GROUNDWATER FLOW PATHS AND IMPLICATIONS FOR DRYLAND SALINITY IN THE RIVERINE PROVINCE, SOUTHEASTERN MURRAY BASIN, AUSTRALIA

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Location:
Riverine Province, Southeastern Murray Basin, Australia.

Main Problem Illustrated:
Increases in groundwater levels cause dryland salinity in a major agricultural region.

Summary:
Rise of groundwater levels in unconfined aquifers can cause dryland salinity to increase by several processes including; dissolution of windblown halite, and incorporation of saline clay pore water. The primary process of increased groundwater salinity is evaporation of shallow groundwater as it rises to within a few meters of the ground surface. In Murray Basin, Australia, the effect of dryland salinity on agriculture and natural ecosystems is severe, and threatens approximately 6,000,000 ha (6 to 7%) of arable land. Evaporation is the dominant factor in producing the high-salinity groundwater, which means that the region is at risk from expanding salinity as long as the water table remains shallow, regardless of whether salt sources exist in the unsaturated zone.

Traces Used:
$^{87}\text{Sr}/^{86}\text{Sr}$, $^{18}\text{O}$, $^{2}H$, $^{14}\text{C}$, total dissolved solids (TDS), alkalinity, cations, and anions.

Hydrogeological Setting:
Murray Basin occupies about 300,000 km2 of southeast Australia and has up to 600 m of late Paleocene to recent sediments that overlie Proterozoic to Mesozoic basement (Figure 1). Murray Basin has three sub-basins that are separated by basement ridges: Riverine Province (focus of this case study), Scotia Province, and Mallee-Limestone Province (Figure 2). Except for a small southeast section that discharges to the Southern Ocean, the basin is closed, with primary groundwater discharges to rivers, salt lakes, and playas. The Murray River is the only major surface water feature draining the basin.

Groundwater flow is generally from the uplands to the plains (Figure 2) with corresponding increases in age and salinity, however younger and more dilute groundwater is present in the plains and is associated with ancestral drainage channels. Groundwater recharge occurs throughout the basin, and is not limited to upland locations (Figure 2). In addition, some groundwater discharge locations become recharge locations in the winter during high rainfall years.
The primary aquifers are the older Calivil–Renmark Formation (comprised of fluvial clays, silts, sands and gravel), and the younger Shepparton Formation (comprised of discontinuous fluvo-lacustrian clays, sands, and silts). In the Calivil–Renmark Formation, ancestral drainage channels enhance hydraulic conductivities, with a lateral hydraulic conductivity range of 7–200 m/day. Vertical hydraulic gradients are typically <0.2 m/m down, however the gradient is reversed in some locations.

In the Shepparton Formation estimated lateral hydraulic conductivity is 30 m/day, and vertical hydraulic conductivity is $10^{-5}$ to $10^{-4}$ m/day. Vertical hydraulic gradients are varied probably due to the heterogeneous composition of the aquifer matrix, and are both upwards and downwards (from approximately 3 m/m down to 0.06 m/m up) however, the hydraulic gradient is primarily downward at the surface.

**People Affected, Environmental, Ecological Impacts:**
Dryland salinity is caused by evaporation of increasing water table elevation, which in turn is caused by the removal of native vegetation that previously consumed most of the precipitation in semiarid areas. The rise in water table elevation causes an increase in groundwater salinity by dissolving salts in the unsaturated zone, aiding leakage of saline water from confined aquifers, and promoting direct evaporation of shallow groundwater. The effects of dryland salinity on agriculture and natural ecosystems include: dieback of deep-rooted trees due to water logging of their root systems; replacement of grasses by salt-tolerant flora; formation of salt scalds; destruction of soil structure; increased saline water discharge into rivers and lakes; and damage to buildings and infrastructure in rural communities. The Murray Basin is one of Australia’s most important and productive agricultural regions, producing approximately 40% of Australia’s income from agriculture and grazing. In 1996, dryland salinity was estimated to affect 0.3% of the total arable land (approximately 300,000 ha), however in a few decades dryland salinity is estimated to effect 6–7% of the total arable land (approximately 6,000,000 ha). Dryland salinity threatens the viability of soil in many semiarid locations, including the western United States, Argentina, China, the Middle East, India, and Australia.

**Water Sampling and Analysis Summary:**
Groundwater samples were obtained over approximately two decades from multiple piezometers installed as part of a long-term salinity monitoring study, as well as domestic and irrigation wells in the study area. $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$, $\delta^{44}C$ were analyzed using mass spectrometers. $3H$ was analyzed by liquid scintillation. $^{14}C$ was analyzed by an accelerator mass spectrometer. Alkalinity was measured using a digital titrator. Cations were analyzed on an ICP-AES. Anions were analyzed on an ion chromatograph. Please see references below for specific sampling and analytical procedures.

**Results of Tracer Studies:**
Total dissolved solids (TDS) of groundwater in the southeast Riverine Province generally increases from the upper
slope to the plains, with accompanying groundwater chemistry evolution. With increasing TDS, the Cl\(^-\) anion and the Na\(^+\) cation dominate (up to 95% and 80%, respectively), and Mg\(^{2+}\) increases as Ca\(^{2+}\) declines. This change in groundwater chemistry marks a change from the more dilute groundwater in the uplands to the more saline groundwater in the plains. Additionally, groundwater from ancestral river channels on the plains has relatively less saline water (TDS<3000 mg/L) and is younger, as compared to adjacent groundwater that has high saline water (TDS up to 60,000 mg/L) and is older.

The \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios range from 0.7107 to 0.7191, and vary between subcatchments. Generally these ratios decline with distance from the basin margins. This reflects the primary aquifer mineralogy, and exchange of Sr\(^{2+}\) on clays (especially smectite) derived from weathering of the silicate minerals. The low groundwater flow rates in the Riverine Province combined with a clay-rich aquifer matrix promote Sr exchange, inhibiting Sr applications to constrain flow path properties.

Vertical age profiles show that \(^{14}\text{C}\) activities decline with depth (Figure 3), implying dominantly vertical recharge, which is further supported by a homogenization of Cl/Br ratios and \(\delta^{18}\text{O}\) values with depth, and elevated concentrations of surface tracers (such as F from potable water treatment) at depth. Though vertical recharge dominates flow, there is a greater component of vertical flow through the shallower Shepparton Formation than the deeper Calivil–Renmark Formation. Calculated average vertical infiltration rates are ~4.8 mm/year for ancestral river channels, and ~1.4 mm/year for adjacent areas, with recharge rates of 0.5 to 1.4 mm/year and 0.1 to 0.4 mm/year, respectively. \(^{14}\text{C}\) activities show variations due to native vegetation prior to land-clearing activities, indicating that these infiltration estimates are probably for pre-land development conditions. Additional pre-land development infiltration rates were obtained by Cl mass balance, with estimated recharge rates of 0.05 to 1.4 mm/year, which is in agreement with the \(^{14}\text{C}\) recharge estimates. Water table depths have risen 20 to 30 m in the last 200 years, implying that recharge has increased to 5 to 30 mm/year. These estimates agree with recharge estimates from \(^3\text{H}\) of 4 to 90 mm/year. Recharge rates are similar across the basin, indicating that recharge occurs everywhere in the basin. This is further supported by simultaneous seasonal variations in salinity and \(\delta^{18}\text{O}\) values across the basin, and the presence of \(^3\text{H}\) in all samples throughout the basin.

\(\delta^{18}\text{O}\) and \(\delta^{2}\text{H}\) values are similar across subcatchments, and define an evaporation trend with a slope of 4.5 (see Figure 4, next page), which implies a humidity of ~0.7. However, in the deeper Calivile–Renmark Formation the water was predominantly recharged prior to land clearing, and shows a lack of correlation between \(\delta^{18}\text{O}\) values and Cl\(^-\) concentrations, indicating a transpiration effect, rather than an evaporative effect. In the shallower Shepparton Formation groundwater contains a larger component of recent recharge, and shows a correlation between evaporative

![Figure 3. Age represented by percent modern carbon (pmc) is plotted versus depth for the groundwater from the Shepparton Formation. The decline in pmc with depth indicates predominant vertical recharge. (Cartwright et al., 2006).](image-url)
signature $\delta^{18}$O values and an increase in Cl- concentrations, indicating a stronger evaporative effect. Additionally, Cl/Br ratios (600 to 1000) for high salinity groundwaters indicate that salinity did not originate solely from halite dissolution, implying at least part of the salinity is from evaporation.

**Findings and Conclusions:**
Salinity is generally lowest in the uplands and in the ancestral river channels, and highest in the plains, however, recharge to the Shepparton Formation and the Calivil–Renmark Formation occurs throughout the valley, implying that salinity sources are widespread. There are many sources of salinity in the Riverine Province in the Murray Basin, including windblown halite, clay pore water, and evaporation of shallow groundwater. Precipitation on the plains dissolve minor amounts of windblown halite as it recharges the Shepparton Formation, causing the highest salinity waters to occur on the plains. However, mixing occurring at depth between precipitation recharge on the plains, and laterally transported groundwater from the uplands, mid lands, and low lands dominates the groundwater chemistry in the Shepparton Formation and, to a lesser extent, in the Calivil–Renmark Formation. Extensive dual porosity in the Shepparton Formation may also add to salinity as the previously immobile saline clay pore water becomes mobilized with the rising water table. Finally, evaporation of shallow groundwater is the dominant process of increasing salinity in the groundwater, as demonstrated by evaporative $\delta^{18}$O signatures with increasing Cl- concentrations, implying that salinity will increase as long as the water table remains shallow.

**Take Home Message:**
As recharge occurs at similar rates across the Riverine Province rather than only in the upland areas, dryland salinity landscape management strategies must focus on the entire region, and not solely on the uplands. The finding that evaporation is the dominant factor in producing the high-salinity groundwater means that the region is at risk from expanding salinity as long as the water table remains shallow, regardless of whether salt sources exist in the unsaturated zone.

**Credits:**
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Further Reading for Groundwater Flow Paths:


Further Reading for Surface Water/Groundwater Interactions:


