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Assessment of groundwater–surface water interaction using long-term hydrochemical data and isotope hydrology: Headwaters of the Condamine River, Southeast Queensland, Australia

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HIGHLIGHTS

- Two distinct surface water groups identified by multivariate statistical analysis
- Groundwater contribution into creek flows estimated using hydrochemistry and ^{222}Rn
- Stable and radioisotopes greatly assisted in assessing GW–SW interactions.
- A conceptual model describing GW–SW connectivity was developed.

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ABSTRACT

A spatial analysis of hydrochemical data of groundwater and surface water was undertaken to identify groundwater-surface water connectivity in the headwaters of the Condamine River catchment, Southeast Queensland, Australia. An assessment of long-term hydrochemical and water level data supplemented by stable- and radioisotope measurements following a prolonged dry period dominated by baseflow, helped in determining patterns of interaction in different tributaries of the upper Condamine catchment. A conceptual hydrological model representing the major hydrochemical processes and their implications for stream-aquifer connectivity was developed and tested using multiple lines of evidence.

The results of a multivariate statistical analysis highlight that there are two main regions with distinct hydrochemical facies (salinity, alkalinity, and predominant ions) in surface water. Geomorphology, geology, anthropogenic and climate influence were identified as the most relevant controlling factors of the spatial variability in water quality.

Stable isotope data confirmed a clear evaporation trend in almost all surface water samples during baseflow conditions. Two water types can be identified and separated by the degree of evaporation and the proximity of one group to the local meteoric water line. The results confirm the discharge of groundwater from aquifers recharged by rainfall and located upstream of the surface water sampling sites.

Overall, ^{222}Rn data show a trend of increased activity in surface water towards the upstream portions of these tributaries, validating the use of this tracer to estimate groundwater input to the local creeks. The proportion of groundwater contribution to stream flow calculated by ^{222}Rn and chloride mass balance is in agreement, and ranges between 20–70% in tributaries in the northern areas, and between 8–50% in the upper reaches of the main river channel.

This study shows the efficacy of an integrated approach combining long-term hydrochemical data interpreted via multivariate statistics, hydraulic water level data and stable and radiogenic isotope hydrology for the determination of groundwater–surface interactions in headwater catchments.

1. Introduction

The Condamine River catchment forms the headwaters of the Murray–Darling Basin, Australia's largest surface water basin, and overlies the Clarence-Moreton and Surat sedimentary basins, two major Australian coal basins in southeastern Queensland. The Condamine

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catchment faces considerable water resource pressures as a result of land use changes, with about 90% of groundwater extracted from the Central Condamine Alluvium (CCA) currently utilised by agriculture, mainly for cotton, wheat and sorghum irrigation (Tan et al., 2012).

Understanding pathways and quantifying the fluxes between groundwater (GW) and surface water (SW) systems are essential to evaluate water resource allocations and to assess potential impacts of increasing water use on groundwater dependent ecosystems (Banks et al., 2011; Kalbus et al., 2006; Sophocleous, 2002). Furthermore, a comprehensive understanding of GW–SW interactions will support the identification of pathways where pollutants can migrate and potentially impact ecological systems within the aquatic environment.

GW–SW interactions on a catchment scale are controlled by three major factors (Yu et al., 2013): a) the position of the river channel within the landscape and the morphology of the catchment; b) hydraulic conductivity of the river bed sediments and associated alluvial deposits and; c) the relation of the stream elevation to the water table level of the adjacent aquifer. Winter (1999) and Menció et al. (2014) suggested that the degree of GW–SW interaction is also influenced by fluvial, anthropogenic and geological processes.

Analysis of physical data, including heat tracer/electrical conductivity (EC), mass balance modelling of stream discharge volumes, stream–aquifer head gradients as input to Darcy's law equation and numerical models are amongst the most reported techniques in the literature for the investigation of GW–SW connectivity (e.g. Brunner et al., 2009; Giambastiani et al., 2012; Kalbus et al., 2006; Keery et al., 2007). These studies cover scales from stream reaches of several hundred metres to large scale catchments. Scale of the study area together with the type of connectivity expected (such as gaining versus losing conditions or connected versus disconnected) are the main criteria for the selection of the most suitable techniques (Banks et al., 2011).

Several authors demonstrated that a combination of different techniques is necessary to achieve an appropriate level of knowledge on the stream–aquifer interaction (Kalbus et al., 2006; Menció et al., 2014) and its spatial and temporal variability. The advantages of using multiple techniques simultaneously, including physical data analysis, hydrochemistry and environmental tracers (e.g. stable isotopes of oxygen and hydrogen and radioisotopes — radon222, or ^{222}Rn), have been highlighted by Négrel et al. (2003), Menció and Mas-Pla (2008), Baskaran et al. (2009), Cartwright et al. (2011), Gusyev et al. (2013), Unland et al. (2013), and Oyarzún et al. (2014).

The use of multivariate statistical analysis (MSA) such as hierarchical cluster analysis (HCA) for the identification of groundwater facies and processes from large hydrochemical datasets demonstrated promising results. However, the majority of MSA studies focused on either groundwater (Cloutier et al., 2008; Güler and Thyne, 2004; Raiber et al., 2012; Woocay and Walton, 2008) or surface water (McNeil et al., 2005; Panda et al., 2006; Shrestha and Kazama, 2007). Guggenmos et al. (2011) showed that areas and mechanisms of GW–SW interaction could also be identified in a rapid and cost-effective manner using both groundwater and surface water chemical data. These authors made use of a large dataset of major ion chemistry, and extracted relationships between site specific median values using multivariate statistical analysis (MSA). There are few examples where MSA is applied to large hydrochemical datasets for the investigation of GW–SW interactions at the catchment scale, by combining its outputs with stable isotopes and environmental tracer measurements, e.g. King et al. (2014); and Oyarzún et al. (2014).

In addition, several studies have demonstrated the importance of groundwater in upland catchments, showing its influence on the hydrology and hydrochemistry of streams (McDonnell, 2003; Shand et al., 2005; Soulsby et al., 2007). In these areas, fractured rock aquifers and more permeable colluviums are commonly found and may form significant aquifers. Headwater catchments also comprise important recharge areas, responsible for most of the recharge of alluvial systems, which are vulnerable to anthropogenic contamination due to their low storage and fast flow rates, restricting natural attenuation processes (Thyne et al., 2004).

Investigations by CSIRO (2008) indicated that most tributaries within the immediate study area are gaining streams of a low rate, whereas downstream, the Condamine River was considered to be connected and potentially losing between the junction with Hodgson Creek and the Elbow Valley (Fig. 1), a reach of approximately 80 km. However, the degree of temporal variation of GW–SW interactions is unknown and only limited tracer-based estimates of groundwater inflows are available in the literature for this region.

Furthermore, according to Biggs (2011), baseflow is an important component in tributaries of the Condamine River headwaters, and particularly within the Hodgson Creek subcatchment located in the northern part of the study area (Fig. 1). This tributary was investigated in detail by Cresswell et al. (2006), who compared groundwater chemistry with stream base-flow and reached the conclusion that a large amount of salt (9000 tonnes/a) is exported following large and intermittent flooding events of low salinity. In the same region, groundwater extraction is accounted for a reduction of approximately half of baseflow, causing impacts to the stream flow salt export (Dutta et al., 2005). The same tributary has been identified as a gaining stream with estimated baseflow ranging from 5 to 9 mm/year, or 10–17% of the total flow in the creek (Reid et al., 2009).

The objective of this current study is to develop a conceptual model of GW–SW interaction in the headwaters of the Condamine River catchment, an area under intense groundwater and surface water extraction, through the integrated assessment of long-term hydrochemical records, hydrochemistry and environmental tracer data. Multivariate statistics are used to determine the hydrochemical characteristics of bedrock, and alluvial aquifers and surface water, and together with stable isotopes provide information on aquifer mixing and groundwater–surface water interaction. Following this, ^{222}Rn and chloride mass balance were used to quantify the input of groundwater into streams during dry conditions at the tributary scale.

1.1. Study area

The Condamine River headwaters are located approximately 200 km southwest of Brisbane, Queensland, Australia (Fig. 1). The total area covers approximately 6040 km^2 and its boundaries form the drainage of the Condamine River watershed upstream of Six Mile and Hodgson Creeks in their confluence with the Condamine River.

Grazing pastures make up approximately 96% of the land use, whereas only 2.6% is occupied by irrigated cultures, which constitutes either cropping, perennial horticulture, irrigated modified pastures or intensive horticulture. While grazing is the major land use, irrigated cropping covers up to 75% of the alluvial deposits in some tributaries. This becomes more evident in the mid to lower subcatchments where the alluvium system is wider, thicker and has the highest permeability values (Hansen, 1999).

1.2. Climate

The headwaters of the Condamine River catchment are characterised by warm summers in the southeast, where ground elevation reaches over 1000 m Australian Height Datum (AHD), whereas hot summers with temperatures generally above or equal to 22 °C dominate the remaining parts of the study area with average elevations of 400 m AHD. The spatial distribution of annual rainfall based on 20-year average (1986–2005) suggests that in the south eastern parts of the catchment, average values can reach over 1600 mm/a, reducing towards the centre of the study area, with a mean of 800 mm (Bureau of Meteorology, 2014b).

The average annual rainfall at the Clifton Post Office (station N^{o}. 041018, Fig. 1) is 665.5 mm (Bureau of Meteorology, 2014b) for the period between 1896 and 2013. Approximately 40% of the annual precipitation falls during the summer months (December to February),