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Groundwater flow estimation using temperature-depth profiles in a complex environment and a changing climate

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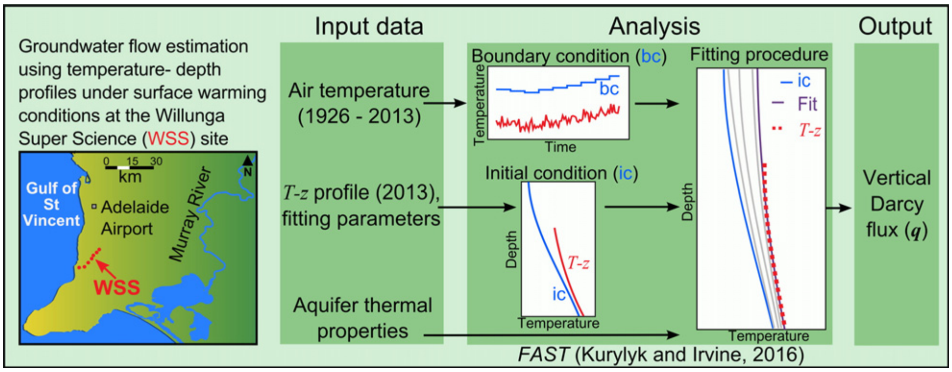
HIGHLIGHTS

- Understanding vertical water flux is vital for effective groundwater management.
- Obtaining vertical flux estimates is challenging in highly modified environments.
- Fluxes estimated using new temperature method that accounts for land surface warming.
- Fluxes can be estimated from temperature data, where other commonly used methods fail.
- Analyses relate to the hydrosphere, lithosphere, atmosphere and anthroposphere.

GRAPHICAL ABSTRACT



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ABSTRACT

Obtaining reliable estimates of vertical groundwater flows remains a challenge but is of critical importance to the management of groundwater resources. When large scale land clearing or groundwater extraction occurs, methods based on water table fluctuations or water chemistry are unreliable. As an alternative, a number of methods based on temperature-depth (T-z) profiles are available to provide vertical groundwater flow estimates from which recharge rates may be calculated. However, methods that invoke steady state assumptions have been shown to be inappropriate for sites that have experienced land surface warming. Analytical solutions that account for surface warming are available, but they typically include unrealistic or restrictive assumptions (e.g. no flow initial conditions or linear surface warming). Here, we use a new analytical solution and associated computer program (*FAST*) that provides flexible initial and boundary conditions to estimate fluxes using T-z profiles from the Willunga Super Science Site, a complex, but densely instrumented groundwater catchment in South Australia. T-z profiles from seven wells (ranging from high elevation to near sea level) were utilised, in addition to mean annual air temperatures at nearby weather stations to estimate boundary conditions, and thermal properties were estimated from down borehole geophysics. Temperature based flux estimates were 5 to 23 mm y^{-1},

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which are similar to those estimated using chloride mass balance. This study illustrates that *T-z* profiles can be studied to estimate recharge in environments where more commonly applied methods fail.

1. Introduction

Groundwater makes up over 98% of all fresh, liquid water on Earth and is the third largest store of water after the ocean and water stored as snow and ice (Shiklomanov, 2000; Kundzewicz and Döll, 2009). With a rapidly growing human population and increasing wealth and industrial activity, more stress is being placed on global water resources. The impact of climate change on water resources is also an area of key concern (Vörösmarty et al., 2000) as future environmental change is expected to cause increased variability in surface water availability and decreased groundwater recharge in some regions (Kundzewicz et al., 2007; Green et al., 2011). With greater uncertainty in the reliability of surface water resources, many regions will further exploit their groundwater resources, highlighting the need for appropriate management. For groundwater resources to be utilised sustainably in the future, understanding fluxes to and from groundwater storage will be as important as understanding the volume of groundwater available (Kundzewicz and Döll, 2009).

A key challenge for the management of groundwater is the estimation of groundwater recharge and, more generally, vertical groundwater flow (Scanlon and Cook, 2002). Numerous methods are available to estimate recharge and vertical groundwater flow, each applicable over specific spatial and temporal scales, and each characterised by distinct sources of uncertainty and assumptions that can be restrictive in some settings. Methods available include those based on water table fluctuations (e.g. Crosbie et al., 2005; Cuthbert, 2010), chloride mass balance (e.g. Guan et al., 2010; Deng et al., 2013), analyses of either stable or radioactive isotopes (e.g. Cook and Solomon, 1997; Cartwright and Morgenstern, 2012; Wood et al., 2015) or numerical modelling (e.g. Keese et al., 2005; Ordens et al., 2014).

Because groundwater transports thermal energy and disturbs subsurface thermal regimes, subsurface temperature data can be utilised to estimate vertical groundwater flow (and by extension recharge rates). The use of heat as a tracer of groundwater flow dates back to the 1960s (e.g. Bredehoeft and Papadopulos, 1965; Stallman, 1963). Following reviews by Anderson (2005) and Constantz (2008), the number of studies using heat to study groundwater-surface water interaction has increased rapidly, with a number of new analytical solutions (e.g. Hatch et al., 2006; Luce et al., 2013), and computer programs to facilitate their application now available (e.g. Gordon et al., 2012; Irvine et al., 2015a). Several analytical solutions are also available to use groundwater temperature data to infer vertical groundwater flow in deeper environments (Saar, 2011). For example, the Bredehoeft and Papadopulos (1965) solution has been often used to estimate vertical fluxes in aquifers (e.g. Cartwright, 1970; Ferguson et al., 2003). Groundwater temperatures can also be used to estimate past land surface temperature increases. For example, Gunawardhana and Kazama (2012) used numerical simulations to determine the likely increase in surface temperatures by fitting numerical models to field measured temperature-depth (*T-z*) profiles from the Kanto plain, Japan. They were able to estimate both the influence of urbanisation and climate change from their profiles, although it is generally acknowledged that disentangling the influence of climate and land use change is a challenge (Colombani et al., 2016; Westaway and Younger, 2016).

Land surface warming invalidates the steady state assumptions of the Bredehoeft and Papadopulos (1965) steady state flux estimation methods for near surface wells, particularly those in recharge zones (Ferguson and Woodbury, 2005; Irvine et al., 2016), as multi-decadal surface temperature changes can induce temporal variability in subsurface temperature even at great depths (Kurylyk et al., 2014). Simple representations of surface warming have been included in a number of analytical approaches, including the assumption of constant linear warming (Taniguchi et al., 1999a) or the influence of a single step change in temperature (Taniguchi et al., 1999b). Menberg et al. (2014) utilised the principle of superposition to allow multiple step changes in temperature. However, each of these solutions still includes limiting assumptions (e.g. a linear initial temperature-depth profile which tacitly assumes no flow). Recently, Kurylyk and Irvine (2016) provided an analytical solution and associated computer program (*FAST*) that includes both complex non-linear initial conditions as well as multiple step changes to represent multi-decadal land surface temperature change. Given the uncertainties in the estimation of vertical groundwater flow, it is typically recommended that several methods are applied that utilise data from multiple sources (Scanlon and Cook, 2002; Saar, 2011). However, many techniques are difficult to apply in highly modified systems (e.g. where land clearing or groundwater extraction has occurred). Additionally the timescale over which different techniques estimate recharge vary. For example, water table fluctuations or the use of short-lived radioisotopes such as ^{3}H estimate recharge rates over a few years whereas longer-lived radioisotopes such as ^{14}C or chloride mass balance estimate average recharge rates over hundreds to thousands of years (Scanlon and Cook, 2002; Cartwright et al., 2007). The interpretation of *T-z* profiles offers an opportunity to provide further information on groundwater flows over the decadal scale, which can be used in conjunction with other methods to constrain groundwater recharge estimates (Saar, 2011).

The overall objective of this study is to assess if reasonable estimates of vertical groundwater fluxes can be obtained from *T-z* profiles where surface warming and land use change exert an important control on the subsurface thermal regime. This approach differs from studies that attempt to assess the influence of surface warming on groundwater temperatures (e.g. Salem et al., 2004; Gunawardhana and Kazama, 2012; Westaway and Younger, 2016). Temperature profiles at the data rich Willunga Super Science site (WSS) in South Australia are fitted to the analytical solutions provided by *FAST* (Kurylyk and Irvine, 2016). The WSS is in the Willunga Embayment, which contains a complex multi-aquifer system where natural groundwater flows have been highly modified by significant groundwater extraction and large scale land use change since the 1830s. The area is classified as semi-arid and has been identified as a region of water scarcity (Vörösmarty et al., 2000). Temperature based flux estimates complement other recharge estimation methodologies, which are all plagued by the hydrological disequilibrium that has existed since European settlement in the 19th century. The intent is to not only to obtain improved vertical flow estimates, but also to demonstrate the applicability and limitations of the method.

2. Methods

2.1. Site description

The WSS is located within the McLaren Vale Prescribed Wells Area (PWA), along a regional flow path from the Adelaide hills towards the Gulf of St Vincent (Fig. 1). The WSS was set up as part of the National Collaborative Research Infrastructure Strategy (NCRIS) by the Australian Government, featuring over 140 piezometers that were installed to study surface water-groundwater interaction, seawater intrusion and to monitor head gradients between the different aquifer units (http://groundwater.anu.edu.au/fieldsite/willunga). In particular, we focus on seven sites (Site 1 to Site 7, Fig. 1c), where each site has