Applied Geochemistry 61 (2015) 146–159

Contents lists available at ScienceDirect

Applied Geochemistry

journal homepage: www.elsevier.com/locate/apgeochem

Hydrochemical processes in a shallow coal seam gas aquifer and its overlying stream–alluvial system: implications for recharge and inter-aquifer connectivity

Clément Duvert [a,*], Matthias Raiber [b], Daniel D.R. Owen [a], Dioni I. Cendón [c], Christelle Batiot-Guilhe [d], Malcolm E. Cox [a]

[a] *School of Earth, Environmental & Biological Sciences, Queensland University of Technology, Brisbane, QLD 4001, Australia*
[b] *CSIRO Land & Water, Dutton Park, Brisbane, QLD 4102, Australia*
[c] *Australian Nuclear Science and Technology Organisation, Locked Bag 2001, Kirrawee DC, NSW 2232, Australia*
[d] *HydroSciences Montpellier, UMR 5569, Université de Montpellier, 34000 Montpellier, France*

ARTICLE INFO

Article history:
Available online 3 June 2015
Editorial handling by I. Cartright

ABSTRACT

In areas of potential coal seam gas (CSG) development, understanding interactions between coal-bearing strata and adjacent aquifers and streams is of highest importance, particularly where CSG formations occur at shallow depth. This study tests a combination of hydrochemical and isotopic tracers to investigate the transient nature of hydrochemical processes, inter-aquifer mixing and recharge in a catchment where the coal-bearing aquifer is in direct contact with the alluvial aquifer and surface drainage network. A strong connection was observed between the main stream and underlying alluvium, marked by a similar evolution from fresh Ca–Mg–HCO_3 waters in the headwaters towards brackish Ca–Na–Cl composition near the outlet of the catchment, driven by evaporation and transpiration. In the coal-bearing aquifer, by contrast, considerable site-to-site variations were observed, although waters generally had a Na–HCO_3–Cl facies and high residual alkalinity values. Increased salinity was controlled by several coexisting processes, including transpiration by plants, mineral weathering and possibly degradation of coal organic matter. Longer residence times and relatively enriched carbon isotopic signatures of the downstream alluvial waters were suggestive of potential interactions with the shallow coal-bearing aquifer. The examination of temporal variations in deuterium excess enabled detection of rapid recharge of the coal-bearing aquifer through highly fractured igneous rocks, particularly at the catchment margins. Most waters collected from the coal-bearing aquifer also showed an enhanced influence of weathering during the wet season, which was likely triggered by the water–rock interaction with fresh recharge waters. An increase in both residual alkalinity and carbon isotopic ratios at two locations indicated inter-aquifer mixing between alluvium and bedrock during the wet season. The results of this study emphasise the need for conducting baseline hydrochemical surveys prior to CSG development in order to describe the transient nature of recharge and inter-aquifer mixing processes.

1. Introduction

Understanding interactions between different groundwater bodies is a crucial step towards sustainable management of water resources. Scientists have long attempted to trace groundwater flowpaths and aquifer interactions, and a range of tools have been developed for this purpose, including natural tracers such as major ions, trace elements and isotopes (e.g. Taylor et al., 1989; Schramke et al., 1996; Cartwright et al., 2006, 2010; Gassama et al., 2012; Martínez-Santos et al., 2012; Négrel et al., 2012; Hofmann and Cartwright, 2013; Brenot et al., 2015). At a catchment scale, aquifer connectivity can be complex and, where shallow aquifers are involved, the influences on groundwater may include subsurface processes as well as dynamic surface processes. In such instances, a combination of hydrochemical and isotopic tools is necessary to target specific processes. In areas where coal seam gas (CSG; also known as coal bed methane) is extracted from coal-bearing formations, understanding interactions between aquifers and surface water is particularly important. Where they occur at shallow depths, coal-bearing aquifers may contribute baseflow to streams during low flow periods. Because large quantities of groundwater

* Corresponding author at: Queensland University of Technology, GPO Box 2434, Brisbane, QLD 4001, Australia. Tel.: +61 424 631 059.
E-mail addresses: clement.duvert@gmail.com, clement.duvert@hdr.qut.edu.au (C. Duvert).

http://dx.doi.org/10.1016/j.apgeochem.2015.05.021
0883-2927/

need to be extracted from the coal seams in order to release the adsorbed gas, concerns have been raised for potential impacts of CSG activities to both overlying aquifers and streamflow (Commonwealth of Australia, 2014). Under scenarios where the coal-bearing bedrock is in direct contact with alluvial aquifers and streams, the development of accurate conceptual models that consider seasonal influences is necessary to inform and develop sound numerical models for use in the CSG industry (Dahm et al., 2014).

In CSG environments, scientific attention has initially been directed to the chemistry of produced waters (e.g. Van Voast, 2003; Taulis and Milke, 2007; Alley et al., 2011; Dahm et al., 2014) and to their fate after extraction (e.g. Stearns et al., 2005; Healy et al., 2011; Sharma and Baggett, 2011; Meng et al., 2014). Along with the global expansion of the CSG industry (Moore, 2012; Hamawand et al., 2013), focus has more recently shifted towards developing a baseline understanding of interactions between the coal-bearing bedrock and adjacent aquifers and streams prior to CSG development. The hydrochemistry of CSG groundwater is typically characterised by sulphate, calcium and magnesium depletion, and sodium and bicarbonate enrichment (e.g. Van Voast, 2003; Taulis and Milke, 2007; Alley et al., 2011; Dahm et al., 2014). Recent studies have used these characteristics to delineate flowpaths associated with CSG aquifers (Healy et al., 2011; Moya et al., 2015). Other studies have shown that, because of variations in mineralogy of different formations, strontium isotopic ratios could be useful in identifying areas where mixed contributions of CSG groundwater and shallower systems occur (Frost et al., 2002; Campbell et al., 2008). Similarly, dissolved inorganic carbon (δ^{13}C-DIC) signatures were reportedly good indicators of the infiltration of produced CSG waters into adjacent systems (Sharma and Frost, 2008; Sharma and Baggett, 2011). This is due to the prevalence of enriched δ^{13}C-DIC values in organic-rich systems where methanogenesis occurs, because this biogenic process preferentially removes the lighter ^{12}C isotope from water (Schlegel et al., 2011). Some authors also used an integrated approach considering both hydrochemistry and isotopes to infer the degree of inter-aquifer mixing in different CSG settings (Grossman et al., 1989; Frost et al., 2011; Hofmann and Cartwright, 2013; Kanduč et al., 2014). While these previous studies provided some foundation for investigating aquifer connectivity associated with CSG groundwaters, few studies have been carried out in settings where the coal-bearing aquifers occur at shallow depths; as a result, the effects of recharge on CSG groundwaters have been largely overlooked. Another difficulty stems from the complex geology of the CSG aquifers: coal-bearing formations are typically heterogeneous and, consequently, not all these groundwaters may present a typical CSG water signature.

In this study, we test the value of a number of hydrochemical (major and trace elements) and isotopic (deuterium, oxygen, carbon, strontium, and tritium) tracers – and their combinations – for the delineation of inter-aquifer and stream–aquifer interactions in a CSG environment. A small catchment located in Southeast Queensland (Australia) was chosen for our research, because it features the interface between a coal-bearing sedimentary bedrock and a set of fractured Cenozoic rocks forming the headwaters and peripheral ranges. The overarching purpose of this study is to determine whether conventional hydrochemical and isotopic methods are sufficient to establish the interactions between fractured igneous aquifers, shallow coal-bearing sedimentary bedrock aquifers, exploited alluvial aquifers, and streams. In particular, the following research questions will be addressed: (1) what are the hydrochemical processes responsible for the chemical and isotopic facies in each hydrological component? (2) How do these facies vary pre/post a major flood event, and can seasonal variations help understand the recharge processes occurring in each aquifer? (3) What are the most effective tracer combinations to assess potential interactions between the coal-bearing aquifer and adjacent aquifers and streams?

2. Site description

2.1. Climate and geology

The Teviot Brook catchment is a sub-catchment of the Logan River (Southeast Queensland), with its headwaters in the Great Dividing Range (Fig. 1). Elevations range between 65 and 1375 m above Australian Height Datum (m AHD), and climate in the region is humid subtropical (*Cfa* in Köppen classification) with extremely variable rainfall. The annual average precipitation for the 1966–2012 period is 1190 mm in the headwaters and 850 mm in the floodplain, most of which falls from November to April. Following the wet season, winter months are dominated by much drier conditions, although significant rainfall may occur from May to October. The headwaters support undisturbed subtropical rainforest, while the valley supports open woodland, grassland and irrigated agriculture. Geologically, the catchment forms part of the Clarence-Moreton Basin, a Mesozoic sedimentary basin that covers about 38,000 km^2 at the border between Queensland and New South Wales. The Clarence-Moreton Basin contains fluvial sedimentary deposits that form interbedded sequences of aquifers and aquitards. The shallowest bedrock unit of the basin is a Jurassic sedimentary sequence named the Walloon Coal Measures, which outcrops over much of the Teviot Brook catchment (Fig. 1). The Walloon Coal Measures consist of irregular beds of sandstone, siltstone, claystone, carbonaceous shale and coal (Wells and O'Brien, 1994), and their thickness is around 120–240 m in the study catchment (Rassam et al., 2014). A Quaternary alluvial formation composed of eroded catchment materials overlies the sedimentary bedrock. The alluvium has a thickness ranging between 5 m upstream and over 20 m downstream. The catchment headwaters feature a steep morphology with an outcropping Cenozoic basalt sequence known as the Main Range Volcanics. In addition, numerous intrusive dykes and sills associated to the Main Range Volcanics cap the ranges of the catchment as well as occur on the valley floor. The Walloon Coal Measures host a number of coal seams (Wells and O'Brien, 1994), and CSG exploration has commenced in the area and surrounding region about ten years ago and recently intensified.

2.2. Hydrogeological setting

Several water-bearing layers exist within the Walloon Coal Measures, and the formation is referred to as 'bedrock aquifer' in the following. It is assumed that recharge of the bedrock and alluvial aquifers occur through a combination of mountain front recharge via the highly fractured igneous rocks and diffuse recharge over the catchment. The alluvium provides groundwater for irrigation, while the bedrock contains groundwater that is typically brackish (total dissolved solids up to 13,000 mg/L) and mostly used for livestock watering. Groundwater of medium to high salinity has been observed in sections of the alluvium as well as in the stream, which has been interpreted by some authors as the result of mixing between the different systems (Li and Cox, 1996). Vertical hydraulic gradients indicate upward flow from the bedrock aquifer to the alluvium and from the alluvium to the stream network, both under dry and wet conditions. The general groundwater flow direction follows the surface topography and is essentially from the southwest to the northeast (Fig. 1). Regardless of the aquifer considered, groundwater levels are