Applied Geochemistry 73 (2016) 35–48

Contents lists available at ScienceDirect

Applied Geochemistry

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

Assessing groundwater-surface water connectivity using radon and major ions prior to coal seam gas development (Richmond River Catchment, Australia)

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ARTICLE INFO

Article history:
Received 22 March 2016
Received in revised form
22 July 2016
Accepted 22 July 2016
Available online 25 July 2016

Keywords:
Groundwater
Radon
Major ions
Coal seam gas
Catchment
Unconventional gas

ABSTRACT

Coal seam gas (CSG, or coal bed methane) mining is rapidly growing, with poorly understood impacts on groundwater and surface water systems. Here, we use chemical tracers to investigate groundwater-surface water connectivity in an Australian river system (Richmond River Catchment, New South Wales) prior to CSG extraction but after ~ 50 exploratory CSG wells were drilled. We performed four surveys of 29 interconnected creek and river sites, over contrasting hydrological conditions. Radon was used to determine if a surface water segment was gaining groundwater. Radon observations over four seasons revealed that 28 out of 77 surface water segments were clearly gaining groundwater, 5 were possibly gaining groundwater and 44 were undetermined. This is equivalent to gaining segments in 333 km (39%) of surface water from the 864 km being investigated. High spatial and temporal variability in groundwater gaining segments was found. Na/Cl ratios were used to determine the fraction of groundwater in surface water. Overall, the groundwater contribution in surface waters was 14–24% higher in post flood conditions than during the other three surveys of baseflow and moderate flow conditions. The results serve as a regional baseline assessment of river water chemistry and groundwater-surface water connectivity prior to the planned development of CSG fields. Our geochemical tracer approach allows for a quick qualitative assessment of groundwater-surface water connectivity in poorly gauged river systems and can define priority locations where groundwater extraction for CSG mining should be carefully managed.

1. Introduction

Rapid growth in unconventional gas extraction such as coal seam gas (CSG) has occurred over the last decade, allowing a substantial energy resource to be utilised. However, unconventional gas extraction may potentially impact groundwater and surface water systems (Jackson et al., 2013; Osborn et al., 2011; Varade and Meshram, 2010). During CSG extraction, water is removed from the coal seam, potentially creating drawdown within aquifers and altering groundwater-surface water connectivity. Defining surface water segments that gain groundwater during various seasons is important in areas potentially subject to CSG development to allow effective groundwater and surface water management. However, the lack of studies focusing on groundwater-surface water exchange in potential CSG extraction regions renders it difficult to assess the possible long term impacts of CSG (Tait et al., 2013).

Groundwater-surface water exchange is related to many factors such as geology, hydrological conditions and landscape alterations (Atkins et al., 2013; Sophocleous, 2002), and can be both spatially and temporally dynamic (Bailly-Comte et al., 2009; Cartwright et al., 2014a). Baseflow conditions occur during drier periods when groundwater input generally sustain river flow (Chen et al., 2006; Smerdon et al., 2012). High flow conditions occur a few days or weeks after flooding events and are often followed by large increases in groundwater discharge (Atkins et al., 2013; Cey et al., 1998; de Weys et al., 2011; Hrachowitz et al., 2013; Unland et al., 2015). For both baseflow and high flow conditions, the river water composition integrates inputs from multiple groundwater sources (Brodie et al., 2007; Schwartz, 2007). Precipitation events,

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http://dx.doi.org/10.1016/j.apgeochem.2016.07.012

or lack thereof, may alter the direction of groundwater flow, changing a losing segment to a gaining segment or vice versa (Andersen and Acworth, 2009; Kalbus et al., 2006; Konrad, 2006). Establishing gaining and losing sections within riverine systems during varying hydrological conditions is critical for sustainable river management and for the ability to determine potential impacts resulting from climate change or anthropogenic activities (Cartwright et al., 2011, 2014a; Unland et al., 2013).

Groundwater seepage is usually patchy, diffuse, and spatially and temporally variable with multiple driving forces controlling discharge (Burnett et al., 2001), rendering assessments of groundwater discharge difficult. In order to assess groundwater-surface water exchange in riverine ecosystems, numerous tracers such as stable isotopes of water ($\delta^{18}O$ and δD), radioactive isotopes (such as radon), major ions, temperature, SF_6 or conductivity are available and have been successfully applied in different contexts (Cook et al., 2003; McCallum et al., 2012; Meredith et al., 2009; Shaw et al., 2014; Smerdon et al., 2012; Stellato et al., 2008; Yu et al., 2013). Simultaneously applying complementary tracers often provides a better overview of river-groundwater exchange (Batlle-Aguilar et al., 2014; Kalbus et al., 2006; Oyarzún et al., 2014; Santos et al., 2008b) than when using a single tracer. Utilising groundwater tracers to assess groundwater and river water mixing will be most effective when end member (groundwater, rainwater and/or surface water) concentrations or isotope values are distinctly different (Cartwright et al., 2011; Cook, 2013; Crandall et al., 1999; McCallum et al., 2012).

Radon (^{222}Rn) has become a common natural groundwater tracer in the last decade following analytical developments (Burnett et al., 2007). Radon is part of the uranium decay chain and groundwater will acquire a radon signal because uranium is present in most sediments, and radon is more soluble than its radioactive parents (Schubert, 2011). Therefore, groundwater often contains radon concentrations 2 to 4 orders of magnitude higher than radon activities in surface water (Burnett et al., 2001; Dulaiova et al., 2005). Radon is a noble gas and has a relatively short half-life ($t_{1/2} = 3.84$ days), making it detectable only in surface water near the groundwater source (Cook et al., 2006; Lamontagne and Cook, 2007; Schmidt et al., 2010; Schwartz, 2003; Stellato et al., 2008; Swarzenski et al., 2006). Radon is orders of magnitude higher in groundwater than river water (Burnett and Dulaiova, 2003; Cook et al., 2006) and may provide a tool for mapping gaining segments.

Quantifying groundwater discharge using radon in large river catchments can be challenging. However, many investigations have successfully applied a radon mass balance to quantify groundwater and surface water exchange in rivers (Burnett et al., 2010; Cook et al., 2006; de Weys et al., 2011). Knowledge of river morphology is required to understand surface water residence times, radon decay rates and hyporheic exchange, and estimating radon evasion can be difficult when required parameters are not adequately constrained. Therefore, using radon as a qualitative or quasi quantitative tracer is more appropriate when site specific information is unavailable. The lack of basic hydrogeological information is common in many remote regions requiring large spatial scale investigation. Groundwater discharge qualitative assessments using radon have been successfully applied in freshwater ecosystems (Schubert et al., 2006; Wilson and Rocha, 2014) and coastal zones (Dulaiova et al., 2010; Macklin et al., 2014; Maher et al., 2015; Stieglitz et al., 2010; Wilson and Rocha, 2012).

Major ion geochemistry has often been studied in riverine settings to explain spatial and temporal variations controlling the ecosystem and the role of groundwater and surface water interactions (Guggenmos et al., 2011; Gurumurthy et al., 2015; Sheldon and Fellows, 2010; Varol et al., 2013; Xiao et al., 2015; Yuan et al., 2011). In order to utilise major ions as groundwater tracers, consideration of evapotranspiration and evaporation processes is required (Cartwright et al., 2014a). Therefore, using the ratios of major ions can be more effective than using concentrations because ratios are often unaffected by evaporation. The approach requires water sources (usually rainwater and groundwater) to have different ion ratios (Santos et al., 2008a).

In this study, we combine major ions and radon observations to gain insight into groundwater-surface water exchange in a river/catchment system containing substantial CSG resources that may be eventually developed. Our investigation provides baseline information on specific gaining river segments under contrasting hydrological conditions. In addition, we offer a framework for a rapid assessment of groundwater-surface water connectivity in systems with complex morphology and limited background hydrogeological information. This study builds on recent groundwater (Atkins et al., 2015, 2016) and atmospheric baseline investigations in the region flagged for CSG development (Tait et al., 2015).

2. Material and methods

2.1. Study site

The study site was located in the Richmond River Catchment (RRC) (Fig. 1) which is situated in the far north coast of New South Wales, Australia, and has a catchment area of almost 7000 km^2. The Richmond River begins in the far north catchment and stretches for 170 km past several townships, meeting the Pacific Ocean at Ballina. The study sites extends from north of Kyogle to south of Casino, excluding the southern Bungawalbin Catchment (Fig. 1). The region experiences a mild sub-tropical climate and high rainfall with an annual median precipitation greater than 1000 mm in most areas, although the region is known to experience long periods of drought (Atkins et al., 2013 and references therein).

Detailed information on groundwater flow systems in the specific study area is very limited and currently we are unable to provide a conceptual model specifying hydraulic vertical gradients and recharge zones. While a number of previous studies have used radon to assess groundwater-surface water connectivity elsewhere in the broader Richmond River Catchment (Atkins et al., 2013; de Weys et al., 2011; Gatland et al., 2014; Looman et al., 2016; Perkins et al., 2015; Santos and Eyre, 2011), this is the first investigation focusing on the area flagged for CSG exploration. In the absence of detailed hydrogeological data, this chemical tracer investigation contributes to increasing knowledge of regional groundwater and surface water hydrology.

The RRC contains considerable CSG reserves within the Walloon Coal Measures and is currently targeted as a potential CSG extraction region. Approximately 50 exploration wells with depths from ~620 m–1520 m have been drilled in this catchment (Fig. 1) with no associated infrastructure. Operations were suspended by the leaseholder in March 2013; however, there is potential for future CSG extraction. Complex geological sequences are characterised by Mesozoic consolidated sediments overlain by Cenozoic volcanics and Quaternary alluvial sediments (McElroy, 1962). The Quaternary alluvial sediments represent unconfined to semi-unconfined groundwater systems with deep channels composed of gravel, sand, silt, clay and minor woody fragments with detrital quartz, volcanic sediments and coal fragments from underlying basalt and bedrock units (Drury, 1982). The Cenozoic basalt aquifers are mainly located in the upper catchment of the study site, and are characterised by shallow unconfined to deeper semi-confined systems (Duggan and Mason, 1978; Ewart et al., 1987). Measured hydraulic conductivities at cross section sites on the Richmond River approximately 6 km north and south of Kyogle, ranged