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Key Points:
- Freshwater lenses occur in saline aquifers adjacent to gaining reaches of the River Murray
- Buoyancy effects lead to freshwater lenses despite saline groundwater flow towards the river
- Analytical solution defines lens occurrence and controlling factors under idealized conditions

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Terrestrial freshwater lenses in stable riverine settings: Occurrence and controlling factors

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Abstract Rivers in arid and semiarid regions often traverse saline aquifers, creating buoyant freshwater lenses in the adjoining riparian and floodplain zones. The occurrence of freshwater lenses where the river is otherwise gaining saline groundwater appears counterintuitive, given that both hydraulic and density forces act toward the river. In this paper, an analytical solution is presented that defines the extent of a stable, sharp-interface terrestrial freshwater lens (in cross section) in a riverine environment that otherwise contains saline groundwater moving toward the river. The method is analogous to the situation of an island freshwater lens, except in the riverine setting, the saltwater is mobile and the lens is assumed to be stagnant. The solution characterizes the primary controlling factors of riverine freshwater lenses, which are larger for situations involving lower hydraulic conductivities and rates of saltwater discharge to the river. Deeper aquifers, more transmissive riverbeds, and larger freshwater-saltwater density differences produce more extensive lenses. The analytical solution predicts the parameter combinations that preclude the occurrence of freshwater lenses. The utility of the solution as a screening method to predict the occurrence of terrestrial freshwater lenses is demonstrated by application to parameter ranges typical of the South Australian portion of the River Murray, where freshwater lenses occur in only a portion of the neighboring floodplains. Despite assumptions of equilibrium conditions and a sharp freshwater-saltwater interface, the solution for predicting the occurrence of riverine freshwater lenses presented in this study has immediate relevance to the management of floodplains in which freshwater lenses are integral to biophysical conditions.

1. Introduction

Freshwater lenses are most commonly associated with coastal or island settings, where saline groundwater is derived from the sea [e.g., *Underwood et al.*, 1992; *Werner et al.*, 2013]. However, naturally occurring saline groundwater of terrestrial origins is also found in many arid or semiarid regions of the world, such as the Middle East [*Vengosh and Rosenthal*, 1994; *Young et al.*, 2004], Southern Africa [*Adams et al.*, 2001; *Bauer et al.*, 2006], Australia [*Evans*, 1988; *Jolly et al.*, 1998], central South America [*Jayawickreme et al.*, 2011; *Houben et al.*, 2014], and the USA [*James et al.*, 1996; *Pataki et al.*, 2005]. Saline groundwater in terrestrial settings may result from the evapoconcentration of meteoric water, rock dissolution, marine transgressions, or anthropogenic activities [e.g., *Sowayan and Allayla*, 1989; *Knight and Martin*, 1989; *Marie and Vengosh*, 2001].

Saline aquifers that are traversed by rivers carrying freshwater may contain freshwater lenses in the adjoining riparian and floodplain regions [*Bauer et al.*, 2006; *Cartwright et al.*, 2010; *Cendón et al.*, 2010]. In situations of losing rivers, the occurrence of freshwater lenses is the intuitive outcome of groundwater-surface water exchange in the downward direction of the hydraulic gradient. Where freshwater rivers are gaining saline groundwater (i.e., saline water table levels in connected aquifer are higher than the river water level), both the hydraulic and density-driven forces appear prima facie to be acting to suppress near-river freshwater lens formation. However, in the Lower River Murray, South Australia, freshwater lenses observable in airborne electromagnetic (AEM) data are found in otherwise saline aquifers adjacent to rivers, despite gaining river conditions [e.g., *Berens et al.*, 2009; *AWE*, 2012a, 2012b]. The reader is directed to *Spies and Woodgate* [2005] for guidance on the methods and limitations of AEM surveys to assess salinity conditions in Australian settings. Notwithstanding the occurrence of groundwater freshening from overbank flooding and significant fluctuations in river water levels causing temporary losing river conditions, the occurrence of freshwater lenses where the river is otherwise gaining saline groundwater appears counterintuitive.

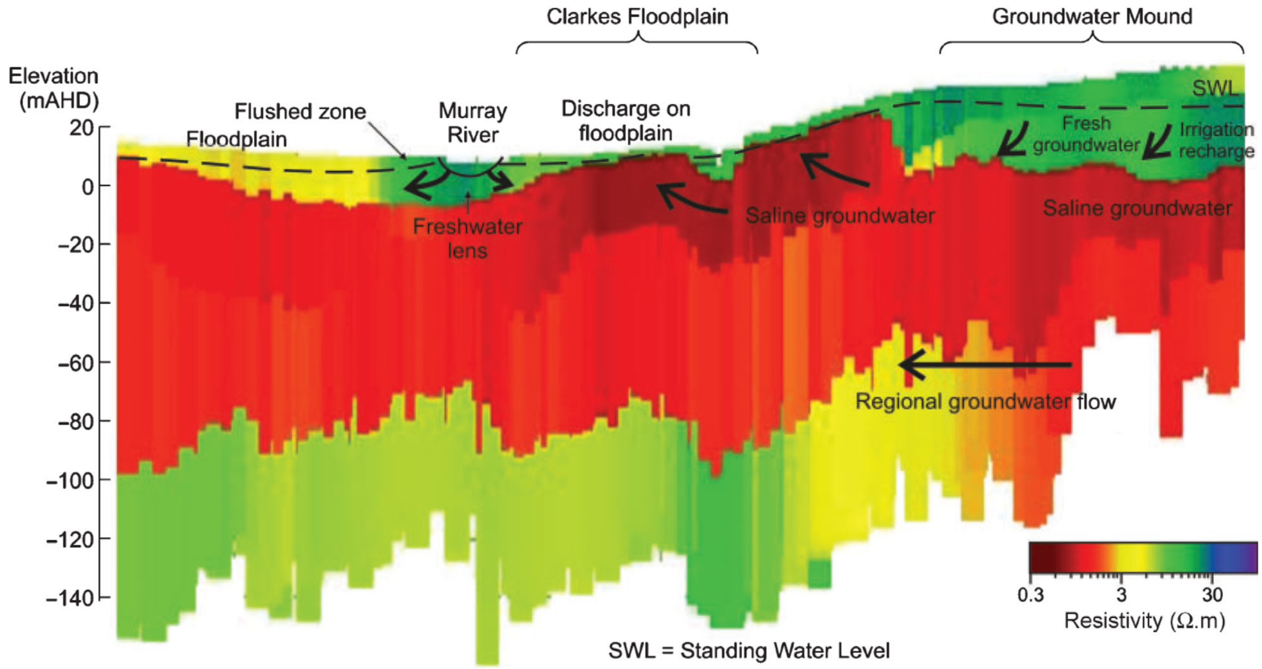

Figure 1. Resistivity-depth section of the Bookpurnong area (approximately 12 km upstream of the township of Loxton) on the Murray River, South Australia. Reproduced from *Viezzoli et al.* [2009], with permission from CSIRO Publishing.

Aside from River Murray freshwater lenses, few other examples of freshwater rivers in saline aquifers exist in the literature. The majority of examples report losing river conditions. For example, *Bauer et al*. [2006] investigate the formation and subsequent depletion of the Shashe River Valley freshwater lens (Botswana), where groundwater salt concentrations exceed 25,000 mg/L. AEM data were used to identify the locations and extents of lenses. *Bauer et al*. [2006] concluded that evapoconcentration of salt was a key process influencing lens characteristics. *Cendón et al*. [2010] investigated the formation of freshwater lenses beneath Cooper Creek floodplain (Australia), where an ephemeral stream contains waterholes that provide windows through thick surficial clays to the underlying sandy aquifer, which otherwise contains a saline water table. Their investigation identified that the lenses are recharged through the base of the waterholes in wet seasons when the stream flows, and subsequently discharge during extended dry seasons to sustain waterholes and dependent local fauna.

The lens-creation mechanisms described by *Bauer et al*. [2006] and *Cendón et al*. [2010] do not explain the occurrence of freshwater lenses adjacent to gaining reaches of the River Murray. Freshwater lenses in losing reaches of the River Murray have been studied by *Cartwright et al*. [2010], *Alaghmand et al*. [2014], and *Alaghmand et al*. [2015]. *Cartwright et al*. [2010] analyzed field measurements from the Nyah-Colignan floodplain to develop a conceptual model explaining the response of the lens to river-stage variation. *Alaghmand et al*. [2014] and *Alaghmand et al*. [2015] used numerical modeling to examine the freshwater lens within Clark's floodplain, where a lens is artificially created in a naturally gaining reach through manipulation of the head gradients by pumping. The modeling results indicated that the lens could not be sustained under gaining river conditions; however, buoyancy effects were neglected.

Presently, there is some evidence that freshwater lenses occur adjacent to gaining rivers connected to saline aquifers, although the controlling factors remain unexplained. Field measurements are presently insufficient to define specific characteristics such as lens geometry and head gradients of freshwater lenses. The reader is directed to articles by *Viezzoli et al*. [2009] and *Munday et al*. [2006] for geophysical evidence of River Murray freshwater lenses, including the cross-sectional AEM results given in Figure 1. While other processes likely contribute to the occurrence of fresh groundwater in these situations, including overbank flooding, transient effects, paleoconditions, and dispersion, there is a need to examine whether freshwater lenses can occur despite saline groundwater flow towards the river. Additionally, the key factors controlling freshwater lenses that occur in these settings need to be articulated. In this paper, we first evaluate the simplest situation of a

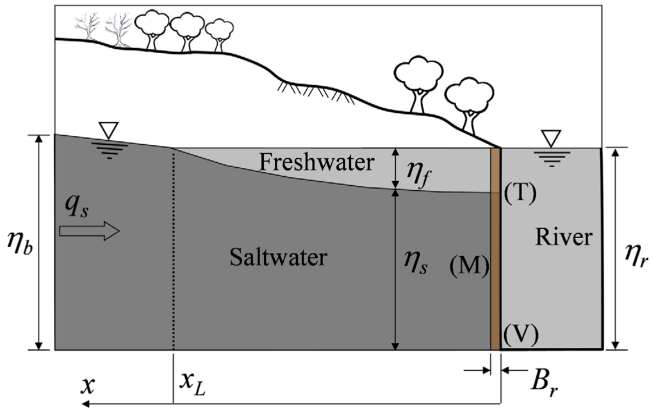

Figure 2. Schematic of a freshwater lens in a stable, unconfined aquifer adjacent to a fully penetrating freshwater river. The river and aquifer are connected through a layer of resistive material (e.g., representing riverbed sediments) of thickness B_r. At the riverbank, (T) represents the base of freshwater, and (M) and (V) are the middle and base of the saltwater region, respectively.

gaining river and an adjacent saline aquifer using the same sorts of assumptions commonly used in studying coastal aquifers, described by *Strack* [1976], *Werner et al.* [2012], and *Morgan and Werner* [2014]. The mathematical solution that is derived from this analysis is then used to elucidate combinations of parameters that control freshwater lens occurrence and extent. The method applied here does not address the question of lens formation (or lens transience of any kind), but rather, we examine whether current conditions allow for freshwater lenses to persist. Finally, the method is compared to evidence from relevant field settings along the River Murray (Australia).

2. Sharp-Interface, Steady State Solution

The conceptual model of a steady state, riverine freshwater lens in an otherwise saline unconfined aquifer is illustrated in Figure 2. The lens, which extends to a distance x_L [L] from the riverbank, is stable (stagnant) and no recharge or evapotranspiration occurs. Hence, the lens water table is horizontal to reflect this stability. No mixing occurs between the lens and underlying saltwater, creating a sharp interface, along which the freshwater and saltwater pressures are equal. Saltwater flows toward and enters the river at a rate q_s [L^2/T] with density ρ_s [M/L^3]. The freshwater lens thickness η_f [L] and saltwater thickness η_s [L] vary with distance x from the riverbank. There is a resistance to groundwater-river interactions due to riverbank material of hydraulic conductivity K_r [L/T] and thickness B_r [L]. The river is treated as fully penetrating to an impermeable basement at η_r [L] below the river water level. However, in a similar manner to the treatment of river-groundwater interaction in MODFLOW [e.g., *Harbaugh*, 2005], and by *Hantush* [1965], K_r and B_r may also represent the contribution to resistance to flow caused by the partial penetration of the river.

The hydraulic head in the saltwater region below the freshwater lens (h_s) is the sum of freshwater and saltwater effects, and is given in equivalent saltwater head terms as:

$$h_s = \eta_s + \frac{\rho_f}{\rho_s}\eta_f \tag{1}$$

Here, both the pressure distributions in the freshwater and saltwater bodies are assumed hydrostatic. The flow of saltwater (through a unit-width cross-section) below the freshwater lens follows Darcy's Law:

$$q_s = -K\eta_s \frac{dh_s}{dx} \tag{2}$$

Substituting equation (1) into equation (2), and recognizing that $\eta_f = \eta_r - \eta_s$ produces:

$$q_s = -K\eta_s \left(1 - \frac{\rho_f}{\rho_s}\right)\left(\frac{d\eta_s}{dx}\right) \quad (0 \le x \le x_L) \tag{3}$$

Integrating (3) produces the following definite integral for two distances (x_1 and x_2, with corresponding saltwater thicknesses $\eta_{s,1}$ and $\eta_{s,2}$) from the riverbank:

$$q_s(x_2 - x_1) = -K\left(1 - \frac{\rho_f}{\rho_s}\right)\left(\frac{\eta_{s,2}^2}{2} - \frac{\eta_{s,1}^2}{2}\right) \quad (0 \le x \le x_L) \tag{4}$$

The head difference across the resistive material at the riverbank occurs partly because of the density difference between river water and saltwater in the aquifer. Note that here, we presume that the river contains freshwater across its entire depth, whereas in reality, pockets of saltwater likely occur within the lower domain of the river. Flow variability in the river is likely to disrupt salinity stratification in the river, and in any case, attempting to define the depth of saltwater in a flowing river is not possible using the current analysis, so we adopt the simplifying assumption of an entirely freshwater river. We account for the river-aquifer density difference by considering the head in the river in terms of saltwater density. The resulting head difference drives groundwater-surface water exchange fluxes (according to Darcy's Law), and is zero in the freshwater part (i.e., in accordance with the lack of freshwater flow) and increases linearly with depth in the saltwater region (due to the density difference between fresh river water and saline groundwater). That is, the head drop across the resistive material is 0 m at (T), has a maximum value at (V), and has an average value for the saltwater region at (M) (see Figure 2). The linear pressure distribution allows us to use the head difference across the resistive layer at (M) (Figure 2) in applying Darcy's Law to determine the saltwater discharge. The head drop across the resistance layer at (M), in saltwater head terms, is:

$$h_{s,M}-h_{f,M}=\frac{\eta_{sr}}{2}\left(1-\frac{\rho_f}{\rho_s}\right) \tag{5}$$

Here, $h_{s,M}$ is the saltwater head at (M) to the left of the resistive layer, $h_{f,M}$ is the saltwater head at (M) to the right of the resistive layer (i.e., in the river), and η_{sr} is the saltwater thickness adjacent to the river (see Figure 2). Applying (5) to Darcy's Law across the resistive layer, and rearranging in terms of η_{sr}, we obtain:

$$\eta_{sr}=\sqrt{-\frac{2B_r q_s}{K_r}\left(\frac{\rho_s}{\rho_s-\rho_f}\right)} \tag{6}$$

If the extent of the freshwater lens is known, the saltwater discharge to the river can be obtained by substituting equation (6) into equation (4), and recognizing that at $x=x_L$, $\eta_{s,2}=\eta_r$, producing:

$$q_s=-\frac{K\left(1-\frac{\rho_f}{\rho_s}\right)\frac{\eta_r^2}{2}}{\left(x_L+\frac{KB_r}{K_r}\right)} \tag{7}$$

If a head (and therefore saltwater thickness η_b at some distance x_b, see Figure 2) inland of the freshwater lens is known rather than knowledge of x_L (as described above), then application of Darcy's Law for $x>x_L$ in combination with equation (7) gives rise to:

$$q_s=\frac{K\left(\frac{\rho_f}{\rho_s}\frac{\eta_r^2}{2}-\frac{\eta_b^2}{2}\right)}{\left(x_b+\frac{KB_r}{K_r}\right)} \tag{8}$$

Equation (7) can be used to determine the saltwater discharge to the river if the extent of the freshwater lens x_L is known whereas equation (8) is applied using a known water level in the saltwater region beyond the extent of the lens. Then, the thicknesses of saltwater (η_{sr}) and freshwater (η_{fr}) at the river can be calculated using equation (6) and recognizing that $\eta_{fr}=\eta_r-\eta_{sr}$. The lens extent x_L can be obtained by a rearranged form of equation (7), using q_s from (8), and the general lens shape is obtained from a rearranged form of equation (4).

3. Example Application and Controlling Factors

The analytical solution provided above is applied to field examples of terrestrial freshwater lenses in riverine environments, using parameters applicable to the Lower River Murray (South Australia) and its floodplain aquifers. The river traverses a number of saline aquifers within South Australia, where it is known to be receiving saline groundwater discharge in numerous places [*Allison et al*., 1990; *Leaney et al*., 2003; *Burnell et al*., 2013]. Saline groundwater in the Murray basin appears to be from sea spray and evapoconcentration over the past 500,000 years, leading to salinity levels that can range up to 500,000 μS/cm [*Murray-Darling Basin Commission*, 1999]. Intuitively, the source of saltwater is not linked to the origins of freshwater lenses, and rather, sources of freshwater lenses remain largely unclear. A base case is adopted that represents the

Table 1. Parameter Ranges Typical of Conditions in the River Murray (South Australia) and Adjoining Aquifers

Parameter	Base Case	Range
Aquifer hydraulic conductivity (K) of the Monoman sands formation	20 m/d	6–30 m/d
Depth to base of aquifer below river water level (η_r)	26 m	10–46 m
Freshwater total dissolved solids (C_f)	350 mg/L	
Freshwater density (ρ_f)	1000 kg/m^3	
Saltwater total dissolved solids (C_s)	53,000 mg/L	20,000–60,000 mg/L
Saltwater density (ρ_s)	1037 kg/m^3	1012–1042 kg/m^3
Conductance of resistive layer (K_r/B_r)	0.01 d^{-1}	0.001–20 d^{-1}
Driving head (Δh), defined as the boundary saltwater level (η_b) relative to river water level (η_r)	1 m	0–6.0 m
Distance to boundary saltwater level (x_b)	6000 m	

Murtho floodplain, adjacent to the Lower River Murray near Renmark (South Australia). Due to the presence of weirs, there is little variation in river water levels in this area. Electromagnetic surveys of the bed of the River Murray and longitudinal river salinity variations indicate that the river is gaining saline groundwater in this reach [*AWE*, 2012a]. Table 1 lists base case parameters, as used by *Woods et al*. [2014] in their investigation of salt fluxes from groundwater to the River Murray and Murtho floodplain. Table 1 also contains parameter ranges that represent a wider variety of conditions in other South Australian River Murray floodplain settings, based on field and modeling investigations by *Jarwal et al*. [1996], *Jolly et al*. [1998], *Doble et al*. [2006], *Banks et al*. [2009], and *Alaghmand et al*. [2014].

The resulting base case freshwater lens obtained from the analytical solution is shown in Figure 3. According to equations (6) to (8), q_s is -0.096 m^2/d, x_L is 502 m, and η_{fr} is 2.8 m. The freshwater lens extent is in broad agreement with the AEM survey of the Murtho region by *AWE* [2012b] that shows groundwater of distinctly lower salinity at distances of up to 400 m from the river, notwithstanding the inherent uncertainty of AEM interpretations of groundwater salinity [*Spies and Woodgate*, 2005]. Indeed, the AEM results of Figure 1 show freshwater below the river that is not expected, at least intuitively, if the river is gaining. This highlights that there is insufficient knowledge of freshwater lenses in the River Murray system to accurately compare AEM results with the predictions of the current methodology.

The primary factors controlling the extent of a stable freshwater lens in a saline aquifer-fresh riverine setting can be assessed using the analytical solution provided above, albeit under simplified conditions. This is achieved through sensitivity analysis, involving the modification of each of the Table 1 parameters (holding other parameters at Table 1 values) and recalculation of freshwater lens extent. The results are illustrated in Figure 4.

Figure 4 identifies important relationships between the problem parameters and x_L. For example, increasing values of K, $|q_s|$, ρ_f/ρ_s, and Δh produce decreasing freshwater lens extents, whereas higher η_r and K_r/B_r values result in more extensive lenses. The linearity of relationships is variable. Only the K-x_L relationship is approximately linear, while the K_r/B_r-x_L relationship exhibits highly nonlinear, threshold behavior.

A noteworthy condition in Figure 4 is the situation of no freshwater lens, i.e., where sensitivity functions identify parameter values causing $x_L = 0$. Values of $x_L < 0$ in Figure 4 are nonphysical. The conditions that preclude a freshwater lens can be obtained by modifying equations (1)–(8). The resulting equations and the associated parameter values (using otherwise base case parameters) that allow a freshwater lens to develop are listed in Table 2.

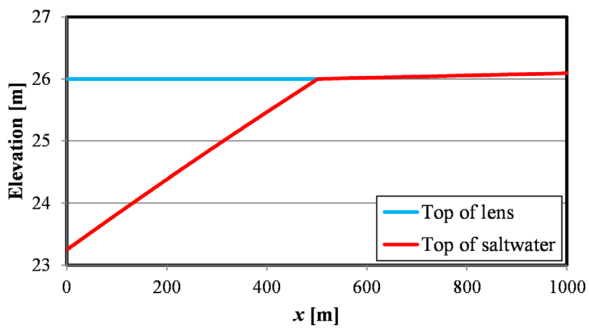

Figure 3. Freshwater and saltwater elevations in cross section, obtained from applying Table 1 base case parameters to equations (1)–(8).

Table 2 equations are applied to discrete locations along the River Murray to determine the validity of the solution in predicting the occurrence and extent of a freshwater lens, giving due consideration to the assumptions of steady state, sharp-interface conditions. For example, at Pike floodplain,

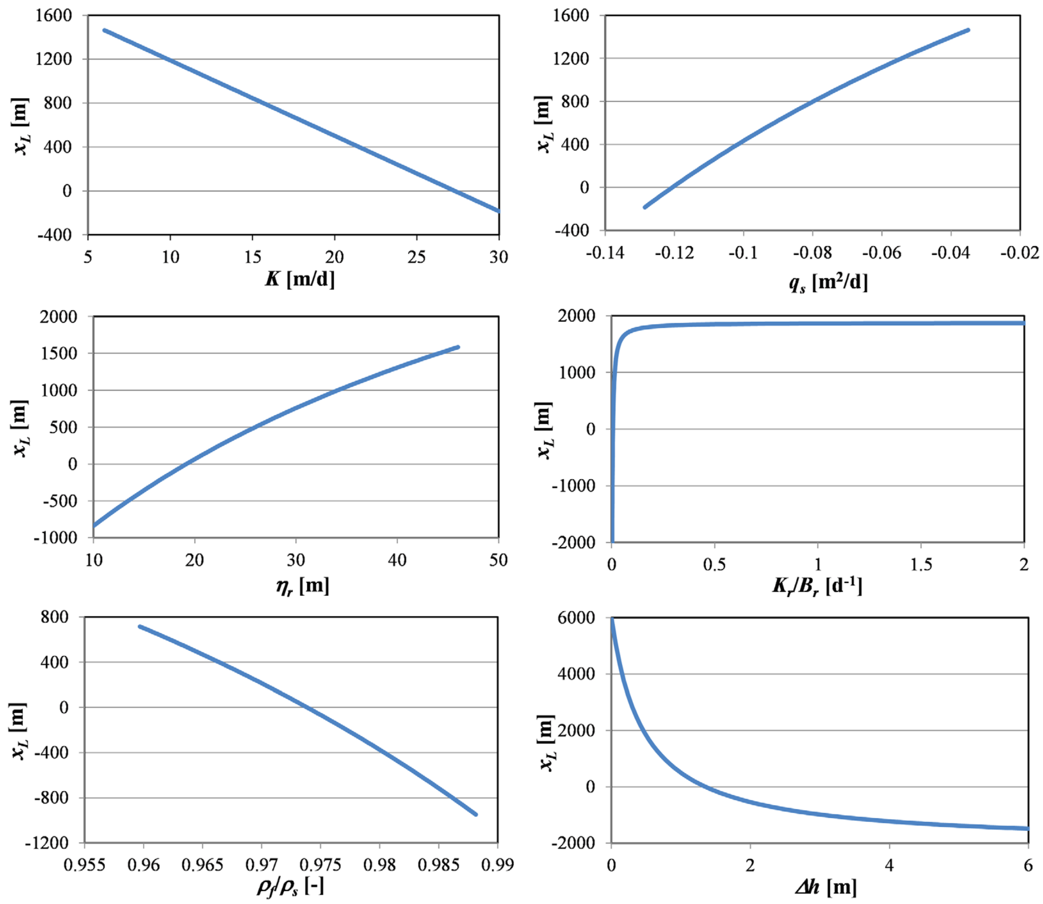

Figure 4. Sensitivity of x_L to the primary controlling factors, using base case parameters as given in Table 1. Δh is the difference between the boundary saltwater level (η_b) and the river water level (η_r).

the parameter combination of (K, η_r, Δh, x_b, ρ_f/ρ_s, K_r/B_r) equal to (16 m/d, 29.2 m, 0.2 m, 1000 m, 0.97, 0.01 d^{-1}), obtained from *AWE* [2012c], gives rise to the following estimates of (q_s, x_L, η_{fr}) equal to (−0.11 m^2/d, 166 m, 1.4 m). AEM surveys of the floodplain by *Fitzpatrick et al.* [2007] indicate groundwater of reduced salinity to a distance of 100 m, in general agreement with the analytical solution. At Katarapko floodplain, the parameter set (K, η_r, Δh, x_b, ρ_f/ρ_s, K_r/B_r) equal to (16 m/d, 29.2 m, 0.3 m, 1200 m, 0.97, 0.01 d^{-1}) given by *AWE* [2012c] leads to lens characteristics of (q_s, x_L, η_{fr}) equal to (−0.12 m^2/d, 38 m, 0.34 m). In this case, AEM data do not detect a significant lens adjacent to the riverbank.

Jolly et al. [1998] used the parameters (K, η_r, Δh, x_b, ρ_f/ρ_s, K_r/B_r) equal to (16 m/d, 43 m, 3.2 m, 1000 m, 0.97, 0.06 d^{-1}) in calibrating a numerical model of Chowilla floodplain. The analytical solution predicts no

Table 2. Parameter Limits for the Occurrence of a Freshwater Lens, Using Table 1 Base Case Values

Parameter Limit	Limit Type	Equation	Limiting Value
$\lvert q_s \rvert$	Upper limit	$q_s=-\left(1-\frac{\rho_f}{\rho_s}\right)\frac{\eta_r^2}{2}\frac{K_r}{B_r}$	0.12 m^2/d
K	Upper limit	$K=\frac{K_r x_b \eta_r^2}{B_r}\frac{\left(1-\frac{\rho_f}{\rho_s}\right)}{\left(\eta_b^2-\eta_r^2\right)}$	27 m/d
η_r	Lower limit	$\eta_r^2\left(\frac{K_r}{B_r}-\frac{K_r}{B_r}\frac{\rho_f}{\rho_s}\right)-\frac{K}{x_b}2\eta_r\Delta h-\frac{K}{x_b}\Delta h^2=0$	19 m
$\eta_b-\eta_r$	Upper limit	$\frac{K}{x_b}\Delta h^2+\frac{K}{x_b}2\eta_r\Delta h-\eta_r^2\left(\frac{K_r}{B_r}-\frac{K_r}{B_r}\frac{\rho_f}{\rho_s}\right)=0$	1.4 m
ρ_f/ρ_s	Upper limit	$\frac{\rho_f}{\rho_s}=1-\frac{KB_r}{x_b K_r \eta_r^2}\left(\eta_b^2-\eta_r^2\right)$	0.97
K_r/B_r	Lower limit	$\frac{K_r}{B_r}=\frac{K}{x_b\eta_r^2}\frac{\left(\eta_b^2-\eta_r^2\right)}{\left(1-\frac{\rho_f}{\rho_s}\right)}$	0.0073 d^{-1}

freshwater lens for these conditions, and the AEM data provided by *Munday et al*. [2007] for this area finds no appreciable freshwater lens.

4. Discussion

The results of this study demonstrate that a stable freshwater lens with a horizontal water table can persist adjacent to a fresh river, despite saline groundwater flow toward the river. While this seems counterintuitive at first, given that both density and hydraulic forces are toward the river, a simple explanation is possible to summarize the physics of the problem. If one considers a hydrostatic column of saline groundwater, of height slightly less than the water level of an adjoining river, then the hydraulic force is away from the river based on the water table elevation relative to the river, but the hydraulic force may be toward the river at the base of the aquifer, depending on the saltwater density, the depth of the aquifer, and the water table height. That is, Bernoulli's equation indicates that the river may be both losing freshwater and gaining saltwater simultaneously. In our case, the freshwater body is stagnant, but the thought experiment summarizes the physics nonetheless.

The analytical solution developed in this study is based on comparable assumptions and conditions to seawater intrusion situations, except the saltwater is mobile in the terrestrial case whereas the freshwater is moving in coastal aquifer settings. Given the similarities in the analysis of terrestrial and coastal lenses, it is unsurprising that there are corresponding consequences of the simplifying assumptions. For example, sharp-interface approaches to seawater intrusion overestimate the extent of the saltwater wedge [*Volker and Rushton*, 1982]. In our case, the freshwater lens is likely to be overestimated because circulation within the freshwater lens and accompanying head losses that normally accompany dispersion processes are neglected (i.e., the lens is assumed stagnant). Also, the solution presented here does not account for the dispersive interface between freshwater and saltwater, transient effects, heterogeneities, and other aspects that may bear significant influence over the lens characteristics.

In a similar manner to coastal settings, the landward boundary condition will modify how the lens responds to changes in the river water level. This is analogous to the investigation of sea-level rise by *Werner and Simmons* [2009] and *Werner et al*. [2012]. Based on the findings of these studies, it is expected that greater changes in the terrestrial lens will occur under constant-head rather than constant flux aquifer boundary conditions, when the river water level changes. The sensitivity of the lens to various controlling parameters, illustrated in Figure 4, shows trends that can be compared to those related to seawater intrusion. For example, *Werner and Simmons* [2009] showed that deeper coastal aquifers have more extensive seawater wedges, while deeper riverine aquifers host more extensive terrestrial freshwater lenses. In island settings, the depth of the aquifer typically has no bearing on the extent of the freshwater lens [*Morgan and Werner*, 2014], at least under flux-controlled conditions. Thus, terrestrial freshwater lenses are expected to display different behavior in response to stress changes compared to coastal lenses.

The analytical solution given here is expected to serve as a valuable and informative screening tool for the existence of freshwater lenses under natural conditions, at least where the hydrology is somewhat stable (e.g., in the absence of variable pumping and episodic flooding) and where the lens is not expected to vary significantly in time. In particular, the method will have immediate relevance to regions where freshwater lenses are modified to optimize their benefit to floodplain vegetation [*Berens et al*., 2009, *Alaghmand et al*., 2015]. Remediation strategies for salinized floodplains are currently being trialed along reaches of the Lower River Murray with a focus on enhancing or preventing the degradation of existing freshwater lenses [*Alaghmand et al*., 2014, 2015], and yet no quantitative analysis has yet been undertaken to investigate lens controls.

In our applications, predictions were produced that were largely consistent with field observations, albeit at the present time, there is a considerable lack of field examples of freshwater lenses in terrestrial, riverine settings, and therefore, application of the method was restricted to only a handful of cases. Another significant barrier to applying the method is the need to consider factors that are not included in the mathematics. Further investigation is warranted of the vulnerability of the lens to changes in the forces that control lens extent, and that relate to transient processes [e.g., *Lamontagne et al*., 2005] and factors that are not considered here, such as parameter heterogeneities, flooding, evaporation, vegetation, recharge, river salinity variability, and unsaturated zone effects. The current analysis neglects the factors leading to the original causation of the lens, which may result from river variations and/or overbank flooding. The lenses along the River Murray are likely to have ages in the order of years to decades, given the frequency of high flow events, although there is a lack of age dating of the lenses to confirm their origins. Additionally, the cross-sectional nature of the solution precludes the analysis of processes occurring in three dimensions, such as radial pumping and variability in the direction parallel to the river.

5. Conclusions

The occurrence of freshwater lenses in situations where saline groundwater flows toward gaining rivers, which otherwise contain freshwater, initially appears unlikely, and few examples of these have been observed in field situations. However, unexpected freshwater lenses, indicated by airborne electromagnetic (AEM) surveys, have been found adjacent to a handful of gaining reaches along the River Murray (Australia). To examine whether these lenses are plausibly sourced from the river, despite hydraulic and density forces in the aquifer acting toward the river, an analytical solution has been developed based on similar assumptions used to study coastal aquifers and seawater intrusion. The solution adopts steady state, sharp-interface assumptions and thereby considers the simplest conditions of a stable (stagnant) freshwater lens devoid of dispersive effects and overbank flooding.

The analytical solution demonstrates that freshwater lenses are indeed plausible in gaining river reaches adjacent to saline aquifers, due to the buoyancy forces that accompany the density-dependent flow field in the aquifer. Using base case parameters typical of the Lower River Murray, we demonstrate that under certain conditions, freshwater lenses of several hundred meters in width laterally from the river are likely to be found in the adjoining floodplains. Larger freshwater lenses occur where the aquifer hydraulic conductivity is lower, the magnitude of saltwater flow towards river is lower, the resistance to flow through the riverbed is lower, the head difference between the aquifer and the river is less, the thickness of the aquifer is larger, and the freshwater-saltwater density contrast is higher.

Manipulation of the analytical solution identifies the conditions under which no lens will occur, and the relevant equations are provided. Using the base case parameters and the new equations, we find that lenses are precluded when the aquifer hydraulic conductivity exceeds 27 m/d, the aquifer thickness is less than 19 m, the aquifer-river water level difference at 6 km from the river is higher than 1.4 m, the freshwater-saltwater density ratio is greater than 0.97, and the hydraulic resistance of the riverbed material is less than 0.0073 d^{-1}. Under the base-case conditions adopted here, the density ratio of 0.97 indicates that lenses are more likely where hypersaline groundwater is found adjacent to the river. By application to three situations along the River Murray, the method proves to be a useful screening tool for an initial determination of whether a freshwater lens will occur in the floodplain aquifer, given reasonable consistency with reduced salinity groundwater indicated by AEM surveys of the River Murray floodplains.

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