

UNSATURATED ZONE DYNAMICS INFERRED FROM Cl^- AND ^{36}Cl : CENTRAL NEW SOUTH WALES, AUSTRALIA

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INTRODUCTION

Vertical infiltration of rainwater through sediments in the unsaturated zone commonly recharges groundwater in unconfined aquifers. During recharge, water changes in composition from that of rain water to one approaching the local groundwater composition. The change is a function of how quickly the water flows through the unsaturated zone and the physical and chemical processes occurring during recharge. Evapotranspiration, mineral dissolution and mixing have often been viewed as limitations to the application of ^{36}Cl in hydrogeologic studies. However, these mechanisms can be quantified though the combined use of Cl^- and ^{36}Cl , providing a means for understanding solute dynamics and for estimating recharge rates. This application has particular relevance in Australia, where clearing of native vegetation and subsequent alteration to the hydraulic budget has resulted in the mobilization of solutes previously accumulated in the unsaturated zone. However, relatively little is known of past and present arid to semi-arid unsaturated zone dynamics, in particular, solute mobility. This study provides an example of how soil pore water Cl^- concentrations and $^{36}\text{Cl}/\text{Cl}$ ratios can be utilized to identify and quantify unsaturated zone Cl^- dynamics, estimate groundwater recharge rates, and establish a reliable $^{36}\text{Cl}/\text{Cl}$ input value for age calculations of regional groundwater. The influences of evapotranspiration, mixing and infiltration rates on unsaturated zone pore water chemistry have been investigated to help understand the chemical evolution and timeframes of groundwater recharge to a saline aquifer system in central New South Wales, Australia.

STUDY AREA BACKGROUND

This study focuses on a low-lying alluviated basin in central New South Wales, Australia (Figure 1). Up to 100 m of highly weathered, unconsolidated Cenozoic sediments comprise a heterogeneous hydrogeologic system that hosts brackish to saline groundwater ($\text{TDS} > 30,000 \text{ mg/L}$). A low hydraulic

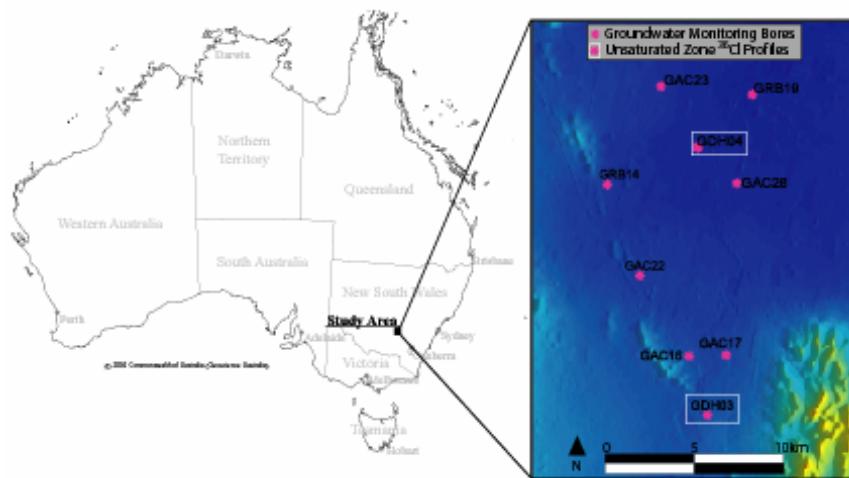


Figure 1: Study area and sampling locations on a digital elevation model

gradient ($< 0.2 \text{ m/km}$) and hydraulic conductivity values of 10^{-5} m/s result in an average linear velocity of $\sim 15 \text{ cm/yr}$. Groundwater recharge is likely the result of vertical infiltration of rainwater at outcropping areas along the basin margins and through near surface sandy-clay sediments present in the southern portion of the basin. Mean annual rainfall is 48 cm/yr. The majority of the study area has been cleared of native Eucalypt forest.

SAMPLING AND ANALYSIS

Pore water was sampled from regolith materials collected proximal (GDH03) and distal (GDH04) to the recharge zone. Laser grain size analyses were performed on regolith materials by Geoscience Australia

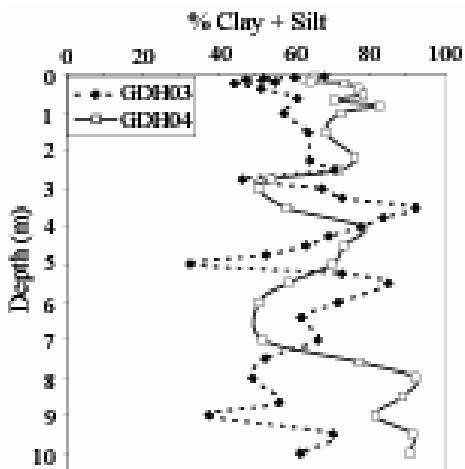


Figure 2: Grain size distribution for diamond cores GDH03 and GDH04

region of lower Cl⁻ concentration in Figure 3b. In combination, the data implies preferential flow along root paths and cracks resulting in less evapotranspiration and mixing during infiltration. Bomb pulse ³⁶Cl at 5 m indicates a vertical infiltration rate of ~ 14 cm/yr and a high degree of solute mobility. It appears that clearing of native vegetation has resulted in enhanced downward transport of unsaturated zone solutes and represents a significant mechanism of secondary salinization. This contradicts current salinization models which attribute increases in groundwater salinity to the mobilization of solutes in the unsaturated zone by rising groundwater tables.

GDH03

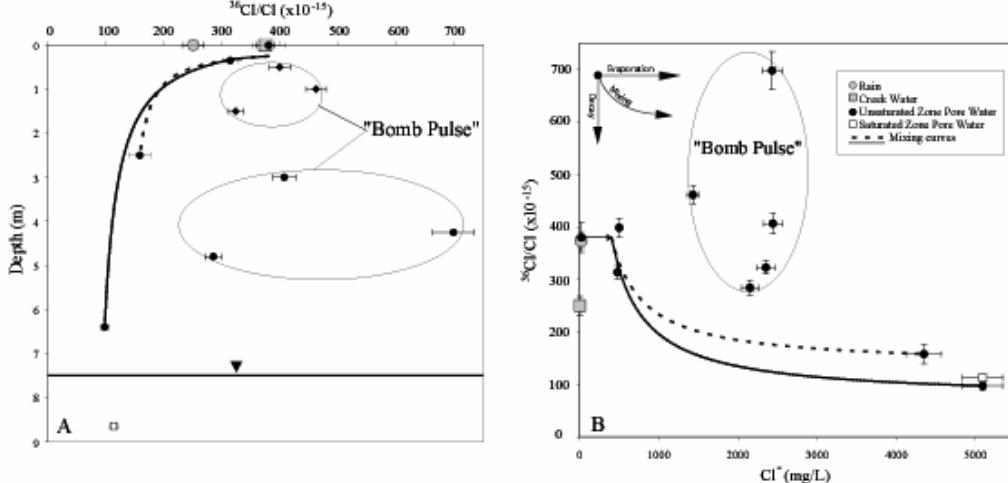


Figure 3 (a)-(b): ³⁶Cl/Cl depth profile (a) and ³⁶Cl/Cl (b) ratio versus Cl⁻ concentration for rainwater, creek water and GDH03 pore waters

Water not infiltrating the unsaturated zone via preferential flow is likely moving under steady, piston-like flow conditions and is subjected to a high degree of evapotranspiration in the near surface. This process results in long term solute accumulation in the low permeability regolith materials. Numerical mixing models were constructed to estimate the effects of evapotranspiration, mixing and halite dissolution under one-dimensional piston flow conditions (Figure 3b). Based on meteoric-like Br/Cl ratios at both sampling locations, halite dissolution does not appear to be affecting the Cl⁻ concentrations or ³⁶Cl/Cl ratios of unsaturated zone pore water (Lenahan et al., in prep.). Chloride and ³⁶Cl/Cl trends indicate evapotranspiration of rainwater to 400-500 mg/L Cl⁻ in the upper 0.5 m. Below this depth, the dominant mechanism appears to be mixing of modern, low salinity pore water with older, saline pore water. At GDH03, soil pore water at the base of the unsaturated zone may represent an appropriate input value for ³⁶Cl dating of groundwater. At GDH04, finer grained sediments near the surface result in a greater degree of evapotranspiration, although mixing is still dominant. Pore waters in the upper 0.5 m exhibit constant ³⁶Cl/Cl ratios with increasing Cl⁻ concentrations (Figures 4a & 4b). This trend is indicative of evapotranspiration and suggests a Cl⁻

(Figure 2). Soil pore water was extracted via uniaxial compression at the Australian Bureau of Rural Sciences. Chloride analyses were performed by ion chromatography at The Australian National University (ANU) Department of Earth and Marine Sciences. The analyses of ³⁶Cl were performed using Accelerator Mass Spectrometry at ANU Department of Nuclear Physics.

RESULTS AND DISCUSSION

High resolution depth profiles of Cl⁻ and ³⁶Cl/Cl in the unsaturated zone were compiled at two locations. The two profiles differ in grain size distribution (Figure 2), resulting in two distinct Cl⁻ and ³⁶Cl/Cl profiles. Coarser grained materials are present in the near surface at the proximal location, resulting in a greater infiltration rate and lower degree of evapotranspiration. Elevated ³⁶Cl/Cl ratios were detected in several samples from within the upper root zone (<1.5m) and from 3-5 metres (Figure 3a). These are likely the result of ³⁶Cl fallout from nuclear weapons testing during the 1950's and 1960's. The deeper "bomb pulse" region corresponds to a

accumulation timeframe of approximately 3,500 yrs. The consistent $^{36}\text{Cl}/\text{Cl}$ ratio observed in the near surface pore waters has also

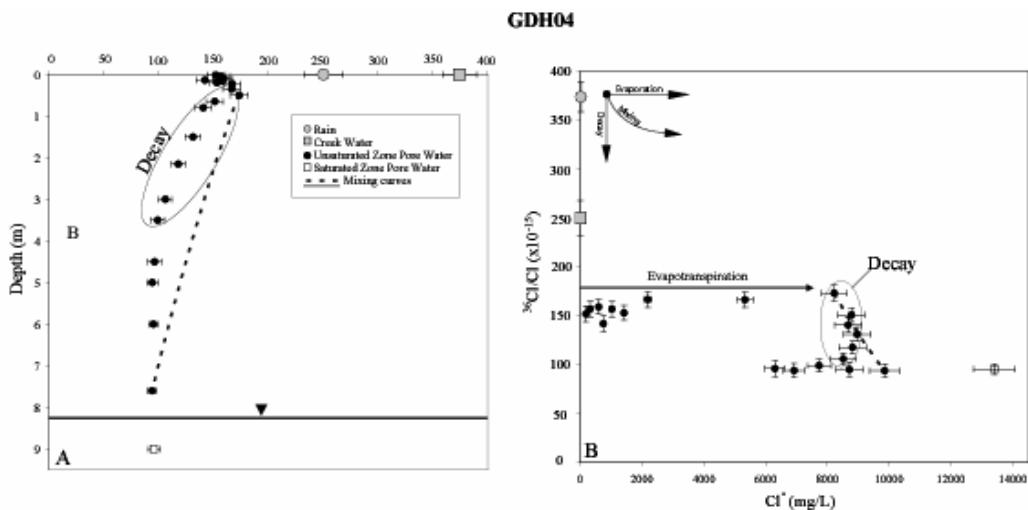


Figure 4 (a)-(b): $^{36}\text{Cl}/\text{Cl}$ depth profile (a) and $^{36}\text{Cl}/\text{Cl}$ (b) ratio versus Cl⁺ concentration for rainwater, creek water and GDH04 pore waters

been observed in modern groundwater from numerous studies within Australia (Bird et al., 1989; Turner et al., 1991; Cresswell et al., 1999a; Cresswell et al., 1999b) and may be representative of an average meteoric input ratio over the last several thousand years. However, this ratio is significantly less than the present meteoric ratio. The results suggest that the present day meteoric values are significantly higher than in the past, and may reflect a short term trend attributable to variation in natural cosmogenic nuclide production rates or due to fallout of anthropogenic ^{36}Cl from nuclear weapons testing in the 1950's and 1960's. This is significant for groundwater dating studies that require establishing an accurate $^{36}\text{Cl}/\text{Cl}$ input value. The data indicate that near surface soil pore water in low permeability regolith materials in arid and semi-arid regions may provide a long term record of ^{36}Cl fallout and provide a more accurate input value for age calculations of regional groundwaters. Below the near surface zone at GDH04, pore waters exhibit steady Cl⁺ with decreasing $^{36}\text{Cl}/\text{Cl}$ ratios. This indicates present day meteoric Cl⁺ or ^{36}Cl deposition is not occurring below 0.5 m and that isotope decay is responsible for the observed $^{36}\text{Cl}/\text{Cl}$ trend. The calculated age difference between pore water at 0.5 m and 3.5 m is ~ 210,000 years. The large time difference is due to a lack of vertical infiltration and demonstrates the timeframes for solute accumulation in the unsaturated zone. These timeframes correspond well with mass balance calculations based on modern Cl⁺ deposition.

CONCLUSIONS

Our results show how Cl⁺ and ^{36}Cl contents of soil pore water can be utilized to determine and quantify unsaturated zone Cl⁺ dynamics, estimate groundwater recharge rates and to establish a $^{36}\text{Cl}/\text{Cl}$ input value for age calculations of regional groundwater. Detection of bomb-pulse ^{36}Cl in saline pore water at a depth of 5 m indicates rapid preferential flow through the unsaturated zone and a high degree of solute mobility. This process is likely responsible for enhanced secondary salinization of the regional groundwater. Measurement of high resolution $^{36}\text{Cl}/\text{Cl}$ profile at one location revealed consistent near surface ratios that are likely indicative of the average $^{36}\text{Cl}/\text{Cl}$ ratio of meteoric water over the past several thousand years. This is significant for age calculations of groundwater in this area, and suggests that ^{36}Cl analyses of near surface pore waters may provide similar information to groundwater dating studies in other arid and semi-arid regions.

REFERENCES

- BIRD J.R., CALF, G.E., DAVIE, R.F., FIFIELD, L.K., OPHEL, T.R., EVANS, W.R., KELLETT, J.R. AND HABERMEHL, M.A., 1989. The Role of ^{36}Cl and ^{14}C Measurements in Australian Groundwater Studies. Radiocarbon, 31: 877-883.
- CRESSWELL, R., WISCHUESEN, J., JACOBSON, G. AND FIFIELD, K., 1999a. Assessment of recharge to groundwater systems in arid Southwestern part of Northern Territory, Australia, using chlorine-36. Hydrogeology Journal, 7: 393-404.
- CRESSWELL, R.G., JACOBSON, G., WISHUSEN, J. AND FIFIELD, L.K., 1999b. Ancient groundwaters in the Amadeus Basin, Central Australia: evidence from the radio-isotope ^{36}Cl . Journal of Hydrology, 223: 212-220.

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- LENAHAN, M.J., KIRSTE, D., CRESSWELL, R.G., BARROWS, T.T., MCPHAIL, D.C. AND FIFIELD, L.K., In Prep. Unsaturated zone Cl-, Br, and ^{36}Cl dynamics: Central New South Wales, Australia.
- TURNER, J.V., WAITE, T.D. AND BRADD, J.M., 1991. The Conjunctive Use of Isotope Techniques to Elucidate Solute Concentration and Flow Processes in Dryland Salinized Catchments, International Hydrology & Water Resources Symposium, Perth, Australia.