Reliability of recharge rates estimated from groundwater age with a simplified analytical approach

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Abstract

Groundwater age is often used to estimate groundwater recharge through a simplified analytical approach. This estimated recharge is thought to be representative of the mean recharge between the point of entry and the sampling point. However, given the complexity in actual recharge, whether the mean recharge is reasonable is still unclear. This study examined the validity of the method to estimate long-term average groundwater recharge and the possibility of obtaining reasonable spatial recharge pattern. We first validated our model in producing reasonable age distributions using a constant flux boundary condition. We then generated different flow fields and age patterns by using various spatially-varying flux boundary conditions with different magnitudes and wavelengths. Groundwater recharge was estimated and analyzed afterwards using the method at the spatial scale. We illustrated the main findings with a field example in the end. Our results suggest that we can estimate long-term average groundwater recharge with 10% error in many parts of an aquifer. The size of these areas decreases with the increase in both the amplitude and the wavelength. The chance of obtaining a reasonable groundwater recharge is higher if an age sample is collected from the middle of an aquifer and at downstream areas. Our study also indicates that the method can also be used to estimate local groundwater recharge if age samples are collected close to the water table. However, care must be taken to

determine groundwater age regardless of conditions.

Key words: simplified analytical approach; groundwater age; spatial groundwater recharge

1. Introduction

Groundwater recharge is defined as water reaching water table to replenish an aquifer. It occurs in a number of forms including diffuse recharge, focused recharge and artificial recharge and is an important component of a groundwater water balance (de Vries & Simmers, 2002). Recharge rates are critical for determining sustainable groundwater extraction rates, properly understanding groundwater flow and storage and reducing uncertainty in groundwater numerical models. A variety of methods have been developed to estimate groundwater recharge, such as soil water balance, water table fluctuation and age tracer methods (Allison, Gee, & Tyler, 1994; Healy, 2010; Scanlon, Healy, & Cook, 2002). The age tracer method is often used in recharge estimation because groundwater age usually integrates flow information across large areas and over long periods (Cook & Böhlke, 2000).

The use of age tracers to estimate groundwater recharge needs to rely on a simplified analytical method, introduced by Vogel (1967). The equation is given by

$$R_V = \frac{H\theta}{t} \ln\left(\frac{H}{H-h}\right) \qquad (1)$$

where R_V is the Vogel-based recharge [L T^{-1}], t is the time since recharge at a point in the aquifer [T], θ is the porosity [-], H and h are the aquifer thickness [L] and the vertical distance between the point of sampling and the land surface [L], respectively.

This method is based on several assumptions including horizontal flow, uniform recharge, homogeneous aquifer material and negligible dispersion effect. The relevant conceptualization is shown in Figure 1. Because this method requires very few parameters compared to some other analytical equations (Chesnaux, Molson, & Chapuis, 2005; Chesnaux, Santoni, Garel, & Huneau, 2018), it has been widely used in many different conditions despite assumptions made (Hinkle, Böhlke, Duff, Morgan, & Weick, 2007; Harrington, Cook, & Herczeg, 2002; Hagedorn, El-Kadi, Mair, Whittier, & Ha, 2011; Kozuskanich, Simmons, & Cook, 2014; McMahon, Plummer, Böhlke, Shapiro, & Hinkle, 2011). For example, Hagedorn, El-Kadi, Mair, Whittier, & Ha (2011) used this method to estimate recharge in a fractured aquifer on the Jeju Island by assuming that groundwater flow in fractures and porous media are equivalent. Hinkle, Böhlke, Duff, Morgan, & Weick (2007) estimated large-scale recharge with this method in order to examine distribution of nitrate and ammonium in groundwater.

Compared to the assumption of this analytical method, actual groundwater recharge is known to vary in space because of spatial distributions of controlling factors including climate, soil and vegetation (Cook & Böhlke, 2000; Cook, Walk, & Jolly, 1989; Kim & Jackson, 2012; Keese, Scanlon, & Reedy, 2005; Scanlon et al., 2006; Xie, Crosbie, Simmons, Cook, & Zhang, 2019; Xie, Crosbie, Yang, Wu, & Wang, 2018). It is evident that different spatial patterns in recharge may result in different flow fields which lead to different groundwater age patterns. Hence, groundwater recharge estimated from the Vogel method would differ from location to location. Whether and under what conditions this simplified analytical method still produces representative long-term average estimates is still unclear.

Spatially varying groundwater recharge is one of several important factors in determining groundwater flow fields (Sanford, 2002). Estimating spatial groundwater recharge has been difficult. Therefore, many studies usually use a limited number of estimates to represent large areas (e.g., Xie, Cook, Shanafield, Simmons, & Zheng, 2016; Yang et al., 2019). Groundwater tracers underneath water table result mostly from local recharge and so groundwater age must vary spatially (McMahon, Bohlke, & Carney, 2007). It is likely that the analytical method could also estimate spatial recharge and infer water table behavior by examining groundwater age at shallow parts of aquifers (McMahon, Bohlke, & Carney, 2007; Wood, Cook, & Harrington, 2015). However, as the Vogel method was developed based on several assumptions, whether it can yield reasonable results warrants careful assessment.

This study attempted to examine whether the Vogel method is capable of estimating long-term average groundwater recharge and the possibility of estimating spatially-varying groundwater recharge with such a method. We first established a groundwater flow and age transport model with a constant recharge rate along the top boundary and examined it by comparing groundwater age distribution to that calculated with the analytical method. Afterwards, we changed constant groundwater recharge to different spatially-varying recharge that varies in different sinusoidal patterns. The simulated groundwater age in the model was used to estimate recharge with the analytical method. The estimated recharge was then compared to the actual recharge to shed light on the feasibility of the Vogel method for estimating recharge under spatially changing conditions. A field example was employed in the end to illustrate how our theoretical analysis could assist in the interpretation of real-world data.

2. Methods

2.1 Governing equations

Several numerical experiments were performed to investigate groundwater age distribution and examine the validity of the simple method to estimate groundwater recharge. To simulate groundwater flow and age transport simultaneously, the numerical code HydroGeoSphere (Aquanty Inc., 2018) was selected. HydroGeoSphere uses the 3-D Richards equation to simulate variably saturated groundwater flow. As our system is fully saturated, the equation can be simplified into the follow form:

$$S_s \frac{\partial \psi}{\partial t} = -\nabla \cdot q + Q \qquad (2)$$

Where S_s is the specific storage [L^{-1}], Q is the source and sink [T^{-1}], $\boldsymbol{q}$ is the Darcy flux tensor [$L\ T^{-1}$], ψ is the pressure head [L]. $\boldsymbol{q}$ is given by

$$q = -K \cdot \nabla(\psi + z) \qquad (3)$$

where $\boldsymbol{K}$ is the hydraulic conductivity tensor [$L\ T^{-1}$] and z is the elevation head [L].

Groundwater age transport was simulated with the mean age approach (Goode, 1996). As a groundwater sample contains a large number of water particles, mean age is usually used in analyses. It is reasonable to assume that the mean age of mixed water particles is a volume-weighted average if density is constant, and so the mean age will vary in a similar fashion to the concentration of a conservative solute. Hence, mean age transport can be described by a variant of the advection-dispersion equation. The governing equation is given by

$$\frac{\partial(\phi A)}{\partial t} = -\nabla \cdot A\,q + \nabla \cdot (D \cdot \nabla A) + \phi + Q_A \qquad (4)$$

where A is the mean groundwater age [T], ϕ is the porosity [-], **D** is the hydrodynamic dispersion tensor [L] and Q_A is the source/sink term of the age mass [-]. The first two terms on the right-hand side of the equation describe advective and dispersive transport of age mass, respectively. The third term is age increase at the rate of 1 year per year along flow paths. The last term represents the exchange of age mass with other domains. The reader is referred to Aquanty Inc. (2018) for a detailed description of numerical implementation.

2.2 Model setup

The numerical model employed is rectangular in shape (10,000 m in length and 100 m in thickness) as shown in Figure 1. Kozuskanich, Simmons, & Cook (2014) examined the effect of aquifer heterogeneity on the applicability of the Vogel method with the same model setup but smaller size. The model was used to perform groundwater flow and mean groundwater age transport simulations. For the groundwater flow simulation, a flux boundary condition was applied to the top surface to represent actual groundwater recharge. A constant rate of 100 mm/y was used in this study. A head boundary condition of 100 m was specified to the right-hand side boundary. All the other sides were given no-flow boundary conditions. It should be noted that this model represents an unconfined aquifer with the sloping bottom despite the rectangular shape. For the mean age transport simulation, a mean age of zero was specified at the top boundary where the actual recharge occurred. The model was discretized with a grid size of 2 m vertically and 10 m laterally, resulting in a total of 50,000 elements. A porosity θ of 0.3 and a hydraulic conductivity K of 0.8 m/d were specified to the model. Note that K does not affect modeling results given flux boundary conditions used. For the flow simulation, the model was simulated in steady state. For the age transport simulation, the model was run for 10,000 years. If evident change was observed between the last two time steps, the model was run again for 10,000 years.

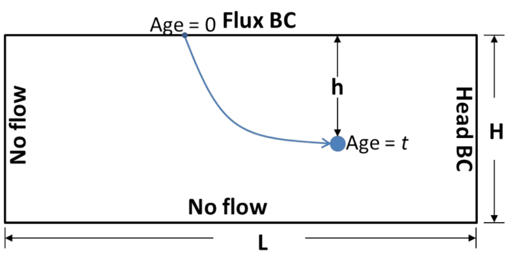

Figure 1 Schematic diagram of the model used in this study. L and H are 10,000 m and 100 m, respectively. A constant flux of 100 mm/y was used at the top boundary and a head of 100 m was specified to the right-hand side boundary. These values were chosen for demonstrative purposes only. Other values could also be used.

2.3 Spatially-varying actual recharge

In order to examine the validity of the Vogel method to estimate groundwater recharge, we generated groundwater flow fields with different spatially-varying actual recharge conditions along the top surface, realized through flux boundary conditions. The spatially-varying actual recharge is given by

$$R_m = A\left(\sin\frac{2\pi}{B}x\right) + C \qquad (5)$$

where R_m is the modelled recharge [L T^{-1}], A, B and C represent the amplitude [L T^{-1}], the wavelength [L] and the mean recharge [L T^{-1}], respectively, x is the distance from the left end of the top surface [L]. R_m is the theoretical recharge as opposed to the estimated recharge with the Vogel method R_V. In order to be consistent with conventional uses, we use millimeters per year for a recharge rate and meters for length.

Two types of variations in the recharge were used, including changes in the amplitude and changes in the wavelength. Four recharge amplitudes were considered including 12.5, 25, 35 and 50 mm/y and six recharge wavelengths were simulated including 500, 1000, 1250, 2000, 3500 and 5000 m. C was constant at 100 mm/y for all the scenarios. Figure 2a and Figure 2b demonstrate how R_m varies with A and B spatially, respectively. Apart from the mean recharge of 100 mm/y, we also examined several different mean values, including 150 mm/y, 50 mm/y. The corresponding amplitudes were varied between 10% and 50% of the mean values, and the wavelengths remained unchanged. A total of 72 scenarios were simulated.

It should be noted that R_m is dependent on several factors including climate, soil, vegetation, topographic relief. Spatial R_m patterns are difficult to quantify precisely. Despite highly idealized, the R_m patterns used in this study are expected to help improve theoretical understanding of using the Vogel method in complex conditions.

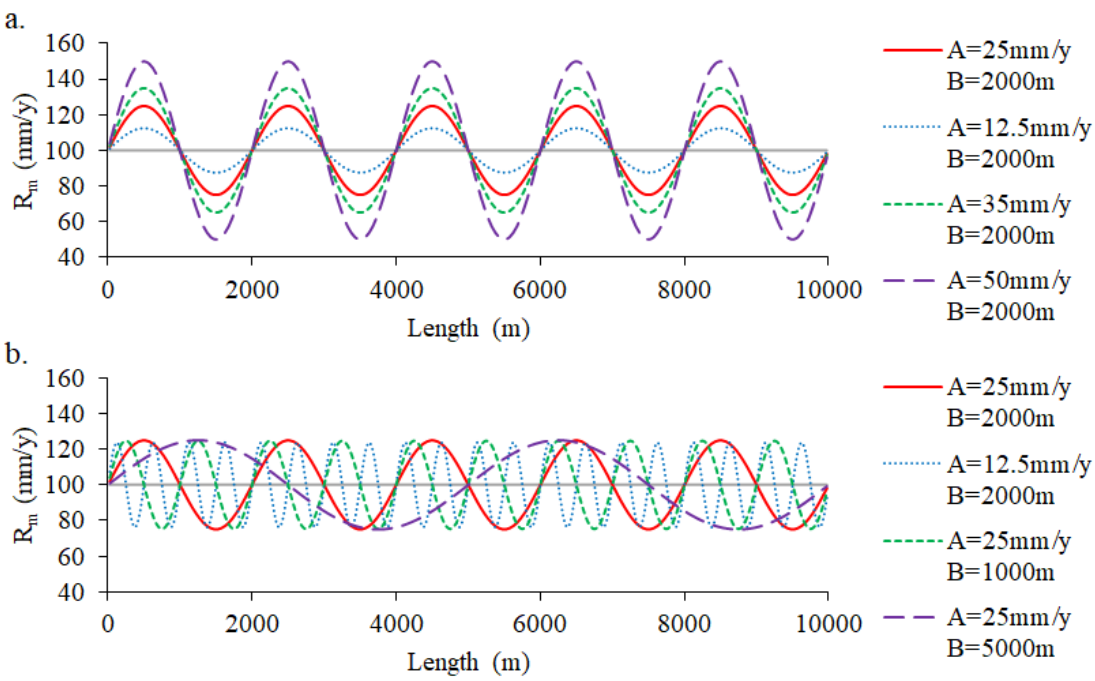

Figure 2 Demonstrative sinusoidal variation in modelled groundwater recharge (R_m) with (a) the change in the amplitude A, and (b) the change in the wavelength B.

3. Results

3.1 Model validation

Model validation was performed by examining the age distribution with constant recharge. The result shows that simulated groundwater age is constant horizontally for most part of the aquifer domain (approximately the range of Z = 20 to Z = 100 m) (Figure 3a). Close to the bottom (Z = 0 to 10 m), the simulated age was slightly greater on the left than that on the right due to bottom boundary effect. Figure 3b shows an excellent match between the simulated and the analytical age profiles at X = 5000 m. It can be seen that under ideal conditions the groundwater age increases with depth exponentially. The comparison suggests that our numerical model closely matches the analytical solution and therefore can be used to simulate more complex groundwater flow and age simulations.

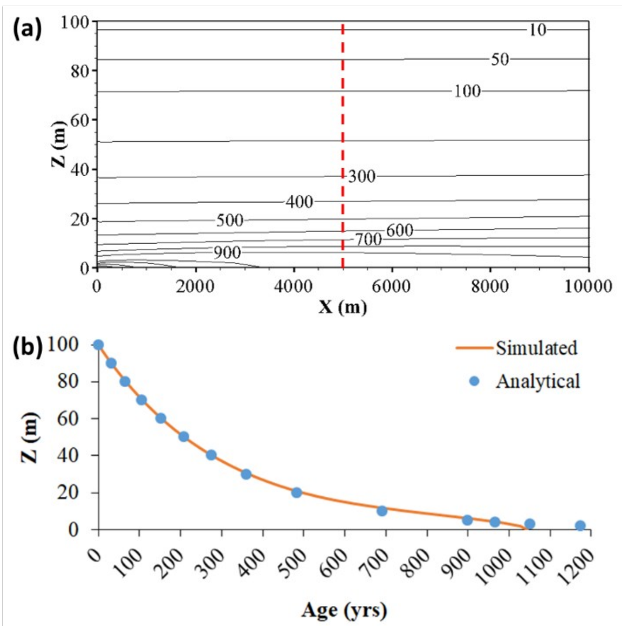

Figure 3 Numerical modeling results: (a) simulated groundwater age distribution with constant actual groundwater recharge at 100 mm/y for the entire top surface; (b) comparison of simulated to analytical groundwater age profiles at 5000 m as indicated with a red dashed line in (a). The analytical groundwater age was calculated by rearranging Equation (1) to obtain *t*.

3.2 Spatial distributions in simulated age and estimated recharge

We first simulated groundwater age with a specific R_m recharge case along the top surface (A = 25 mm/y and B = 2000 m, red solid curves in Figure 2). The spatial variation in the specific R_m causes groundwater age to vary with depth and also with distance further downgradient (Figure 4b). In general, large recharge forces groundwater to flow deeper than small recharge. As a result, areas with larger recharge tend to have younger groundwater at the same depth. The variation in the groundwater age weakens with depth because of the effect of the bottom boundary. This negative correlation between R_m and the groundwater age attenuates with distance downgradient due to the cumulative effect of the spatial recharge.

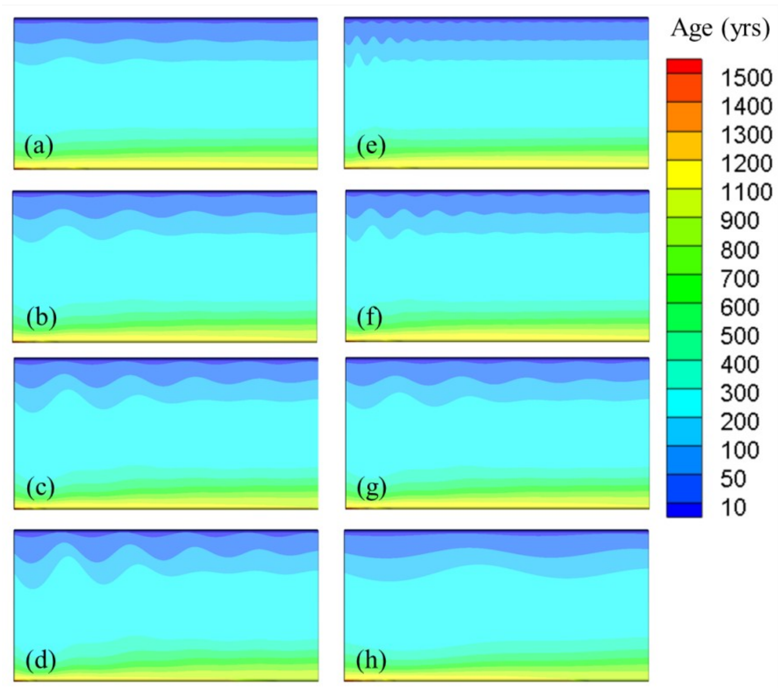

Figure 4 Selected distribution of simulated groundwater age with R_m in sinusoidal patterns shown in Equation 2: (a) – (d): specified R_m parameters with same B at 2000

mm/y, but A at 12.5, 25, 35 and 50 mm/y, respectively; (e) – (h): specified R_m parameters with same A at 25 mm/y, but B at 500, 1000, 2000 and 5000 mm/y, respectively. (g) is the same as (b).

The variability in the groundwater age distribution correlates well with the variability in R_m. As the amplitude of the sinusoidal recharge increases, the groundwater age fluctuates more strongly at the same location on the left side of the aquifer domain (Figure 4a to Figure 4d). As groundwater age is controlled by groundwater hydrodynamics, the age fluctuation weakens laterally (the amplitudes of the age isolines decrease from left to right). The change in the age distribution is more evident with the increase in B (Figure 4e to Figure 4g). Larger wavelength results in weaker variation in the age on the left of the domain but stronger variation on the right.

We then calculated R_V with the analytical method shown in Equation (1). At the lateral direction, the estimated recharge is strongly variable close to the land surface and becomes relatively stable deeper in the aquifer (Figure 5). Most of the estimated recharge falls in the range of 90–110 mm/y. The recharge close to the left boundary is more likely to deviate from the mean recharge (100 mm/y).

The variation in the groundwater recharge amplitude and wavelength strongly affects the groundwater recharge estimation. It can be seen that R_V at a certain depth (e.g., Z = 25 m, close to the bottom) becomes more variable as the amplitude increases. The wavelength of R_V also changes in response to the change in the groundwater wavelength. The probability of overestimating or underestimating recharge rates increases with both the amplitude and the wavelength increase.

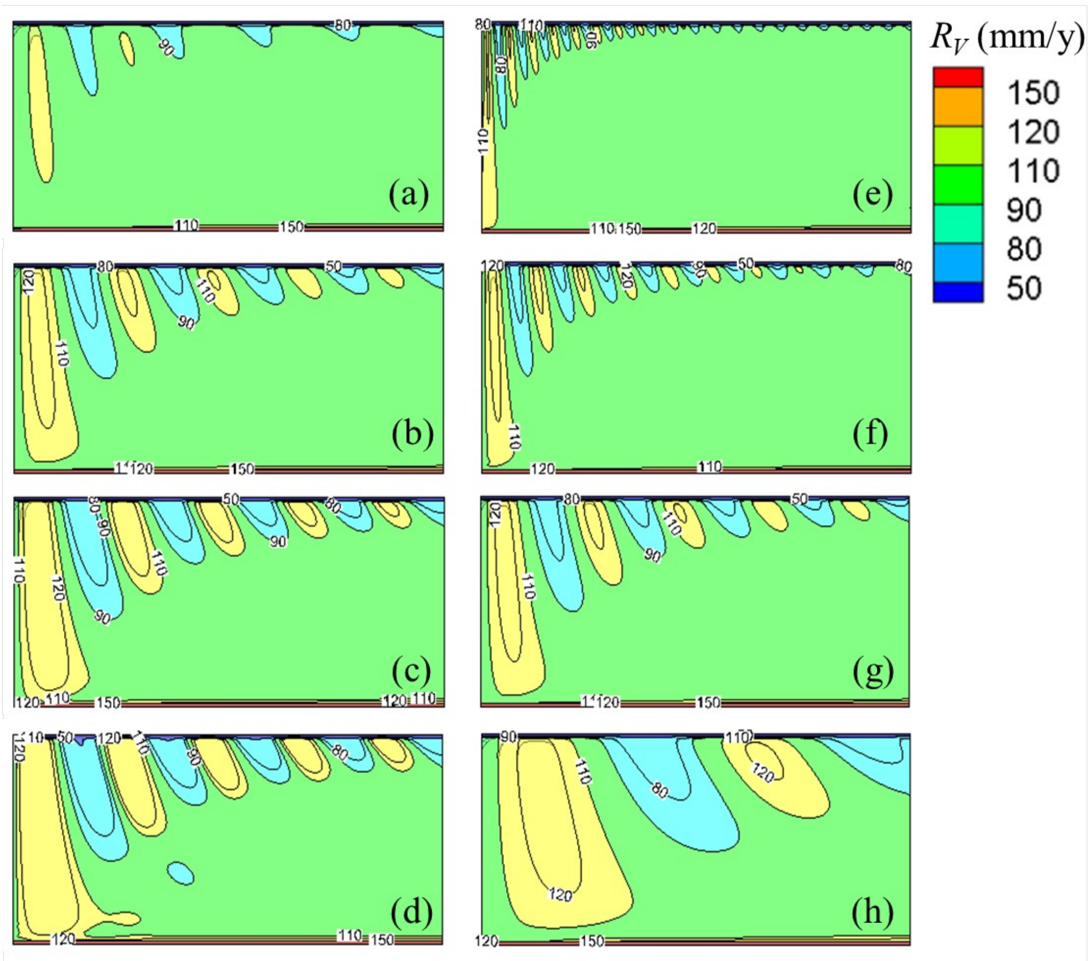

Figure 5 Selected R_V distribution using simulated groundwater age (shown in Figure 4) and Equation 1: (a) – (d): specified R_m parameters with same B at 2000 mm/y, but A at 12.5, 25, 35 and 50 mm/y, respectively; (e) – (h): specified R_m parameters with same A at 25 mm/y, but B at 500, 1000, 2000 and 5000 mm/y, respectively. (g) is the same as (b). It should be emphasized that the R_V distribution indicates potential groundwater recharge for the top surface.

3.3 Estimating long-term average recharge

As shown in Figure 6, R_V varies with depth. At the shallow part of the aquifer, R_V could strongly deviate from the mean R_m. But this R_V would be more representative of local recharge because of limited mixing of local water with regional groundwater passing by. Depending on the location of a sampling well, R_V near the water table could be lower or greater than the mean R_V.

In addition, Figure 6 suggests that R_V would generally be greater than the mean R_m closer to the bottom boundary regardless of locations. This is because the bottom boundary restricted groundwater from flowing deeper down and so horizontal flow component becomes greater closer to the bottom boundary. This boundary effect results in younger groundwater age and therefore larger groundwater recharge. Despite different degrees of variability in R_V at different sampling well locations, All the mean R_V values estimated from these three locations fall in the accepted mean recharge range (103.9, 103.2 and 97.1 mm/y for X = 2500, 5000 and 7500 m, respectively).

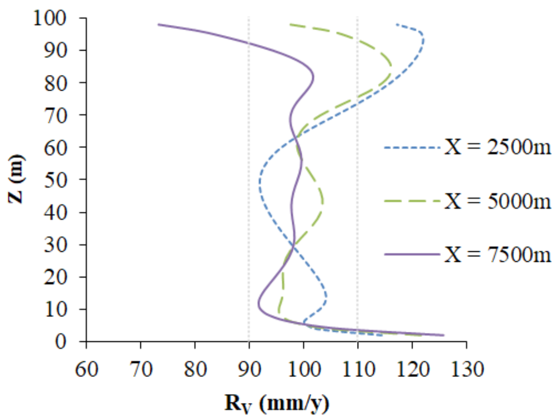

Figure 6 Comparison of estimated recharge for the case with A = 25 mm/y and B = 2000 m at individual sampling well locations. Numbers shown on the legend indicate the distance from the model left boundary. Grey lines show the upper and lower bounds of the acceptable recharge range.

Recharge estimates are known to be uncertain. If 10% error is assumed in the mean recharge in our case, then R_V will be reasonable if it falls in the range of 90–110 mm/y (see grey bounds in Figure 6). We can obtain reasonable recharge estimates from all the sites if sampling is conducted within a reasonable sampling depth far from both the water table and the bottom boundary (e.g., Z = 25–75 m in our case). R_V still fluctuates vertically but all the values are located between the uncertainty bounds of the actual recharge. Of course, R_V variability becomes weaker further downgradient if the sampling activity occurs at downstream locations (Compare the profile of X = 7500 m to the other two profiles in Figure 6).

We can calculate the percentage of area (PA) that may yield acceptable recharge between 90 and 110 mm/y (green area in Figure 5). As seen in Figure 7, as high as 95% of the aquifer domain can provide the recharge in the acceptable range. PA generally decreases with the increase in A and also B. When A is small (12.5 mm/y), the estimated recharge does not change significantly with the increase in B (the lowest PA is 89% for A at 5000 m). However, dramatic change can be observed for the other A values. Only 36% of the aquifer domain can result in the recharge within the reasonable range for the worst scenario.

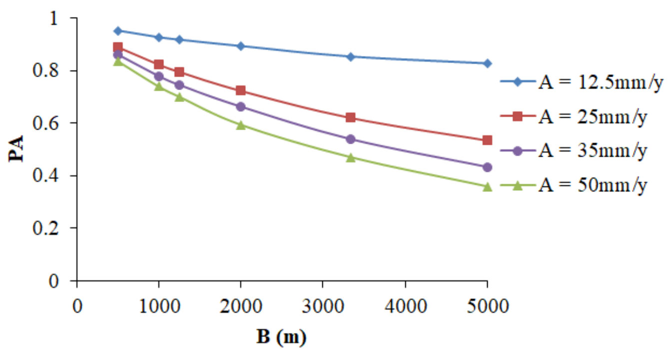

Figure 7 Variation in the percentage of area (PA) with wavelength (B) for different amplitudes (A). Each PA was calculated by deriving the area with mean recharge between 90 and 110 mm/y first and then dividing this area by the domain area. A higher PA indicates a greater chance of obtaining true mean recharge.

Several depths can be sampled to obtain multiple recharge rates to compute mean R_V. The mean R_V in Figure 6 would be 101.0, 102.1 and 98.0 mm/y if we used samples from three depths at Z = 25, 50 and 75 m. We computed the mean R_V for all the other cases. At the location of X = 5000 m (Figure 8a), most mean R_V values are located between 90 and 110 mm/y, except when B is 5000 m. All the mean R_V values are within the acceptable range at the location of X = 7500 m (Figure 8b). In comparison to Figure 7, there is no clear trend in the mean R_V with the change in A or B. This is because groundwater age patterns are highly dependent on the forcing at the top boundary. A fixed sampling site could be located at either low or high values of the boundary forcing. Overall, it is more likely to obtain reasonable mean R_V if we use multiple depths and place a sampling well at a downstream site.

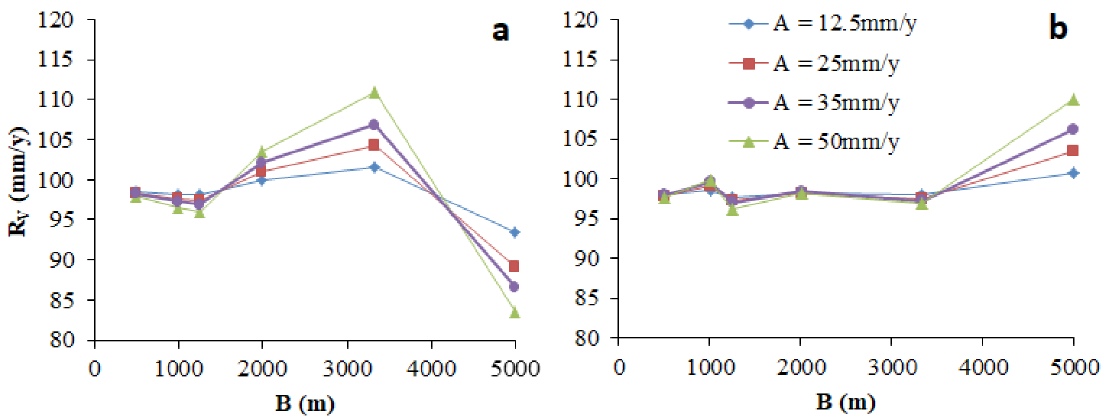

Figure 8 Mean recharge at the depth range of 25–75 m at (a) X = 5000 m; (b) X = 7500 m

3.4 Estimating spatially-varying recharge

Figure 9 compares the recharge estimated from the Vogel method for different depths. As R_m varies in a sinusoidal manner, R_V also varies periodically with distance but its amplitude diminishes with the increase in the number of recharge cycles. It can be seen that the Vogel method slightly underestimate the recharge pattern when using the groundwater age at 98 m from the bottom (2 m beneath the water table) but overall the performance is reasonable in obtaining spatial R_V. When the groundwater age at 25 to 75 m is used, the Vogel method works better for estimating spatial R_V on the left-hand and mean R_V on the right-hand side of the model.

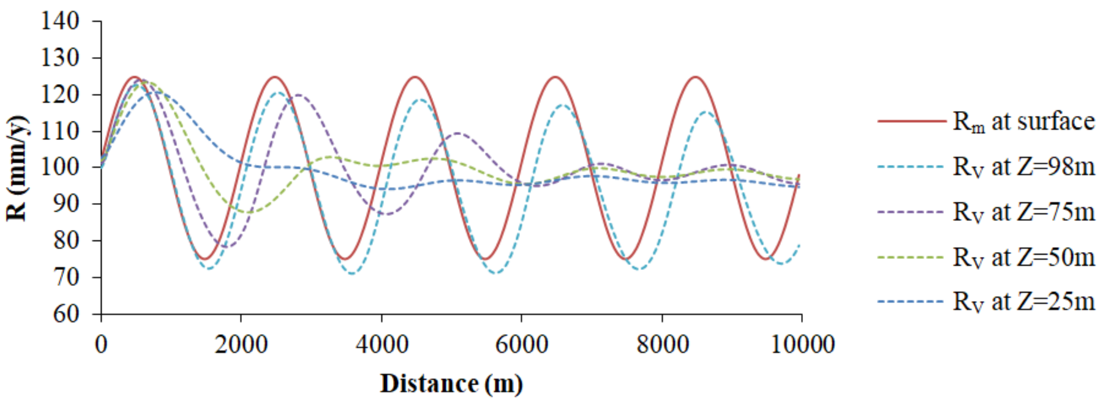

Figure 9 Comparison of estimated recharge (R_V) to modeled recharge (R_m) for the case with A = 25 mm/y and B = 2000 m at different depths. Numbers shown on the legend indicate the distance from the model bottom. Root mean squared error (RMSE) between R_V and R_m is 18.2, 18.1, 17.9 and 8.1 mm/y for 25 m, 50 m, 75 m and 98 m from the bottom, respectively.

The spatial variation in R_V may be estimated reasonably for small magnitudes and large wavelengths, particularly for large wavelengths (B = 5000 m in Figure 10). This condition generally occurs in fluvial plains with less variation in terrain topography. The ability of the method to estimate spatially-varying R_V becomes worse as the variable A increases and B decreases. This is mostly because larger variation in R_m causes stronger hydrodynamic mixing. Hence, it is difficult to estimate spatial R_V in mountainous regions with the Vogel method.

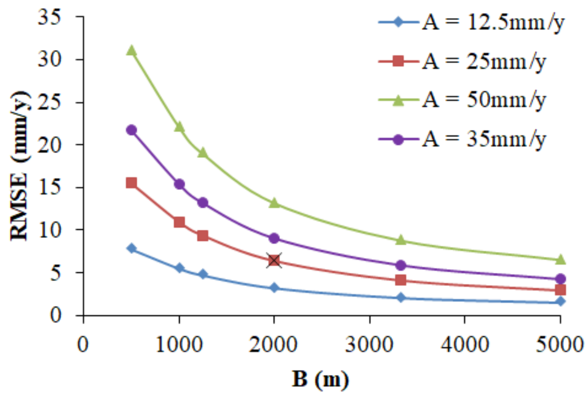

Figure 10 Root mean squared error (RMSE) between spatial R_m and spatial R_V using groundwater age at Z = 98 m (2 m below the water table) under different variability conditions. The black cross represents RMSE between the curves of R_m and R_V at Z = 98m in Figure 9.

It needs to be noted that we also conducted other scenarios with different mean recharge values (150 mm/y and 50 mm/y). The modeling shows similar trends in the changes of age, R_V distributions and RMSE between spatial R_m and spatial R_V presented above due to similar variation in R_m (not shown).

4. Field example

4.1 Field site and data description

Lower Campaspe catchment in southeast Australia was employed to demonstrate the variation in recharge rates (Figure 11). The entire catchment covers an area of 7,949 km^2 and forms part of the Murray-Darling Basin. The southern edge of the catchment is the Great Dividing Range (not shown in the map) and the lower part belongs to the floodplains of the Campaspe and Murray rivers. Soils in this area are generally Sodosols and Vodosols with varying thicknesses according to the Australian Soil Classification system. The aquifers are composed of a shallow unconfined aquifer with interbedded sand and clay and a deep semi-confined aquifer consisting of coarse sand. The water table is usually 10–15 m below the land surface. Long-term annual mean rainfall is around 400 mm/y in the north, whereas long-term annual mean potential evapotranspiration is 1700 mm/y.

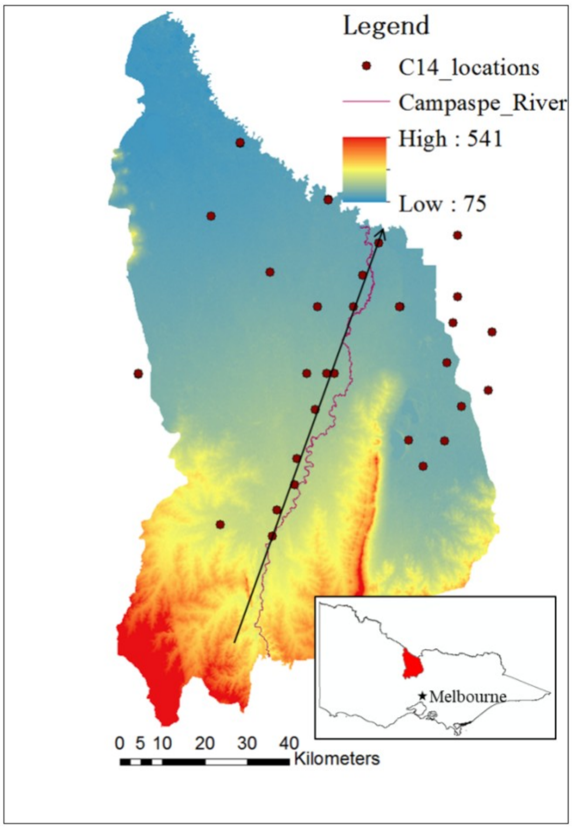

Figure 11 Location of the study area and groundwater ^{14}C sampling sites. The black arrow indicates the cross-section where C-14 data were examined.

Dozens of Carbon-14 (^{14}C) samples were collected over the past years, including those published in previous studies (Cartwright, 2010) and those collected afterwards but not published. These data scattered in the lower Campaspe catchment, mostly along the river or close to the northern boundary. The screen depths of the bores where ^{14}C samples were taken were lower than 20 m below the ground surface and the screen lengths were smaller than 10% of the screen depth. ^{14}C was used to understand groundwater residence times and therefore help conceptualize the groundwater flow system which is critical for groundwater resource management. As shown in Figure 12, some bores have ^{14}C activities greater than 100 pMC. This indicates that the groundwater around these bores was recharged after nuclear weapon tests in the 1950s to 1960s. However, this recharge process occurs usually in the shallow part of the aquifer, mostly likely in areas that have shallow water table. ^{14}C values in most bores are usually lower than 100 pMC. There is a general negative correlation between ^{14}C activity and groundwater depth.

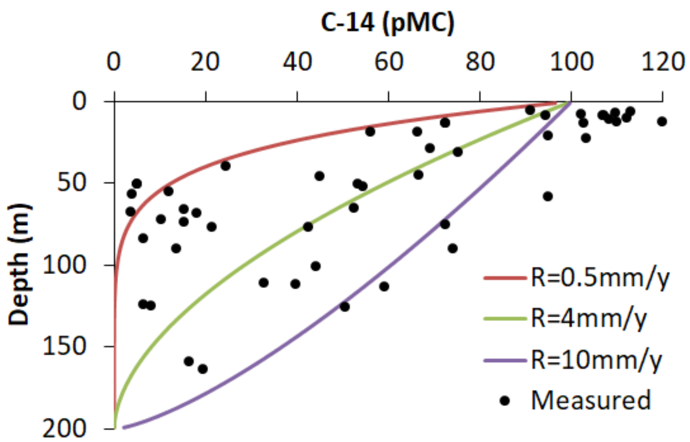

Figure 12 Relationship between ^{14}C and groundwater depth. Black dots are measured ^{14}C, whereas curves show ideal relationship for different recharge rates calculated

with Equation 1 and the ^{14}C decay formula.

4.2 Groundwater recharge estimates

All the data could be used to estimate long-term average recharge over the entire catchment. We first assumed certain recharge rates and back calculated groundwater age with Equation (1). We then inferred ^{14}C activities from the radioactive decay formula where the half life is 5730 years. The theoretical relationship between ^{14}C and depth is shown in Figure 12 for different recharge scenarios. We can see that the average recharge may range from 0.5 mm/y to 10 mm/y. This recharge represents long-term average recharge over the entire area. Of course, some data are still outside of the ^{14}C-depth curves for lower and upper recharge bounds. These data may indicate smaller or larger recharge rates in some parts of the catchment.

Individual ^{14}C data can be used to estimate recharge spatially. It can be seen that recharge rates are generally larger in the south of the catchment but become lower towards the north (Figure 13). According to our theoretical analysis in Section 3, the data in the northern part are more representative of larger-scale recharge rates. Hence, if we have only limited data, it is best to make use of data located in the downgradient area. This finding is consistent with the recharge bounds identified from all the data above.

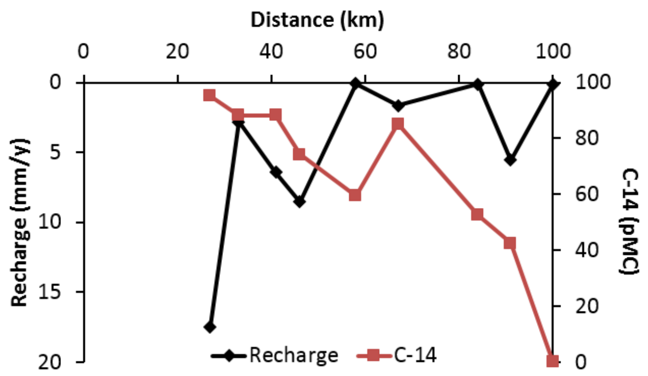

Figure 13 Groundwater ^{14}C data and recharge rates versus distance from the designated starting point along a transect shown in Figure 11.

Our theoretical analysis also indicates that combined use of tracers at different depths could be used to obtain recharge representative of larger areas. It is not very common to have ^{14}C data at different depths in one bore. This is also the case in our field site. However, if we could combine tracer data close to the downstream (e.g., the three sites close to the 100 km), we would obtain the average recharge rate of 1.9 mm/y. This recharge estimate is still within the range identified in Figure 12. However, according to our theoretical analysis, this recharge estimate may be more representative of true recharge rates, although it is still very subjective.

5. Discussion

This study examined the validity of the popular Vogel method to quantify mean groundwater recharge and the possibility of using this method to estimate recharge reliably. Several numerical experiments were performed to simulate groundwater age distribution under different boundary conditions and one field example was provided.

5.1 Estimation of long-term average groundwater recharge

Our study showed that groundwater age determined from certain part of an aquifer can be used to infer long-term average groundwater recharge through the Vogel method (Vogel, 1967) under spatially-varying conditions. This ability of the Vogel method to estimate long-term average recharge is because age tracers are largely driven by advection and dispersion which is related to hydraulic forcing at the top surface (Sanford, 2010). Of course, as actual recharge is usually spatially varying (McMahon, Plummer, Böhlke, Shapiro, & Hinkle, 2011), estimated recharge will be closer to the actual long-term average value if samples are collected from a downgradient monitoring well and at a relatively large depth.

Our study indicates that long-term average groundwater recharge could be estimated reasonably if groundwater age samples are collected properly. However, it is often hardly possible to ascertain whether groundwater wells are placed in proper places, as groundwater age is strongly influenced by groundwater hydrodynamics and dispersion effects (McMahon, Plummer, Böhlke, Shapiro, & Hinkle, 2011). Therefore, any samples could be biased from the actual recharge like many existing studies (e.g., Hinkle, Böhlke, Duff, Morgan, & Weick, 2007; Harrington, Cook, & Herczeg, 2002; Hagedorn, El-Kadi, Mair, Whittier, & Ha, 2011; McMahon, Plummer, Böhlke, Shapiro, & Hinkle, 2011). Hence, combining recharge estimates from multiple depths would yield more reliable long-term average recharge estimates (Harrington, Cook, &

Herczeg, 2002). This is particularly true if our sampling sites are located upgradient where estimated recharge may vary strongly with depth (see Figure 6). In reality, many groundwater wells are determined beforehand and probably with long screens for water supply purposes. These wells could also be utilized for estimating long-term average recharge if the entire screens are located within the unconfined aquifer, because groundwater from different depths will mix completely during sampling.

5.2 Spatial groundwater recharge estimation

Actual groundwater recharge is known to vary in space and time. Many efforts have been made to derive spatial groundwater recharge (e.g., Crosbie, McCallum, Walker, & Chiew, 2010; Harrington, Cook, & Herczeg, 2002; Keese, Scanlon, & Reedy, 2005; Nolan, Baehr, & Kauffman, 2003; Xie, Crosbie, Simmons, Cook, & Zhang, 2019). Most methods make use of unsaturated zones as they are easily accessible and cost is relatively low (Keese, Scanlon, & Reedy, 2005; Nolan, Baehr, & Kauffman, 2003; Xie, Crosbie, Simmons, Cook, & Zhang, 2019). While they reflect on the variation in spatial groundwater recharge, the results are in fact potential groundwater recharge. Whether potential recharge is equal to actual recharge is dependent on a number of factors including thickness of unsaturated zones, degree of soil heterogeneity, and moisture content of underlying soil layers. Our study proposes that the Vogel method can also be used to estimate spatially varying actual recharge directly without the need to consider the factors mentioned above. What is required is to reliably determine groundwater age close to the water table. Although this method may be theoretically better than the soil water balance method, it is much more expensive to obtain a sufficient number of groundwater age samples for the same purpose. Therefore, combinations of field methods including groundwater age method, soil water balance, chloride mass balance and tritium profile method are encouraged (e.g., Healy, 2010; Scanlon, Healy, & Cook, 2002).

This study assumed that groundwater age at the water table is zero. This assumption is appropriate in humid regions where water table is shallow. Infiltrating water can reach the water table within a short time. However, this assumption is not always valid in arid and semiarid regions. In thick arid unsaturated zones it can take hundreds and even up to thousands of years for infiltrating water to reach the water table (Cook, Edmunds, & Gaye, 1992; Love et al., 2013; Wood, Cook, & Harrington, 2015). Therefore, under these conditions when estimating recharge in arid and semiarid regions, groundwater age above the water table must also be known in priori.

5.3 Limitations

Our study suggests that both long-term average and spatially varying groundwater recharge could be estimated with the Vogel method under spatially varying conditions. Our study represents a further step towards better quantifying groundwater recharge with existing methods. We built our study on the simple homogeneous and isotropic aquifer conceptualization to examine the potential impact of complex boundary conditions on groundwater recharge estimation. We are acutely aware that aquifer heterogeneity may significant affect flow fields and therefore recharge estimation as shown by Kozuskanich, Simmons, & Cook (2014). Given that numerous existing studies assume homogeneous settings (e.g., Hinkle, Böhlke, Duff, Morgan, & Weick, 2007; Harrington, Cook, & Herczeg, 2002; Hagedorn, El-Kadi, Mair, Whittier, & Ha, 2011) and our main objective was not on assessing the impact of aquifer heterogeneity, we based our model on those existing studies with homogeneous conceptualization.

In addition, actual groundwater recharge is variant both in space and time. As the Vogel method assumes a steady state setting, this study did not consider temporal changes in recharge. Temporal variation in recharge are best examined through numerical modeling which has been frequently studied (e.g., Xie, Crosbie, Simmons, Cook, & Zhang, 2019). Dispersive mixing is another factor that may contribute to the complexity in estimating recharge with this method, but it is beyond the scope of our study. Greater dispersivity causes stronger mixing in water particles and decay isotopes and likely results in a younger age and a greater recharge rate. This impact of dispersion needs be studied in a future study.

6. Conclusions

This study performed several numerical experiments in order to examine the validity of the simplified analytical method to estimate spatial recharge. We first generated different flow fields and age patterns with different spatially-varying fluxes as model upper boundary conditions. We then estimated groundwater recharge using the analytical method at the spatial scale and examined the differences between analytical and modelled recharge rates. A field example was provided in the end to illustrate our results as much as possible. Several remarks can be made based on this study.

Long-term average groundwater recharge can be estimated reasonably well provided that the age sample is collected from the middle of an aquifer and at downstream areas. Multiple groundwater age measurements can be averaged to improve the precision of the long-term average groundwater recharge. This simple analytical method can also be used to estimate local groundwater recharge if age samples are collected below the water table.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability

Data used in this study can be provided by the corresponding author upon request.

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