Environmental Modelling & Software 72 (2015) 117–125

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Reliability of water supply from stormwater harvesting and managed aquifer recharge with a brackish aquifer in an urbanising catchment and changing climate

R. Clark [a], D. Gonzalez [b,*], P. Dillon [b], S. Charles [c], D. Cresswell [a], B. Naumann [d]

[a] Clark and Associates, Adelaide, Australia
[b] CSIRO Land and Water, PMB2 Glen Osmond, SA 50564, Australia
[c] CSIRO Land and Water, PMB Wembley, WA 6014, Australia
[d] City of Salisbury, PO Box 8, Salisbury, SA 5108, Australia

ARTICLE INFO

Article history:
Received 7 April 2015
Accepted 13 July 2015
Available online xxx

Keywords:
WaterCress
Downscaling
MAR
Runoff
Artificial recharge
Reliability

ABSTRACT

Recent research shows stormwater harvesting with Managed Aquifer Recharge (MAR) and complementary treatment can deliver safe potable water supplies. To address supply reliability the "WaterCress" hydrological model was used iteratively to simulate runoff, recharge and recovery for different rainfall, catchment and aquifer conditions, and operational scenarios based on the Parafield scheme in Salisbury, South Australia. Using historical rainfall and current catchment and operating conditions, annual demand equating to 12.8% of catchment rainfall could be met with 99.5% volumetric reliability. Using projected rainfalls from a high emission climate scenario resulted in a smaller harvestable volume decline than the increase expected from urban consolidation. Freshwater storage depletion in the brackish aquifer was expected to reduce the supply by 10% with 99.5% reliability compared with zero depletion. This simple generic modelling approach was useful for estimating reliability of stormwater MAR systems to assist planning and design and provide a basis for investor confidence.

Software availability

WaterCress model software and manual are freely available at: http://www.waterselect.com.au/download/download.html.

1. Introduction

A stormwater harvesting and aquifer storage and recovery (ASR) system has been operated at Parafield Airport in Adelaide, South Australia, since 2003 by the City of Salisbury. Urban runoff from a residential and industrial catchment of 1590 ha has been diverted from a stormwater drain into an adjacent capture basin set below the drain invert level. High rate pumps lift the captured water into a holding basin from where it is released via a constant flow rate reedbed for treatment and injection into an underlying confined limestone aquifer. Injection and subsequent recovery has been via a combination of two ASR wells (where water is recovered from the injection wells), or a field of aquifer storage transfer and recovery (ASTR) wells where four injection wells surround two separate recovery wells. Recovered water is used for irrigation and industrial supplies and to dilute a separate recycled water supply for non-potable household use.

Urban runoff and stormwater system modelling has historically focussed on modelling runoff generation and performing flood risk analyses, modelling hydraulics and stormwater infrastructure, and stormwater quality modelling. The nature of these modelling approaches were examined by Zoppou (2001) and Elliot and Trowsdale (2007) reviewed and compared the features of a range of commonly used stormwater modelling codes. The stormwater recycling system modelling approach applied in this study differs from published studies in that stormwater hydrology was coupled with a subsurface storage component and customer demand and volumetric reliability of supply using different scenarios were determined through an iterative process. The modelling code chosen is similar in many ways to other water balance based

* Corresponding author.
E-mail addresses: richardc@chariot.net.au (R. Clark), dennis.gonzalez@csiro.au (D. Gonzalez), peter.dillon@csiro.au (P. Dillon), steve.charles@csiro.au (S. Charles), bnaumann@salisbury.sa.gov.au (B. Naumann).

http://dx.doi.org/10.1016/j.envsoft.2015.07.009
1364-8152/

hydrological models (Elliot and Trowsdale, 2007) but contains additional components to account for storage losses from the subsurface and collection of statistics from multiple simulations of each scenario.

MAR operations at Parafield have been studied extensively including for public health and environmental risk assessment, hydraulic modelling, operational management, impacts to infrastructure and water aesthetics, economics and public acceptance (Dillon et al., 2014). Much of this research addressed water quality assurance to support potable and non-potable supplies and this paper focuses only on the reliability of supply. Water utilities are generally required to meet a prescribed level of supply reliability. Gao et al. (2014) used a Monte Carlo technique accounting for variations in reservoir storage to model municipal water supply to determine the most cost effective supply configurations of groundwater replenishment with recycled water or desalination that met a 99.5% supply reliability. In this current study the relationship between water demand and reliability of supply was determined for the various scenarios. For potable supplies a 99.5% volumetric reliability standard was adopted, and for non-potable supplies, 95%. During a recent drought affecting most Australian capital cities, seawater desalination plants were built to secure water supplies. Levelised costs were considerably higher than the pre-existing average costs of water supplies, mostly from rural catchments within those cities, showing the high value placed on water security. Although urban stormwater is a climate-dependent source, impervious catchments are much less vulnerable to reduced runoff than pervious catchments during drought, and if coupled with aquifer storage, their reliability could be high.

The observed and projected drying climate for southern Australia reduces confidence in historical rainfall reliability as a guide to future water availability (Charles et al., 2003). In this paper daily rainfall was simulated based on historical records and also downscaled from a global circulation model (GCM) representing one of the more severe climate change scenarios. In growing cities the impervious area also grows through infill developments that may generate more runoff. The contrasting effects of more runoff from increased impervious area and reduced runoff from lower rainfall were compared. Furthermore the effects on the yield-reliability relationship were evaluated for several stormwater harvesting design and operating parameters, and for the rate of depletion of recoverable fresh water due to mixing in an originally brackish aquifer.

2. Methods

2.1. Modelling scenarios

A hydrologic model (WaterCress as described in Section 2.3) with a daily time step was used to:

- Convert daily rainfall to stormwater runoff at the harvesting location at Parafield
- Route the stormwater that can be accommodated through the harvesting system based on current and proposed designs and operating criteria for recharge to the aquifer
- Account for the water balance in the aquifer, based on the sequences of seasonal recharge and recovery and depreciating the residual fresh water storage to account for mixing with native brackish groundwater
- Record the daily recovery based on pre-defined demand, subject to freshwater storage in the aquifer being adequate
- Maintain accounts for rainfall, runoff, recharge, recovery and unmet demand, and track the volume in the harvesting facility detention storage and in the aquifer

Simulations with 100 synthetic sequences each of 51 years of daily rainfall were used to determine the volume and reliability of supply for eight different scenarios. The input parameters for these scenarios are summarised in Table 1. Using a stepwise approach, each scenario tested the sensitivity of the reliability of supply to different rainfall sequences (1A-historical; 1B- downscaled from a GCM), increased impervious area (by 20%) through urbanisation, increased wetland detention time, a lower recharge rate, various aquifer freshwater storage depreciation rates and a change in the minimum aquifer fresh water storage threshold before recovery ceases. The rest of this methodology section sequentially addresses each component of the modelled system.

2.2. Rainfall sequences

In order to determine reliability of supply, 100 synthetic sequences of daily rainfall (along with other climatic data) were produced for Parafield airport for historical and future simulation periods of 51 years for use in rainfall-runoff and harvesting system simulations. Two representations of synthetic rainfall sequences were used; (1A) was representative of the historical rainfall sequence 1959–2009 inclusive, and (1B) represented a 2010–2060 climate downscaled from a GCM projection representative of a drying climate in southern Australia.

The sequences were generated by a stochastic downscaling model, the nonhomogeneous hidden Markov model (NHMM), which simulates daily multi-site rainfall via a discrete set of 'weather states' representing distinct spatial patterns of rainfall across a network of stations. The simulation of daily sequences of the weather states, and hence station rainfall, was conditional on a small set of atmospheric predictors (such as mean sea level pressure, wind speeds and moisture contents at several levels in the atmospheric profile) selected on a seasonal basis to optimise the reproduction of observed rainfall variability across daily to interdecadal scales (Charles et al. 2003). For calibration and historical downscaled simulations the NCEP/NCAR Reanalysis data (Kalnay et al. 1996) were the source of atmospheric predictors, which were extracted for the South Australian region. The NHMM performed well compared to other downscaling approaches (Frost et al. 2011) and has been used in hydrological investigations of observed variability (Fu et al. 2013) and impacts of projected climate change in Australia (Crosbie et al. 2011).

The statistics of the 100 simulations of historical rainfall 1959–2009 (1A) compare very favourably with those of the actual record for the historical period of its availability (Table 2). A Monte Carlo analysis of volumetric supply reliability depends on accumulated net storage to meet demand. Hence drought in early years of a system's operation was considered to be more likely to cause failure than in later years when storage had opportunity to accumulate. It was found that the mean annual rainfall for any individual year over the 100 simulations of the historical rainfall (1A) could be more than one standard deviation different from the mean annual rainfall over all 51 years and 100 sequences. To remove bias through always starting model runs on the same year (1959), start years for the 100 simulations were randomised. When the end of the each sequence was reached (2009) rainfall data recommenced from the beginning until all data were used once. Whilst this data sampling strategy marginally affects serial correlation it was considered necessary for reliability analysis. For downscaled GCM rainfalls there was a distinct downward trend in the data so start dates were not randomised.

For each scenario and demand combination evaluated, the reliability analysis therefore relied on 5100 years of resampled synthetic daily data. To represent a realistic start-up for stormwater harvesting-MAR operations each 51 year simulation started in mid-