STOTEN-21485; No of Pages 13

Science of the Total Environment xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Science of the Total Environment

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

Assessing the recharge of a coastal aquifer using physical observations, tritium, groundwater chemistry and modelling

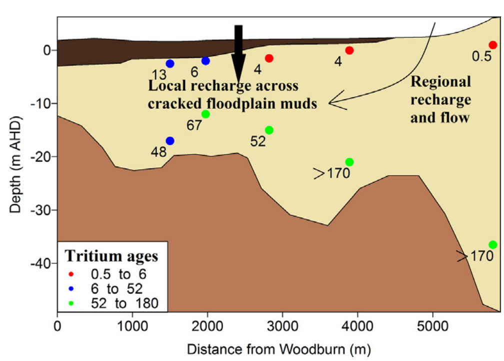
Isaac R. Santos [a,b,*], Chenming Zhang [c], Damien T. Maher [a,b], Marnie L. Atkins [a,b], Rodney Holland [d], Uwe Morgenstern [e], Ling Li [c]

[a] National Marine Science Centre, Southern Cross University, Coffs Harbour, NSW 2450, Australia
[b] School of Environment, Science and Engineering, Southern Cross University, Lismore, NSW 2480, Australia
[c] School of Civil Engineering, The University of Queensland, Brisbane, QLD 4072, Australia
[d] Rous Water, PO Box 230, Lismore, NSW 2480, Australia
[e] GNS Sciences, PO Box 30368, Lower Hutt 5040, New Zealand

HIGHLIGHTS

- We assess groundwater recharge through a pervasive layer of floodplain muds.
- Modelled groundwater flow paths were consistent with tritium dating.
- The clay layer did not prevent recharge because of macropores and cracks.
- Fine-grained floodplain soils do not necessarily protect underlying aquifers from pollution.
- Combining multiple techniques gives more confidence in recharge estimates.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 15 September 2016
Received in revised form 25 November 2016
Accepted 25 November 2016
Available online xxxx

Editor: D. Barcelo

Keywords:
Tritium
Radon
Pollution
Aquifer
Carbon
Coastal

ABSTRACT

Assessing recharge is critical to understanding groundwater and preventing pollution. Here, we investigate recharge in an Australian coastal aquifer using a combination of physical, modelling and geochemical techniques. We assess whether recharge may occur through a pervasive layer of floodplain muds that was initially hypothesized to be impermeable. At least 59% of the precipitation volume could be accounted for in the shallow aquifer using the water table fluctuation method during four significant recharge events. Precipitation events <20 mm did not produce detectable aquifer recharge. The highest recharge rates were estimated in the area underneath the floodplain clay layer rather than in the sandy area. A steady-state chloride method implied recharge rates of at least 200 mm/year (>14% of annual precipitation). Tritium dating revealed long term net vertical recharge rates ranging from 27 to 114 mm/year (average 58 mm/year) which were interpreted as minimum net long term recharge. Borehole experiments revealed more permeable conditions and heterogeneous infiltration rates when the floodplain soils were dry. Wet conditions apparently expand floodplain clays, closing macropores and cracks that act as conduits for groundwater recharge. Modelled groundwater flow paths were consistent with tritium dating and provided independent evidence that the clay layer does not prevent local recharge. Overall, all lines of evidence demonstrated that the coastal floodplain muds do not prevent the infiltration of rainwater into the

* Corresponding author at: National Marine Science Centre, Southern Cross University, Coffs Harbour, NSW 2450, Australia.
E-mail address: isaac.santos@scu.edu.au (I.R. Santos).

http://dx.doi.org/10.1016/j.scitotenv.2016.11.181

underlying sand aquifer, and that local recharge across the muds was widespread. Therefore, assuming fine-grained floodplain soils prevent recharge and protect underlying aquifers from pollution may not be reasonable.

1. Introduction

Groundwater recharge is usually a transient process controlled by climate variables, land use, and soil characteristics. Quantifying groundwater recharge is important to determine sustainable yields when groundwater is extracted for public, industrial or agricultural purposes (Herrmann et al., 2016; Hornero et al., 2016). Climate change (Ehlers et al., 2016), as well as changes in land and water use, including agriculture and drainage (Crosbie et al., 2010), may alter groundwater recharge processes. For example, artificial drains and canals breach impermeable layers and function as windows to the aquifer by enhancing the connectivity of surface water and groundwater (Awan and Ismaeel, 2014; Harvey and McCormick, 2009; Santos et al., 2008; Webb et al., 2016). Groundwater recharge may occur slowly via diffuse flow through the soil matrix or through preferential flow through macropores (Meixner et al., 2016). Soil macropores, similar to fractures, may rapidly transmit nearly unaltered precipitation to the water table, but are very difficult to characterize because of high spatial heterogeneity and three dimensional structure (Johnston et al., 2009; Macpherson and Sophocleous, 2004).

Shallow aquifers underlying coastal floodplains may be particularly vulnerable to climate change, groundwater over-pumping, and salt water intrusion (Kaplan and Muñoz-Carpena, 2014; Werner et al., 2013). In Australia, coastal floodplain aquifers are usually overlain by fine-grained flood deposits. These floodplain deposits are often assumed to be impermeable, preventing effective groundwater recharge and thus protecting aquifers from pollution. However, this assumption has rarely been tested. Coastal floodplains in Australia and elsewhere commonly contain coastal acid sulphate soils (CASS). When disturbed, these soils oxidize, releasing sulphuric acid to shallow groundwater, creating extremely low pH conditions, and high concentrations of heavy metals, nutrients and greenhouse gases (de Weys et al., 2011; Gatland et al., 2014; Johnston et al., 2004; Santos et al., 2011). CASS oxidation is also associated with the formation of large cracks and macropores that may be effective conduits for groundwater flow (Jeffrey et al., 2016; Johnston et al., 2009; Santos et al., 2013).

Estimating groundwater recharge across shallow floodplain soils can be challenging. Since long term changes to groundwater recharge may be very difficult to observe, recharge is commonly investigated using numerical models (Herrmann et al., 2016). Groundwater geochemistry and chemical tracers can also provide information about groundwater recharge when recharged water is chemically distinct from resident groundwater. The use of geochemical tracers may be particularly useful in characterising recharge through macropores because they are difficult to characterize using models and direct observations. Estimating groundwater ages (i.e., the time elapsed since the groundwater entered the subsurface) can also provide insight into groundwater recharge (Jasechko, 2016).

Tritium (^3H) is a radioactive isotope of hydrogen (half-life 12.3 years) that can be used to date groundwater from 0 to about 100 years of age and estimate groundwater recharge. Tritium is produced naturally in small amounts by interactions between cosmic rays and gases in the atmosphere and is part of meteoric water. Once rain water enters aquifers, the water is separated from atmospheric tritium production and radioactive decay becomes the only loss term since tritium is not altered by biogeochemical reactions in groundwater (Morgenstern and Daughney, 2012). In the past, tritium dating was problematic due to interference from the artificial tritium produced by nuclear weapons testing in the early 1960′s. However, considering its short half-life, the bomb-derived tritium has now faded and the approach is considered reliable for groundwater with residence times < 200 years in the southern hemisphere (Morgenstern and Daughney, 2012).

In this paper, we use a combination of groundwater level observations, groundwater geochemistry, tritium dating, and modelling to assess groundwater recharge in an Australian aquifer underlying a coastal floodplain. The concomitant use of multiple approaches allows for a discussion of their advantages and caveats, an interpretation of different times scales relevant to groundwater management, and builds on the literature that often relies on a single approach to estimate recharge rates (de Vries and Simmers, 2002). By combining these approaches, we investigate whether groundwater recharge occurs through the pervasive floodplain muds that are suspected to prevent diffuse recharge, and assess recharge over time scales ranging from days (i.e., groundwater response to rain events) to decades (i.e., tritium dating and modelling). The system investigated is similar to many other floodplains in Australia and elsewhere in that coastal floodplain deposits overlay a prolific sand aquifer. In most cases, fine-grained floodplain deposits are assumed to be impermeable, preventing significant local groundwater recharge. By testing this hypothesis using multiple approaches, our investigation can provide insight into the management of similar aquifers.

2. Material and methods

2.1. Study site

This investigation was performed in the Woodburn Sand Aquifer (WSA) in Eastern Australia (Fig. 1). The floodplain along the western part of the study site represents a former back barrier lagoon filled with Holocene sediments mostly near 1 m relative to the Australian Height Datum (AHD) (Drury, 1982). Pleistocene (Tarantian Stage) sequences of permeable coastal barrier marine sands (Woodburn Sand Aquifer) and estuarine clays are overlain by the Holocene floodplain sediments. The floodplain clays may be pyritic and can potentially develop into coastal acid sulphate soils (Morand, 1994). As in most other lowland areas in Eastern Australia, agricultural drains dissect the area. These drains were designed to reduce periodic inundation for grazing and sugar-cane areas. Their sizes range from roadside table drains < 1 m deep to shallower drains in the sugar cane fields located close to the town of Woodburn.

The Woodburn Sand Aquifer is of major importance as a source of irrigation, stock, domestic and town water supply. The local water supply agency has a bore field consisting of 3 bores that have been inactive for about 10 years. The Woodburn Sand Aquifer ranges in thickness from 36 m on the East to <5 m on the West near Rocky Mouth Creek (Drury, 1982). The sands are overlain by a 1–2 m layer of floodplain silt and clay deposits that is suspected to be impermeable and prevent local recharge of the Woodburn Sand Aquifer. The upper layer of floodplain deposits thickens towards Woodburn and becomes absent ~ 3000 m to the East of the town of Woodburn (Fig. 1). Earlier Pleistocene (Ionian Stage) sediments laid down 134–118 ka during the Eamian Interglacial underlie the Woodburn Sand Aquifer (Drury, 1982). The Ionian Stage sediments consist mainly of estuarine clays of the Gundurimba and Doonbah formations and are thought to be impermeable. The hydraulic conductivity of the Woodburn Sand Aquifer has been estimated to be 30 m/day (Drury, 1982). The general topography of the region implies that active Holocene coastal sand dunes to the East are the major