Applied Geochemistry 75 (2016) 9–19

Contents lists available at ScienceDirect

Applied Geochemistry

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

Using tritium to document the mean transit time and sources of water contributing to a chain-of-ponds river system: Implications for resource protection☆

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A R T I C L E I N F O

Article history:
Received 26 July 2016
Received in revised form
29 September 2016
Accepted 9 October 2016
Available online 12 October 2016

Keywords:
Tritium
Groundwater
River water
Residence times

A B S T R A C T

Documenting the interaction between groundwater and rivers is fundamental to understanding hydrological systems. While many studies have examined the location and magnitude of groundwater inflows to rivers, much less is known about the transit times of water in catchments and from where in the aquifer the groundwater originates. Resolving those questions is vital for protecting riverine ecosystems, assessing the impact of contamination, and understanding the potential consequences of groundwater pumping. This study uses tritium (^3H) to evaluate the mean transit times of water contributing to Deep Creek (southeast Australia), which is a chain-of-ponds river system. ^3H activities of river water vary between 1.47 and 2.91 TU with lower ^3H activities recorded during cease-to-flow periods when the river comprises isolated groundwater-fed pools. Regional groundwater 1–2.5 km away from Deep Creek at depths of 7.5–46.5 m has ^3H activities of between <0.02 and 0.84 TU. The variation in ^3H activities suggest that the water that inflows into Deep Creek is dominated by near-river shallow groundwater with the deeper groundwater only providing significant inflows during drier periods. If the water in the catchment can be represented by a single store with a continuum of ages, mean transit times of the river water range between <1 and 31 years whereas those of the groundwater are at least 75 years and mainly >100 years. Alternatively the variation in ^3H activities can be explained by mixing of a young near-river water component with up to 50% older groundwater. The results of this study reinforce the need to protect shallow near-river groundwater from contamination in order to safeguard riverine ecosystems and also illustrate the potential pitfalls in using regional bores to characterise the geochemistry of near-river groundwater.

1. Introduction

Documenting groundwater inflows to streams, lakes, and wetlands is a fundamental part of understanding catchment hydrology and a necessary step in the management and protection of surface water resources and ecosystems (Winter 1999; Sophocleous, 2002; Brodie et al., 2007). Geochemical tracers including major ions, stable isotopes, and radioactive isotopes (especially ^{222}Rn) have been successfully applied in discerning the location and magnitude of groundwater inflows to surface water bodies (e.g., Brodie et al., 2007; Cook, 2013). In certain cases it may be possible to use river geochemistry to identify specific aquifers from which the groundwater that inflows to the river was derived (Batlle-Aguilar et al., 2014; Atkinson et al., 2015). Long-lived radioisotopes (such as ^4He and ^{14}C) have also been utilised to detect an older component of groundwater contributing to the groundwater inflows (Gardner et al., 2011; Bourke et al., 2014). In many aquifers, however, the major ion and stable isotope geochemistry of groundwater is relatively uniform over areas of up to several hundreds of km^2 and to depths of several tens of metres. In such cases, river geochemistry may indicate that groundwater inflows to surface water has occurred, but not distinguish from where in the aquifer the groundwater was derived. In addition, the time that groundwater

☆ This paper has been recommended for acceptance by Prof. M. Kersten.

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http://dx.doi.org/10.1016/j.apgeochem.2016.10.007
0883-2927/

takes to flow through the aquifer system and discharge into the surface water (the transit time) remains poorly understood in many catchments (McGuire and McDonnell, 2006; McDonnell et al., 2010).

Documenting from where in the aquifer system groundwater is derived and the transit times is important. Shallow groundwater is more susceptible to contamination; hence, if the majority of groundwater inflows are from shallow aquifers, the connected surface water bodies are at higher risk of contamination. Additionally, as the concentrations of some contaminants are attenuated by reactions within the aquifer, longer transit times may result in lower net fluxes of contaminants into the surface water. Nitrate represents the most common contaminant in agricultural areas, and nitrate concentrations in older groundwater may be reduced by denitrification (e.g., Hiscock et al., 1991). Where attenuation does not occur, the transit times controls the lag time between contamination occurring and those contaminants impacting the surface water (Morgenstern et al., 2015). Buffer zones ranging from metres to hundreds of metres are commonly set up around streams to limit the inflow of groundwater impacted by urban development; however, the efficacy of this approach requires that the connection of groundwater and stream water be well understood. Finally, understanding the potential impacts of groundwater pumping adjacent to surface water bodies requires a detailed understanding of the connections between groundwater and surface water.

Tritium (^{3}H) may be used to determining the transit times of shallow groundwater, soil water, or surface water (e.g., Cook and Bohlke, 2000; Morgenstern et al., 2010; Cartwright and Morgenstern, 2015; Morgenstern et al., 2015). Since it is part of the water molecule, ^{3}H activities are not impacted by geochemical or biological reactions in the aquifers or soils and depend only on the initial activities and the residence times in the catchment. Other potential tracers that may be used to determine transit times of young waters such as ^{3}He, the chlorofluorocarbons, or SF_6 are dissolved gases that degas to the atmosphere and are difficult to use in surface water systems (McGuire and McDonnell, 2006). Because ^{3}H activities are not impacted by exchange with soil gasses, ^{3}H transit times reflect the passage of water through the both unsaturated and saturated zones.

Using models that describe the distribution of flow paths within an aquifer (Cook and Bohlke, 2000; Maloszewski, 2000; McGuire et al., 2005), ^{3}H activities may be used to estimate transit times of waters that are up to ~100 years old. Globally, the ^{3}H activities in rainfall over the last several decades are well known (e.g. International Atomic Energy Association, 2016) and many region-specific compilations exist (e.g., the Tadros et al., 2014 compilation for Australia). Rainfall ^{3}H activities peaked in the 1950s–1960s due to the atmospheric nuclear tests that increased atmospheric ^{3}H activities (commonly termed the "bomb-pulse"). The ^{3}H activities of bomb-pulse rainfall in the southern hemisphere were several orders of magnitude lower than those in the northern hemisphere (e.g., Clark and Fritz, 1997) and the ^{3}H activities of this water have now decayed below those of modern rainfall. This situation permits unique transit times to be estimated from single ^{3}H measurements, which in turn does not require an assumption that the flow in catchments is steady state (Morgenstern et al., 2010). By contrast, the ^{3}H activities of remnant bomb pulse waters in the northern hemisphere are currently above those of modern rainfall, which requires time-series of ^{3}H activities to be used to estimate transit times (Morgenstern et al., 2010).

1.1. Objectives

This study examines the transit times of water contributing to Deep Creek (Maribyrnong Catchment) in southeast Australia, which is a chain-of-ponds river system that receives groundwater inflows (Cartwright and Gilfedder, 2015). Specifically ^{3}H is used to determine mean transit times of the river water at a variety of streamflows, including the cease-to-flow conditions when the river consists of isolated groundwater-fed pools. These transit times are compared with those of groundwater to assess the proportion of deeper (7.5–46.5 m) regional groundwater that inflows into the river at different flow conditions. Resolving the mean transit times and the proportion of deeper groundwater that infiltrates the pools is important for managing and protecting Deep Creek and its riverine ecosystems.

While based on a specific river system, the issues discussed here are generally applicable. In common with many catchments globally, Deep Creek has limited groundwater monitoring bores and most of these bores are located a few (in this case 1 to 2.5) kilometres from the river and at depths of several metres. This bore network permits a broad understanding of the groundwater system but not a detailed understanding of groundwater-river interaction.

1.2. Setting

Deep Creek (Fig. 1) is a tributary of the Maribyrnong River in central Victoria, Australia, that comprises numerous 1–2 m deep and up to 15 m wide pools connected by narrower river sections (Cartwright and Gilfedder, 2015), a form commonly referred to as chain-of-ponds or swampy meadows (Mactaggart et al., 2008). The floodplain of the Deep Creek catchment comprises lava flows of the Quaternary to Recent basaltic Newer Volcanics that are overlain by thin Recent alluvium and colluvium deposits. The Newer Volcanics landscape is relatively young and irregular with lakes and pools developed where lava flows fill pre-existing drainage lines (Joyce, 1988). Groundwater in the Newer Volcanics in general is preferentially recharged through scoria deposits that have high permeabilities and groundwater flow is hosted both in fractures and more permeable units (Tweed et al., 2007). Underlying the Newer Volcanics is a basement of indurated Ordovician-Silurian turbidites, Devonian granites, and Devonian granodiorites. The basement rocks host groundwater flow in fractures and weathered zones that are developed close to the present day or pre-Newer Volcanics land surfaces.

The average annual rainfall at Lancefield (Fig. 1) is ~680 mm (Bureau of Meteorology (2016). June, July, and August are the wettest months (65–70 mm rainfall each month). Rainfall in the late austral summer and autumn (February–April) is typically 35–40 mm and potential evapotranspiration rates exceed rainfall at those times (Bureau of Meteorology (2016)). Streamflows in Deep Creek are highest in the winter months (Fig. 2) and Deep Creek commonly does not flow over the summer months. In drier years (e.g., 2015), there may only be continuous flow for a few weeks in late winter or spring (Fig. 2); however, most of the pools along Deep Creek persist during the no-flow periods and are the habitat of the Yarra pygmy perch (*Nannoperca obscura*), which is a threatened native fish species with limited distribution (Hammer et al., 2010).

Due to the paucity of bores, groundwater flow in this region is only broadly understood. Groundwater is recharged on the hills and flows towards Deep Creek. The presence of springs at the edge of and within the floodplain in parts of the upper catchment (Melbourne Water, 2016a) imply that groundwater locally discharges close to the river. From a combination of major ion, stable isotope, and ^{222}Rn geochemistry, Cartwright and Gilfedder (2015) concluded that the river between Cobar and Darraweit Guim (Fig. 1) was largely gaining and that the permanent pools represent points of groundwater discharge.