Using 3D geological modelling and geochemical mixing models to characterise alluvial aquifer recharge sources in the upper Condamine River catchment, Queensland, Australia

Jorge L. Martinez [a,*], Matthias Raiber [b], Dioni I. Cendón [c,d]

[a] Queensland University of Technology, Brisbane, Australia
[b] CSIRO Land and Water, Brisbane, Australia
[c] Australian Nuclear Science and Technology Organisation, Lucas Heights, Australia
[d] Connected Water Initiative, School of Biological, Earth and Environmental Sciences, University of New South Wales (UNSW), Sydney, Australia

HIGHLIGHTS

- Approach integrates 3D geological modelling with EMMA and mixing calculations
- Successful characterisation of alluvial recharge sources and controlling factors
- Four end-members identified: rainfall and groundwater inflow from adjacent aquifers
- High contribution rates of mountain front recharge to alluvial hydrochemistry
- Mixing, evapotranspiration and water-rock interaction control groundwater evolution

GRAPHICAL ABSTRACT
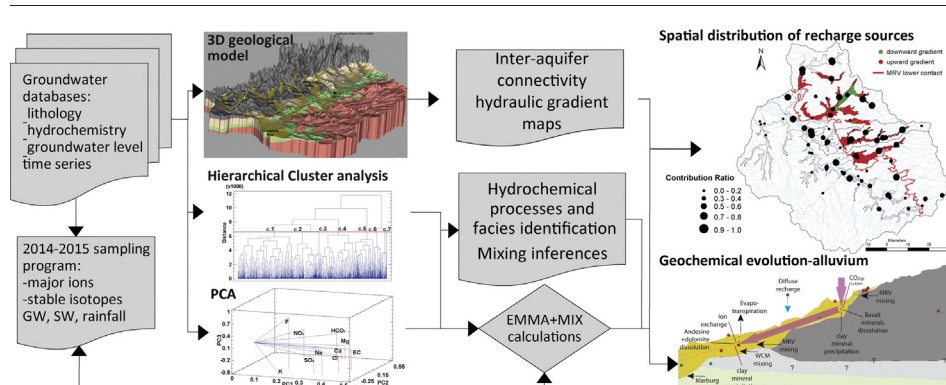
ARTICLE INFO

ABSTRACT

The influence of mountain front recharge on the water balance of alluvial valley aquifers located in upland catchments of the Condamine River basin in Queensland, Australia, is investigated through the development of an integrated hydrogeological framework. A combination of three-dimensional (3D) geological modelling, hydraulic gradient maps, multivariate statistical analyses and hydrochemical mixing calculations is proposed for the identification of hydrochemical end-members and quantification of the relative contributions of each end-member to alluvial aquifer recharge.

The recognised end-members correspond to diffuse recharge and lateral groundwater inflows from three hydrostratigraphic units directly connected to the alluvial aquifer. This approach allows mapping zones of potential inter-aquifer connectivity and areas of groundwater mixing between underlying units and the alluvium. Mixing calculations using samples collected under baseflow conditions reveal that lateral contribution from a regional volcanic aquifer system represents the majority (41%) of inflows to the alluvial aquifer. Diffuse recharge contribution (35%) and inflow from two sedimentary bedrock hydrostratigraphic units (collectively 24%) comprise the remainder of major recharge sources.

A detailed geochemical assessment of alluvial groundwater evolution along a selected flowpath of a representative subcatchment of the Condamine River basin confirms mixing as a key process responsible for observed spatial variations in hydrochemistry. Dissolution of basalt-related minerals and dolomite, CO_2 uptake, ion-exchange,

* Corresponding author.
E-mail address: jorgelmarti@gmail.com (J.L. Martinez).

precipitation of clay minerals, and evapotranspiration further contribute to the hydrochemical evolution of groundwater in the upland alluvial aquifer.

This study highlights the benefits of undertaking an integrated approach that combines multiple independent lines of evidence. The proposed methods can be applied to investigate processes associated with inter-aquifer mixing, including groundwater contamination resulting from depressurisation of underlying geological units hydraulically connected to the shallower water reservoirs.

1. Introduction

In semi-arid regions, a substantial proportion of valley alluvial aquifer replenishment occurs as mountain front recharge (Voeckler, 2012). This process is the result of a combination of various factors; e.g., occurrence of thinner soil profiles, higher orographic/hydraulic gradients and lower evapotranspiration potential, commonly associated with such mountainous terrains (e.g.Wilson and Guan, 2004). Even under more humid conditions, aquifers positioned in lower parts of catchments also receive contributions from mountain front systems along the mountain-plain transition zone (Liu and Yamanaka, 2012; Mikita et al., 2011).

Alluvial valley aquifers are usually hydraulically connected to the subsurface component of mountain front recharge, commonly named mountain block recharge (Aishlin and McNamara, 2011). The identification of mountain block recharge sources and the understanding of spatial variability in infiltration rates due to the influence of climatic variability and land use changes to catchments are key elements for sustainable management practices of water resources.

In groundwater resource investigations, three-dimensional (3D) geological models have historically been used to provide the model structure for numerical modelling simulations (Robins et al., 2005). However, the increased availability of digital geological datasets and low- and high end modelling software packages together with improved hardware capabilities allow the development of 3D geological models for a wider variety of hydrogeolological objectives, including the development of improved hydrogeological conceptual models (Giambastiani et al., 2012; Kelly et al., 2014; King et al., 2014; Moya et al., 2014; Raiber et al., 2015; Raiber et al., 2012).

In many hydrogeological settings, the chemical composition of a groundwater sample can be derived from mixing of water from different sources with distinct chemical compositions. Inter-aquifer exchanges and groundwater interaction with surface water and rainfall are commonly the major factors controlling the hydrochemical evolution of shallow groundwaters (Gómez et al., 2014), followed by evapotranspiration, water-rock interactions and/or microbiological activities.

Mixing between aquifers is controlled by several factors, including the geometry and lithology of the geological host formations. Mixing zones between aquifers can occur, for example, where deeper aquifers 'pinch out' or sub crop beneath shallower aquifers, or where faults impede horizontal groundwater flow, e.g. Moya et al. (2014); Cartwright et al. (2010).

Groundwater sources involved in mixing can be characterised as end-members and their relative contribution to a mixed sample can be estimated using mixing models (Doctor et al., 2006). End-member mixing analysis (EMMA) uses Principal Component Analysis to identify the minimum number of end-members necessary to explain the variability of a set of chemical species in a group of samples (Tubau et al., 2014). This approach has been explored for identification of stream water recharge sources (Christophersen et al., 1990; Hooper, 2003), in karst environments (Doctor et al., 2006; Miller et al., 2015), coal mine groundwater (Sun and Gui, 2015) and at different catchment scales (James and Roulet, 2006).

Mixing models have been used in groundwater studies for a variety of purposes, including the quantification of vertical intra- and inter-aquifer exchanges (Gómez et al., 2014; Morales-Casique, 2012; Rueedi et al., 2005) and to estimate the degree of interaction between surface and groundwater (Kalbus et al., 2006; Oyarzún et al., 2014). The selection of tracers for such calculations ranges from the use of conservative species such as chloride and stable isotopes of water (Cendón et al., 2010; Liu and Yamanaka, 2012; Nakaya et al., 2007; Vanderzalm et al., 2011) to a set containing multiple tracers including major ions, minor elements (F, Li), and various isotopes (e.g. $\delta^{13}C_{DIC}$, $\delta^{34}S_{SO4}$, and $\delta^{18}O_{SO4}$) (Jurado et al., 2013; Ramos-Leal et al., 2007). For example, multi-tracer approaches have been used to estimate the contribution of anthropogenic recharge sources to shallow aquifers in urban settings (Jurado et al., 2012; Vázquez-Suñé et al., 2010).

Several authors highlighted that for successful identification of recharge sources to an aquifer system and the estimation of their relative significance, such sources need to be underpinned by a solid conceptual model of a regional hydrogeological system. The model should represent the understanding of the hydrological dynamics and hydrochemical processes and is ideally based on multiple independent lines of evidence (Gómez et al., 2014; Morales-Casique, 2012; Raiber et al., 2015; Tubau et al., 2014). Hydraulic data can greatly assist in the identification of flow paths and zones where possible inter-aquifer exchanges occur, whereas the interpretation of hydrochemistry can guide the identification of end-members and selection of appropriate chemical constraints for mixing calculations (Vázquez-Suñé et al., 2010).

The objectives of this study are to:

(i) develop a hydrogeological conceptual model of the headwaters of the Condamine River basin from geological and hydrogeological data, in order to identify zones of inter-aquifer connection;

(ii) use end-member mixing models to estimate relative inflow contributions to the alluvial aquifer in the headwaters of the Condamine River basin; and

(iii) identify physical, geomorphological and chemical processes affecting the hydrochemical evolution of alluvial groundwater by examining spatial variations along a single representative flow path.

2. Study area background

2.1. Climate and land use

The upper reaches of the Condamine River catchment are located approximately 200 km west of Brisbane in southeast Queensland, Australia. The study area covers approximately 6000 km² and comprises five major tributary systems located east of the main Condamine River channel (Fig. 1).

Long-term rainfall data of several gauging stations within the study area (Bureau of Meteorology, 2015) indicate a seasonal trend with highest rainfall months between November and March. Approximately 40% of annual precipitation, with an average of 665.5 mm (Clifton post office station), occurs between December and February (Martinez et al., 2015). However, the spatial distribution of rainfall is strongly influenced by an orographic effect caused by the steep escarpments of the Great Dividing Range to the east, where ground elevation can reach up to 1300 m above Australian Height Datum (AHD) with a gradual decrease to the west reaching an average altitude of 400 m AHD in the main drainage line of the Condamine River. In the upper reaches of the tributaries, both annual mean rainfall and evapotranspiration are approximately 1600 mm, whereas in the central to northwest