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Long-Term Quantification of Stream-Aquifer Exchange in a Variably-Saturated Heterogeneous Environment

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Abstract A variably-saturated finite element model HYDRUS-2D was used to simulate the spatiotemporal dynamics of stream-aquifer exchange for a perennial stream flowing through an undulating catchment and underlain by heterogeneous geology. The model was first calibrated and validated using piezometric heads measured near the stream. The model was then used a) to quantify the long-term dynamics of exchange at stream-aquifer interface and the water balance in the domain, and b) to evaluate the impact of anisotropy of geological materials, thickness (w) and hydraulic conductivity (K_s) of the low permeability layer at the streambed, and water table fluctuations on the extent of exchange. Simulated pressure heads in the domain revealed that seasonal groundwater fluctuations were more pronounced near the stream. Daily discharge to the stream varied from 0.05 to 0.3 mm/day, annual discharge ranged from 59 to 74 mm, and the overall water balance showed a discharge (−54 mm) from the domain during 2000–2012. A five-fold increase in K_s of the low permeability layer enhanced discharge to the stream by 14% (10 mm/year) whereas an increase in the thickness of the layer by 1 m had a low impact (2.4 mm/year). A 2-m drawdown of the water table transformed a connected and gaining system into a

The original version of this article was revised: The last page was missing and it contained the below references.

Taylor AR, Lamontagne S, Crosbie R (2013) Measurements of riverbed hydraulic conductivity in a semi-arid lowland river system (Murray-Darling Basin, Australia). Soil Res 51:363–371

Thompson S (2003) Using Hydrus 2D to model tree belts for salinity and recharge control. Submitted in partial fulfilment of the requirements of the Degree of Bachelor of Engineering (Environmental) with Honours. Centre for Water Research, The University of Western Australia, Perth

Xian Y, JinM, Liu Y, Si A (2017) Impact of lateral flow on the transition from connected to disconnected stream–aquifer systems. J Hydrol 548:353–367

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losing, disconnected system. These results suggest that depletion of groundwater due to climate change or excessive pumping could have a pronounced impact on the availability of water resources and sustainability of the existing water-dependent ecosystem.

Keywords Stream-aquifer exchange · HYDRUS-2D · Low permeability layer · Anisotropy · Groundwater

1 Introduction

Exchange between surface water and groundwater (SW-GW) is a complex process, which plays an important role in the assessment of riparian systems (Sophocleous 2002). Proper quantification of this process helps in decision making about the allocations of water to different users, including environmental water to preserve the natural ecosystem. SW-GW exchange depends on many factors, including topography, subsurface hydraulic properties, climate, and vegetation (Banks et al. 2011). The exchange of water has a controlling influence on the stream chemistry, nutrient fluxes, near stream biota, and biogeochemical conditions in the vicinity of the creek and creek flow during dry periods (Frei et al. 2009). To better understand the nature of interactions between groundwater and stream requires reliable estimation of the flux across the stream.

There are numerous measurement techniques and approaches for quantification of flow between stream and groundwater (e.g. Kalbus et al. 2006; Chu et al. 2017). However, in most cases, a limited number of data points results in the lack of detailed understanding of groundwater-surface water interactions which hinders the evaluation of continuous flow within a spatiotemporal domain. Numerical modelling approaches, on the other hand, can be valuable tools for developing a better understanding of the system by combining information obtained from various field methods. Once a model is accurately conceptualized, sufficiently calibrated and validated, it can be used to quantify water fluxes and water balance, and to predict their spatiotemporal changes under different scenarios.

Many reviews have summarized the empirical, analytical and process-based numerical solutions employed to understand the complex nature of SW-GW flow systems at different scales (e.g. Barthel and Banzhaf 2016; Chu et al. 2017). Nevertheless, the major complexity in the use of these models is the requirement of spatiotemporal input data for climate, vegetation, stream-flow, groundwater fluctuations, and heterogeneous geological formations. In addition to this, calibration and validation of process based models under such situations also poses enormous challenges. Numerous physically based SW-GW coupled modelling tools (e.g. Guzman et al. 2015) have been used over different scales which often undermine the impact of near stream water dynamics, temporal and spatial hydrological and geological heterogeneity, and anisotropy on SW-GW exchange. Banks et al. (2011) evaluated the importance of vegetation on the nature of the connection between SW-GW and conceptualized the impact of a clogging layer (a low hydraulic permeability layer at the bed), evapotranspiration, and the slope of the catchment using the 2-D HydroGeoSphere model, assuming both homogeneous and isotropic conditions. Batlle-Aguilar et al. (2015) calibrated and validated a 2D model for an ephemeral stream assuming isotropic and no flow conditions at the soil surface. Similarly, Xian et al. (2017) analyzed the importance of lateral flow on SW-GW using conceptual transient simulations for the 2D and 3D systems in the context of heterogeneous streambeds.

The importance of heterogeneities at the stream-groundwater interface and in the hyporheic zone on the exchange has been emphasized in many short-term conceptual studies (e.g. Frei et al. 2009). Meanwhile, Doble et al. (2012) evaluated the overbank flood recharge using a numerical model and found that an increase in the conductance of the clogging layer at the riverbed increased the infiltration volume. Similarly, infiltration rates from a losing, disconnected river obtained from measurements and modelling studies were found to be more sensitive to the clay layer hydraulic conductivity than to its thickness (Crosbie et al. 2014). Normally, the estimation of SW-GW interactions in these studies (e.g. Doble et al. 2012; Crosbie et al. 2014; Rivière et al. 2014) has been conducted assuming either homogeneous and isotropic conditions, or groundwater normal to the stream. However, biophysical modelling studies, with models calibrated and validated on data from sites involving multiple hydrogeological heterogeneities, such as anisotropic flow and/or the presence of poorly permeable layers, are scarce. It is thus essential to develop long-term detailed knowledge on SW-GW interactions based on proper calibration and validation of a numerical model considering vegetation, geology and the permeability of the streambed in the vicinity of the stream in order to derive quantitative information about the system.

This study uses a finite element two-dimensional numerical model (HYDRUS-2D; Šimůnek et al. 2016) to quantify the extent of stream-aquifer connectivity involving real-time climatic, vegetative, and stream flow conditions under complex heterogeneous geological formations. The objectives of the study were i) to calibrate and validate HYDRUS-2D for spatiotemporal dynamics in the piezometric heads at multiple locations in the vicinity of a stream, ii) to quantify the long-term exchange between stream and groundwater and to estimate the overall water balance in the 2D domain, and iii) to evaluate the impact of thickness and conductivity of a low permeable layer at the streambed, anisotropy of geological materials and the depletion of the water table on the extent of exchange between stream and groundwater.

2 Material and Methods

2.1 Site Description

The study site is located at Scott Bottom (35° 06′ S and 138° 40′ E) in Scott Creek, in the Mount Lofty Ranges of South Australia. The study site comprises of natural vegetation mostly dominated by the *Eucalyptus* species. The soils at Scott Bottom are duplex (Chittleborough 1992), that is 0.3–0.5 m of light-textured sandy loam overlays heavy-textured clay. The soil is underlain by saprolite (1.3–2.4 m to 6–18 m) and then fractured rock (Banks et al. 2009). The climate at the site is Mediterranean with warm dry summers and cool wet winters. The Scott Bottom gauging station (SA Water) has rainfall and run off records from 1991 until present, with mean and median annual rainfall of 804 and 764 mm/year, respectively. The gauging station also measures daily stream flow and the water level in the creek at Scott Bottom which were used in the present investigation. Details on the drilling, installation, measurements and monitoring of piezometric wells are described in previous studies (James-Smith and Harrington 2002; Harrington 2004; Banks et al. 2009).

2.2 Numerical Modelling

Temporal and spatial movement of water in a two-dimensional transport domain (Fig. 1) was simulated using HYDRUS (2D/3D), version 2.xx (Šimůnek et al. 2016) which has been widely used in both vadose zone and groundwater studies. The governing two-dimensional water flow equation is described by a modified form of the Richards equation which assumes that the air phase plays an insignificant role in the liquid flow process and that water flow due to thermal gradients can be neglected:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(K(h)\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z} + K(h)\right) - S(h) \tag{1}$$

where θ is the soil water content [$L^3\ L^{-3}$]; t is time [T]; h is the pressure head [L]; x is the horizontal coordinate; z is the vertical coordinate (positive upwards); $K(h)$ is the hydraulic conductivity [LT^{-1}], and $S(h)$ is the sink term representing root water uptake [T^{-1}]. Water extraction $S(h)$ was computed according to the Feddes model (Feddes et al. 1978). Feddes parameters for native vegetation (*Eucalyptus* species) were taken from Thompson (2003), optimized for Australian conditions. Readers are referred to the HYDRUS web site (http://www.pc-progress.com/en/default.aspx) for more details about the software and its applications.

2.3 Modelling Domain

The modelling domain (Fig. 1) represents the creek at Scott Bottom which was 335 m wide (x = 0 at the left boundary, positive in the right direction) and 42 and 56 m deep (z, positive upwards) on the western and eastern sides of the creek, respectively. The creek is located at x = 135 m and is represented by a bed width of 2.5 m, a top width of 5 m, and a depth of 4 m (Banks et al. 2009). The colours in Fig. 1 differentiate the complex geology including soil, saprolite and fracture rock. Fig.1 also shows the location of piezometers and boundary conditions. The domain was discretized into 44,171 triangular elements with a fine grid around the creek (0.2 m) and along the sides with time-variable pressure head boundary conditions. The grid size was gradually increased farther from these locations with a maximum element size of 1 m.

2.4 Soil Hydraulic Parameters for Modelling

Retention parameters of duplex soils were obtained from ROSETTA embedded in HYDRUS-2D and K_s values were obtained from Banks et al. (2009). Similar hydraulic conductivities of A and B

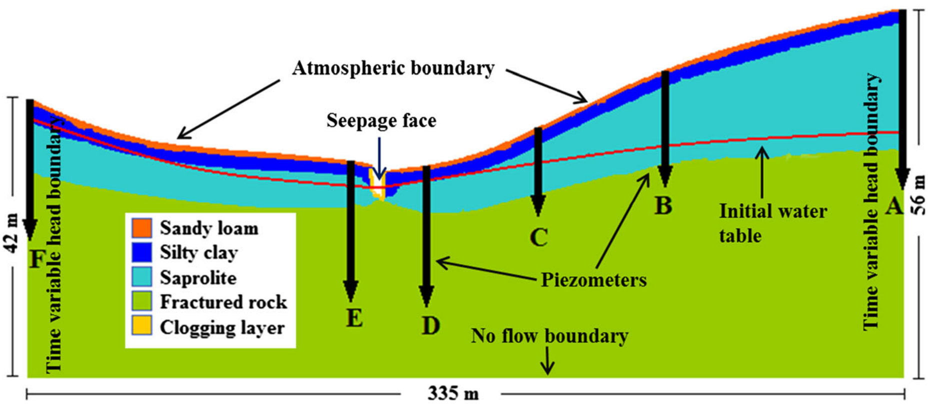

Fig. 1 A schematic (stretched in the vertical direction) of the model domain showing material distribution, boundary conditions, the initial position of the water table, and the location of piezometers

horizons of the soil were reported by Cox and Pitman (2002) in the Mount Lofty Ranges of South Australia. The hydraulic conductivities of the saprolite and fractured rock layers were crucial for simulating flow to the creek while maintaining the elevation heads measured at nested piezometers. Flow in a fractured rock depends on the relative proportion and properties of the fracture and matrix systems, such as the size, conductivity, tortuosity of fractures, and porosity and conductivity of the matrix which makes it hard to model (Šimůnek et al. 2003). Although dual-porosity and dual-permeability models exist for such complex environments, the difficulty in determining many dual-permeability model parameters largely limits the applicability of these models (Köhne et al. 2009). Hence, the modelling of the fractured rock system was simplified by assuming it to be represented by a single-porosity material.

Since the geology of the site is dominated by sandstone, siltstone and dolomite, the saturated water content for fractured rock was considered to be 20% (Leaney et al. 2011) and the shape parameter α was taken from Banks et al. (2011). Banks et al. (2009) reported a wide range of K_s values measured using single well aquifer tests for saprolite (0.04–2.5 m/day) and fractured rock (1.5–14 m/day) at locations near Scott Creek. In order to realistically represent the flow conditions at the site, the soil hydraulic parameters were calibrated against the piezometric water level fluctuations and a sensitivity analysis was performed for the hydraulic conductivity of saprolite and fractured rock. Final van Genuchten parameters used in the model are shown in Table 1. Note that parameters θ_r, α, n, and l are not needed for layers that are fully saturated.

2.5 Estimation of Potential Transpiration, Evaporation and Root Distribution

Daily potential evapotranspiration (*PET*) for natural tree (*Eucalyptus*) vegetation for the experimental site were obtained from the SILO database (Jeffrey et al. 2001). The data were converted to potential transpiration (T_p) and potential evaporation (E_s) based on the leaf area index and rainfall correlation developed by Ellis and Hatton (2008) for South Australian catchments under natural *Eucalyptus* vegetation. The daily *PET* values were split into T_p and E_s as follows (Belmans et al. 1982):

$$E_s = PET \cdot e^{-K_{gr} \times \mathrm{LAI}} \tag{2}$$

$$T_p = PET - E_s$$

Here, K_{gr} is the light extinction coefficient for global solar radiation and its value was taken as 0.5 for forest systems (Aubin et al. 2000). Estimated E_s and T_p values were used as input for HYDRUS-2D simulations.

Table 1 Calibrated soil hydraulic parameters of different materials used in the model

Material	$^*\theta_r$ (m^3 m^{-3})	$^*\theta_s$ (m^3 m^{-3})	$^*\alpha$ (m^{-1})	$^*n$	$^*Ks$ (m day^{-1})	$^*l$
Sandy loam	0.06	0.41	4	1.89	1.05	0.5
Silty clay loam	0.06	0.41	2	1.35	0.05	0.5
Saprolite	0.06	0.35	2.2	1.4	0.5	0.5
Fractured rock	0.06	0.26	4	1.9	0.03	0.5
Low permeability layer	0.06	0.41	1.9	1.31	0.05	0.5

* θ_r is the residual water content (L^3 L^{-3}), θ_s is the saturated water content (L^3 L^{-3}), K_s is the saturated hydraulic conductivity (LT^{-1}), l is a shape factor, α is an inverse of the air-entry value and n is an empirical parameter

Rooting depth of *Eucalyptus* trees was obtained from the literature (Canadell et al. 1996). Since imposing an exact rooting depth along the hill slope was difficult, the simulated rooting depth varied between 6 and 7 m. The root water uptake distribution was assumed to be linearly distributed with depth between a maximum at the top and zero at the bottom.

2.6 Initial and Boundary Conditions and Model Calibration

The initial pressure head condition in the domain was specified by interpolating measured mean piezometric elevation heads (of nested piezometers) while considering hydrostatic equilibrium from the lowest located nodal point. The seepage face boundary condition specified in the creek was coupled with special boundary condition options allowing for the interpolation of variable pressure heads in time and imposing the seepage face boundary condition when the specified nodal pressure head was negative. Hence, the specified water levels in the creek were linearly interpolated in time, in order to smooth the impact of daily fluctuations of water levels in the stream. Measured values at nested piezometers A and F (Fig. 1) were used to define time-variable pressure head boundary conditions at the side boundaries. This initial pressure head condition at side boundaries was further optimized during calibration so that it maintains the piezometric head fluctuation close to the measured level in the nested piezometers in space and time. The bottom boundary was assumed to be a "no flow" boundary. The atmospheric boundary condition was imposed at the surface where rainfall, evaporation, and transpiration changes over time. Since HYDRUS cannot reliably simulate overland flow on slopes, rainfall minus run off was assumed to instantaneously infiltrate into the soil.

Simulations were carried out for 535 days from 15th July 2005 till 31st December 2006 to calibrate the model by comparing the measured and modelled spatiotemporal piezometric heads at four locations (B, C, D, and E) shown in Fig. 1. The model was calibrated via a trial-and-error manipulation of hydraulic parameters and validated for 365 days from 1st January 2007 till 31st December 2007. The model was then employed to assess the long-term (2000 to 2012) dynamics of SW-GW connectivity in the creek at Scott Bottom under *Eucalyptus* (trees) vegetation by employing measured daily water level and climate parameters.

2.7 Impact of a Low Permeability Layer, Anisotropy and Water Table Drawdown

The calibrated model was run for different K_h/K_v ratios (0.75, 1, 1.5, 2.0, 2.5, 3.0) of soil, saprolite and fractured rock zone to evaluate the impact of anisotropy on the extent of discharge to the creek. Similarly, the impact of the low permeability layer at the bottom of the stream was evaluated by considering five thicknesses (0.00 m, 0.25 m, 0.50 m, 0.75 m and 1.00 m) and four hydraulic conductivities (K_s = 0.02, 0.05, 0.075 and 0.1 m/day) of the streambed. These characteristics were selected on the basis of field studies of the thickness and hydraulic conductivity measurements of the low permeability layers in the Murray Darling Basin (Taylor et al. 2013). Scenarios with different levels of water table drawdown (0.25, 0.5, 0.75, 1.0, and 2.0 m) along the slope of the domain were performed to evaluate the impact on the state of connection between the stream and aquifer system. These scenarios were developed as a result of declining trends in groundwater levels (0.02–1.7 m/year) in 71% of the observation wells over the five years (2010–2015) in the study area (DEWNR 2016).

3 Results and Discussion

3.1 Comparison of Pressure Heads

The measured piezometric heads at four nested sites (Banks et al. 2009), situated at x = 125 (E), 160 (D), 190 (C), and 260 m (B) from the left side of the domain (Fig. 1) are compared in Fig. 2 with corresponding heads generated by HYDRUS-2D during the calibration (from 15th July 2005 to 31st December 2006) and validation (from 1st January 2007 to 31st December 2007) periods (900 days). While there was a good temporal match between simulated and measured pressure heads at 3 locations (C, D, and E), the model simulated lower heads at x = 260 m (B). Here, both measured and simulated values showed much smaller seasonal response and modelled pressure heads were lower than measured values. Simulated seasonal amplitude in pressure heads also matched well with water table fluctuations in piezometers at locations D and E. However, the simulated seasonal response at location C was low compared to measured values. The results revealed that seasonal variations in the pressure heads are enhanced near the creek and gradually dissipate away from the creek (Fig. 2).

Differences between modelled and measured values, particularly at location B, may be due to localized hydrogeological heterogeneity. This cannot be captured by the model simulations, since the flow patterns in the fractured rock are highly sensitive to the size, shape, and connectivity of fractures, as well as to matrix properties. Nevertheless, modelled variability of heads near the creek (i.e., at locations D and E) showed much higher correspondence with measured values and these locations are likely to have a much greater effect on surface-groundwater exchanges at the creek. In contrast, Batlle-Aguilar et al. (2015) observed that matching measured and simulated piezometric heads under ephemeral streams and for disconnected stream-aquifer interface (Lamontagne et al. 2014) does not imply that a model simulates stream infiltration well in all situations. They reported that groundwater mounding can affect the model simulations which is normally absent under gaining system as observed in the present study.

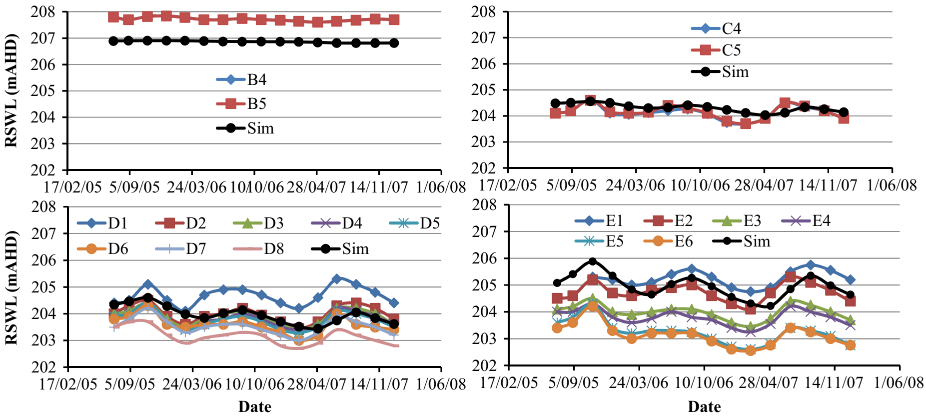

Fig. 2 Comparison of measured and simulated RSWLs (reduced standing water levels) during calibration (15th July 2005 to 31st December 2006) and validation (1st January 2007 to 31st December 2007) at 4 locations (B, C, D, and E). AHD is the Australian height datum

3.2 Long-Term Discharge to the Creek and Annual Water Balance

Simulated long-term (2000 to 2012) daily discharge to creek at Scott Bottom showed a distinct annual pattern of flow over the years influenced by the amount of rainfall and the hydrological flux exchange within the domain (Fig. 3a). The impact of low rainfall during 2007 to 2009 is clearly visible on the daily magnitude of discharges to the creek. Low rainfall not only reduced the magnitude of flow in the creek but also the amount of discharge to the creek. Daily discharge to the creek varied from 0.05 to 0.31 mm/day. Normally, high intra-annual discharges occurred during September–October and low during April–May. Since the rainfall season usually occurs from June to August, this indicates that the impact of rainfall on water movement to the creek is not immediate but it has a lag time depending upon the rainfall amount, intensity, and geology since recharge flows through complex geological pathways, as speculated by Banks et al. (2009). Baseflow conditions (between 0.05–0.1 mm/day) in the Scott Creek typically occurred during February to May period (Fig. 3a). Annual discharge to the creek varied from 58.9 to 73.8 mm and the impact of low rainfall was observed during 2006–2008.

These results (positive discharge to the creek) also confirm that the Scott creek at Scott Bottom is a gaining creek which corroborates with other studies (James-Smith and Harrington 2002; Banks et al. 2009). However, these studies could not quantify the contribution of lateral groundwater flow to the creek. Our calibrated and validated model showed that most lateral flow (83–86%, Fig. 3b) to the creek was contributed from the left side of the domain at piezometer F (see Fig. 1) due to the continuously higher groundwater table level, and a correspondingly higher vertical hydraulic gradient, than from a comparatively constant groundwater level and a low gradient at the right side of the domain at piezometer A.

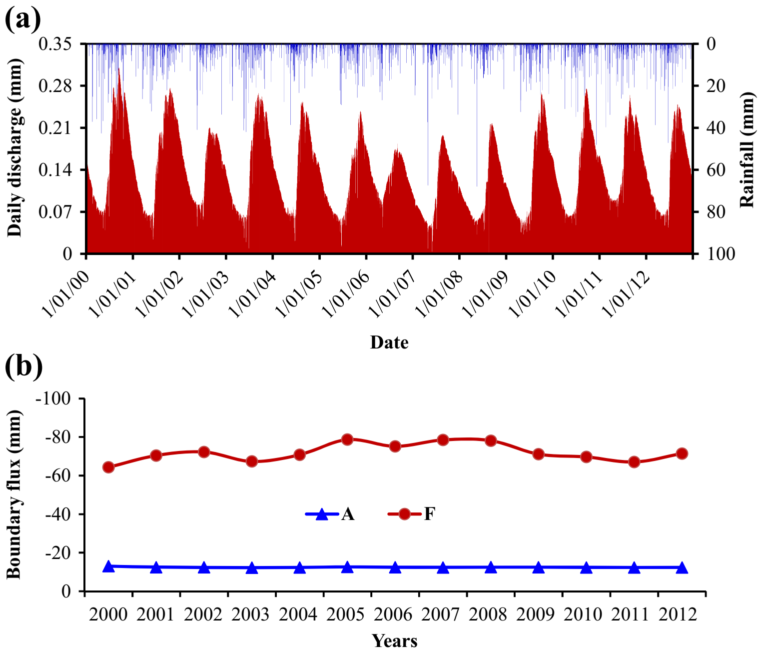

Fig. 3 Long-term daily dynamics in **a**) discharge to the creek and rainfall, and **b**) simulated annual boundary fluxes through the *A* and *F* piezometer (see Fig. 1) boundaries of the flow domain

The model-simulated annual *ET* losses for native trees (*Eucalyptus* species) varied from 698 to 832 mm, while the mean annual *ET* losses over a period of 13 years amounted to 772 mm (Fig. 4a). Despite low precipitations during 2006, the annual *ET* losses were maintained near mean value. This implies that the *ET* demand was continuously met and the groundwater table depths were also remained at the same level due to continuous replenishment by lateral groundwater flow towards the stream. However, the impact of low rainfall during 2006 and 2007 was visible during 2008 as the *ET* losses reduced to a great extent but maintained at a higher level than annual rainfall. Actual *ET* under natural *Eucalyptus* vegetation can often exceed precipitation (Sun et al. 2011) which can strongly influence the connectivity of losing streams in dry years (Banks et al. 2011).

On the other hand, water balance estimation showed an overall positive balance (i.e. groundwater recharge condition) in the domain under *Eucalyptus* trees during 2001, 2003, 2005, 2007–2010 (Fig. 4b). However, in the remaining years, an overall negative balance prevailed. The maximum annual discharge from groundwater storage (−151.6 mm) was observed during 2006, when the region experienced severe low rainfall conditions. Overall water balance over the study period (2000–2012) showed a discharge of 54 mm from the domain. This discharge has not been replenished at Scott Bottom by lateral or regional flows, which feed the creek system. Similar observations were made by Ivkovic et al. (2009) in the Cox Creek catchment where groundwater discharge was observed. Nevertheless, discharge/recharge conditions at Scott Bottom are affected by a number of interrelated factors: a) the experimental site has a shallow water table along the creek, which is being replenished with regional flow due to a gaining stream system; b) the roots of *Eucalyptus* trees extend to a depth of more than 5 m, drawing water from both the vadose zone and groundwater; c) high evapotranspiration demand under the semi-arid conditions of the catchment; and d) relatively less rainfall during the study period. This type of situation generally exists in areas where the evapotranspiration demand is very high in comparison to precipitation and an easy access to shallow groundwater is maintained by deep rooted vegetation along the stream (Landmeyer 2012). Under shallow water table conditions and deep rooted systems, it is mainly vegetation that controls groundwater recharge, as observed in this study. Groundwater discharge conditions have also been reported in other studies (Ordens et al. 2014) involving deep rooted Mallee trees (*Eucalyptus* species), similar to those in the Scott Creek catchment. In contrast, other studies (e.g., Green and Zulfic 2008) reported groundwater recharge ranging from 16 to 111 mm/year in various catchments of South Australia. Such dramatic contrasts often exist

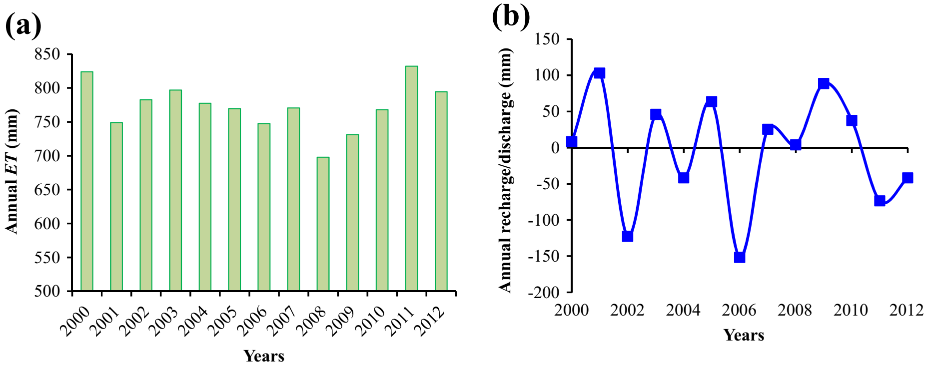

Fig. 4 Model-simulated **a**) annual evapotranspiration (*ET*) of native vegetation (*Eucalyptus* species) and **b**) the annual water balance in the domain at Scott Bottom during 2000–2012

when there is a huge variation in methodology, and different sites, climate, topography, vegetation, and other parameters needed for recharge estimation.

The results also reveal that vegetation plays an active role in affecting the stream flow and the nature of the hydraulic connection between SW-GW through its influence on water extraction patterns from the soil. This impact varies depending on evapotranspiration, reflecting different climates, leaf areas, root systems, and different stress response mechanisms. Numerous studies (e.g. Leaney et al. 2011; Ordens et al. 2014) have shown a pronounced impact of vegetation on recharge to groundwater and on surface-subsurface hydrological interactions (Li et al. 2013). Undoubtedly, the *ET* losses due to vegetation drive the nature of the connection between SW-GW.

3.3 Impact of Low Permeability Layer, Anisotropy and Water Table Dynamics

Discharge to the creek increased nonlinearly with an increase in the hydraulic conductivity (K_s) of the layer (0.5 m width) at the streambed (Fig. 5a). An initial increase of K_s from 0.02 m/day to 0.05 m/day produced a 9.4-mm increase in discharge to the creek. However, further increases in K_s from 0.05 m/day to 0.075 and to 0.1 m/day resulted in diminishing increases in discharge to the creek (2.4 and 1.4 mm, respectively). Hence, decreasing K_s of the streambed layer from 0.1 m/day to 0.02 m/day resulted in a 14% (10 mm/year) reduction in the amount of discharge to the creek. On the other hand, increasing the thickness of the streambed layer (*w*) to 1 m had a relatively much smaller impact on discharge to the creek (reduced discharge to stream by 3%; Fig. 5b). Hence, the relative impact of K_s of the streambed layer as compared to its thickness *w* was four times larger, indicating the crucial role of K_s of the streambed of a gaining system. In contrast, the impact of anisotropy of saprolite was much higher than that of the fractured rock and soil zone (data not shown). For the anisotropy ratio of 3 for saprolite, the creek discharge almost doubled, which is quite significant. This happens because the water table is situated within the saprolite zone and lateral flow towards the creek is highly influenced by the hydraulic properties of this zone. Frei et al. (2009) showed that spatial and

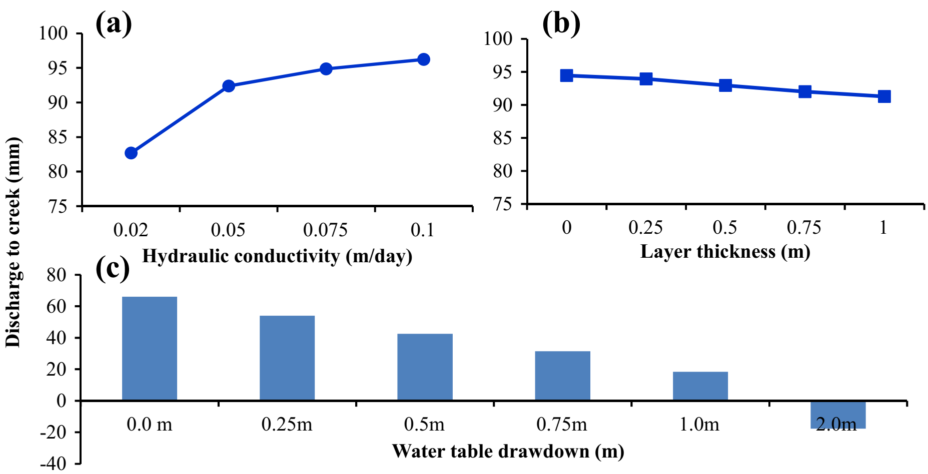

Fig. 5 Changes in the discharge to the creek in relation to **a**) the hydraulic conductivity (*Ks*), **b**) the thickness of the low-permeability layer (*w*), and **c**) the water table depletion at Scott Bottom from 15th July 2005 till 31st December 2006

temporal heterogeneity can cause distinct patterns of dynamics of river seepage in an alluvial aquifer overlying a deep water table and most seepage occurs along preferential flow zones. Nevertheless, these preferential flow paths are difficult to consider in numerical simulations.

The water table decline has a pronounced effect on stream discharge, which continues to decrease linearly with the decrease in the depth to water table (Fig. 5c). Discharge decreased to 18.4 mm with a 1.0-m drop in the water table during the period from 15th July 2005 to 31st December 2006 (535 days). This decrease in discharge is equal to about one-third of discharge under existing conditions. However, detailed simulations of daily values showed that the initial losing state (Fig. 6) at the stream interface was quickly transformed to a discharge state as long as the water table decrease was less than 1 m. This condition resembles the losing-connected stream, as described by Lamontagne et al. (2014). In this situation, the water table is quickly raised near the river by increased infiltration rates, because of a large hydraulic gradient (Rivière et al. 2014). However, a 2.0-m drawdown from the original position produced persistent losing conditions for much longer time (400 days, Fig. 6) as compared to other scenarios. This condition seems to resemble losing-disconnected rivers defined by Lamontagne et al. (2014). Hence, regaining connection or the discharge state does not occur quickly as the infiltration rate is already at its maximal under losing-disconnected rivers (Brunner et al. 2009) and a compensating effect cannot occur rapidly when the regional water table falls. However, the situation (disconnection to connection) here is different from most other conceptual modelling studies (Brunner et al. 2009; Rivière et al. 2014) where flow processes from connection to disconnection of the stream-aquifer are discussed for homogeneous and isotropic conditions. Under natural conditions with complex hydrological heterogeneity and with water table along the slope, flow processes may react quite differently than reported in these studies. Therefore, the process of connection and disconnection seems to depend on site-specific hydrogeological, vegetation, climatic, and aquifer conditions; while treatment and management strategies are thus vary site specific as well.

These results suggest that seasonal water table fluctuations created by low rainfall or groundwater pumping may have a profound impact on the state of the connection between the stream and groundwater. The most crucial impact may be inflicted to the survival of the flora and fauna along the creek that is dependent on the stream flow system for their existence. Future climate change (Beecham 2015) in southern Australia is likely to produce considerable changes in volumes and intensities of rainfall and may have a tremendous impact on the hydrological state of connection in the Scott Creek.

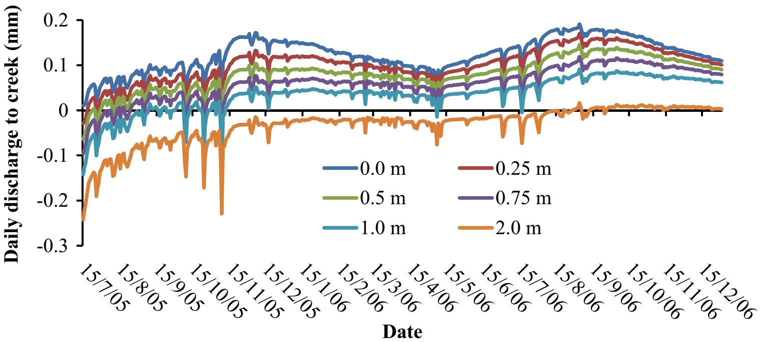

Fig. 6 Simulated daily discharge to the creek at Scott Bottom in relation to the indicated water table depletions at Scott Bottom from 15th July 2005 till 31st December 2006

4 Conclusions

Reliable long-term quantification of discharge fluxes at a stream-aquifer interface is required for the sustainable management of water resources at local and regional level. This study revealed that deep-rooted vegetation and site specific geological heterogeneity play a key role on the nature of hydraulic connection and water-flow patterns at the stream-groundwater interface. The outcomes suggest that when water tables are shallow, deep-rooted vegetation maintains higher *ET* losses for a longer time even during low rainfall periods due to continuous lateral inflow from elevated groundwater zones in the lateral directions. The calibrated and validated model quantified lateral groundwater flow, which maintained the perennial nature of the creek at Scott Bottom even during the drought period. Nevertheless, the overall water balance over 13 years showed more often discharge conditions than recharge under *Eucalyptus* trees. It was highly influenced by precipitation coupled with other hydraulic fluxes like lateral flow and *ET* losses.

It is well known that uncontrolled pumping, depletion of groundwater resources due to land use change, or climate change could have a serious impact on the amount of discharge to a stream. This study showed that a groundwater drawdown of 2 m at Scott Creek could lead to a significant reduction in stream discharge. Gaining systems can quickly become losing systems, which transforms a perennial stream to a seasonal or ephemeral stream. However, a considerable drop in the water table is required before a connected system transitions into a disconnected system. This can have serious implications on the sustainability of ecosystem and a pronounced impact on the management of water resources.

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