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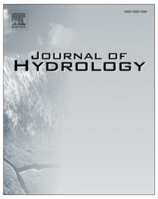

Research papers

Quantitative assessment of resilience of a water supply system under rainfall reduction due to climate change

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ABSTRACT

A water supply system can be impacted by rainfall reduction due to climate change, thereby reducing its supply potential. This highlights the need to understand the system resilience, which refers to the ability to maintain service under various pressures (or disruptions). Currently, the concept of resilience has not yet been widely applied in managing water supply systems. This paper proposed three technical resilience indictors to assess the resilience of a water supply system. A case study analysis was undertaken of the Water Grid system of Queensland State, Australia, to showcase how the proposed indicators can be applied to assess resilience. The research outcomes confirmed that the use of resilience indicators is capable of identifying critical conditions in relation to the water supply system operation, such as the maximum allowable rainfall reduction for the system to maintain its operation without failure. Additionally, resilience indicators also provided useful insight regarding the sensitivity of the water supply system to a changing rainfall pattern in the context of climate change, which represents the system's stability when experiencing pressure. The study outcomes will help in the quantitative assessment of resilience and provide improved guidance to system operators to enhance the efficiency and reliability of a water supply system.

1. Introduction

Reliability of a water supply system depends on its ability to provide a sufficient quantity of water of a specified quality to end users without disruptions (Hwang et al., 2014). However, disruptive forces can act on a water supply system, reducing the supply potential (Bhamra et al., 2011). Climate change is one of the most significant disruptive forces (pressures), since it is predicted to lead to high variability in rainfall patterns, with more frequent extreme weather events including droughts and high intensity rainfall (Abbs et al., 2007; van der Pol et al., 2015; Chen et al., 2014; Teng et al., 2012). For example, the reduction in rainfall will decrease the water volume contributed to a rain-fed water supply system, leading to reduced system resilience (Paton et al., 2014).

The successful management of a water supply system depends on an in-depth understanding of the system's resilience, which is defined as the capacity for absorbing external pressures or disturbances (such as rainfall reduction) and re-organising while still retaining its functionality (Watts et al., 2012; Hosseini et al., 2016; Mereu et al., 2016). In the context of a water supply system in a changing climate, resilience refers to the ability of the system to maintain its service despite experiencing reduction in rainfall due to climate change impacts. Taking system resilience into consideration offers significant operational benefits to improve the reliability of water supply under uncertain climatic conditions. It allows system operators to prevent catastrophic failure by identifying trigger points for timely action and implementation of remedial measures.

Unfortunately, the resilience concept has not yet been widely applied in the management of water supply systems, although a few researchers such as Moy et al. (1986), Hashimoto et al. (1982) and Watts et al. (2012) have undertaken studies on the resilience of water supply systems. These previous studies have primarily focused on the recovery capacity of the system after experiencing pressures and the system performance during a consecutive drought. However, focusing on the water volume supplied by the system due to changes in rainfall reduction arising from climate change is quite limited. This constrains the identification of

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the critical rainfall reduction threshold at which the system can maintain its functionality without failure, which is crucial for the effective operation of a water supply system. Since system resilience involves system performance under particular pressures, a reliable resilience assessment must be developed specifically for the system and the pressures it faces (Bhamra et al., 2011; Rochas et al., 2015). In the case of a water supply system, and in the context of predicted climate change impacts, it requires the development of an approach to assess water supply service under decreasing rainfall scenarios, which is the key pressure or disruptive influence on the system. This highlights the need to identify appropriate indicators which can quantitatively evaluate resilience.

A conventional water supply system is a combination of complex subsystems, consisting of the water supply catchment, water storage reservoir, water treatment plant and water distribution network. Water storage is determined by the storage capacity and inflow (primarily from surface runoff from the catchment and streamflow), while water treatment and distribution closely depend on the availability of water in the storage (Ahmad and Simonovic, 2000). Therefore, water inflow, which influences water storage, is among primary determinants of the successful functioning of the entire water supply system. In this regard, developing an approach to assess the water supply system resilience (capacity for maintaining service) under rainfall reduction can provide useful insights into effective system management. For example, understanding resilience can assist in identifying the threshold rainfall reduction where the water supply system can maintain its operation without failure. It can also help to understand the sensitivity of the water supply system to a changing rainfall pattern so that the operators are well aware of the system's stability when experiencing pressure or disruptive influences.

Resilience assessment is commonly undertaken to assess the performance of a system under specific scenarios for which modelling approaches can be used. In this context, this paper presents a suite of technical resilience indicators which can be employed to quantitatively assess the resilience of a water supply system under decreasing rainfall. Use of these indicators is expected to provide improved guidance to system operators to enhance the efficiency and reliability of water supply systems under threats posed by climate change impacts.

2. Methods and materials

2.1. Case study area

The case study was the Southeast Queensland (SEQ), Australia, Water Grid system. The Water Grid is a diverse system of water reservoirs and treatment facilities with an interconnecting network of pipelines. It consists of 12 main reservoirs with each reservoir forming a subsystem including a catchment, a reservoir and a treatment plant. These 12 reservoirs are Maroochy, Ewen Maddock, Lake Macdonald, Lake Kurwongbah, Maroon, Moogerah, Gold Coast, Leslie Harrison, Somerset, Wivenhoe, North Pine and Baroon pocket.

The supplies to the Water Grid system are from surface sources which convey and store water using reservoirs and weirs. As the Water Grid system encompasses an area of 22,420 km^2, hydrologic and climatic characteristics of the individual catchments in the system have high spatial variability. A schematic of the Water Grid system is shown in Fig. 1. The SEQ region is expected to experience low rainfall, higher temperature and higher evaporation in the future, due to climate change. This decreasing trend of rainfall due to climate change has the potential to increase stress on the Water Grid system and thereby reduce its resilience.

2.2. Modelling approach and model development

2.2.1. Modelling approach

System dynamics modelling was selected as the primary analytical tool for this study, as it can be readily used to investigate the relationships between a system's behaviour over time and its structure (Zhu et al., 2015; Sahin et al., 2016). The modelling software, STELLA, was selected as the modelling platform due to its high performance and fast simulation capability (Mereu et al., 2016). The simulations undertaken using STELLA primarily consisted of mathematical equations describing the functions of the system through time and space (Costanza and Gottlieb, 1998). Based on these equations, when the system state and conditions are known at a point in time, the system state and condition at the next point in time can be determined. Repeating these processes, the system behaviour can be simulated through step-wise progression over any desired time period (Feng et al., 2013).

As this study was to investigate variations in system behaviour with respect to the pressures applied on the system rather than evaluating hydrologic characteristics of a catchment, the generic response of the system to selected scenarios was considered appropriate for the assessment of system behaviour. In this regard, the important concern was to identify the interdependencies and the relationships between different subsystems of the water supply system. Accordingly, the purpose of developing the Water Grid model was to undertake simulations under different pressure scenarios and thereby to understand the system capabilities, which in turn would allow the formulation of proactive management strategies.

The SEQ Water Grid model developed included a mix of characteristics suited to both, deterministic as well as stochastic modelling. Deterministic models produce an output with fixed input data while stochastic model simulations provide changed output for unique input for different model simulations due to the inclusion of random components in the modelling process. In this context, multiple runs of a stochastic model are used to estimate probability distributions (Silva-Santos et al., 2006). For each selected rainfall scenario, a number of simulations were undertaken in order to generate a data population for analysing the system performance such as failure probability.

2.2.2. Model development

The model development included three stages, namely, conceptualisation, formulation and model calibration. Detailed information regarding model development including input data used is provided in the Supplementary Information and Appendix. In brief, conceptualisation stage was to establish the complete system in a schematic form to correlate each sub-system such as rainfall, surface flow and reservoir storage. The steps to conceptualising the Water Grid system were: (1) to conceptualise the governing factors influencing the final outputs; (2) to define the objective of modelling; (3) to identify the model boundaries; (4) to identify the rate of output from the system; (5) to develop the causal loop diagram (see Fig. 2); (6) to establish the mechanism for changing the rainfall input; and (7) to undertake the water balance analysis for a reservoir. Detailed information regarding model development including input data used is provided in the Supplementary Information and Appendix.

A causal loop diagram was developed for each reservoir while the diagram for the entire Water Gird system was composed of the 12 reservoir diagrams. As shown in Fig. 2, the causal loop diagram included a number of elements such as rainfall, catchment characteristics, evaporation, water treatment and water supply. The (+) or (−) sign represents positive or negative correlation. For example, there is a (+) sign between 'surface runoff' and 'in-