Groundwater

Issue Paper/

A New Assessment Framework for Transience in Hydrogeological Systems

by Matthew Currell[1], Tom Gleeson[2], and Peter Dahlhaus[3]

Abstract

The importance of transience in the management of hydrogeologic systems is often uncertain. We propose a clear framework for determining the likely importance of transient behavior in groundwater systems in a management context. The framework incorporates information about aquifer hydraulics, hydrological drivers, and time scale of management. It is widely recognized that aquifers respond on different timescales to hydrological change and that hydrological drivers themselves, such as climate, are not stationary in time. We propose that in order to assess whether transient behavior is likely to be of practical importance, three factors need to be examined simultaneously: (1) aquifer response time, which can be expressed in terms of the response to a step hydrological change (τ_{step}) or periodic change (τ_{cycle}); (2) temporal variation of the dominant hydrological drivers, such as dominant climatic systems in a region; (3) the management timescale and spatial scale of interest. Graphical tools have been developed to examine these factors in conjunction, and assess how important transient behavior is likely to be in response to particular hydrological drivers, and thus which drivers are most likely to induce transience in a specified management timeframe. The method is demonstrated using two case studies; a local system that responds rapidly and is managed on yearly to decadal timeframes and a regional system that exhibits highly delayed responses and was until recently being assessed as a high level nuclear waste repository site. Any practical groundwater resource problem can easily be examined using the proposed framework.

Introduction

Since the recognition of hydrogeology as a discipline, numerous practitioners have invoked the concept of steady state groundwater flow systems. The common definition of this is that recharge and discharge are effectively equal, and flow conditions on average constant over some spatiotemporal scale. For example, Theis' seminal paper on the impacts of well development argues that as a general rule, prior to groundwater development, rates of recharge and discharge in a basin should have become equal over "recent geologic time" and any inequality should balance "over a complete season or climatic cycle" (Theis 1940). It is now well recognized that climate and other hydrological inputs are not stationary through geologic time, or in many cases on shorter timescales (e.g., Milley et al. 2008; Wagenar et al. 2010). It is also known that aquifer systems respond physically and chemically to hydrological change on very different timescales (Gelhar and Wilson 1974; Alley et al. 2002), and are in continual states of flux (Kooi and Groen 2003). A number of studies have shown that aquifers exhibit time lags in response to hydrological change and in some cases may be out of equilibrium with present climate and hydrological regimes (e.g., Person et al. 2007; Lemieux et al. 2008; Morrissey et al. 2010; Schwartz et al. 2010; Post et al. 2013; Rousseau-Gueutin et al. 2013). Yet, discussion of the combined effects of time-varying hydrological inputs, and different hydraulic response times in groundwater systems has to date been limited in the context of water management (Kendy and Bredehoeft 2006; Walton

[1]Corresponding author: School of Civil, Environmental and Chemical Engineering, RMIT University, 124 La Trobe St, Melbourne, 3001 VIC, Australia; +61 3 9925 0402; fax: +61 3 9639 0138; matthew.currell@rmit.edu.au

[2]Department of Civil Engineering, McGill University, 817 Sherbrooke St West, Montreal, Quebec, Canada.

[3]Faculty of Science, Federation University Australia, Ballarat, Victoria, Australia.

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2011). The issue of how important transient behavior is likely to be and the appropriateness of steady state approximations for specific aquifers and management questions is rarely discussed (e.g., Haitjima 2006). Few simple methodological techniques are available to make an assessment of the degree of "steady state-ness" or "disequilibrium" likely to be experienced during a planning period, which can hamper water management decisions in both long- and short-term planning.

The objective of this paper is to propose a new framework for assessing the importance of transience in hydrogeological systems in a groundwater management context. The framework involves simultaneous consideration of three key factors: (1) the time-dependent hydraulic response of the aquifer system; (2) the nature of the hydrological input(s) such as climate, which vary over time and may cause temporary or long-term disequilibrium; (3) the management timeframe and spatial scale over which an aquifer's response to change is considered important. We argue that there are particular combinations of these three factors which result in a greater or lesser emphasis required on understanding transient behavior. In some cases steady state approximations may be adequate, but this cannot be clear without some analysis of the three factors above. We contend that there is value in examining this issue explicitly, and that a framework for assessing practical importance of transience will prove beneficial when deciding how to manage the response of hydrogeological systems to a range of natural and human-induced changes.

We first briefly review the concept of aquifer response time, and outline simple established methods for understanding how hydrogeological properties control the timing and location of the response to a hydrological change. The second section reviews major inputs to hydrogeological systems ("drivers") that are variable through time, and may cause different responses on different spatiotemporal scales. The third section discusses the importance of selecting the relevant management timeframe and spatial scale. We then demonstrate ways in which these factors can be examined together, in order to assess the likely importance of transient behavior for a given system. This includes the use of graphical tools designed for use with the framework. Two examples of how the framework can be applied in a water management context are also discussed with the aid of these tools. We argue that adoption of this methodological framework could assist groundwater management in many scenarios.

Aquifer Response Time

A number of studies have examined the nature of the time-lag or "response time" of aquifer systems to changes in water balance, land use, or sea-level (e.g., Gelhar and Wilson 1974; Kooi et al. 2000; Cook et al. 2003; Haitjima 2006; Schwartz et al. 2010; Walton 2011; Rousseau-Gueutin et al. 2013; Simpson et al. 2013). A general measure which describes the time-dependent response of an aquifer is the "Basin time constant" (τ), shown in Equation 1 (units in time) (Domenico and Schwartz 1990; Schwartz et al. 2010). This can be used to predict the hydraulic head response at a particular time (t) and distance (L) away from a disturbance, measured in terms of an instantaneous head change (Equation 2). The change ($h_1 - h_0$) propagates through the flow system in proportion to the specific storage and hydraulic conductivity, and is conceptualized as an exponential decay in head with time at a given location (Equation 2). When $t = \tau$, approximately 63% of the head change associated with the perturbation should have occurred at a given location, defined using the L term (Equation 1). Cuthbert (2014) recently demonstrated that this exponential decline in unconfined aquifers is in fact a subset of the overall response, that applies after a critical time is reached (on the order of tens to hundreds of days in typical aquifers). Simpson et al. (2013) also recently explored this concept of a "critical time" in unconfined aquifers subject to different recharge rates, using analytical solutions to the Boussinesq equation, and laboratory scale porous media experiments. An important finding was that the time required to reach steady state following a step-change in recharge rate is independent of the rate itself. Hence, the time dependency of a groundwater system's response is a function of aquifer geometry and hydraulic properties, rather than the magnitude of hydrological change. For the purpose of the framework presented here, the basin time constant is considered to be a useful and appropriately simple measure of response time, although more detailed measures can also be applied. The basin time constant can be simplified for use in both confined and unconfined aquifers (Equation 3), using the hydraulic diffusivity (D_h) appropriate to each case (Rousseau-Gueutin et al. 2013). In this paper we denote this "τ_{step}" (units in time) to indicate its applicability when analyzing the timescale of transient response to a step change, such as a major episodic recharge event or rapid climatic transition.

$$\tau = \frac{L^2 S_s}{K} \quad (1)$$

where τ is the basin time constant [T]; L is the length of the flow system [L]; S_s is the specific storage [L^{-1}]; K is the hydraulic conductivity [L/T].

$$h(t) = h_0 + (h_1 - h_0)\left[1 - e^{-t/\tau}\right] \quad (2)$$

where h is the hydraulic head; h_0 is the initial head; h_1 is the post disturbance head (all in units [L]); and t is time.

$$\tau_{\text{step}} = \frac{L^2}{D_h} \quad (3)$$

where D_h is the hydraulic diffusivity (T/S), composed of the transmissivity T[L^2/T], and storativity S (dimensionless).

Recently, Rousseau-Gueutin et al. (2013) also presented a definition of the "time to near steady state" t_{ne} (units in time) for different aquifer settings, including a mixed aquifer with unconfined recharge area and a confined section (Equation 4). This is defined as the time after which 95% of the change in response to a rapid hydrological shift has occurred. Under the definition in Equations 1 and 2, this occurs at approximately $t = 3\tau$. An analytical model was developed to allow estimation of t_{ne} for the mixed aquifer type (Equation 4), as well as fully confined and unconfined aquifers. Assumptions in their analytical models include the Dupuit assumption (negligible vertical flow relative to horizontal flow); that S for unconfined aquifers (S_u) $\gg S$ for confined aquifers (S_c), and that changes in saturated thickness have minimal effect on transmissivity:

$$t_{ne} \approx \frac{3S_u L_u}{T}\left(L_c + \frac{L_u}{2}\right) \tag{4}$$

where L_u and L_c are the lengths of the unconfined and confined portions of the aquifer, respectively and S_u is the storativity of the unconfined part of the aquifer

Schwartz et al. (2010) and Rousseau-Gueutin et al. (2013) used both analytical and numerical approaches to explore the degree of dis-equilibrium induced by large changes in infiltration through geologic time in regional flow systems, and made important discoveries. Firstly, response times for regional scale groundwater systems are long, on the order of tens or hundreds of thousands of years. Thus, paleo-climate must be considered in the interpretation of current-day water level responses for some aquifers (see also Kooi and Groen [2003]). Secondly, groundwater age patterns in regional flow systems were found to be complicated by long-term transient behavior. This is due to the variable rates of recharge and discharge through time, and the resulting complex propagation of water and solutes. Schwartz et al. (2010) also noted that analytical expressions such as the basin time constant may not always approximate the time-scales of response to change accurately when compared to outputs from a transient numerical model. This is particularly true when there is geological complexity. Rousseau-Gueutin et al. (2013) found good agreement in the results from their analytical and numerical models in terms of estimates of t_{ne}; nevertheless, these models contain simplifications, and caution should be applied when using the expressions above (Equations 1–4) to estimate response times in specific hydrogeological settings. The expressions give a first-pass indication of the timescale on which transience is likely to be important, rather than a detailed description of the transient response.

Another time constant herein called τ_{cycle} (dimensionless) that is applicable to hydrogeological systems was presented by Haitjima (2006) (Equation 5). This measure is highly relevant to our framework, as it includes two parts: terms describing the hydraulic characteristics of the aquifer system, similar to τ_{step}, and an additional term describing the periodicity of a cyclic hydrological input function (P) such as rainfall, recharge, sea-level, or cyclic pumping (more detailed formulations for a range of responses to periodic forcings are presented in Townley [1995]). As both the time-dependent hydraulic response of the aquifer and the temporal characteristics of the hydrological input are incorporated into the expression, it allows a preliminary assessment to be made of whether steady state approximations are likely to be appropriate, based on the combination of these key variables. It is the argument of this paper that having information on both of these, as well as defining the spatiotemporal scale of interest, are prerequisite for assessing the importance of transient behavior in a given setting.

$$\tau_{cycle} = \frac{SL^2}{4TP} \tag{5}$$

where P is the period of a cyclic input or boundary condition such as recharge or tidal stage [T].

According to the classification outlined in Haitjima (2006); where large values of τ_{cycle} occur ($\gg$1), an overall steady state approximation may be appropriate, as many cycles of the input will be integrated into the long-term, averaged aquifer response. This can occur either when an aquifer is large and hydraulically slow to respond and/or where the dominant hydrological driver has a relatively short period (such as seasonal rainfall patterns or tides in a regional aquifer system). When $\tau_{cycle} \ll 1$, such as when the aquifer has a rapid hydraulic response, or the period of the driver is very long, the aquifer constantly adjusts to cyclic changes in the hydrological input, without any significant time-lags. Such systems could in some cases be approximated reasonably well by steady state models; although multiple states at hydrological extremes should be considered (Haitjima 2006). Where values of τ_{cycle} are intermediate (e.g., $\approx$1), transience is likely to be of great significance, as the lag in the aquifer's response is of a similar timescale to variation in the hydrological input and as such, the system will be constantly "out of phase" with the input. In such cases, any modeling or flow calculations for management purposes should be conducted in transient mode, with detailed analysis of time-dependency of the outputs (e.g., heads and fluxes). Note the relationship between τ_{step} and τ_{cycle}; where P of a periodic hydrological driver (e.g., a climate cycle) is between 0.25 and 2.5 times the value of τ_{step}, τ_{cycle} will range between 1 and 0.1, respectively. Haitjima (2006) classified such systems as being highly susceptible to transience. It should be noted that τ_{cycle} was derived for radially symmetrical flow systems, and is therefore most applicable in such settings although we argue that it has broad applicability as a "first pass" indicator of susceptibility to transience in many settings. A number of more detailed formulations of the time-dependent hydraulic response of aquifers to changes in infiltration are presented in Gilfedder et al. (2009) and Cuthbert (2014). These involve subdividing the response into different characteristic time phases, for example, unsaturated flow, vertical, and lateral saturated flow. From a practical standpoint, any measure of the time-dependent hydraulic response of an aquifer can be used within our framework, provided the lag can be expressed in units of time, and compared with a hydrological input time-series.

Drivers of Transience in Hydrogeological Systems

Major drivers that can induce transient behavior in groundwater systems can be classified by the timescale(s) on which they vary, the type of variation (e.g., cyclic vs. monotonic) the location or spatial scale of the driver, and likely impacts on groundwater systems. Table 1 provides a summary of this information for a range of important global and regional hydrological drivers.

Historic Climatic Change, Sea-Level Change, and Landscape Evolution

Earth's climatic systems are variable on a wide range of timescales, and there are many systems occurring on global to local scales which dictate hydrological conditions (e.g., Table 1). Many climate systems exhibit periodic behavior; however, the period and shape of the resulting hydrological time-series (e.g., rainfall or precipitation/evaporation ratio) may vary. For example, in arid and semi-arid regions, wet-periods often occur as extreme, short-lived events that have proportionally larger effects on groundwater recharge ("episodic" recharge, see Crosbie et al. [2012]; Macumber [1978]). In a given setting, multiple systems overlap to produce the climatic-hydrological conditions that affect groundwater systems.

Linked to climatic change are rises and falls in sea-level, which in some circumstances may drive transience by impacting flow velocities and fluxes of groundwater discharge to the ocean. These effects are limited to coastal aquifers, and depend on the degree of hydraulic connection between aquifer and ocean. It was recognized by Kooi et al. (2000) that many large coastal aquifers are in a state of disequilibrium with respect to current sea-level and hydrological conditions.

Other environmental changes that may drive transience in hydrogeological systems are the evolution of vegetation, soils, and geomorphology, which can affect rates, locations, and mechanisms of recharge and discharge. Examples include:

- Changes in sediment deposition and erosion rates which can affect location and characteristics of recharge and discharge areas
- Shifting distribution patterns for different types of vegetation which intercept infiltration and drive evapotranspiration
- Evolution in response to de-glaciation such as the formation of lakes in depressions or drainage network evolution during isostatic rebound

Few studies have been conducted to investigate combined impacts of both landscape change and hydrological change on groundwater systems. At the continental scale, Garven (1995) reviews relationships between geological processes and flow system evolution. Investigation of these interplays requires complex models that can account for processes occurring during landscape evolution, and link these to transient hydrogeological models. An example is Lemieux et al. (2008) who coupled outputs from a Glacial Systems Model of North America to a regional hydrogeological model.

Anthropogenic Hydrological Drivers

Arguably the most important type of driver affecting hydrogeological systems in the current era is anthropogenic activity (Wagener et al. 2010). It is widely recognized that in many systems the impact of human activity often overwhelms natural processes (Williams and Crutzen 2013). The major classes of change are:

1. Land-use change, such as deforestation for agriculture and urbanization or afforestation for land rehabilitation or plantation forestry;
2. Groundwater extraction—either for irrigation, domestic water, or mining;
3. Anthropogenic climate change and related sea-level rise.

In contrast to the other drivers, which are predominantly cyclic and related to natural climatic variation, the anthropogenic drivers generally produce monotonic changes in recharge or discharge rates, although the rates of these monotonic changes are variable and/or greater in magnitude. For "step changes" (rapid monotonic increase or decrease in a hydrological input), the response of a groundwater system can in some cases be predicted in terms of a transition from an initial steady-state to a new steady-state (e.g., Bredehoeft and Durbin 2009), although there should be no a priori assumption that hydrological inputs prior to the change were stationary.

Management Timeframes and Spatial Scales

If our framework is to be applied in a meaningful way to groundwater management problems, then the assessment of transience based on the combination of aquifer response times and hydrological inputs must also consider the management timeframe. If this time is particularly long or short, then steady state approximations of a system may be a useful and adequate approach. For example, where aquifer response times are very slow (large values τ_{step} of or τ_{cycle}), steady state approximations may be relevant over short management timeframes, as little transient response to hydrological change will occur on the timescale of interest. This will become less applicable as the management timeframe increases—during which the transient response is increasingly likely to manifest. On the other hand, where the aquifer response time is rapid, transient behavior will likely become more important as the management timeframe decreases. For example, where a seasonal subset of the overall aquifer response to climate is considered important, short-term transience may be of consequence in such systems. On longer timeframes, many cyclical changes will be integrated into an overall time-averaged response, for which a steady state model or set of minimum/maximum steady states may be applicable. Selection of the appropriate management timeframe is therefore an extremely important part of the framework outlined in this paper.

Table 1
Drivers of Transience in Groundwater Systems

Name of Climate Driver	Timescale	Type of Signal	Spatial Scale of Importance	Likely Impacts on Groundwater
Milankovich (orbital) cycles and Quaternary Glaciation	100 kyr glacial/interglacial cycles. Important effects on timescales of >10 kyr	Periodic, but with "step changes" rather than smooth transitions between states	Global; affects much of Earth's climate	Major impacts through control on ice and permafrost extent; global sea level, rainfall, and ET patterns
El Niño-Southern Oscillation (ENSO)/Pacific Decadal Oscillation	Multi-year to decadal	Periodic; asymmetrical. e.g., periods of neutral conditions punctuated by droughts and floods (El-Niño or La Niña events)	Pacific rim countries and islands; Southwest USA; Australia; South America	Produces extended droughts and major flood periods east or west of the Pacific depending on mode
North Atlantic Oscillation/Northern Annular Mode	Varies from monthly to decadal variability	Periodic	Mostly affects western Europe, also North America	Strong control on rainfall amounts in northern hemisphere
Indian Ocean Dipole and Asian Monsoon	Yearly to decadal; strength and position vary on timescales from years up to centuries	Periodic	South and East Asia; Australia	Control on rainfall amounts in Asia and Australia
Seasons (Earth's axial tilt)	Yearly cycle, four subperiods (in the temperate globe)	Periodic	Sub-yearly, most of the inhabited globe—depending on latitude	Seasonal recharge patterns in temperate climates
Anthropogenic climate change	Decades	Monotonic step changes—adding fuel to the climate system; hard to predict all impacts	Global, affects whole climate, with localized regional effects highly varied and difficult to predict	Potential impacts on recharge and discharge rates; direction and magnitude of local changes as yet poorly constrained (Treidel et al. 2011)

Equally important is the spatial scale considered to be of interest to management. The time response of a hydrogeological system is strongly dependent on the length scale being considered (e.g., Equations 1 through 5). If the total basin response is of primary interest, then $\tau_{\text{step,}}$ or other time-response factors should be calculated taking L as the total distance from recharge to discharge area(s). However, if local sub-sets of the system are important, as is often the case in groundwater management, then τ_{step} should be re-calculated with shorter length scales appropriate to the problem. One approach could be to create contour maps of τ_{step} throughout a basin, so that management time scales and length scales can be more easily related to each other. This was an approach suggested by Jenkins (1968) using "stream depletion factors" to examine the time dependent response of stream-aquifer systems to pumping.

The applicability of steady state modeling vs. more detailed transient modeling is naturally also contingent on the type of question investigated. For example, with increasing awareness of the dynamics of groundwater-ecosystem interactions and interest in understanding the time-dependence of fluxes of groundwater to ecosystems, short term transient responses are increasingly important (e.g., Hancock et al. 2009). Therefore, we are by no means saying that our framework should be used as a basis to reject completely the influence of transience under certain combinations of the three factors. Rather, it is a guide to determining how important it is likely to be given different combinations of these factors, and assist managers with understanding (for example), which drivers are most likely to result in transient behavior during a relevant planning period.

Relating Aquifer Response Times and Hydrological Drivers in a Management Context

Figure 1 is a graphical tool designed to facilitate assessment of the three factors in our framework—aquifer hydraulic response times, hydrological drivers, and the spatiotemporal scale of interest—in order to help determine the likely importance of transient behavior in a groundwater management context. Figure 1a is designed to be used to assess the influence of transience in response to periodic drivers such as climatic cycles, while Figure 1b is used to assess the response to step changes, such as episodic hydrological events or a change from one recharge rate to a new rate. Figures 2 and 3 provide step-by-step guidance for how to make use of Figures 1a and 1b, respectively, within our proposed framework.

On Figure 1a, the time constant for a system of interest is selected on the x-axis based on aquifer hydraulic properties (Equation 3). This can range from local, rapidly responsive aquifers to regional, slow-responding systems. On the left hand y-axis the period of cyclic hydrological drivers that may be important is then selected. This can comprise major climatic systems, ranging from short term cycles like seasonal rainfall, to long term global systems like glacial-interglacial cycles. On this basis, a point can be plotted in x–y space to assess whether the combination of these two variables is likely to result in transience (see Figures 1a and 2). The management timeframe for the aquifer and problem in question is then encompassed (by inspection) using the right-hand-axis, which can range from short term planning (e.g., year-to-year water allocations) up to long-term management issues, such as nuclear waste disposal (Figure 1a). Plotting τ_{step} for the aquifer in question and then examining which driver(s) on the left-hand y-axis result in combinations that plot within the "zone of transience" in x–y space allows determination of which combinations of the first two factors in the framework are likely to result in a high degree of transience. Subsequent inspection of the right-hand y-axis then allows assessment of whether the period of the relevant hydrological driver that induces transience is encompassed within the management timeframe or not. This is shown as a step-by-step process in Figure 2.

The area in Figure 1a between the diagonal lines ("zone of transience") is where the combination of hydraulic properties (τ_{step}) and cyclic hydrological drivers (P) result in values between 0.1 and 1. As per the definitions in Haitjima (2006), this is likely to result in highly transient responses that cannot be approximated accurately using steady state models. This occurs when the period of a cyclic hydrological driver is between 0.25 and 2.5 times the value of τ_{step}. If the combination of τ_{step} and P plot within or close to this zone, and the management timeframe encompasses this, then the transient response of the system needs to be carefully considered and modeled.

It should be noted that the "hydrological drivers" and the "management timeframe" are not completely independent. There are cases where hydrological or climatic drivers may define the management scales that are of most interest; for example in highly seasonal climates, management practices may be geared toward balancing seasonal supply and demand. Interplay or feedback between management actions and hydrological drivers may also result in complicated responses that are not well accounted for in our framework. An example would be where water allocations are rapidly adjusted in response to climate variability without considering the time-lag in the aquifer's response. In such a case, the time-dependent response of the aquifer system could be rendered further out of phase with the driver—an unforseen feedback. Our graphical method is designed as a "first pass" tool to be used within the framework for assessing the importance of transience, and is not designed to predict or incorporate these feedbacks. The framework is however in part designed to assist in avoiding overly "reactive" short-term management actions such as the above scenario, by illustrating the likely timeframes over which particular drivers are likely to manifest as hydrogeological changes.

Figure 1b is designed to assist the management of hydrogeological systems when affected by a step change or rapid monotonic increases in a hydrological input (e.g., a change from one recharge rate to another under changed land-use). In this figure τ_{step} can be plotted on the x-axis, for assessment against a timeframe on the right hand y-axis, for example, a specified timeframe of interest to management. The bold line indicates the point at which $t = 3\tau_{\text{step}}$; this is the approximate time that would be required to reach a "near steady state" in response to a step hydrological change (Schwartz et al. 2010; Rousseau-Gueutin et al. 2013). Hence by inspection it can be seen whether an aquifer system is likely to reach a new steady state following the step change within the management timeframe (refer to Figure 3 for a step-by-step guide on using this figure). If this is not the case, then the response of the system will be entirely transient during the management timeframe, and this should be taken into account when conducting modeling, prediction, or making decisions about groundwater management (e.g., Bredehoeft and Durbin 2009).

Case Studies

In this section we briefly describe two contrasting case studies where the framework and graphical tools are used to attain a better understanding of the importance of transience in a groundwater management context. The first example is a relatively small-scale aquifer system, which responds rapidly to hydrological change and is managed on a timeframe of years to decades. The second is a regional aquifer system that responds on long time scales to global climatic shifts, and for which discussions about management have required consideration of long timeframes, appropriate for the disposal of high-level nuclear waste (Alley and Alley 2012). Colored dots are added to our graphical tools that are relevant to the two case studies—blue for the Werribee Delta and green for Yucca Mountain—and this is shown as a new figure (Figure 4). The roman numerals in the colored dots indicate the combinations of different aquifer response times and hydrological drivers investigated, as outlined in Table 2.

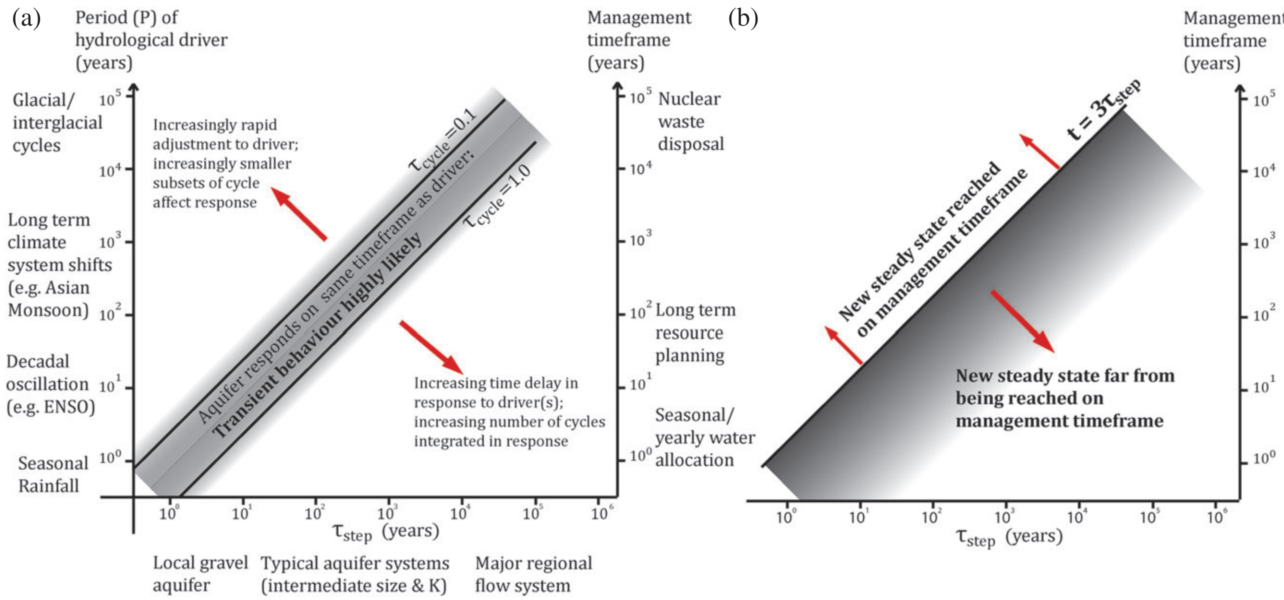

Figure 1. Graphical tool for assessing likely importance of transient behavior in a groundwater system in response to periodic drivers (a) and episodic drivers (b). Step-by-step guides for how to use the figure to aid the assessment of the importance of transience are given in Figures 2 and 3, and Figure 4 shows example case studies using the tools.

Rapid Response Aquifer: The Werribee Delta

The Werribee Delta aquifer in southeast Australia is an important local water supply for horticultural production, and an unconfined coastal aquifer that is vulnerable to seawater intrusion (Salzman 2010). The length of flow systems from recharge to discharge are generally between 1 and 10 km, while transmissivity and specific yield are on the order of 20–200 m^2/day and 1% and 15%, respectively (Leonard 1992; Dahlhaus et al. 2003). Given these parameters, τ_{step} values range between ~1 and 100 years (Table 2; Figure 4a). The aquifer is known to respond rapidly to climate variation, e.g., water levels declined rapidly in a recent multi-year drought (1998 to 2004), and recovered rapidly following a recent wet period (La Niña) in 2010. Management timeframes for this system range between yearly to decadal—the main consideration being limiting seasonal groundwater extraction to prevent saline intrusion into the delta sediments. The dominant climatic systems that affect the region within the management timeframe are seasonal rainfall and the ENSO, which is an extremely important control on rainfall patterns in southern Australia, producing multi-year droughts (El Niño) punctuated by major wet (La Niña) periods, with a recurrence interval of approximately 5–10 years.

Here we use the graphical tools introduced earlier to assess the importance of transience in response to these drivers, in accordance with our framework (Figure 4). A median value of τ_{step} for the system was first estimated, arriving at a value of ~35years, and this was selected on the x-axis of Figure 4a. We then chose three hydrological drivers (in this case climatic systems) with different periods: seasonal rainfall, ENSO, and glacial cycles, using the left hand y-axis of Figure 4a. Plotting three points corresponding to these combination of τ_{step} and the relevant P values (marked as points I, II, and III, respectively on Figure 4a), allows inspection of which driver is the most likely to induce transience. It can be seen that when the combination of time constants (=35years), and the period of ENSO (~10 years) are considered together (this is marked as point II on Figure 4a), transient behavior is likely to be highly important, as the τ_{cycle} values lie between 0.1 and 1 (~0.85). By inspection of the RHS y-axis, we can see that the management timeframe of decades encompasses the period of this driver (ENSO cycles). Hence, management of the Werribee Delta system should always be mindful of transient shifts in the aquifer's condition in response to the multi-year climate oscillations that are driven by the ENSO (as is well understood by those involved in management of the system). On the other hand, for short-term hydrological shifts, such as seasonal rainfall (point I on Figure 4a) the degree of transience induced is likely to be less significant, as many cycles are integrated into the averaged response of the aquifer. For longer term climatic shifts such as glacial cycles (point III) this system will respond with such relative rapidity that any residual, long term effects of these cycles are unlikely to manifest as delayed transience. Therefore, the influence of past glacial/interglacial cycles on this aquifer is likely to be minimal, as the hydraulics ensures the system "catches up" with prevailing climate quickly.

Using Figure 4b, we can also explore the likely "time to reach steady state" in response to a step change in a hydrological input in this system. Such a change may occur if, for example, there is a shift to a new land-use in the area which causes a rapid change in recharge rates.

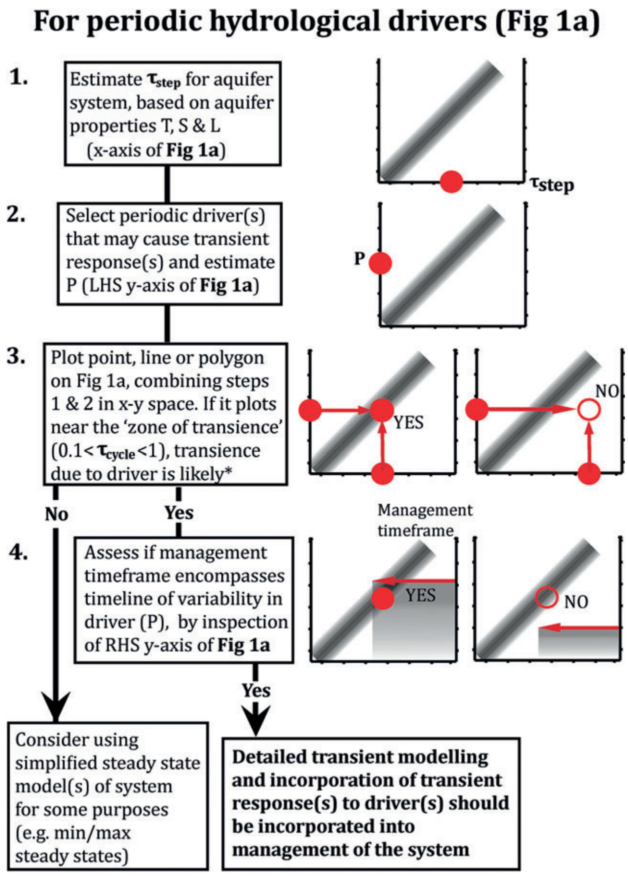

Figure 2. Step-by-step guide to using the graphical tool (Figure 1a) within our framework for assessing the likely importance of transience driven by cyclic hydrological inputs (e.g., climate) on a specified management timeframe. *The combination of τ_{step} and P allows calculation of τ_{cycle}.

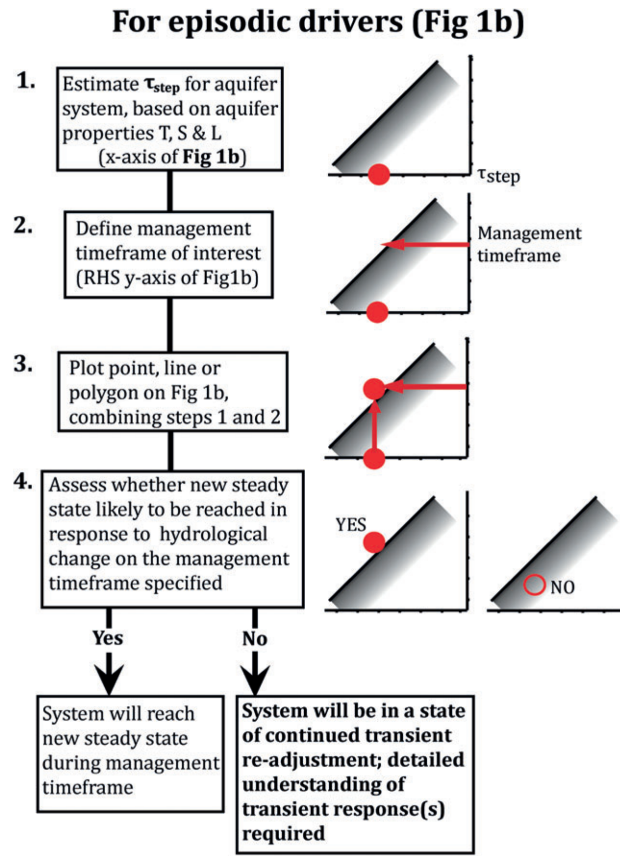

Figure 3. Guide to using graphical tool (Figure 1b) to assess transience driven by a step change in a hydrological input.

Specifying a value of 35 years on the x-axis of Figure 4b, it can be seen that the system would be likely to reach a new steady state in about ~100 years in response to such a change. The new steady state will be reached within a management timeframe of decades, but at the very upper limit of this timeframe. Hence, point IV on Figure 4b plots close to the "new steady state reached on management timeframe" line. Evidently, land-use actions taken now will have long-term impacts, even in this relatively fast responding system. This underscores the great importance of inter-generational knowledge transfer in the management of hydrogeological systems.

Slow Response Aquifer: Yucca Mountain Flow System

For the case of a slow-responding aquifer system, where long term management has been intensively debated, the Yucca Mountain flow system presents an ideal scenario to apply our proposed framework (green points on Figure 4a and 4b). The transient nature of this system has already been well described by Schwartz et al. (2010). They determined that τ_{step} values for the system are on the order of 10^2 years at the water table, up to 10^4 years at the discharge areas (Table 2). In the following examples we will look at the flow system as a whole, and thus use the upper estimate of τ_{step} of around 10kyrs. Using Figure 4a to assess which climatic systems are likely to drive transience, it can be seen by inspection that glacial-interglacial cycles are the most likely hydrological driver to produce major transience, as the combination of τ_{step} and P in x–y space plots near the "zone of transience" (point V on Figure 4a).

Because of the special significance of this system as a (former) proposed candidate for nuclear waste disposal, the timeframe of this long-term transient response to glacial cycles is encompassed within the management timeframe (see the right-hand y-axis of Figure 4a). Thus detailed consideration of the relationships between the global climate system and the transient response of this aquifer system would be a necessary consideration in planning for a repository. On the basis of our framework, it is reasonable to conclude that transience driven by major long-term climatic shifts like future glacial-interglacial transitions must be considered in the modeling of future hydrogeological scenarios; just as previous glacial cycles need to be considered in examining the present-day responses. The difficulty in selecting suitable model initial conditions in such systems, in the context of persistent disequilibrium with climate, is an important related topic (Schwartz et al. 2010).

On shorter timescales, climatic oscillations that are significant at Yucca Mountain such as the Pacific Decadal

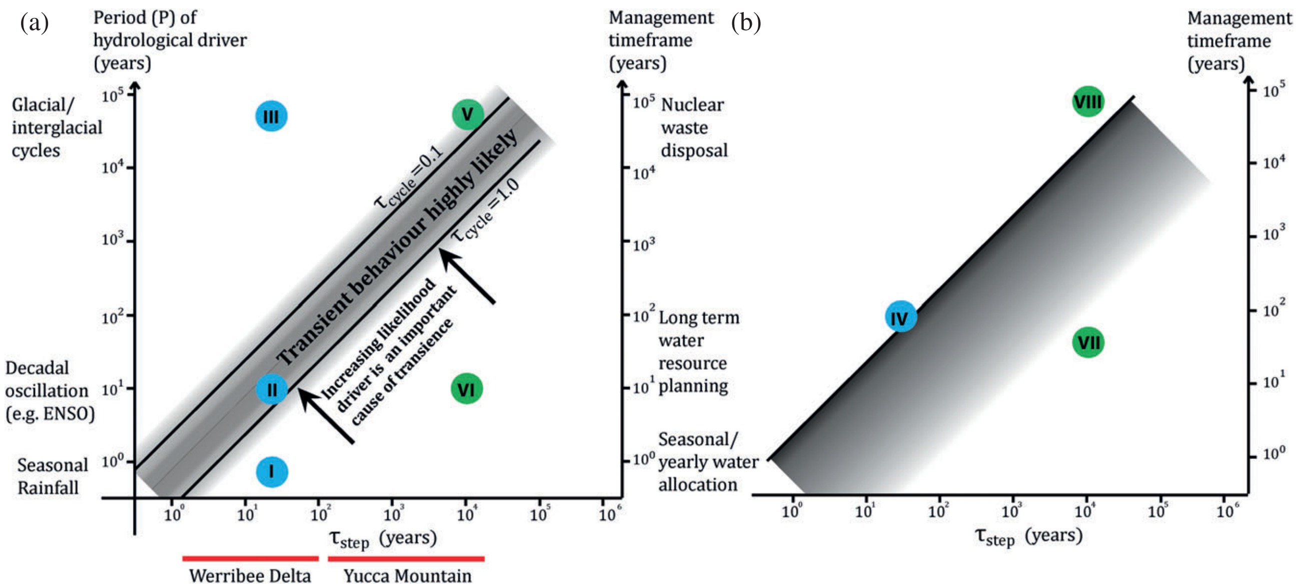

Figure 4. Examples of how the graphical tools can be used to assess transience within the framework, using two case studies. Blue circles are points relevant to the Werribee Delta case study; green points to the Yucca Mountain case study. Key to the placement of points is shown in Table 2 and discussed in text.

Table 2

Summary of Input Data Used to Generate Colored Dots of Figure 4, in Order to Assess the Importance of Transience in a Management Context, Using the Two Case Study Aquifer Systems

Point No. and Figure Where It Appears (4a or 4b)[1]	τ_{step} Value (Years)	Driver Being Assessed as a Potential Cause of Transience	Management Timeframe Considered Relevant	Transience Important Based on Framework and Figure 1?
I (a)	35[2]	Seasonal rainfall	Decades (up to 100 years); water resources planning	N
II (a)	35	El Nino Southern Oscillation (ENSO)		Y
III (a)	35	Glacial/Interglacial cycles		N
IV (b)	35	Step change in recharge rate		Y
V (a)	10,000[3]	Glacial/Interglacial cycles	100 s of kyr (nuclear waste disposal)	Y
VI (a)	10,000	Pacific Decadal Oscillation (PDO)		N
VII (b)	10,000	Step change in recharge rate		Y
VIII (b)	10,000	Step change in recharge rate	Decades (water resource plans)	Y

[1]Points I to IV are marked in blue for the Werribee Delta, and points V to VIII in green for the Yucca Mountain case study on Figure 4.
[2]Werribee Delta values estimated using $T = 20\,m^2$/day and $S = 0.01$.
[3]Estimated by Schwartz et al. (2010) based on the outputs of a transient flow model.

Oscillation are unlikely to be a major cause of long-term transience (Table 3). Overall, the aquifer responds too slowly for individual PDO cycles to manifest as important transient shifts (e.g., in discharge rates); many cycles will be integrated into the long-term response. This combination of variables is represented as point VI on Figure 4a. If management of the Yucca Mountain system on decadal timescales was considered important, as is standard practice for most groundwater systems that are not being considered as nuclear repository sites (e.g., Gleeson et al. 2012), then steady state approximations might be adequate for water management in some contexts, although local sub-sets of the regional system would be affected by transience driven by this climate system. Short to medium-term management of the system would also need to be mindful of the influence of major climatic shifts in the past, which will be exerting influence on the current heads, fluxes, and patterns of groundwater age (albeit slowly).

In terms of the response to a step-change in hydrological inputs, during short-term management timeframes, this system will never come close to the point of equilibration or new steady state. This is represented as Point VII on Figure 4b, combining the large τ_{step} values and

Table 3
Summary of Key Drivers of Transience for Two Case Study Systems Based on Our Proposed Framework

	Werribee Delta	Yucca Mountain
τ_{step} values	1–100 years	100–10,000 years
Management timeframe considered	Years to decades	Millenia to geological timescales
Management scale	<1 km up to 10 km	10s of km
Key hydrological drivers which may drive transience	ENSO	Glacial/interglacial cycles; palaeo-climate

a typical planning horizon for most aquifer systems of ~50 years. On this basis, it is reasonable to conclude that Yucca Mountain and other systems like it should always be considered out of equilibrium with current climate, and in a constant state of re-adjustment (Rousseau-Gueutin et al. 2013). In the special case where very long management timeframes are being considered, e.g., for nuclear waste repositories, the time required to reach a new steady state in response to a step change may in fact be reached within the management timeframe (Point VIII of Figure 4b), and therefore the system may adjust to an individual step change within this timeframe. However, hydrological conditions will not remain steady during the intervening 1000s of years, meaning this is of little practical significance.

Summary and Conclusions

We have proposed a new framework and graphical tools to assist in understanding the importance of transience in hydrogeological systems. Three factors should be considered when examining the likely importance of transience:

- The time response of the aquifer system, which can be estimated using a series of analytical approximations based on aquifer properties.
- The degree of variability in the dominant hydrological drivers through time, such as climatic cycles or other drivers of recharge variability.
- The management timeframe and spatial scale that is of interest to the study. While some systems may approximate steady state behavior if viewed over a long time period or spatial extent, these scales may not be what is most relevant to water planning.

The framework can be used to understand which hydrological drivers are likely to be important causes of transience for a system, the timescales on which transience is likely to manifest, and the relevance to groundwater management, incorporating relevant timeframes, and spatial scales. The framework can also be used to assess the likely validity of steady state approximations of a system compared to more detailed transient modeling. Applying our framework in a water management context using the graphical tools developed, could be greatly beneficial in determining the importance of transience in many scenarios, such as predicting impacts of climate and land-use change on groundwater, or long-term hydrological scenario planning for water resources supply or waste disposal.

A limitation in the approach described is the use of simple analytical measures of the time response of aquifer systems. As noted in Schwartz et al. (2010), these simple formulations can be misleading in complex flow systems. Also, not all drivers of change in hydrogeological systems are well approximated by either a step change or a periodic cycle. Hence, the metrics τ_{step} and τ_{cycle}, and the graphical tools may have limited applicability where more complex drivers of hydrological change require consideration. The framework is not meant to yield detailed information about the response of individual flow systems to particular hydrological changes; rather it is designed to assist in determining the drivers and timescales important for transience at the "first pass" level, in a management context. Following application of the framework and graphical tools, we recommend that systems identified as being susceptible to transience undergo more detailed analysis based on transient numerical modeling.

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