



Identifying fluvial recharge and artesian upwards leakage contributions to arid zone shallow, unconfined groundwater

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ARTICLE INFO

Article history:

Received 24 January 2012

Received in revised form 11 July 2012

Accepted 13 August 2012

Available online 24 August 2012

Editor: B. Sherwood Lollar

Keywords:

Evaporation

Major ions

Stable isotopes

Evapoconcentration modelling

ABSTRACT

Evaporation losses from unconfined groundwater can form an important part of the water balance of arid zone groundwater systems. However, in artesian groundwater systems, the discrimination between artesian leakage and surface recharge contributions to the unconfined water table is required. We use hydrochemical analysis techniques and isotopic data to investigate the provenance of unconfined groundwater in zones of artesian discharge along the margin of the Great Artesian Basin (GAB) of Australia. Forward modelling of evapoconcentration and use of trilinear plots identified unconfined groundwater that was largely derived from fluvial recharge, compared to upwards artesian leakage, particularly in areas where the artesian groundwater had a Na-HCO₃-Cl composition in contrast to the Na-Cl-SO₄ composition more typical of arid zone meteoric recharge. Mixing models, combined with forward evapoconcentration models, confirmed that the contribution of artesian groundwater was minimal in areas of Na-Cl-SO₄ unconfined groundwater underlain by Na-HCO₃-Cl artesian groundwater. However, the evaporation modelling was still useful in identifying probable artesian versus meteoric contributions from Na-Cl-SO₄ composition artesian groundwater. Stable isotope data were consistent with the unconfined groundwater being evapoconcentrated from the artesian groundwater end-member and were unable to discriminate between contributions from fluvial recharge and artesian discharge. The hydrochemical analysis techniques can assist in water balance studies of aquifers with Na-HCO₃-Cl composition groundwater discharging into semi-arid and arid environments, in addition to identifying areas of local fluvial recharge.

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1. Introduction

Regional artesian groundwater is a vital resource for human, stock and industrial requirements in many arid and semi-arid areas (Habermehl, 1980; Danielopol et al., 2003). Understanding the water balance for such systems is critical for the sustainable management of the resource. Upwards discharge (or vertical leakage) into the unconfined water table from a confined aquifer, and consequent loss by evapotranspiration, may represent a significant part of the water balance of the artesian resource (Habermehl, 1980; Sultan et al., 2007). A number of studies have estimated the evaporation losses from unconfined groundwater, using such techniques as eddy covariance or Bowen ratio stations to measure evapotranspiration fluxes (Tyler et al., 1997; Kampf and Tyler, 2006; Sanderson and Cooper, 2008) or applying the advection–diffusion model to soil profile concentration data (Allison and Barnes, 1985; Ullman, 1985; Woods, 1990; Brunner et al., 2008). These techniques use a basic assumption that the evaporation loss to the atmosphere is in steady-state balance

with groundwater flux into the unconfined water table; however, this is rarely independently demonstrated. In order to apportion evaporation losses to the water balance of the artesian system, we need to discriminate between the artesian discharge and surface recharge contributions to the unconfined water table in arid environments.

Along down-gradient artesian basin margins, the regional groundwater can be discharging through active vents and springs to the surface and also discharging, or leaking, into shallow, unconfined groundwater systems (Habermehl, 1980; Mudd, 2000; Sultan et al., 2007). The artesian springs provide rare stable water supplies in arid environments and often have very high ecological and cultural values (Kodric-Brown and Brown, 1993; Fensham and Price, 2004; Harvey et al., 2007). In arid environments, the evaporation supplied from the water table usually results in large build-ups of solutes and/or salts in near surface positions (Rose et al., 2005) resulting in saline environments. As a consequence, these saline areas may have significantly lower ecological and cultural values than those of artesian springs. Utilization of the artesian groundwater resource in basin marginal areas can decrease flow to the ecologically and culturally important surface springs (Mudd, 2000; Fensham and Price, 2004; Patten et al., 2008). Conceptually, some of the utilised artesian water could be harvested from water that would otherwise be

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discharged by upwards leakage into the less important unconfined water table (Sultan et al., 2007). Hence, identifying the contributions of leakage from artesian groundwater compared to fluvial/pluvial (i.e. meteoric) recharge to the water table is required for robust water balance estimation and sustainable management of artesian groundwater resources.

Calculating the relatively small fluxes involved in the leakage from regional artesian groundwater to the local water table is fraught with uncertainties (Kampf and Tyler, 2006). Monitoring of unconfined groundwater level fluctuations to identify meteoric fluxes to the groundwater is rarely undertaken because of the high salinity and low yield that are common features of these systems (Tweed et al., 2011). Unconfined groundwater evaporation zones typically occur in topographically low areas and are often associated with drainage lines and therefore are areas that may also be a focus of recharge to the unconfined water table. Hydrochemical data have the potential to discriminate between artesian leakage and meteoric recharge but the occurrence of distinctive end-members is critical for this task.

Stable isotopes of water (^2H , ^{18}O), dissolved SO_4 (^{34}S , ^{18}O), strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) and major ions have been used in semi-arid to arid environments to attempt to discriminate end-members (e.g. Collerson et al., 1988; Dogramaci et al., 2001; Sultan et al., 2007; Harrington et al., 2008; Cendón et al., 2010) with varying degrees of success. Strontium isotope ratios have shown the capacity to discriminate between young and old regional groundwater (Collerson et al., 1988) and $^{36}\text{Cl}/\text{Cl}$ ratios also have potential in this regard (Love et al., 2000). In conjunction with auxiliary data, stable isotopes have been used to define artesian discharge in comparison to the local unconfined groundwater where end-members show significant separation along the global meteoric water line (GMWL) (Sultan et al., 2007). However, in arid zone areas where the unconfined groundwater shows an evaporative enrichment signature along a local evaporation line (i.e. deviating away from the GMWL) it may not be possible to identify evaporated artesian discharge from evaporated meteoric recharge (Tweed et al., 2011). The effects of evaporative overprinting on the major ion composition can be used to determine artesian and meteoric recharge end-members in arid zone unconfined groundwater settings if these end-members have differing compositions. In the semi-arid Murray Basin of Australia, Harrington et al. (2008) found that regional groundwater and local meteoric recharge both had a similar Na-Cl composition and their relative contributions could not be distinguished. Discrimination using stable isotopes and major ions has the advantage of these analysis techniques being relatively inexpensive and existing databases are more likely to exist than for less commonly used isotopes and trace elements.

Bicarbonate-dominant artesian groundwaters are widely distributed globally (Schofield and Jankowski, 2004) and evaporative enrichment of these waters can potentially result in the formation of a distinctive end-member in comparison to the Na-Cl- SO_4 dominant composition of unconfined groundwaters recharged under arid conditions (Zilberbrand, 1995). The Eugster–Jones–Hardie models (Drever, 1997) modified for Na-Cl dominant groundwater systems (Radke et al., 2002) indicate that the first critical branching point in the evolution of the groundwater under evaporation is the ratio of calcium to alkalinity (Alk). Theoretically, if $\text{Ca} > \text{Alk}$ then the groundwater evolves towards Na-Cl- SO_4 -Ca-Mg (Type 1) compositions, while if $\text{Alk} > \text{Ca}$ then the groundwater evolves towards Na- HCO_3 -Cl (Type 2) compositions. Modelling of evapoconcentration processes indicates that the Ca/Alk ratios only need to be less than 0.5 to generate alkaline brines rather than the theoretical ratio of one (Herczeg and Lyons, 1991), otherwise circum-neutral pH, Cl-rich brines are generated.

We analyse hydro-chemical data to determine if evaporation modelling of the major ion assemblage can identify the relative contributions from downward percolation and upwards leakage to the

shallow water table around the margin of an arid zone, artesian groundwater basin. Understanding the hydro-chemical processes linking the artesian groundwater discharge to the unconfined shallow groundwater is important for determining if the evaporation loss flux from the water table represents the upwards leakage flux and for identifying areas of local recharge. We firstly present piezometric monitoring data that demonstrate the existence of significant recharge events around an artesian discharge zone. Chemical data analysis tools are then used to characterise the artesian and unconfined groundwater systems. Finally, we use modelling techniques to test the hypothesis that Na-Cl- SO_4 unconfined groundwaters, typical of arid zones (Zilberbrand, 1995), are not the evaporated product of Na- HCO_3 -Cl artesian groundwater.

2. Site description

2.1. Regional characteristics

The study area encompasses the southwestern portion of the Great Artesian Basin (GAB), one of the largest groundwater basins in the world (Fig. 1). Upwards leakage from the Jurassic–Cretaceous (J–K) main artesian aquifer occurs sporadically over significant sections of the southwestern GAB margin (Habermehl, 1980; Woods, 1990; Woods et al., 1990). The study area can be divided into two major groundwater provinces with differing flow directions, source areas and water chemistry. The larger eastern province has recharge areas along the eastern margin of the GAB and a westerly to south-westerly flow direction of water with Na- HCO_3 dominant chemistry (Habermehl, 1980; Herczeg et al., 1991). The smaller western province has recharge beds along the western margin of the GAB and easterly to southerly flow directions of water with a Na-Cl- SO_4 chemistry (Habermehl, 1980; Herczeg et al., 1991). The study area (Fig. 1) covers flow paths from both provinces and a large zone of mixing between the two provinces (Habermehl, 1980; Herczeg et al., 1991; Love et al., 2000). The pattern of artesian springs (Fig. 1) broadly illustrates the location of areas with relatively high rates of evaporation loss from the water table.

The study area coincides with the arid core of Australia with typical conditions measured at Marree (Station 017031, www.bom.gov.au, near location HE in Fig. 1) having a mean annual rainfall of 162 mm (range 39–409 mm y^{-1}) and a mean annual areal potential evapotranspiration (APET) rate of 1300 mm. The mean monthly APET rate exceeds the mean monthly rainfall in all months and the mean number of raindays with ≥ 25 mm daily rainfall per year is 1.2. Streamflow events through most of the study area are not monitored but to the north of the study area (around Peake-Denison Ranges, Fig. 1) flow events are observed to occur only once or twice a year (Costelloe et al., 2005). These climatic conditions favour high rates of evapotranspiration and only rare rainfall events that are likely to lead to significant meteoric recharge to the unconfined groundwater.

2.2. Field data

In order to characterise the chemistry of the discharge zones, water samples were collected from the major components of the system. These were artesian groundwater from bores cased within the J–K aquifer, artesian discharge from springs, unconfined shallow groundwater and one sample of streamflow. Samples were collected from 13 sites spread over 500 km of the southwestern margin of the GAB and site locations referred to in the text are shown in Fig. 1. Some data were also used from previous groundwater sampling reported in a South Australian groundwater database (<https://des.pir.sa.gov.au>) and these are identified in Table 1.

Boreholes were drilled at each site to depths between 2.0 and 5.5 m and, if intersected, groundwater was sampled and analysed for $\delta^2\text{H}$, $\delta^{18}\text{O}$ and major ions. Some existing monitoring bores in the

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