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Episodic extreme rainfall events drive groundwater recharge in arid zone environments of central Australia

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ABSTRACT

Understanding the factors controlling groundwater recharge in arid vadose zones is critical for sustainable groundwater management in the face of climate variability and change. Here we estimated groundwater recharge in data sparse regions under arid climate by implementing a multi-model approach using HYDRUS-1D for a century-long time series of meteorological data and site-specific regolith hydraulic properties of a bare soil and a Mulga savanna-type soil in central Australia. Grain-size analysis provided a contiguous 12-m deep profile of hydraulic properties that were generated by means of pedotransfer functions. To account for conceptual model uncertainty in hydraulic properties, eleven pedotransfer functions were applied. Climate data from three stations accounted for spatial heterogeneity in local climate of the Ti Tree Basin study area. Simulated water fluxes in the vadose zone indicated that only rainfall events of more than 150–200 mm resulted in groundwater recharge. Recharge was linked to extreme rainfall associated with monsoonal cyclones. Based on the 130-year climate record, average recharge for the savanna-type vegetation ranged from 4.3 to 7.4 mm/a across the three climate stations, with an overall mean of 4.6 mm/a. The bare soil had an overall mean recharge of 29.5 mm/a, ranging from 23.5 to 35.8 mm/a. Results from this study provide a better understanding of the highly episodic recharge in arid environments and are critical input to sustainably manage groundwater resources.

1. Introduction

In many parts of the world, groundwater is used at a faster rate than it can be replenished by nature, resulting in a continuous decline of groundwater tables (Groundwater Estimation Committee (G.E.C.), 1996; Hughes et al., 2012; Kath et al., 2014; National Research Council, 2012). Facing the threat of water deficits, the accurate quantification of recharge rates and a sound understanding of the effects of climate variations and change on groundwater replenishment are essential for sustainable groundwater management, especially in arid regions with often limited water resources. Determining the sustainability of groundwater resources requires accurate estimates of the groundwater balance, i.e. the storage volumes, extraction and recharge rates (Chen et al., 2014). In semi-arid

Abbreviations: BOM, Bureau of Meteorology; FAO, Food and Agriculture Organization; LAI, Leaf Area Index; PTF, pedotransfer function; SILO, Scientific Information for Land Owners; SPI, Standardized Precipitation Index; USDA, United States Department of Agriculture.

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and arid regions, increasing the reliability of estimates of available water resources will to a large degree depend on the ability to reduce the uncertainty about the rate of groundwater recharge (De Vries and Simmers, 2002; NTGov (Northern Territory Government), 2009; Scanlon et al., 2006).

Main impediments to the estimation of recharge in arid and semi-arid regions are the low values of total annual recharge amounts and the highly infrequent nature of recharge that is not necessarily coupled to seasonality (Berry et al., 2011; Morton et al., 2011). Recharge in arid and semi-arid regions is hypothesised to be highly intermittent and related to extreme precipitation and associated flooding events (Villeneuve et al., 2015). In Australia's arid interior, recharge to aquifers is related to soil infiltration of rainfall during extreme rainfall events, seepage from river channels and other topographic depression, and the infiltration from flood-out areas (Harrington et al., 1999, 2002; Magee, 2009; Read and Tickell, 2007; Zhang et al., 1999a, 1999b).

Recharge estimation in Australia's arid zones have most often relied on the use of environmental tracers. For instance, using a tracer-based approach, Harrington et al. (2002) found that rainfall events of at least 150–200 mm are required to generate significant recharge in the Ti Tree Basin (Northern Territory). Despite numerous other studies on recharge in Central Australia's arid regions (e.g. Calf et al., 1991; Harrington et al., 1999; Harrington et al., 2002; Knapton, 2005, 2006a, 2007; Ride, 1968; Wood et al., 2014), recharge rates are found to vary widely depending on the methodology. For instance, recharge varied between 0.1 and 50 mm/a (mean 3.5 mm/a) based on a C-14 tracer approach while recharge derived from the chloride mass balance method was between 0.1 and 2 mm/a (mean 0.8 mm/a) (Harrington et al., 2002). For the same region, analysis of groundwater level data resulted in a recharge rate of 2 mm/a (NTGov (Northern Territory Government), 2009).

An alternative approach to estimating recharge from tracer analysis is by means of simulation modelling of vadose zone processes (Garcia et al., 2011). Hydrodynamic process-based vadose zone models such as HYDRUS-1D (Šimůnek et al., 2008) are commonly used tools for the estimation of groundwater recharge. However, comprehensive vadose zone modelling is often limited by the requirement for many input parameters for climate, soil and vegetation (Gaiser et al., 2000). Unfortunately, the availability of reliable data on water retention characteristics and hydraulic conductivity of soils in arid and semi-arid regions is often poor (Gaiser et al., 2000). As a result, the complexity and variability of the relationships between rainfall, soil water flow and groundwater recharge remain insufficiently understood. One way to overcome the paucity of soil hydraulic properties is through pedotransfer functions that use readily available soil data in statistical relationships to obtain soil hydraulic properties; they have proven to be a valuable tool to close this data gap (Bouma, 1989; Gaiser et al., 2000; Guber et al., 2006; Guber and Pachepsky, 2010; Jacques and Mallants, 2009; Jaiswal et al., 2013; Pachepsky and Rawls, 2004; Patil and Singh, 2016; Wang et al., 2009; Wösten et al., 2001).

This study uses a numerical multi-model approach to gain a better understanding of highly episodic and landcover dependent recharge in an arid environment by identifying recharge generating events. We analyse local recharge mechanisms and annual recharge rates based on the vadose zone simulator HYDRUS-1D (Šimůnek et al., 2008). We generate hydraulic properties for the approximately 12-m thick unsaturated regolith from a set of 11 pedotransfer-functions (PTFs) that use grain size, organic matter, and bulk density data collected from core samples as predictor variables. Multiple PTFs were used to account for conceptual model uncertainty in generating hydraulic properties. The value of multi-model approaches to address conceptual model uncertainty in hydrogeology was recently highlighted by Enemark et al. (2019). The study area is placed within the Ti-Tree Basin (Northern Territory), located in Australias̀ arid interior. To cover sufficient temporal variability in rainfall data, and thus temporal variability in recharge, meteorological records over a century-long timescale were used. The variability in recharge across the landscape due to spatial variability in climatologic boundary conditions will be tackled by running the simulations for several meteorological datasets recorded

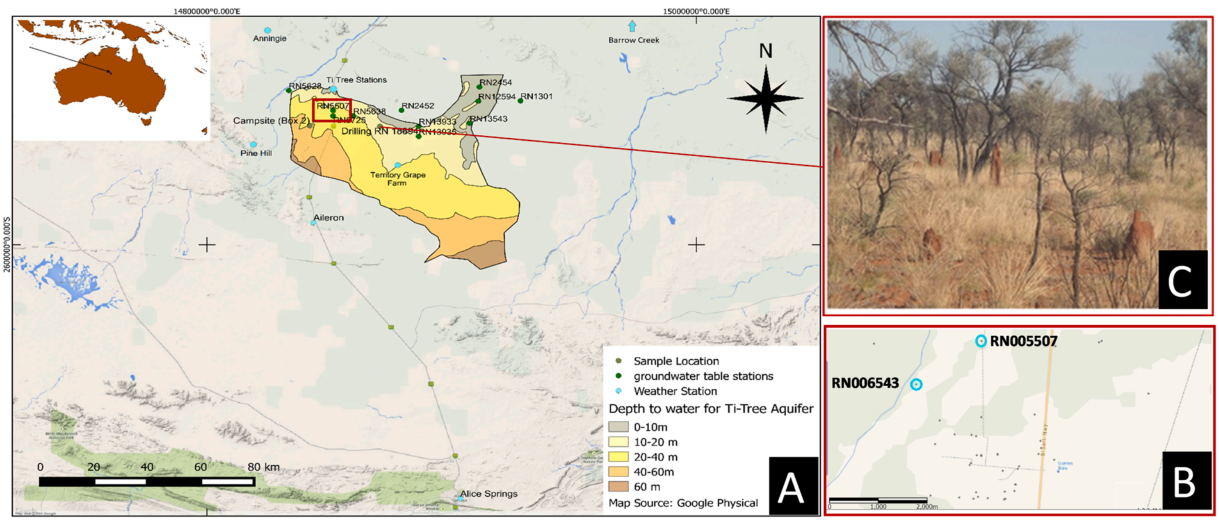

Fig. 1. A: Map of the Ti-Tree basin, Northern Territory, Australia. Colour coding on the map indicates typical groundwater table depths of the Ti-Tree aquifer. B: Inset shows location of groundwater monitoring wells RN005507 and RN006543. C: Typical Mulga savanna vegetation near the borehole site.

at three different weather stations throughout the study area. The effect of landcover variability on recharge was tested by considering a bare soil and a soil covered by a savanna-type vegetation.

2. Materials and method

2.1. Site characteristics

The Ti-Tree Basin covers an area of approximately 5500 km^2 between latitude 22° and 23° south, approximately 200 km north of Alice Springs (Northern Territory, Australia) (Knapton, 2005, 2006a, 2006b) (Fig. 1). The Ti-Tree Basin contains several Cainozoic unconfined or semi-confined aquifers located within the undifferentiated sandy Tertiary and Quaternary sediments (Magee, 2009). The main stratigraphic sequence of the basin is built up by an upper low permeability layer and a basal layer with higher permeability (Magee, 2009). The depth to the groundwater table varies from up to 50 m depth in the south-western and south-eastern parts of the basin to less than 2 m depth in the north (Harrington et al., 2002; Read and Tickell, 2007; Magee, 2009). Natural discharge from the aquifer is mainly limited to the northern part of the basin where shallow groundwater tables result in water loss by evaporation through the vadose zone (Magee, 2009). Among the several monitoring wells in the Ti-Tree Basin, only two (RN005507 and RN006543, Fig. 1) had a sufficiently long record of groundwater levels (between 1970 and 1990) without being influenced by nearby groundwater abstraction for irrigation (data available via Australian Groundwater Explorer, Bureau of Meteorology). Both stations are about 10 km south from the Tea Tree Well climate station and 19 km east from the borehole drilling site (see further). Monitoring well RN005507 has a screen from 46 to 52.4 m below surface in a sand layer (33.8–52.1 m) overlain by a clay layer. Monitoring well RN006543 has its screen from 43.7 to 91.7 m in Tertiary to Quaternary sediments. Groundwater level data will be used in a qualitative comparison with time series of predicted groundwater recharge as a means to test the different PTFs.

The surface hydrology of the basin is determined by four ephemeral rivers and creeks (Harrington et al., 2002). These ephemeral rivers and creeks are flooded only after significant rainfall events, e.g. Villeneuve et al. (2015) documented that the Woodforde River flooded on 34 occasions in 16 years (Villeneuve et al., 2015).

The predominant soil types are red earthy sands with fine to medium grain sizes (silt loam) covering most of the surface area in the central basin. Alluvial deposits such as gravels and coarse sands are found in the main surface drainage lines, Hanson River, Woodforde River and Allungra Creek (Harrington et al., 2002; Magee, 2009).

2.2. Climate

The Ti-Tree Basin is located within the arid zone of Central Australia (Köppen classification: BW Desert Climate). The region is characterised by moderate dry winters (May–October) and hot long summers (November–April) with daily temperatures often exceeding 40 °C. An average annual precipitation rate of 320 mm/a (1981–2016 average) and an average number of 30 rain-days per year were measured at the meteorological station Territory Grape Farm Station in the centre of the basin (BOM (Bureau of Meteorology, Australia), 2015, 2016).

The actual evapotranspiration rate in the region was estimated by the Australian Bureau of Meteorology (BOM) to be around 300–400 mm/a. Arid regions in Central Australia experience most of the annual rainfall during extreme rainfall events in the summer months. Those events are generally linked to monsoonal thunderstorms that arise in the tropics, travel southwards and precipitate over Central Australia (Hobday and Lough, 2011). Thus, spatial and temporal variability of precipitation can be very high throughout the basin. To account for the spatial variability in rainfall, climate records from three nearby stations were used.

Meteorological data including daily precipitation, wind speed, solar radiation, and maximum and minimum temperatures were gathered from the Scientific Information for Land Owners (SILO) project website. The SILO database provides patched point datasets on a daily time step constructed from observational data. In this study a time series of approximately 130 years (1889–2016) was available for two weather stations within the study area, i.e. Tea Tree Well at 19 km and Territory Grape Farm at 52 km from the centre of the Basin, and one station outside the Basin, i.e. Alice Springs Airport (at 164 km from the centre of the Basin) (Fig. 1).

2.3. Vegetation

Evapotranspiration plays an important role in regional water balance assessments especially in arid and semi-arid regions where the potential evapotranspiration (pan evaporation in Ti-Tree is about 3100 mm/a (Jeffrey et al., 2001)) equals or surpasses average precipitation (National Research Council, 2004). The importance of vegetation on infiltration rates and hydrologic fluxes in the vadose zone of arid climates has been studied in detail (e.g. Chen et al., 2014; Eamus et al., 2013; Dunkerley, 2002; Garcia et al., 2011; Scanlon et al., 2005, 2006). Simulated recharge rates at 4 m soil depth for the Ti-Tree Basin by Chen et al. (2014) varied from an average of 6 mm per year for vegetated soil to an average of 236 mm per year for bare soil (for relatively short timeseries, 1981–2012). Several lysimeter studies in arid environments showed that evapotranspiration from vegetated soils were up to 10 times higher than evaporation rates from bare soils at the Nevada Test Site (US) (Scanlon et al., 2002, 2005; Walvoord et al., 2002, 2004). Studies of recharge rates in un-vegetated and vegetated areas in the Tengger Desert (China) and the Chihuahuan and Mojave Deserts (US) indicated that vegetation inhibited recharge up to 100% (Wang et al., 2004; Scanlon et al., 2005).

Vegetation in the Ti-Tree Basin is limited in its diversity due to the arid climatic conditions. The most common vegetation are small Mulga trees (*Acacia aneura* and related species, Fig. 1) that grow predominantly on dark red massive clay and loam rich soil and large areas of Spinifex grass (*Trioda spp.*) that cover the better drained red earthy sands. Mulga shrubs generally reach a canopy height of

2–8 m with an average height of about 6.5 m and a relatively shallow rooting depth (Chen et al., 2014; Eamus et al., 2013). Studies by Anderson et al. (2008) and Hill and Hill (2003) indicated that root water uptake by Mulga trees becomes irrelevant at soil depths greater than 5 m, even under extremely dry conditions. Chen et al. (2014) and Eamus et al. (2013) derived a maximum rooting depth for Mulga trees of 4 m. Estimated leaf area indices (LAI) for vegetation in the Ti-Tree Basin ranged from 0.12 to 0.35 for the overstory canopy and 0.07–0.21 for the understory canopy (Chen et al., 2014). Other literature values for Mulga LAI ranged from 0.2 to 0.3 (e.g. Cleverly et al., 2013; Eamus et al., 2013). In this study, the rooting depth and root distribution data after Cleverly et al., (2013, 2016) and average LAI values after Chen et al. (2014) were applied because their study sites coincided with ours. The effects of vegetation on groundwater recharge rates were evaluated by performing alternative simulations for a bare soil and for a savanna-type vegetation (i.e. Mulga).

2.4. Soil sampling and analysis

Undisturbed core samples were obtained from a drill core collected in the centre of the basin (RN018894C; 133.586059 Long, − 22.282595 Lat) and were taken every 0.5 m from 0 to 12 m depth. The water table in the borehole was recorded to be deeper than 12 m. The relatively homogenous regolith profile consisted mostly of loamy sands and sands showing layering of silt loams towards the top of the profile (at 0 – 2 m and 2.5 – 3.5 m depth). Grain size measurements and physical properties (i.e. gravimetric water content, pore water suction, dry bulk density, and solid density) of regolith cores were determined to provide input data for the pedotransfer functions. The simplified regolith profile consists of 8 lithologic layers, varying from 50 to 250 cm in thickness (Fig. 2). Three materials (horizons) are distinguished (USDA (United States Department of Agriculture), 1951 taxonomy used): silt loam, loamy sand, and sand. The clay content for all three materials was rather low (i.e. less than 11%).

2.5. Pedotransfer functions

Detailed parameterisation of soil water retention characteristics and the hydraulic conductivity are required for any vadose zone flow modelling (Guber et al., 2006; Wang et al., 2009; Wösten et al., 2001). However, temporal and spatial variability in hydraulic characteristics of the soil as well as costly and time-consuming measurements with sophisticated instruments often impede the collection of field data on water retention characteristics, especially if large areas need to be covered. Pedotransfer functions (PTFs) have proven to be a cost-effective tool for the estimation of soil hydraulic properties based on readily available soil data such as textural fractions, bulk density, and organic matter content (Guber et al., 2006; Jacques and Mallants, 2009; Minasny and McBratney, 2000; Vereecken et al., 1989; Wang et al., 2009; Wösten et al., 2001).

To account for conceptual model uncertainty in generated soil hydraulic properties, we adopted a multi-model approach using eleven different PTFs. The selection of PTFs was based on available input data obtained from core samples and on their applicability to

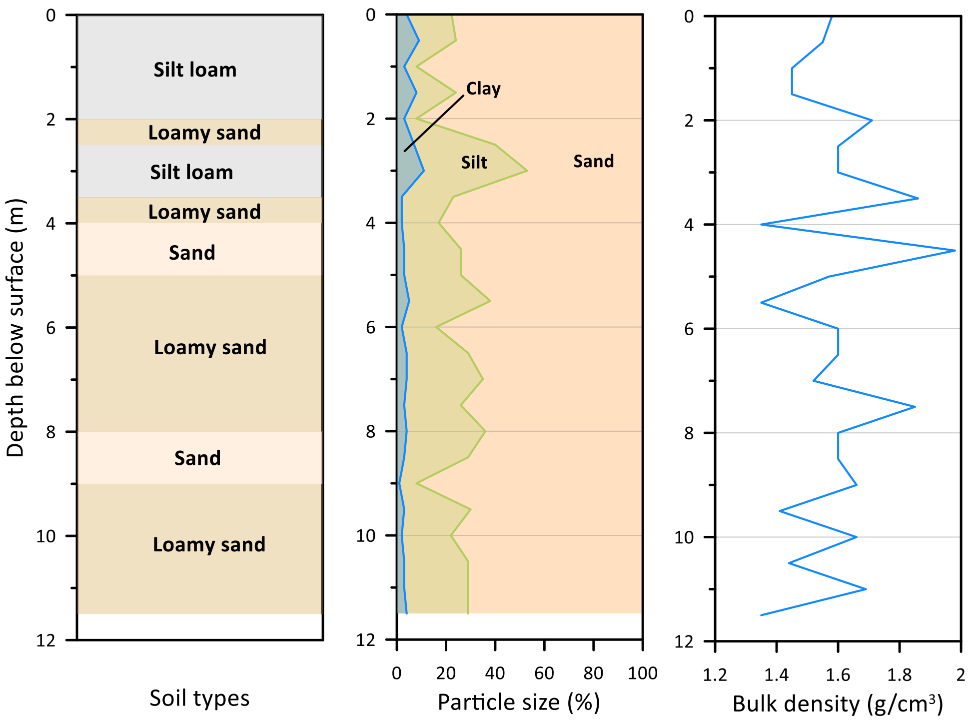

Fig. 2. (a) Lithological profile with soil materials, (b) particle size distribution and (c) bulk density.

Table 1
PTFs used in this study, number of soil samples used to derive the PTFs, and basic input soil parameters. Between brackets the region with sampled soil data to derive the original PTFs: B = Belgium, EU = Europe, F = central France, H = Hungaria, R = Romania, US = United States of America.

PTF			Number of samples	Sand content [%]	Silt content [%]	Clay content [%]	Organic Carbon [%]	Organic Matter [%]	Bulk density [g/cm^3]
Point Estimation	**1**	Bruand et al. (1994)	20 [F]			+			
	2	Canarche (1993)	Unknown [R]			+			+
	3	Gupta and Larson (1979)	43 [US]	+	+	+		+	+
	4	Hall et al. (1977)	261 [UK]		+	+			+
	5	Petersen et al. (1968)	1267 [US]			+			
	6	Varallyay et al. (1982)	Unknown [H]	+	+	+		+	
Para-metric	**7**	Vereecken et al. (1989)	182 [B]			+	+		+
	8	Wösten et al. (1999)	4030 [EU]	+	+	+		+	+
Class Averaged	**9**	Meyer et al. (1997)	[US]	average parameter for USDA classification					
	10	Schaap et al. (2001)	–	Rosetta computer programme					
	11	Wösten et al. (1999)	5521 [EU]	average parameter for FAO subsoil classification					

generate the van Genuchten-Mualem model parameters (Mualem, 1976; van Genuchten, 1980) that were used for the numerical simulations with HYDRUS-1D. The parametric van Genuchten water retention model describes the mathematical relation between soil pressure head h (L) and the soil moisture content θ (L^3/L^3) (van Genuchten, 1980):

$$\theta(h) = \theta_r + \frac{(\theta_s - \theta_r)}{(1 + |\alpha h|^n)^m} \quad (1)$$

where θ_r and θ_s are the residual and saturated water content [L^3/L^3], respectively, and α [L^{-1}], n [-], and m [-] (= 1 − 1/n) are curve

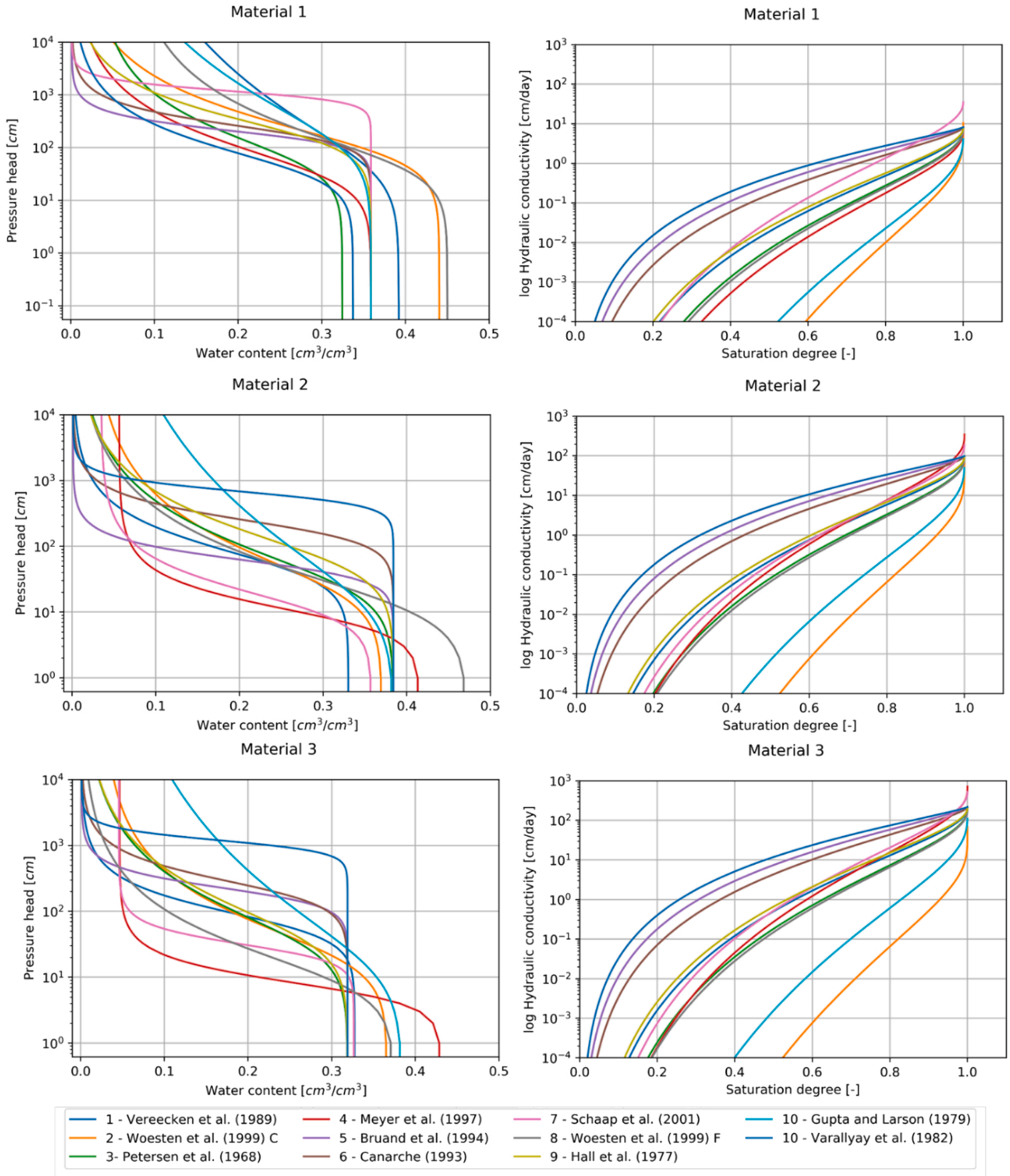

Fig. 3. Water retention curves (left) and hydraulic conductivity curves (right) calculated with the different PTF approaches for material 1 – silt loam, material 2 – loamy sand and material 3 – sand. The legend numbering of PFT approaches indicates the ranking of mean annual recharge estimates for vegetated soil from highest to lowest (see Supp. Mat. 4).

shape parameters. The van Genuchten-Mualem model (Mualem, 1976) unsaturated hydraulic conductivity relationship, is defined by the:

$$K(S_e) = K_s S_e^l \left[1 - \left(1 - S_e^{\frac{1}{m}} \right)^m \right]^2 \tag{2}$$

where K_s is the saturated hydraulic conductivity [L/T], $S_e = (\theta\text{-}\theta_r)/(\theta_s\text{-}\theta_r)$ is effective saturation [-], and l is the pore connectivity parameter [-] set to 0.5 (Mualem, 1976).

Three types of PTFs were used: point estimation, parametric, and class PTFs. PTFs based on point estimation (Table 1: PTFs 1–6) generate specific water content-pressure head points {θ, h} on the water retention curve. Most commonly, the soil water content at field capacity (− 33 kPa) and at the permanent wilting point (− 1500 kPa) is estimated. Those two-point estimates are necessary to determine water availability for plants (Minasny et al., 1999). The point estimation PTFs used in this approach provided only those two points of the soil water retention curve. Two additional points were generated by fixing the residual water content θ_r at 0.001 [L^3/L^3] while the saturated water content θ_s was set equal to the total porosity (η) derived from the measured bulk density, fixing mineral density at 2.65 g/cm^3 (e.g. Jacques and Mallants, 2009). This approach generates a total number of four {θ, h} data points that are used as input for the nonlinear least-squares optimisation program RETC to fit the van Genuchten parameters (θ_r, θ_s, α and n) (van Genuchten et al., 1991).

Parametric PTFs (Table 1: PTFs 7–8) consist of parametric functions that can be used to directly predict parameters of a certain retention model such as the van Genuchten-Mualem model (Mualem, 1976; van Genuchten, 1980), the Brooks and Corey (1964) model or the Campbell (1974) model. As such, those PTFs yield continuous water retention curves and are therefore considered very suitable for soil-water balance modelling. Finally, class averaged PTFs (Table 1: PTFs 9–11) provide average estimates of soil hydraulic properties based on textural classes in the USDA (United States Department of Agriculture) (1951) or the FAO (Food and Agriculture Organisation) (1990) classification schemes.

The resulting van Genuchten (1980) water retention curves from using the eleven PTFs for the three identified soil materials, silt loam, loamy sand and sand are illustrated in Fig. 3 (for parametric values see Supp. Mat. 1–3). In general, water retention curves display a similar shape with an expected degree of conceptual variability. However, there are some curves that deviate from the main group, including the PTF of Varallyay et al. (1982) and Gupta and Larson (1979). Both are point estimation PTFs.

The point estimation PTF by Gupta and Larson (1979) predicts a retention curve which has the overall smallest n-parameter for material 2 (1.192) and 3 (1.134) combined with a large α-parameter for material 2 (0.713) and material 3 (0.107). The curves show a relatively straight trend with relatively high water contents even at high negative pressure heads. As will be shown later, simulations with soil properties calculated with the PTF by Gupta and Larson (1979) result in the lowest and second-lowest recharge for the bare and vegetated soil, respectively.

Water retention curves estimated with the PTF by Varallyay et al. (1982) show another distinct trend where the water content barely changes up to negative pressure heads of around 1000 cm (material 1 and 3) and 500 cm (material 2), consistent with the very small values for the α parameter (Supp. Mat. 2–3). For the vegetated soil this PTF results in the lowest recharge whereas for a bare soil the recharge ranks 7/11 (see further).

A 12-m deep regolith profile with hydraulic properties was generated from each of the 11 PTFs. The ensemble of profiles thus generated is considered to capture conceptual uncertainty associated with the soil hydraulic models which are highly approximative, an inherent drawback of PTFs (Espino et al., 1995).

Only a limited number of PTFs applied in this study also provided an approach to estimate the saturated hydraulic conductivity (K_s). The saturated hydraulic conductivity was calculated with the class averaged PTFs by Meyer et al. (1997), Schaap et al. (2001) and Wösten et al. (1999). Rawls et al. (1998) calculated median values of the saturated hydraulic conductivity for 12 different USDA textural classes in an analytical approach (Guber et al., 2006; Rawls et al., 1998). Average values of K_s for 12 USDA textural classes reported by Rawls et al. (1998) were used here for the PTF models that did not provide estimates of K_s (i.e. all parametric and point estimation PTFs). As a result, the variability in hydraulic conductivity relationships will be smaller compared to the variability of water retention curves. However, even though mean values of the hydraulic conductivities from Rawls et al. (1998) were combined with most of the PTF-generated water retention curves, unsaturated hydraulic conductivity curves plotted versus the saturation degree (S_e) (Eq. (2)) still display significant differences as they use parametric values for α and n from their respective water retention models (Fig. 3).

2.6. Multi-model recharge simulation

The numerical model was set up within HYDRUS-1D (Šimůnek et al., 2008), which uses a finite element scheme to numerically solve the Richards equation for variably-saturated flow. Soil hydraulic properties are described using the analytical functions by van Genuchten (1980) and Mualem (1976), see Eqs. (1) and (2). Simulations were conducted for each of the 11 different profiles of soil hydraulic properties. To account for spatial variability in climate throughout the basin, three different meteorological input datasets were applied for each of the soil datasets. Time series of daily meteorological data span the period from January 1889 to December 2015. Although only two out of three climate stations are within the catchment boundary (Tea Tree Well and Territory Grape Farm) and located relatively close to the studied soil profile, we assumed that similar soil profiles exist at or nearby the Alice Springs station located outside the catchment. Each simulation was run for a bare soil and for a vegetated soil to quantify the effect of plant water uptake on recharge. Runoff and hysteresis were considered negligible in this study. Initial conditions of the water content were selected to be at field capacity. In HYDRUS-1D the 'atmospheric upper boundary condition with surface layer' was selected which allows water to build up on the soil surface once the infiltration capacity has been exceeded. The depth of this ponding water layer will increase with precipitation and decrease due to infiltration and evapotranspiration (Šimůnek et al., 2013). The maximum ponding depth prior to runoff initiation was set to 10 cm in order to display realistic conditions for depression storage in desert soils (e.g. Garcia et al., 2011), especially during cyclone events. The lower boundary condition was set to free drainage, a condition which is applied when the water table lies well below the bottom of the soil profile (Šimůnek et al., 2013), here deeper than 12 m. Average values for the specific leaf area index (LAI) of Mulga vegetation found in literature ranged from 0.2 to 0.3 (e.g. Chen et al., 2014; Cleverly et al., 2013; Eamus et al., 2013). The mean annual LAI for Mulga vegetation reported by Chen et al. (2014) from the same study site as ours ranged from 0.12 to 0.35 m^2/m^2 for the overstory canopy and 0.07–0.21 m^2/m^2 for the understory canopy. In this study, we applied an average canopy height of 6.5 m, a mean rooting depth of < 5 m and an average annual LAI of 0.3 m^2/m^2 based on the studies mentioned above.

3. Results

3.1. Rainfall statistics

Mean annual rainfall amounts recorded at the three different pluviographic stations ranged from 262 mm/a at Alice Springs Airport, 277 mm/a at Tea Tree Well up to 320 mm/a at Territory Grape Farm. Due to the daily resolution of the applied SILO climate datasets (BOM (Bureau of Meteorology, Australia), 2016), rainfall events were defined as a continuous time period of rainfall separated by at least 24 h of dry weather conditions. Using this definition, a single rainfall event can include several bursts of rainfall with short periods (i.e. < 24 h) of dry weather in between. Heavy rainfall events were defined as events of 100 mm of rainfall or more and further

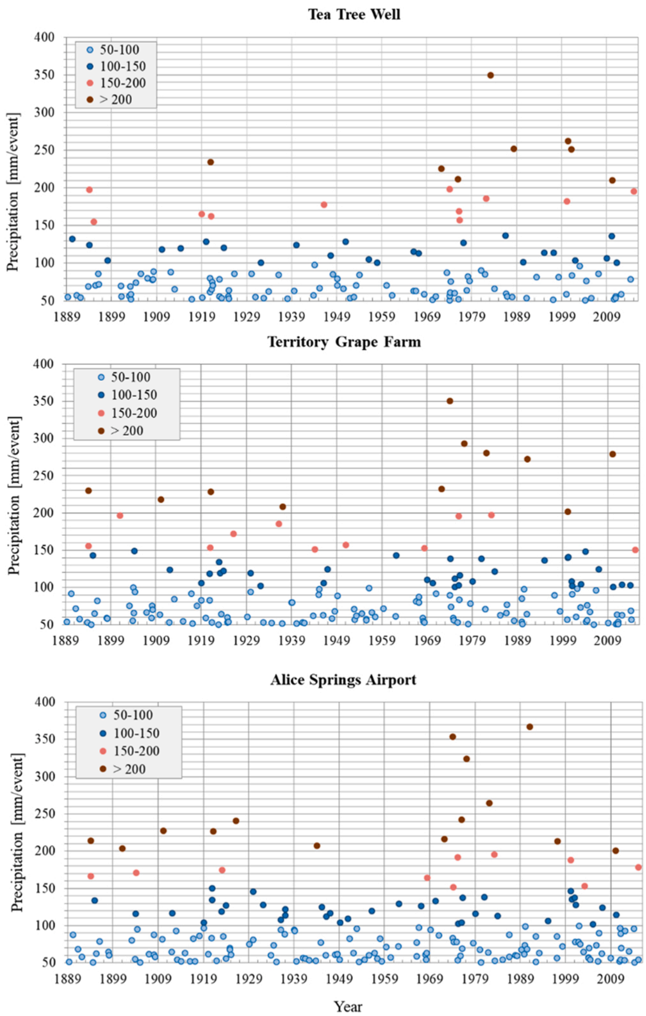

Fig. 4. Rainfall events at Tea Tree Well, Territory Grape Farm and Alice Springs Airport from 1889 to 2016.

differentiated into extreme rainfall events if the total amount of rain exceeded 150 mm or more (Fig. 4).

Rainfall events of 50–100 mm precipitation were found to occur approximately every year. Rainfall events of 100–150 mm were recorded with an average return period of approximately 3.5 years at the weather stations Tea Tree Well and Territory Grape Farm and Alice Springs Airport, and less frequent with approximately 5 years recurrence period at Tea Tree Well (Fig. 5). These heavy rainfall events up to 150 mm were generally most likely to occur during the summer wet season (December–February). Extreme rainfall events with total rainfall amounts between 150 and 200 mm were found to have an average return period of approximately 9 years at Alice Springs Airport and 11.6 years at Tea Tree Well and Territory Grape Farm. Events with more than 200 mm of precipitation occurred less frequent at Tea Tree Well station (approximately once every 16 years) than at Alice Springs Airport (once every 12.8 years), while at Territory Grape Farm they are equally frequent as the 150–200 mm events. Most of the 150–200 mm and > 200 mm events took place between February and April during the summer monsoon season (November–April) and can be linked to the El Niño–Southern Oscillation (ENSO) (King et al., 2014).

3.2. Simulated soil water balance for vegetated soil

Estimated mean annual recharge rates for a Mulga savanna-type vegetated soil calculated for the three weather stations ranged from 0.18 (model 4) to 27.03 (model 7) mm/a between the different PTF models, with an average of 5.49 mm/a across all three stations and all PTF models (Fig. 6) (see Supp. Mat. 4 for details). In general, estimated recharge rates are highest for the Tea Tree Well with an average annual recharge rate of 7.36 mm/a compared to the Territory Grape Farm (4.87 mm/a) and the Alice Springs Airport (4.25 mm/a) datasets. The uncertainty in hydraulic properties captured by the multi-model approach is largest for the Tea Tree Well site (range is from 0.18 to 27.03 mm/a) and smallest for the Alice Springs Airport dataset (range is from 0.18 to 15.12 mm/a).

Estimated mean annual actual evapotranspiration rates for bare soil ranged from about 368 mm/a (class averaged PTF by Wösten et al., 1999) to approximately 268 mm/a (point estimation PTF by Varallyay et al., 1982), averaging at about 317.7 mm/a. Root water uptake (plant transpiration) ranged greatly between the different models, from 33 mm/a (point estimation PTF by Varallyay et al., 1982) to 130 mm/a (parametric PTF by Vereecken et al., 1989) (Supp. Mat. 5).

For vegetated soil, the three lowest recharge rates were all from point estimation PTFs (models 6, 3, and 4), while the highest and second highest recharge were from a parametric (model 7) and a class averaged (model 11) PTF. The overall lowest recharge rates were simulated using soil hydraulic properties calculated with the point estimation PTFs by Varallyay et al. (1982) (model 6), Gupta and Larson (1979) (model 3), and Hall et al. (1977) (model 4). The largest recharge (27.0 mm/a) was 150 times larger than the smallest (0.18 mm/a). The estimation of soil hydraulic properties with the PTF model by Varallyay et al. (1982) resulted in water retention curves that were very similar for the three soil materials, with the parameters $\alpha = 0.001$, 0.002, 0.001 and $n = 4.3$, 4.185, 4.957 for materials 1, 2, and 3 respectively, and a distinct shape that is more typical for a clayey soil. During major precipitation events, rainfall rates easily exceed the infiltration capacity of the soil with water then building up on the surface and evaporating. This is reflected in the low water uptake by transpiration and high evaporation rates calculated with the PTF model by Varallyay et al. (1982).

The Gupta and Larson (1979) PTF is distinct from the others as it has the overall smallest n parameters for all three materials, typical of a clay soil. This results in unsaturated hydraulic conductivity values that are much smaller than all the other models (Fig. 3), reducing the ability of the model to transmit water to deeper layers.

The hydraulic properties generated with the PTF model 4 by Hall et al. (1977) also resulted in relatively low recharge rates (0.38 mm/a). The ability to retain more soil moisture in the surface layers resulted in estimated transpiration rates that were moderately higher compared to the other point estimation models (102 mm/a compared to 85 mm/a for model 3), thus most of the infiltrating water did not pass the root zone (Supp. Material 5).

The parametric PTF model by Vereecken et al. (1989) (model 7) and the class averaged PTFs by Meyer et al. (1997) (model 9) and Wösten et al. (1999) (model 11) resulted in the highest station-averaged recharge estimates (20 mm/a, 7 mm/a, and 14.1 mm/a). The corresponding water retention curves are more characteristic for sandy soils that release pore water relatively easy for all three materials (Fig. 3).

Actual evapotranspiration rates among the three sites displayed a different behaviour compared to recharge (Supp. Material 5). Tea Tree Well now has the largest uncertainty (range is from 277.57 to 357.27 mm/a), while Alice Springs airport has the smallest

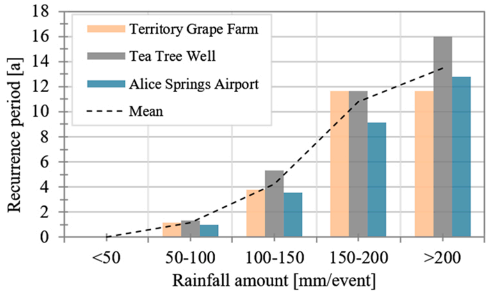

Fig. 5. Recurrence period of rainfall events with different magnitudes at Territory Grape Farm, Tea Tree Well, Alice Springs Airport and mean over all the three weather stations (1889–2016).

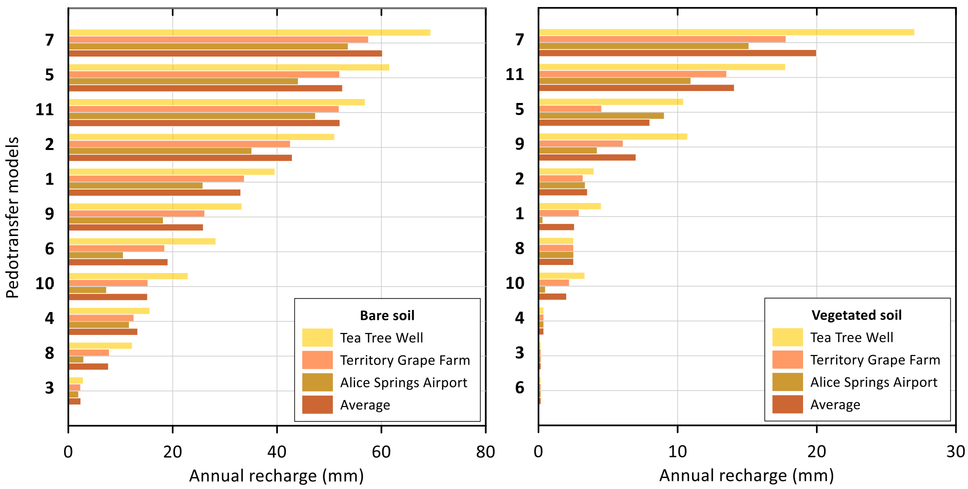

Fig. 6. Mean annual recharge for bare soil (left) and vegetated soil (right) for individual weather stations and averaged over weather stations (for pedotransfer models see Table 1).

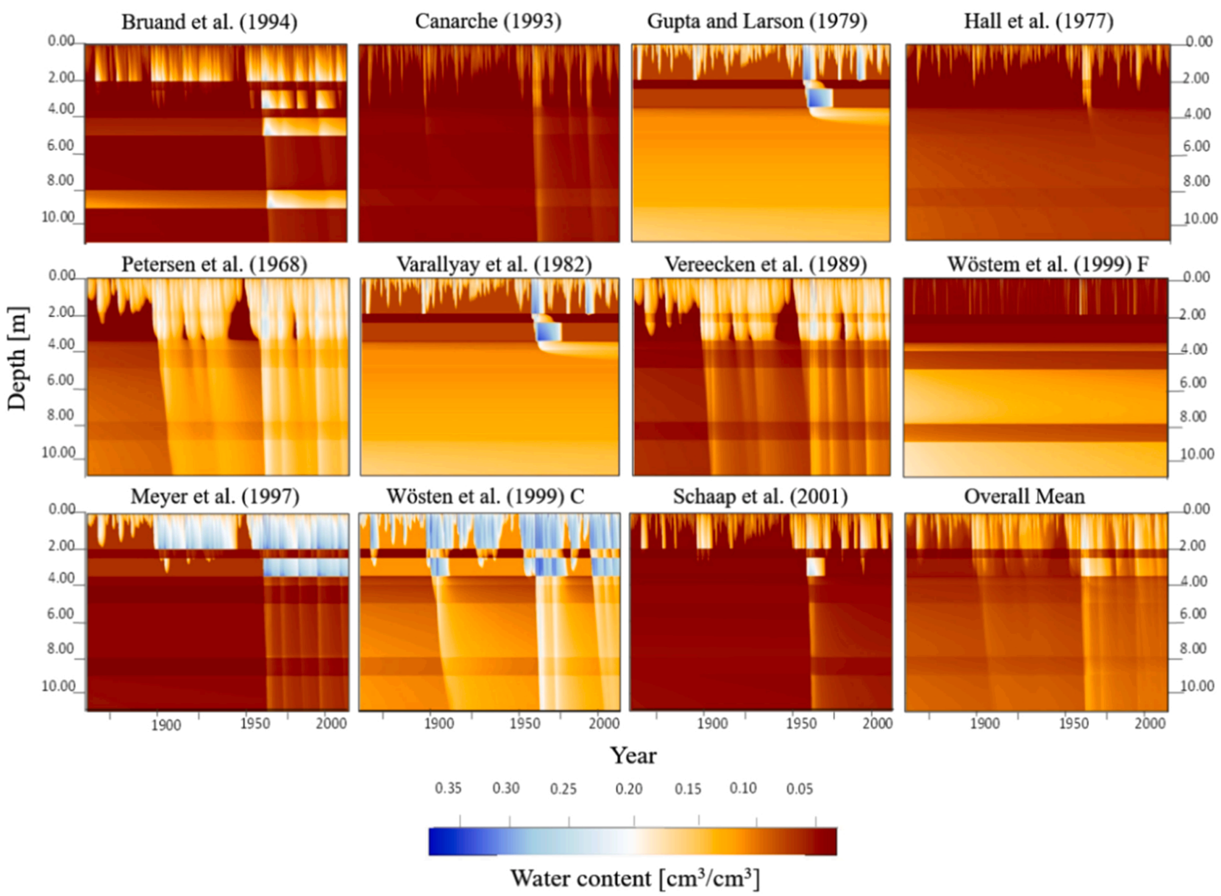

Fig. 7. Detailed moisture content time series throughout the vegetated regolith profile for the Tea Tree Well dataset calculated for 11 PTF models; the overall mean moisture profile is also included. (Graphics created with R - language and environment for statistical computing and graphics).

uncertainty (range is from 299.33 to 338.53 mm/a).

3.3. Simulated soil water balance – bare soil versus vegetated soil

As is evident from the previous discussion, water uptake by plants exerted a significant influence on recharge estimates, with all estimates equal to or smaller than 20 mm/a. Simulated recharge rates for a bare soil, on the other hand, were up to 157 times higher (28.3 versus 0.18 mm/a) than for a savanna-type vegetation when calculated with the PTF model after Varallyay et al. (1982) and about 5 times higher than the average of all PTFs (29.5 versus 5.5 mm/a) (Fig. 6 and Supp. Mat. 4). The smallest difference between bare and vegetated was about a factor 2.5, using the PFT model from Vereecken et al. (1989). The overall largest recharge value for bare soil at Tea Tree Well, Territory Grape Farm, and Alice Springs Airport was 69.45, 57.52, and 53.63 mm/a, respectively (Supp. Mat. 5). The largest recharge (69.5 mm/a) was 24 times larger than the smallest (2.9 mm/a).

Estimated mean annual evaporation rates from the bare soil ranged from 218.03 mm/a calculated with PFT after Bruand et al. (1994) for Alice Springs Airport to 276.71 mm/a calculated with the class averaged PTF by Wösten et al. (1999), averaging at about 245.50 mm/a. The highest estimate of evaporation (264 mm/a) was up to 1.2 times higher than the smallest estimate (219 mm/a) for all three stations, thus showing a very similar range between the different PTF approaches compared to simulated evapotranspiration rates (highest 1.25 times larger than smallest). The variation in evapotranspiration introduced by using different PFTs is thus much smaller than the variation in recharge. Thus, different components of the soil water balance display different sensitivity towards the use of different PTFs.

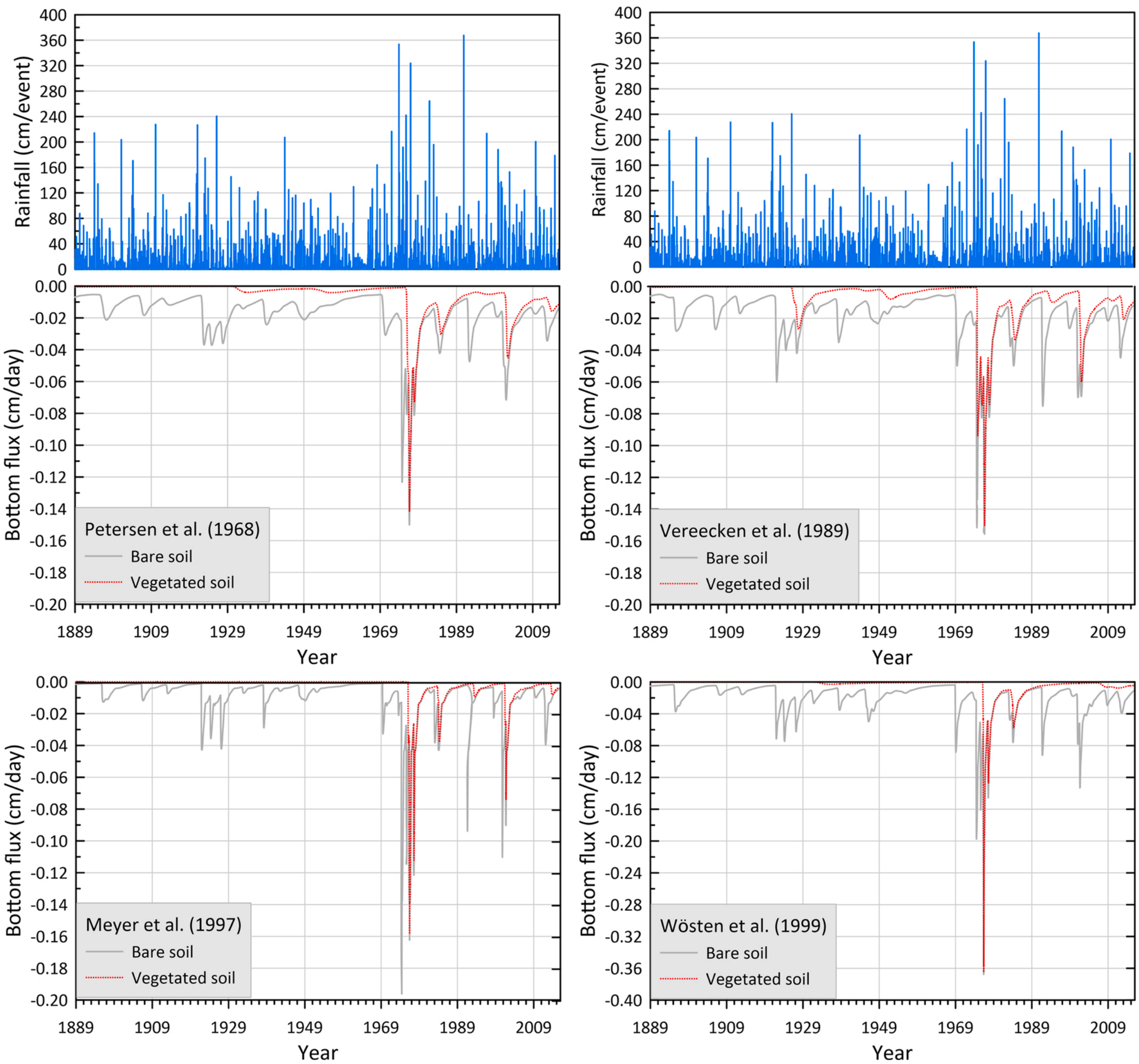

Fig. 8. Water flux at the bottom of the soil profile for PFTs 5, 7, 9, 11 for 1889–2016 time series forced with Tea Tree Well dataset and corresponding rainfall events at the same station.

Because considerable portions of the arid zone landscape where recharge occurs have patches of bare soil (Cleverly et al., 2013), large spatial heterogeneity in recharge is expected based on the above differences between bare and vegetated surfaces. Such heterogeneities complicate the estimation of regional scale recharge values and require explicit consideration of land cover variability for recharge calculations. Topographic depressions that accumulate runoff will further contribute to recharge heterogeneity. An example of such focused recharge is available from Wood et al. (2017) who, using a groundwater model calibrated to C-14 and hydraulic head data, found the highest recharge rates (between 10 and 15 mm/a) in the inferred flood out area of the Allungra Creek (Ti Tree basin).

3.4. Space-time analysis of intermittent recharge

Numerically simulated water contents for vegetated soil in the unsaturated regolith displayed in a space-time window illustrate the relationship between extreme rainfall events at the Tea Tree Well climate station and deep recharge at the bottom of the 12 m model profile (Fig. 7). These graphs were based on simulated grid data with a vertical spatial resolution of approximately 1 cm (i.e., 1000 data points) and a temporal resolution of 134 days (346 data points). This dataset revealed the highest number of recorded extreme rainfall events and resulted in the highest simulated recharge rates.

The depth-time visualisations of simulated water content based on the PTF models by Gupta and Larson (1979), Hall et al. (1977) and Varallyay et al. (1982) illustrate that the water content in the bottom layer barely changes over the entire time series and that the major amount of infiltrating water did not pass through the root zone and thus did not reach the bottom of the soil profile. These models resulted in the lowest estimates of mean recharge rates.

Simulations based on the PTF models by Vereecken et al. (1989), Meyer et al. (1997), Petersen et al. (1968) and Wösten et al. (1999) resulted in the highest estimates of annual recharge. This is also reflected in the corresponding visualisations of the water content distribution throughout the profile that illustrate elevated water contents in the bottom layer of the profile after extreme rainfall events (Fig. 7). The corresponding bottom flux at the lowest layer of the soil profile for both bare and vegetated soil is illustrated for these PFT models in Fig. 8.

4. Discussion

The large variation in water retention curves and hydraulic conductivity relationships and the corresponding variation in estimated recharge emphasises the large conceptual model uncertainty introduced when estimating soil hydraulic properties using different PTFs. The significant difference in estimated soil hydraulic properties emphasises the importance of a multi-model approach in order to capture such uncertainty and provide an ensemble of outputs rather than a single output based on a single PTF (e.g. Wang et al., 2009). Our study revealed that the recharge component of the water balance model is most sensitive to the specified soil properties, especially to those of the upper soil layer. Guber et al. (2006) stated that the uncertainty in PTF predictions due to their use outside of the geographical regions where they were derived represents one of the major limitations about PTFs. In this study, no PTFs developed for Australian soils were implemented although several studies regarding water retention characteristics are available for Australian soils (Bristow et al., 1997; Cresswell and Paydar, 1996; Kaur et al., 2002; Williams et al., 1992; Smettem and Gregory, 1996). Minasny et al. (1999) noted that, due to the distinctive properties of Australian soils, PTFs developed for other regions might not be suitable to yield appropriate estimates when applied to Australian soils. Despite these recommendations, many studies have used a range of PTFs developed for various types of soil from specific geographical regions for the estimation of soil hydraulic properties in other regions (e.g. Cresswell et al., 2006; Jacques and Mallants, 2009; Wang et al., 2009). Thus, rather than using a single PTF, multiple PTFs were used

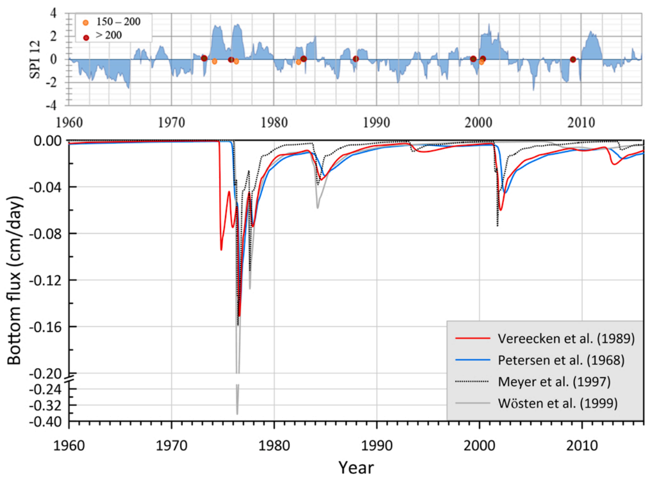

Fig. 9. (Top) Standardized Precipitation Index (SPI - 12) at Tea Tree Well with rainfall events of 150–200 mm and > 200 mm indicated in orange and red respectively, and (bottom) water fluxes at the bottom of the soil profile, simulated with PTFs 5, 7, 9 and 11 for vegetated soil between 1960 and 2016.

in this study to account for conceptual model uncertainty in generating soil hydraulic properties as proposed by several authors (e.g. Gaiser et al., 2000; Guber et al., 2006; Jacques and Mallants, 2009; Wang et al., 2009; Wösten et al., 2001).

This approach yielded average annual recharge rates for a vegetated soil of approximately 5.49 mm/a (station-averaged range: 0.18–20 mm/a), which is roughly consistent with results from previous studies in the same study area but using different approaches. Harrington et al. (2002) conducted a study in the Ti-Tree Basin using radiocarbon (^{14}C) as a tracer for local groundwater recharge and estimated recharge rates in flood-out areas along the ephemeral streams Woodforde River and Allungra Creek ranged from approximately 0.2 to 50 mm/a, while estimated rates of diffuse recharge for other regions in the basin were generally less than 1 mm/a. Another approach based on the chloride mass balance method by the same authors resulted in recharge rates with a range of 0.1 to approximately 2 mm/a. In a modelling study in the Ti-Tree Basin, Chen et al. (2014) used the coupled water and carbon ecohydrological model WAVES (Water Atmosphere Vegetation Energy and Solutes) and found annual mean average recharge rates of approximately 6 mm/a under Mulga vegetation. Harrington et al. (2002) used the stable isotopes deuterium (^{2}H) and oxygen-18 (^{18}O) as tracers to identify the spatial extent of local and diffuse recharge mechanisms. They concluded that groundwater had been evaporated to a certain extent prior to recharge due to its isotopic composition. By comparing the general trend of groundwater ^{2}H and ^{18}O compositions relative to the mean composition of monthly rainfall and the rainfall line, the authors found that events of 150–200 mm rainfall are required to provide significant recharge. Furthermore, large variations in measured ^{2}H and ^{18}O compositions of the basińs groundwater indicated large spatial and temporal variability in recharge rates and recharge mechanisms throughout the basin (Harrington et al., 2002).

While these observations are consistent with our numerical study, simulated fluxes at the bottom of the regolith profile over a century-long time scale realised in this study indicated that only events of more than 200 mm led to a significant replenishment of the aquifer. The simulated bottom flux response to extreme rainfall events for most selected PTFs also correlates well with relatively high values for the Standardized Precipitation Index (SPI) (Fig. 9). The SPI represents a probability index for the identification of wet and dry climatic cycles that can be used as an indicator for soil moisture (small time scales of several months), reservoir storage and groundwater table development (long time scales of 12 months or more) (McKee et al., 1993). Negative values indicate various levels of drought, with values as low as − 2 referred to as extreme drought (McKee et al., 1995). Although this study focusses on wet conditions and not on drought, the positive SPI values are a useful indicator of recharge-generating wet spells. The SPI used in our study compared 12 consecutive months of precipitation record to the mean value based on the long-term precipitation record. The highest consecutive SPI for several months was reached in 1974 and 1975 where the SPI reaches up to 3 for almost two years except for a short period in between. During this time, two relatively short separated > 200 mm events were recorded at Tea Tree Well. The

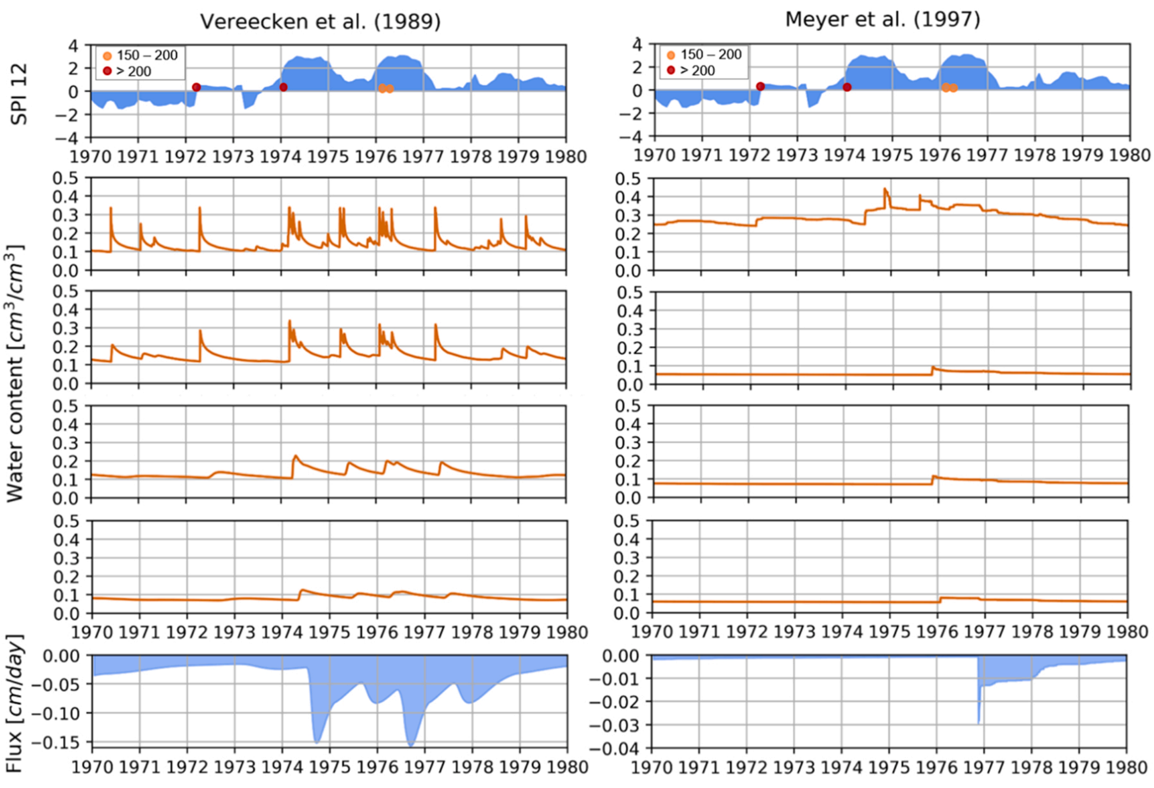

Fig. 10. (Top) Standardized Precipitation Index (SPI - 12) at Alice Springs Airport with rainfall events of 150–200 mm and > 200 mm indicated in orange and red respectively, (middle) water content in the vadose zone at 0.90, 3.50, 6.00, 9.50 m depth (top down) and (bottom) water fluxes at the bottom of the soil profile, simulated with PTFs 11 (left) and 7 (right) for vegetated soil between 1970 and 1980.

largest downward bottom flux was simulated around 1974–77 corresponding to a record series of consecutive extreme rainfall events separated by relatively short time intervals (Fig. 9). For the years 1982–1984 the SPI is almost constantly above 1 and reached a maximum of above 2 in 1984. The peak in SPI in 1984 can be linked to single high rainfall events of almost 190 mm in February 1982 and of about 350 mm in March 1983 (Fig. 4). All of the displayed significant bottom fluxes seem to respond to these wet periods. For the 1983 event response times between the extreme rain event and peak recharge vary between PTF approaches by up to 6 months. The large bottom flux in 1984 is generated by the extreme rainfall event in March 1983 (~ 350 mm) in combination with the wetter antecedent soil conditions that were caused mainly by the event in February 1982 (~ 190 mm). Between 1989 and 2000 significant rainfall events occurred very infrequently and the SPI depicts a pronounced frequency of dry periods (i.e. negative SPI values), reflected in relatively low bottom fluxes (less than − 0.01 mm/a) (Fig. 9). Another relatively wet period with two > 200 mm events in April 2000 and January 2001 again results in considerable bottom fluxes.

The impact of the antecedent moisture conditions is very pronounced also for the Alice Springs Airport case. Fig. 10 shows simulation results for soil moisture variations in the vadose zone at different depth and the bottom flux for the PFT after Vereecken et al. (1989) and Meyer et al. (1997) and the corresponding SPI 12 for the Alice Springs Airport data set. The effect of antecedent moisture can be demonstrated by comparing the effects of the > 200 mm event in 1972 that is preceded by a dry period with negative SPI with those of the > 200 mm event in 1974 that happens within a wet period and is preceded by several month of positive SPI. For the Vereecken et al. (1989) PFT, the 1972 event displays an infiltrating water front that is only pronounced in the upper layers of the soil profile (at 0.9 and 3.5 m depth) while after the event in 1974 the water front progressed until the lowest layers of the profile and thus generated a significant bottom flux. This effect is also noticeable for the smaller 150–200 mm events in 1976, where the wetter than usual soil condition generated a significant bottom flux. Another factor that contributed to the magnitude of recharge next to the soil moisture condition is the water that is provided to the soil profile by subsequent rainfall events. For the first event in 1972, there is little or no additional rainfall, whereas for the events in 1974 and 1976 there is considerable additional rainfall after the extreme events that contributed to the generation of recharge. The propagation of the water pulse through the vadose zone is similar for all recharge generating events with the peak in bottom flux occurring approximately 200 days after the rainfall events. For the PTF after Meyer et al. (1997), only the two events in 1976 that happened in close temporal proximity and are both preceded by a significant period of wetter soil conditions as well as followed by again a relatively long and pronounced wet period led to a significant bottom flux.

Further details of the rain events with total rainfall exceeding 150 mm for Tea Tree Well and Territory Grape Farm stations are provided in Table 2 for the period 1970–1990. The period 1970–1979 represents the wettest decade of the entire 130-year rainfall record, with 449 mm/year on average (based on Tea Tree Well). Although the period 1980–1989 was not particularly wet (283 mm/year on average), it was added to the previous decade to have a sufficiently long time series for analysis. Both stations are within the Ti Tree Basin and separated by approximately 40 km, with both stations at nearly the same distance from the drill site. Especially the first decade of this period is characterised as relatively wet with six rain events > 150 mm in the period 1972–1977. The longest period of uninterrupted rain days was 14, with a total rainfall of 353.4 mm (Tea Tree Well). By comparison, the long-term annual mean rainfall at Tea Tree Well station is 277 mm. Daily rainfall distribution during these eight events is similar (correlation coefficient = 0.91) between Tea Tree Well and Territory Grape Farm station (see Supp. Material 6). Start and end of these rain events is nearly identical, although the total rain amount does differ with the largest difference nearly 80 mm for event 4 (Table 2). The recharge events linked to each of these rain events will be discussed next based on the rainfall data from Tea Tree Well as example. As discussed above, this station produced the largest average recharge across all PTFs (Supp. Material 4).

Out of the eight events listed in Table 2, only three experienced ponding conditions (event 1, 2, and 6). The ponding depth was typically less than 2 cm, while the duration of the ponding was 0.5 day for event 1, 1 day for event 2 and 1.5 days for event 6. This shows that at least for the time series 1970–1990 the assumption of 10 cm maximum head at the surface is justified. Note that for the

Table 2
Characteristics of rain events with total rainfall > 150 mm (TTW = Tea Tree Well station; TGF = Territory Grape Farm; period 1970–1990). Per cent of total annual rain in parentheses.

Event number	Rain event (from to)		Number of uninterrupted rain days	Total rainfall (mm)
1	TTW	From 26/02/1972 to 8/03/1972	12	216.4 (86%)
	TGF	From 26/02/1972 to 7/03/1972	11	232.0 (92%)
2	TTW	From 19/01/1974 to 1/02/1974	14	353.4 (37%)
	TGF	From 19/01/1974 to 1/02/1974	14	350.5 (37%)
3	TTW	From 18/02/1974 to 27/02/1974	10	151.6 (16%)
	TGF	From 17/02/1974 to 27/02/1974	11	138.6 (14%)
4	TTW	From 16/02/1975 to 24/02/1975	9	191.7 (23%)
	TGF	From 16/02/1975 to 24/02/1975	9	112.0 (17%)
5	TTW	From 12/12/1975 to 18/12/1975	7	242.0 (29%)
	TGF	From 12/12/1975 to 18/12/1975	7	196.0 (29%)
6	TTW	From 15/02/1977 to 27/02/1977	13	323.7 (61%)
	TGF	From 16/02/1977 to 27/02/1977	12	293.0 (63%)
7	TTW	From 8/02/1982 to 18/02/1982	11	264.3 (80%)
	TGF	From 8/02/1982 to 18/02/1982	11	280.4 (81%)
8	TTW	From 10/03/1983 to 19/03/1983	10	195.7 (41%)
	TGF	From 10/03/1983 to 19/03/1983	10	197.6 (44%)

entire period 1889–2016, the threshold of 10 cm pressure head was exceeded only once (1991) due to a rainfall event that recorded 293 mm in just two days. In reality, ponding is likely to occur more frequently and with greater ponding depths; however, the simulations are limited by the daily timestep at which rainfall data is available. Because the rainfall intensities are averaged out over an entire day, there is probably and underestimation of higher intensity rain bursts within a day. Indeed, rainfall-intensity-duration curves (e.g. for Alice Springs) clearly show high-intensity, short-duration (sub-daily) rain events up to 50 mm/h for an hourly event, given a return period of 20 years (Gyasi-Agyei and Mahbub, 2007). The effect of using hourly or daily rainfall data on runoff and recharge was demonstrated by Batalha et al. (2018) for fine-textured soil in Brazil. Their simulations showed considerable runoff for hourly rainfall data compared to almost no runoff for daily data. As a result, recharge for hourly data was smaller by a factor of 2 than when daily data was used.

The rainfall distribution from 1970 to 1990 is shown in Fig. 11, with indication of eight rain events that exceeded 150 mm (numbers as per Table 2). The water flux at the bottom of the soil profile calculated with the PTF of Vereecken for bare and vegetated soil can be linked to nearly all these events (Fig. 11). As will be shown later, this is the only PTF for which the bottom flux responds to nearly each rain event > 150 mm. Only the first rain event does not generate any significant recharge above the background; this is due to the drier antecedent moisture conditions compared to the subsequent events. For the rain events 2–6 the time between the occurrence of the rain and the peak flux ranges from 200 (event 2) to 300 (event 6) days. For rain event 7 and 8 it takes between 440 (event 8) and 500 (event 7) days for the rain event to propagate through the entire soil profile. The larger transit times for events 7 and 8 compared to events 2–6 are due to the drier antecedent moisture conditions for the former.

The impact of the antecedent moisture condition is also visible when comparing fluxes calculated for the bare and vegetated soil. For the latter, fluxes are nearly as high as those for the bare soil only when the previous history was wet, e.g. for events 4, 5, and 6. When the prior condition was drier, as for event 2/3 and 7 and 8, the fluxes from vegetated soil are considerably smaller than for the bare soil (Fig. 11).

The predictive capacity of the PFTs to generate realistic fluxes was tested by comparison with observed groundwater levels in two nearby monitoring wells (RN005507 and RN006543). The response of the groundwater levels to major rain events is clearly visible (Fig. 11, bottom panel), with groundwater levels increasing by approximately 2 m for RN005507 and 2.5 m for RN006543 in response to a series of rain events (2–6). The observed response has a limited temporal resolution of one month at best, therefore the response curve is somewhat smoothed and reflect the integral effect of several events rather than showing detailed responses to each individual event. Nevertheless, the series of calculated fluxes agree relatively well in terms of their timing and relative magnitude: rain event 5 generates the overall largest flux which corresponds with the greatest single increase in groundwater level.

Rain events 7 and 8 generate a visibly smaller bottom flux which again is relatively well represented in the groundwater level for both monitoring wells (Fig. 11, bottom panel). There is again a good agreement with the timing of the increase in groundwater level, while the magnitude of the increase is proportional to the flux: roughly 0.5 m (RN005507) for a peak flux of about 0.03 cm/day (event 8) versus 2 m for a maximum peak flux of 0.15 cm/day (events 2–6).

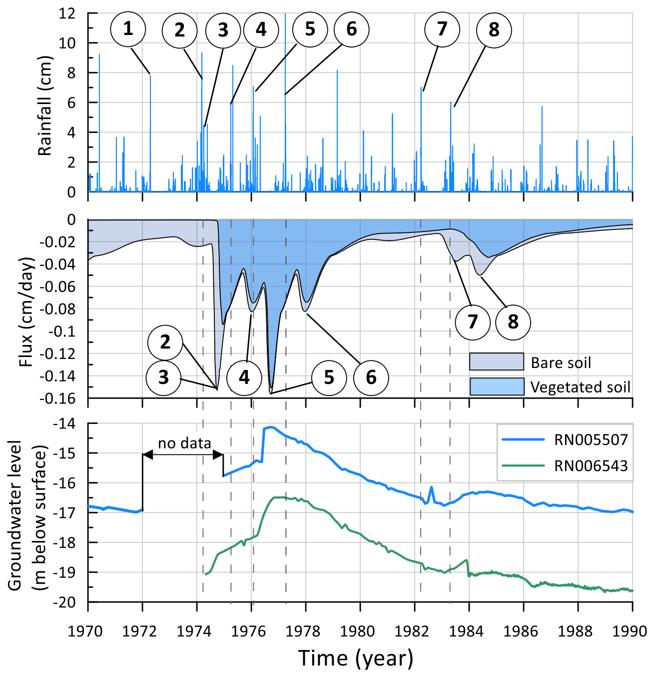

Fig. 11. Top panel: rainfall at Tea Tree Well station (period 1970–1990) with indication of rain events with total rainfall > 150 mm (for details of rain events, see Table 2). Middle panel: Flux at bottom of soil profile for PTF Vereecken (bare and vegetated soil). Numbers refer to rain events linked to peak fluxes. Bottom Panel: Observed groundwater levels in monitoring wells nearby the Tea Tree Well station.

After a peak in groundwater level linked to event 5, a decreasing trend in groundwater level is observed. There may be several reasons why event 6 does not result in a significant increase in groundwater level. One possible reason is the highly localised nature of some of the rain events; note that the distance between groundwater bores and the Tea Tree Well weather station was about 10 km. Testing this assumption based on total rainfall across the Tea Tree Well station and Territory Grape Farm (approximately 30 km from the groundwater bores) revealed a total cumulative rainfall of 324 mm for Tea Tree Well station (event 6 included 12 consecutive days of rain) while 293 mm for Territory Grape Farm (based on 11 consecutive days of rain). While these amounts are not the same, they are of a similar magnitude and therefore rainfall variability could be discounted as explanation.

A more plausible explanation is that the groundwater response due to recharge from event 6 is masked – to some degree - by the already high groundwater level after the greatest recharge flux associated with event 5. Close inspection of groundwater bore RN006543 shows some flattening of the groundwater level at the time of the peak flux, i.e. at year 1978. In other words, event 6 causes a delay in the decrease in groundwater level after reaching its highest level (about 16.5 m below ground surface for RN006543 and just over 14 m for RN005507) linked to event 5.

The good agreement between timing of peak bottom fluxes and observed rise in groundwater level is not unique for the PTF of Vereecken. Three more PTFs display a relatively similar behaviour (Fig. 12): Meyer, Petersen, and Woesten C. While each of the time series of bottom fluxes is unique for a given PTF, their overall behaviour is very similar. There are several spikes corresponding to the series of rain events 2–6, while only a single flux is predicted for the rain events 7–8. Within each of these two groups of events the magnitude of the fluxes is comparatively similar. Each of these four PTFs therefore has a similar ability to predict groundwater recharge.

The cumulative recharge averaged over the period 1970–1989 for the PTFs of Vereecken, Woesten C, Petersen and Meyer is 84, 84, 72, and 43 mm/a, respectively. These 20-year averaged recharge values correspond to 23%, 23%, 20%, and 12% of the total annual rainfall (based on Tea Tree Well). The annual rainfall for the period 1970–1989 amounts to 366 mm compared to 277 mm as the long-term average (or 31% higher than the average). Recall that the long-term average recharge (% of rainfall in Tea Tree Well in parentheses) for these four PTFs was 27 (9.8%), 17.8 (6.2%), 10.4 (3.8%) and 10.7 (3.9%) mm/a (Supp. Mat. 4).

Among the PTFs that displayed a minimal recharge rate even for the wetter period 1970 – 1989 only the PTFs of Bruand, Canarche and Schaap showed a response to the series of extreme rain events, while the PTFs of Gupta, Hall and Woesten F remained unresponsive (Fig. 12). The cumulative recharge averaged over the period 1970–1989 for the PTFs of Bruand, Canarche and Schaap is 19, 21, and 20 mm/year, respectively. These 20-year averaged recharge values correspond to 5%, 6%, and 5% of the total annual rainfall (based on

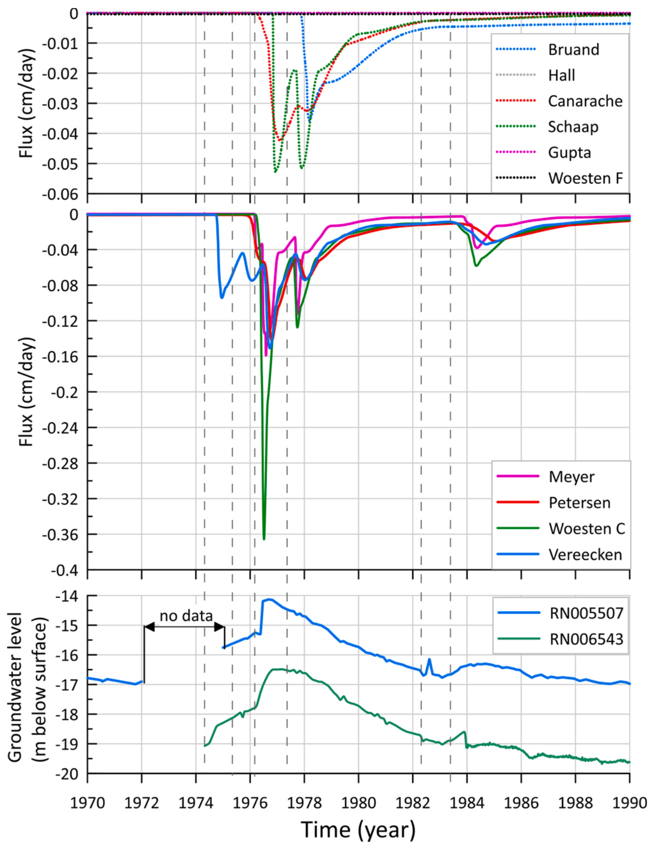

Fig. 12. Top panel: Flux at bottom of profile for PTFs with minimal response to rain events 1–8. Middle panel: Flux at bottom of profile for PTFs with maximal response to rain events 1–8. Bottom panel: Observed groundwater levels in monitoring wells nearby the Tea Tree Well station.

Tea Tree Well).

Estimated total recharge for the period 1970–1989 was calculated on the basis of recharge from events 2–6 and from events 7–8. For the first series of events, total recharge amounted to 1044 and 202 mm, or 1246 mm in total. This represents 75% of the total recharge for the 20-year period. Based on the recharge generated for the full 130-year timeseries (3442 mm), the 1970–1989 recharge represents 36% of overall total recharge. The recharge generated during the wettest decade 1970–1979 only corresponds to 30% of the overall total recharge. For events 2–6 the total duration of recharge was calculated to be 1463 days. For events 7–8 the recharge lasted 1344 days. These results underscore again the importance of consecutive extreme rainfall events in generating significant groundwater recharge. The more these events are clustered (in this case five extreme events in three years), the more they generate recharge owing to wetter starting conditions at the onset of the rain events.

Analysis of climate data from the study area revealed a high spatial variability in rainfall throughout the basin. Running the simulations with multiple profiles of soil hydraulic properties for several different climate datasets, as well as for a bare and a vegetated soil, revealed that the spatial variation of precipitation, soil hydraulic properties, vegetation and hydrologic conditions results in essentially diversifying groundwater recharge across the landscape. Although mean annual rainfall amounts recorded at Territory Grape Farm were higher compared to the mean annual record at Tea Tree Well and Alice Springs Airport, the highest annual recharge rates were calculated for the Tea Tree Well dataset. Analysis of rainfall records from the three different pluviography stations revealed that a smaller number of extreme rainfall events with more than 200 mm was recorded at the weather station Tea Tree Well (average return period of about 16 years) than at the other two stations (average return period of 11.6 and 12.8 years at Territory Grape Farm and Alice Springs Airport respectively). This emphasises again the hypothesis that local recharge rates are not governed by the total annual rainfall, but rather by highly infrequent and geographically constrained extreme rainfall events.

For regional scale estimates of recharge, simulations should account for spatial variations in soil properties and topographic features of the region, especially topographic depressions, stream beds, and flood-out areas. In general, vadose zone methods provide estimates of potential recharge, while techniques based on groundwater data yield estimates of actual recharge (Scanlon et al., 2002). Thus, implications for a further extension of the numerical model include the incorporation of topographic characteristics such as the percentage of surface area that experiences flooding after extreme rainfall events, and specific ponding characteristics of the soil (e.g. depression storage, ephemeral streams, flood plains). This would allow the application of the model to a regional scale and the estimation of regional scale total recharge amounts. Furthermore, a combination of a modelling approach and tracer-based studies could be useful to validate and constrain the hydrologic model and to accurately identify the provenance of infiltrating water.

Several global circulation models indicate that the frequency of extreme rainfall events will decrease while both variability and unpredictability of those events will increase (Cai et al., 2012; Charles et al., 2008). According to CSIRO (Commonwealth Scientific and Industrial Research) (2015) global and regional studies point towards a lower frequency of tropical cyclones but with greater proportion of high intensity events (heavy precipitation and strong winds). Under the assumption that those extreme rainfall events represent the major source of groundwater recharge, a decrease of those events would potentially entail a decrease of groundwater replenishment. We see future research potential in studying those boundary conditions under the assumption of potential climate pathways, e.g. less frequent but higher magnitude rainfall events.

The uncertainties in different recharge estimation methods emphasises the importance of applying multiple models to increase the reliability of estimates (Scanlon et al., 2002). Furthermore, realistic estimations of water-use by vegetation and a sound understanding of climate related land cover changes are essential for the realistic estimation of groundwater recharge which is a key input to sustainable groundwater management (Chen et al., 2014; Zhang et al., 1999a, 1999b).

Estimated mean annual evapotranspiration rates of about 324 mm/a are consistent with actual evapotranspiration rates calculated by the Australian Bureau of Meteorology (BOM (Bureau of Meteorology, Australia), 2016). The comparison of simulations for bare soil and vegetated soil emphasises the significant effect of vegetation on local recharge rates. The influence of vegetation on hydrologic fluxes in shallow desert soils and thick unsaturated zones was previously demonstrated by Garcia et al. (2011) and Scanlon et al. (2006). In their study, Garcia et al. (2011) analysed the effects of plant water uptake and its interaction with vapour flow processes in the unsaturated zone. They found that plant roots are mainly supplied by thermally driven vapour fluxes and corresponding condensation supplemented moisture during the dry seasons and emphasised the major effects of plant water uptake on water balances in desert soils where total water fluxes are generally low. Furthermore, the same authors determined that root water uptake is also coupled with non-isothermal vapour flow. Thus, a combination of the present modelling approach of water fluxes and root water uptake with vapour flow modelling could provide a more profound overview of hydrologic fluxes in the unsaturated zone in arid environments.

Chen et al. (2014) and Eamus et al. (2013) found that seasonal variations of the LAI and vegetation water-use have a significant influence on root water uptake. Variations in simulated LAI of 0.12–0.35 for the overstory canopy and 0.07–0.21 for the understory canopy resulted in a change of the annual plant water uptake ranging from 64 to 600 mm/a (Chen et al., 2014). Furthermore, Scanlon et al. (2006) found that a rapid increase in vegetation productivity due to an elevation in seasonal water supply by precipitation reduced the soil pore water volume by half inhibiting groundwater recharge. Hence, the implementation of time variable vegetation parameters, seasonal variations of the LAI and seasonal root growth tables to account for seasonal changes in land cover and vegetation characteristics can help to draw a more realistic scenario of vegetation properties in this semi-arid region. However, an accurate incorporation of root growth tables into the model can prove to be a challenging task as native vegetation does not mainly change due to seasonality but its growth is rather coupled to the infrequent water supply.

5. Conclusions

This study used a vadose zone numerical modelling study conducted in the Ti-Tree Basin, central Australia, to confirm the hypothesis that recharge in the arid Ti-Tree Basin is strongly dependent on infrequent extreme rainfall events. Analysis of the century-long precipitation records revealed extreme rainfall events linked to monsoonal thunderstorms during the summer months that have an average return period of 11–12 years for a 150 mm rainfall event and up to almost 16 years for events with more than 200 mm rainfall.

A multi-model approach by means of multiple PTFs provided a convenient tool when facing data scarcity on soil properties. Results of the century-long recharge simulations revealed the highly infrequent nature of groundwater recharge in arid Central Australia and the strong dependency of the regional water budget on extreme rainfall events. Analysis of detailed moisture content distributions throughout the soil profile over the century-long time series revealed that events of at least 200 mm are required to overcome evaporation and root water uptake and thus to potentially generate recharge to the aquifer. Multiple extreme rainfall events occurring within shorter time frames are more likely to result in a replenishment of the groundwater aquifer due to the higher antecedent moisture condition of the soil.

Results from this study contribute to a better comprehension of highly episodic and land cover dependent recharge in this semi-arid environment by identifying and quantifying recharge generating events and drawing an important connection between groundwater replenishment and specific climatological features. Further characterisation of vegetation parameters will help to minimise the model uncertainty and to yield a more realistic depiction on vegetation water use. The current model can be extended regarding temperature gradients and vapour flow processes which have an influence on vegetation properties and evapotranspiration processes. An integrated modelling approach would combine this model with a land-surface component that can yield regional scale recharge values. Such an integrated model could be used to assess and predict future recharge amounts, the effects of climate change and changes in land use on the local water budget.

CRediT authorship contribution statement

Theresa Boas: Conceptualization, Data curation, Visualization, Methodology, Modelling, Writing – original draft. **Dirk Mallants:** Conceptualization, Methodology, Modelling, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101005.

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