Hydrogeology Journal (2019) 27:2447–2470
https://doi.org/10.1007/s10040-019-02004-0

PAPER

Do groundwater management plans work? Modelling the effectiveness of groundwater management scenarios

E. K. White[1] · J. Costelloe[1] · T. J. Peterson[1] · A. W. Western[1] · E. Carrara[2]

Received: 31 October 2018 / Accepted: 15 June 2019 / Published online: 4 July 2019

Abstract

In contrast to management optimisation methods, which quantify decision variables to create plans, this study does not seek the "best" strategy. Instead, it simulates the sequential decision-making process implicit in environmental management, so that the effectiveness of management scenarios, when implemented as intended, can be evaluated. The purpose was to develop a methodology to quantitatively evaluate the effectiveness of groundwater management plans by simulating sequential management decisions that evolve based on aquifer/management feedback. A groundwater management scheme was structured as a system control loop to capture the aquifer/management feedback, and management decisions were based on realistically sparse observation times and locations. The method indicates how a plan may proceed in reality under alternate timings and frequencies of management decisions and in systems with differing response times. A synthetic example quantified the impact of a generic plan, specifying environmental objectives, extraction restrictions and entitlement limits (maximum volume/year that users are permitted), relative to no-management by combining a numerical model of "reality" with management rules under a stochastic climate. The management decision-making frequency varied from daily to decadal. Generally, effectiveness decreased as the interval between management interventions increased and intervals greater than annual showed minimal improvement compared to entitlement only. The timing of management decisions relative to the irrigation season also impacted plan effectiveness, and when decisions were made prior to the irrigation season, quarterly management was less effective than annual and biannual management. By testing the capacity of plans to achieve objectives, groundwater management can be systematically and objectively improved.

Keywords Groundwater management · Numerical modelling · Water resources conservation · Groundwater protection

Introduction

On the eve of his death, Socrates described the flow of "*monstrous, unceasing, subterranean rivers*", which, he believed, originated from the centre of the earth (Plato 2003). Despite the presence of underground water being understood in antiquity, the nature and providence of it was highly uncertain. And today, despite all our scientific advances and technological innovations, there is still great uncertainty in the location, volume and yield of aquifer systems, which regularly confounds groundwater managers. In an 1861 Ohio (USA) court case, management of groundwater was described as "*hopelessly uncertain and therefore; practically impossible*" (Frazier vs Brown 1861). More than 150 years later, groundwater management is still described as "*flying blind*" (Currell et al. 2016), "*a free for all*" (Famiglietti 2014); management plans are described as "*neglected*" (Foster et al. 2015), and groundwater legislation as the "*Cinderella of water laws*" (McKay 2006). It is precisely that uncertainty identified as far back as the nineteenth century that is to blame, because it is hard to manage something that you cannot see.

The World Economic Forum has consistently rated water crises in the top five global risks for the past 7 years (World Economic Forum 2018) and in many regions, the value of groundwater as a water resource cannot be overstated.

✉ E. K. White
whitee1@student.unimelb.edu.au

[1] Department of Infrastructure Engineering, University of Melbourne, Victoria 3010, Australia

[2] Bureau of Meteorology, Docklands, Victoria 3001, Australia

Therefore, effective management is crucial. Yet, it is only relatively recently that the frightening prevalence of overextraction and groundwater level declines across the globe (Famiglietti 2014; Giordano 2009; Konikow and Kendy 2005; Wada et al. 2010), are being acknowledged and reflected in legislation, with groundwater management plans becoming increasingly common (California Legislature 2014; Government of Australia 2007). Despite this progress, one of the important questions that is being neglecting is: How well do groundwater management plans work?

Plans are rarely quantitatively assessed for effectiveness and, in many cases, are not conducive to quantitative analysis (White et al. 2016). In the past, aquifer state—e.g. *hydraulic head levels, well yields, minimum stream or base flow volumes, fluxes, and status of groundwater-dependent ecosystems (GDEs)*—has been taken as a proxy of plan effectiveness, despite the potential for plans to have unexpected consequences and the frequent absence of established causality between management action and aquifer state. Stemming from an implicit belief that sequential decision-making management improves environmental outcomes, it is often assumed that management is responsible when an aquifer remains in an acceptable state (White et al. 2016). However, it cannot be concluded that management is effective until the system has been stressed such that plan mechanisms are enacted, and causality of any system change attributed to management action. This research presents a numerical modelling method that evaluates plan effectiveness. To the authors' knowledge, there are no existing approaches that evaluate plan effectiveness because management modelling tends to search for the "best" management strategy and neglects the effectiveness of the management process itself.

Historically, groundwater management modelling has focused on simulation-optimisation studies (Gorelick and Zheng 2015), and reviews include (Singh 2014b, 2012, 2015; Gorelick 1983; Wagner 1995; Yeh 1992; Loucks and Van Beek 2005; Ahlfeld and Mulligan 2000; Ahlfeld and Heidari 1994). Management optimisations are generally solved for the decision variables (i.e. extraction/injection rates or management strategy) of "least cost" (Wagner 1995) or "maximum benefit" within specified constraints. The optimal solution is found by minimizing (or maximising) a particular objective function, for example MODFLOW GWM (Ahlfeld et al. 2005; Banta and Ahlfeld 2013) has been developed to determine optimal solutions to various groundwater management problems. MODFLOW GWM has been applied to numerous management challenges, including potential baseflow decline due to groundwater extraction (Fienen et al. 2018), optimising recharge and injection rates for managed aquifer recharge (Ebrahim et al. 2015), evaluating model solver error in optimal management solutions (Ahlfeld and Hoque 2008), and maintaining aquifer productivity by optimizing extractions (Banta and Ahlfeld 2013). However, in these studies, the "optimal" management solution was sought instead of the effectiveness of management under a stochastic climate.

A vast range of water resource problems have been informed by optimisation studies, including optimal allocation of water resources (Habibi Davijani et al. 2016, Singh 2014c, 2014a, Bear and Levin 1967), multi-objective water resource management optimisation (Reed et al. 2013), monitoring network design (Reed and Minsker 2004), saline intrusion management (Emch and Yeh 1998; Rejani et al. 2008; Reichard and Johnson 2005; Park and Aral 2004; Werner et al. 2013; Sreekanth and Datta 2011), groundwater policy and management evaluation (Mulligan et al. 2014; Esteban and Dinar 2012; Brown et al. 2015; Bredehoeft et al. 1995), hydro-economic modelling (Peña-Haro et al. 2011), and optimizing management uncertainty (White et al. 2018). Balancing the conflicting uses of groundwater by evaluating trade-offs and navigating political currents are herculean tasks and optimisation modelling has proved an invaluable tool. However, management of water resources is more complex than what models can produce due to the interplay between the physical, social, political, ecological and biophysical systems that govern aquifer systems (Loucks 1992). As a result, certain management problems are not readily optimisable because the optimisation process is likely too restrictive to handle policy evaluation and resource allocation problems involving rules, compromises and hierarchical decision-making (Gorelick and Zheng 2015).

Groundwater management is dynamic, influenced by feedback and sequential decision-making, and is often determined by aquifer state, all of which make optimisation difficult. Many management plans implement extraction restrictions or other management actions when certain groundwater trigger levels are reached (GMW 2011, 2006, 2012). In this way, the aquifer state dictates the management action, yet this natural system/human feedback is rarely captured by traditional optimisation approaches, which aim to identify an "optima" and do not modify pumping rates based on heads modelled during simulations. Furthermore, the outcomes of coupled natural and human systems are unpredictable due to the potential for nonlinear feedback and irregular systems dynamics (Sivapalan et al. 2012; Gordon et al. 2008; Elsawah and Guillaume 2016; Peterson et al. 2012). Sequential decision-making has been shown, due to feedback and unpredictable system dynamics, to produce unexpected outcomes in other environmental fields including, contaminant management of surface waters (Janssen and Carpenter 1999; Carpenter et al. 1999) fisheries management (Anderies et al. 2007), and exploitation of an unspecified shared resource (Lade et al. 2013). Due to potential unforeseen aquifer dynamics, groundwater management plans may not actually be working the way they are thought to be (White et al. 2016). Gorelick and Zheng (2015), call for new types of quantitative policy and planning models that combine simulation methods, decision-making processes and objectives, and address the complex interactions between human behaviour and aquifer systems.

Agent-based modelling has been applied to groundwater management problems to highlight water-usage trade-offs, feedbacks, and decision-consequences, and to evaluate the dynamics between agent behaviour and aquifer systems (Castilla-Rho 2017; Castilla-Rho et al. 2015). Mulligan et al. (2014) combined groundwater and economic models to evaluate management policy while considering human behaviour in the form of agents (farmers). Guillaume and El Sawah (2014) state that modelling does not necessarily translate into how a plan will operate in reality, and used iterative closed-question modelling to stress-test groundwater management planning. Plan limitations and how preconceptions influence management success were demonstrated (Guillaume and El Sawah 2014). Understanding how beliefs can compromise management success is important, and may help frame realistic expectations, but the study was not concerned with quantifying plan effectiveness.

In contrast to optimisation studies, which quantify decision variables to create plans (Brown et al. 2015), this study does not seek the "best" strategy but instead, aims to test the sequential decision-making management process, *the act of management* itself. Modelling the effectiveness of the sequential decision-making process of management has, to our knowledge, not been conducted in a groundwater context. A simplified system analysis approach was used to frame groundwater management as a system control problem, which allowed management to change during the simulation in response to water level fluctuations. System control has previously been used in groundwater studies (Jones et al. 1987; Bauser et al. 2010; Ghorbanidehno et al. 2017; Ahn 2000; Tankersley and Graham 1994; Andricevic 1990) but the authors are not aware of any studies that both utilise system control to evaluate sequential decision-making and consider climatic uncertainty with stochastic forward forcing data.

The purpose of this study was to develop and demonstrate a method to quantitatively evaluate the effectiveness of a groundwater management plan by simulating the sequential decision-making process of management with a numerical groundwater model. Additionally, the impact upon plan effectiveness of making management decisions on various timescales and within aquifers with varying response times was assessed. Synthetic management scenarios were used that encapsulated elements from multiple groundwater management plans and simulations were designed to answer the following questions:

1. How effective is the sequential decision-making process that implements water restrictions and entitlement volumes (*here defined as maximum volume a user can take per year*), at maintaining groundwater levels at a wetland and two domestic wells compared to no management and entitlement only?
2. To what degree does altering the management decision-making period (how often management decisions are made, i.e. the frequency with which groundwater levels are compared to triggers) improve the effectiveness of management?
3. What is the impact upon irrigation supply reliability required to achieve environmental and domestic objectives?

The methodology presented in this paper provides a statistical evaluation of how well a plan achieves objectives when management decisions are made frequently, compared to infrequently and at different times of the year. Comparing scenario effectiveness allows a qualitative assessment of the trade-offs between achieving the plan's environmental objectives, maintaining irrigation supply and balancing management budgetary constraints under a variable climate. By modelling the act of management, the trade-offs between differing objectives and management actions can be considered in conjunction with stakeholders to set the most appropriate management period, and determine the most important uses and acceptable levels of impacts. For example, achieving 100% of an environmental goal may result in too many days of supply deficit or cause an unacceptable reduction in supply reliability. Manipulating the levels of "unsatisfactory" demand can indicate how often supply will not be met in order to achieve an environmental goal. Stakeholders can not only determine an acceptable proportion of days with restricted supply, but also, the degree of supply restrictions necessary to achieve environmental objectives and explore the consequences of management decisions. Stakeholder involvement in groundwater management promotes cooperation, accountability and a sense of resource ownership that can lead to more equitable and sustainable water management (Barthel et al. 2017), and the importance of stakeholders is being recognised by the policy system (Head 2010). This study constitutes the first step towards evaluating the effectiveness of real plans.

Methodology

A simple example is presented to demonstrate the method by evaluating the capacity of a synthetic management plan to achieve a measurable objective. The act of management was simulated by creating a numerical model of a managed aquifer that represented "reality", and in which, the effect of management decisions could be evaluated. However, management decisions were only based upon groundwater levels at two monitoring wells and not informed by the entire simulation suite. A management plan was formulated for the aquifer and the impact of plan implementation at various frequencies—daily, monthly, four-monthly, yearly, bi-yearly, five-yearly, decadal—of management decision-making was assessed compared to an unmanaged baseline.

Modelling the act of management

Structuring groundwater management as a system control problem, where dynamic systems are modified by feedback in order to maintain particular system states (Astrom and Murray 2008; Åström and Wittenmark 2008) was introduced in White et al. (2016) and allows for aquifer/management feedback and adaptive control of aquifer systems. A control loop was created by programming management rules (plan) in Python (Python Software Foundation 2019) and combining the plan with a MODFLOW-NWT (Niswonger et al. 2011) numerical groundwater model.

Simulation of the act of management requires adaptive change to management action in response to groundwater level fluctuations that occur during a modelling simulation (Fig. 1). This functionality is unavailable with standard MODFLOW without altering the source code; therefore, the process was facilitated using FloPy, a python package that reads and writes MODFLOW files (Bakker et al. 2016). FloPy allowed the comparison of modelled heads to groundwater trigger levels and well depths that were defined in Python, a process that is analogous to groundwater monitoring and management supervision. To prompt immediate management action when triggers were reached, a separate MODFLOW model was run for each daily time step in the climate record. In this way the entire climate record was simulated, day by day, as today's aquifer state informed tomorrow's management action. Starting hydraulic heads, pumping rates, recharge and evapotranspiration values were updated daily by replacement of MODFLOW input files. At certain decision-making intervals, when trigger levels were reached, extraction rates were amended during the model simulation. The dewatering of both domestic and irrigation wells was detected by comparing simulated heads to predefined well depths in the Python code. If dewatering threshold depths were reached, the pumping rate for that well was assigned to zero for the subsequent model run. Unlike traditional management models where stresses are predetermined prior to the simulation, this methodology enabled management to change in response to simulated levels in the aquifer.

Management evolving in response to water level fluctuations minimises potential mismatch between management action and aquifer response that may occur with static management. Naturally, if drivers are stationary, an aquifer system reaches a dynamic equilibrium. The time required to reach a new equilibrium after application of a hydraulic stress is termed the aquifer response time (Rousseau-Gueutin et al. 2013; Walton 2011). Consequently, there is a delay between management action and the observed result, which is termed the lag time (Meals et al. 2010). When management timescales are discordant with aquifer response times, unsustainable development and over-exploitation can occur (Gleeson et al. 2012). Robust plans that perform well under a diverse range of climatic conditions are required (Jakeman et al. 2016), so that managers can account for climatic extremes and unpredictability, and understand the impact of climate upon the efficiency of management plans (Gorelick and Zheng 2015; Alley 2016; Alley et al. 2002). In the following example, implementation of a plan in different responding systems at various decision-making frequencies and under various potential future climates is demonstrated.

Synthetic example

Numerical groundwater model

A synthetic, homogeneous model of an unconfined aquifer was created using MODFLOW-NWT (Niswonger et al. 2011) and designated as the "reality" in which management scenarios were explored. A simple groundwater conceptualisation sufficed because the purpose was not to model a real system under management, but to demonstrate how sequential decision making could be incorporated into a groundwater model. While simple, this system captured required dynamics and if management was shown to be ineffective in simple scenarios, then additional scenario complexity would be superfluous. The example system was designed to mimic a simplified crop irrigation operation situated on the floodplain of an alluvial upland valley. The farm was subject to extraction restrictions to maintain groundwater levels at a wetland and two domestic wells. The dimensions of the aquifer were 2.5 km × 2.5 km, and discretised by a 352 × 229 rectangular finite difference grid with background spacing of 15 m. The grid was incrementally tightened to 2.5-m intervals around each pumping well (Fig. 2) to capture groundwater level fluctuations due to pumping that caused well dewatering. The vertical thickness of the aquifer was 92 m in the north east and reduced to a thickness of 70 m in the south west corner. A no-flow boundary was applied to the horizontal base to represent impermeable bedrock. Natural groundwater flow direction was from uplands in the north east to the wetland region in the south west adjacent to a river boundary comprising the western margin of the model domain. The eastern boundary was defined as general head, and the northern and southern as no flow boundaries.

Groundwater pumping volumes were estimated based on simulated soil moisture content from a vertically integrated one-dimensional (1D) soil moisture model. The pumping occurred in three irrigation zones with dimensions of 350 m ×

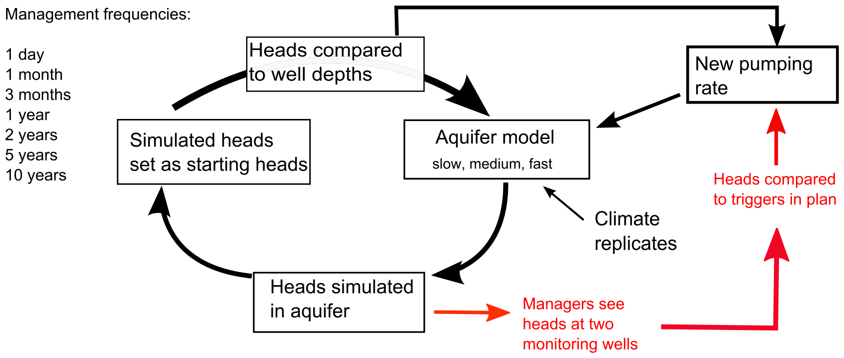


Fig. 1 The act of management modelling loop (adapted from White et al. 2016). The inner black loop cycled daily and updated starting heads with heads simulated the previous day. Pumping rates were updated if groundwater levels declined below the depth of the well. When the management cycle occurred (shown in red) groundwater levels in monitoring wells were compared to triggers in the plan and restrictions were implemented for the subsequent management period. In the example, the frequency the management cycle iterated was varied from daily to decadal

450 m (each containing four pumping wells) in the eastern region. While, realistically, an irrigation operation of this scale is likely to have only one or two wells, it was necessary to spread extraction volumes across multiple wells for each irrigation zone to maintain model stability and focus on the effect of the management plan rather than having extractions limited by aquifer flow capacity. The volume extracted from irrigation wells was reported as a total combined irrigation volume from all wells. Two domestic wells each extracted 2 ML/year in the north-western quadrant, and two monitoring wells, with four specified groundwater level triggers, were located adjacent to the wetland and the domestic wells respectively.

Stochastic climate replicates were used to reflect climatic variability and explore management under various climatic conditions. Rainfall and evapotranspiration data recorded from 1900 to 2016 at the Nhill weather station in Western Victoria were extracted from the Australian Water Availability Project (AWAP) database (Raupach et al. 2008; CSIRO 2016). The stochastic Climate Library (SCL) (Srikanthan et al. 2006) was used to generate 20 stochastic replicates of daily historical precipitation (climate replicates). The climate replicates shared the statistical characteristics of the historical AWAP data and accounted for climatic variability and uncertainty. For this study, the climate is assumed to be statistically stationary, although the method could be extended to include nonstationary climate.

Soil moisture model Groundwater usage varies with climate and irrigation demand fluctuates seasonally. To capture this variability, a simple soil moisture model was developed to determine demand, recharge, and actual groundwater evapotranspiration values based on the climate replicates. The soil moisture model used was a vertically integrated 1D model adapted from Peterson and Western (2014) to include irrigation demand:

$$\frac{dS}{dt} = P - \mathrm{PET}\left(\frac{S}{S_{\mathrm{cap}}}\right) - K_{\mathrm{s}}\left(\frac{S}{S_{\mathrm{cap}}}\right)^{\alpha} + D \qquad (1)$$

where S [L] is the soil moisture storage, t [T] is time, P [L/T] is the daily precipitation, PET [L/T] is the daily areal potential evapotranspiration, S_{cap} [L] is the soil moisture storage capacity (set as 100 mm), K_{s}[L/T] is the soil vertical saturated hydraulic conductivity, α [−] is a power term (set to 2) controlling the threshold response of free-drainage to the soil moisture and D [L/T] is the irrigation depth within the irrigation regions and is defined as follows:

$$D = \begin{cases} \max\left[0, \left(S_{\mathrm{cap}} - S - P\right)\left\{\frac{S}{S_{\mathrm{cap}}} \le \delta\left[1 - N\left(0, \sigma^2\right)\right]\right\}\right] & \textit{if } t \ge t_{\mathrm{start}} \quad \& \quad t \le t_{\mathrm{start}} \\ 0 & \textit{if } t < t_{\mathrm{start}} \quad \& \quad t > t_{\mathrm{start}} \end{cases} \qquad (2)$$

where t_{start}[T] is the start of the irrigation season (1 November), t_{end}[T] is the end of the irrigation season (31 March), δ[−] is a soil moisture threshold (set at 0.8) defining the average relative soil moisture at which irrigation occurs, $N(0, \sigma)$ is a random normal function with a mean of zero and standard deviation of σ[−] (set to 0.25). The parameters δ and σ produced randomness in the irrigation demand and timing so that the random changes that occur in real-world irrigation operations could be captured.

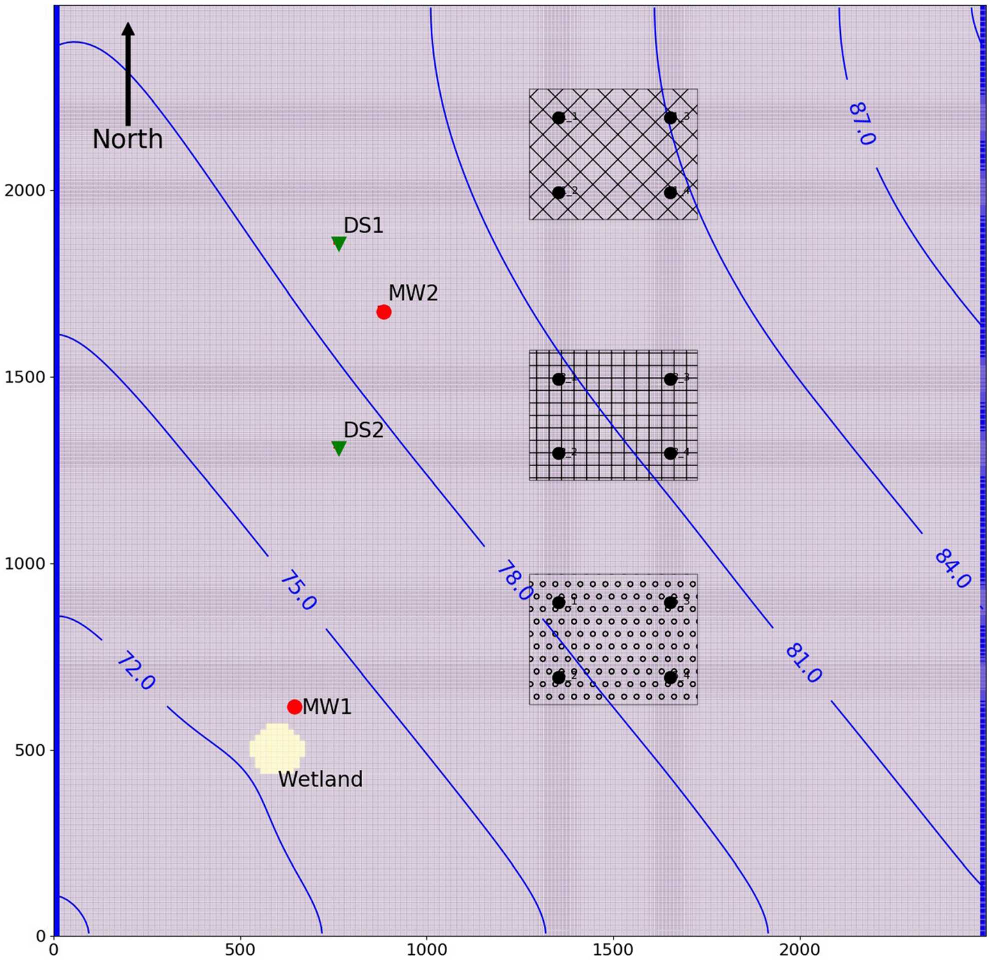


Fig. 2 Synthetic example model domain of 2.5 km × 2.5 km showing three irrigation areas (patched regions), wetland (yellow circle) and grid discretisation. There were four pumping wells (black circles) per irrigation area, two domestic wells (green triangles) and two monitoring wells (red circles), which were used to make management decisions for the entire aquifer. The western boundary was a river (thick blue line on LHS of figure) and the eastern a constant head boundary (thick blue line on RHS of figure). North and south boundaries were no flow. Groundwater flow was from the north east to the south west (thin blue lines)

Irrigation water was only applied to the crop when the soil reached the soil moisture threshold of σ, which occurred approximately every 10 days, and for the remaining days of the month, irrigation demand was zero. However, due to the daily time-step of the numerical model, daily irrigation demand volumes were required; therefore, the daily pumping demand for each irrigation zone was derived by summing the monthly demand and averaging it over each day in the month. Daily demand volumes were then multiplied by the area of each zone to get a daily zone demand.

To account for energy already consumed by soil water evapotranspiration (see Eq. 1), the potential evapotranspiration from groundwater was simulated as:

$$\mathrm{PE}_{\mathrm{groundwater}} = \mathrm{PET}\left(1 - \frac{S}{S_{\mathrm{cap}}}\right) \tag{3}$$

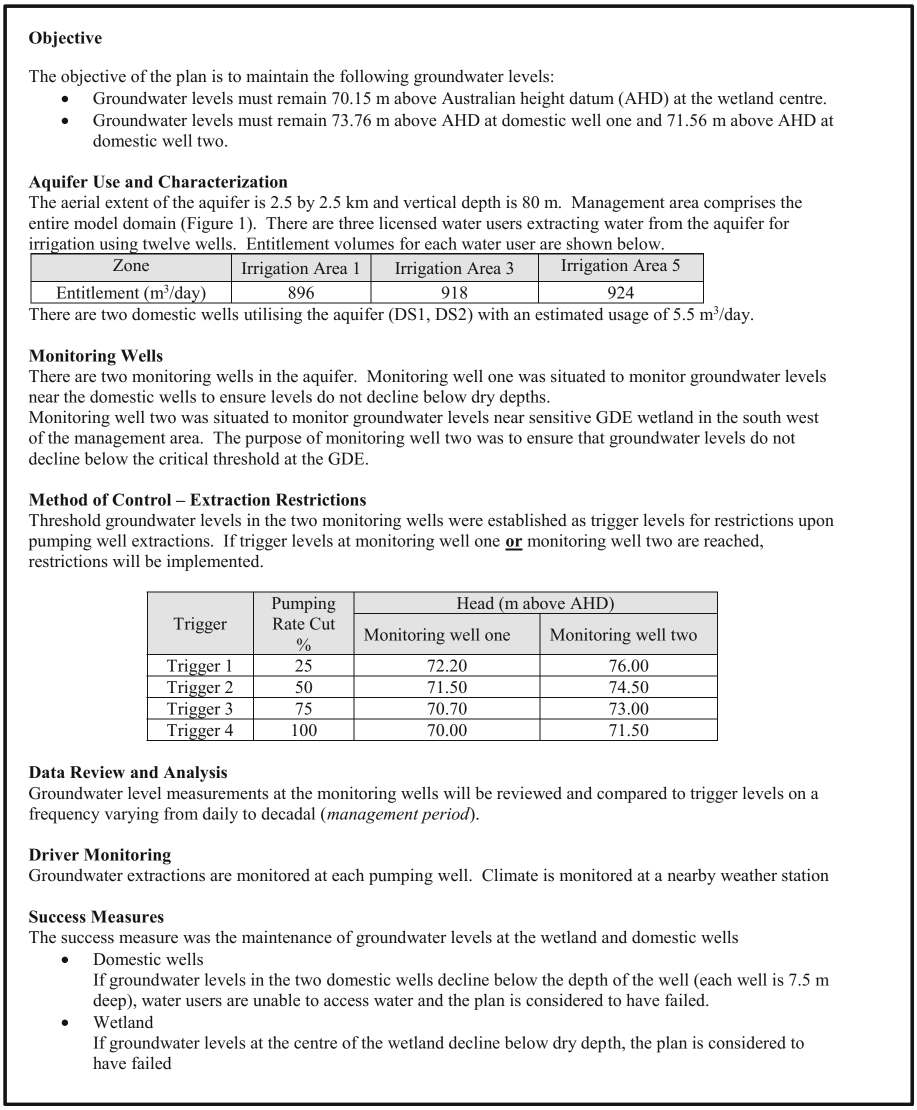
Potential evapotranspiration, drainage and demand generated by the soil moisture model provided the "reality" groundwater model with input values for evapotranspiration, recharge and well extraction volumes.

Groundwater management plan

The objective of the management plan, shown on Fig. 3, is maintenance of groundwater levels at the wetland and two domestic wells. Protection of environmental and domestic uses was selected as the objective due to its prevalence in Australian groundwater management planning (GWM 2001, 2009; SRW 2010; NREATS 2009; DOW 2009; SAAL NRM 2009) and the increasing consideration of groundwater dependant ecosystems (GDEs) in management plans (DELWP 2015b, a; DLRM 2016). The plan consisted of entitlement volume limits, groundwater level triggers and extraction restrictions upon three irrigators within the model domain. While more complex management scenarios involving water-trading, entitlement carryover and non-compliance could be simulated, they are beyond the scope of this study.

Modelled scenarios

Scenarios included various combinations of management decision-making period, timing and aquifer response times.



Objective

The objective of the plan is to maintain the following groundwater levels:

- Groundwater levels must remain 70.15 m above Australian height datum (AHD) at the wetland centre.
- Groundwater levels must remain 73.76 m above AHD at domestic well one and 71.56 m above AHD at domestic well two.

Aquifer Use and Characterization

The aerial extent of the aquifer is 2.5 by 2.5 km and vertical depth is 80 m. Management area comprises the entire model domain (Figure 1). There are three licensed water users extracting water from the aquifer for irrigation using twelve wells. Entitlement volumes for each water user are shown below.

Zone	Irrigation Area 1	Irrigation Area 3	Irrigation Area 5
Entitlement (m^3/day)	896	918	924

There are two domestic wells utilising the aquifer (DS1, DS2) with an estimated usage of 5.5 m^3/day.

Monitoring Wells

There are two monitoring wells in the aquifer. Monitoring well one was situated to monitor groundwater levels near the domestic wells to ensure levels do not decline below dry depths.

Monitoring well two was situated to monitor groundwater levels near sensitive GDE wetland in the south west of the management area. The purpose of monitoring well two was to ensure that groundwater levels do not decline below the critical threshold at the GDE.

Method of Control – Extraction Restrictions

Threshold groundwater levels in the two monitoring wells were established as trigger levels for restrictions upon pumping well extractions. If trigger levels at monitoring well one **or** monitoring well two are reached, restrictions will be implemented.

Trigger	Pumping Rate Cut %	Head (m above AHD)	
		Monitoring well one	Monitoring well two
Trigger 1	25	72.20	76.00
Trigger 2	50	71.50	74.50
Trigger 3	75	70.70	73.00
Trigger 4	100	70.00	71.50

Data Review and Analysis

Groundwater level measurements at the monitoring wells will be reviewed and compared to trigger levels on a frequency varying from daily to decadal (*management period*).

Driver Monitoring

Groundwater extractions are monitored at each pumping well. Climate is monitored at a nearby weather station

Success Measures

The success measure was the maintenance of groundwater levels at the wetland and domestic wells

- Domestic wells
  If groundwater levels in the two domestic wells decline below the depth of the well (each well is 7.5 m deep), water users are unable to access water and the plan is considered to have failed.
- Wetland
  If groundwater levels at the centre of the wetland decline below dry depth, the plan is considered to have failed

Fig. 3 Groundwater Management Plan to be evaluated, outlining the management objective, extraction restriction triggers and required components for a testable groundwater management plan

Management period The management period varied from daily to decadal to explore the benefit provided by more frequent, yet more resource intensive management, compared to less resource costly management. In addition to the seven management period scenarios, two baseline scenarios of the aquifer were simulated: entitlement-only and unmanaged. Entitlement only was designed to evaluate the impact on effectiveness of setting an entitlement volume compared to no management. In this scenario, extractions from the aquifer were subject to entitlement volumes but were not modified by restrictions and, pumping only ceased when the wells became dry. Due to the daily timestep of the model, daily maximum extraction volumes were required as model input; therefore, entitlement volumes were set at typical daily usage volumes and imposed as daily maximums. In the entitlement-only scenario and all the managed scenarios, demand from pumping wells was compared to the maximum daily entitlement volume, which if exceeded, resulted in amendment of pumping rate down to entitlement volume. The unmanaged scenario had neither entitlement volume nor extraction restrictions and demand was only constrained by the area under crop cultivation. In this way, the aquifer was a common pool resource as defined by Hardin (1968), and supply was prioritised above all else. In the managed scenarios, groundwater levels were periodically compared to trigger levels defined in the plan at the two monitoring wells. If trigger levels were reached in either monitoring well, restrictions were applied to the pumping wells for the subsequent management period. For example, if the management period was monthly, entitlement volumes were reduced for the entire subsequent month. Domestic wells were not subject to water restrictions. Sustainable groundwater management is infinitely more complex than the simple scenario modelled here and depends upon legal, social, environmental, political and economic factors. It was assumed irrigators comply with restrictions for the purposes of this study, so that the impact of plans, if implemented as intended, could be evaluated; however, the authors acknowledge non-compliance is a great challenge for managers. Restrictions were chosen because during the Australian Millennium Drought (1999–2009), restrictions were imposed in certain management areas and several plans outlined sequential restrictions based on usage volumes or groundwater recovery levels. Evaluating the impact sequential decision had upon objective failure rate was a study objective.

Management timing The effect of making management decisions at different times of the year was explored by replicating all simulations at two different decision-making timings during the (southern hemisphere) irrigation season: mid-season (January) and early season (November). For the mid-season timing, annual, bi-annual, five- and ten-yearly management decisions were made on January 1st of each year, and four-monthly (120 day) management decisions were made on January 1st, May 1st and September 1st of each year. For the early-season (November) timing, annual and greater decisions were made on November 1st, and four-monthly decisions were made on November 1st, March 1st, and July 1st of each year. For both decision timings, daily management decisions were made each day, and monthly decisions were made on the first of each month.

Aquifer response time To determine the impact of aquifer response time upon plan effectiveness, hydraulic conductivity (K_s) was varied from 0.026 to 1.43 m/day in six steps, resulting in six aquifers that responded to hydraulic disturbance on different timescales. Specific yield remained constant at 0.2 for each aquifer hydraulic conductivity/response time. All scenarios were replicated in the six aquifers and the plan effectiveness determined. To assess the interaction between aquifer response time, management period, and plan effectiveness, all scenario combinations were repeated for each of the 20 stochastic climate replicates to evaluate management under climatic variability.

Evaluation framework

In this example, plan effectiveness was defined by the maintenance of minimum groundwater levels at a wetland and two domestic wells and was directly evaluated by calculating the objective failure rate—*how often the wetland levels declined below minimum depths and domestic wells went dry*—during the simulation period. Additionally, the plan was indirectly assessed by evaluating the impact of restrictions upon irrigation supply reliability to determine any trade-offs required to achieve the environmental and domestic objective.

Objective failure rate (frequency with which wetland and domestic wells go dry) When levels declined below the threshold dry depths at the wetland and domestic wells, the plan failed. Each day groundwater levels at the wetland and domestic wells were compared to objectives and the number of failures across all climate replicates was calculated for each scenario. The objective failure frequency F_{freq} of each replicate was calculated using Eq. (4).

$$F_{\mathrm{freq},i} = \frac{O_{\mathrm{fails},i}}{N_{\mathrm{days}}} \tag{4}$$

where $F_{\mathrm{freq},i}$ is the plan objective failure frequency for the i^{th} replicate; $O_{\mathrm{fails},\ i}$ is total number of days in which objective was not met for the i^{th} replicate; and N_{days} is total number of time intervals in simulation.

Equation (4) yielded 20 failure frequency values for each management period scenario, which were averaged to produce a mean failure rate for each management period (Eq. 5). This yielded one value of objective failure frequency at each location for each management period, which allowed comparison between management periods.

$$\overline{F}_{\mathrm{freq}} = \frac{\sum\left(F_{\mathrm{freq},i}\right)}{N_{\mathrm{replicates}}} \tag{5}$$

where $\overline{F}_{\mathrm{freq}}$ is the average failure frequency for that management period and $N_{\mathrm{replicates}}$ is the number of replicates (20).

Irrigation supply reliability Reliability is the probability that demand can be met by the aquifer system and is defined in terms of either time (*probability that demand will be met within a particular time period*) or volume—*total supplied volume divided by the total demanded volume* (McMahon and Adeloye 2005). While irrigation supply was not an explicit objective of the plan, temporal and volumetric reliability were determined to illustrate the potential irrigation supply trade-off required to achieve the environmental/domestic objective. Reliability of irrigation wells was calculated during the irrigation season when pumping occurred.

Temporal reliability was calculated with Eq. (6) at a daily scale using a total extraction volume from all irrigation wells.

$$R_{\mathrm{t}} = \frac{N_{\mathrm{s}}}{N} \tag{6}$$

where R_{t} is the temporal reliability; N_{s} is total number of time intervals in which demand was met; and N is total number of time intervals in the simulation (McMahon and Adeloye 2005).

Temporal reliability does not account for the length or severity of the shortage and treats a few long severe shortages the same as many short mild ones (McMahon and Adeloye 2005). Considering that a severe shortfall can result in crop failure and wetland desiccation, shortage severity is an important consideration for managers. Volumetric reliability (Rv) provides an indication of the magnitude of the shortfall and was calculated on a daily time-step using Eq. (7):

$$\mathrm{Rv} = 1 - \frac{\sum\left(D_j - D'_j\right)}{\sum D_j} \tag{7}$$

Where D'_j is the supply from the aquifer during the j^{th} failure period; D_j is the demand during the j^{th} period; N is the number of periods in the simulation.

Results

While scenarios were modelled in aquifers with six different response times (K_s values), three of the six aquifers did not show a difference between objective failure rate at daily management and the entitlement-only scenario, i.e. management was indistinguishable from unmanaged. Daily management (extraction restrictions + entitlements) and the entitlement only (no restrictions) failure rates area shown in Fig. 4 and management only differs to the entitlement only scenario within

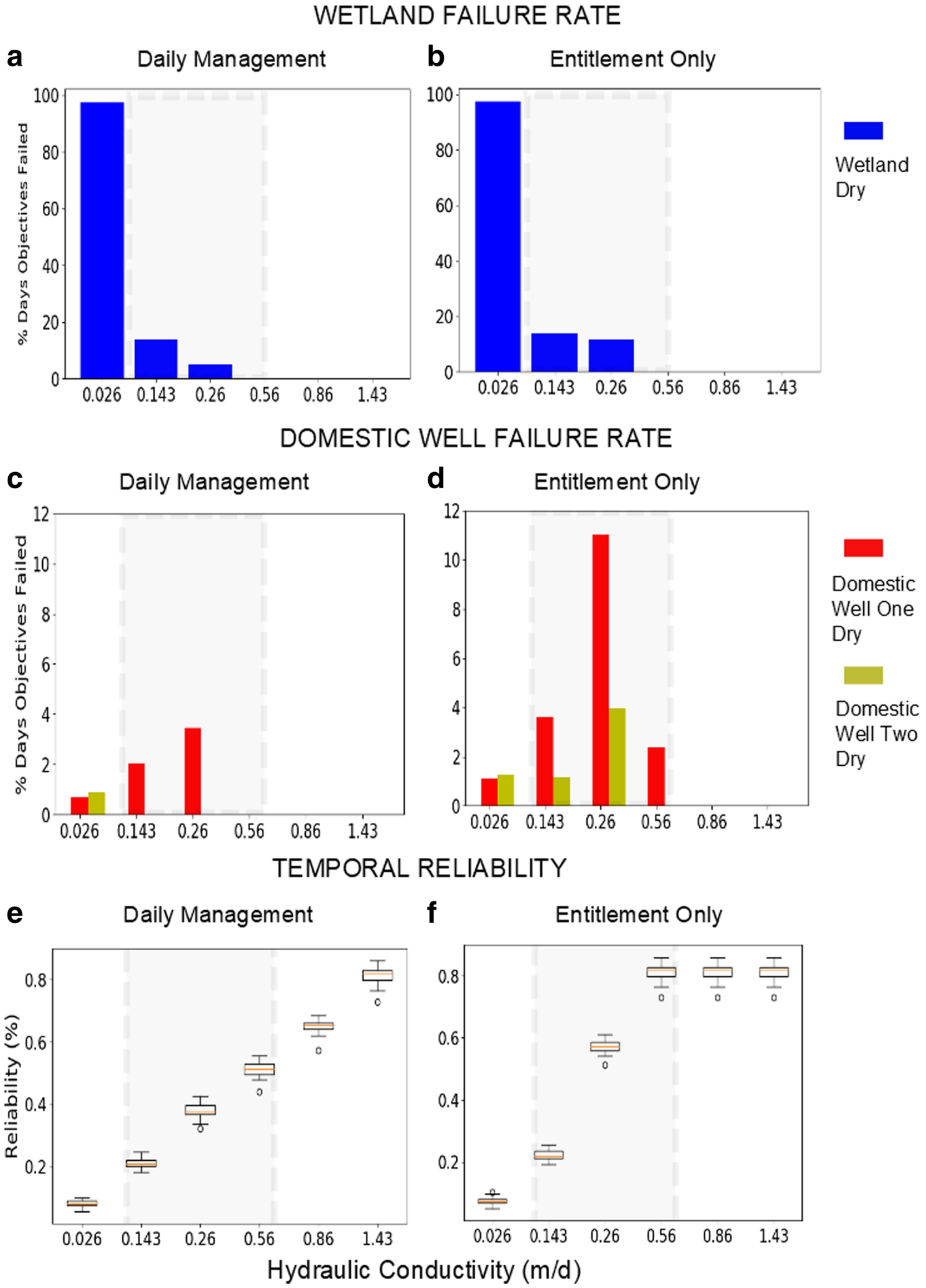


Fig. 4 The daily management and entitlement-only scenarios illustrate the range of hydraulic conductivities (x-axis) within which extraction restrictions had an impact upon the failure rate at the wetland (**a**–**b**) and domestic wells (**c**–**d**), and upon the value of temporal irrigation supply reliability (**e**–**f**). For each figure pair, the greatest difference between the daily management and the no-restrictions occurs in the grey-shaded region, between K_s values of 0.143 and 0.56 m/s. Outside of this range, daily management implementing water restrictions has no benefit over the entitlement-only scenarios

the grey shaded region. Figure 4 shows the failure rate for each K_s value at the wetland (Fig. 4a,b); domestic wells (Fig. 4c,d); and the temporal irrigation supply reliability (Fig. 4e,f) for both daily and entitlement-only management. Management had the greatest impact on aquifers with K_s values between 0.143 and 0.56 m/day (grey-shaded region) for each figure pair. In aquifers with a K_s value outside of this range, the impact of management on failure rate and reliability is negligible, because fast responding systems accessed water from greater distances and were better able to meet demand than slower responding systems that primarily met demand from storage. In these systems, daily management provided no greater benefit over simply setting an entitlement volume. This is further illustrated with average daily water balances for the unmanaged scenarios of the slow, medium and fast aquifers (with K_s values of 0.026, 0.26 and 1.43 m/day respectively; Fig. 5) that illustrate the discrepancy in water availability between aquifer response times. Figure 5 shows that systems responding on different scales have very different water availability and consequently, exhibit very different outcomes due to the plan.

The decrease in irrigation supply reliability due to daily management compared to setting an entitlement volume can be seen by comparing Fig. 4e,f, and illustrates the economic toll required to achieve environmental objectives. Management only influenced failure rate in aquifers where demand and aquifer capacity to supply were relatively balanced, which is, realistically, the type of aquifer in which a small-scale irrigation operation of this type would be installed and managed under a plan of this nature. Irrigation at an inappropriate scale would not be pursued in an aquifer that consistently failed to meet demand, nor would extraction restrictions be required when demanded volume was easily supplied. Consequently, exploring management impacts for a small irrigation operation upon nearby receptors is most appropriate in the medium aquifer ($K_s = 0.26$ m/day), where not only is management required, but has a measurable impact upon the domestic and environmental outcomes. The observed sensitivity of plan effectiveness to response time is expected and reinforces that management plans must be tailored to specific systems and that blanket application of management is unwise and most likely ineffective or unnecessary. The remainder of the results section will focus on the impact of various management periods upon the plan effectiveness and well reliability in the medium aquifer. Results of the seven management decision-making periods are presented for decision timings synchronised to January (mid-irrigation season) and November (early-irrigation season) timings.

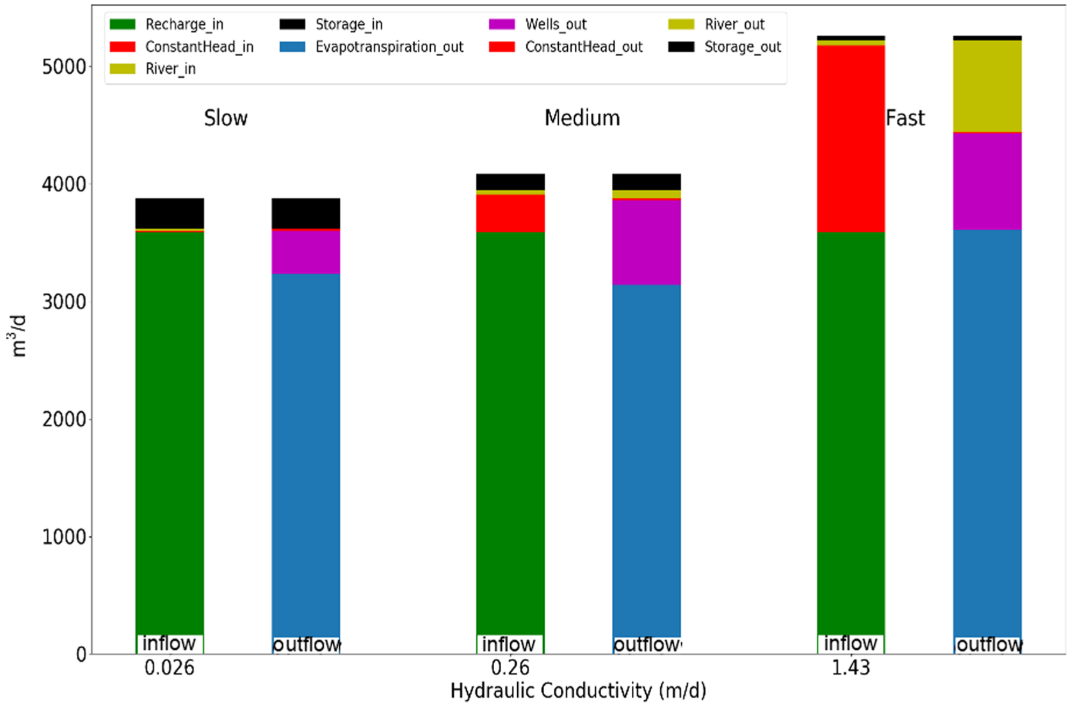


Fig. 5 Selected average daily water balance in the entitlement-only baseline aquifer scenario for $K_s = 0.026$, 0.26 and 1.43 m/day. While recharge remains constant across aquifer types, the slow aquifer has the lowest inflow from constant head (red). This is because the drawdown cone caused by pumping extractions (wells_out) in the slow aquifer does not propagate as far to access distant water. As a result, there is no additional source of water available to the slow aquifer and any extractions (red) must be predominantly supplied by storage (black). Consequently, the slow aquifer has the lowest well extraction volume (purple) and the aquifer is unable to meet the demand. The medium and fast aquifers have higher transmissivity and can access water from the constant head boundary (red). As a result, the volume of outflow due to pumping wells (purple) is greater, reflecting the ability to meet supply

Plan objective failure rate

The failure rate at the wetland and domestic wells for mid-season management decision timing is shown on Fig. 6a. The number of days in which supplied volume was less than demanded volume (days of limited supply) is shown in green on the secondary axis and indicates periods when restrictions are in place, entitlement volumes are in place or the well is dry. Generally, the failure rate increased as the period between management decisions increased and the unmanaged scenario had the greatest occurrence of plan failures (Fig. 6a). The fewest instances of objective failure at the wetland (5.1%), domestic well one (3.6%) and domestic well two (0%) occurred under daily management (Fig. 6a). Increasing the

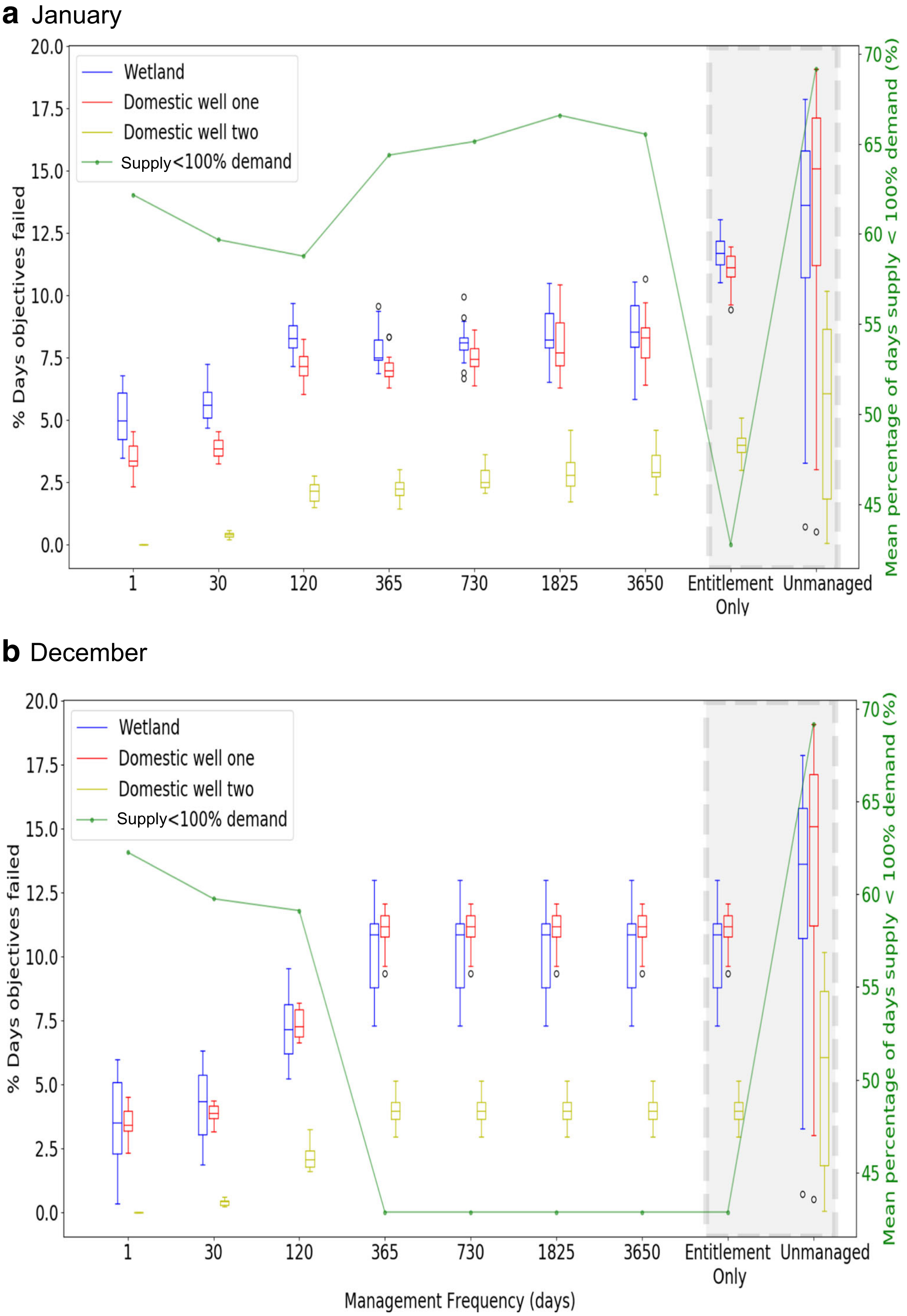


Fig. 6 Percentage of days when plan objectives failed. Wetland (blue), Domestic well one (red), Domestic well two (yellow). The number of days when supply was less than demand is shown in green on the secondary axis. **a** January decision (mid-irrigation season): Daily management had the lowest plan failure rate and entitlement-only (in grey-shaded region) had the second highest failure rate but the fewest days when supply was less than demand. Unmanaged had the highest failure rate and was variable. Generally, failure frequency increased as the length of management period increased, except for 120-day management, which showed slightly more plan failures than annual management due to an interaction between timing of the irrigation season and the management decision. **b** December decision (prior to irrigation season): Shifting the timing of the decision from mid-season (January) to early-season (November) decreased the failure rate of the 120-day management period and resulted in a trend of increasing failure rate. The management period trend plateaued at annual management period. All management periods of annual or greater had the same failure rate as the entitlement-only scenario. Unmanaged was highly variable and reported the greatest failure rate. Wetland (blue); domestic well one (red); domestic well two (yellow)

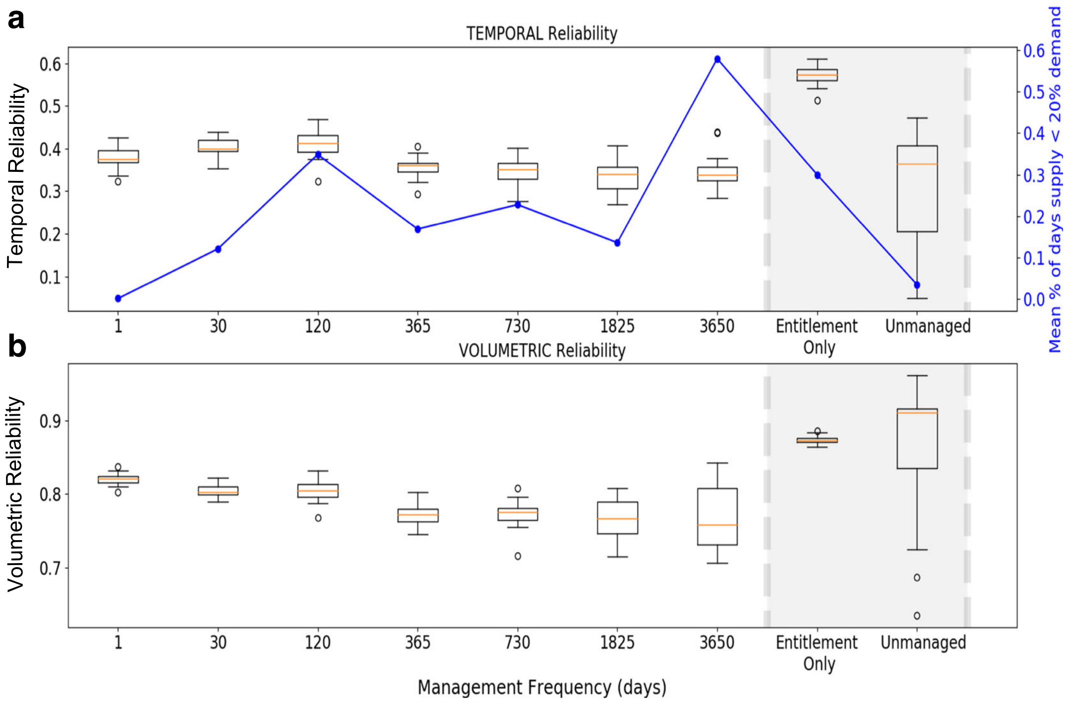


Fig. 7 **a** Temporal and **b** volumetric reliability of irrigation supply wells mid-irrigation season in the medium aquifer (January decision). The blue line shows the mean percentage of days of extreme shortfalls (supply less than 20% of demand) which is lowest for a daily management period. Supply reliability, both temporal and volumetric, is greatest in the entitlement-only scenario (grey-shaded region) and lowest for the longer management frequencies (yearly–decadal) where restrictions may persist longer than required. Reliability under the unmanaged scenario is highly variable

management period from daily to monthly resulted in less than a 0.5% increase in failure rate at each monitoring location, and a 2.5% decrease in the number of days of limited supply.

An increase in the management period from daily to annual, increased the wetland and domestic well one failure rate by 2.8 and 3.6% respectively. The average number of days with restricted supply also increased by 2.2% when managed annually compared to daily (Fig. 6a). The exception to the increasing failure with increasing decision-making period trend was the 120-day management period, which reported a small increase of failure rate compared with annual management. This was due to an interaction between the management decision-making timing and the irrigation season and is further discussed in section ‘Management timing’. A Welch t-test found a statistical difference between the failure rates of each management period at the three locations. Statistical significance analyses are provided for the wetland, domestic well one and domestic well two in Appendix 1, Appendix 2 and Appendix 3 respectively. While there are differences between management periods, the failure rate results could be divided into four groups—daily/monthly, management periods of 120 days and greater, entitlement-only, and unmanaged—between which the statistical difference is large (Fig. 6a; Appendix 1, Appendix 2, and Appendix 3). This means that the biggest differences in failure rate occur between these four groups. The trade-off between environmental, domestic and commercial uses that is required when managing groundwater is clearly illustrated on Fig. 6a. For management periods of 120 days and greater, imposing restrictions to attain plan objectives increases the days when supply is less than the demanded volume. The managed scenarios all show a greater proportion of days where demand was not met compared to the entitlement-only scenarios due to imposition of restrictions (Fig. 6a).

The failure frequency at the wetland and domestic wells for early-season timing is shown on Fig. 6b. Daily and monthly management show the lowest failure rate. Managed scenarios of annual or greater, had the same failure rate as the entitlement-only scenario, showing that in this case, management provided no benefit for the early-season timing. A t-test found no statistical difference between objective failure rate or irrigation supply reliability between entitlement-only and management periods of annual and greater (Appendix 1, Appendix 2, Appendix 3 and Appendix 4) indicating that restrictions were not an effective management action for this combination of management timing and period. Regardless of management timing, entitlement volumes improved environmental and domestic outcomes compared to the unmanaged scenario.

Irrigation supply reliability

Temporal and volumetric reliabilities for mid-season (January) timing are shown on Fig. 7. More frequent management increased reliability compared to less frequent management because extractions were restricted for a shorter period. The entitlement-only scenario provided the highest temporal reliability with a median value of 0.57. Temporal reliability in the unmanaged scenario was highly variable and significantly lower than the entitlement-only scenario (Fig. 7). Interestingly, a t-test showed that irrigation supply reliability of all management frequencies was significantly lower than the entitlement-only scenario, and that there were statistical differences between the management periods (*p* values are shown in Appendix 4). There was a statistically significant difference between the reliabilities of daily, monthly and 120-day periods and the management periods of annual and greater (Appendix 4). Additionally, there was a large difference between entitlement-only and all managed scenarios. Mean reliability values for daily, monthly and 120-day management frequencies ranged from 0.38 to 0.41 and were statistically indistinguishable between monthly and 120-day management. The longer management frequencies, annual to decadal, all had similar reliability values of 0.36 to 0.34 that were lower than the shorter management period values (Fig. 7a). Selection of an appropriate management period is therefore an important management consideration, as discussed in section ‘Management period’.

The average number of extreme shortfalls—arbitrarily defined as days where supply is less than 20% of demand and shown as a blue line on reliability plots (Figs. 7 and 8)—for each scenario was determined by summing the number of days of extreme shortfalls for each of the twenty replicates per period. Extreme shortfalls occurred on less than 0.6% of days across all scenarios and were lowest for daily and monthly management frequencies. This indicates that while there were more days where full demand was not met (due to implementation of restrictions); the occurrence of extreme shortfalls was curtailed under daily and monthly management as compared to the unmanaged scenario. The largest number of extreme shortfalls occurred under decadal management and the 120-day management period reported a similar number of extreme shortfalls to the entitlement-only scenario (Fig. 7a). Results were similar for volumetric reliability, which provide an indication of

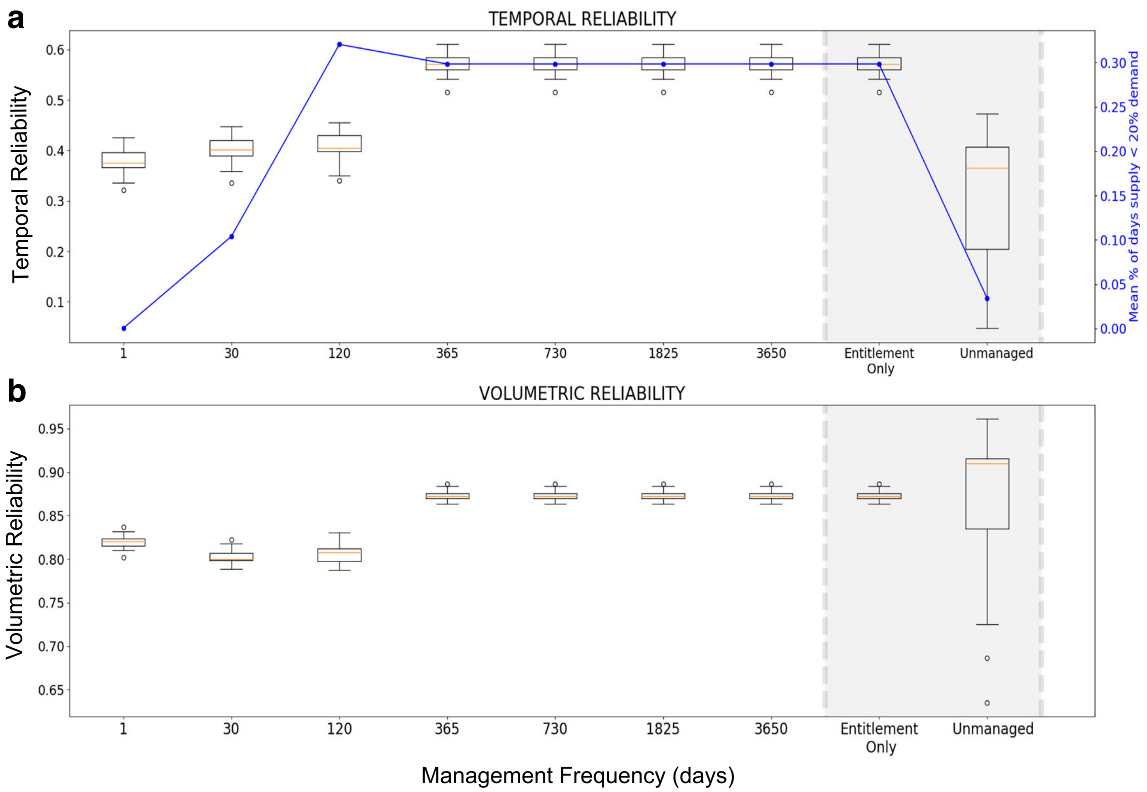


Fig. 8 **a** Temporal and **b** volumetric reliability of irrigation supply wells early-season in the medium aquifer - November decision. The blue line shows the mean percentage of days of extreme shortfalls (supply less than 20% of demand) which is lowest for a daily management period. Supply reliability for annual and greater management is the same as the entitlement-only scenario (grey-shaded region). Reliability is lowest daily to 120-day management when restrictions are enacted. Reliability under the unmanaged scenario is highly variable

the severity of the shortfall. Volumetric reliability was greatest for entitlement only and unmanaged, though the unmanaged scenario showed a high degree variability with wells supplying all or nothing. Of the managed scenarios, daily management had the highest volumetric reliability followed by monthly (Fig. 7b). Longer management scenarios (5 years and decadal) showed higher variability in volumetric than temporal reliability. Temporal and volumetric reliability for early-season (November) timing is shown on Fig. 8 and management at greater frequency than four monthly (120 days) has no benefit compared to entitlement only.

Discussion

A simple synthetic model was used to develop and demonstrate a methodology to test the effectiveness of sequential decision making in groundwater management. This allowed for an assessment of the effectiveness of a management plan within a system control framework. Model simplicity was chosen over site-specific complexity to keep the results generalisable and avoid concentrating on case-specific idiosyncrasies. However, the method is easily extended to complex groundwater systems and management actions, provided they can be modelled adequately. The example demonstrates a methodology for using numerical groundwater models to evaluate groundwater management plans. In a realistic context, this method could be used to test current or proposed plans in management areas where numerical models exist. The method could be part of a stakeholder engagement process where the simulation results are shared with the community to explain the impact and consequences of various management actions. The open source platform of both MODFLOW and Python makes this method freely available and customizable.

Aquifer response time

As expected, plan effectiveness was highly sensitive to hydraulic conductivity and in this example, management was only effective within aquifers with K_s values of between 0.143–0.56 m/day. This band of K_s values in which a management signal was discernible corresponded to a situation where demand was relatively similar to the aquifer's ability to provide water. While this might seem like a restricted set of conditions, it is where groundwater resource exploitation is maximised within sustainability constraints. The management plan provided no benefit compared to entitlement-only when outside of this range because water availability was either physically constrained (low K_s) or plentiful (high K_s), resulting in uniform failure or uniform success respectively (Fig. 4). This simple example illustrates the importance of incorporating aquifer response time into management design and demonstrates the folly of a “one size fits all” management approach. Figures 4 and 5 show the same plan had very different outcomes in systems responding on differing scales. The slow responding aquifer predominantly accessed water from storage and was unable to meet extraction demand, resulting in overexploitation and almost uniform plan failure (Figs. 4 and 5). If management action occurs too rapidly in a slowly responding aquifer, then the impact of the action may have long-reaching implications that will not become apparent for some time. Walton (2011), states that when management planning horizons are shorter than aquifer response times, the impact of extractions may be underestimated. Long-term climatic and geological changes must be accounted for in systems responding on long timeframes (Alley et al. 2002), which considering the rate and potential impacts of climate change, further complicates management.

In contrast to the slow system, the drawdown cone propagated rapidly through the fast aquifer and accessed water from the constant head boundary condition, easily maintaining extraction demand from wells and negating the need for a plan (Figs. 4 and 5). In this simple scenario, the plan was successful because water from further away could be accessed and the localised receptors (wetland and domestic wells) that were plan objectives were not adversely impacted. However, in more complex scenarios, if management action occurs too slowly then it may fail to prevent adverse impacts, for example, drawdown cones due to extractions propagating through the aquifer and desiccating a wetland. Furthermore, receptors to extractions change with the aquifer response time. It can be seen in Fig. 5 that the constant head boundary provides most of the inflows for the fast aquifer, which is balanced by an increase in river and well extractions, compared to the slow aquifer which pulls from storage. The drawdown cone of a fast aquifer will be of lower amplitude but further reaching and so the potential receptors will be different because they will be further away. The difference between receptors depending upon response times should also be considered in management design.

Management period

More frequent management resulted in fewer plan failures and increased temporal reliability compared to less frequent management. Management periods greater than annual showed minimal improvement compared to entitlement only scenarios, while reducing temporal and volumetric reliability. The frequency that management decisions were made directly impacted the effectiveness of the plan. This is an important point because the cost of management action must be balanced by the benefit provided. Daily management is expensive and thus, very uncommon. This study showed that increasing the investment in management, in this scenario, decreased the plan failure rate; however, the increase in plan failure rate between daily and monthly management periods was relatively small and may be acceptable to managers due to the lower resource expenditure required for monthly compared to daily management. Additionally, as demonstrated by this study, the objective failure rate increases with increasing length of management period and the best environmental/domestic outcomes are often achieved at the detriment of supply. These are considerations and trade-offs that managers face and that can be informed by modelling the act of management.

Management timing

The time of year management decisions were made directly impacted plan effectiveness. For example, when management decisions were made in January (mid-way through the irrigation season), the 120-day management period was the exception to the increasing failure with length of management period trend and was consistently less effective than annual and bi-annual management. This was due to an interaction between the timing of the management decisions (January, May and September) and the irrigation season (November–March). The 120-day-management cycle compared groundwater levels to triggers in January, May and September and, because May and September were during the nonirrigation season when levels were high, restrictions were not enacted. By the time the next decision was made in January, 2 months after irrigation began, water levels had declined and, restrictions were implemented for the remainder of the irrigation season. However, for the first part of the season (November and December), pumping was unrestricted, and the aquifer was essentially unmanaged; whereas, for annual and bi-annual management frequencies, decisions were also made in January, but the restrictions persisted for 1 or 2 years until the next decision was made.

When levels in monitoring wells were compared to triggers in November, heads were above triggers and no restrictions were implemented. If management decisions were made often (daily or monthly), this was not a concern because the water level declines during the irrigation season were detected and pumping rates were reduced. However, if the management period was annual or greater, decisions were only ever made during the nonirrigation season, and the allocations that were provided when levels were high remained in place until the following November. This shows that when decisions are made prior to the irrigation season, annual, and all subsequent, management periods exhibited the same plan failure rate as the entitlement-only scenario (Fig. 7). Often, allocation volumes are announced prior to the commencement of irrigation seasons to provide irrigations with certainty so they can decide upon cropping types and schedules. However, this analysis suggests that when decisions are made prior to the irrigation season, and the management period is annual or greater, extraction restrictions provide no benefit for the system considered. Nonetheless, this is highly dependent upon aquifer response time and had the systems responded on a decadal or greater timeframe, the impact of management would be quite different. The difference between the entitlement-only scenario and the unmanaged scenarios shows that, in this case, entitlement volume limits increased the effectiveness of the plan. This is important because applying an entitlement volume in a management region is relatively inexpensive compared to other management intervention and these results indicate entitlement volumes improve management outcomes compared to no management. The results of the study illustrate the unpredictability of aquifer system management and underscores the need for cautious management.

Usage of methodology

This method is intended as a management tool that can be used in various ways:

1. To evaluate how effective a given plan is at achieving stated objectives. Scenario modelling can assist in guiding the development of plans and help inform managers of appropriate objectives, triggers and management techniques. Additionally, the method can identify the most effective management period, timing, inappropriate or unachievable objectives, pumping demands or unacceptable impacts and highlight the consequences of management decisions. For example, if the method shows objectives cannot be achieved under any decision-making period, that indicates either the objectives or the mechanisms of the plan may be unsuitable for that particular aquifer resulting in plan redevelopment. The high failure rate in slower responding systems (Figs. 4 and 5) indicates that plans based on inflated entitlement volumes, where the aquifers' ability to supply is unbalanced with the (potential) demanded volume, may not work due to this disparity, depending on how entitlements are utilised during periods of stress. If an aquifer does not have the capacity to meet unrealistic entitlement volumes, then the plan will be ineffectual regardless of management decision frequency.
2. Trigger levels can be adjusted and simulated to determine the potential impact of making decisions under various degrees of risk. For example, if stakeholders thought

occasional wetland desiccation was acceptable, the trigger levels may be set lower. Quantification of the impact on effectiveness helps with risk-based management.

3. As part of a cost-benefit analysis where managers can test various decision-making frequencies to decide whether any reduction in failure rate is worth the increased cost of more frequent management. The cost benefit analysis can also be used to balance environmental protection with supply reliability—for example, managers and stakeholders can evaluate if a particular proportion of days with reduced supply is worth it to achieve the environmental objective.
4. Stakeholders are more likely to accept management actions when they are part of the process and understand the consequences of management action and are equipped to evaluate trade-offs. Effective communication between lawmakers, managers and stakeholders is very important (Nelson 2013) and this method could facilitate understanding and collaboration.

Alternate management scenarios

While this study demonstrated the methodology with a simple system, and predictions of effectiveness depended on model geometry and hydrogeological settings, the method could and should be applied with a realistic site-specific model to inform specific problems. For example, alternative scenarios that can be used with this method include various well numbers, locations and extraction volumes. In the demonstration case, results are sensitive to hydraulic conductivity and model geometry influences the prediction of effectiveness. Changes in aquifer dimensions, transmissivity, boundary types and locations alter the aquifer response time (Walton 2011), upon which effectiveness depends. Increased extractions are likely to increase plan failures due to larger extraction related drawdown cones. Moving wells closer to a boundary such as the river could increase reliability because recharge from the river would be accessed. While this scenario would likely not increase plan failures, other adverse impacts that are not plan objectives may occur, such as a reduced stream flow.

Various combinations of well numbers and location and extraction volume could be explored with the method to aid management design and explore potential impacts to effectiveness and reliability. The method is not limited to water level objectives, various SMART—*specific, measurable, achievable, realistic, timely*—objectives can be evaluated with the method including water quality thresholds, and extraction volume requirements. Any measurable objective that can be adequately modelled can be assessed—for example, the management decision-making period timing was selected to be uniform in order to compare the effectiveness of various periods. However, realistically, decision periods often fluctuate and inserting randomness into the decision-making period would allow an evaluation of the impact of varying decision timing. Water trading and Entitlement carry overs could easily be incorporated into the methodology and various percentages of entitlements and lengths of carryovers could be explored.

Limitations

Groundwater models are uncertain, labour-intensive, and are often prohibitively expensive for groundwater managers who must operate on finite budgets, which limits the applicability of this method and others. Also, the variation in failure rates between aquifer response time (Fig. 4) indicates the method is sensitive to hydraulic conductivity. Therefore, if the model of the groundwater system is highly uncertain, the capacity to evaluate plan effectiveness will be compromised. Management may then be deemed either unnecessary or ineffectual due to erroneous assumptions about the groundwater response during modelling. Models with sparse calibration datasets and hence a wide range of plausible parameters may be of little value for testing management effectiveness. In the example, a numerical model that was perfectly known sufficed as reality and was used to evaluate a plan. However, application of the methodology to a real system subject to variable aquifer properties faces additional challenges due to parameter/predictive uncertainty. Consideration of both conceptual model and model parameter uncertainty that accounts for incomplete knowledge of the subsurface (Bredehoeft 2005) would be required.

Uncertainty in groundwater management modelling is a well-established challenge (Guillaume et al. 2016). The reality of a natural system is always unknown and the feasibility of assessing management with a model that is incapable of perfectly replicating the system is yet to be determined. The level of model fidelity required to adequately represent system reality so that a plan can be assessed is difficult to ascertain and is the subject of ongoing research. In the example, two types of uncertainty were considered, firstly climatic uncertainty was assessed using stochastic climate replicates and secondly, parameter uncertainty was considered in a simplified and heuristic manner with the six different K_s values to demonstrate the impact upon plan effectiveness of parameter variations. It is recognised this is a very basic representation of parameter uncertainty. While rigorous uncertainty studies have been conducted (Sreekanth et al. 2016; Doherty et al. 2010; Gallagher and Doherty 2007), the purpose here was simply to highlight the impact of parameter change upon plan effectiveness, not to realistically represent uncertainty in a synthetic example. An evaluation of the impact of parameter uncertainty on the ability to evaluate management plans is a future research direction currently being pursued.

This simple assessment demonstrates the importance of monitoring data in the groundwater management planning process because the effectiveness of the plan varied widely depending upon hydraulic conductivity values used. These observations suggest that a high degree of system understanding is required to evaluate the effectiveness of management plans. Lacking such data, experimentation upon plan effectiveness may not be possible and resources could be better utilised increasing system understanding.

Conclusion

Currently many groundwater management modelling studies focus on finding the optimal solution of management problems and neglect the management process itself. Groundwater management plans, the primary means of managing groundwater, are not systematically and quantitatively evaluated for effectiveness and currently it is unknown how well they work. This paper develops and demonstrates a method to quantitatively assess the effectiveness of sequential decision-making inherent to groundwater management. Groundwater management was structured as an engineering control loop to capture the aquifer/management feedback and determine if the successive decision-making process improves outcomes compared to no management. The methodology was demonstrated using a simple numerical model constituting “reality” where the impact of implementation of a management plan (consisting of environmental objective, extraction restrictions and entitlement limits) could be assessed at seven different management decision-making frequencies (daily, monthly, four-monthly, yearly, bi-yearly, five-yearly, decadal).

In the synthetic case study, management effectiveness was found to be highly sensitive to aquifer response time and a small change in hydraulic conductivity had a large impact on plan success rate. Of the six response times simulated, management was effective in only three (within the range of K_s values 0.143–0.56 m/day), where demand and capacity were relatively balanced. Outside of this range, management had a negligible impact compared to no management. The observed sensitivity to response time is expected and reinforces that management plans must be tailored to specific systems and that blanket application of management is unwise and most likely ineffective or unnecessary.

In the example case, management improved domestic and environmental outcomes at all decision-making periods compared to the unmanaged scenario. More frequent management resulted in fewer plan failures and increased reliability compared to less frequent management. Management periods greater than annual showed minimal improvement compared to entitlement only, while reducing reliability. Generally, as the length of management period increased, the plan effectiveness decreased. The best environmental and domestic outcomes occurred at daily and monthly management periods when the decision-making period was shorter but resulted in a decrease in temporal irrigation supply reliability. The need for trade-offs was demonstrated because as environmental outcomes increased, supply reliability decreased. If management decisions were made prior to the irrigation season, management was less effective than if decisions were made in the middle of the irrigation season. Annual or greater management period was no more effective than entitlement only when decisions were made prior to the irrigation season. However, the results of the example depend upon system response time and may vary for a large system with a long response time. The sensitivity of the method to aquifer response time suggest that high degree of system understanding is required to evaluate the effectiveness of management plans.

The flexible methodology allows for more complex management involving trading and economic implications or analysis of multiple conceptual models. An understanding of the compromises required to achieve objectives, can assist in the evaluation of priorities and inform the community consultation process of plan development. The systematic evaluation of management plan effectiveness can lead to improvements in the planning process. The main conclusions from this study are:

- Plan effectiveness can be evaluated by simulating the sequential decision-making process of management and the timing and frequency decisions are made impacts plan effectiveness.
- Implementation of restrictions at an inappropriate timescale provides no greater improvement to plan effectiveness than setting an entitlement limit.
- When management decisions are made on annual or longer periods, as frequently occurs in practice, plan effectiveness can be highly uncertain. Additional factors such as noncompliance, which was not considered in this study, could further decrease effectiveness in the considered scenarios.

This study constitutes a step towards evaluating the effectiveness of established groundwater management plans.

Acknowledgements Climate data used in this study can be found on the AWAP (Australian Water Availability Project) database.

Funding information The authors acknowledge Australian Research Council Linkage Project LP130100958 and funding partners, Bureau of Meteorology (BoM) and the Department of Environment, Land, Water and Planning (DELWP) for valuable contributions.

Appendix 1

Table 1 Welch's statistical significance t-test for January decision timing: wetland fail data at daily (1), monthly (30), four-monthly (120), yearly (365), two-yearly (730), five-yearly (1,825) and ten-yearly (3,650), entitlement-only and unmanaged

	1		30		120		365		730		1,825		3,650		Entitlement Only		Unmanaged	
	t	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*
1	0.0000	1.0000	1.9675	0.0576	11.1706	0.0000	9.1878	0.0000	10.0371	0.0000	9.7985	0.0000	9.6755	0.0000	22.5117	0.0000	6.8994	0.0000
30	−1.9675	0.0576	0.0000	1.0000	12.0179	0.0000	9.2665	0.0000	10.3732	0.0000	9.6697	0.0000	9.3874	0.0000	26.6924	0.0000	6.4570	0.0000
120	−11.1706	0.0000	−12.0179	0.0000	0.0000	1.0000	−2.0628	0.0461	−1.0103	0.0319	0.4596	0.6489	1.1567	0.2564	15.6019	0.0000	3.9730	0.0008
365	−9.1878	0.0000	−9.2665	0.0000	2.0628	0.0461	0.0000	1.0000	1.0048	0.3213	2.0407	0.0490	2.5559	0.0156	16.5850	0.0000	4.3996	0.0003
730	−10.0371	0.0000	−10.3732	0.0000	1.0103	0.3188	−1.0048	0.3213	0.0000	1.0000	1.2239	0.2293	1.8246	0.0776	15.6811	0.0000	4.7156	0.0005
1,825	−9.7986	0.0000	−9.6697	0.0000	−0.4596	0.6489	−2.0407	0.0490	−1.2239	0.2293	0.0000	1.0000	0.6458	0.5224	11.4155	0.0000	3.7951	0.0011
3,650	−9.6755	0.0000	−9.3874	0.0000	−1.1577	0.2564	−2.5586	0.0156	−1.8246	0.0776	−0.6458	0.5224	0.0000	1.0000	9.4516	0.0000	3.5455	0.0019
Entitlement Only	−22.5117	0.0000	−26.6924	0.0000	−15.6019	0.0000	−16.5850	0.0000	−15.6811	0.0000	−11.4155	0.0000	−9.4516	0.0000	0.0000	1.0000	0.7987	0.4339
Unmanaged	−6.8994	7.8736	−6.4570	0.0000	−3.9730	0.0008	−4.3996	0.0003	−4.1756	0.0005	−3.7951	0.0011	−3.5455	0.0019	−0.7987	0.4339	0.0000	1.0000

t t-score; *p* p-value

Table 2 Welch's statistical significance t-test for November decision timing: wetland fail data at daily (1), monthly (30), four-monthly (120), yearly (365), two-yearly (730), five-yearly (1,825) and ten-yearly (3,650), entitlement-only and unmanaged

	1		30		120		365		730		1,825		3,650		Entitlement Only		Unmanaged	
	t	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*
1	0.0000	1.0000	1.5225	0.1365	7.6762	0.0000	13.1746	0.0000	13.1746	0.0000	13.1746	0.0000	13.1746	0.0000	13.1746	0.0000	8.1176	0.0000
30	−1.5225	0.1365	0.0000	1.0000	6.8929	0.0000	12.9785	0.0000	12.9785	0.0000	12.9785	0.0000	12.9785	0.0000	12.9785	0.0000	7.5954	0.0000
120	−7.6762	0.0000	−6.8929	0.0000	0.0000	1.0000	6.8407	0.0000	6.8407	0.0000	6.8407	0.0000	6.8407	0.0000	6.8407	0.0000	4.9125	0.0001
365	−13.1746	0.0000	−12.9785	0.0000	−6.8407	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	2.0103	0.0562
730	−13.1746	0.0000	−12.9785	0.0000	−6.8407	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	2.0103	0.0562
1,825	−13.1746	0.0000	−12.9785	0.0000	−6.8407	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	2.0103	0.0562
3,650	−13.1746	0.0000	−12.9785	0.0000	−6.8407	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	2.0103	0.0562
Entitlement Only	−13.1746	0.0000	−12.9785	0.0000	−6.8407	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	2.0103	0.0562
Unmanaged	−8.1176	0.0000	−7.5954	0.0000	−4.9125	0.0001	−2.0103	0.0562	−2.0103	0.0562	−2.0103	0.0562	−2.0103	0.0562	−2.0103	0.0562	0.0000	1.0000

t t-score; *p* p-value

Appendix 2

Table 3 Welch's statistical significance t-test for January decision timing: domestic well one fail data at daily (1), monthly (30), four-monthly (120), yearly (365), two-yearly (730), five-yearly (1,825) and ten-yearly (3,650), entitlement-only and unmanaged

	1		30		120		365		730		1,825		3,650		Entitlement Only		Unmanaged	
	t	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*
1	0.0000	1.0000	2.3992	0.0224	19.9388	0.0000	19.4861	0.0000	21.6845	0.0000	15.0438	0.0000	17.1724	0.0000	37.0851	0.0000	7.9792	0.0000
30	−2.3992	0.0224	0.0000	1.0000	21.4270	0.0000	20.9522	0.0000	23.5561	0.0000	14.6688	0.0000	17.0122	0.0000	40.7383	0.0000	7.7023	0.0000
120	−19.9388	0.0000	−21.4270	0.0000	0.0000	1.0000	−0.6537	0.5173	1.6404	0.1092	2.6539	0.0131	3.8005	0.0007	18.8642	0.0000	4.9775	0.0001
365	−19.4861	0.0000	−20.9523	0.0000	0.6537	0.5173	0.0000	1.0000	2.3144	0.0261	3.0673	0.0048	4.2531	0.0002	19.6200	0.0000	5.0759	0.0001
730	−21.6845	0.0000	−23.5561	0.0000	−1.6404	0.1092	−2.3144	0.0261	0.0000	1.0000	1.6448	0.1114	2.7142	0.0111	17.4509	0.0000	4.7330	0.0001
1,825	−15.0438	0.0000	−14.6688	0.0000	−2.6539	0.0131	−3.0673	0.0048	−1.6448	0.1114	0.0000	1.0000	0.7141	0.4796	9.7789	0.0000	4.2591	0.0004
3,650	−17.1724	0.0000	−17.0122	0.0000	−3.8005	0.0007	−4.2531	0.0002	−2.7142	0.0111	−0.7141	0.4796	0.0000	1.0000	9.5992	0.0000	4.0694	0.0006
Entitlement Only	−37.0851	0.0000	−40.7383	0.0000	−18.8642	0.0000	−19.6200	0.0000	−17.4806	0.0000	−9.7789	0.0001	−9.5992	0.0007	0.0000	1.0000	1.8775	0.0001
Unmanaged	−7.9792	0.0000	−7.7023	0.0000	−4.9775	0.0001	−5.0758	0.0001	−4.7330	0.0001	−4.2591	0.0036	−4.0694	0.0006	−1.8775	0.0754	0.0000	1.0000

t t-score; *p* p-value

Table 4 Welch's statistical significance t-test for November decision timing: domestic well one fail data at daily (1), monthly (30), four-monthly (120), yearly (365), two-yearly (730), five-yearly (1,825) and ten-yearly (3,650), entitlement-only and unmanaged

	1		30		120		365		730		1,825		3,650		Entitlement Only		Unmanaged	
	t	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*
1	0.0000	1.0000	2.5881	0.0147	21.2813	0.0000	36.0620	0.0000	36.0620	0.0000	36.0620	0.0000	36.0620	0.0000	36.0620	0.0000	7.9747	0.0000
30	−2.5881	0.0147	0.0000	1.0000	23.9658	0.0000	40.1143	0.0000	40.1143	0.0000	40.1143	0.0000	40.1143	0.0000	40.1143	0.0000	7.6843	0.0000
120	−21.2813	0.0000	−23.9658	0.0000	0.0000	1.0000	18.1318	0.0000	18.1318	0.0000	18.1318	0.0000	18.1318	0.0000	18.1318	0.0000	4.8507	0.0001
365	−36.0620	0.0000	−40.1143	0.0000	−18.1318	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	1.8574	0.0783
730	−36.0620	0.0000	−40.1143	0.0000	−18.1318	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	1.8574	0.0783
1,825	−36.0620	0.0000	−40.1143	0.0000	−18.1318	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	1.8574	0.0783
3,650	−36.0620	0.0000	−40.1143	0.0000	−18.1318	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	1.8574	0.0783
Entitlement Only	−36.0620	0.0000	−40.1143	0.0000	−18.1318	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	1.8574	0.0783
Unmanaged	−7.9747	0.0000	−7.6843	0.0000	−4.8507	0.0001	−1.8574	0.0783	−1.8574	0.0783	−1.8574	0.0783	−1.8574	0.0783	−1.8574	0.0783	0.0000	1.0000

t t-score; *p* p-value

Appendix 3

Table 5 Welch's statistical significance t-test for January decision timing: domestic well two fail data at daily (1), monthly (30), four-monthly (120), yearly (365), two-yearly (730), five-yearly (1,825) and ten-yearly (3,650), entitlement-only and unmanaged

	1		30		120		365		730		1,825		3,650		Entitlement Only		Unmanaged	
	t	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*
1	0.0000	1.0000	15.3104	0.0000	23.9253	0.0000	22.7615	0.0000	27.0300	0.0000	17.6079	0.0000	22.9102	0.0000	34.5452	0.0000	6.5701	0.0000
30	−15.3104	0.0000	0.0000	1.0000	18.9465	0.0000	18.4596	0.0000	22.4846	0.0000	15.1514	0.0000	19.8283	0.0000	30.5995	0.0000	6.1100	0.0000
120	−23.9253	0.0000	−18.9465	0.0000	0.0000	1.0000	1.2525	0.2182	4.0243	0.0003	4.1884	0.0002	6.2055	0.0000	12.8917	0.0000	3.9780	0.0008
365	−22.7615	0.0000	−18.4596	0.0000	−1.2525	0.2182	0.0000	1.0000	2.5929	0.0134	3.1911	0.0032	4.9684	0.0000	11.1641	0.0000	3.7696	0.0012
730	−27.0300	0.0000	−22.4846	0.0000	−4.0243	0.0003	−2.5929	0.0134	0.0000	1.0000	1.3139	0.1985	2.8451	0.0074	8.8791	0.0000	3.3326	0.0034
1,825	−17.6079	0.0000	−15.1514	0.0000	−4.1884	0.0002	−3.1911	0.0032	−1.3139	0.1985	0.0000	1.0000	1.0572	0.2973	5.4354	0.0000	2.9913	0.0071
3,650	−22.9102	0.0000	−19.8283	0.0000	−6.2055	0.0000	−4.9684	0.0000	−2.8451	0.0074	−1.0572	0.2973	0.0000	1.0000	4.8543	0.0000	2.7388	0.0126
Entitlement Only	−34.5452	0.0000	−30.5995	0.0000	−12.8917	0.0000	−11.1641	0.0000	−8.8791	0.0000	−5.4354	0.0000	−4.8513	0.0000	0.0000	1.0000	1.7063	0.1036
Unmanaged	−6.5701	0.0000	−6.1100	0.0000	−3.9780	0.0008	−3.7696	0.0012	−3.3326	0.0034	−2.9913	0.0071	−2.7388	0.0126	−1.7063	0.1036	0.0000	1.0000

t t-score; *p* p-value

Table 6 Welch's statistical significance t-test for November decision timing: domestic well two fail data at daily (1), monthly (30), four-monthly (120), yearly (365), two-yearly (730), five-yearly (1,825) and ten-yearly (3,650), entitlement-only and unmanaged

	1		30		120		365		730		1,825		3,650		Entitlement Only		Unmanaged	
	t	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*
1	0.0000	1.0000	14.3057	0.0000	21.4401	0.0000	33.3087	0.0000	33.3087	0.0000	33.3087	0.0000	33.3087	0.0000	33.3087	0.0000	6.5701	0.0000
30	−14.3057	0.0000	0.0000	1.0000	16.9947	0.0000	29.3251	0.0000	29.3251	0.0000	29.3251	0.0000	29.3251	0.0000	29.3251	0.0000	6.0995	0.0000
120	−21.4401	0.0000	−16.9947	0.0000	0.0000	1.0000	11.6419	0.0000	11.6419	0.0000	11.6419	0.0000	11.6419	0.0000	11.6419	0.0000	0.9340	0.0009
365	−33.3087	0.0000	−29.3251	0.0000	−11.6419	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	1.7490	0.0958
730	−33.3087	0.0000	−29.3251	0.0000	−11.6419	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	1.7490	0.0958
1,825	−33.3087	0.0000	−29.3251	0.0000	−11.6419	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	1.7490	0.0958
3,650	−33.3087	0.0000	−29.3251	0.0000	−11.6419	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	1.7490	0.0958
Entitlement Only	−33.3087	0.0000	−29.3251	0.0000	−11.6419	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	1.7490	0.0958
Unmanaged	−6.5701	0.0000	−6.0995	0.0000	−3.9340	0.0009	−1.7490	0.0958	−1.7490	0.0958	−1.7490	0.0958	−1.7490	0.0958	−1.7490	0.0958	0.0000	1.0000

t t-score; *p* p-value

Appendix 4

Table 7 Welch's statistical significance t-test for January decision timing: irrigation supply reliability data at daily (1), monthly (30), four-monthly (120), yearly (365), two-yearly (730), five-yearly (1,825) and ten-yearly (3,650), entitlement-only and unmanaged

	1		30		120		365		730		1,825		3,650		Entitlement Only		Unmanaged	
	t	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*
1	0.0000	1.0000	3.3577	0.0018	3.7136	0.0007	−2.7490	0.0091	−3.2960	0.0022	−4.4866	0.0001	−3.1968	0.0031	25.8166	0.0000	−1.9090	0.0713
30	−3.3577	0.0018	0.0000	1.0000	1.0351	0.3080	−6.1725	3.5956	−6.3222	0.0000	−7.2571	0.0000	−5.7251	0.0000	23.8010	0.0000	−2.7342	0.0132
120	−3.7136	0.0007	−1.0351	0.3080	0.0000	1.0000	−6.0140	0.0000	−6.2582	0.0000	−7.1483	0.0000	−5.8552	0.0000	17.9143	0.0000	−2.9884	0.0072
365	2.7490	0.0091	6.1725	0.0000	6.0140	0.0000	0.0000	1.0000	−0.8333	0.4101	−2.2228	0.0329	−1.0990	0.2799	28.1187	0.0000	−1.1893	0.2488
730	3.2960	0.0022	6.3223	0.0000	6.2582	0.0000	0.8333	0.4101	0.0000	1.0000	−1.3520	0.1845	−0.3611	0.7201	25.7217	0.0000	−0.9333	0.3618
1,825	4.4866	0.0001	7.2571	0.0000	7.1483	0.0000	2.2228	0.0329	1.3520	0.1845	0.0000	1.0000	0.8621	0.3941	24.8594	0.0000	−0.4588	0.6512
3,650	3.1968	0.0031	5.7251	0.0000	5.8552	0.0000	1.0990	0.2799	0.3611	0.7201	−0.8621	0.3941	0.0000	1.0000	22.1062	0.0000	−0.7875	0.4397
Entitlement Only	−25.8166	0.0000	−23.8010	0.0000	−17.9143	0.0000	−28.1187	0.0000	−25.7217	0.0000	−24.8594	0.0000	−22.1062	0.0000	0.0000	1.0000	−8.2745	0.0000
Unmanaged	1.9090	0.0713	2.7342	0.0132	2.9884	0.0072	1.1893	0.2488	0.9333	0.3618	0.4588	0.6512	0.7875	0.4397	8.2745	0.0000	0.0000	1.0000

t t-score; *p* p-value

Table 8 Welch's statistical significance t-test for November decision timing: irrigation supply reliability data at daily (1), monthly (30), four-monthly (120), yearly (365), two-yearly (730), five-yearly (1,825) and ten-yearly (3,650), entitlement-only and unmanaged

	1		30		120		365		730		1,825		3,650		Entitlement Only		Unmanaged	
	t	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*
1	0.0000	1.0000	3.0889	0.0037	3.5959	0.0009	25.9106	0.0000	25.9106	0.0000	25.9106	0.0000	25.9106	0.0000	25.9106	0.0000	−1.8835	0.0748
30	−3.0889	0.0037	0.0000	1.0000	0.7153	0.4789	21.9878	0.0000	21.9878	0.0000	21.9878	0.0000	21.9878	0.0000	21.9878	0.0000	−2.6978	0.0141
120	−3.5959	0.0009	−0.7153	0.4789	0.0000	1.0000	19.4823	0.0000	19.4823	0.0000	19.4823	0.0000	19.4823	0.0000	19.4823	0.0000	−2.8894	0.0091
365	−25.9106	0.0000	−21.9878	0.0000	−19.4823	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	−8.2505	0.0000
730	−25.9106	0.0000	−21.9878	0.0000	−19.4823	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	−8.2505	0.0000
1,825	−25.9106	0.0000	−21.9878	0.0000	−19.4823	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	−8.2505	0.0000
3,650	−25.9106	0.0000	−21.9878	0.0000	−19.4823	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	−8.2505	0.0000
Entitlement Only	−25.9106	0.0000	−21.9878	0.0000	−19.4823	0.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000	1.0000	−8.2505	0.0000
Unmanaged	1.8835	0.0748	2.6978	0.0141	2.8894	0.0091	8.2505	0.0000	8.2505	0.0000	8.2505	0.0000	8.2505	0.0000	8.2505	0.0000	0.0000	1.0000

t t-score; *p* p-value

References

Ahlfeld D, Heidari M (1994) Applications of optimal hydraulic control to ground-water systems. J Water Resour Plan Manag 120(3):350–365. https://doi.org/10.1061/(ASCE)0733-9496(1994)120:3(350)

Ahlfeld DP, Hoque Y (2008) Impact of simulation model solver performance on ground water management problems. Groundwater 46(5): 716–726. https://doi.org/10.1111/j.1745-6584.2008.00454.x

Ahlfeld DP, Mulligan AE (2000) Optimal management of flow in groundwater systems. Academic, San Diego

Ahlfeld D, Barlow PM, Mulligan AE (2005) GWM: a ground-water management process for the U.S. Geological Survey modular ground-water model (MODFLOW-2000). US Geological Survey, Reston, VA

Ahn H (2000) Ground water drought management by a feedforward control method 1. JAWRA 36(3):501–510

Alley WM (2016) Drought-proofing groundwater. Groundwater 54(3): 309–309. https://doi.org/10.1111/gwat.12418

Alley WM, Healy RW, LaBaugh JW, Reilly TE (2002) Flow and storage in groundwater systems. Science 296(5575):1985–1990. https://doi.org/10.1126/science.1067123

Anderies JM, Rodriguez AA, Janssen MA, Cifdaloz O (2007) Panaceas, uncertainty, and the robust control framework in sustainability science. Proc Natl Acad Sci 104(39):15194–15199

Andricevic R (1990) A real-time approach to management and monitoring of groundwater hydraulics. Water Resour Res 26(11):2747–2755. https://doi.org/10.1029/WR026i011p02747

Astrom KJ, Murray RM (2008) Feedback systems, an introduction for scientists and engineers. Princeton University Press, Princeton, NJ

Åström KJ, Wittenmark B (2008) Adaptive control: Dover, Mineola, NY

Bakker M, Post V, Langevin CD, Hughes JD, White JT, Starn JJ, Fienen MN (2016) Scripting MODFLOW model development using Python and FloPy. Groundwater. https://doi.org/10.1111/gwat.12413

Banta ER, Ahlfeld DP (2013) GWM-VI: groundwater management with parallel processing for multiple MODFLOW versions. US Geol Surv Techniques Methods 6-A48

Barthel R, Foster S, Villholth KG (2017) Interdisciplinary and participatory approaches: the key to effective groundwater management. Hydrogeol J 25(7):1923–1926. https://doi.org/10.1007/s10040-017-1616-y

Bauser G, Franssen H-JH, Kaiser H-P, Kuhlmann U, Stauffer F, Kinzelbach W (2010) Real-time management of an urban groundwater well field threatened by pollution. Environ Sci Technol 44(17):6802–6807

Bear J, Levin O (1967) The optimal yield of an aquifer. Water Resour Res 8(1):178–181

Bredehoeft J (2005) The conceptualization model problem—surprise. Hydrogeol J 13(1):37–46

Bredehoeft JD, Reichard EG, Gorelick SM (1995) If it works, don't fix it: benefits from regional ground-water management. In: Groundwater models for resources analysis and management. CRC, Boca Raton, FL, pp 101–121

Brown CM, Lund JR, Cai X, Reed PM, Zagona EA, Ostfeld A, Hall J, Characklis GW, Yu W, Brekke L (2015) The future of water resources systems analysis: toward a scientific framework for sustainable water management. Water Resour Res 51(8):6110–6124

California Legislature (2014) *The Sustainable Groundwater Management Act*. California Legislature, Sacramento, CA

Carpenter SR, Brock W, Hanson P (1999) Ecological and social dynamics in simple models of ecosystem management. Ecol Soc 3(2). https://doi.org/10.5751/ES-00122-030204

Castilla-Rho JC, Mariethoz G, Rojas R, Andersen MS, Kelly BFJ (2015) An agent-based platform for simulating complex human–aquifer interactions in managed groundwater systems. Environ Model Softw 73:305–323

Castilla-Rho JC (2017) Groundwater modeling with stakeholders: finding the complexity that matters. Groundwater. https://doi.org/10.1111/gwat.12569

CSIRO (2016) Australian water availability project. http://www.csiro.au/awap/#maps. Accessed June 2019

Currell M, Gleeson T, Dahlhaus P (2016) A new assessment framework for transience in hydrogeological systems. Groundwater 54(1):4–14. https://doi.org/10.1111/gwat.12300

DELWP (2015a) Ministerial guidelines for groundwater licensing and the protection of high value groundwater dependent ecosystems. Government of Victoria, Victoria, Australia

DELWP (2015b) Resource share guidelines. Planning the take of Victoria 's groundwater resources. Dept. of Environment Land Water and Planning, Victorian Government, Victoria, Australia

DLRM (2016) Alice Springs Water Allocation Plan 2016–2026. Dept. of Land Resource Management, Northern Territory Government, Alice Springs, Australia

Doherty JE, Hunt RJ, Tonkin MJ (2010) Approaches to highly parameterized inversion: a guide to using PEST for model-parameter and predictive-uncertainty analysis. US Geol Surv Sci Invest Rep 2010–5211

DOW (2009) Gnangara groundwater areas allocation plan. Dept. of Water, Government of Western Australia, Perth, Australia

Ebrahim, Girma Yimer, Andreja Jonoski, Ali Al-Maktoumi, Mushtaque Ahmed, and Arthur Mynett (2015) Simulation-optimization approach for evaluating the feasibility of managed aquifer recharge in the Samail lower catchment, Oman. J Water Resour Plan Manag 142(2):05015007

Elsawah S, Guillaume JHA (2016) Incorporating human aspects into groundwater research and policy making: a soft and critical systems thinking approach. In: Anthony J, Jakeman O, Barreteau RJ, Hunt, JD, Rinaudo JD, Ross A (eds) Integrated groundwater management: concepts, approaches and challenges. Springer, Heidelberg, Germany

Emch PG, Yeh WW-G (1998) Management model for conjunctive use of coastal surface water and ground water. J Water Resour Plan Manag 124(3):129–139. https://doi.org/10.1061/(ASCE)0733-9496(1998)124:3(129

Esteban E, Dinar A (2012) Modeling sustainable groundwater management: packaging and sequencing of policy interventions. J Environ Manag 119C:93–102

Famiglietti JS (2014) The global groundwater crisis. Nature Clim Change 4(11):945–948. https://doi.org/10.1038/nclimate2425

Fienen, Michael N, Kenneth R Bradbury, Maribeth Kniffin, and Paul M Barlow. (2018) Depletion mapping and constrained optimization to support managing groundwater extraction. Groundwater 56(1):18–31

Foster S, Evans R, Escolero O (2015) The groundwater management plan: in praise of a neglected 'tool of our trade'. Hydrogeol J 23(5):847–850. https://doi.org/10.1007/s10040-015-1261-2

Frazier vs Brown (1861) Frazier vs Brown. Ohio Supreme Court, Columbus, OH

Gallagher M, Doherty J (2007) Parameter estimation and uncertainty analysis for a watershed model. Environ Model Softw 22(7):1000–1020. https://doi.org/10.1016/j.envsoft.2006.06.007.

Ghorbanidehno H, Kokkinaki A, Kitanidis PK, Darve E (2017) Optimal estimation and scheduling in aquifer management using the rapid feedback control method. Adv Water Resour 110:310–318

Giordano M (2009) Global groundwater? Issues and solutions. Ann Rev Environ Resour 34(1):153–178. https://doi.org/10.1146/annurev.environ.030308.100251

Gleeson T, Alley WM, Allen DM, Sophocleous MA, Zhou Y, Taniguchi M, VanderSteen J (2012) Towards sustainable groundwater use: setting long-term goals, backcasting, and managing adaptively.

Ground Water 50(1):19–26. https://doi.org/10.1111/j.1745-6584.2011.00825.x

GWM (2001) Murrayville area groundwater management plan. Goulburn Murray Water, Victoria, Australia

GWM (2006) Groundwater management plan for the Katunga water supply protection area. Goulburn Murray Water, Victoria, Australia

GMW (2009) Mid-Loddon groundwater management area local management rules. Goulburn Murray Water, Victoria, Australia

GMW (2011) Upper Ovens River water supply protection area water management plan. Goulburn Murray Water, Victoria, Australia

GWM (2012) Loddon highlands water supply protection area groundwater management plan. Goulburn Murray Water, Victoria, Australia

Gordon LJ, Peterson GD, Bennett EM (2008) Agricultural modifications of hydrological flows create ecological surprises. Trends Ecol Evol 23(4):211–219

Gorelick SM (1983) A review of distributed parameter groundwater management modeling methods. Water Resour Res 19(2):17

Gorelick SM, Zheng C (2015) Global change and the groundwater management challenge. Water Resour Res 51(5):3031–3051. https://doi.org/10.1002/2014WR016825

Government of Australia (2007) Water Act. Government of Australia, Canberra, Australia

Guillaume JHA, El Sawah S (2014) Fostering assumption-based stress-test thinking in managing groundwater systems: learning to avoid failures due to basic dynamics. Hydrogeol J 22(7):1507–1523. https://doi.org/10.1007/s10040-014-1153-x

Guillaume JHA, Hunt RJ, Comunian A, Blakers RS, Baihua FU (2016) Methods for exploring uncertainty in groundwater management predictions. In: Jakeman AJ (ed) Integrated groundwater management. Springer, Heidelberg, Germany

Hardin G (1968) The tragedy of the commons. Science 162(3859):1243–1248. https://doi.org/10.1126/science.162.3859.1243

Head B (2010) Water policy: evidence, learning and the governance of uncertainty. Polic Soc 29:11

Jakeman AJ, Barreteau O, Hunt RJ, Rinaudo J-D, Ross A, Arshad M, Hamilton S (2016) Integrated groundwater management: an overview of concepts and challenges. In: Anthony J, Jakeman O, Barreteau RJ, Hunt, JD, Rinaudo JD, Ross A (eds) Integrated groundwater management: concepts, approaches and challenges. Springer, Heidelberg, Germany

Janssen MA, Carpenter SR (1999) Managing the resilience of lakes: a multi-agent modeling approach. Conserv Ecol 3(2):15

Jones LD, Willis R, Yeh WW-G (1987) Optimal control of nonlinear groundwater hydraulics using differential dynamic programming. Water Resour Res 23(11):2097–2106

Konikow L, Kendy E (2005) Groundwater depletion: a global problem. Hydrogeol J 13(1):317–320. https://doi.org/10.1007/s10040-004-0411-8

Lade SJ, Tavoni A, Levin SA, Schlüter M (2013) Regime shifts in a social-ecological system. Theor Ecol 6(3):359–372. https://doi.org/10.1007/s12080-013-0187-3

Loucks DP (1992) Water resource systems models: their role in planning. J Water Resour Plan Manag 118(3):214–223. https://doi.org/10.1061/(ASCE)0733-9496(1992)118:3(214)

Loucks DP, Van Beek E (2005) Water resources systems planning and management: an introduction to methods, models and applications. UNESCO, Paris

Habibi Davijani M, Banihabib ME, Nadjafzadeh Anvar A, Hashemi SR (2016) Multi-objective optimization model for the allocation of water resources in arid regions based on the maximization of socioeconomic efficiency. Water Resour Manag 30. https://doi.org/10.1007/s11269-015-1200-y

McKay J (2006) Groundwater as the Cinderella of water laws, policies, and institutions in Australia. International Symposium on Groundwater Sustainability (ISGWAS), Alicante, Spain, January 2006

McMahon TA, Adeloye AJ (2005) Water resources yield. Water Resources, Littleton, CO

Meals DW, Dressing SA, Davenport TE (2010) Lag time in water quality response to best management practices: a review. J Environ Qual 39: 1. https://doi.org/10.2134/jeq2009.0108

Mulligan KB, Brown C, Yang YE, Ahlfeld DP (2014) Assessing groundwater policy with coupled economic-groundwater hydrologic modelling. Water Resour Res 50(3):2257–2275

Nelson R (2013) Taking policy from paper to the pump: lessons on effective and flexible groundwater policy and management from the Western U.S. and Australia. Comparative Groundwater Law and Policy Program, Stanford University, Palo Alto, CA

Niswonger RG, Panday S, Ibaraki M (2011) MODFLOW-NWT: a Newton formulation for MODFLOW-2005. https://www.usgs.gov/software/modflow-nwt-a-newton-formulation-modflow-2005. Accessed June 2019

NREATS (2009) Water allocation plan for the Tindall Limestone Aquifer Katherine 2009–2019. Dept. of Natural Resources Environment, the Arts and Sport, Northern Territory Government, Katherine, NT, Australia

Park C-H, Aral MM (2004) Multi-objective optimization of pumping rates and well placement in coastal aquifers. J Hydrol 290(1):80–99

Peña-Haro S, Pulido-Velazquez M, Llopis-Albert C (2011) Stochastic hydro-economic modeling for optimal management of agricultural groundwater nitrate pollution under hydraulic conductivity uncertainty. Environ Model Softw 26(8):999–1008. https://doi.org/10.1016/j.envsoft.2011.02.010.

Peterson TJ, Western AW (2014) Nonlinear time series modeling of unconfined groundwater head. Water Resour Res 50(10):25. https://doi.org/10.1002/2013wr014800

Peterson TJ, Western AW, Argent RM (2012) Analytical methods for ecosystem resilience: a hydrological investigation. Water Resour Res 48(10). https://doi.org/10.1029/2012WR012150

Plato (2003) The last day of Socrates, ed. by Harold Tarrant. Penguin, London

Python Software Foundation (2019) Python language reference, version 2.7. http://www.python.org. Accessed June 2019

Raupach MR, Briggs PR, Haverd V, King EA, Paget M, Trudinger CM (2008) Australian water availability project (AWAP). CSIRO Marine and Atmospheric Research Component: final report for phase 3, CSIRO, Canberra, Australia

Reed PM, Minsker BS (2004) Striking the balance: long-term groundwater monitoring design for conflicting objectives. J Water Resour Plan Manag 130(2):140–149. https://doi.org/10.1061/(ASCE)0733-9496(2004)130:2(140)

Reed PM, Hadka D, Herman JD, Kasprzyk JR, Kollat JB (2013) Evolutionary multiobjective optimization in water resources: the past, present, and future. Adv Water Resour 51:438–456. https://doi.org/10.1016/j.advwatres.2012.01.005.

Reichard E, Johnson T (2005) Assessment of regional management strategies for controlling seawater intrusion. J Water Resour Plan Manag 131(4):280–291. https://doi.org/10.1061/(ASCE)0733-9496(2005)131:4(280)

Rejani R, Jha MK, Panda SN, Mull R (2008) Simulation modeling for efficient groundwater management in Balasore Coastal Basin, India. Water Resour Manag 22(1):23–50. https://doi.org/10.1007/s11269-006-9142-z

Rousseau-Gueutin P, Love AJ, Vasseur G, Robinson NI, Simmons CT, de Marsily G (2013) Time to reach near-steady state in large aquifers. Water Resour Res 49(10):6893–6908. https://doi.org/10.1002/wrcr.20534

SAAL NRM (2009) Water allocation plan for the Far North Prescribed Wells area. South Australian Arid Lands Natural Resources Management Board, Government of South Australia, Adelaide, Australia

Singh A (2012) An overview of the optimization modelling applications. J Hydrol 466–467(0):167–182. https://doi.org/10.1016/j.jhydrol.2012.08.004.

Singh A (2014a) Simulation and optimization modeling for the management of groundwater resources. II: combined applications. J Irrig Drain Eng 140(4):04014002. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000689

Singh A (2014b) Groundwater resources management through the applications of simulation modeling: a review. Sci Total Environ 499(0): 414–423. https://doi.org/10.1016/j.scitotenv.2014.05.048.

Singh A (2014c) Simulation and optimization modeling for the management of groundwater resources I: distinct applications. J Irrig Drain Eng 140(4):04013021. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000688

Singh A (2015) Review: computer-based models for managing the water-resource problems of irrigated agriculture. Hydrogeol J 23(6):1217–1227. https://doi.org/10.1007/s10040-015-1270-1

Sivapalan M, Savenije HHG, Blöschl G (2012) Socio-hydrology: a new science of people and water. Hydrol Process 26(8):1270–1276

Sreekanth J, Datta B (2011) Coupled simulation-optimization model for coastal aquifer management using genetic programming-based ensemble surrogate models and multiple-realization optimization. Water Resour Res 47(4). https://doi.org/10.1029/2010WR009683

Sreekanth J, Moore C, Wolf L (2016) Pareto-based efficient stochastic simulation–optimization for robust and reliable groundwater management. J Hydrol 533:180–190

Srikanthan S, Chiew F, and Frost, A (2006), Stochastic Climate Library Version 2.2. eWater, Canberra

SRW (2010) Groundwater management plan Koo Wee Rup water supply protection area. Southern Rural Water, Maffra, Australia

Tankersley CD, Graham WD (1994) Development of an optimal control system for maintaining minimum groundwater levels. Water Resour Res 30(11):3171–3181. https://doi.org/10.1029/94wr01790

Wada Y, van Beek LPH, van Kempen CM, Reckman JWTM, Vasak S, Bierkens MFP (2010) Global depletion of groundwater resources. Geophys Res Lett 37(20):L20402. https://doi.org/10.1029/2010gl044571

Wagner BJ (1995) Recent advances in simulation: optimization groundwater management modeling. Rev Geophys 33(S2):1021–1028

Walton WC (2011) Aquifer system response time and groundwater supply management. Ground Water 49(2):126–127. https://doi.org/10.1111/j.1745-6584.2010.00770.x

Werner AD, Bakker M, Post VEA, Vandenbohede A, Lu C, Ataie-Ashtiani B, Simmons CT, Barry DA (2013) Seawater intrusion processes, investigation and management: recent advances and future challenges. Adv Water Resour 51:3–26. https://doi.org/10.1016/j.advwatres.2012.03.004.

White EK, Peterson TJ, Costelloe J, Western AW, Carrara E (2016) Can we manage groundwater? A method to determine the quantitative testability of groundwater management plans. Water Resour Res 52(6):4863–4882. https://doi.org/10.1002/2015WR018474

White JT, Fienen MN, Barlow PM, Welter DE (2018) A tool for efficient, model-independent management optimization under uncertainty. Environ Model Softw 100:213–221. https://doi.org/10.1016/j.envsoft.2017.11.019.

World Economic Forum (2018) The global risks report 2018, 13th edn. World Economic Forum, Geneva, Switzerland

Yeh WG (1992) Systems analysis in ground: water planning and management. J Water Resour Plan Manag 118:13