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Can we manage groundwater? A method to determine the quantitative testability of groundwater management plans

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Key Points:

- Effective groundwater management is crucial for resource security so plans must be testable
- Framing groundwater management as a control problem allows development of a testability rubric
- Many groundwater management plans are not conducive to quantitative assessment of effectiveness

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Abstract Groundwater is the world's largest freshwater resource and due to overextraction, levels have declined in many regions causing extensive social and environmental impacts. Groundwater management seeks to balance and mitigate the detrimental impacts of development, with plans commonly used to outline management pathways. Thus, plan efficiency is crucial, but seldom are plans systematically and quantitatively assessed for effectiveness. This study frames groundwater management as a system control problem in order to develop a novel testability assessment rubric to determine if plans meet the requirements of a control loop, and subsequently, whether they can be quantitatively tested. Seven components of a management plan equivalent to basic components of a control loop were determined, and requirements of each component necessary to enable testability were defined. Each component was weighted based upon proposed relative importance, then segmented into rated categories depending on the degree the requirements were met. Component importance varied but, a defined objective or acceptable impact was necessary for plans to be testable. The rubric was developed within the context of the Australian groundwater management industry, and while use of the rubric is not limited to Australia, it was applied to 15 Australian groundwater management plans and approximately 47% were found to be testable. Considering the importance of effective groundwater management, and the central role of plans, our lack of ability to test many plans is concerning.

1. Introduction

Groundwater provides the main source of drinking water for almost two billion people, half the irrigation water used for global food production and represents the world's largest freshwater resource [*Aeschbach-Hertig and Gleeson*, 2012; *Famiglietti*, 2014; *Gleeson et al.*, 2010]. With increasing demand and excessive extraction, water levels have declined in many regions of the world, including Australia, the Middle East, China, USA, India, Northern Africa, and Southern Europe. These declines have resulted in decreased well yields and increased pumping costs [*Konikow and Kendy*, 2005], water quality deterioration [*Fogg and LaBolle*, 2006; *Shah et al.*, 2001], stream and wetland desiccation [*Wada et al.*, 2010], land subsidence [*Giordano*, 2009], and other adverse environmental and social impacts [*Gleeson et al.*, 2010; *Wada et al.*, 2010]. Therefore, with most of the easily accessible groundwater resources developed or overdeveloped, and the era of groundwater exploration mostly over; detailed evaluation and careful management of known aquifers has become of the utmost importance [*Freeze and Cherry*, 1979; *Gleeson et al.*, 2012; *Pigram*, 2006]. The extent and severity of these impacts suggests effective groundwater management remains elusive, and considering plans are a primary method of managing groundwater, ensuring they are robust and effective is vital. Logically, the only way to tell if plans are robust and effective is by testing them. And it follows that if plans cannot be tested, effectiveness will remain unknown. We contend there are two critical aspects of determining the effectiveness of a management plan:

1. Plans are constructed in a way to make them testable.
2. An evaluation is undertaken to assess effectiveness. There are two components to this evaluation process, (a) the aquifer system has been stressed such that plan management actions are activated and (b) causality of any observed change in aquifer state has been attributed to management interventions.

This research concerns the first part; that is, the testability of plans. The purpose of this paper is to present a method to assess if management plans *can* be tested for effectiveness. The evaluation of *how* effective plans are is a topic of current research but is beyond the scope of this paper. It is not contended that testability equates to effectiveness but simply, that testability is a crucial, yet oft disregarded, prerequisite of evaluating the effectiveness of management plans.

1.1. An Acceptable Aquifer State Does Not Equate to an Acceptable Management Plan

Measures used to describe the condition of an aquifer system include hydraulic head levels, well yields, minimum stream or base flow volumes, fluxes, and status of groundwater-dependent ecosystems (GDEs), which combined, comprise the state of the aquifer system. Many external and management-related drivers impact this aquifer state, including precipitation, recharge, discharge, evapotranspiration, pumping extractions, previous management actions, and geological environment [*Konikow and Kendy*, 2005]. Isolating the individual impact of management actions toward achieving objectives, or maintaining head at acceptable levels, from that of external drivers is very difficult.

Consequently, an acceptable aquifer state can often be misinterpreted as evidence of plan success. But the state of an aquifer is not equal to plan efficacy, for example, consider a scenario where a management plan has governed a semiconfined aquifer for 10 years in a region utilizing both surface and groundwater. Throughout the decade, the region experienced a severe drought and surface water availability declined, prompting increased groundwater demand. Head levels dropped until groundwater restrictions were triggered, and, despite sequential implementation of increasingly severe restrictions, levels continued to fall. When the drought broke, recharge increased, extractions reduced and heads recovered to predrought levels. Conversely, consider the same aquifer during a decade in which conditions were particularly wet, with plentiful recharge, minimal pumping, and management intervention was not required. Consequently, the plan mechanisms designed to manage the system under stress were not enacted. The same management plan is perceived differently based on climatic conditions, because clearly, both climate and management influence head levels and the respective impacts influencing an aquifer are difficult to disentangle [*Shapoori et al*., 2015].

As a result of interwoven impacts and the realities of groundwater management, assumptions are made. We believe the assumption that a groundwater management plan is the causative factor if an aquifer remains in an acceptable state, is pervasive in groundwater management. Yet evidence of the validity of this assumption is difficult to amass. It cannot be stated that a plan is effective unless the system has been stressed such that management actions are activated, and causality of any observed system change established. Proclaiming plans as effective without verification is ill-advised and borrowing the words of Sir Arthur Conan Doyle, "the temptation to form premature theories upon insufficient data is the bane of our profession." [*Doyle*, 1915]. Efficacy must be demonstrated not assumed. Despite routine measurement of aquifer states, plan efficacy is rarely analyzed and in many cases, cannot be analyzed. Nonetheless, plan review reports frequently state "successful implementation" of plans e.g., [*Golburn Murray Water* (*GMW*), 2014a, 2014b, 2014c, 2014d, 2014e], as opposed to quantitatively analyzing the specific role of the plan in successful actualization of objectives. Furthermore, stable water levels are often used as a benchmark to determine whether management is appropriate, for example, several Australian plan review reports state "monitoring and metering indicate no significant changes in the condition of the resource or water usage patterns . . . Therefore, it is considered that the groundwater resources are being managed sustainably" [*Southern Rural Water*, 2014b, 2014c, 2014c]. And regularly the success of groundwater management plans is measured against potentiometric surface or broad, qualitative objectives defined in legislation such as "equitable management" [*Government of Victoria*, 1989] or the "protection, maintenance and enhancement of ecosystem value" [*Department of Water* (*DOW*), 2006], despite significant causative uncertainty between management actions and aquifer dynamics. Due to this uncertainty, much ambiguity surrounds the effectiveness of plans. The first step toward resolving this ambiguity is determining if a plan can be tested. That is, does the plan contain the required components that would allow a quantitative analysis to separate and determine the individual effect upon the aquifer of climate and management, and provide quantitative, defensible, proof of plan legitimacy? Such individual analysis seldom occurs, despite its potential to minimize erroneous management conclusions and to lead to more effective plans. Consequently, the efficiency of numerous plans is unknown.

1.2. The Challenge of Environmental Management

Implicit in the management of environmental systems is the assumption that sequential decision making improves outcomes. Considering that aquifers, like many environmental systems, are complex, heterogeneous, and open systems where hypotheses cannot be proven [*Oreskes et al*., 1994], and sequential management decisions are complicated by extensive lag times, scale issues, and data scarcity and uncertainty, this assumption warrants examination. Extractions from aquifers, as with most managed natural resources, are governed by a process in which managers have incomplete system knowledge and receive incomplete data which they use to consider resource demands and other values to decide upon an acceptable usage. Clearly the effectiveness of such decision making is dependent upon the reliability of system knowledge, perceived vs actual risks, and time lags between management actions and the observed response of the system. Quantitatively exploring the impact of sequential environmental management and the coupled social-biophysical dynamics is challenging, and to date the focus has been on simple theoretical numerical modelling studies. Two notable early investigations of potential effects of sequential environmental management are *Janssen et al*. [1999] and *Carpenter et al*. [1999], who explored the management of phosphorus loading to a lake simulated with a positive feedback. Both studies found that various management approaches caused the lake dynamics to oscillate between the desirable oligotrophic, and undesirable, eutrophic states. More recently, *Lade et al*. [2013] explored harvesting of a nonspecific common-pool resource where overexploitation was regulated by social ostracism of noncomplying harvesters. Importantly, and unlike *Janssen et al*. [1999] and *Carpenter et al*. [1999], the natural resource itself did not have a positive feedback but its interaction with society resulted in a positive feedback and consequent overexploitation of the resource. And through modelling alternate management control methods, *Anderies et al*. [2007] found panaceas can be more detrimental than inaction in the case of fisheries management. The authors stated that inappropriate use of feedback in natural resource management can destabilize or destroy ecological systems.

These management investigative studies show that the feedback cycles present in many socioenvironmental systems may, through interactions with management under inadequate system knowledge, be stimulated in unanticipated ways leading to system failure. This concept of stress testing management was explored in a hydrogeological context by *Guillaume and El Sawah* [2014], who used simple one and two cell groundwater models that captured aquifer system dynamics and satisfied predetermined assumptions, to allow stakeholders to explore conditions under which management plans succeeded and failed to achieve objective conditions. Because each policy failed under particular circumstances, insight into system behavior under management was gleaned, plan limitations identified, and the fact that inappropriate preconceptions can result in management failure highlighted. This is important because in groundwater management, reality will always differ from preconceptions due to uncertainty, and because real aquifers and societal responses are orders of magnitude more complex than the aforementioned modelled systems. Thus, it is reasonable to conclude from these studies that the management of a system under uncertainty, such as an aquifer, can result in unforeseen impacts due to unexpected system dynamics. In view of that, our groundwater management plans may not in fact be doing what we think they are.

1.3. How is Groundwater Managed?

All groundwater development has an impact [*Alley and Leake*, 2004]. Acceptable levels of impacts vary depending on the value of the resource, socioeconomic factors, and the importance of the impacted environment. In some regions development pressure is high and aquifer systems are stressed, while in others, development is low, environmental, and social impacts are mostly absent and the aquifers are not under pressure. It follows that the level of acceptable impact is correlated to developmental stress and balanced against system value [*Richardson et al*., 2011]. As a consequence, priorities of management plans and acceptable extraction rates vary: in systems with little development stress where interventionist management is unnecessary, management plans designed to monitor the aquifers for impacts without control mechanism are appropriate. In contrast, regions with intense usage competition, historical, or anticipated water shortage stresses, statutory management plans detailing control measures are required to prevent and manage overexploitation. Broadly, groundwater extractions can be considered as either sustainable or nonsustainable depending upon the hydrogeological environment and management time frame. Sustainable groundwater development is defined as the "use of groundwater resources in a manner that can be maintained indefinitely without causing unacceptable environmental, social or economic consequences" [*Alley and Leake*, 2004]. Unsustainble development is defined as consciously finite and consuming. However, as articulately stated in *American Society of Civil Engineers* [1987] "it is not a sin to mine groundwater." The idea that all aquifers can be developed sustainably is erroneous [*Kalf and Woolley*, 2004], and as long as more water is extracted from the aquifer than is replenished through recharge, the aquifer is mined [*Custodio*, 2002]. Social, economic, or political reasons may necessitate groundwater mining to sustain communities or economic productivity in arid regions with little recharge or alternate water sources, and in this way groundwater use is determined through a (often implicit) cost benefit analysis. As long as the benefits afforded by groundwater use exceed the social, economic and environmental costs, usage will proceed until exhaustion, or until costs rise to outweigh benefits or the price of alternate sources [*Koundouri*, 2004; *Tietenberg and Lewis*, 2000]. Clearly, water has economic value in all its competing uses and its management as a commodity is crucial for fair, sustainable, and efficient usage [*ICWE*, 1992], and yet, tariffs are generally below full cost of supply [*Rogers et al*., 2002]. Pricing water at the true cost of the resource prompts rationing and would result in reduction of demand, supply supplementation, and efficient transfer of water to the most valuable use [*Rogers et al*., 2002]. Presently, in most cases, water pricing does not reflect true costs and alternate rationing and management methods are employed, including extraction limits, water licensing, water sharing [*Council of Australian Governments* (*COAG*), 2004], buybacks [*Commonwealth of Australia*, 2014], water trading [*National Water Commission*, 2016b], managed aquifer recharge [*Dillon et al*., 2009], and carryover, [*Department of Sustainability and Environment*, 2012; *National Water Commission*, 2016a] among others. These techniques are increasingly enacted through management plans and leave water managers with the problematic task of deciding where to invest limited resources based upon fragmentary knowledge and often, conflicting factors. Writing a comprehensive, multidisciplinary management plan under uncertainty is a herculean task, with many aspects to consider, stakeholders to appease, and political whims and pressures to navigate through. As a consequence, testability is rarely in the forefront of groundwater management planning.

1.4. How Are Management Plans Tested?

Since the latter part of the 20th century, there has been an increasing focus on groundwater policy and many regions now mandate groundwater management plan development.

Qualitative guides on groundwater management, policy guidelines, [*Department of Environment and Primary Industries*, 2014; *Department of Envrionment Land Water and Planning* (*DELWP*), 2015; *Murray-Darling Basin Authority*, 2013; *National Water Commission*, 2010; *United Nations Educational Scientific and Cultural Organization et al*., 2003], sustainability strategies [*Aeschbach-Hertig and Gleeson*, 2012; *Garduno and Foster*, 2010; *Gleeson et al*., 2010; *Hamstead*, 2009], and nuanced technical investigations abound. To date, the focus has been on writing plans to satisfy legislative requirements and community concerns with testability not prioritized. To our knowledge, very few studies have examined the effectiveness of groundwater management plans distinct from aquifer state, or elucidated causes of groundwater management success or failure. Considerable effort has been put into using numerical models to evaluate technical aspects of groundwater management. For example, numerical models have been used to predict impacts of groundwater extraction upon aquifers [*Ebraheem et al*., 2002; *Gorelick*, 1983], optimize extraction rates [*Bear and Levin*, 1967; *Casola et al*., 1986; *Makinde-Odusola and Mariño*, 1989; *McPhee and Yeh*, 2004; *Singh*, 2012, 2014; *Tankersley and Graham*, 1994; *Wagner*, 1995], adjust control based on actual system response [*Jones*, 1992], manage seawater intrusion [*Reichard and Johnson*, 2005; *Rejani et al*., 2008], and investigate implications of economic considerations [*Booker et al*., 2012; *Bredehoeft and Young*, 1970; *Bromley*, 1991; *Gisser and Sánchez*, 1980; *Koundouri*, 2004; *Mulligan et al*., 2014], among others. These studies do not, however, investigate if sequential management decisions result in successful resource management or assess the effectiveness of the plan separate from the state of the aquifer.

Many numerical modelling studies have also investigated the impact of various aquifer management decisions [*Government of Western Australia*, 2009; *Guillaume and El Sawah*, 2014]. *Gallagher* [2015b] developed the Groundwater Operational Management Package (GWOMP), an integrated MODFLOW-MT3DMS-SEAWAT modeling package that simulates an aquifer under various management regimes to allow for testing of allocation volumes, carryover, and groundwater trading with a range of triggers and operational rules. The package was implemented on the Pioneer Basin in Queensland and the Campaspe Catchment, Victoria. The aquifer response under various management scenarios was simulated [*Gallagher*, 2015a; *Queensland Government*, 2002]. While these exciting studies hold great potential to investigate the intricacies of management, they did not separate the effectiveness of the plan from the state of the aquifer and because they were single site studies; nor did they elicit general attributes of a groundwater management plan that lead it to be testable.

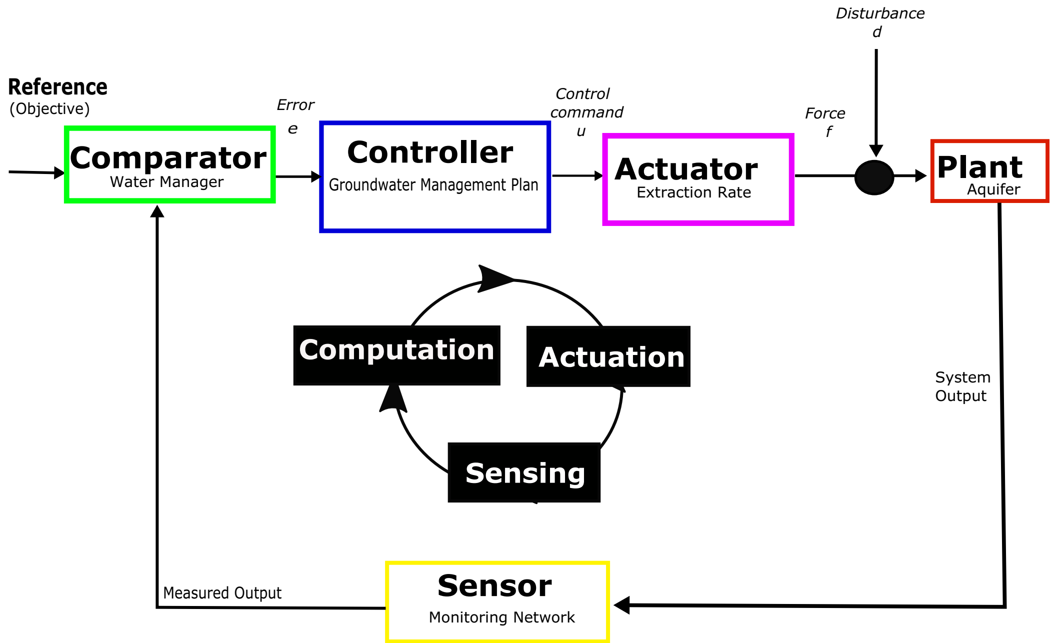

Figure 1. Classical control theory loop. The five components forming a classical control loop are shown in the five boxes. A desired input value (reference) is input into the system, compared to the actual system value by the comparator, and depending on the error, corrective action is computed by the controller and effected upon the system by the actuator. If the system is functioning correctly, the error should be zero and the reference value maintained.

This paper takes the first step toward the quantification of management plan effectiveness distinct from aquifer state, by determining the components of a plan that permit it to be quantitatively evaluated, and is ordered as follows. First, engineering control theory is presented as a framework to structure the process of management within an aquifer system and subsequently; to create a robust, novel, and holistic rubric for assessing plan testability. The rubric, comprising of seven components upon which management plans are evaluated, divides testable plans from nontestable plans. Following the description of the rubric developmental process, a series of 15 Australian groundwater management plans covering a representative range of water uses and challenges, are assessed for testability. Results lead us to contend that many groundwater management plans cannot be quantitatively tested for effectiveness. And that; is a problem.

2. Framework Development

2.1. Control Theory and Application to Hydrogeology

Control is a discipline of engineering concerned with controlling the behavior of dynamic systems modified by feedback, where maintaining system state at a particular value or within certain constraints is the primary objective [*Astrom and Murray*, 2008]. As Control Theory is a highly precise form of system management, loop effectiveness can be tested and quantified using various performance assessment methods and statistics [*Huang and Shah*, 2012; *Harris et al*., 1999], and for that reason it was selected to structure groundwater management plan testability. Control Theory is applied in a diverse range of fields, and the main iterative actions of the control loop are sensing, computation, and actuation, which together form a five component feedback loop (comparator, controller, actuator, plant, and sensor) shown in Figure 1 and detailed in Table 1 [*Astrom and Murray*, 2008; *Owen*, 2015].

In a control system, the desired system value is input as a reference, compared to the actual value by the comparator, and depending upon the error, corrective action is computed by the controller and effected upon the system by the actuator [*Astrom and Murray*, 2008; *Owen*, 2015]. This results in maintenance of a system close to the desired conditions, and depending upon the manner in which the control mechanism is engaged (with a particular gain or on/off), the system state may oscillate around the desired state. Uncertain system dynamics, and noise in sensing and actuation systems, can introduce uncertainty into the control loop [*Astrom and Murray*, 2008] and external disturbances, both predictable and unpredictable, act

Table 1. The Primary Components of an Engineering Control Theory Loop[a]

	Control System			
Loop Components	Classical Control Theory Definition	What it does	Automotive Cruise Control	Groundwater Management
Reference	The objective state that the system strives to maintain and constantly compares to actual system state	Defines the zero error state of a control system	Speed	A measurable management objective such as hydraulic head, well yield, etc.
Comparator	Where actual value is compared to desired value	Calculates error between actual and desired value and inputs it into controller	Onboard computer	Water Managers
Controller	The mechanisms that exerts some control measure on the system to maintain the reference	If error is not equal to zero, controller decides appropriate action	Onboard computer	A groundwater management plan dictating control measures and trigger thresholds
Actuator	The means by which the controller influences the plant	Exerts a force upon plant to actuate desired response	Throttle	Extraction rate
Plant	The system acted upon by the controller	Fluctuates between system states depending on disturbances and control measures	Car	Aquifer system
Sensor	Device or observation that monitors actual system state	Measures actual value and inputs it into comparator	Speedometer	Aquifer state is monitored with transducers, water level measurements, and water user's observations

[a]The example of an automotive cruise control system is contrasted with aquifer system equivalents shown in the groundwater management control system.

upon the system and may cause control failure if the controller is unable to adapt to changing conditions [*Koenig*, 2009]. As there are certain external conditions under which the system cannot maintain the reference, selection of an appropriate and achievable objective is required for successful system control.

The concept of control theory is closely comparable to the objective of natural resource management, which generally aims to maintain developmental impacts within acceptable levels and studies utilizing varying types of control appear in the literature. *Anderies et al*. [2007] used robust control to manage the uncertainty in social-ecological dynamics typical of fisheries management. They found a trade-off between the robustness and vulnerability of various parameters, where increasing the robustness of certain parameters, was at the expense of others. *Roseta-Palma and Xepapadeas* [2004] considered the use of robust control "natural" in their assessment of surface water management decisions given the high level of uncertainty associated with climatic variables. *Foo et al*. [2014] designed a control system to improve management of a river system and balance irrigation requirements within environmental constraints, and several additional studies investigated water management under control, through irrigation channel operation [*Choy and Weyer*, 2008; *Ooi and Weyer*, 2008].

However, to date, studies considering groundwater management as a control problem are few. Exceptions include, *Ahn* [2000] who designed a feedforward/feedback control system to manage groundwater during times of drought by forecasting groundwater levels based on current measurements and calculated extraction cuts when forecasted levels dropped below targets. *Brown and Rogers* [2006] presented an adaptive groundwater management model with an embedded feedforward control system that used forecasted seasonal rainfall and groundwater elevations to calculate a price for water that maximized social benefits. To our knowledge, groundwater management plans have not been placed within a conceptual framework encompassing the entire managed system and doing so, provides structure and a foundation to assess their testability.

Control theory applied to a managed aquifer system results in the control loop shown in Figure 2.

A reference aquifer state (i.e., hydraulic head levels, well yield, minimum stream, or base flow volumes) is defined as the desired system state and actual aquifer state is monitored, compared to the reference, and if a discrepancy is detected, corrective action is dictated by the groundwater management plan. However, the groundwater management plan does not act upon the aquifer itself, but upon water users and consequently, within the controller is nested control subsystem involving management rules, users, and metering, required to ensure users compliance with management rules (Figure 2). Within this subsystem loop, rules

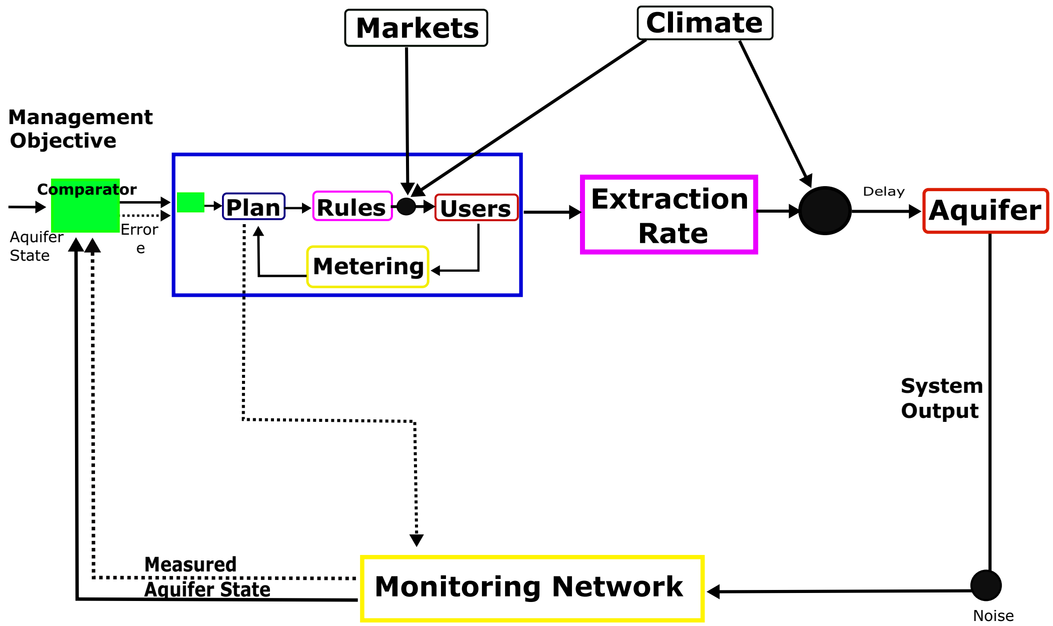

Figure 2. Groundwater management control theory loop. A reference aquifer state (i.e., hydraulic head levels, well yield, minimum stream, or base flow volumes) is defined as the desired system state. Actual aquifer state is monitored, compared to the reference, and if a discrepancy is detected; corrective action is dictated by the groundwater management plan. The groundwater management plan does not act upon the aquifer itself, but upon water users and consequently within the controller is a nested control loop involving management rules, users, and metering. This nested loop is required to ensure user's compliance with the management rules. The solid lines represent the path of a management plan where control measures are periodically enacted to act upon the aquifer state. The dotted lines represent the path of a monitoring plan which is appropriate for unstressed systems and does not exert control upon the aquifer state.

are dictated to users, translated to extraction rates, and compliance is monitored through metering. A subsystem is not required in many control systems where control laws are implemented by embedded microprocessors, but is necessary in natural systems due to the fact that policy is implemented by people and institutions, which adds additional error and uncertainty [*Anderies et al*., 2007]. Just because the plan stipulates restrictions does not necessarily mean users will comply. This is due to the fact that aquifers are common pool resources and any water not pumped today may be pumped by others tomorrow [*Gisser and Sánchez*, 1980; *Negri*, 1989]. Measuring extractions through metering and other methods confronts the issue of noncompliance.

Fluctuations in extraction rates and external disturbances, including agricultural market variations and climate perturbations, act upon the aquifer system and result in changes to user behavior (extraction rates) and the aquifer state (Figure 2). The dashed lines in Figure 2 represent the path of a monitoring plan which as described in section 1.3, is appropriate for unstressed systems. Monitoring plans are concerned with observing the system state to ensure it remains within acceptable levels and generally contain the proviso that more interventionist management will proceed if monitoring indicates the occurrence of unacceptable impacts. The solid line control loop represents the path of a management plan where control measures are periodically enacted.

Groundwater management is, however, more complex and nuanced than is captured by classical control theory. The frequency of the control loop cycle is low, generally yearly, and complex time lags exist between action and response. In addition, due to three-dimensional aquifer heterogeneity, considerable uncertainty surrounds the plant and the monitoring network. More advanced approaches exist (i.e., adaptive [*Åström and Wittenmark*, 2013], optimal [*Kirk*, 2012], stochastic [*Åström*, 2012], and robust control [*Dullerud and Paganini*, 2000]) that may allow a greater exploration of the intricacies of groundwater management but are less conducive to a broad assessment of multiple plans and are beyond the scope of this paper.

2.2. Methodology

Control systems are structured to form feedback loops that almost always contain the five components described in section 2.1. Therefore, in order to set up a groundwater management control loop, hydrogeological elements equivalent to the five components, the reference, and external disturbances were determined (Table 1) through an iterative process of control loop appraisal and management plan review. Components of a groundwater management control loop are as follows:

1. Reference: Management Objective
2. Comparator: Data Review and Analysis
3. Controller: Groundwater Management Plan/Users
4. Actuator: Method of Control
5. Plant: Aquifer characterization
6. Sensor: Monitoring
7. Disturbances: Driver Monitoring

The role of each component in a groundwater control system is listed in Table 2, and together the components form the basis of the testability rubric. In general, the components forming the rubric were identified in cited groundwater management guidelines, and plan guidelines recommended definition of acceptable level of stress, aquifer characterization, control measures, and the description of a measurable management objective for groundwater dependent values [*DELWP*, 2015; *NWC*, 2010]. Commonly, the guidelines focused predominantly on risk assessment and stakeholder engagement which befitted their purpose of effective management rather than testability. The purpose of the rubric is to determine whether a management plan contains the required components of a control loop because, only plans forming complete control loops are testable. Certain factors relevant to comprehensive groundwater management plans such as market/trading rules; environmental water entitlements, and connectivity of ground and surface water while not mentioned explicitly in the framework, may be incorporated into management plans through the definition of the objective. The objective does not necessarily just pertain to groundwater head, but to any measureable aspect of the aquifer system.

To obtain a relative and systematic indication of the testability of various plans, an index method was adopted to allow calculation of a numerical testability value. The method adopted was similar to the DRASTIC methodology developed by the United State Environmental Protection Agency (USEPA). DRASTIC allows a numerical value reflecting the relative susceptibility of groundwater to pollution, to be systematically calculated, in any hydrogeological setting [*U.S. Environmental Protection Agency* (*USEPA*), 1987]. Greater index values indicate higher vulnerability to pollution. DRASTIC uses seven physical factors relevant to contaminant transport to construct a numerical ranking system composed of weights, categories, and ratings. The relative importance of each factor is evaluated in respect to all other factors and assigned a *weight* between 1 and 5, with most important factors receiving a weight of five and least important weights of one. Then each factor is divided into categories with differing impacts on pollution potential and assigned a *rating* from 1 to 10, again based on significance. Factors strongly influencing pollution potential, such as shallow water table or highly conductive sediments, are given high ratings and less important factors (deep water tables, confining layers) are rated lower [*USEPA*, 1987].

A similar numerical ranking system was applied to the control loop components. Relative weights were determined based upon the user estimated importance of the particular component to a functioning control loop. Weights ranged from 1 to 5, with 5 being most important for testability (Table 3). A SMART management objective, defined as Specific, Measureable, Assignable, Realistic, and Timely [*Doran*, 1981], and an adequate monitoring network, were determined to be the most significant components to a functioning control loop and rated at five (Table 3). High weights were assigned to objective and monitoring because it is impossible to test plans without an objective, acceptable impact, or if monitoring is unable to determine system relative to the objective. Conversely, driver monitoring was weighted at one because while unpredictable external disturbances can influence system state, driver monitoring is not crucial for control loop function. It is important to make the distinction that an appropriate method of control is important for effective function of a control loop, but is less important for a testable loop and was weighted at three.

For each component, certain requirements must be met in order to fully adhere to the control theory framework. The components were divided into categories based on the level to which specified requirements were met—from completely to incompletely—and were evaluated against each other to determine relative importance (Table 3). Ratings were assigned to categories and varied between 1–10, with 10 being greatest adherence to the control framework and 1 being the least (Table 3). For example, to fully meet criteria 1

Table 2. Plan Testability Assessment Components[a]

Component		Relevance of Component	Control Equivalent
SMART Objective or Acceptable Impact (O)	1	An objective serves as a reference for the control loop and is required for comparison between current and desired state. An objective dictates management actions and informs the control loop. Appropriate objectives include aquifer systems states such as water levels, stream base flows, or well yields. The SMART acronym [*Doran*, 1981] is used in management to define meaningful objectives and stands for: Specific: Measurable: Achievable/Assignable: Realistic/Relevant: Timely: OR, Quantitative level of acceptable aquifer impact.	Reference
Aquifer and Use Characterization (A)	2	Reliable hydrogeological data, specifically the amount, location, availability, and demand upon groundwater resources is crucial to make informed management decisions, accurately evaluate potential impacts, determine acceptable levels of impact, anticipated use and establish a baseline state. (Aquifer type, yield, water balance, head, GDEs, pumping rate). If the potential response of a system to stimuli is unknown, management by classical control theory is challenging.	Plant
Method of Control (C)	3	The control is the actuation mechanism engaged by controller (the groundwater management plan) to effect system change and minimize the error between objective and actual system state. Control mechanisms utilized by management plans include hydrogeological investigation-based license entitlement capping, water restrictions, restricted groundwater trading, carryover, buyback, and managed aquifer recharge and have been demonstrated (through experience or numerical modeling simulations) to influence the aquifer state.	Actuator
Aquifer System Monitoring (M)	4	Monitoring, used to evaluate system state and inform management decisions, must be sufficient to determine system state to allow comparison with objective so that dependent on the aquifer state; the controller can dictate necessary action.	Sensor
Data Review and Analysis (D)	5	At appropriate frequency monitoring, data should be analyzed and aquifer state computed and compared to the objective state. The discrepancy between objective and actual state determines control actions. For example, if a threshold aquifer level is reached, the groundwater management plan may mandate restrictions and water entitlements.	Comparator
Driver Monitoring (E)	6	Drivers include external disturbances and groundwater extractions. External disturbances can perturb control loops. Management-related system impacts must be separated from impacts due to external drivers to determine plan efficiency and driver (e.g., weather, extractions) monitoring data are required for this purpose.	Disturbance
Frequency and Review (F)	7	The frequency of the control loop cycle determines how often the actual state is compared to desired state. This influences speed at which issues are addressed. Review timeframe of a plan indicates if a plan is static or dynamic.	Controller

[a]The following components are required for a management plan to form a control loop and thus manage an aquifer using systems control.

and receive a rating of 10, the plan must define a SMART objective, and quantitatively define an acceptable level of system impact. Plans that define neither are assigned a rating value of 1 (Table 3).

An additive model allows for calculation of a relative testability index, T:

$$T = O_r O_w + A_r A_w + C_r C_w + M_r M_w + D_r D_w + E_r E_w + F_r F_w \tag{1}$$

Where the right hand variables are as defined in Table 3, the subscript r denotes the rating for the criteria and the subscript w denotes the weight of the criteria. The greater the testability index, the more closely the plan adheres to the control framework and the greater the likelihood the plan is conducive to quantitative assessment. To reflect the diversity of plans, assessments were divided into two types: monitoring and management, depending on whether regional aquifer stress necessitates observation or management of

Table 3. Plan Testability Assessment Rubric[a]

SMART Objective and Acceptable Impact (O)		R	W	Component Category
		10	5	Plan defines SMART objective. Plan quantitatively defines an acceptable level of impact.
		8		Plan defines SMART objective. Plan subjectively defines an acceptable level of impact.
		5		Plan subjectively defines objective. Plan subjectively defines an acceptable level of impact.
		3		Plan subjectively defines objective. Plan does not define acceptable level of impact.
		1		Plan does not define objective or acceptable level of impact.
Aquifer Use and Characterization (A)		R	W	Component Category
		10	1	Plan describes baseline system state, hydrogeological parameters and environment.
		8		Plan describes baseline system state, but not hydrogeological parameters and environment.
		3		Plan describes hydrogeological parameters and environment but not baseline system state.
		1		Plan does not describe hydrogeological parameters, environment or baseline system state.
Method of Control[b] (C)		R	W	Component Category
		10	2	Plan has method of control demonstrated through simulation or practice to influence aquifer state sufficiently to meet objective; or method of control is based on hydrogeological analysis.
		5		Plan has unproven method of control
		1		Plan has no method of control
Aquifer System Monitoring (M)		R	W	Component Category
	A	10	5	Monitoring design as described in plan is adequate to determine aquifer state relative to objective or acceptable impacts.
		5		Monitoring design as described in plan is inadequate to determine aquifer state relative to subjective objective or acceptable impacts.
		1		Monitoring design as described in plan is inadequate to determine aquifer state relative to objective or acceptable impacts.
		1		Monitoring network is not described in plan and adequacy is unknown OR objective or acceptable impacts are unknown.
	B	10	4	Monitoring design can establish if aquifer is responding to development in a manner consistent with understanding of aquifer characteristics and if not; a review is triggered.
		7		Monitoring design can establish aquifer response and behaviour is not consistent with current aquifer understanding, but no review is triggered.
		1		Monitoring design is unable to establish aquifer response, or monitoring design is unknown.
	C	10	1	Plan contains a means to determine adequacy of monitoring and method to rectify if inadequate.
		1		No means to determine or rectify monitoring inadequacies or monitoring design is unknown.
Data Review and Analysis (D)		R	W	Component Category
	A	10	3	Sufficiently reliable monitoring data were periodically analyzed and compared to objective.
		5		Variable quality data are analyzed and compared to objective.
		3		Analysis frequency detailed but not analytical process.
		1		Data are unreliable and not analyzed or compared to objective, or analytical process is not detailed.
	B	10	1	Review frequency consistent with decision making frequency and aquifer response time.
		5		Definite plan review frequency specified.
		3		Review frequency variable.
		1		Review frequency inconsistent with decision making frequency and aquifer response time, or no decisions are made (no adaptability).
Driver Monitoring (E)		R	W	Component Category
		10	1	External disturbances monitored and accounted for in plan. Groundwater extractions are monitored and recorded.
		5		Certain external disturbances monitored and accounted for.
		1		External disturbances not monitored or accounted for in plan. Bores not metered.
Frequency and Review (F)	A	R	W	Component Category
		10	2	Plan contains clear quantitative triggers for review and switch to different management action or plan type.
		5		Plan contains qualitative trigger for review OR switch of management actions.
		1		Plan does not contain trigger for review or switch of management actions.
	B	10	2	Contingency plan for unexpected response.
		5		Inadequate contingency plan.
		1		No contingency plan.

[a]Plan Testability Assessment Rubric. Each component is divided into several rated categories dependent upon degree of fit to the control theory framework, and higher-rated categories have a greater fit to the framework. Each component is weighted dependent upon perceived importance to control loop, with 5 being greatest and 1, least. Notes: R denoted Rating and W denotes Weighting.

[b]Not required for Monitoring Assessment.

extractions. Table 4 outlines a series of questions to determine if a management or monitoring assessment is appropriate. Calculation of testability indexes for monitoring plans does not include the control criteria ($C = 0$).

2.3. Data

In Australia, groundwater plan development is mandated under the Federal Government's National Water Initiative [*COAG*, 2004], and the nation is divided into 361 groundwater management areas with 256 commenced plans. While policy guidelines exist, such as the National Water Initiative Water Planning Guidelines [*National Water Commission*, 2010], a statutory, nationally consistent groundwater management plan

Table 4. Questionnaire to Determine Management or Monitoring Assessment Type

Question	Monitoring Plan	Management Plan
What is the degree of aquifer stress? Is the aquifer overallocated?	Low-No	High-Yes
What is the projected increase in pumping demand?	Low	High
Is aquifer system and external monitoring conducted?	Yes	Yes
Is management intervention required?	No	Yes

development methodology is lacking in Australia, with States granted autonomy to develop plans. As a consequence plans vary broadly in methodology. Due to the volume of management plans within Australia, it was necessary to select a representative sample of plans as case studies to evaluate the testability assessment method. The rationale behind selection of each plan is detailed in Appendix Table A1. Fifteen plans were assessed from across Australia with a broad spread of jurisdictions, geological environments, aquifer stresses, and primary uses of the resource, including: urban water supply, irrigation, oil/gas development. Objectives, impacts, and issues represented the breadth of challenges faced in Australia and included water supply, salinity control, seawater intrusion, mining impacts, and reliance upon nonrenewable water sources. Selected plans are shown in Table 5, and for ease of reading individual plans are referred to by corresponding Plan Number.

2.4. Application of Testability Assessment Method

The methodology used to apply the rubric (Table 3) to the plans was as follows:

1. Plans and supporting documentation were reviewed for control components defined in rubric.
2. Plans were assigned a score out of 10 for each criteria and total score was summed to yield a T index value.

In this assessment, it was assumed that groundwater monitoring occurred as specified in the plan, and only data specified in the management plan and one supporting document were considered.

3. Results

This section presents the overall requirements considered necessary for a plan to be testable, followed by a detailed presentation of the seven components of the rubric, and the degree each plan met them (Table 6).

3.1. Plan Testability Assessment Overview

Assuming causality has been established, and from a purely physical perspective, whether a plan improves aquifer state, avoids unacceptable impacts or achieves objectives are the only standards upon which effectiveness can be measured. Therefore, a plan must describe a quantitative objective or level of impact to be

Table 5. Australian Groundwater Management Plans Selected for Testability Assessment Using Testability Rubric

	Management Plan	References
1	Hopkins Corangamite Groundwater Catchment Statement	*SRW* [2014a]
2	Warrion WSPA GWMP	*SRW* [2010]
3	Upper Oven River WSPA Water Management Plan	*GMW* [2011]
4	Shepparton Irrigation District LMP	*GMW* [2015a, 2015b]
5	Lower Campaspe WSPA GWMP	*GMW* [2012a, 2012b]
6	Water Sharing Plan for Upper and Lower Namoi Groundwater	*DOW* [2006]
7	Water Sharing Plan for the NSW Great Artesian Basin	*DOW* [2011]
8	GAB Water Resource Plan and Resource Operation Plan	*Queensland Government* [2006]
9	Alice Springs Water Resource Strategy	*Department of Land Resource Management* [2013]
10	Tindall Limestone Aquifer Water Allocation Plan	*Department Of Natural Resources Environment The Arts And Sport* [2009]
11	Gnangara Groundwater Areas Allocation Plan	*DOW* [2009]
12	Pilbara Groundwater Allocation Plan	*DOW* [2013]
13	Water Allocation Plan Far North Prescribed Wells Area	*South Australian Arid Lands Natural Resource Mangement Board* [2009]
14	Sassafras Wesley Vale Water Management Plan	*Department of Primary Industries Parks Water and Environment* [2012]
15	Murray Darling Basin Plan	*Murray Darling Basin Authority* [2012]

Table 6. Australian Management Plan Testability Assessment Results[a]

		Management Criteria											Normalized T Indexes		Testability
					M			D			F				
	Management Plan	O	A[b]	C	A	B	C	A	B	E	A	B	PW[c]	EW[d]	Is Plan Testable?
	Proposed Component Weights	5	1	2	5	4	1	3	1	1	2	2			
	Equal Component Weights	1	1	1	1	1	1	1	1	1	1	1			
1	Hopkins-Corangamite Groundwater Catchment Statement and Geragamete Local Management Plan	3	3		1	1	1	1	5	10	5	1	0.23	0.31	No
2	Warrion WSPA Groundwater Management Plan	3	9		5	7	1	3	5	10	1	1	0.42	0.45	No
3	Upper Ovens River Water Supply Protection Area Water Management Plan	8	10	10	10	7	1	10	10	10	10	1	0.82	0.79	Yes
4	Shepparton Irrigation District Local Management Plan	5	10	10	5	7	1	10	5	5	1	1	0.57	0.55	No
5	Lower Campaspe WSPA Groundwater Management Plan	3	10	10	5	10	1	10	9	10	10	1	0.67	0.72	No
6	Water Sharing Plan for the Upper and Lower Namoi Groundwater Sources and Information Sheet	5	10	10	5	5	1	10	9	10	10	1	0.64	0.69	No
7	Water Sharing Plan for the NSW GAB Groundwater and Background document	3	3	10	1	1	1	10	10	10	5	1	0.41	0.50	No
8	Great Artesian Basin Water Resource Plan and ROP	5	3	5	1	1	1	7	1	10	1	1	0.31	0.33	No
9	Alice Springs Water Resource Strategy	10	10	10	10	7	1	10	5	10	10	1	0.84	0.76	Yes
10	Tindall Limestone Aquifer Water Allocation Plan	10	10	10	10	7	1	10	9	10	10	1	0.85	0.80	Yes
11	Gnangara groundwater areas allocation plan	8	10	10	10	7	1	10	3	10	10	1	0.79	0.73	Yes
12	Pilbara groundwater allocation plan	10	3	10	10	7	1	10	9	10	10	1	0.83	0.74	Yes
13	Water Allocation Plan Far North Prescribed Wells Area	5	10	10	7	5	1	5	1	10	10	1	0.59	0.59	No
14	Sassafras Weseley Vale Water Management Plan	10	9	10	10	7	1	10	5	5	10	1	0.81	0.71	Yes
15	Murray Darling Basin Plan	10	10	10	10	7	1	10	9	10	10	1	0.85	0.80	Yes

[a]Seven of the 15 plans were found to be testable using the Control Theory Testability Rubric. Normalized T Index values were calculated using the proposed weighting system and an equal weighting system to allow comparison. Notes NA represents not applicable and NT represents Normalized T Index.
[b]Monitoring Assessment was used for Plans 1 and 2.
[c]Normalized T Indexes calculated using proposed component weighting.
[d]Normalized T Indexes calculated using equal component weighting.

considered testable regardless of the overall T Index. Several plans considered untestable achieved medium T Index values showing the importance of accompanying use of the rubric with a detailed discussion of each component score. For this purpose, an interpretation of T Index values for each component is provided in Table 7. Use of Table 7 in conjunction with the rubric illuminates positive and negative aspects of plans, explains why particular scores may have been obtained, and suggests mechanisms for increasing plan T Index scores.

Results of the Management Plan Testability Assessment are shown in Table 6. Seven of the 15 (46%) assessed plans were determined to be testable and normalized values of T Index calculated using the proposed weighting system ranged from 0.23 to 0.85 (with one being full marks). For ease of discussion, ratings were divided into high (10–7), medium (6–4), and low (3–1) divisions. It is reiterated here that T Indexes indicate testability and are not reflective of the overall effectiveness of each plan, which is currently unknown. Plans receiving high T Index values are not necessarily effective plans and vice versa.

3.1.1. Objective or Level of Acceptable Impact

The requirements for component one were the definition of a SMART objective or defined level of acceptable impact (Table 2) and seven plans [3, 9, 10, 11, 12, 14, 15] received a high rating for component one. Objectives receiving a high score included minimum river flow volume or level [3, 10], rate of aquifer depletion [9], maximum extraction volumes [14], groundwater levels, and quality [11, 12, and 15]. The remaining plans [1, 2, 4, 5, 6, 7, 8, 13] only qualitatively stated objectives, which included mitigation of particular impacts, for instance, salinity [4] or more generally that resources be managed in an equitable and sustainable manner and adverse impacts avoided [1, 2, 5]. The common limitation of these objectives was the omission of defined measurable acceptable impacts.

3.1.2. Aquifer Characterization

A description of the baseline system state, hydrogeological parameters, and environment was required for a high rank of aquifer characterization and this was achieved by 73% of plans. All plans named target aquifers and the level of hydrogeological detail varied from extensive descriptions, maps, or figures of geological environment, aquifer characteristics, and baseline state [3, 4, 9, 10, 11, 13, 15], to a brief description of main target aquifers, system state, and hydrogeological parameters [2, 5, 6, 14]. Plans receiving a low score

Table 7. What Do the Scores Mean? Interpretation of T-Values to Allow for the Assessment of Individual Management Plans[a]

Component	Interpretation of T Index
SMART Objective and Impact (O)	Plans scoring medium or low for this component require work explicitly defining what the plan aims to achieve, or avoid, in a manner that can be measured. Examples include: indicators of aquifer state such as groundwater levels, quality, or rate of decline, maximum extraction volumes, and minimum streamflow volumes. Plans scoring medium to low are considered untestable and require prompt review.
Aquifer Use and Characterization (A)	A medium to low score indicates the need for further hydrogeological investigation. Such investigation would require greater detail on aquifer characteristics, baseline system state, hydrogeological parameters, main uses, geologic maps, environment, groundwater-dependent ecosystems (GDEs) etc.
Method of Control[b] (C)	Management plans scoring medium to low contain an inadequate method of control. Methods of control demonstrated to influence aquifer state include: extraction caps or restrictions with specified hydrogeological trigger levels; entitlement, and allocation systems; fees and tariffs; water trading; etc.
Aquifer System Monitoring (M)	Plans will score low if monitoring network is not described (number and location of monitoring bores, monitoring purpose and frequency, historical trends); an objective is undefined; if it cannot be determined if the monitoring network is capable of measuring or capturing changes in objective parameters; or if unexpected system responses (i.e., rapid propagation of drawdown cones) cannot be detected by current network. In order to ensure the network monitors everything necessary, the objectives and requirements of the monitoring network must be clearly stated. Plans lacking this detail will score low because it cannot be determined if monitoring is adequate.
Data Review and Analysis (D)	Plans scoring low require either greater investment in data collection to ensure more reliable data or more frequent assessment of the data because low scores indicate data are generally unreliable or are not used to their full potential. A low score could also mean review frequency is not specified or appropriate and remedial actions include specification of review period and aquifer lag time.
Driver Monitoring (E)	Plans scoring medium to low indicate that expansion of external driver monitoring is required. External drivers include climate data such as temperature, precipitation, humidity, and evapotranspiration. Additionally, monitoring of volume extractions through metering of wells, field log books, or a review of extractions rates reported to regulatory agencies is required for a high score in this component.
Frequency and Review (F)	Plans scoring low lack alternate management triggers such as minimum flow rates, groundwater levels in wells and GDEs or water quality, maximum extraction volumes. A lack of plan review triggers, such as minimum groundwater levels or change in availability of water, could also result in a low score for this component.

[a]This table is designed to be used in conjunction with Table 3 to allow examination of individual component scores.
[b]Not required for Monitoring Assessment.

lacked detail on baseline system state [1, 7, 8, 12]. Generally, the degree of aquifer characterization increased with intensity of aquifer use.

3.1.3. Method of Control

Two monitoring plans [1, 2] were not assessed against the control criteria due to low aquifer stress and projected pumping demand (Table 4). Of the remaining plans all except one, which contained a control measure where allocation volume was not restricted [8], contained control measures based on hydrogeological analysis or methods demonstrated to influence aquifer head levels (Table 2), and subsequently, received a high ranking. All plans required, or contained provisions detailing the planned introduction of [14], the licensing of commercial extractions. All except one [4], where pumping was encouraged for salinity mitigation, contained extraction volume caps, frequently manifested as current licensed volumes. Extraction limits were commonly managed through various annual or seasonal entitlement allocations with volume determinations based on estimated available water [6], rolling average recovery levels [5], model predictions [10], and recharge estimations [11]. Most plans detailed a restriction strategy with three plans outlining staged restrictions, based on river flow rates [3, 10], or head levels in trigger wells [5]. Other plans reporting restriction triggers were at the discretion of management authorities under various Water Acts [6, 7, 9], and included a subjective definition of adverse impacts. Additional methods of control included trading (most plans), carryover [6, 7, 15], or potential for implementing carryover [5], entitlement buy-back [15], [*Commonwealth of Australia*, 2014] and managed aquifer recharge [11, 9].

3.1.4. Aquifer Monitoring

The monitoring criteria were divided into three subcriteria (a) whether monitoring can determine system state relative to objective or acceptable impacts, (b) aquifer response, and (c) adequacy of monitoring. In order for the first part to be assessed, plans were required to describe the monitoring network. Plans omitting monitoring descriptions received a low rating [1, 7, 8]. The majority of plans described monitoring bores, gauging stations, frequency, type and purpose of monitoring, historical trends, thresholds and triggers adequately, and hence, from a qualitative assessment, appear capable of detecting unexpected aquifer responses. Whether the monitoring network was capable of determining aquifer state compared to an acceptable impact could only be determined for plans with defined acceptable impacts (i.e., scoring highly for Criteria 1) and plans [2, 5, 6] with subjective objectives received a low score. Despite the extensive monitoring network described in [4], the lack of a defined impact precluded this plan from receiving a high score.

Review triggers were present in two plans relating to groundwater level in wells [5] and change in water availability, land use, or aquifer understanding [11]. The stated monitoring purpose of most plans was evaluation of aquifer head levels but monitoring was also conducted for water quality purposes [4] and extraction rate [9]. Assessing the adequacy of a monitoring network is difficult and resource intensive and none of the plans contained specific provisions to determine if monitoring was adequate. Where specific objectives or aquifer impacts were specified, monitoring design was appropriate to capture changes in the aquifer system. Several plans [13, 14] reported a high degree of uncertainty surrounding the hydrogeological environment and recommended expansion of the monitoring network. Consequently, they were assigned medium scores due to questionable data reliability. The sparse nature of data collection introduces additional uncertainty, but provided data are adequate, infrequently monitored plans, and plans covering regions with high hydrogeological uncertainty can be testable [14].

3.1.5. Data Review and Analysis

Most plans described the data collection and analysis processes. Plan review frequency and data reliability were predominantly high. Generally, aquifer state was compared to the objective state annually when triggers defined in the plan were used to determine allocation volumes for the following year. This was consistent with the data review and reporting period. However, two plans dictated immediate introduction of restrictions when threshold river flow rates [5] or groundwater heads in wells [14] [*Chris Cleary*, 2016] were reached, making response and review time considerable faster. Aquifer response time was mentioned in the background information of the NSW Great Artesian Basin Plan [7] but remaining plans did not cover aquifer lag times, which varied from rapid in the unconsolidated sedimentary aquifers of the Upper Ovens System [3], to very slow in fossil aquifers where extractions have greatly exceeded recharge replenishment, such as the Amadeus Aquifers of Alice Springs [9] and the Great Artesian Basin [7, 8].

3.1.6. Driver Monitoring

Driver monitoring includes climate and extractions volumes. Considering that climate data, including temperature, humidity, and rainfall, are recorded by the Bureau of Meteorology at many sites across Australia (http://www.bom.gov.au/climate/data/), to receive a high rating plans must specify monitoring of extractions and degree of system stress. Generally, in unmetered wells, extraction rates were recorded by water users in log books and reported to the appropriate regulatory body, and in metered wells, meters were read directly or measured by telemetric systems. Data are held by managing authorities in each state of territory; for example, Victorian extraction information is stored in the Victorian Water Registry [*Government of Victoria*, 2014]. Metering requirements varied from nonexistent [4], to mandatory [5, 9, 10], to volume-dependent requirements such as all licensed wells producing volumes greater than 10 mL/yr [1, 3], or wells producing greater than 0.5 mL/yr [11] requiring meters. In the NSW plans, whether bores require meters or log books was dependent on the water source [6, 7]. All plans except two, where metering was not yet conducted [14], or planned to be discontinued [4], achieved a high score for driver (climate and extraction) monitoring. However, it is acknowledged that extractions from many wells are not metered or monitored and extraction volumes are crude estimates.

3.1.7. Feedback and Review

Clear quantitative alternate management triggers were present in 11 plans and included; river flow rates [3], model predicted base flow volumes (10), groundwater levels in wells [5, 9, 14], or GDEs [12, 15], and water quality [15]. The response to triggers was generally a decrease in water available to users, or increased monitoring and altered extraction regimes [12]. Other plans had extraction volume triggers, for example, reaching, or exceeding allocation volumes that corresponded to actions such as license and allocation capping or reduction, introduction of efficiency measures, and plan review and update [6, 11]. The supporting documentation of one plan indicated extraction volumes could trigger a review of extractions and environmental requirements [7]. None of the plans detailed contingency plans for unexpected aquifer responses, however, two plans contained plan review triggers; specific groundwater level [5] and a change in the availability of groundwater [11]. The decision-making frequency of plans was generally annual, with seasonal allocation determined upon trigger levels, and most plans were revisited and reviewed on a five yearly basis.

A review of not only whether objectives were achieved but also the objective itself is important. This is because objectives valued by society shift through time and affect management through altered priorities. *Wei et al.* [2015] examined how newspaper coverage of water issues in Australia changed during the period 1843–2011 and found that prior to 1994, media coverage was dominated by water development issues, but post-1994 observed a decline in development-related articles relative to environmental and sustainability focused articles. This illustrates the increased emphasis placed upon sustainable development and environmental protection that has occurred in the public consciousness during the past few decades. If a plan review determines the objective is no longer relevant, or appropriate, and has resulted in plan failure, reconsideration of objectives may be necessary.

4. Discussion

Uncertainty is a fundamental reality of groundwater management that at times can lead to a management style that is more reactive than proactive, even somewhat, impromptu. It is recognized that despite the best intentions, circumstances such as an extended droughts, climate change impacts, or approval of water intensive resource developments, may conspire to prevent the implementation of management plans precisely as written. It is beyond the scope of this paper to evaluate the meticulousness of plan implementation, but it is recognized that this is an important aspect of water governance.

4.1. Testability Rubric Performance

The testability rubric gave an indication of plan testability by determining if required criteria were present and isolated structural shortcomings of the plans. Overall, the rubric was robust in that it was capable of evaluating plans spanning a range of aquifer types and extraction drivers. Fundamentally, the rubric highlighted the critical importance of clearly defined acceptable levels of developmental impacts and SMART objectives. Plans lacking defined levels of impact or specific objectives; could not be quantitatively assessed for effectiveness.

4.2. Testability Rubric Critique

4.2.1. Subjectivity of Ranking System

The testability rubric is a subjective rating method where numerical scores were assigned to various attributes to produce categories of potential testability. The point rating system was developed using professional judgment, and is somewhat subjective, and arguments could be made for altering values, and subsequently, testability indexes. This subjectivity is unavoidable because criteria were rated and weighted to reflect user—decided importance. Criteria with the greatest weighting are keystone criteria and subsequent criteria are dependent upon them. For example, if an objective is not defined it makes it difficult to assess if a method of control is adequate to meet objectives, or whether monitoring can assess the objective, or if the analysis method is capable of comparing the reference to the system state. It was determined that an objective or acceptable impacts is fundamental to management and analysis, but depending upon management objectives; other criteria are less critical. For example, if the management objective is maintenance of water levels, it could likely be achieved through careful monitoring of water levels and detailed aquifer characterization would not be required. Moreover, a change in one criterion impacts other criteria, i.e., if the objective is changed from monitoring water levels to maintaining a wetland, a modification of the monitoring network is required.

The capacity of individual components to skew T Index score was examined by comparing plan scores obtained under the proposed weighting system with those obtained using an equal weighting system, where each component was assigned a weighting of one. Testability indexes for each plan were then normalized and the percentage change due to the altered weighting system was calculated for each plan. Using an equal weighting system resulted in up to a 33% percentage increase in T Indexes for plans [1, 6] that scored low in highly weighted categories such as Objective and Monitoring. The T Index of plans with high overall scores generally decreased on the order of 5–10% (Table 6). Clearly, T Index scores are sensitive to highly weighted components. This is an intentional artifact of the method and reflects component importance. The degree of sensitivity of the scoring system to the weighting of individual components was explored by alternatively scoring a plan highly in all components except for a highly weighted, and subsequently, low weighted component. The percentage increase from a low to a highly weighted component score was 16% (Table 6). As shown on Table 6, several plans attained T Index values of around 0.65 [5, 6] using the proposed rubric weighting, yet were considered untestable due to a lack of SMART objective. When equal weighting was used, the T Indexes increased by approximately 7%, and illustrated the necessity of evaluating the t index value in conjunction with an examination of individual component scores.

The rubric was developed to be applicable to a range of plans and is not site specific. Hence, it is inevitable that some plan deficiencies and nuances may be overlooked. Aquifers are complex, dynamic systems with multiple scales; micro and macro-scale phenomena may have multiple layers of feedback loops. Many real-world complexities are not accounted for in the framework, including the extensive variation in groundwater flow rates and considerable lag times between pumping and observed aquifer response, which may cause amplification or dampening. For example, a water level drop at a sensitive GDE may prompt an allocation cut and reduced pumping, but due to the delayed response time, by the time pumping reduces, levels may have recovered or alternately, dropped perilously low [*Bredehoeft and Young*, 1970]. Very few plans mentioned aquifer response time even though consideration of this parameter is crucial to set appropriate management objectives and realistic expectations [*Meals et al*., 2010].

4.2.2. Application Challenges

Challenges encountered applying the rubric included difficulties reviewing a large diversity of plans using a single framework because aspects present in some plans were absent in others, and variations in plan format made pinpointing the presence of criteria difficult. Plans generally fell into two format types: legislative and report style. Legislative plans [6, 7, 8, 15] were scribed in characteristic legislative language; "archaic, foreign and with uncommon words, long complex sentences, repetition and a total absence of color and humanity" [*Maley*, 1987]. The legalistic language made comprehension challenging and *Maley* [1987] reports even lawyers and judges find legislative language can present at times "an impenetrable barrier to understanding," which "for ordinary people; might as well be in a foreign language." The comprehensibility and accessibility of such plans was an issue, with the loss of assessment criteria within legislative jargon or burial beneath irrelevant information and elegant, yet circumspect, language. Plans can be theoretically sound yet the manner in which they are written introduces unnecessary complication and confusion. Previous research indicates that when users understand the rationale behind management actions and the likely effect upon the future availability of water, they are more likely to comply with management actions [*Nelson and Casey*, 2013]. Management plans are a primary way to convey management actions to users, and while not necessary for testability; accessibility and comprehensibility are important for plan effectiveness.

In practice, management of groundwater is very difficult due to great uncertainty, limited resources, imperfect data to base decision making upon and various other pressures. Consequently, evaluation of plans is expensive, time-consuming and not currently possible in some regions. To make the evaluation process easier, the testability assessment rubric aims to prove a quick and inexpensive method to highlight areas of plans requiring improvement and, where possible, may also be used to quantitatively assess plans as part of a review framework.

4.2.3. Are the Plans Working?

The period since implementation of the seven testable plans ranged from 3 to 9 years and provided empirical evidence of aquifer state under plan management. Whether stated objectives were reached during this period and the associated degree of management intervention was examined, to illustrate the fact that often there is a lack of causality between achieving objectives and management intervention. For example, a specific objective of one plan [3] was prevention of extraction-related cease to flow events in the Upper Ovens River and tributaries. During the four years the plan was in place, a roster system for groundwater extraction was enacted three times ranging in duration from 3 to 8 weeks at a time. Twice allocations were cut to 75% of entitlements for periods of 1 month and approximately 6 weeks, respectively [*GMW*, 2012a, 2012b,, 2014a, 2015a, 2015b]. Ultimately there were no recorded cease to flow events [*Pethybridge*, 2016], yet without further stress to the plan and an analysis of the individual impact of the roster system and allocation cuts upon aquifer base flow to streams, reaching objectives may have been simply happenstance of a few relatively wet years.

Another plan stated an objective as maintenance of groundwater levels within historical norms [14], and set allocation volumes equal to historical use. There were provisions for extraction restrictions within the plan, however, levels remained above thresholds during the 3.5 years of plan management and no restrictions were imposed. Thus the primary control mechanisms of the plan were not activated. In both examples, plan objectives were reached, but we contend the effectiveness (or ineffectiveness) of the plans remains unknown for two reasons:

1. Causality for achieving objective aquifer states must be attributed to management interventions, but this was not clearly demonstrated [3].
2. The control measures of the plan must be activated due to systems stress [14].

These two points comprise the evaluation of plan effectiveness detailed in the introduction. Evaluation of effectiveness is the second of the two components required to determine the effectiveness of management plans, the first being that the plan is testable. Determining the effectiveness of plans is a current topic of research and a numerical method to evaluate the effectiveness of testable plans is presently under development.

5. Conclusion

Groundwater management plans lacking a clearly defined objective or acceptable level of developmental impact cannot be tested for effectiveness and approximately 47% of analyzed plans were not conducive to quantitative assessment. These results are significant because through testing, plans improve, and effective groundwater management is crucial to ensure water resource security. Control theory presented a useful framework to structure groundwater management upon in order to develop a testability rubric capable of assessing a diverse range of groundwater management plans. The importance of groundwater as a resource demands effective management, and that plans are constructed in a manner to make them testable, is a fundamental prerequisite of an assessment of the effectiveness. The presented testability assessment rubric provides a pathway for the development of rigorous management plans that can be quantitatively analyzed. Only by quantitatively assessing the effectiveness of groundwater management plans, can we systematically learn how to develop better management plans.

Appendix A

Table A1 outlines the rationale behind the management plan selection process.

Table A1. Plan Selection Rationale[a]

	Management Plan	Main Water Use	Issues	Selection Rationale
1	Hopkins Corangamite Groundwater Catchment Statement and Gerangamete Local Management Plan	Urban	Paucity of data in some areas.	Hopkins Corangamite Local Management Plan is an example of a nonstatutory Local Management Plan. Geelong sources most of its water from the West Barwon Reservoir in the Otways covered by the Gerangamete plan. Victorian Plan
2	Warrion WSPA Groundwater Management Plan	Dairy, Irrigation, D&S	Minimal aquifer stress, aquifer uncertainty	The Warrion Plan is a statutory Monitoring Plan with no explicit control measures. Victorian Plan
3	Upper Ovens River Water Supply Protection Area Water Management Plan	Irrigation, Urban	Fast aquifer response, high surface and water connectivity	The Ovens plan conjunctively manages surface and groundwater, has a very short system lag time and immediate restrictions when thresholds are reached. Victorian Plan
4	Shepparton Irrigation District Local Management Plan	Salinity control, Irrigation	Salinity	Groundwater pumping is encouraged under the Local Management Plan to mitigate impacts of salinity, alternate objective. Victorian Plan
5	Lower Campaspe WSPA Groundwater Management Plan	Irrigation, D&S, Urban	Salinity in some areas, water shortages	High seasonal drawdowns, sequential restrictions form a part of the plan, good example of triggers and corresponding actions. Victorian Plan
6	Water Sharing Plan for the Upper and Lower Namoi Groundwater Sources	Irrigation, Farming	Water shortages, high demand, over allocation	Example of a highly legislative water sharing plan. High value resource. New South Wales Plan

Table A1. (continued)

	Management Plan	Main Water Use	Issues	Selection Rationale
7	Water Sharing Plan for the NSW GAB Groundwater	Irrigation, D&S	Nonrenewable resource	Legislative. Very slowly responding system, management challenges (remote location, cost, wells). New South Wales Plan
8	Great Artesian Basin Water Resource Plan	Irrigation, D&S	Nonrenewable resource	Slow response time, long lag, nonrenewable source. Queensland Plan
9	Alice Springs Water Resource Strategy	Urban, D&S	Nonrenewable resource	Example of managed depletion management. Northern Territory Plan
10	Tindall Limestone Aquifer Water Allocation Plan	D&S, Urban, Irrigation	Water shortage, seasonal rainfall	Model prediction used for management. Lots of pumping in dry season and base flow dictates the amount of pumping allowed. Northern Territory Plan
11	Gnangara groundwater areas allocation plan	Urban	Water shortages	High reliance and value source. Western Australian Plan
12	Pilbara groundwater allocation plan	Industry, Urban	Remote location	Extensive water-intensive mining developments. Western Australian Plan
13	Water Allocation Plan Far North Prescribed Wells Area	D&S, Irrigation	Remote location, aridity	Remote, arid location, management challenges. South Australian Plan
14	Sassafras Wesley Vale Water Management Plan	Irrigation, Urban, D&S	Anticipated shortages	Conjunctive management of groundwater and surface water. Tasmanian Plan
15	Murray Darling Basin Plan	Irrigation, Urban, D&S	High aquifer stress and value	Example of federal, state, and territory cooperation. Federal Plan

[a]Notes: D&S represents Domestic and Stock usage.

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