'depth' of loss of functionality during these detrimental periods. Kjeldsen and Rosbjerg (2004) calculated resilience in three alternative ways: the inverse of the mean value of the time the system spends in an unsatisfactory state, the maximum duration of an unsatisfactory state and the duration of the 90th fractile of observed unsatisfactory periods. They concluded that the maximum duration metric provided the most accurate and comprehensible estimation of performance. A direct maximum duration calculation was also the resilience metric of choice by Moy et al. (1986) who selected it to enable and simplify the quantification of resilience and its incorporation into a mathematical programming model. Kundzewicz and Kindler (1995) also argued that a resilience definition based on maximum value is better than one based on a mean value, as the presence of small insignificant events may lower the mean value and present an inaccurate picture of actual overall system performance.

As research into resilience principles increases throughout the water industry it is important to begin to bridge the gap between theory and practice. This study aims to select, analyse and compare several of the more 'industry understood' metrics, i.e. those that could be readily applied to indicate the changing performance of a water resource system to uncertain future circumstances (e.g. future system states). The variation in resilience metrics explored previously (several listed above) highlights how the interpretation of resilience is wide ranging across the literature and that often only individual, isolated aspects of water system performance are assessed, without attention given to the full comprehensive picture of this complex issue.

This work assesses a more 'complete' picture of resilience, by evaluating multiple aspects of water system performance simultaneously. Whilst expressing the complexity of the resilience paradigm beyond a conceptual or theoretical definition may be difficult, as discussed above, a comparative analysis of the outputs of alternative resilience indicators/metrics from a real-world case study can help clarify the sensitivity and correlation between different potential criterions of performance, validating whether multiple, or a single, metric is suitable to quantitatively assess water system resilience. Identifying a set of candidate metrics to define resilience would also be highly beneficial in consolidating WRM adaptation investigations outputs across the industry.

This paper explores and analyses ten performance metrics using a detailed simulation of a real-world WRM case system. The alternative metrics address a wide variety of potential resilience aspects that could be considered when evaluating a water supply system's resilience to uncertain climate change and population growth, i.e. to uncertain future supply and demand over a pre-specified long-term time horizon.

2 Methodology

2.1 Overview

The objective is to select, analyse and compare a range of different metrics that could be used to assess and indicate the resilience of a water resource management system. The metrics measure system performance, in terms of maintaining the long-term supply-demand balance, when planning for uncertain climate change and/or population growth. The chosen metrics are tested on a real-world case study, incorporating a range of plausible future scenarios of supply and demand as well as the application of future adaptations to the system in order to assess the effect changes in the system state/parameters have on the resilience metric outputs.

2.2 Resilience metrics characteristics

In order to select a range of metrics for analysis first a set of desirable metric characteristics are explored, derived by reviewing a range of WRM documents and reports (Defra, 2011; 2013; 2016; Environment Agency, 2013; 2015; UKWIR, 2016). Some characteristics of a good metric in the context of WRM are listed in Table 1 (in reference to the resilience of a water supply system; in no particular order):

Table 1. Characteristics of a good performance metric for WRM adaptation planning

Item	Description	Rationale
1	Practical	Quantitative rather than qualitative.
2	Comprehensive	Covers all important aspects of system resilience (how well is the system prepared to, affected by, responds to and recovers from a deficit event), including attributes of deficit events (frequency, time/duration and magnitude).
3	Understandable/ transparent	Easy to understand, and explain to, different non-technical stakeholders.
4	Non-redundant	A set of independent and specific metrics.
5	Minimal	As small as possible number of resilience metrics adopted eventually.
6	Defensible	Enables calculation of and comparison to relevant conventional measures in the context (reliability, risk / likelihood / impact, etc.).
7	Industry focused	Enables water industry to express its current goals and objectives.
8	Strategic	Embodies a strategic objective and can provide sufficient information to correctly monitor, plan and adapt a water supply system.
9	Accurate	Can be accurately projected/calculated for a given system, free of approximates and indistinct values.
10	Sensitive	The metrics need to provide a clear indication of improvement or deterioration.
11	Standardised	Deriving a metric definition that all respective parties can agree on that can be easily examined/calculated and understood by all relevant companies/organisations/individuals.
12	Informative	The metrics need to provide useful information that a decision maker can accurately utilise to quantify the relevant social, environmental and economic benefits/costs associated to the performance of a system.

Different definitions of resilience exist within WRM practice in the UK and no quantitative metrics are currently used (Ofwat, 2015; UKWIR, 2016; Water UK, 2016). For the purpose of this paper (and to be compatible with current UK engineering practice), the resilience metrics introduced here below all relate to aspects surrounding threshold levels and trigger points of low water resource periods, i.e. water deficit events. Given this, *resilience* of a water resources management system to uncertain future changes in supply and/or demand (caused, in turn, by uncertain climate change and/or population growth) is defined here in the ‘engineering resilience’ form (Holling, 1996), i.e. as the recovery time of a system to return to equilibrium following a water deficit event, but here also incorporating aspects of deficit magnitudes and frequency. A water deficit *event* is defined as the point at which a water system requires a temporary water restriction to be put in place (e.g. a temporary use ban) due to a critical threshold of low resource being surpassed. A water deficit *period* is defined as the period of consecutive days/months that the water system remains in deficit. Avoiding the initiation of a water deficit period is a ‘resistive’ quality of a system. Ideally a water resource system will have high resistance to deficits, however this metric investigation concentrates on the resilient characteristics of a system, i.e. the way a system reacts once its resistance has been broken.

The circumstances that entail a water deficit event occurring are dependent on the system under study. For instance, in the case study assessment to follow (see section 3) a water deficit is counted if the stored water levels in the main system reservoirs fall below an unacceptable pre-specified (threshold) trigger level on a given time step (day or month). A water deficit may be allowed to occur occasionally, in order to manage the water supply system during periods of drought; however, a particularly severe deficit event or prolonged deficit periods could lead to unacceptable levels of restrictions and, at worst, a failed system (inability to meet necessary demands).

2.3 Proposed Resilience Metrics

The proposed resilience metrics are shown in Table 2 and Figure 1.

Table 2. Resilience Metrics

Metric code	Metric description (units)
Duration based metrics	
M1	Total time system is under water deficit (months)
M2	Duration of the longest water deficit period (months)
M3	Time to reach water deficit of greatest magnitude (months)
M4	Time to recover from water deficit of greatest magnitude (months)
M5	Average duration of water deficit periods (months)
Frequency based metrics	
M6	Number of water deficit periods recorded
Magnitude based metrics	
M7	Water deficit of greatest magnitude recorded (Ml/month)
M8	Average magnitude of water deficits (Ml/month)
M9	Average magnitude of water deficit period peaks (Ml/month)
Volume based metrics – magnitude x duration	
M10	Total volume of all water deficits recorded (Ml)

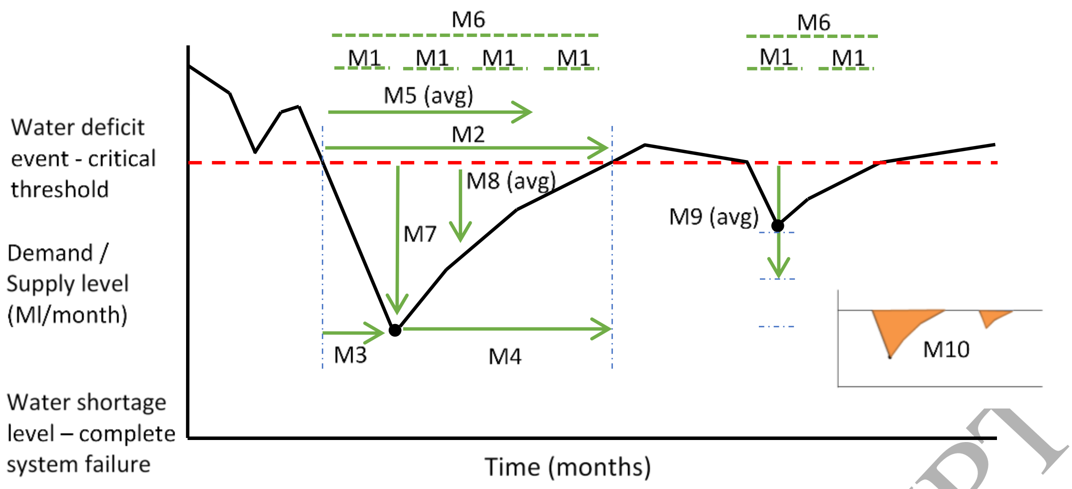


Figure 1. The ten performance/assessment metrics as calculated from a series of example water deficit periods. The black line represents a water systems changing supply level, indicating when it falls below a critical threshold, i.e. initiates a water deficit event. In this example, an initial dip in water supply levels is maintained above the critical threshold, however, this recovery is subsequently followed by two recorded water deficit periods, i.e. water restriction periods. In this example, M1 would equal 6 months, M2 would equal 4 months, M6 would equal 2 periods and so on.

The ten metrics were selected to cover the whole range of different assessment features of water deficit events/periods (i.e. duration, magnitude, frequency, volume of water not delivered) and because they encapsulate many of the highlighted characteristics of what would make a good resilience-based performance metric for WRM adaptation planning (see Table 1). For instance, the metrics are all quantitative rather than qualitative (item (1) in Table 1); are transparent in their direct calculation (item (3)); are highly specific (i.e. do not encompass too many aspects into one calculation – item (4)); are industry focused (i.e. can be used to quantitatively express the industries qualitative goals – item (7)); can be used to directly monitor and adapt strategic plans (item (8)); can be calculated to an exact (non-approximated) figure during uncertainty/future scenario examinations (item (9)), and can be easily standardised (i.e. examined, understood and agreed upon by all relevant parties – item (11)).

A detailed assessment is carried out here on a real–world case study to examine several quantitative aspects of suggested resilience metrics. A comprehensive range of system performance/water deficit aspects are examined (item (2) in Table 1). This included an assessment of metrics sensitivity (item (10)) with the aim to identify metrics that are more sensitive to different supply/demand scenarios and adaptation strategies hence more useful to assess resilience. In addition, a correlation analysis was carried out to identify the minimum number of independent metrics required to characterise and quantify resilience (item (5)). The metric outputs are also evaluated as to how informative they are to decision makers (item (12)), in terms of their consistency of outputs over varying future scenarios/uncertainties and whether they adequately provide an accurate picture of water deficit periods to ultimately identify a metric(s) of resilience that is/are defensible against conventional practices (item (6)).

3 Case Study

Bristol Water currently manages a region in the south-west of the UK supplying approx. 1.2 million customers (as of 2015), which is expected to experience increasing pressures on local water resources from rising populations (with a 15% projected increase in demand by 2045) and increased climate variability that could cause further reductions in the availability of established resources. The climate variability is primarily exacerbated by expected increasing annual temperatures, leading to a greater variation in projected rainfall patterns; ultimately leading to increased and more regular periods of drought conditions (Bristol Water, 2014).

The existing water resources are shown in Figure 2 and listed in Table 3. They consist of a variety of sources, with approximately half of the required supply coming from the River Severn (via the Sharpness canal); a third from reservoirs fed from the Mendip Hills; and the remainder from small wells and springs throughout the supply area (Bristol Water, 2014).

Table 3. BWRZ existing water sources and abstraction priority ordering (Bristol Water, 2014)

Resource Abstraction Priority	Resource Description	Deployable Output[a] (DO) Annual Average - In Ml/d (% of total system output)	Projected by Bristol Water to be Affected by Climate Change?
1	Sharpness canal	210 (57%)	Not Significantly
2	Groundwater sources	65 (18%)	Not Significantly
3	Mendip reservoirs	91 (25%)	Significantly

[a] DO is the yield of the source subject to additional system constraints such as the abstraction license, infrastructure capacity and environmental requirements.

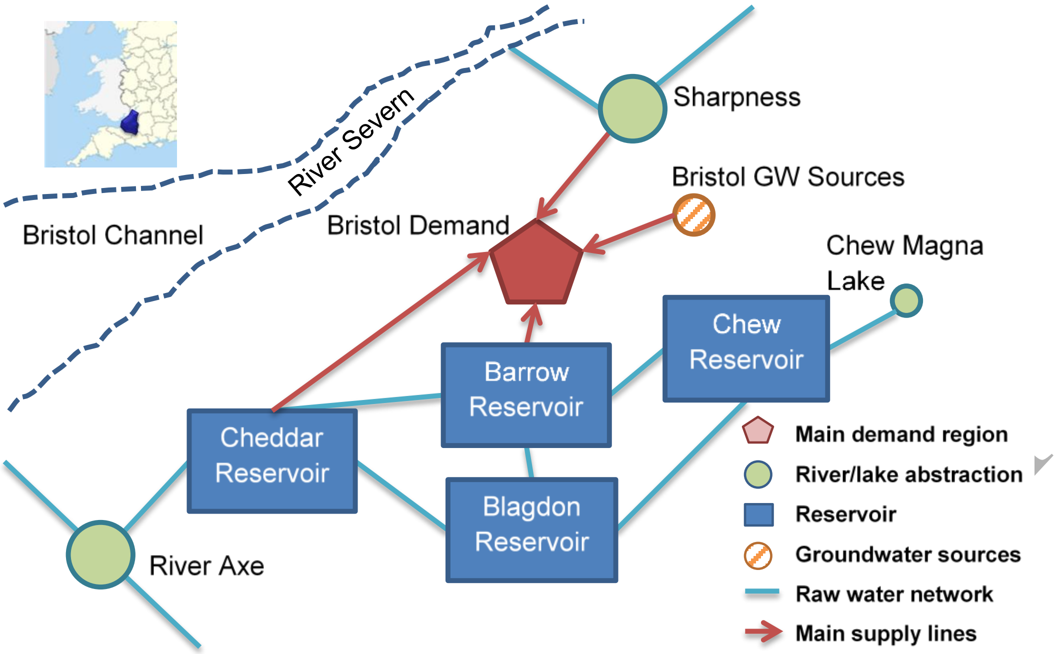


Figure 2. Bristol Water resource zone schematic.

The Bristol Water resource zone is based upon the operation of the company area as a single resource zone. This means that all water resources (river, groundwater and reservoirs) within the company area are capable of being shared throughout the zone at all times of the year via a comprehensive pipe transfer network and using multiple water treatment works (Bristol Water, 2014). In this way, no part of the zone is solely dependent upon the yield of a single water source. The priority order for abstraction of each resource (shown in Table 3) is based on the BWRZ system priority of use. The primary river and groundwater sources are considered reliable and sustainable over the next planning period (2015-2039) following the results of BW's company-wide climate change 'vulnerability assessment' (Bristol Water, 2014); whereas the resource available from the Mendip Reservoirs is anticipated to be impacted by climate change. There are three main components to the reservoir system to be modelled when projecting climate scenarios. These are: the Mendip catchment region (direct reservoir inflows); the river Axe at Cheddar and the lake at Chew Magna (see Figure 2).

The examination of the Bristol Water system in Roach et al. (2015) included the generation of multiple discrete future supply and demand scenarios, utilising the Future Flow scenarios methodology (Prudhomme et al., 2012) to model the reservoir components listed above, and demand projections from Bristol Water's Water Resources Management Plan (WRMP) (Bristol Water, 2014), which were subsequently ordered into a range of severity. The Future Flow projections provide 11 plausible realisations of future river flows (at various sites across the UK) that are then resampled multiple-times to provide a range of variable future supply source inputs. The demand projects (produced by Bristol Water) are derived from projections of low to high population growth and include additional variable factors such as potential changes in per capita consumption and metering levels. In order to examine the sensitivity of the metrics across a range of uncertain future supply and demand scenarios a subset of these scenarios (20 supply and 3 demand scenarios) of varying severity (but fixed monthly values) are selected at intervals from across the range of uncertainty, using a systematic sampling approach. This produced a total of 60 future scenario combinations (of supply and demand) for assessment purposes that encompass projections of low to high demand and low to high changes in future supply availability but ensuring that the more extreme projections are also included, to see how the system responds to being stressed beyond what it has been designed to.

Four adaptation strategies (i.e. combinations of different intervention options sequenced over a planning horizon) are selected for the evaluation of the metrics, with the aim to assess how resilience metrics perform under these conditions. A 25-year planning horizon is selected for the analysis, in order to resemble current UK water company planning horizons. Alternative planning horizons could also be examined, to ascertain the effect changing this variable has on the metric results, however this is an area for further work. The four adaptation strategies selected entail a varying degree of system adaption and include a strategy of “no” adaptation (i.e. no intervention options applied across the planning horizon) through to “low”, “moderate” and “high” level adaptation where multiple intervention options are applied, as detailed in Table 4.

Table 4. Adaptation strategies selected for assessment

Intervention option	DO addition to system (Ml/d)	Selected adaptation strategies – year of intervention option implementation No adaptation	 Low adaptation	 Moderate adaptation	 High adaptation
Options to reduce water losses					
Pressure reduction	2.8	-	2015	2015	2015
Supply pipe replacement	2.2	-	2025	2015	2015
Active leakage control	4.4	-	2025	2015	2015
Options to provide additional supply resources					
Reduction of bulk-transfer agreements	4.0	-	-	2025	2015
Huntspill Axbridge transfer	3.0	-	-	-	2020
Honeyhurst well transfer to Cheddar	2.4	-	-	-	2025
Options to reduce water consumption					
Selective metering of domestic customers	3.2	-	-	-	2025

Each intervention option will carry a level of uncertainty in their projected deployable output (DO). However, a single fixed daily DO has been assumed for this study to simplify the simulation model operation, as the focus here is on analysing the metric results not on accounting for uncertainties. The four adaptation strategies were applied to the existing Bristol Water system configuration and tested over the 60 future scenario combinations of supply and demand over a 25-year planning horizon. The resulting water deficits and resilience metric values were then assessed in relation to each listed performance metric (M1-M10).

The above was done by using a dynamic water resource simulation model that simulates, using a monthly time step, the supply and demand balance of the Bristol Water WRZ in the UK over a pre-established time horizon (25 years). The developed model simulates the existing Bristol Water system and is fully described in Roach et al. (2015). Different adaptation strategies can be examined over different future scenarios of supply and demand and their performance analysed under each resilience indicator (see Table 2). This allows us to compare the performance of resilience metrics across varying adaptation strategies and future conditions.

4 Results and Discussion

4.1 Resilience metrics analysis – sensitivity assessment

The aim of the metrics sensitivity analysis is to assess the response of each of the proposed metrics to a range of stresses in order to identify its performance in describing system resilience. To do so, the resilience metrics values are calculated for each adaptation strategy over each future scenario combination of supply and demand, resulting in 60 individual results for each performance metric under each strategy. Box plots are then produced for each set of metric results in order to gauge the sensitivity of each metric across the scenarios (representing uncertain future) and across different, increasing levels of adaptation applied to the system (see Figure 3).

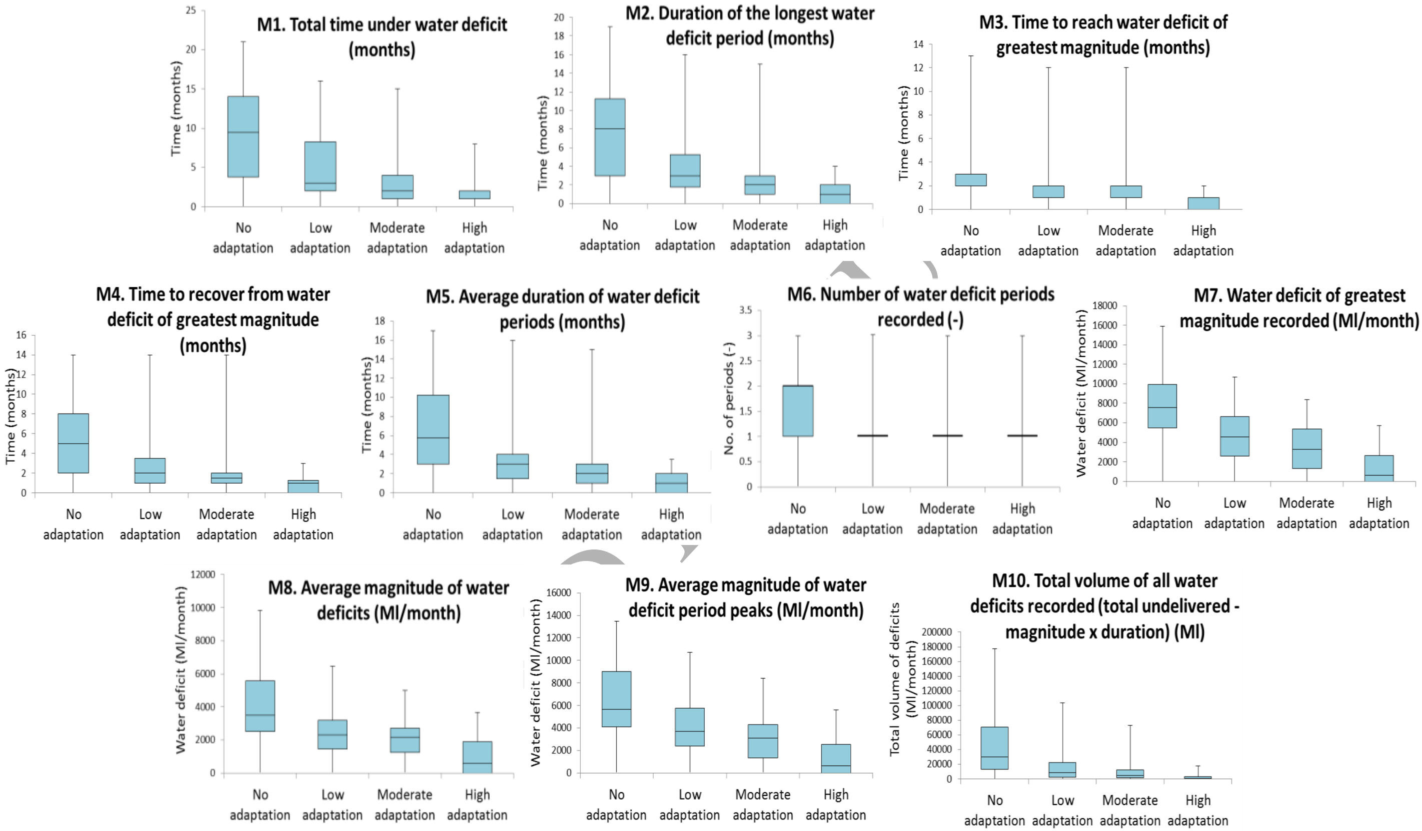


Figure 3. Box plots of performance metric results for all strategies across all scenarios

The following can be noted from Figure 3: (a) most metrics' median (i.e. trend) values reduce (i.e. improve) with increasing levels of adaptation but not always, as can be seen with metric M6, where the number (e.g. frequency) of water deficit periods detected from low to high adaptation exhibit the same median and min to max values. The increasing level of system adaptation reduces the duration and magnitude of the detected water deficit periods. This, however, highlights the misperception that can arise from using frequency only based metrics that do not make a more detailed assessment of water deficit duration or absolute magnitude; (b) the variation (e.g. min to max and interquartile range) of most of metric values also reduces with increasing level of adaptation although again not necessarily always (e.g. M3 and M6). Therefore, utilising metrics M3 and M6 would likely only lead to the recommendation of a lower level of adaptation, whereas applying the alternative metrics would lead to greater adaptation recommendations to increase overall system resilience.

Metrics that are more sensitive to changing conditions are preferable to those that indicate little change in system performance (see Table 1), as sensitive metrics can provide a clear indication of system improvement or deterioration. In contrast, overly sensitive measurements might over-estimate the improvement or deterioration in resilience, suggesting that a moderate and uniform sensitivity is most-preferable. To evaluate the relative sensitivity of each potential resilience metric, heat surface graphs are plotted which show the normalised sensitivity of each metric for each strategy for all scenarios (Figure 4). Normalisation was carried out on a 0-1 range in the min-max form. All metrics recorded an output minimum of 0, therefore normalisation is carried out by dividing each scenario / adaptation strategy output value by the maximum output value for each metric (for example if a given metric output for scenario/strategy combination *a* is 3 months and the largest output for this metric recorded across all scenario/strategy combinations is 12 months, then the normalised value for combination *a* is 0.25.

Each coloured cell on Figure 4 represents one individual discrete future scenario of supply and demand / adaptation strategy combination and its respective normalised value for each metric. Metrics M1-M10 are indexed along the horizontal x-axis with four columns under each metric title displaying the results for adaptation strategies of 'no' to 'high' adaptation (from left to right) with the 60 supply/demand scenarios indexed down the vertical y-axis.

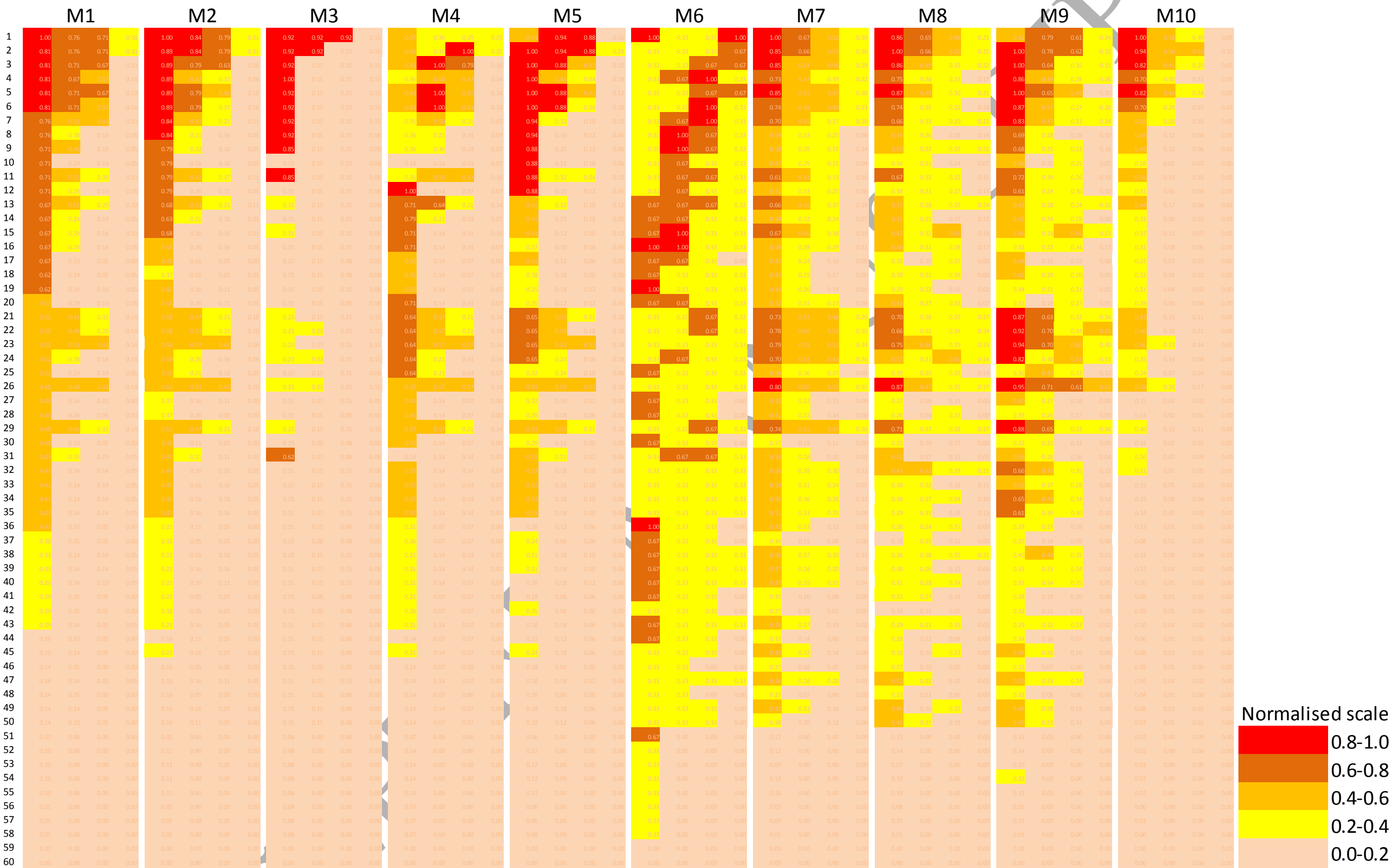


Figure 4. Normalised sensitivity of 10 metrics (M1-M10) across 60 scenarios (of increasing severity from scenario of low demand/increased supply to scenario of high demand/reduced supply) and 4 adaptation strategies (columns from left to right under each metric title displaying the range of ‘no’ to ‘high’ adaptation) as heat surfaces (the darker the shaded cell the closer the value is to 1 on the normalised scale of 0-1)

Figure 4 illustrates how one given scenario can produce very different results when analysed to one metric rather than another. It also shows that magnitude metrics (M7-M9) are the most sensitive of all metrics and maintain the greatest sensitivity across the increasing adaptations to the system, as shown in the largest spread of colours across the scenarios/strategies. The least sensitive metrics are time to water deficit of greatest magnitude (M3) and number of water deficit periods (M6). The duration based metrics, total time under water deficit (M1) and the duration of the longest water deficit (M2), maintain the greater sensitivity across the scenarios.

Figure 4 also shows that metrics M3-M5 tend to cluster more often around common values for multiple scenarios (demonstrated by colours showing less variation across scenarios and adaptation strategies) making the difference in performance under each scenario, or from one strategy to another, harder to ascertain. The variation in recorded performance for the time to reach (M3) and recover from (M4) a water deficit of greatest magnitude also often tend to fluctuate between scenarios (as shown by colours not matching when moving from one scenario to the next). This presents a problem if utilising metrics M3 and M4 individually; as the time for the system to recover (M4) may be of low duration under a given scenario, leading a decision analyst to believe this strategy is performing well over this scenario; however, it may instead exhibit a long duration of time to reach the deficit of greatest magnitude (M3) and vice versa.

Figure 4 also highlights the considerable sensitivity variation between metric M6 and the other metrics, with multiple mid-high cells on the normalised scale appearing across the range of scenario/strategy combinations, making the overall performance of the water system under this metric difficult to clearly ascertain across the range of adaptations and scenarios. This lack of sensitivity in the frequency-based metric M6 is shown more clearly in Figure 5.

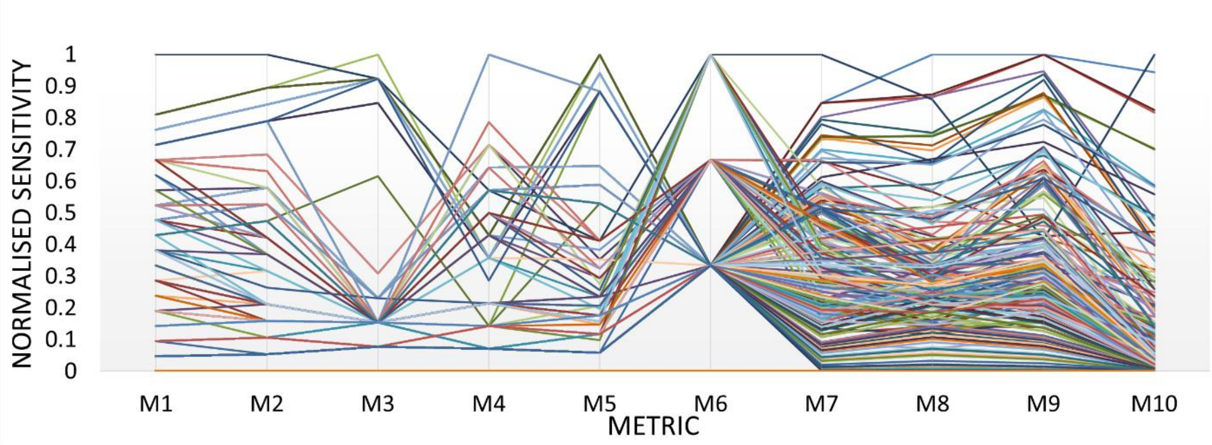


Figure 5. Normalised sensitivity of each metric across all scenarios and adaptation strategies (each coloured line represents one scenario/adaptation strategy combination)

Each coloured line in Figure 5 depicts normalised metrics' values for a specific scenario/adaptation strategy combination. The scenario lines on Figure 5 illustrate again how the performance of an adaptation strategy to a given future scenario of supply and demand can produce very different results when analysed to one metric rather than another (i.e. how the lines cross). Figure 5 displays the significant clustering (low sensitivity) of metrics M3 and M6, the lowest clustering (high sensitivity – possibly overly so) for magnitude metrics M7-M9 and the moderate clustering for metrics M1, M2 and M4, demonstrating their more uniform/moderate sensitivity to analysed scenarios and adaptation strategies.

To investigate the low variation of the time to reach water deficit of greatest magnitude (M3) and the performance of the alternative metrics, the largest deficit periods within a selection of scenarios are isolated and given a more detailed assessment. Three scenarios are selected from across the scenario severity range and the longest water deficit periods are examined in more detail, as shown in Figure 6.

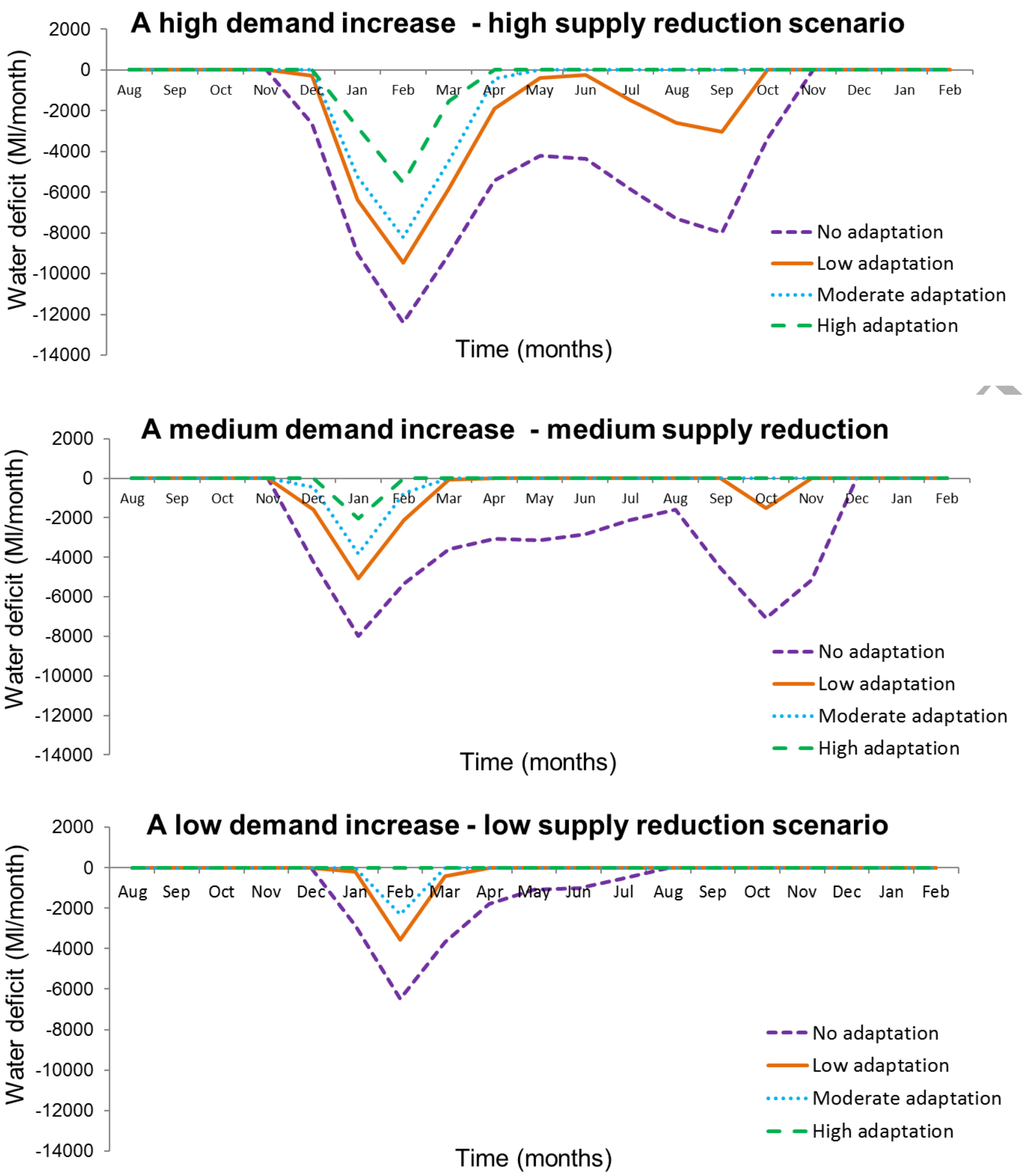


Figure 6. Analysis of largest water deficit periods recorded for three isolated scenarios for all adaptation strategies

Figure 6 shows how the time to reach the water deficit of greatest magnitude (M3) is constant (for most scenarios) across the strategies and it is the time to recover from largest deficits (M4) that is more variable. It is only possible to observe the above when a water deficit period is separated into the absorption (M3) and recovery (M4) periods, i.e. it is not possible to observe this when an aggregate type metric is used for resilience (e.g. M1, M6 or M10), which is what is currently proposed in the literature and utilised in current practice. In addition, Figure 6 shows that the duration of the longest water deficit (metric M2) provides a fairly comprehensive picture of the complete water deficit period without separating out the ‘time to’ and ‘recovery from’ aspects of the deficit period, which, as mentioned previously, can produce variable performance results in the two aspects across the scenarios. Finally, Figure 6 shows that the water deficit of greatest magnitude (M7), although highlighted previously as being very sensitive (which is good) also exhibited a fairly uniform reduction across the three scenarios and four strategies. This may not provide the most informative assessment of the deficit periods as they are shown to have a clearly non-uniform variation in the changes in maximum durations of the deficit periods recorded (M2) and time to recover (M3).

The maximum and average magnitudes of water deficits are slightly less variable (by percentage change) but are still good indicators of the adaptation impacts on system performance. The short time to reach the point of greatest deficit magnitude (exhibited in most scenarios) followed by the longer duration of recovery time, suggests it is individual severe drought months that cause initial water deficit periods to form, which are then recovered from over time. The follow up peaks shown in the high and medium scenarios are caused by repeated water scarcity conditions occurring later in the same deficit period. Note that the above cannot be captured by using a single frequency-based or aggregated type resilience metric.

The above observations clearly demonstrate that the choice of metric(s) has implications on the choice of interventions to implement. Decision makers could decide that small or medium magnitude deficit events can be dealt with via water restrictions alone; however, unforeseen extended duration/recovery times could be costly and more detrimental to the system (and to customers) and require more extensive interventions. From this examination, at least moderate to high adaptation to the case study system would be recommended to reduce water deficit periods of protracted duration over the more extreme projections (i.e. the high demand increase – high supply reduction scenario in Figure 6), whereas only low adaptation may be recommended if targeting a reduction in the magnitude or frequency of water deficits. This example illustrates how examining a more diverse range of resilience metrics can better inform policy makers and strategic planners.

4.2 Resilience metrics analysis – correlation assessment

In order to see how the duration, magnitude and frequency metric values cross-over and compare with each other the correlation between individual metric values obtained is explored. This is important as using two highly correlated metrics for resilience assessment is not desirable.

Figure 7 shows the correlation results obtained for the ten metrics analysed across the 60 supply/demand scenarios and four adaptation strategies. As it can be seen from this figure, strong correlations tend to exist within groups of the same metrics types (e.g. M7-M9) and weaker correlations tend to exist across different metric groups.

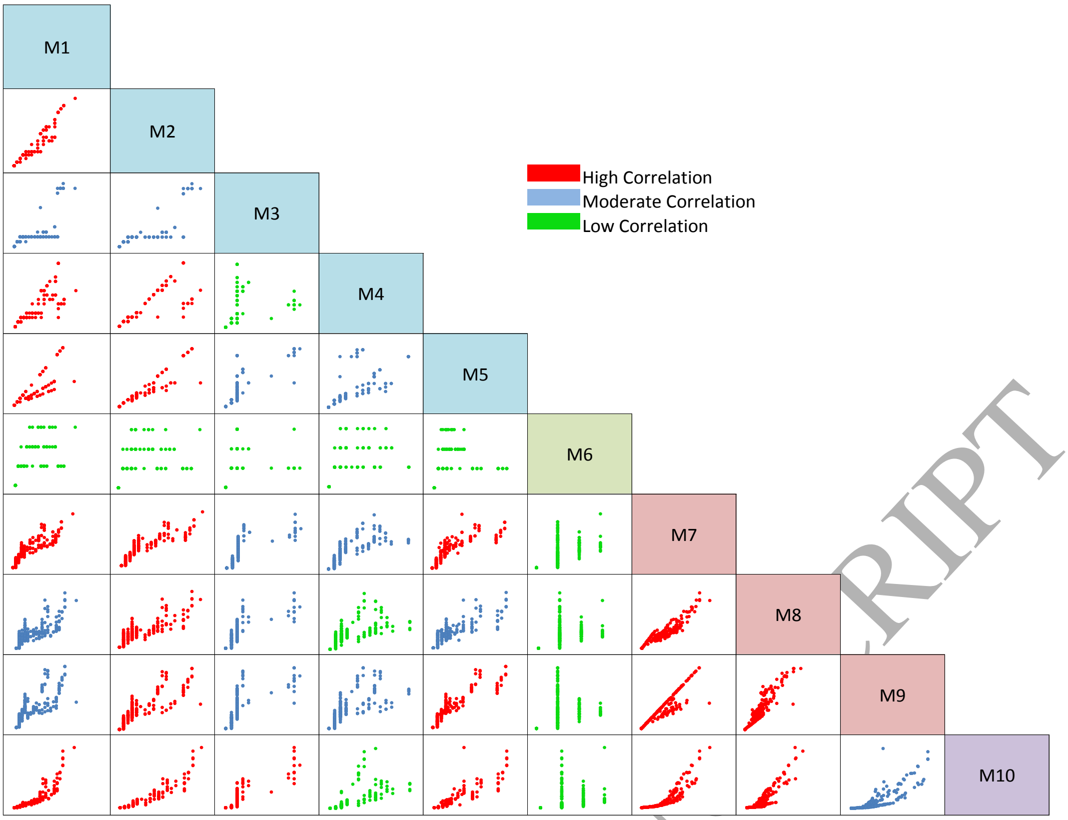
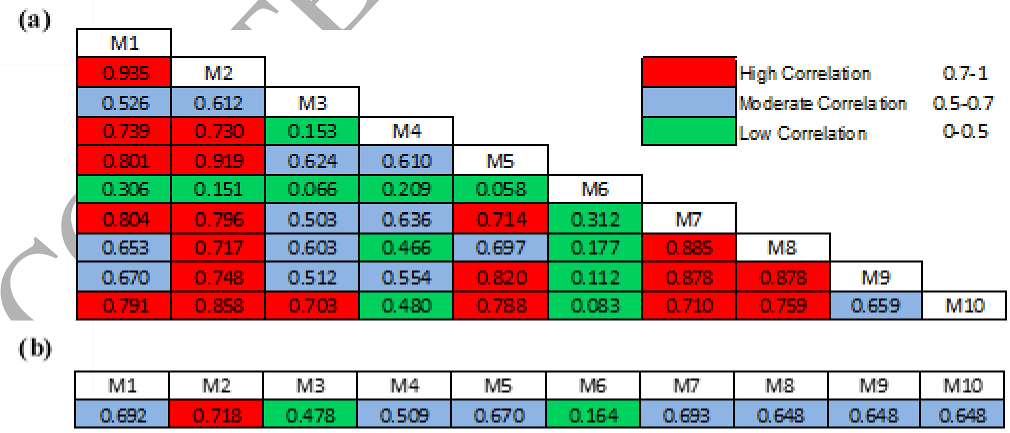


Figure 7. Complete metric correlation results

To further examine the above, the coefficients of determination (i.e. the R^2 values) of each metric correlation are calculated and shown in Figure 8. Note that the R^2 values obtained indicate the proportion of variance between two variables and are scored between 0 and 1 (with 1 indicating perfect correlation between two variables).



(a)

M1									
0.935	M2								
0.526	0.612	M3							
0.739	0.730	0.153	M4						
0.801	0.919	0.624	0.610	M5					
0.306	0.151	0.066	0.209	0.058	M6				
0.804	0.796	0.503	0.636	0.714	0.312	M7			
0.653	0.717	0.603	0.466	0.697	0.177	0.885	M8		
0.670	0.748	0.512	0.554	0.820	0.112	0.878	0.878	M9	
0.791	0.858	0.703	0.480	0.788	0.083	0.710	0.759	0.659	M10

🟥	High Correlation	0.7-1
🟦	Moderate Correlation	0.5-0.7
🟩	Low Correlation	0-0.5

(b)

M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
0.692	0.718	0.478	0.509	0.670	0.164	0.693	0.648	0.648	0.648

Figure 8. (a) Coefficient of determination (R^2 values) for all metrics; (b) the average of the R^2 values for each metric

Figure 8 (a) highlights the low correlation between the frequency of water deficit periods metric (M6) with all other metrics. This low statistical correlation with the other metrics indicates that there is low connection between the changing frequency of water deficit periods and the changing duration/magnitude aspects; however, the frequency-based metric was also shown to be the least sensitive metric, which will inherently reduce the correlation exhibited between this metric and others (as can be seen by the straight lines for M6 on Figure 7). This suggests that metric M6 can provide important deficit information that other metrics do not encompass, but also that it cannot predict other performance aspects, so should not be used on its own.

Figure 8 (a) also indicates (again) that the metrics with the highest correlation are those within the same group, suggesting that using more than one metric from within the same group is unnecessary. It also shows that the aggregated total volume metric (M10) incorporating both magnitude and duration of deficits has the highest correlation with metric M2. This is suggesting that metric M2 can cover multiple performance aspects in a single criterion of performance, further highlighting its potential as a comprehensive duration based metric and as a potential candidate for a WRM resilience measure.

Taking the average of all R^2 values for each metric reveals the most all-encompassing indicators (see Figure 8 (b)). It shows that metric M2 has the highest average R^2 value, again indicating that evaluation of this particular duration-based metric provides a wider indication of more system performance aspects in a single assessment. For example, it demonstrates high correlation with the volume metric (M10) mentioned above, as well as all magnitude (M7-M9) and other duration-based metrics (M1-M5). Indicating it can best encompass these multiple individual assessment aspects in a single metric. Information not as well encompassed by the assessment of the other metrics (as displayed in Figure 8 (b)) include metrics M3, M4 and M6. Additional evaluations of these metrics would be required if the exact characterisation of the time to reach (M3) and time to recover from (M4) the worst magnitude deficits, and the total number of water deficits experienced (M6), was desired.

5 Conclusions

Ten different metrics that could be potentially used to characterise the resilience of a water resources management system to uncertain future changes (i.e. a given scenario of supply and demand) were investigated. An in-depth analysis of the metrics was carried out on a real-world case study of Bristol Water’s supply system, including an examination of metric sensitivity and correlation, and a detailed examination of the behaviour of water deficit periods. The results obtained lead to the following key recommendations for the selection of an appropriate resilience-based performance metric:

1. Simultaneous use of multiple metrics covering different aspects of resilience and related water deficit events is recommended. This does not seem to be the case currently in the literature (where typically a single metric is used to assess water system's resilience) nor in engineering practice (where quantitative resilience metrics are not used much, if at all).

2. Metric M2 ("the duration of longest water deficit period" metric) was observed to be one of the more informative and comprehensive performance metrics followed closely by metric M7 ("the water deficit of greatest magnitude recorded" metric). However, the analysis demonstrated a relatively high correlation between the two metrics and therefore considering just a single metric may prove sufficient to evaluate the resilience of a water resource system. A duration based metric would be a more logical assessment metric to use of the two types, as it is the duration of temporary water restrictions that most impact on customers and supply, whereas the magnitude of water deficit events is of less direct concern to customers and water companies so long as the magnitude is maintained within acceptable threshold levels. All this seems consistent with the resilience metric suggested by Hashimoto et al. (1982) now supported with actual evidence.

3. Frequency type resilience metrics (M6, and in essence M1) cover important aspects/information and would also prove beneficial to measure, as emphasised by the low correlation between M6 and all other metrics; however, metric M6 was also found to be highly un-sensitive and unable to capture the size of 'impact' on the system from water deficit periods, so should not be used on its own.

4. Aggregated type resilience metrics (e.g. averaging metrics M5/M8/M9 or sum/volume type metrics such as M10) are fairly sensitive to different adaptation strategies and supply/demand scenarios but there is also a considerable uncertainty in their calculation due to their nature (i.e. is it a single big or several small deficit periods occurring to give the final values) making it harder to clarify exact adaptation strategy and system performance.

5. Magnitude type resilience metrics (M7-M9) are highly sensitive and provide useful information, especially in terms of proximity to critical threshold levels; however, they do not provide a full picture of deficit events/periods.

6. Duration type resilience metrics are also highly sensitive with "the duration of longest water deficit period" metric (M2) providing the more complete picture of a deficit event. It is also the metric that exhibits the highest correlation to all other metrics. Splitting the duration of a water deficit period into the time to max peak deficit (M3) and time to recover from max peak deficit (M4) (as suggested in Linkov et al. (2014)) provides more detailed water deficit

period information, but the relative performance of each aspect tends to be highly variable when assessed across multiple scenarios of future supply and demand, reducing the clarity of each as a consistent measure of performance.

The above findings are limited to the Bristol case study analysed here. The metrics proposed in the paper are generic and hence could be readily applied to improve the resilience analysis of any number of different water resource systems. The drawback is that a dynamic water resources network simulation model with a daily or monthly timestep would be required to accurately measure them. The effect of utilising a single duration (resilience) based metric or a single 'current practice' frequency (reliability) based metric for WRM adaptation planning should be examined more in-depth (on additional case studies) to derive if both, or a single metric, is sufficient for effective resilience assessment, i.e. optimal adaptation planning. The effect of utilising a daily rather than monthly time-step could also be examined, as this will likely favour some of the metrics over others, i.e. a single month duration deficit recorded may theoretically have multiple frequency individual deficits occurring within this single month. A potential aspect not captured in a monthly time-step. This investigation also centralised around water deficit periods to define and analyse the various resilience metrics, further work could investigate the definition of resilience beyond these concepts and whether the metrics investigated here could be applied to alternative sectors or systems, i.e. forms of ecosystem resilience.

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References

Angeler, D. G., & Allen, C. R. (2016). Quantifying resilience. *Journal of Applied Ecology*, *53*(3), 617–624. http://doi.org/10.1111/1365-2664.12649

Bristol Water. (2014). *Water resources management plan 2014*. Bristol, UK. Retrieved from http://www.bristolwater.co.uk/

Butler, D., Ward, S., Sweetapple, C., Astaraie-Imani, M., Diao, K., Farmani, R., & Fu, G. (2016). Reliable, resilient and sustainable water management: The Safe & SuRe approach. *Global Challenges*, 1–15. http://doi.org/10.1002/gch2.1010

Carpenter, S. R., Westley, F., & Turner, M. G. (2005). Surrogates for resilience of social-ecological systems. *Ecosystems*, *8*(8), 941–944. http://doi.org/10.1007/s10021-005-0170-y

Carpenter, S., Walker, B., Anderies, J. M., & Abel, N. (2001). From metaphor to measurement: Resilience of what to what? *Ecosystems*, *4*(8), 765–781. http://doi.org/10.1007/s10021-001-0045-9

Davidson, J. L., Jacobson, C., Lyth, A., Dedekorkut-Howes, A., Baldwin, C. L., Ellison, J. C., … Smith, T. F. (2016). Interrogating resilience: Toward a typology to improve its operationalization. *Ecol. Econ.*, *21*(2). http://doi.org/10.5751/ES-08450-210227

Defra. (2011). *Climate resilient infrastructure: Preparing for a changing climate*. The Stationery Office, London, UK.

Defra. (2013). *Updating the general duties with respect to the water industry to reflect the UK Government's resilience priorities*. London, UK. Retrieved from www.gov.uk

Defra. (2016). *Creating a great place for living: Enabling resilience in the water sector*. Retrieved from https://www.gov.uk/government/publications/water-sector-improving-long-term-resilience

Environment Agency. (2013). *Water resources management plans 2019 – preparing for the future (main report)*. Halcrow Group Ltd, Swindon, UK.

Environment Agency. (2015). *Water supply and resilience and infrastructure: Environment Agency advice to Defra*. Retrieved from https://www.gov.uk

Folke, C. (2006). Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environ. Chang.*, *16*(3), 253–267. http://doi.org/10.1016/j.gloenvcha.2006.04.002

Fowler, H. J., Kilsby, C. G., & O'Connell, P. E. (2003). Modeling the impacts of climatic change and variability on the reliability, resilience, and vulnerability of a water resource system. *Water Resour. Res.*, *39*(8), 1222. http://doi.org/10.1029/2002WR001778

Groves, D. G., Yates, D., & Tebaldi, C. (2008). Developing and applying uncertain global climate change projections for regional water management planning. *Water Resour. Res.*, *44*(12), W12413. http://doi.org/10.1029/2008WR006964

Hashimoto, T., Stedinger, J. R., & Loucks, D. P. (1982). Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resour. Res.*, *18*(1), 14–20. http://doi.org/10.1029/WR018i001p00014

Holling, C. S. (1986). *The resilience of terrestrial ecosystems: local surprise and global change*. Clark, W.C., Munn, R.E. (Eds.), Sustainable Development of the Biosphere. Cambridge University Press, Cambridge, UK.

Holling, C. S. (1996). Engineering resilience versus ecological resilience. *Engineering Within Ecological Constraints*, (1996), 31–44. http://doi.org/10.17226/4919

Hosseini, S., Barker, K., & Ramirez-Marquez, J. E. (2016). A review of definitions and measures of system resilience. *Reliab. Eng. Syst. Safe.*, *145*, 47–61. http://doi.org/10.1016/j.ress.2015.08.006

Jung, D. (2013). *Robust and resilient water distribution systems*. PhD thesis. University of Arizona, USA.

Kjeldsen, T. R., & Rosbjerg, D. (2004). Choice of reliability, resilience and vulnerability estimators for risk assessments of water resources systems. *Hydrol Sci J*, *49*(5), 755–767. http://doi.org/10.1623/hysj.49.5.755.55136

Kundzewicz, Z. W., & Kindler, J. (1995). Multiple criteria for evaluation of reliability aspects of water resource systems. In *Modelling and Management of Sustainable Basin-scale Water Resources Systems* (pp. 217–224). (ed. by S. P. Simonovic, Z. Kundzewicz, D. Rosbjerg & K. Takeuchi) (Proc. Boulder Symp., July 1995), 217–224. IAHS Publ. 231. IAHS Press, Wallingford, UK. Retrieved from http://www.scopus.com/scopus/inward/record.url?eid=2-s2.0-0029519707&partnerID=40

Lansey, K. (2012). Sustainable, robust, resilient, water distribution systems. In *In Proceedings of the 14th Water Distribution Systems Analysis Conference*. Adelaide, Australia.

Linkov, I., Bridges, T., Creutzig, F., Decker, J., Fox-Lent, C., Kröger, W., … Thiel-Clemen, T. (2014). Changing the resilience paradigm. *Nature Clim. Change*, *4*(6), 407–409. http://doi.org/10.1038/nclimate2227

Loucks, D. P. (1997). Quantifying trends in system sustainability. *Hydrological Sciences Journal*, *42*(4), 513–530. http://doi.org/10.1080/02626669709492051

Maier, H. R., Guillaume, J. H. a., van Delden, H., Riddell, G. a., Haasnoot, M., & Kwakkel, J. H. (2016). An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together?

Environ. Modell. Softw., *81*, 154–164. http://doi.org/10.1016/j.envsoft.2016.03.014

Matrosov, E. S., Padula, S., & Harou, J. J. (2012). Selecting portfolios of water supply and demand management strategies under uncertainty—contrasting economic optimisation and “robust decision making” approaches. *Water Resour. Manage.*, *27*(4), 1123–1148. http://doi.org/10.1007/s11269-012-0118-x

Matrosov, E. S., Woods, A. M., & Harou, J. J. (2013). Robust decision making and info-gap decision theory for water resource system planning. *J. Hydrol.*, *494*, 43–58. http://doi.org/10.1016/j.jhydrol.2013.03.006

Moody, P., & Brown, C. (2013). Robustness indicators for evaluation under climate change: Application to the upper Great Lakes. *Water Resour. Res.*, *49*(6), 3576–3588.

Moy, W.-S., Cohon, J. L., & ReVelle, C. S. (1986). A programming model for analysis of the reliability, resilience, and vulnerability of a water supply reservoir. *Water Resour. Res.*, *22*(4), 489–498. http://doi.org/10.1029/WR022i004p00489

Ofwat. (2015). *Resilience Task and Finish Group - final report*. Retrieved from http://www.ofwat.gov.uk/wp-content/uploads/2015/12/rpt_com20151201resiliencetaskfinish.pdf

Paton, F. L., Dandy, G. C., & Maier, H. R. (2014). Integrated framework for assessing urban water supply security of systems with non-traditional sources under climate change. *Environ. Modell. Softw.*, *60*, 302–319. http://doi.org/10.1016/j.envsoft.2014.06.018

Prudhomme, C., Dadson, S., Morris, D., Williamson, J., Goodsell, G., Crooks, S., … Lafon, T. (2012). “Future flows climate.” Retrieved from http://dx.doi.org/10.5285/bad1514f-119e-44a4-8e1e-442735bb9797.

Roach, T., Kapelan, Z., & Ledbetter, R. (2015). Comparison of info-gap and robust optimisation methods for integrated water resource management under severe uncertainty. *Procedia Engineering*, *119*, 874–883. http://doi.org/10.1016/j.proeng.2015.08.955

Seekell, D., Carr, J., Dell’Angelo, J., D’Odorico, P., Fader, M., Gephart, J., … Tavoni, A. (2017). Resilience in the global food system. *Environmental Research Letters*, *12*(2). http://doi.org/10.1088/1748-9326/aa5730

Smit, B., Burton, I., Klein, R. J. T., & Wandel, J. (2000). An anatomy of adaptation to climate change and variability. *Climate Change*, *45*, 223–251. http://doi.org/10.1023/A:1005661622966

UKWIR. (2016). *WRMP 2019 methods – decision making process: Guidance*. Report Ref. No. 16/WR/02/10. Retrieved from https://www.ukwir.org/146387?object=151577

Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social – ecological Systems. *Ecol. Soc.*, *9*(2), 5. http://doi.org/10.1103/PhysRevLett.95.258101

Walker, B., & Salt, D. (2006). *Resilience thinking*. Island Press, Washington, DC.

Water UK. (2016). *Water resources long term planning framework (2015-2065)*. Retrieved from http://www.water.org.uk/

Yazdani, A., Otoo, R. A., & Jeffrey, P. (2011). Resilience enhancing expansion strategies for water distribution systems: A network theory approach. *Environ. Modell. Softw.*, *26*(12), 1574–1582. http://doi.org/10.1016/j.envsoft.2011.07.016