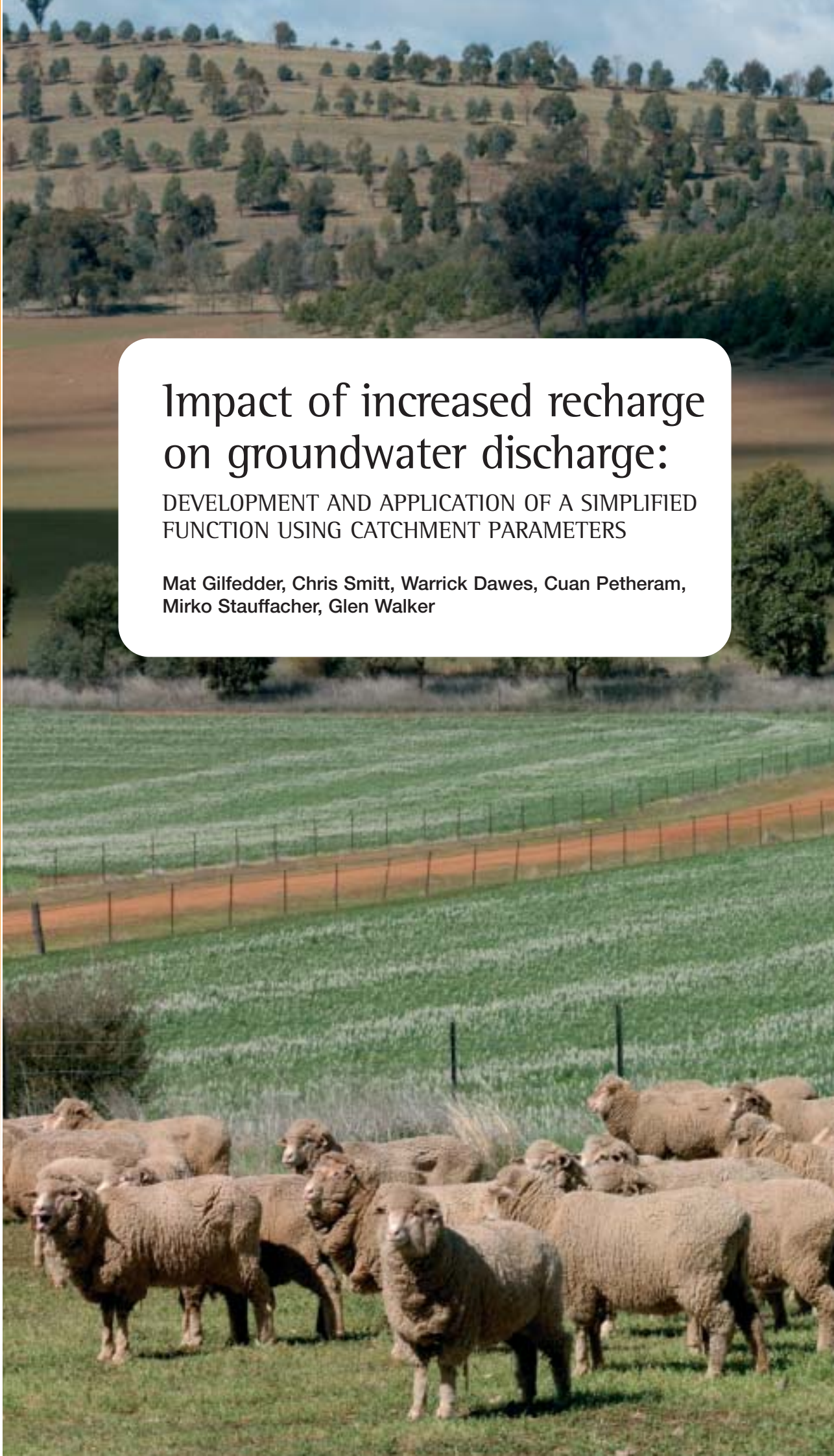


Impact of increased recharge on groundwater discharge:

DEVELOPMENT AND APPLICATION OF A SIMPLIFIED
FUNCTION USING CATCHMENT PARAMETERS

Mat Gilfedder, Chris Smitt, Warrick Dawes, Cuan Petheram,
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Executive summary

The objective of the present report is to develop a simple approach towards estimating the response of groundwater systems to changes in recharge that arise from changes in land use. The emergent properties of a groundwater system are examined using scaling arguments, by combining the effect of aquifer properties into a single dimensionless groundwater system similarity parameter (G).

The expansion of areas of saline land, and rising river system salinities is occurring in many parts of Australia. Such environmental change has increased the need for an ability to predict the effects of salinity into the future. Without this predictive capability, management strategies will continue to try to treat symptoms caused by salinity rather than develop preventative and more effective management solutions.

The timing of salinity changes in response to land use changes is not well understood. While changes in land use may cause relatively rapid changes in surface run-off and evapotranspiration, the time lag between recharge to groundwater systems and their subsequent discharge to surface water can be much longer. Since groundwater discharge is the main pathway by which salt is moved into streams, understanding the time lags between management change and groundwater change is paramount.

Unfortunately there is a lack of detailed measured data at catchment and regional scales, even in the well-studied parts of Australia's dryland regions. This fact alone means that any suitable approach at this large scale must be simple.

A dimensionless similarity parameter (G) is introduced in this report, which simplifies the characterisation of a groundwater system by combining transmissivity, specific yield, recharge, length and head. G can be visualised as a measure of the ratio of the system's *ability to fill* (t_v) compared to its *ability to drain* (t_d). As such, G gives an indication of the state of balance of a groundwater system.

A simple approach incorporating G is used to estimate groundwater system response times for five case studies under different increased recharge scenarios. This approach offers an important step towards a more rigorous estimate of catchment's overall response to changes in land use for their component groundwater systems. This approach had three main steps:

1. The time to drain (t_d) factor was scaled to give a *baseline* response (i.e. where no surface discharge occurs) to an increase in recharge.
2. G was then used to obtain an estimated response, by scaling this *baseline* response. For $G < 4$, the groundwater response time was faster than the *baseline* response (because surface discharge allowed faster change to a new equilibrium).
3. The *estimated* response was then converted into a 50% response time (which was then used to parameterise the discharge function in Eq. 21). This correction process relied on the good correlation ($r^2 = 0.92$) between the *estimated* response and modelled FLOWTUBE predictions for several case study catchments.

This study has shown that there is a strong relationship between variations in G and groundwater system behaviour. The plan-view shape of a system and the slope-profile also impact upon groundwater system response to changes in recharge. The analysis has demonstrated that there is a relationship between G and the time to surface discharge in response to increased recharge. Therefore, in the absence of more detailed hydrogeological and hydrological data, G provides a tool to simplify investigation of catchment behaviour.

This report investigates the response of both generic and case-study groundwater systems to increased recharge. Further work is required to test how such systems will respond to reforestation or other recharge reduction strategies.

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1. Introduction

The expansion of areas of saline land, and the rising salinities of river systems have increased the need for an ability to predict the likely environmental effects into the future (PMSEIC 1999). Salinity is a surface expression of hydrological change to groundwater systems. Therefore, an understanding of groundwater systems, and their responses to land use change, should lie at the core of any method used to predict changes in land and stream salinisation into the future.

Regional or catchment scale methods must take into account the fact that features of salinity are related to the scale and type of groundwater systems, which can vary significantly both within and between catchments. As such, the first step in prediction at a regional or catchment scale will involve the disaggregation of the landscape into smaller components that exhibit similar behaviour in terms of their hydrology and salinity processes (Gilfedder and Walker 2001). An approach currently favoured in Australia is the classification of groundwater flow systems at a range of scales (local, intermediate and regional) which are also related to the topographical and hydrogeological processes leading to salinity in each system (Coram et al. 2000). This classification offers a systematic landscape disaggregation, useful at a national or regional scale.

The second important step is the identification and simplification of relevant landscape characteristics to predict groundwater response to land use change. The complexity of these methods must be low, because of the paucity and irregularity of available data at the catchment scale. Previous research has examined relationships at a catchment scale between evapotranspiration and vegetation type with respect to rainfall (Holmes and Sinclair 1986; Zhang et al. 2001). The complement of this is that the non-evaporated component of rainfall (runoff + recharge = yield) will also follow the inverse relationship. This has been used to investigate the relationship between

rainfall and yield, with changes in land use for catchments in the Murray-Darling Basin (Bradford and Zhang 2001). It has also been used to study the effects of strategic reforestation over part of the Murrumbidgee catchment in New South Wales (Vertessy and Bessard 1999). The investigation of how this relationship might relate to groundwater recharge has also been reviewed by Petheram et al. (2002), who looked at possible relationships between groundwater recharge and vegetation type for a range of soil types with respect to rainfall.

The third step is to predict the timing of groundwater response, following a change in recharge. The previous studies mentioned did not attempt to look at the temporal response of catchments to land use change. Instead they were based on the assumption of long-term mean annual condition, at a steady state. However, the effect of changes in land use on catchment yield is not instantaneous. While the evaporated and run-off components may respond relatively quickly to a land use change, increased recharge to a groundwater system may not necessarily express itself as a corresponding increase in surface discharge for many years. The *timing* of effects of a large-scale land use change on catchment yield will be different for a range of groundwater systems within a catchment. This timing is very important. It affects the physical and economic viability of possible management options, since groundwater discharge is the process which mobilises salt to the land surface and also to surface water bodies. Dawes et al. (2001) considered relationships between catchment yield and land use, using a two-parameter groundwater discharge function as an estimate of the expected shape of the response for each of the three groundwater flow system types. This work identified the need for further, more scientifically rigorous investigation of discharge behaviour, that takes into account the characteristics and impacts of the groundwater system.

1.1 Objective and outline

The objective of this report is to develop a simple approach to estimate the response groundwater emergent properties of a groundwater system are examined using scaling arguments, by combining the effect of aquifer properties into a single dimensionless groundwater system response similarity parameter (G).

- The first part of this report uses dimensional analysis to derive a groundwater system scaling argument that is used to obtain G . Some features of G are then explored of for both steady state and transient scenarios. The steady state component looks at changes with groundwater system parameters, and also aquifer shape and profile.

- The second uses the FLOWTUBE groundwater model to investigate the effect of these changes on the temporal response of an idealised groundwater system systems to changes in recharge that arise from changes in land use.
- The third part investigates the modelled behaviour of five case studies to increased recharge. A simple approach that uses G is developed, to estimate transient groundwater system response following increased recharge.

2. Scaling the groundwater equations

Dimensional analysis is a mathematical technique that can be applied to complex physical systems to help determine relationships between variables. By identifying the factors involved in a physical situation, dimensional analysis can be used to form a relationship between them. Thus, it can be used to combine several variables into a single parameter to simplify the inter-comparison of different groundwater systems. Examples of this include the Reynolds number for viscous flow, and Froude number for open channel flow.

This type of analysis allows the simplification of a range of aquifer properties into a single similarity parameter (G) for a groundwater system. The first step in this analysis is to take a control volume within a groundwater system (**Figure 1**).

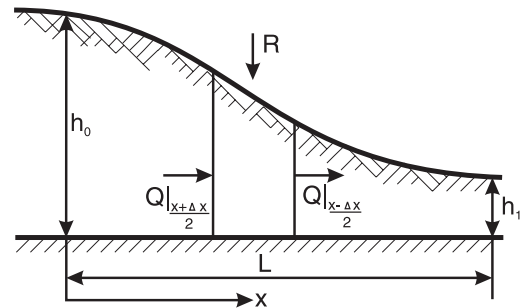


Figure 1. Mass balance variables for control volume within a groundwater system. R is recharge, h_0 and h_1 are aquifer thickness, L is length, x is distance along the aquifer, and the Q terms are groundwater flow into and out of the control volume.

The mass balance equation for the control volume in **Figure 1** can be expressed as:

$$-\frac{\partial Q}{\partial x} + Rw = Sw \frac{\partial h}{\partial t} , \quad (1)$$

where Q is flow, R is recharge, w is the width, S is specific yield, h is groundwater head, x is the distance along the groundwater system, and t is time. Substituting Darcy's Law into equation (1) yields:

$$\frac{\partial h}{\partial t} = \frac{1}{S} \frac{\partial}{\partial x} \left(T \frac{\partial h}{\partial x} \right) + \frac{R}{S} , \quad (2)$$

where T is aquifer transmissivity ($= kd$), k is hydraulic conductivity, and d is aquifer thickness (it is assumed that d does not change with time).

We assume that for the upper boundary condition $x = 0$ is a groundwater divide or that there is no groundwater recharge from upslope.

$$x = 0, \quad \frac{\partial h}{\partial x} = 0 , \quad (3)$$

A constant head has been used for the lower boundary condition since the system is likely to feed into a surface water feature.

$$x = L, \quad h = h_1 , \quad (4)$$

where h_1 is the groundwater head at the system outlet, and L is the length of the system.

The area of surface discharge is where the groundwater system is assumed to be incapable of carrying all of the up-slope recharge. We assume for this report that this occurs only in the area x_1 to x_2 . For this area:

$$x_1 < x < x_2 , \quad h = h_{surface} , \quad (5)$$

where $h_{surface}$ is the ground surface elevation, and where x_1 and x_2 are defined by:

$$-Tw \frac{\partial h}{\partial x} \Big|_{x_1, x_2} = Q_{max} \Big|_{x_1, x_2} , \quad (6)$$

where Q_{max} is the aquifer discharge capacity.

Generally, with land salinisation it would be expected that up-gradient recharge exceeds the discharge capacity. Once this is exceeded, the groundwater system can only carry so much flow, hence it is expected that the aquifer flow will be greater at x_1 than at x_2 . As there is a time lag for increases in the up-gradient recharge to reach x_1 , it is expected that x_1 would respond by moving up the system, but x_2 would remain relatively fixed.

The following dimensionless variables for distance, thickness and time are defined as:

$$x^* = x/L , \quad (7)$$

$$h^* = (h - h_1)/\Delta h , \quad (8)$$

$$t^* = t\bar{T}/SL^2 , \quad (9)$$

where Δh is the difference in groundwater elevation between the upslope end and the outlet of the system, and \bar{T} is a representative transmissivity of the system (such as mean transmissivity).

We also define the following non-dimensional variables:

$$T^*(x) = T(x)/\bar{T} , \quad (10)$$

$$w^*(x) = w(x)/\bar{w} , \quad (11)$$

where $T^*(x)$ is a transmissivity shape-factor, $w^*(x)$ is a width shape-factor, and \bar{w} is a representative width (such as mean width).

By substituting equation (7-11) into equation (2), we obtain:

$$\frac{\partial h^*}{\partial t^*} = \frac{1}{w^*} \frac{\partial}{\partial x^*} \left(\frac{\partial h^*}{\partial x^*} w^* T^* \right) + G^*, \quad (12)$$

$$G^* = \frac{1}{G} = \frac{1}{T \Delta h / RL^2}, \quad (13)$$

where G is analogous to the dimensionless similarity parameter TH/QD^2 used by O'Loughlin (1981), who used the parameter to determine the steady-state extent of hillslope seepage areas. Seepage occurred where this parameter was exceeded by a geometric function (ratio of planform geometry factor to slope profile factor).

We also define a non-dimensional flux:

$$Q^*_{max} = \frac{Q_{max} k}{RL}, \quad (14)$$

and for groundwater systems expressing land salinisation it is expected that:

$$0 < Q_{max}|_{x_2} < Q_{max}|_{x_1} < 1, \quad (15)$$

2.1 Dimensionless G parameter

Another way of conceptualising G is as the ratio of two time factors. The first of these is the time factor for *groundwater discharge* (t_H). This time factor is related to the lateral draining of an aquifer and can be expressed as:

$$t_H = \frac{SL^2}{T}, \quad (16)$$

The second of the time factors is that for *groundwater response to recharge* (t_V). This is related to the vertical filling of an aquifer in response to recharge and can be expressed as:

$$t_V = \frac{\Delta h S}{R}, \quad (17)$$

The ratio of these two time factors provides a dimensionless parameter for the groundwater system:

$$G = \frac{t_V}{t_H} = \frac{\left(\frac{\Delta h S}{R} \right)}{\left(\frac{SL^2}{T} \right)} = \frac{\Delta h T}{RL^2}, \quad (18)$$

This type of analysis allows the simplification of a range of aquifer properties into a single similarity parameter (G) that gives a measure of the ratio of the system's ability to fill compared to its *ability to drain*. As such, G gives an indication of the state of balance of the groundwater system, which can be used to determine how well a system is likely to cope with a given rate of recharge without discharge to the surface.

3. Steady-state surface discharge

The G parameter can be used to identify generalised surface discharge behaviour for a groundwater system at steady state. As a first part of investigating groundwater system sensitivity, G was calculated for a range of recharge scenarios for an idealised groundwater system. This idealised system had: 20 nodes, each 250 m apart; constant aquifer thickness of 20 m with the top of the aquifer at the ground surface; initially a constant surface slope (four per cent); uniform aquifer properties and recharge; and width was varied for different scenarios.

A steady-state analysis was undertaken for a range of recharge values to estimate where surface discharge is likely to occur along the groundwater system. This was done by determining the upper-most node where the 'recharge volume upslope of the node' exceeds the 'discharge capacity at the node' (given by Darcy's Law) for a range of recharge scenarios (Figure 2, equation 19):

$$Q_{max}^* = \frac{Q_{max}k}{RL} \quad (19)$$

where the left side of equation 19 is the recharge volume upslope of x_1 , and the right side is the aquifer capacity at x_1 . Where w is the system width, and T is the transmissivity. This calculated x_1 provides a simple way of interpreting how a groundwater system's aquifer discharge capacity varies with respect to changes in recharge (by using G).

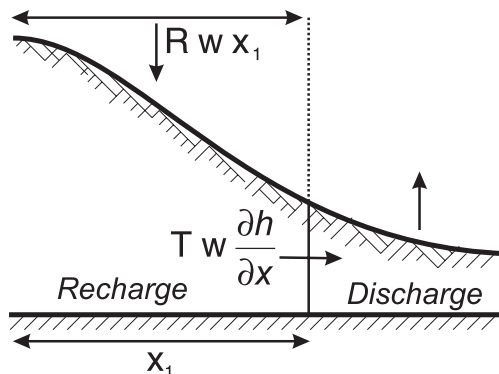


Figure 2. Position of surface discharge. Node at position x_1 (where the recharge up-slope from x_1 is equal to the discharge capacity at x_1).

3.1 Steady state results

For this example, aquifer properties (k, S, d), and the surface slope were uniform throughout the groundwater system. The effect of changing the groundwater system shape was investigated by using a range of convergent, parallel and divergent cases. Each case was identified by the ratio of 'system width at the outlet' to the 'width at the top' (for a trapezoidal shaped system). Figure 3 shows these cases as separate curves; each curve presents the changing position (x) of surface discharge against the G for a particular steady-state recharge. Generally, as G decreases (due to increased recharge), the position where surface discharge occurs also moves up along the system. The threshold value of G for which surface discharge begins to occur for a convergent system was significantly greater (i.e. lower recharge) than for the divergent case.

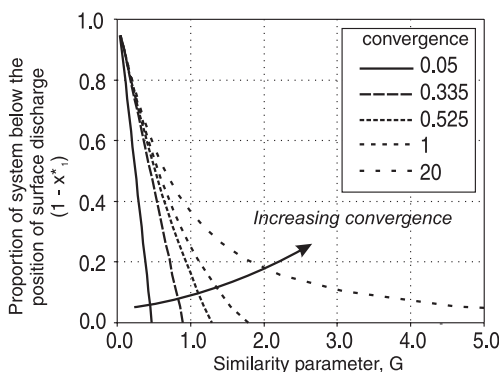


Figure 3. Steady-state effect of groundwater system shape on position of surface discharge: divergent, parallel and convergent (the legend gives the ratio of 'width at outlet:width at top').

A similar investigation was undertaken to see the effect of changing the slope profile of the groundwater system along its length. The profile was made convex and concave by changing the elevation of the initial constant slope (upper elevation 200 m, lower elevation 10 m) example by adding an amount determined by:

$$A \sin(x * \pi), \quad (20)$$

where x^* is given in equation (7), and A is a scaling variable which was varied (between -50 and +50) to provide a range of convex and concave profiles. **Figure 4** shows the variation in the position of surface discharge with changing recharge for different slope profiles (constant slope case (bold), and concave ($A < 0$) and convex ($A > 0$) groundwater systems). For a concave profile the aquifer discharge capacity is exceeded for higher values of G , while for a convex profile the discharge capacity is exceeded only for much lower values of G .

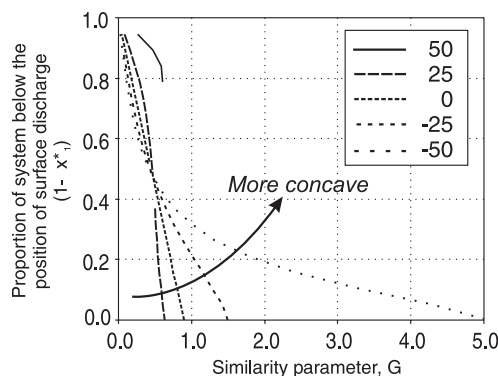


Figure 4. Steady-state effect of groundwater system profile on position of surface discharge; convex (+), constant, concave (-). (the legend indicates the curved profiles given by equation 20).

3.2 Summary of steady-state investigation

This steady-state exercise reinforces the argument that while G is a parameter for assessing similarity between groundwater systems, the importance of divergence/convergence (plan view), and changes in slope profile (convex/concave in elevation view), also play an important role in the sensitivity of surface discharge to changes in recharge. Both the shape and the profile of a groundwater system will have significant impacts on where surface discharge may occur for a given scenario. Concavity increases the value of G where surface discharge began to occur. A G with no surface discharge is likely to be greater than unity (as high as five in this case). The temporal response of these relationships is explored in more detail in the next section.

4. Transient response to land use changes

4.1 Groundwater modelling

The relationship between G and the temporal response of a groundwater system to recharge change was investigated. A simple groundwater flow model was used to model the same idealised groundwater system as for the steady-state case (see §3 of this report). Groundwater heads and discharge fluxes for this system were simulated using the FLOWTUBE model (Dawes et al. 1997, 2000). FLOWTUBE was developed as a simplified model, which is easier to parameterise than some of the more complex conventional models (such as TOPOG-IRM, MODFLOW, or MIKE-SHE). This makes it a useful tool to apply to many of the dryland groundwater systems that do not have much available hydrogeological data.

FLOWTUBE is a simple mass balance model that uses a finite difference solution to Darcy's Law to estimate the flux of water between any two points. Groundwater flow is modelled only in one-dimension, that is in the direction of flow, only a single conducting aquifer layer is considered, and it is assumed that the boundaries of each flow strip are known, and they do not change over the length of any simulation run. At the bottom end of the tube a flux loss was calculated by specifying a constant head 500 m below the down-slope end of the tube. Vertical diffuse recharge is allowed to vary in FLOWTUBE both spatially, across the groundwater system, and temporally, changing as the simulation proceeds. The value is allowed to be either positive, implying water addition, or negative, implying a net extraction. There are three options for vertical recharge input. Vertical recharge rates were specified, with the same value at each node. When head at a node becomes artesian, surface discharge can occur, although this is moderated by a maximum surface discharge capacity parameter in FLOWTUBE. This parameter enables the area of surface discharge to move back up through the groundwater

system, rather than being contained at a single point above a system constriction.

FLOWTUBE was used to investigate functional behaviour and response of a groundwater system under a range of recharge scenarios and with variation in aquifer parameters.

4.2 Transient state results

The similarity parameter G was used in the steady-state to identify surface discharge. Under transient state analysis, G 's relationship to the temporal response of groundwater systems will now be examined. As for the previous section, three groups of groundwater system scenarios were simulated:

1. parallel sides, constant slope
2. divergent/convergent sides, constant slope
3. parallel sides, convex/concave slope profile.

An idealised groundwater system (same as for §3) was used as input into the FLOWTUBE groundwater model. The timing of the groundwater response pattern following a step increase in recharge was then investigated. The aim of this exercise was to investigate how the variation in recharge and aquifer parameters affected the timing response of a *single groundwater system* and its characteristic dimensionless similarity parameter (G).

4.2.1 Simple case: parallel sides and constant slope

FLOWTUBE was used to model the response of a groundwater system to a step increase in recharge. This scenario is based on obtaining equilibrium under native vegetation (recharge = 1 mm/yr) and then running a series of separate scenarios with a range of recharge rates. The time in the

x-axis has been normalised by the 'time to drain' (t_H in equation 16), such that normalised time, $t_H^* = t / t_H$. The results presented start at the time of clearing, $t_H^* = 0$.

The groundwater system response to a change in recharge is shown by a normalised recharge:discharge ratio. This ratio is normalised so that the ratio is zero immediately following a change in recharge, and returns to a value of one once a new equilibrium is reached. As such, the results shown in the following figures give a relative response and not an absolute one. **Figure 5** shows the modelled groundwater system response to a range of different recharge scenarios.

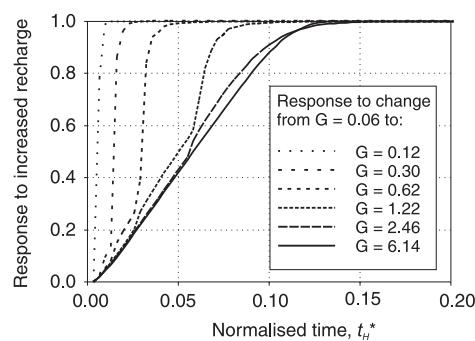


Figure 5. The groundwater system response over normalised time. Each curve is for a different recharge scenario from an initial 1 mm/yr to 2, 5, 10, 20, 40, 100 mm/yr at $t_H^* = 0$.

For relatively minor increases in recharge, the modelled groundwater system discharge is wholly contained within the aquifer—there is no discharge to the land surface. When this was the case, all curves with $G > 4$ collapsed to a single curve, and formed the *baseline* response for the groundwater system (which is the case in **Figure 5** for $G = 6.14$). For the *baseline* case, no surface discharge occurred for scenarios where $G > 4$. However, for higher recharge values, surface discharge began to occur. This was indicated by a departure from the baseline curve as the system was able to reach an equilibrium by discharging directly to the surface. As G decreased (i.e. higher recharge) below four in this case, the time to reach a new equilibrium was reduced.

The next stage in this process was to model a range of scenarios for a range of different aquifer properties for a groundwater system with the same dimensions. Hydraulic conductivity and porosity were both altered and FLOWTUBE was used to run a range of recharge values for each. The results are shown in **Figure 6**, with the response plotted

against dimensionless time. Note that the curves collapse together in a similar pattern to that in **Figure 5**, again with a *baseline* response occurring when $G > 4$.

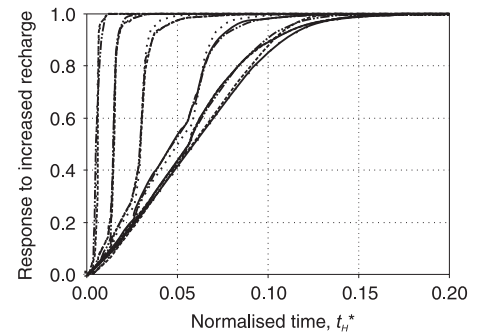


Figure 6. Normalised groundwater system response to a range of increased recharge (from 1 mm/yr to 2, 5, 10, 20, 40, 100 mm/yr), for different hydraulic conductivity (K), and porosity values, over normalised time. G varies left to right from 0.061–6.147.

4.2.2 Groundwater system shape: convergence and divergence

G does not incorporate changes in the width of the groundwater system. As a result, the implications of convergence/divergence may need to be considered. FLOWTUBE was used to model two additional groundwater system shapes, using identical aquifer properties and groundwater system slopes. As expected, the relationship between G and the normalised time to surface discharge changed. **Figure 7** shows the variation in the baseline (no surface discharge) groundwater system response for convergent, parallel and divergent cases. This figure reveals little difference between responses.

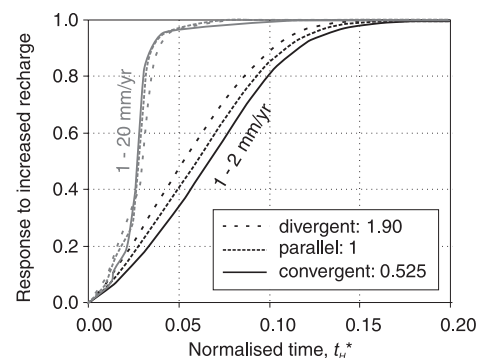


Figure 7. Effect of groundwater system shape on the response of the groundwater system over time, for two different recharge increases (from 1 to 2 mm/yr, and from 1 to 20 mm/yr) for convergent, parallel and divergent cases of an otherwise identical system (legend gives the ratio of width at outlet:width at top).

Effect of changing groundwater system profile

While G includes overall gradient, it does not consider any deviation from a constant gradient, as would be the case with changes in the surface profile of groundwater system. Additional scenarios have been modelled using FLOWTUBE with groundwater system profiles changed using equation 20: convex and concave profiles (Figure 8). For the *baseline* response (no surface discharge), the concave profile responded more slowly than the other cases. Interestingly, although the convex profile responded more quickly in the early stages than the constant slope system, the overall time to equilibrium was almost identical.

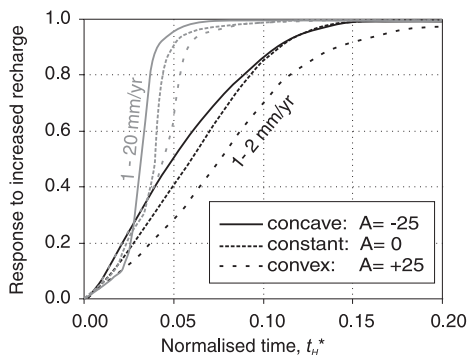


Figure 8. Effect of slope profile on groundwater system response for a: concave, constant and convex profile for two increased recharge scenarios (from 1 to 2 mm/yr, and from 1 to 20 mm/yr). (A is a variable in equation 20).

Effect of increasing the unsaturated zone

The effect of the depth of unsaturated zone above the aquifer was also considered. This will not affect the equilibrium discharge conditions, but will affect the timing of the response to recharge change, since aquifer heads will need to increase to a higher level before surface discharge can occur.

The modelled groundwater system was altered to make the aquifer deeper. For the previous modelling scenarios, the aquifer was 20 m thick with an upper boundary at the ground surface. Two additional runs were carried out where the depth from the ground surface to the upper boundary of the aquifer was 10 m and 20 m. Figure 9 shows the groundwater system response for each of the three modelled aquifer depths following a change in recharge at $t_{tr}^*=0$ from 1 mm/yr to 2 mm/yr for the idealised groundwater system. The deeper aquifer system responded more slowly than the system that was at the ground surface.

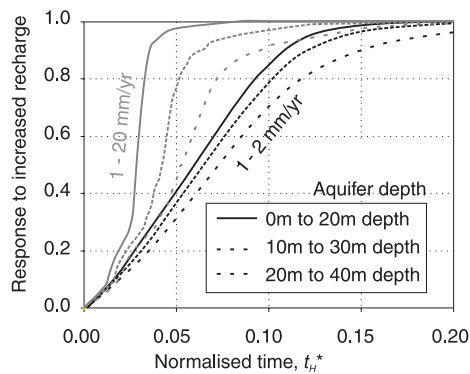


Figure 9. Effect of the depth of unsaturated zone (above the aquifer) on normalised groundwater system response, for two increased recharge scenarios (from 1 to 2 mm/yr, and from 1 to 20 mm/yr).

4.3 Summary of transient modelling

The FLOWTUBE modelling of a range of idealised groundwater flow systems has been a useful exercise in investigating the sensitivity of system response to increased recharge.

For the scenarios that were investigated in this section, there were only relatively minor differences in the response time as a result of changing the convergence/divergence, slope profile, or the depth of the unsaturated zone. These factors are likely to alter the distribution and occurrence of surface discharge, but their effect on the overall response time is likely to be less than other attributes such as length, transmissivity, recharge, and porosity.

The next section of this report investigates five groundwater system case studies, and uses them to develop a simple method for predicting groundwater system response function curves without modelling.

5. Groundwater system case studies

This section of the report describes the modelled results from several case studies around Australia. The case study groundwater systems are introduced, G is estimated for each of them, and the modelled FLOWTUBE responses to increased recharge are shown.

While the behaviour of these systems is not completely understood, they provide the best and most rigorous hydrogeological data sets which we have available. As such, these

case studies are a logical next-step in the development and validation of any new approach to predicting the effects of land use change on the groundwater response.

The general location of the case studies described in this report is shown in **Figure 10**. **Table 1** then gives an overview of some of their attributes, as used within the constraints of a simplified approach that will need to be applied more widely.

TABLE 1. General case study attributes.

Case study	State	Groundwater flow system type (GFS)	Mean rainfall range [mm/yr]	Area [ha]	Length [km]	Main land use
Kamarooka	VIC	Local	427	10,000	4.5	Cropping & grazing
Billabong	NSW	Local/ Intermediate	700	300,000	52	Cropping
Popes	SA	Local	520	18,000	4.25	Cropping & annual pasture
Kyeamba	NSW	Intermediate	650	60,200	68	Pasture & some cropping
Brymaroo	QLD	Local	670	1,370	4.4	Cropping & perennial pasture

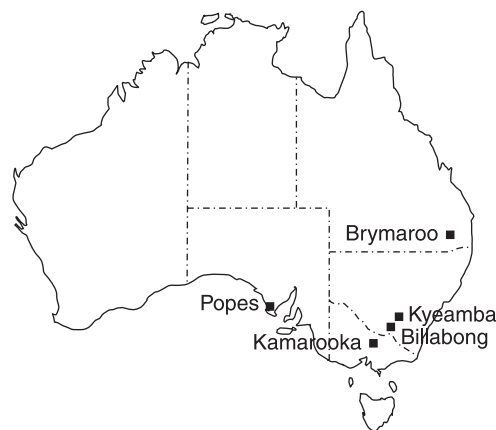


Figure 10. Approximate location of case studies.

5.1 Calculating G for the case studies

G was calculated for the case studies discussed in the previous section. Currently available information and data on the hydrogeological and catchment attributes were used. Where there was a large range in a given attribute, a value close to the mean value was used.

Table 2 shows the attribute values used to estimate G for each of the case studies. Since G varies with catchment recharge, it has been given for both the pre and post change periods for each case study.

5.2 Groundwater response—case studies

This section presents the modelled results from each case study. **Figures 11 to 15**

show the normalised groundwater response for four recharge scenarios against time. In each case, the groundwater system was ‘primed’ by running the model for 1,500 years at 1 mm/yr of recharge, so that it was in equilibrium (recharge=discharge). Recharge was then increased (shown on x-axis as time=0) to the current recharge rate (ranging between 15 to 25 mm/yr, depending on the case study). There are three other curves on each figure, which correspond to an increase from 1 mm/yr to 50%, 25% and 12.5% of current recharge rates.

Figures 11 to 15 show the return of the groundwater system to equilibrium. The y-axis shows the return of the groundwater system to equilibrium following the recharge increase.

TABLE 2. Simplified case study attributes used to calculate G (from equation 18).

Case study	K (m/d)	Thick [D] (m)	Specific yield [S]	Length (m)	Head drop [Δh] (m)	Recharge min/max [R]# (mm/yr)	t _i [SL ² /T] (yr)	t _v [Δh S/R] (yr)	G
Kamarooka	1	20	0.06	4,500	24	2.45	166	588	3.53
						15.06	166	96	0.57
Billabong	10	10	0.05	52,000	168	3.13	3,704	2,684	0.72
						25	3,704	336	0.09
Popes	0.05	25	0.01	4,250	137	3	396	457	1.15
						24	396	57	0.14
Kyeamba	10	20	0.1	68,000	261	2.63	6,334	9,924	1.57
						21	6,334	1,243	0.20
Brymaroo	2	30	0.02	4,400	51	2.5	17.7	408	23.08
						20	17.7	51	2.88

Recharge is initially 1 mm/yr and changed to the increased rate given in this column at t = 0.

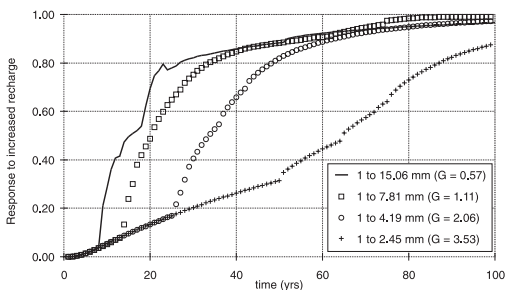


Figure 11. Kamarooka modelled FLOWTUBE groundwater system response to different amounts of recharge. Increase from 1 mm/yr recharge at time=0.

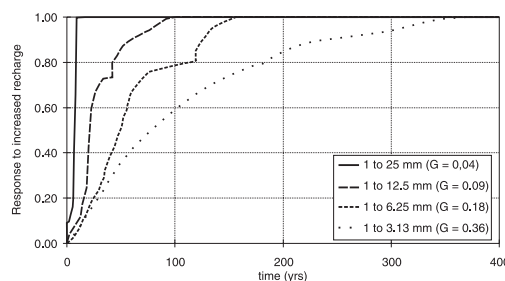


Figure 12. Billabong modelled FLOWTUBE groundwater system response to different amounts of recharge. Increase from 1 mm/yr recharge at time=0.

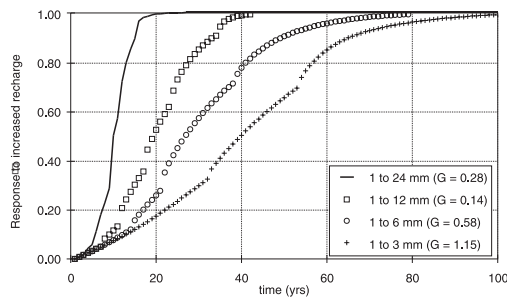


Figure 13. Popes modelled FLOWTUBE groundwater system response to different amounts of recharge. Increase from 1 mm/yr recharge at time=0.

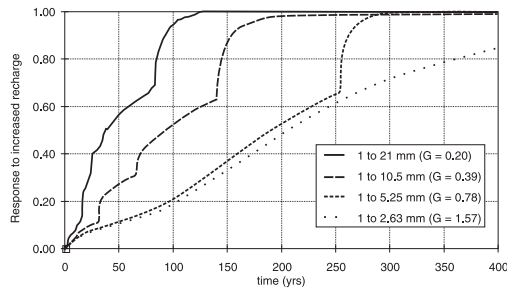


Figure 14. Kyeamba modelled FLOWTUBE groundwater system response to different amounts of recharge. Increase from 1 mm/yr recharge at time=0.

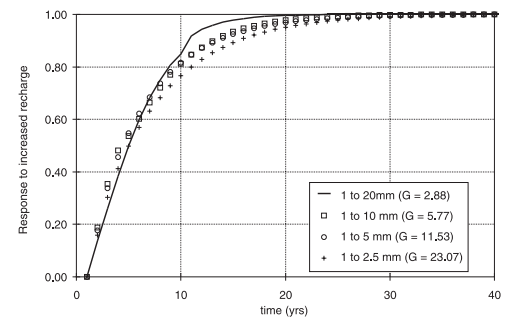


Figure 15. Brymaroo modelled FLOWTUBE groundwater system response to different amounts of recharge. Increase from 1 mm/yr recharge at time=0.

Each of the case studies (Figures 11 to 15) show a similar style of response to that of the idealised modelled system (see Figure 5). The rapid response to large changes in recharge can be seen clearly in the first four case studies as a result of discharge to the surface.

5.3 Groundwater response—overall comparison

This section compares the modelled responses of each case study to increased recharge:

- First, the responses for each case study are shown as figures for two scenarios.
- Second, this modelled time for response is used to calibrate a prediction method using G without modelling.

Two scenarios are shown: (i) response to change from 1 mm/yr to current recharge rates; and (ii) response to change from 1 mm/yr to 12.5% of current rates (referred to as ‘minimum’ rates in the figures).

- The response to a change from equilibrium with a recharge of 1 mm/yr to current recharge rates (ranging between 15–25 mm/yr) is shown in Figure 16.
- The response to a change from equilibrium with a recharge of 1 mm/yr, to a relatively minor increase in recharge rate (12.5% of current recharge rates) is shown in Figure 17.

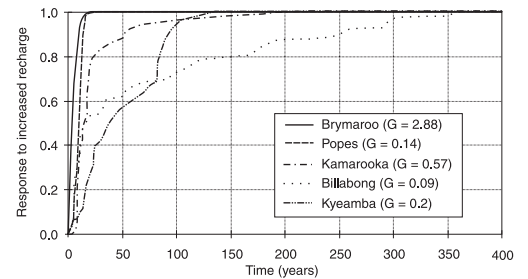


Figure 16. Modelled groundwater system response for each case study to an increase in recharge from equilibrium with 1 mm/yr, to current recharge rates (between 15–25 mm/yr).

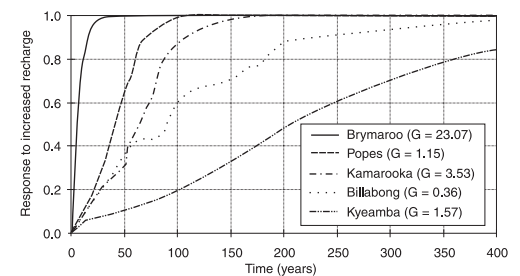


Figure 17. Modelled groundwater system response for each case study to increased recharge from equilibrium at 1 mm/yr, to a new rate of 12.5% of current rates (between 2.5–3.5 mm/yr).

The different response times for the increased recharge for each of the case studies is shown in Table 3. This table shows the time taken for 50% and 90% of a return to equilibrium (this corresponds to 0.5 and 0.9 on the y-axis of Figures 16 and 17). In the absence of measured field data for a range of case study sites, these modelled response times have been used as surrogates for ‘reality’. These modelled response times form the basis for calibrating a non-modelling approach to groundwater response characterisation in the next section of the present report.

TABLE 3. Modelled response times for increase in recharge from 1 mm/yr to a new recharge rate.

Groundwater system	New recharge rate (mm/yr)	G	Time for 50% response (yr)	Time for 90% response (yr)
Kamarooka	2.5	3.53	64	104
	15	0.57	14	51
Billabong	3.1	0.72	88	207
	25	0.09	17	251
Popes	3	1.15	40	68
	24	0.14	10	15
Kyeamba	2.6	1.57	205	458
	21	0.20	36	92
Brymaroo	2.5	23.08	4	15
	20	2.88	4	10

5.4 Predicting case study response

This section of the report describes the formation of a method to generate response curves from simple catchment attributes. A three part method is outlined which uses the results of FLOWTUBE modelling of five case studies. This method is used to generate parameters for a two parameter response function.

Response function

A simple model of response to change was used that weights changes in recharge to changes in discharge, according to a time scale and rate of change (Dawes et al. 2001). The model is a two parameter logistic function and assumes independent annual recharge pulses, that the response is linear and additive, that recharge from year to year is not correlated, and that the discharge response is not hysteretic:

$$D(t) = \frac{1}{1 + \exp\{(t_{half} - t)/t_{slope}\}}, \quad (21)$$

where t_{half} is the time when 50% of the response has occurred, and t_{slope} gives the slope of the central portion of the curve. The t_{slope} parameter has been estimated by assuming that it is directly proportional to t_{half} . For the current examples, t_{slope} has been set as 25% of t_{half} . This is considered a reasonable first guess.

Parameterising the response function

A three step approach was used to predict the response of a groundwater system to an increase in recharge. This involves:

- (i) estimating the *baseline* response time (no surface discharge)
- (ii) scaling this response time using G to predict *estimated* response time (to shorten response due to surface discharge)
- (iii) Correcting this *estimated* response time (using the relationship derived in this report from FLOWTUBE modelling) to obtain a 50% response time (t_{half}) which is used to generate a response function using equation (21).

[e.g. to predict Popes case study response to recharge change from 1 to 24 mm/yr (see **Figure 13**) by: (i) predicting the 1 to 3 mm/yr *baseline* response time; (ii) scaling this down to the shorter time of the 1 to 24 mm/yr response), and (iii) correcting this estimate using the relationship which was derived in this paper's FLOWTUBE modelling of the case studies.]

The first part of this approach is to predict the *baseline* response time (i.e. for a scenario with no surface discharge). From observations of the FLOWTUBE modelling, this time has been estimated as 40% of the time factor related to the lateral draining of an aquifer (t_{H_i} from equation 16).

The second part of this approach is to scale this *baseline* response time using G to predict

the *estimated* response time due to surface discharge occurring. From observations of modelled FLOWTUBE responses, and from the steady state analysis (in §4) a *baseline* response will occur when $G > 4$. When $G < 4$, the *estimated* response time is shorter than this. A linear scalar has been used to reduce the *estimated* baseline response time by $G/4$ for cases where $G < 4$ (e.g. for *baseline* response of 100 years: $G = 10$ gives an *estimated* response of 100 years; $G = 4$ gives 100 years; $G = 2$ gives 50 years, and $G = 0.5$ gives 12.5 years). The *estimated* response time (x-axis in **Figure 18**) is taken as:

$$\begin{aligned}
 &= 0.4 t_H * G/4 \quad (\text{for } G \leq 4), \\
 &= 0.4 t_H \quad (\text{for } G > 4),
 \end{aligned} \tag{22}$$

The third part of this approach is to correct the *estimated* response times using the relationship derived from FLOWTUBE modelling of the five case studies. This relationship for the case studies is shown in **Figure 18**, and provides the t_{half} parameter for the logistic curve (equation 21). The significant finding is that there is high correlation between the *estimated* response and the results for the FLOWTUBE modelling (**Figure 18**). As such, the *estimated* response time has been corrected using equation (23) (trendline from **Figure 18**).

$$t_{half} = 2.107 [\text{estimated response time}]^{0.641}, \tag{23}$$

It was assumed that this relationship will hold more widely, and thus may be used to correct the *estimated* response times for other case studies in a predictive sense without further modelling, with some degree of confidence. Further work on a greater number of case studies is required to strengthen the confidence in a relationship of this type.

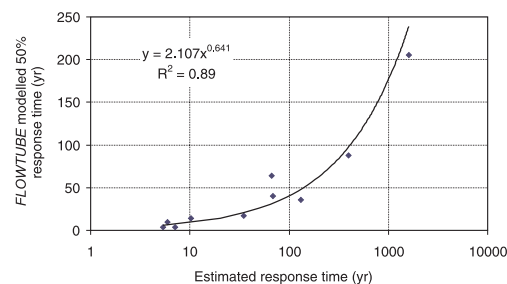


Figure 18. Modelled time for 50% of the response to recharge change, as a function of estimated response time (given in equation 22).

This three step approach was used to generate the following groundwater response functions for the five case studies (**Figures 19 to 23**). These are the same scenarios as for the FLOWTUBE modelling results (see **Figures 11 to 15**). There is good correlation between this approach and the FLOWTUBE modelling results for the case studies.

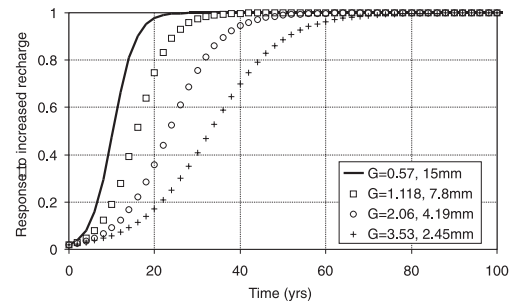


Figure 19. Groundwater system response predicted using the G parameter, for Kamarooka (Victoria), to different amounts of recharge. Recharge increased from 1 mm/yr at time=0.

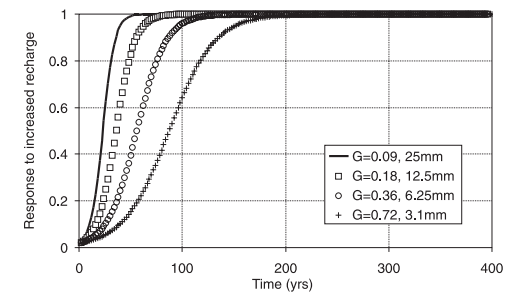


Figure 20. Groundwater system response predicted using the G parameter, for Billabong (New South Wales), to different amounts of recharge. Recharge increased from 1 mm/yr at time=0.

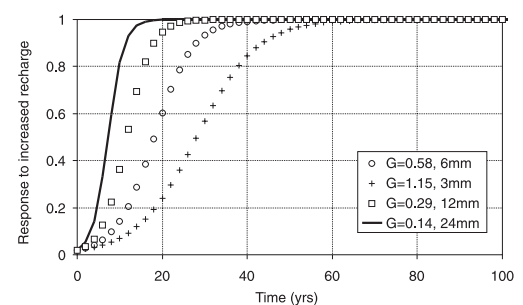


Figure 21. Groundwater system response predicted using the G parameter, for Popes (Eyre Peninsula, South Australia), to different amounts of recharge. Recharge increased from 1 mm/yr at time=0.

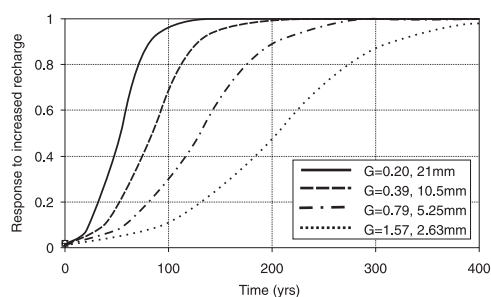


Figure 22. Groundwater system response predicted using the G parameter, for Kyeamba (New South Wales), to different amounts of recharge. Recharge increased from 1 mm/yr at time=0.

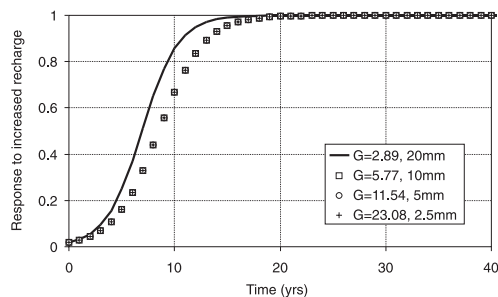


Figure 23. Groundwater system response predicted using the G parameter, for Brymaroo (Queensland), to different amounts of recharge. Recharge increased from 1 mm/yr at time=0.

6. Discussion

Large parts of Australia have a lack of detailed hydrogeological data on which to base future predictions of changes in land and river salinity. There is a need for relatively simple approaches to determine the effect of land use changes on the timing of salinity expansion or remediation at a regional or catchment scale. The simplified approach to characterising groundwater systems presented in this report is a step towards this end.

The simplification of groundwater system responses is a necessary step towards catchment or regional-scale prediction of the effects of land use change on the timing of changes in groundwater discharge. This leads on from the simplified modelling approaches used by groundwater models such as FLOWTUBE, which allow groundwater systems to be conceptualised one-dimensionally. Surface hydrologists have already tackled this type of simplified approach.

The scaling argument approach that was used in this report provides an approach for characterising groundwater systems. It can be seen that the modelled groundwater system response is affected by aquifer properties and the amount of recharge. These properties have been combined through the use of a dimensionless similarity parameter (G) to reduce the complexity of the characterisation. G provides a measure of the ratio of a groundwater system's *ability to drain* compared to its *ability to fill*. What is clear from this study is that while there is a

strong relationship between variations in G and groundwater system behaviour, the influences of *shape* (in plan view) and *slope profile* also exert some effect on groundwater system response to changes in recharge.

The sensitivity of modelled groundwater response to assumptions underlying the FLOWTUBE model is also important. The exact determination of how the maximum surface discharge capacity at a node which is specified as a model input influences the modelled response, particularly with reference to the actual area discharging rather than the discharge volumes. Also, in areas where climatic variability (e.g. episodicity of recharge events) is more significant, the notion of using mean recharge values becomes more tenuous. If the recharge event recurrence interval is similar to the groundwater system response then the approximations will break down. The accuracy of this type of approach is difficult to verify, because of the long time scales involved, and also because of the lack of detailed actual measurements for different groundwater systems. As such, our ability to predict groundwater system response will depend on our knowledge of how actual hydrogeological parameters vary within and between systems.

This report has described the transient response of both generic and real case study groundwater systems to *increased* recharge. The logical next step is to look at how such systems will respond to reforestation or recharge *reduction* strategies (Smitt et al. 2003).

7. Conclusions

The main conclusions from this report are:

- Groundwater system characteristics can be simplified using a dimensionless similarity parameter (G). G is a combination of transmissivity, specific yield, recharge, length and head, and can be visualised as a measure of the ratio of the system's *ability to fill* (t_v) compared to its *ability to drain* (t_d). As such, G gives an indication of the state of balance of a groundwater system.
- A simple three step approach has been developed to generate normalised groundwater system response curves following an increase in recharge:
 - (i) The time to drain (t_d) factor is scaled to give a *baseline* response (i.e. where no surface discharge occurs) to an increase in recharge.
 - (ii) G is then used to scale this *baseline* response. From the case studies, it appears that for $G < 4$, the groundwater response time is less than the *baseline* response (because of surface discharge allowing faster change to a new equilibrium).
 - (iii) This *estimated* response is then calibrated against the FLOWTUBE modelled predictions of the time for 50% of the groundwater response to an increase in recharge (see **Figure 18**). This time is then used in a two-parameter logistic curve (see equation 21) as the t_{half} parameter to generate a response curve over time.

Other conclusions from this report are:

- Analysis of steady-state groundwater systems shows a clear relationship between G and the position of surface discharge within an idealised groundwater system. However, this relationship also varied with the shape (convergence, divergence) and profile (convex, concave) of the groundwater system.
- Analysis of transient groundwater system response to changes in recharge showed a relationship between G and the time from an increase in recharge to the time of surface discharge. Scenario modelling highlighted the effect of system shape and profile on this relationship. The relationship was more affected by convergence than divergence, and more affected by concavity than convexity.

Predictions of groundwater response times are an essential part of predicting likely effects of land use change on stream salinity and salt loads into the future. In the absence of detailed hydrogeological and hydrological data at a regional scale, simple methods are needed. The G parameter provides a tool that can help simplify the investigation of catchment behaviour. It will help improve the prediction of groundwater system responses without the use of process-based models.

8. References

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Integrated catchment management in the Murray–Darling Basin

A process through which people can develop a vision, agree on shared values and behaviours, make informed decisions and act together to manage the natural resources of their catchment: their decisions on the use of land, water and other environmental resources are made by considering the effect of that use on all those resources and on all people within the catchment.

Our values

We agree to work together, and ensure that our behaviour reflects that following values.

Courage

- We will take a visionary approach, provide leadership and be prepared to make difficult decisions.

Inclusiveness

- We will build relationships based on trust and sharing, considering the needs of future generations, and working together in a true partnership.
- We will engage all partners, including Indigenous communities, and ensure that partners have the capacity to be fully engaged.

Commitment

- We will act with passion and decisiveness, taking the long-term view and aiming for stability in decision-making.
- We will take a Basin perspective and a non-partisan approach to Basin management.

Respect and honesty

- We will respect different views, respect each other and acknowledge the reality of each other's situation.
- We will act with integrity, openness and honesty, be fair and credible and share knowledge and information.
- We will use resources equitably and respect the environment.

Flexibility

- We will accept reform where it is needed, be willing to change, and continuously improve our actions through a learning approach.

Practicability

- We will choose practicable, long-term outcomes and select viable solutions to achieve these outcomes.

Mutual obligation

- We will share responsibility and accountability, and act responsibly, with fairness and justice.
- We will support each other through the necessary change.

Our principles

We agree, in a spirit of partnership, to use the following principles to guide our actions.

Integration

- We will manage catchments holistically; that is, decisions on the use of land, water and other environmental resources are made by considering the effect of that use on all those resources and on all people within the catchment.

Accountability

- We will assign responsibilities and accountabilities.
- We will manage resources wisely, being accountable and reporting to our partners.

Transparency

- We will clarify the outcomes sought.
- We will be open about how to achieve outcomes and what is expected from each partner.

Effectiveness

- We will act to achieve agreed outcomes.
- We will learn from our successes and failures and continuously improve our actions.

Efficiency

- We will maximise the benefits and minimise the cost of actions.

Full accounting

- We will take account of the full range of costs and benefits, including economic, environmental, social and off-site costs and benefits.

Informed decision-making

- We will make decisions at the most appropriate scale.
- We will make decisions on the best available information, and continuously improve knowledge.
- We will support the involvement of Indigenous people in decision-making, understanding the value of this involvement and respecting the living knowledge of Indigenous people.

Learning approach

- We will learn from our failures and successes.
- We will learn from each other.

