# Development of Hypersaline Groundwater in Alluvial Aquifers of Ephemeral Rivers

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## EXTENDED ABSTRACT

Hypersaline groundwater is generally restricted to beneath saline playas where density driven convection processes lead to the build-up of solutes in the groundwater. Hypersaline groundwater in alluvial aquifers is rarely observed but salinities of up to 155 $gL^{-1}$ TDS occur in the alluvial aquifer of the ephemeral Neales River, northern South Australia. We propose that the hypersalinity is at least partly driven by evapoconcentration of groundwater through the ephemeral channel and of residual, groundwater-fed pools in the channel. The residual pools reach salinities as high as 307 $gL^{-1}$ TDS (Figure 1). Evaporation from groundwater is facilitated by the shallow depth to the water table resulting from a shallow underlying aquitard layer and occurs despite active recharge during streamflow events. The possibility of density driven convection from the channel pools into the groundwater was investigated using the dimensionless Wooding number that describes the ratio between density driven downwards forces and stabilising forces from upwards evaporative flow. For a range of physical characteristics typical of the aquifer sediments and observed surface pool and groundwater salinities, an evapotranspiration rate of 271 – 3174 $mmyr^{-1}$ (the region has a pan evaporation rate of 3800 $mmyr^{-1}$) is required to achieve a Wooding number of seven, the threshold for initiation of density driven convection. The hypothetical processes were further investigated using the variable density SEAWAT 2000 module within Visual MODFLOW.

The SEAWAT 2000 model was able to simulate the development of a hypersaline plume beneath, and adjacent to, the ephemeral channel. Using a one year run with the absence of any flow events, the development of the hypersaline plume could be driven by ET rates at the base of the ephemeral channel of 500 $mmyr^{-1}$ or the presence of residual channel pools with constant salinities of 100 $gL^{-1}$, which was substantially below the observed salinities in residual pools after prolonged periods without flow. A second SEAWAT 2000 model structure used the river algorithm to simulate the effect of recharge from flow events alternating with periods of evaporation through the base of the ephemeral channel. This model structure resulted in a slight freshening of the groundwater immediately below and adjacent to the channel following flow events but a moderate increase in salinity by the end of the model run after 189 days of no flow.

**Figure 1.** Ephemeral main channel of the Neales River, northern South Australia. Groundwater salinity in the floodplain aquifer 50 m from the channel is 150 $gL^{-1}$ TDS while the residual pools in the channel reach salinities around 300 $gL^{-1}$ TDS. The channel is covered by salt (halite) deposition in the foreground.

## 1. INTRODUCTION

Water quality in arid and semi-arid zone alluvial aquifers can vary widely in terms of salinity but most references in the literature deal with relatively fresh to brackish (<2 $gL^{-1}$ total dissolved solids (TDS)) alluvial groundwater (Harrington et al., 2002; Subyani 2005; Bauer et al., 2006). Saline groundwater in alluvial aquifers of arid and semi-arid zone rivers is usually confined to conditions where saline regional groundwater (recharged via diffuse rainfall infiltration) discharges into alluvial aquifers. An example of this is in the lower reaches of the River Murray in the semi-arid zone of southern Australia, where regional saline groundwater with salinities as high as 40 $gL^{-1}$ TDS underlie the floodplain (Jolly et al., 1993) but the alluvial aquifer within 100 m of the river often has lower salinities (e.g. <0.5 $gL^{-1}$ TDS in the middle reaches of the River Murray, Lamontagne et al., 2005). However, the reported occurrence of hypersaline (>40 $gL^{-1}$ TDS) alluvial aquifers, particularly close to the river channel, is extremely rare. To put these salinities into context, the salinity of seawater is approximately 35 $gL^{-1}$ TDS.

Hypersaline groundwater is more typical of groundwater underlying ‘dry’ salt lakes that act as groundwater discharge areas. Salt lakes can develop hypersaline surface pools or near-surface saturated zones due to evaporation, leading to a layer of hypersaline groundwater overlying less saline groundwater. This can then lead to density driven convection resulting in the export of solutes from the near-surface environment into the deeper parts of the aquifer (Wooding et al., 1997; Simmons and Narayan, 1998). This process has also been observed in the fluvial environment of the semi-arid zone Okavango Delta of Botswana, where hypersaline groundwater forms beneath islands due to evapotranspiration processes (Zimmermann et al., 2006).

Fieldwork in the ephemeral Neales River of northern South Australia has found highly saline to hypersaline groundwater in alluvial aquifers underlying the river system, with salinities as high as 155 $gL^{-1}$ TDS. A feature of the reaches underlain by hypersaline alluvial aquifers was that the ephemeral primary channel frequently contained saline to hypersaline residual pools. This paper investigates whether density convection, driven by high evapotranspiration rates in the near surface environment, can explain the development of hypersaline alluvial aquifers in ephemeral arid zone rivers.

## 2. METHODS

### 2.1. Field data

The Neales River is an unregulated, ephemeral river system with a catchment area of 34,000 $km^2$ in the arid core of the Lake Eyre Basin (Figure 2), with a median annual rainfall of 140 mm and a mean annual pan evaporation of 3800 mm. A previous study found that the salinity of surface waterbodies varied over four orders of magnitude and divided the catchment into a fresh upper reach and a saline lower reach (Costelloe et al., 2005, see Figure 2).

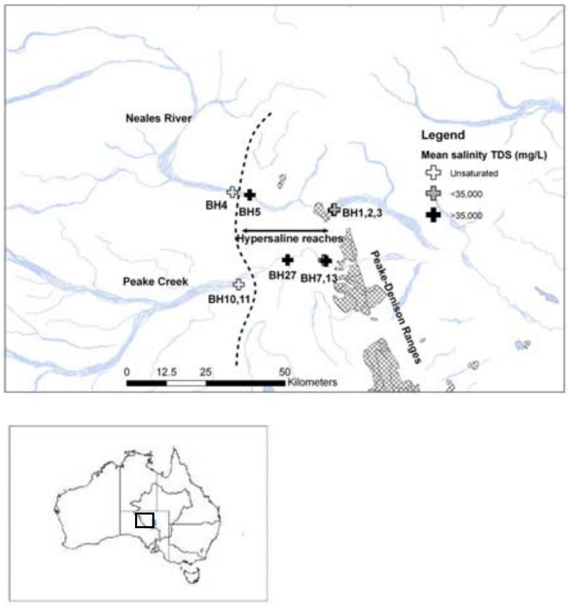


**Figure 2**. Variations in salinity of shallow alluvial groundwater and positions of piezometers and surface water level loggers in the Neales River catchment. The dashed line separates the fresh upper reaches from the more saline surface water and groundwater of the lower reaches.

A field project collected head and salinity data on flow events and shallow groundwater at a number of floodplain sites within the Neales catchment (Figure 2). A total of 12 piezometers were installed in April and November 2004 and monitored groundwater conditions and responses to flow events. This paper concentrates on a mid-catchment reach containing hypersaline groundwater (see Figure 2). Surface flows were monitored by water level loggers at the BH1-3 sites (Neales River) and BH7,13 sites (Peake Creek). Upstream of the hypersaline reach the surface waterholes remained fresh (<5 $gL^{-1}$ TDS) and an aquifer was not always developed in the alluvial sediments. The hypersaline reach, which contained hypersaline groundwater and saline to hypersaline residual pools in the river channel between flow events, extended at least to a range of hills (Peake-Denison Ranges) formed by crystalline basement rocks. Only limited data have been collected downstream of the ranges but the downstream surface waterholes are frequently saline, suggesting that saline alluvial groundwater conditions also occur there. Opportunistic surface water salinities were collected from flowing and static waterbodies during a total of 12 field trips in the period 2000-2006. These consisted on conductivity measurements from 2000-2003 (mostly reported in Costelloe et al., 2005) and chemical analyses of ionic composition and total dissolved solids from 2004-2006.

## 2.2. Dimensionless number analysis

The possibility of density driven convection from residual pools in the channel downwards into the saline groundwater was investigated using the Wooding number, a dimensionless Rayleigh-type number that describes the ratio between buoyancy-density driven downwards forces and stabilising forces from upwards evaporative driven flow (Wooding et al., 1997; Zimmerman et al., 2006). This number is defined by

$$R_{\delta} = \frac{(\rho_m - \rho_a) K_z n_e}{\rho_a ET}, \qquad (1)$$

where $\rho_m$ is the density of the upper boundary layer (i.e. saturated surface layer), $\rho_a$ is the density of the ambient background layer (i.e. alluvial aquifer), $K_z$ is the vertical hydraulic conductivity, $n_e$ is the effective porosity and ET is the evaporation rate. A Wooding number above seven results in instabilities in the boundary layer leading to convective density fingering (Wooding et al., 1997; Zimmerman et al., 2006). The density values for this study were calculated from the typical surface water and groundwater salinities observed during periods of no flow. The vertical hydraulic conductivity range was estimated around the calibrated vertical and horizontal hydraulic conductivity from the numerical modelling (see next section). The effective porosity range was estimated for the sand and gravel sediment of the aquifer and the minimum ET rate required to produce a Wooding number of seven was calculated.

## 2.3. Numerical modelling

The processes leading to the development of hypersaline groundwater were investigated using the variable density SEAWAT 2000 module (Guo and Langevin 2002; Langevin and Guo 2006) within Visual MODFLOW. All MODFLOW models were run at a daily time-step using a strip, or cross-sectional format, perpendicular to the channel direction. Simple representations of the channel and floodplain system were used in the modelling (see Figure 3 for a typical example). The channel was defined using the width and depth measured by surveyed cross-section data nearest to the piezometer. The grid cell size moving perpendicular to the channel was 5 m for the first 100 m and then 25 m width for the remainder of the model domain. The lateral boundaries were represented by constant head boundaries to simulate a connection with a regional shallow groundwater body. The single row of cells defining the cross-section had a width of 20 m along the axis of the channel. The models used up to 30 layers because of the need to model the potential effects of density variations on recharge-discharge dynamics. The layers had a minimum width of 0.1 m and maximum width of 0.5 m below the base of the channel to represent the alluvial sediments with floodplain thicknesses of 7-9 m. The bottom layer/s of each model was a no-flow boundary that represented the base of the alluvial sediments. In the study area, the unit underlying the alluvial sediments was most commonly the Bulldog Shale, a marine mudstone of Tertiary age that also forms the overlying aquitard to Great Artesian Basin aquifer units in the area. The models were initially calibrated against observed data from a single piezometer located on the floodplain 50-100 m from the main channel. These model runs used observed and estimated river stage to simulate the recharge dynamics of the system and to calibrate aquifer property values (saturated hydraulic conductivity and specific yield). Two model structures were then used to simulate the possible density convection processes.

The first model structure placed the initial water table at the base of the river channel and used the evapotranspiration module to drive the evapoconcentration of the groundwater. The constant head lateral boundaries were kept at the same level as the initial head. No flow events were simulated in the channel and the model was allowed to run for a period of one year at a daily time-step. The purpose of this model run was to determine the feasibility of the evapoconcentration process in contributing to the salinity of the alluvial aquifer.

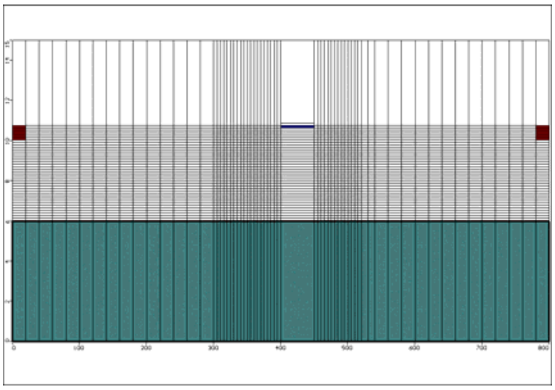

**Figure 3**. Cross-sectional model structure at BH13 site (Peake River). The upper layer includes all of the unsaturated zone while the lower layer is a no-flow boundary. The lateral boundaries are defined by constant head boundaries.

The second model structure used the river algorithm to simulate two sub-bankfull flow events in the channel interspersed with periods of evaporation from the ephemeral channel. The salinity of the recession of the flow events was progressively increased to account for mixing with groundwater. These input conditions approximated the flow events and observed salinities of residual pools during the period of April 2004 to April 2005.

## 3. RESULTS

### 3.1. Field data results

The groundwater intersected in the alluvial aquifer of the middle reaches of the Neales River catchment was consistently of very high salinity (44 – 155 $gL^{-1}$ TDS) and occurred at shallow depths (3.4 – 4.0 m below surface of the floodplain). Despite the very high salinities of the groundwater, all piezometers showed responses to streamflow events indicating some recharge (see example in Figure 4). All three piezometers in the alluvial aquifer of the hypersaline reach (BH5, BH13, BH27) showed increases in salinities of between 2-16% following a sustained period of no flow from November 2004 to April 2005. This was suggestive of either evaporative enrichment of the alluvial groundwater or an influx of more saline groundwater distal to the river.

The (bromide x 1000) / chloride ratios of the groundwater are >0.4 (Figure 5) indicated that solute dissolution from evaporites was not significantly contributing to the high salinity of the alluvial groundwater in the catchment (Davis et al. 1998) and so evapotranspiration processes were likely to be the dominant cause.

During sustained periods of no flow (>6 months), the standing pools of water in the hypersaline reach contained hypersaline water (211 – 307 $gL^{-1}$ TDS, Table 1) that was between two to five times the salinity of the local groundwater (44 – 155 $gL^{-1}$ TDS). During these periods the potentiometric level of the floodplain groundwater was level with, or up to 0.9 m below, the level of the standing pool in the channel.

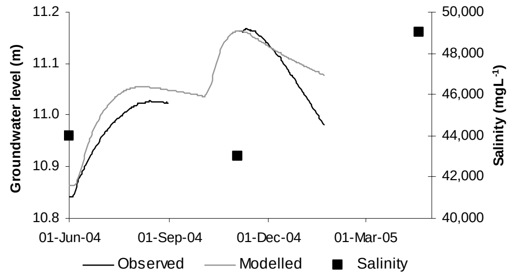


**Figure 4**. Observed and modelled piezometric response in BH13 to flow events in June and October 2004. The salinity of the floodplain aquifer is also shown.

**Table 1**. Observed salinities of residual pools and alluvial aquifers.

| | **Apr04** | **Apr05** | **Apr06** |
|---|---|---|---|
| Neales pools ($gL^{-1}$) | 307 | 296 | 79 |
| BH 5 ($gL^{-1}$) | 155 | 149 | 141 |
| Days since last flow | 388 | 187 | 126 |
| Peake pools ($gL^{-1}$) | 212 | 227 | 269 |
| BH 13 ($gL^{-1}$) | 44 | 49 | 50 |
| Days since last flow | 376 | 155 | 112 |

These hypersaline standing pools had depths of between 0.1 – 0.2 m. The conservative ion ratios ($Na^+/Cl^-$, $Br^-/Cl^-$) of the residual pools are tightly grouped with those of the alluvial groundwater (Figure 5) and were consistent with the pools being derived from groundwater discharge that has undergone evaporative enrichment. The validity of the evapoconcentration process in explaining the high salinity of the pools was also checked using the potential ET rates for this region. The potential ET rates used were the average of the areal and point potential ET rates for each month over the region derived from the Australian Bureau of Meteorology (www.bom.gov.au). This was corrected for the salinity of the residual pool using an algorithm from Morton et al. (1985) and by a calibrated reducing factor for the ET rate. Over the November 2004 to April 2005 period when there was no flow recorded in the rivers, a residual pool (treated as a bucket with an area of 1 $m^2$ and an initial depth of 0.2 m) required an average groundwater inflow rate of 0.03-0.04 $m^3$ per month at the average salinity measured in the nearest piezometer, and an ET reducing fraction of 0.27 – 0.28 (i.e. required actual evaporation rate was 27-28% of the salinity corrected potential evaporation rate), to reach the salinity observed in April 2005 from the starting salinity observed in November 2004. These simple calculations, in combination with the hydrochemical data, indicate that the residual pools form as a result of evapoconcentration of discharging alluvial groundwater.

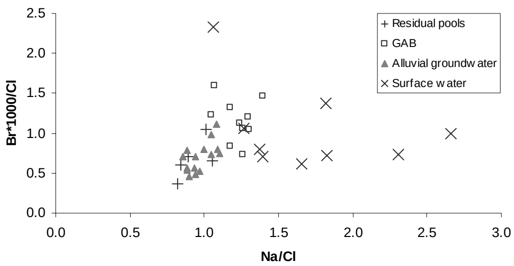


**Figure 5**. Chemical ratio ($Br^-/Cl^-$ and $Na^+/Cl^-$) characteristics of samples from residual channel pools (hypersaline reach), GAB springs, alluvial groundwater (all reaches) and surface water (all reaches).

## 3.2. Dimensionless number analysis

The range of physical characteristics typical of the aquifer sediments and observed surface pool and groundwater salinities are shown in Table 2.

**Table 2**. Ranges of aquifer values used to estimate ET rates required to initiate density convection.

| | BH5 | BH13 |
|---|---|---|
| Aquifer sediment | Gravel | Sand |
| $n_e$ max | 0.3 | 0.3 |
| $n_e$ min | 0.1 | 0.1 |
| $K_z$ modelled ($md^{-1}$) | 1.46 | 0.79 |
| $K_z$ max ($md^{-1}$) | 2.25 | 1.20 |
| $K_z$ min ($md^{-1}$) | 0.75 | 0.40 |
| $S_y$ modelled | 0.10 | 0.12 |
| ET max (mm $yr^{-1}$) | 3174 | 2634 |
| ET min (mm $yr^{-1}$) | 343 | 271 |

Solving (1) to produce a Wooding number of seven (i.e. the threshold for initiation of density driven convection) requires an evapotranspiration rate of 271 – 3174 $mmyr^{-1}$. The region has a pan evaporation rate of 3800 $mmyr^{-1}$ and the mean annual average of the areal and point potential ET rates is between 1190-2100 $mmyr^{-1}$. The maximum estimated ET rates to achieve a Wooding number of seven are probably unrealistically high and equate to the upper end of the saturated hydraulic conductivity and effective porosity values. In comparison, the ET rates estimated to generate the salinity of the observed residual pools were approximately 560 $mmyr^{-1}$ (0.28 times the average of the mean annual areal and point potential ET). In general though, the modelled ET rates required to initiate density convection are physically realistic for this region.

## 3.3. Numerical modelling

The SEAWAT 2000 model was able to simulate the development of a hypersaline plume beneath, and adjacent to, the ephemeral channel. Using a one year run with the absence of any flow events, the development of the hypersaline plume could be driven by ET rates at the base of the ephemeral channel of 500 $mmyr^{-1}$ (simulation A in Figure 6) or the presence of residual channel pools (simulation B in Figure 6) with constant salinities of 100 $gL^{-1}$, which was substantially below the observed salinities in residual pools after prolonged periods without flow.

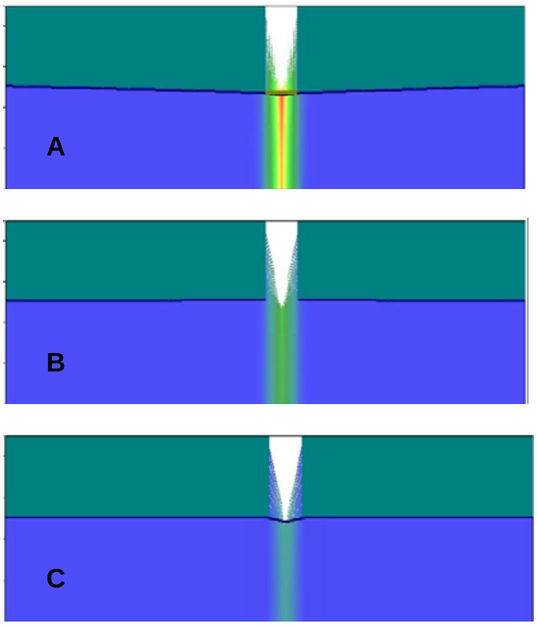


**Figure 6**. Model simulation results for aquifer salinity after a model run of one year. The unsaturated zone (green) has a thickness of approximately 4 m and the saturated zone (blue) to the base of the alluvial aquifer has a thickness of approximately 5 m. The lateral width of the model domain is 800 m. The colour contouring is the same for all model runs. Modelled salinity characteristics are shown in Table 3.

The second SEAWAT 2000 model used the river algorithm to simulate the effect of recharge from flow events alternating with periods of evaporation through the base of the ephemeral channel (simulation C in Figure 6). This model structure resulted in a slight freshening of the groundwater immediately below and adjacent to the channel following flow events but a moderate increase in salinity by the end of the model run after 189 days of no flow. The two sub-bankfull flow events simulated in the year of the model run are relatively typical of the frequency of flow in the Neales River catchment during the study period (2000-2006). The modelled simulations suggest that under its present flow regime, increases in the salinity of the alluvial groundwater can occur but are likely to highly influenced by the frequency and duration of larger flow events that result in higher recharge to the alluvial aquifer.

**Table 3**. Modelled salinity characteristics of the BH13 (Peake River) alluvial aquifer after a one year model run. See text and Figure 5 for definition of model runs A, B and C.

| | **A** | **B** | **C** |
|---|---|---|---|
| | ($gL^{-1}$) | ($gL^{-1}$) | ($gL^{-1}$) |
| Maximum salinity | 66.1 | 54.5 | 50.0 |
| Salinity 10 m from channel. | 46.9 | 44.9 | 43.8 |
| Salinity 20 m from channel | 45.8 | 44.2 | 43.9 |
| Background salinity | 44.0 | 44.0 | 44.0 |

Under the modelled input conditions, the increase in salinity was confined to immediately beneath and adjacent to the ephemeral channel (Table 3). However, increasing the ET rate to 1000 mm $yr^{-1}$ resulted in maximum salinities beneath the channel of 89.7 $gL^{-1}$ and salinities 50 m from the channel edge of 45.0 $gL^{-1}$ (i.e. above background level). Decreasing the initial level of the alluvial groundwater to 0.2 m below the base of the channel made no significant difference to the ET driven increase in groundwater salinity.

## 4. DISCUSSION

The modelling and field data indicate that evaporative driven density convection of residual brine pools in channels of ephemeral rivers is a feasible mechanism for developing hypersaline groundwater in alluvial aquifers. The key features required for this to develop are a water table close to the level of the base of the ephemeral channel and high evaporative demand. In arid zone regions of Australia evaporative demand is consistently high but shallow water tables are probably less common. However, in semi-arid zone rivers where saline regional groundwater discharges into the alluvial aquifer, the channel base of ephemeral creeks and anabranches on the river floodplain may be close enough to the watertable to allow evapoconcentration in the near surface environment. This could provide a mechanism for the increasing the salinity of the alluvial groundwater in semi-arid zone rivers, such as the lower reaches of the River Murray.

Understanding the processes resulting in the development of hypersaline alluvial aquifers will assist in identifying river reaches likely to experience such conditions. Such information is important for water resource management of these river systems and also for evaluating the potential effects of water resource development on the riparian vegetation. Most water resource development (i.e. groundwater pumping or surface water extraction) would lead to the lowering of the water table. However, the periodic discharge of waste water into ephemeral streams could raise the water table to the stage where residual groundwater fed pools in the channel evapoconcentrate to levels that enable density convection. As a result, salt would be exported into the alluvial aquifer and the increase in groundwater salinity may affect riparian vegetation.

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## 6. ACKNOWLEDGEMENTS

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