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PAPER

Review: Current and emerging methods for catchment-scale modelling of recharge and evapotranspiration from shallow groundwater

Rebecca C. Doble[1] · **Russell S. Crosbie**[1]

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Abstract A review is provided of the current and emerging methods for modelling catchment-scale recharge and evapotranspiration (ET) in shallow groundwater systems. With increasing availability of data, such as remotely sensed reflectance and land-surface temperature data, it is now possible to model groundwater recharge and ET with more physically realistic complexity and greater levels of confidence. The conceptual representation of recharge and ET in groundwater models is critical in areas with shallow groundwater. The depth dependence of recharge and vegetation water-use feedback requires additional calibration to fluxes as well as heads. Explicit definition of gross recharge vs. net recharge, and groundwater ET vs. unsaturated zone ET, in preparing model inputs and reporting model results is necessary to avoid double accounting in the water balance. Methods for modelling recharge and ET include (1) use of simple surface boundary conditions for groundwater flow models, (2) coupling saturated groundwater models with one-dimensional unsaturated-zone models, and (3) more complex fully-coupled surface-unsaturated-saturated conceptualisations. Model emulation provides a means for including complex model behaviours with lower computational effort. A precise ET surface input is essential for accurate model outputs, and the model conceptualisation depends on the spatial and temporal scales under investigation. Using remote sensing information for recharge and ET inputs in model calibration or in model–data fusion is an area for future research development. Improved use of uncertainty analysis to provide probability bounds for groundwater model outputs, understanding model sensitivity and parameter dependence, and guidance for further field-data acquisition are also areas for future research.

Keywords Groundwater recharge/water budget · Evapotranspiration · Numerical modelling

Introduction

To improve the predictive capability of groundwater models, it is necessary to enhance the representations of both the aquifer characteristics, such as hydraulic conductivity and storativity, and the model-specified fluxes, such as lake and river interactions, recharge and evapotranspiration (ET). While improvements to estimations of hydraulic conductivity have been outlined in review papers, for example Wen and Gómez-Hernández (1996), this paper considers methods for improved representation of recharge and ET in groundwater models.

Historically, recharge has been represented in saturated groundwater models as a single input per cell per time step. ET has been conceptualised as a linear or piecewise linear relationship with depth (Banta 2000; Harbaugh 2005). These were reasonable approximations as field-based data, such as that from ET flux towers, were relatively sparse; therefore very little information existed with which to calibrate a model. Recently however, estimates of recharge and ET derived by remotely sensed methods such as reflectance and land-surface temperature have become more readily available (Guerschman et al. 2009; Nagler et al. 2005), and are being used as inputs to, and for calibration of groundwater flow models (Morway et al. 2013).

Parallel to this, there has been an increasing volume of research on water resources in areas with shallow water tables (water tables within the root zone, usually < 7 m deep),

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✉ Rebecca C. Doble
rebecca.doble@csiro.au

[1] CSIRO Land and Water, PMB 2 Glen, Osmond, SA 5064, Australia

involving mechanisms such as surface-water/groundwater interactions (Brunner et al. 2011; Brunner et al. 2009; Doble et al. 2012; Lamontagne et al. 2014), ecohydrology and plant use of groundwater (Baird et al. 2005; Benyon et al. 2006; Crosbie et al. 2008; Goodrich et al. 2000; Holland et al. 2006; Lamontagne et al. 2005) and salinisation (Doble et al. 2006; Jolly et al. 2008). The time seems opportune, therefore, to rethink recharge and ET processes, particularly for conditions with shallow groundwater, and to determine what assumptions are physically realistic for these conditions.

This paper provides a review of the current and emerging methods used to incorporate recharge and ET as boundary conditions and as outputs from catchment-scale groundwater models. A robust conceptualisation of recharge and ET is particularly important where groundwater is shallow and these surface processes are more pronounced. The paper does not provide a review of methods for estimating recharge as there are already many quality papers that address this topic (Crosbie et al. 2010; Gee and Hillel 1998; Healy 2010; Kim and Jackson 2012; Petheram et al. 2002; Scanlon et al. 2006). Similarly, good review articles are available for ET processes, particularly in relation to remote sensing (Glenn et al. 2011; Kalma et al. 2008) and ET from groundwater in Australia (O'Grady et al. 2011).

This paper presents a conceptual understanding of recharge and ET processes including factors affecting recharge and ET functions, and the evaluation of field evidence for recharge and ET being dependent on groundwater depth. It outlines various approaches for modelling recharge and ET, discussing advantages and disadvantages and gives general considerations for the representation of recharge and ET, including the use of remote sensing data and uncertainty analysis. Some future research opportunities are also suggested.

Conceptual understanding of recharge and ET processes

Understanding methods for incorporating recharge and ET functions into a groundwater model requires a brief review of the components of the soil-moisture mass balance equation (Delleur 2006):

$$R_{\mathrm{gross}} = P - \mathrm{Int} - E_{\mathrm{uz}} - T_{\mathrm{uz}} - \mathrm{RO} - \mathrm{IF} + \Delta S \tag{1}$$

$$R_{\mathrm{net}} = R_{\mathrm{gross}} - E_{\mathrm{gw}} - T_{\mathrm{gw}} \tag{2}$$

Where R_{gross} is gross recharge to the water table, R_{net} is the difference between R_{gross} and evapotranspiration from groundwater ($\mathrm{ET_{gw}}$), Int is canopy interception, E_{uz} is evaporation from the unsaturated zone, E_{gw} is evaporation from groundwater, T_{uz} is transpiration from the unsaturated zone, T_{gw} is transpiration from groundwater, RO is runoff from the land surface, IF is interflow, and ΔS is the change in soil-moisture storage.

Recharge is defined as the water that crosses the water table into the saturated zone (Fig. 1). Evapotranspiration is divided into evaporation (E) lost through soil processes, and transpiration (T) lost through vegetation water use. It is further divided into components of the flux originating from the unsaturated zone (E_{uz} and T_{uz}) and originating from upward flux from the saturated zone or groundwater (E_{gw} and T_{gw}). Note that there are different physical processes driving the evaporation and transpiration components of the water balance, and that the different subscripts are a technical separation of water originating from the unsaturated or saturated zones, based on the given definition of the groundwater control volume.

The groundwater control volume provides a convenient method of quantifying groundwater for water management purposes and modelling with Darcy-type groundwater models such as MODFLOW (Harbaugh et al. 2000; McDonald et al. 1988) or FEFLOW (Diersch 2005). Previous studies separate evapotranspiration into groundwater ET ($\mathrm{ET_{gw}}$, GWET) and vadose or unsaturated zone ET ($\mathrm{ET_{uz}}$, VZET; Shah et al. 2007), or separate soil-based evaporation processes from transpiration, but none have been found that separate all four components.

More complex fully coupled research code models such as HydroGeoSphere (Brunner and Simmons 2011; Therrien et al. 2006) and MIKE SHE (Refsgaard and Storm 1995) simultaneously model saturated and unsaturated groundwater flow and surface-water flow; therefore, the operational control volume includes the unsaturated zone and possibly a small volume above the soil surface. The relationship between control volumes for fully coupled models will depend on the model being used, but care should be taken that modelled and remotely sensed fluxes are defined identically.

Remote sensing data such as reflectance data and thermal infrared land surface temperature data (Li et al. 2013) from satellites such as NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat, and NOAA's Advanced Very High Resolution Radiometer (NOAA-AVHRR) are increasingly being used in modelling land surface processes. They are presently used for estimating green cover, saturated surfaces, urban space and other masks in hydrological models, and are increasingly being used to estimate recharge and ET specifically for groundwater models, in regions such as semi-arid to arid Botswana and arid Xinjiang Uygur in China (Brunner et al. 2007) and temperate to semi-arid Nebraska Sand Hills, USA (Szilagyi et al. 2011). These remote sensing data have a control volume that includes the land surface plus vegetation and atmospheric processes. There is a mismatch between control volumes, and some kind of representation of the downward (R) and upward ($\mathrm{ET_{gw}}$) fluxes is required. In order to provide an appropriate representation

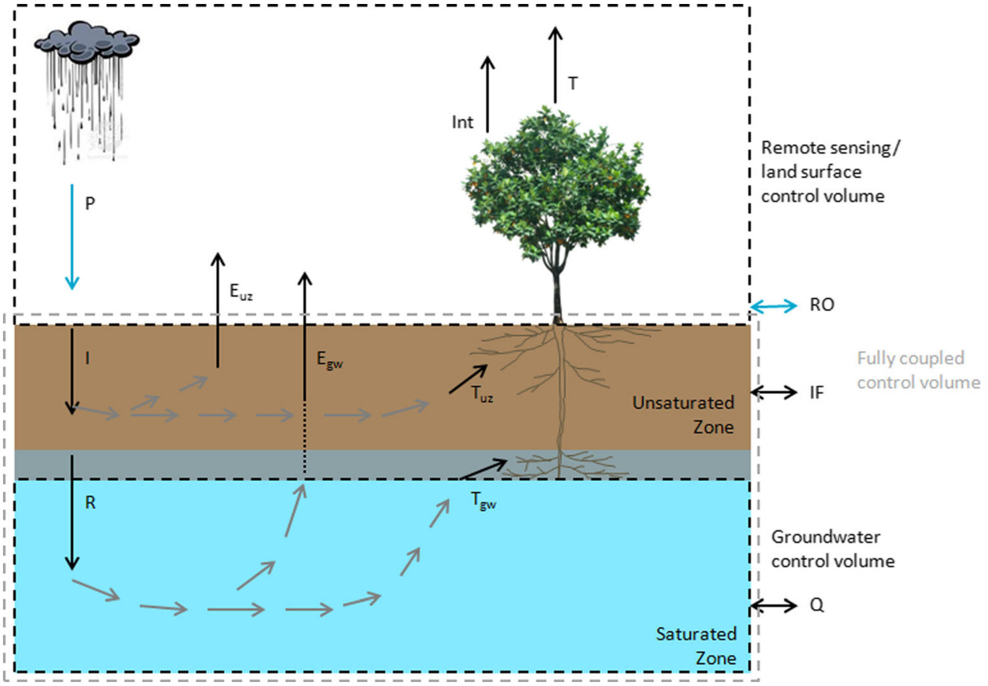

Fig. 1 Conceptual model of recharge and evapotranspiration processes in areas with shallow groundwater. Precipitation (*P*) falls on the site and is intercepted by vegetation (*Int*), runs off down slope (*RO*) or infiltrates into the subsurface (*I*). Infiltrating water is transpired from the unsaturated zone by vegetation (T_{uz}), evaporated from the soil surface (E_{uz}), moves down slope as interflow (*IF*) or crosses the water table as gross recharge (*R*). From within the groundwater control volume, water may flow out from the aquifer (*Q*), be evaporated from the capillary fringe (E_{gw}) or transpired by vegetation (T_{gw})

of recharge and ET_{gw} fluxes, the characteristics of these processes are discussed in the following sections.

Recharge

Recharge may be represented as either gross recharge (the volume of water that infiltrates through the unsaturated zone and crosses the water table) or net recharge (gross recharge minus ET_{gw}). Remote sensing data often describes net recharge. Due to the difficulty in separating ET_{gw} and ET_{uz} in remote sensing evaporation signatures, net recharge may simply be approximated by the difference between rainfall and remotely sensed total ET estimates minus runoff (Crosbie et al. 2015). For field estimates of recharge, the water table fluctuation (WTF) method is commonly used to estimate gross recharge (Healy and Cook 2002; Meinzer and Stearns 1929), while the chloride mass balance (CMB) method provides estimates of net recharge where net recharge is positive (Anderson 1945; Wood 1999). Where solute transport is of interest, for example in salinity problems (Bauer et al. 2006; Jolly et al. 1993), gross recharge must be used to maintain a solute balance. It is critical that recharge is explicitly defined in the reporting of modelling results to avoid double accounting in the water balance.

The review papers previously mentioned all conceptualise recharge as a single time-varying inflow into the groundwater store. It is difficult to find examples of where recharge estimates are related to depth to water table (DTWT); however, a few studies do indicate that where groundwater is shallow, recharge does change as a function of water table depth. These studies include field measurements (Benyon et al. 2006; Crosbie 2003; Sophocleous 1992), remote sensing measurements (Crosbie et al. 2015; Szilagyi et al. 2013) and numerical modelling (Smerdon et al. 2008, 2010; Carrera-Hernández et al. 2011).

For the Smerdon et al. (2008) study of the Boreal Forest of Canada, the Smerdon et al. (2010) study of the Okanagan Basin, Canada, the Crosbie et al. (2015) study of the Mediterranean climate South East region of South Australia, and the Szilagyi et al. (2013) study of Nebraska, the depth dependence is a result of reporting net recharge, i.e. the difference between gross recharge and ET_{gw}. Net recharge is characteristically depth dependent due to the influence of ET_{gw}. However, in the Crosbie (2003) and Crosbie et al. (2005) studies of the humid-subtropical Tomago Sand Beds, Australia, and the Carrera-Hernández et al. (2011) study of Aspen harvesting in the Canadian Boreal Plains, even gross recharge was found to be a function of DTWT.

Crosbie (2003) used aggregated monthly recharge from high-frequency recharge time-series derived from the water table fluctuation method at seven piezometers in the Tomago Sandbeds over a 2-year period to describe the relationship between recharge and DTWT. Details of the calculations are in Crosbie et al. (2005). This relationship between recharge and DTWT shows recharge of zero when the water table is near the surface, increasing to a maximum recharge at a DTWT between 0.5 and 1.25 m, before stabilising at a lower rate below 2.0 m (Fig. 2a). The shape of the curve can be characterised by rejected infiltration for very shallow water tables, followed by a maximum rate of recharge due to minimal evapotranspiration of the water as it moves through the very thin unsaturated zone. With shallow groundwater, rather

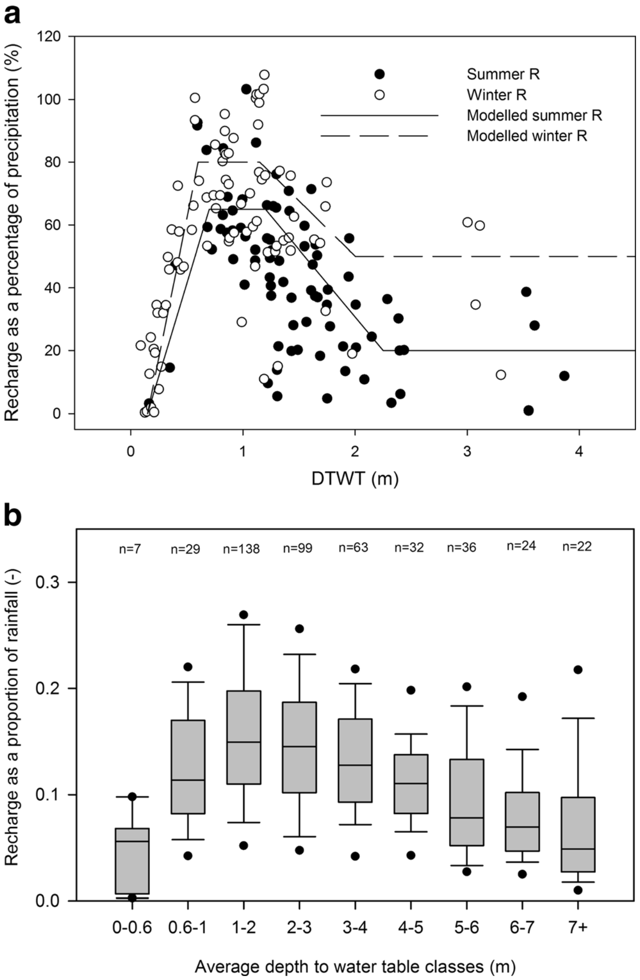

Fig. 2 **a** Gross recharge in the Tomago Sand Beds (Australia) showing dependence on DTWT, after Crosbie (2003), with data from Crosbie et al. (2005). **b** A similar relationship can be found in the Crosbie and Davies (2013) study of the Limestone Coast, a Mediterranean climate region of South Australia, which is also described in Crosbie et al. (2015), with permission from the Goyder Institute for Water Research

than infiltrating precipitation constantly replenishing soil moisture after depletion by ET (Shah et al. 2007), the antecedent moisture conditions that are consistently approaching field capacity provide ideal conditions for maximum rates of recharge. At greater water table depths, recharge as a percentage of rainfall is relatively constant with DTWT. This same relationship has also been shown using long-term average data from the Limestone Coast region of South Australia (Mediterranean climate) for around 400 monitoring bores (Fig. 2b) (Crosbie et al. 2015; Crosbie and Davies 2013).

At a catchment scale, this relationship may also be deduced from water balance studies. It was observed that during the Australian Millenium Drought of 1997–2008, in the Mediterranean climate regions of south Western Australia (Hughes et al. 2012; Petrone et al. 2010) and south eastern Australia (Petheram et al. 2011), that catchments with low relief and moderate rainfall showed significantly more reduction in runoff than higher-relief high-rainfall catchments. The studies suggested that the relatively shallow groundwater levels in these catchments resulted in increased runoff during pre-drought conditions due to a reduced storage capacity in the unsaturated zone. Although this level of detail in the recharge function may not be required for models with larger spatial and temporal scales, it should not be ignored where quantification of recharge to shallow groundwater is required.

The factors that affect groundwater recharge include climate, particularly precipitation and potential evapotranspiration (PET), vegetation cover, soil texture, macropores and preferential pathways, soil moisture, surface topography and depth to groundwater or bedrock. A summary of these factors and their impact on groundwater recharge is given in Table 1.

Evaporation

Shallow water tables also increase the rate of groundwater evaporation. The shape of the relationship between soil evaporation and DTWT has previously been described in soil physics literature (Gardner 1958; Gardner and Fireman 1958; Philip 1957; Talsma 1963). This function has also been observed in more recent modelling and field studies (Shah et al. 2007; Soylu et al. 2011).

Groundwater evaporation is maximised where the water table is at or near the surface and decays exponentially with depth (Fig. 3). This conceptualisation, or a simplification thereof, is used in many groundwater flow models such as MODFLOW EVT and ETS1 packages (Banta 2000; Harbaugh 2005; Harbaugh et al. 2000).

Models with physical representation of the unsaturated zone using Richards equation reproduce this relationship between evaporation and DTWT through their use of the van Genuchten (1980), Brooks and Corey (1964) or Campbell (1974) equations relating pressure, saturation and hydraulic conductivty: for example, HYDRUS (Šimůnek et al. 2003; Vogel et al. 2000), HydroGeoSphere (Therrien et al. 2006), MIKE-SHE (Doummar et al. 2012), and WAVES (Doble et al. 2015; Zhang and Dawes 1998).

Evaporation from the soil surface will lead to salt accumulation and salinisation where groundwater is saline (Peck 1978a, b; Peck and Hatton 2003). Secondary or dryland salinity is of concern in Australia (Jolly et al. 1993; Walker et al. 1994, 1998; Wood 1924), Canada and the United States (Miller et al. 1981), Thailand, South Africa and Argentina (Pannell and Ewing 2006). Allowance should be made for factors that limit evaporation from the soil surface such as mulch, vegetation cover or salt deposits (Benoit and

Table 1 Factors affecting groundwater recharge functions

Factor	Nature of the effect	Relative importance (high, medium, low)	References and examples
Climate	Higher precipitation increases potential for recharge. Impact depends on the timescale as recharge from more intense rainfall may be limited by soil storage capacity. Recharge from snowfall will be delayed until snowmelt. In climates with large potential evapotranspiration (PET), the proportion of precipitation that is intercepted by vegetation canopy and evaporated or evapotranspired from the unsaturated zone is higher than for climates with a low PET	High	Eckhardt and Ulbrich (2003) used SWAT-G to model groundwater recharge response to a changing climate in a small temperate catchment in Germany. Summer recharge decreased by 50 % under warming climate conditions. In the semi-arid Murray Darling Basin, Australia, Crosbie et al. (2013) used 16 global climate models and the hydrological model WAVES to estimate the impact of climate on groundwater recharge
Vegetation cover	Interception and transpiration usually increases for areas with denser vegetation canopies	Medium	In their review of studies estimating recharge throughout Australia (alpine to tropical to arid), Petheram et al. (2002) found that although rainfall explained the majority of variation in recharge, there was a significant difference between recharge under trees vs. annual vegetation
Soil texture	Coarser soils such as sands and loams allow faster rates of infiltration, although dry, hydrophobic sands can limit infiltration initially. Finer soils such as clays and silts have a larger capillary fringe; therefore, infiltration can be evaporated or transpired from the unsaturated zone reducing the volume that recharges groundwater at the water table	High	Carsel and Parrish (1988) suggest van Genuchten (1980) soil parameters for 12 different soil types ranging from sand to silty clay. Wohling et al. (2012) relate deep drainage to field measured soil clay content and rainfall across Australia
Macropores and preferential pathways	Water flowing through preferential pathways such as cracks, root holes and karstic soils will allow groundwater to recharge earlier than through the soil matrix, and a greater proportion of infiltration will reach the water table as recharge without being lost from the unsaturated zone. It is possible to simulate this behaviour with dual-porosity soil characteristics, where a percentage of the soil matrix in a groundwater model is assigned a higher hydraulic conductivity	Medium	Šimůnek et al. (2003) provide a review of models that are used for modelling macropore flow. An example is the Kurtzman and Scanlon (2011) study which described modelling recharge through vertisols in Israel using HYDRUS-1D
Antecedent soil moisture	Generally, a higher proportion of precipitation will recharge groundwater when the unsaturated zone has a higher moisture content. It will impact the recharge from a single rainfall event and possibly monthly or seasonal recharge, but has little impact on long-term averages	Single event: medium. Long-term average: low	There are few studies that quantify the impact of soil moisture on recharge. Gray and Norum (1967) describe some of the dynamics between soil moisture, infiltration, runoff and recharge
Surface topography	A larger slope, usually found higher in catchments, will favour runoff and interflow over recharge. Conversely it will also increase the rate groundwater flows away from the recharge zone allowing more soil capacity for recharge to take place	Medium	Although catchment slope is known to affect infiltration, there are very few references to it impacting groundwater recharge. An exception is Delin et al. (2000), who found greater recharge rates at a lowland site than rates found higher in the catchment. They attributed this to ponding of groundwater on flat surfaces and the soil conditions at the sites
Depth to groundwater or presence of bedrock	Shallow water tables or bedrock can limit the capacity of the unsaturated zone to accept recharge through infiltration rejection	Medium	Crosbie (2003) found that depth to the water table impacted recharge in the humid-subtropical Tomago Sand Beds in eastern Australia. Carrera-Hernández et al. (2011) modelled recharge and ET from Aspen on the humid-continental Western Boreal Plain in Canada where the depth to the water table was found to impact the water balance

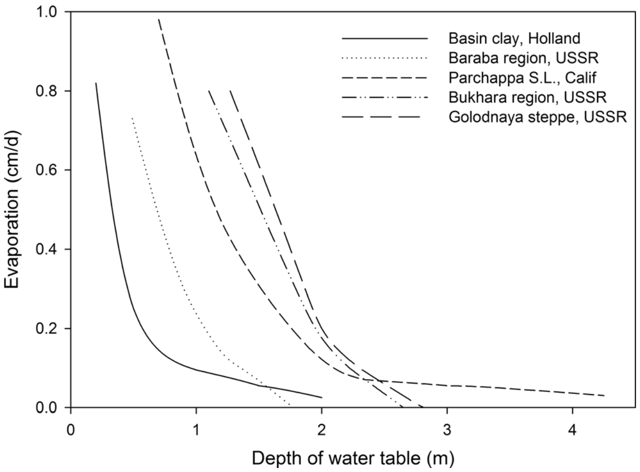

Fig. 3 Dependence of groundwater evaporation rate on depth to water table for five example soil types (Talsma 1963), with permission from Wageningen University

Kirkham 1963; Gardner 1958). A summary of the processes impacting groundwater evaporation is given in Table 2.

Transpiration

Transpiration is also known to be a function of DTWT (Nichols 1994; Smith et al. 1998). Similar to groundwater evaporation, transpiration also reduces to zero below an extinction depth, which is a function of the capillary fringe thickness and plant rooting depth. In contrast to bare soils, though, water tables near the surface create anoxic conditions, which decrease rates of transpiration (Amlin and Rood 2001). Some exceptions exist where vegetation has adapted to inundated and saline environments (Bell 1999). For all but obligate wetland species, transpiration is zero for a water table at or near the soil surface (Baird et al. 2005).

Sapflow measurement of groundwater transpiration (T_{gw}) from willow (*Salix* spp.) and cottonwood (*Populus fremontii*) in semi-arid California and Arizona (USA) was used to develop functional curves for the RIP-ET package in MODFLOW (Fig. 4; Baird et al. 2005). Coupled groundwater–energy–plant growth models produce similar curves in the

Table 2 Factors affecting groundwater evaporation functions

Factor	Nature of the effect	Relative importance (high, medium or low)	References and Examples
PET	Potential evaporation drives the rate of evaporation from the soil, until it is limited by water availability, soil type, the presence of a mulch or groundwater salinity	High for energy limited environments. Medium for water limited environments	Equations for soil evaporation can be found in: (Gardner 1958; Gardner and Fireman 1958; Philip 1957; Talsma 1963). Donohue et al. (2010) reviewed five different methods for calculating PET across the Australian continent
Soil texture	Finer soils such as clays and silts have a thicker capillary fringe and greater decoupling depth (the depth at which all ET is provided by groundwater) and extinction depth (the depth at which evaporation from groundwater ceases). Site soil texture also affects the shape of the evaporation–DTWT curve, as seen in Figure 3	High	The relationship between soil evaporation and DTWT for different soil textures has previously been described in soil physics literature (Gardner 1958; Gardner and Fireman 1958; Philip 1957; Talsma 1963). Shah et al. (2007) developed generic parameters for ET–DTWT functions for soil types in subtropical Hillsborough County, Florida (USA). Soylu et al. (2011) developed ET_a/ET_p–DTWT functions for different soil types at a grassland site in Champion, Nebraska, using HYDRUS-1D
Mulch	The presence of a mulch or other cover over the soil surface will reduce the rate of evaporation by reducing the soil temperature and limiting the movement of water vapour through the mulch layer	High	Benoit and Kirkham (1963) investigated the comparative effectiveness of dust, a corn mulch and a gravel mulch in inhibiting the evaporation of soil water. Gardner (1958) developed some analytical equations to model the effects of mulch on soil evaporation
Vegetation cover	Vegetation cover acts similarly to a mulch, by shading and reducing the soil surface temperature and therefore evaporation potential	Medium	Shah et al. (2007) developed generic parameters for ET-DTWT functions for different vegetation covers. This work did not separate soil evaporation from vegetation transpiration
Groundwater salinity	High groundwater salinity can also reduce evaporation rates. More energy is required to evaporate water molecules as solute concentration increases; subsequently the rate of evaporation decreases exponentially with increasing salinity. Salt crust deposits will also impact the rate of evapotranspiration by acting similarly to a mulch	Low for <30,000 mg L^{-1}. High for > 30,000 mg L^{-1}	Equations describing the relationship between evaporation and solute concentration are available from Bonython (1958), Leaney and Christen (2000) and Turk (1970)

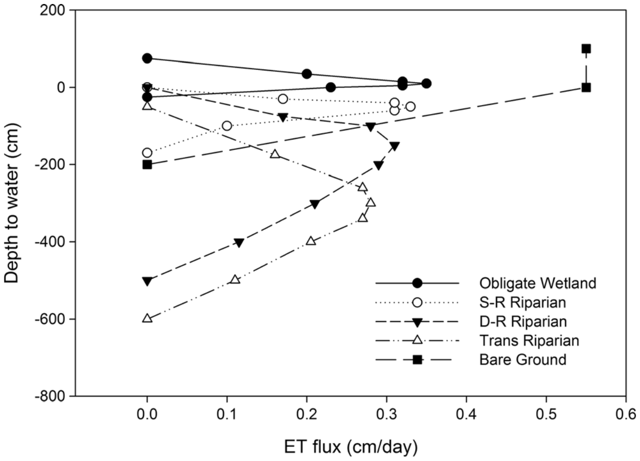

Fig. 4 Mean daily transpiration canopy flux (cm/day) curves for five plant functional groups (obligate wetland, shallow rooted riparian, deep rooted riparian, trans-riparian and bare ground) during summer months. *Positive numbers* denote standing water (Baird et al. 2005); with permission from Springer

Mediterranean climate of southern Australia (Doble et al. 2015). The shape of the transpiration function depends heavily on the characteristics of the site, as presented in Table 3.

Both the maximum transpiration rate and the extinction depth are influenced by the factors described in Table 3. The use of parameters for plant functional groups (riparian, dryland, tropical savannah etc.) may be used to represent the relationship between transpiration and DTWT in regional models, in other areas species-specific information may be required. While vegetation root distribution tends to be concentrated near the surface, deep roots are ecologically significant, with a small proportion of deep roots providing a large percentage of water uptake during dry periods (Canadell et al. 1996).

The temporal characteristics of the groundwater model are also critical for representation of transpiration. Vegetation will respond to hydrologic stimuli such as changes in DTWT, solute concentration and climatic conditions, through root and leaf growth or decline and death (Doody et al. 2015). Care should therefore be taken when upscaling plant behaviour to a hydrogeological time-scale that the vegetation life cycle and adaptations are accounted for.

Net recharge

Net recharge is defined as gross recharge minus ET_{gw}, and is worthy of further consideration as it is becoming more frequently used due to recharge estimation from remote sensing data. The shape of the relationship between net recharge and DTWT will be a combination of those of recharge, evaporation and transpiration with DTWT and is climate dependent. In water-limited environments, net recharge will generally be negative (ET) for shallow water tables, and positive (recharge) as DTWT increases. The relationships between recharge, E_{gw}, T_{gw} and net recharge are dependent on local geology, hydrogeology, vegetation and climate, and examples are shown in the figures by Sanford (2002) and Doble et al. (2015; Fig. 5a,b respectively).

Maxwell and Kollet (2008) plot a form of net recharge, precipitation minus ET (P – ET) against DTWT and propose that net recharge is controlled by temperature where the water table is less than 1 m in depth, groundwater (depth) where DTWT is between 1–6 m, and precipitation at DTWT greater than 6 m. These depth intervals correspond with the depths at which soil-based evaporation is likely to dominate and climate is a driver (<1 m), although DTWT is likely to still have an impact here, the depths at which transpiration is dominant and net recharge is a function of DTWT (1 – 6 m) and where DTWT is below the influence of vegetation and net recharge is controlled by gross recharge (>6 m).

Smerdon et al. (2010) indicated the importance of seasonality in relationships between net recharge and DTWT for the Okanagan Basin in western Canada, modelled using MIKE-SHE. Negative net recharge (ET) was predicted for water tables less than 2 m deep during spring, summer and fall, but winter showed only positive net recharge. Maximum net recharge was highest in spring and fall. Relationships will vary depending on climatic and meteorological conditions of the study site.

Methods for modelling recharge and ET

There are numerous methods for modelling recharge and ET within a catchment-scale groundwater model. Three basic approaches include (1) using a Darcy-based groundwater model with physical or emulated representations of recharge and ET boundary conditions, (2) using groundwater models coupled with 1-D unsaturated models, and (3) using fully coupled saturated–unsaturated models. The modelling methods, advantages and disadvantages, example models and case studies are described in Table 4.

Recharge and ET as a boundary condition

Saturated groundwater flow models provide the simplest means of modelling groundwater recharge and evapotranspiration. These models tend to have faster computational times, and can therefore be more easily applied to regional or continental problems, long time scales and probabilistic risk-analysis modelling. It may be easier to facilitate data assimilation into simpler models, so that observations drive the model outputs. The more linear functions that are associated with this type of model can lead to better model convergence; however as the models are more empirical than physically based, predictions for

Table 3 Factors affecting groundwater transpiration functions

Factor	Nature of the effect	Relative importance (low, medium, high)	References and Examples
Climatic conditions	In energy limited regions such as temperate zones, transpiration depends on seasonal and long-term changes in PET. In water limited arid and semi-arid areas, transpiration is more sensitive to recent and long-term precipitation	High	Reynolds et al. (2000) modelled long-term variation in ET as a function of variability in rainfall and plant functional type in New Mexico, USA. Rodriguez-Iturbe et al. (1999) modelled the impact of climate fluctuations on vegetation dynamics and canopy density in the southwest United States
Vegetation type, functional group and relative dependence on groundwater	Different species have evolved to transpire water at different rates, even under the same environmental conditions. Most vegetation will make use of shallow groundwater as a water source, but vegetation that have evolved to be groundwater dependent, such as riparian species or vegetation found in low-lying and shallow groundwater areas, will be more likely to have higher proportions of groundwater transpiration	High	Larcher (2003) provides an in-depth discussion of plant physiology affecting transpiration, and Eamus et al. (2006) discuss vegetation groundwater dependence. Baird et al. (2005) have developed ET functions for different plant functional groups to be used in MODFLOW. Shah et al. (2007) developed generic parameters for logarithmic ET-DTWT functions for soil types and vegetation covers. This work did not separate soil evaporation from vegetation transpiration
Season	In temperate areas, transpiration is highest in summer when deciduous trees have a maximum leaf canopy and PET is highest (Smerdon et al. 2010). In arid areas, transpiration can be higher in autumn and spring when stomatal conductance is maximised (De Luis et al. 2007). In tropical regions, transpiration of groundwater is often highest in the dry season due to the increased evaporative demand (O'Grady et al. 1999)	Long-term annual average: low. Short term seasonal: high (temperate) or medium (arid or tropical)	Baird and Maddock (2005) developed different ET–DTWT functions for various seasons for riparian vegetation in Arizona. Smerdon et al. (2010) developed DTW vs. net recharge curves in a Canadian forest, showing highest ET dominance in the summer
Life stage of the vegetation	Very young plants use less water than mature, actively growing plants. Water use is reduced again for senescing plants. At a regional scale, life stage is most likely to have an impact for farming or forestry areas, and areas that have recently been burned or destroyed by hurricanes. Transpiration can range from almost zero at germination or planting to close to PET at maturity	For managed monocultures or vegetation impacted by fires: high. For other more temporally stable vegetation cover: low	Dawson (1996) and Ewers et al. (2005) investigated the effect of tree age and size on groundwater transpiration for sugar maples in New York, USA, and boreal forest regeneration after wildfires in Manitoba, Canada, respectively
Salinity of the groundwater	Salinity limits water uptake by plants through processes of increasing the osmotic pressure required to extract water from the soil matrix, and toxicity. Both of these processes also restrict leaf growth, further limiting transpiration. Saline groundwater is more commonly an issue in arid and semi-arid regions where PET exceeds precipitation. Growth of salt sensitive plants such as vegetable crops may be limited at thresholds of 650 mg L^{-1}. Salt tolerant vegetation, such as Mellaleuca and Eucalyptus species, may tolerate over 10,000 mg L^{-1} (Niknam and McComb 2000). Vegetation salinity tolerance is usually higher for shorter periods of exposure	For groundwater with salinity of <1,000 mg L^{-1}: low. Salinity >1,000 mg L^{-1}: medium to high. Species dependant	Munns (2002) describes the physiology of salt stress on plants. Niknam and McComb (2000) compare salt tolerance of Australian woody plants, and Glenn et al. (1998) review salt tolerance of riparian species in the lower Colorado River, USA. Slavich (1997) modelled the use of saline groundwater by plants using the SVAT model WAVES. Thorburn et al. (1995) developed an analytical model for saline groundwater use by plants in arid and semi-arid areas
Rate of change in elevation of the water table	Rapidly declining groundwater levels can move below the plant root zone more quickly than roots can respond and grow further down into the soil profile. Where alternative water sources are not available, this can lead to	Medium	Froend and Sommer (2010) discuss the temporal variability in groundwater dependent vegetation response to climatic and abstraction induced drawdown

Table 3 (continued)

Factor	Nature of the effect	Relative importance (low, medium, high)	References and Examples
	vegetation death. Slower changes in the water table may allow plant root growth to continue to make use of the groundwater source. Long-term average recharge is impacted by vegetation death		
Soil type	Soil type affects the thickness of capillary fringe and, therefore, the height above the water table that groundwater is available for plant use. The capillary fringe is thicker for finer textured soils. Conversely, it also impacts the osmotic potential (plant suction) required to remove water from the soil matrix, with higher matric potential and more osmotic potential required to use water from finer textured soils	Medium	Gardner and Pierre (1966) describe the effects of soil type on plant transpiration. Crosbie et al. (2015) showed that the soil type and DTWT influenced the extinction depth in the transpiration functions of softwood forests
Canopy cover	A higher canopy density increases the total leaf area thereby increasing the potential for transpiration	High	O'Grady et al. (2011) found a relationship between leaf area index (LAI) and groundwater transpiration by terrestrial vegetation communities around Australia. Ellis et al. (2005) describe methods for calculating LAI and its impact on reducing deep drainage through transpiration for tree belts in south west Western Australia
Maximum rooting depth and root distribution	Deeper roots and a greater distribution of root mass at depth make it possible for plants to access deeper water and sustain transpiration through dry periods. Globally, the maximum rooting depth for trees has been estimated at 7 m ±1.2 m, 5.1 ± 0.8 m for shrubs, and 2.6 ± 0.1 m for herbaceous plants (Canadell et al. 1996). However, in some biomes, plant roots have been observed up to 68 m below the surface	Seasonally: high. Long-term annual average: medium	Canadell et al. (1996) provide a comprehensive review of plant rooting depths. Jackson et al. (1996) provide a global review of root distributions, and Jackson et al. (2000a) discuss some of the impacts of root distributions on modelled transpiration outcomes
Hydraulic lift	It has been observed that plants with dimorphc root systems (shallow, lateral roots and deeper, tap roots) can passively move water from the deeper, wetter soil profile, to the shallower, drier profile. This can make soil water available for a greater number of species, including those with only shallow roots. Mostly impacts Mediterranean climates, but also cooler temperate regions and the seasonally dry tropics	Seasonally: medium. Long-term average: low	Caldwell and Richards (1989) and Dawson (1996) describe the effects of hydraulic lift on plant water use. Jackson et al. (2000b) use plant physiological tools to model the process of hydraulic redistribution of water by trees

climatic conditions or land use changes outside of those used for calibration may be compromised. Local scale and small temporal scale results (monthly or seasonal) may not be as accurate as more physically based models.

As an example, the core MODFLOW model (Harbaugh et al. 2000; McDonald et al. 1988) represents recharge as a single time-varying value for each model cell using the recharge (RCH) package, and ET as a linear or piecewise function of groundwater depth using the evapotranspiration (EVT) or segmented evapotranspiration (ETS) packages (Banta 2000). Recently, many other representations of recharge and ET processes have been added to the MODFLOW suite in the form of additional packages and processes.

Coupled saturated–unsaturated groundwater flow models

A saturated groundwater model coupled with a 1-D unsaturated zone model using physically based equations can provide a good conceptualisation of recharge and evapotranspiration processes and is a compromise between the faster, simpler saturated models and slower, more complex fully coupled, physically based recharge. The coupling can involve representations of the subsurface—saturated and unsaturated zones, surface-water processes and often land surface and atmospheric components.

Physically based models can provide better estimates of recharge and ET at monthly or seasonal timescales than water

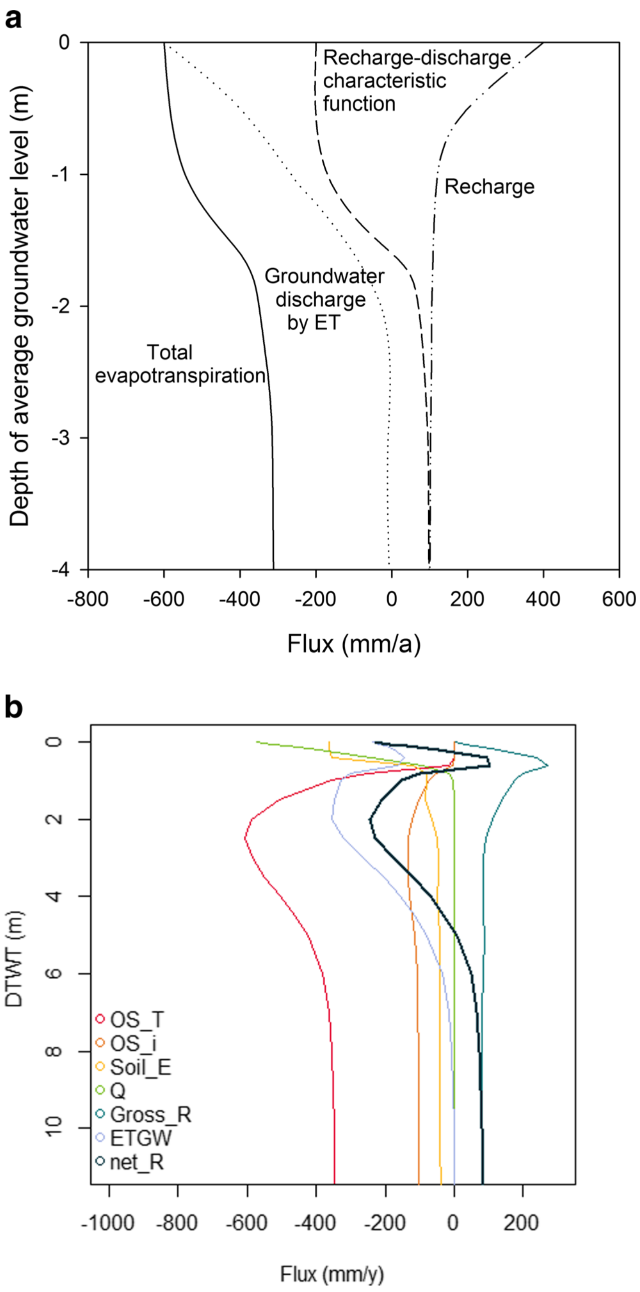

Fig. 5 **a** Example of the relationships between recharge, evapotranspiration (ET) and depth to water table (DTWT) (Sanford 2002) with permission from Springer. Recharge is gross recharge, groundwater discharge by ET represents ET_{gw}, total evapotranspiration represents $ET_{gw} + ET_{uz}$, and the recharge–discharge characteristic function is net recharge (gross recharge; ET_{gw}). **b** Long-term average depth to water table (DTWT) vs. water balance flux curves generated from WAVES modelling for temperate Mount Gambier, Australia, native vegetation on a silty loam, showing overstory transpiration from both soil and groundwater (*OS_T*), overstory interception (*OS_i*), evaporation from the unsaturated zone (*Soil_E*), runoff (*Q*), gross recharge (*Gross_R)*, evapotranspiration directly from groundwater (*ETGW*) and net recharge (*net_R*). After Doble et al. (2015), with permission from the Goyder Institute for Water Research

balance models. The coupled model can be easily tailored to the questions that it is intended to address. It is possible to select or develop an unsaturated model that has functions specific to the site which may not be available from commercially available models such as the impact of salinity on transpiration, or the effects of changing CO_2 levels on plant growth. The groundwater flow facility is maintained through the use of the groundwater model, while a 1-D unsaturated zone model is computationally less intensive than a 3-D unsaturated zone model. Modelling platforms are available to automate linkages between groundwater and unsaturated model zones.

Fully coupled models

Fully coupled models are valuable for modelling sites that are small in spatial and temporal scale, and where more complex processes are involved, for example recharge into hillslope catchments where interflow and recharge rejection are an important part of the water balance. These codes are well suited to developing a better understanding of groundwater/surface-water interactions, and saturated–unsaturated soil processes, as the soil and water are treated as a single store rather than separated into saturated and unsaturated components. However, obtaining separate outputs from the water balance can require extra processing due to this ‘one water’ approach.

Again, fully coupled models have a better predictive capability outside of calibration conditions and at a sub-annual timescale, and there are potentially more types of observations that may be used in calibration such as vegetation greenness indices and remotely sensed soil-moisture data. The long computational times may prohibit probabilistic modelling in larger catchments or for long timescales. Because of this, highly complex models are not generally used in modelling for risk-based water resources management and decision-making. Data-model merging may also be more difficult with more complex models.

A note on model complexity

There are currently two well-justified schools of thought on model complexity. One is that higher complexity is better, and that a thorough, automated calibration will result in better predictive capabilities, even if data are not available for all parameters. The other is that simplified models, with ‘just enough’ functionality, are better as they allow for better model interrogation through uncertainty analysis and therefore better understanding of model and system behaviour and sensitivities.

With reasonable data sets for calibration and realistic bounds for parameters where no data are available, more complex, physically based groundwater models can provide more robust predictions than simple models. Although it is less straightforward, methods have been developed for optimisation and uncertainty analysis on highly non-linear models. The use of surrogate modes and the null-space Monte Carlo method for parameter estimation and uncertainty analysis of a groundwater model is compared against a formal Bayesian approach in Keating et al. (2010).

However, there can be a tendency to use more complex models than are justified for the problem being addressed, particularly since highly complex models often appear more credible to stakeholders. The benefit of increasing model complexity to improve error metrics by 1–2 % is questionable when compared with minimising run times enough to interrogate the model performance, uncertainty and sensitivity to different processes and parameters. Complex models may have over 50 parameters, but in data poor regions, only enough information to form reasonable bounds for five of these. Similarly, model sensitivity analyses often show that only five to ten of these 50 parameters have a significant impact on the model results (Peeters et al. 2014).

Paradoxically, the level of complexity required is only known after a model has been developed and a sensitivity analysis has been undertaken. Appropriate complexity could be attained by incremental increases in model parameters and processes, developing a complex model and using a model emulator for uncertainty analysis, or at least dedicating an adequate proportion of model development effort to develop an optimal conceptualisation. Ultimately, of course, the appropriate model selection will depend on the site conditions and the questions that the modelling is intended to answer.

Emulation modelling

Where recharge and ET relationships are well understood, they can be represented by statistical, empirical or simplified biophysical (lower-fidelity) relationships, linked with groundwater flow models. This method has the potential to maintain adequate representations for recharge and ET, while reducing computational effort. Emulation modelling—also known as substitution modelling, metamodelling or reduced modelling—involves training the model emulator by running a more complex, physically based model with various parameter realisations several hundreds or thousands of times, and approximating the function between each of the training points. The emulator may then be used for predictive modelling, and more powerfully, for uncertainty analysis to better understand system function or in a risk analysis framework (Keating et al. 2010).

Examples of emulation modelling of recharge and ET processes can be found in studies involving: the unconfined Chalk in the Berkshire region of England (UK) by Ireson and Butler (2013); recharge to the Mediterranean climate Gnangara Mound, north of Perth, Australia, by Brown et al. (2014); the semi-arid Murray River, Australia, by Doble et al. (2006); and the Mediterranean climate Limestone Coast, southern Australia, by Doble et al. (2015). General information for using emulation modelling in the water resources sector can be found in O'Hagan (2006), Castelletti et al. (2012), Razavi et al. (2012) and Asher et al. (2015).

The recharge and ET functions that are used in emulation modelling may be tailored to the model purpose, spatial and temporal scale and the site characteristics. Understanding the physical processes of recharge and ET processes is paramount to effective emulation modelling. More detailed modelling on a fine scale may be required to understand the local nuances of these processes.

Considerations for representation of recharge and ET

In many groundwater models, ET is represented as a function of DTWT. This facilitates the use of Cauchy (head dependent) boundary conditions at the surface of the saturated groundwater model. Conventionally, recharge is represented by a Neumann (variable flux) surface boundary condition, independent of depth to groundwater. While this simplifies the model algorithms, in shallow groundwater it may not necessarily be a valid assumption. When saturated groundwater models are coupled with 1-D unsaturated zone models such as HYDRUS or WAVES, recharge and ET are controlled by the lower boundary condition of the 1-D unsaturated model. Where groundwater is deep, a free draining (Neumann) lower boundary condition will be adequate to represent recharge and ET processes. For shallow groundwater, a variable head (Dirichlet) lower boundary is necessary to provide accurate estimations of recharge and evapotranspiration—for example, Lu et al. (2011) and Naylor et al. (2015) used either variable head or free draining boundary conditions in HYDRUS-1D to model groundwater recharge in the semi-arid to semi-humid Hebei Plain, China and the humid-continental Great Lakes region of the USA respectively.

Whatever method is used to conceptualise and model recharge and ET, there are some key points that should be considered. Thorough planning in the conceptualisation stage of modelling, including a rigorous problem description, will improve the way that recharge and ET are represented in groundwater models.

Depth dependence of ET and recharge functions

In water resources management, it is often the water budget that is of interest; therefore, model input and output volumes, rather than groundwater heads, are important. The depth dependence of ET, net recharge and in some cases gross recharge, can therefore sometimes result in a seemingly circular argument between recharge and ET parameter inputs and the resulting recharge and ET model outputs. However, this depth

Table 4 Methods for modelling recharge and evapotranspiration

Modelling method	Advantages, disadvantages and case studies
Saturated groundwater model with recharge and ET as a top boundary condition (BC). (Recharge may range from simple empirical relationship such as a percentage of rainfall to more pre-calculated water balances. ET is often linear or piecewise linear, with head dependent functionality)	
	Advantages:
	• Faster computational times, therefore the method can be more easily applied to regional or continental problems and probabilistic risk-analysis modelling or long time scales
	• Fewer parameters required, which may allow for application in data-poor areas
	• It may be easier to facilitate data assimilation into simpler models, so that observations drive the model outputs
	• More linear functions can facilitate better model convergence
	Disadvantages:
	• Predictions may be compromised if climatic conditions and/or vegetation cover changes from those used in calibration
	• Local and small temporal scale results may not be as accurate as more physically based models
	Case studies:
	- The core MODFLOW model (Harbaugh et al. 2000; McDonald et al. 1988) represents recharge as a single time-varying value for each model cell using the recharge (RCH) package, and ET as a linear or piecewise function of groundwater depth using the evapotranspiration (EVT) or segmented evapotranspiration (ETS1) packages (Banta 2000). There are many examples of using MODFLOW packages to estimate evapotranspiration, particularly in the grey literature. A more recent example is in Wang et al. (2008) where the ETS1 package was used to estimate evapotranspiration in The North China Plain
	- MODFLOW with the riparian ET package, RIP-ET (Baird and Maddock 2005; Maddock and Baird 2002), which applies a more realistic ET–DTWT relationship developed for riparian vegetation, and allows a number of vegetation types and associated rooting depths and ET surfaces to be applied in one model cell. Also available as a GIS tool (Ajami et al. 2012). Ajami et al. (2011) compared groundwater ET using the RIP-ET, EVT and ETS1 packages, in Dry Alkaline Valley in southwest USA
	- FEFLOW (Diersch 2005) using Dirichlet (specified head), Neumenn (specified flux) or Cauchy (head dependent flux) BCs. Unsaturated flow can be modelled using Richards' equation. Zhao et al. (2005) used FEFLOW with a specified flux BC calculated from vegetation coverage in the arid Sangong River watershed in China
Saturated groundwater model coupled with a 1-D physically based unsaturated zone/vegetation model	
	Advantages:
	• It is possible to select the unsaturated zone/vegetation model to be specific to the site, including functions that may not be available from off-the-shelf models, such as the impact of salinity on transpiration
	• Physically based models will provide more appropriate estimates of recharge and ET at a sub-annual timescale
	• A 1-D unsaturated zone model is computationally less intensive than a 3-D unsaturated zone model
	• Platforms are available to link groundwater and unsaturated model zones together
	Disadvantages:
	• The benefits of increasing model complexity depend on the questions that the modelling is intended to address
	• Long computational times may complicate probabilistic uncertainty modelling in large catchments
	Case studies :
	- The coupled groundwater and surface-water flow model, GSFLOW (Markstrom et al. 2008), which combines a precipitation-runoff modeling system (PRMS) with MODFLOW-2005. PRMS models the landscape processes while MODFLOW-2005 models groundwater, lakes and river networks. Tian et al. (2015) used GSFLOW to model the arid/semi-arid Zhangye Basin in northwest China
	- The unsaturated zone package for MODFLOW (UZF; Niswonger et al. 2006), where the unsaturated zone is represented by a 1-D kinematic wave approximation of Richards' equation. Upward evapotranspiration flux is represented by Richards' equation for soil moisture plus the evapotranspiration package (EVT) for any remaining evaporation from the groundwater. Hunt et al. (2008) used the UZF package to approximate unsaturated zone flow in the humid Trout Lake watershed in north-central Wisconsin, USA
	- MODFLOW Farm Process (Schmid and Hanson 2009; Schmid et al. 2006). The farm process uses transpiration based on crop processes, using vegetation parameters that include wilting point and anoxia limits. Hanson et al. (2010) used the Farm Process to model conjunctive water use in the Pajaro and Central valleys in California, USA
	- One water hydraulic flow model, MODFLOW-OWHM (Hanson et al. 2014), builds on the Farm Process, and uses the riparian ET package described previously. Turnadge and Lamontagne (2015) used MODFLOW-OWHM to model wetlands in the temperate to semi-arid region of the Lower Limestone Coast of South Australia
	- MODFLOW-SURFACT uses EVT and ETS1 packages and includes surface-water processes (Panday and Huyakorn 2008). Cooper et al. (2015) used MODFLOW-SURFACT to model the impacts of groundwater pumping on mountain wetlands in a mountain wetland complex, Yosemite National Park, California, USA. Bedekar et al. (2012) compared several approaches to modelling unsaturated zone flow, including MODFLOW-SURFACT

Table 4 (continued)

Modelling method	Advantages, disadvantages and case studies
	- The Soil and Water Assessment Tool, SWAT (Arnold et al. 1998; Neitsch et al. 2011), is a semi-distributed watershed model that models climatic, surface and subsurface flow processes, and allows for upward flux of groundwater from a shallow water table due to evaporation in the unsaturated zone. Sophocleous and Perkins (2000) used SWAT and MODFLOW to model groundwater – watershed processes in Kansas, USA. Kim et al. (2008) developed a SWAT-MODFLOW model for the temperate Musimcheon Basin in South Korea - There are examples of coupling MODFLOW or FEFLOW with 1-D unsaturated zone models such as HYDRUS (Simunek et al. 1988). Twarakavi et al. (2008) compared a MODFLOW–HYDRUS-1D coupled approach with the alternative MODFLOW packages: VSF, UZF1, and REC-ET. Sun et al. (2004) used MODFLOW and HYDRUS-1D to model the impacts of land use change and groundwater pumping on groundwater levels and quality - Similar couplings can be made between MODFLOW or FEFLOW and WAVES (Zhang and Dawes 1998). Ali et al. (2012) and Dawes et al. (2012) modelled the effects of climate change and land use cover in south western Australia using MODFLOW and WAVES
Recharge and ET as physical processes using fully-coupled saturated-unsaturated models	
	Advantages: • Better predictive capability outside of calibration conditions. • Potentially more types of observations available for calibration, including vegetation indices • Physically based models will provide more appropriate estimates of recharge and ET at a sub-annual timescale Disadvantages: • Long computational times may complicate probabilistic uncertainty modelling in large catchments • Data–model merging and data assimilation may be more difficult with more complex models Obtaining separate outputs from the water balance can require extra processing due to the 'one water' approach through saturated and unsaturated zones Case studies: - HydroGeoSphere (Brunner and Simmons 2011; Therrien et al. 2006), a fully integrated surface-water/groundwater model. A modified 3-D Richards' equation is used to represent flow through the unsaturated zone, using either van Genuchten (1980) or Brooks and Corey (1964) functions for saturation – relative hydraulic conductivity relationships. Sciuto and Diekkrüger (2010) and Cornelissen et al. (2013) modeled the water balance in the forested Wüstebach basin, Germany. Evapotranspiration was modelled physically using plant growth parameters. Alaghmand et al. (2014) modelled evapotranspiration in the semi-arid River Murray floodplains, Australia - MIKE SHE (Refsgaard and Storm 1995) simulates water flow, water quality and sediment transport. The model uses the Kristensen and Jensen (1975) method for converting potential ET to actual ET (empirical equations used), with Richards' equation representing the unsaturated zone. Examples using MIKE SHE include studies by Vázquez (2003), who modelled evapotranspiration in the low-lying Gete catchment in Belgium, and Thompson et al. (2004) who modelled a lowland wet grassland in southeast England, UK - ParFlow (Maxwell and Miller 2005), an integrated surface and subsurface flow model using a mixed form of Richards' equation to model the unsaturated zone. This model can alternatively be linked with another land surface model. Atchley and Maxwell (2011) modelled the impacts of vertical hydraulic conductivity and vegetation cover on evapotranspiration at a hillslope scale in the USA using ParFlow - MODHMS (HydroGeoLogic 2006; Panday and Huyakorn 2004), an extension of MODFLOW-SURFACT. A physically based, spatially distributed, conjunctive surface/subsurface flow model that uses a fully 3-D saturated-unsaturated subsurface flow equation. Young et al. (2007) calibrated a MODHMS model of bare soil evaporation using lysimeter data at Davis, California. Werner et al. (2006) used MODHMS to model stream–aquifer interaction in the tropical Pioneer Creek catchment, Queensland, Australia

dependence provides a self-correcting environment for the water table in unconfined aquifers with shallow groundwater, which may lead to improved estimations of groundwater head, especially at a break of slope in the land surface (Doble et al. 2006). Depth dependence does, however, force the model to solve non-linear functions for ET and net recharge, which can increase problems with model convergence. In particular, rewetting of cells during iterations can lead to instability and non-convergence. Convergence may be improved by changing solvers or solver parameters, smoothing parameters across boundaries with large changes, reducing grid sizes, or conducting a preliminary run with a simplified version of the model (alternative steady state or transient, all confined layers, rewetting off, ET represented by a constant flux) then use the final head outputs as initial conditions for the original model.

While it is best practice for any groundwater model, it is imperative that models of shallow groundwater systems should be calibrated using flux observations in addition to the conventional piezometric head observations (Sanford 2002). These flux observations might be in the form of spatial estimations of recharge and ET from field measurements or remote sensing observations or measurements of baseflow from gauged rivers and drains. In particular, the use of remote sensing data has great potential here to improve model calibration in data-poor regions.

Representation of the ET surface

While the estimation of maximum ET and extinction depth (or equivalent soil and vegetation parameters for fully coupled land surface models) is critical, even more important in regional groundwater models is the estimation of the evapotranspiration surface. For larger model cell sizes, the ability to accurately represent the proportion of the cell in which the water table exceeds the extinction depth becomes difficult (Fig. 6), which can lead to errors in estimation of ET rates (Ajami et al. 2011; Kambhammettu et al. 2014; Kuniansky et al. 2009).

There are several methods for reducing this ET error associated with scale. One option is to reduce the size of the model cells, particularly in areas of the model where there is a large variation in elevation such as around rivers and surface-water bodies. Grid refinement in MODFLOW is possible with the Local Grid Refinement (LGR) package or unstructured grid (USG) process. The RIP-ET package allows fractions of cells to be covered by different riparian vegetation subgroups, and the land surface elevation to change within a cell for different plant functional type subgroups, although the groundwater is at a constant elevation within the cell (Maddock III et al. 2012). While the unstructured grid version of MODFLOW, MODFLOW-USG (Panday et al. 2013) currently only supports the RCH and EVT packages, it may provide a means of increasing cell discretisation adjacent rivers and in low-lying areas to improve representation of the evapotranspiration surface. Finite element models such as FEFLOW or HydroGeoSphere, also allow for grid refinement around areas of interest and can be defined using mesh generators such as Algomesh (Merrick 2015), GridBuilder (McLaren 2004), EasyMesh (Niceno 2002) or Triangle (Shewchuk 1996, 2002). It may be possible to calculate cell size as a function of surface slope to obtain more efficient mesh designs.

Where the size and number of cells is limited by the required computational effort, or where elevation information is available at a much finer scale than desired cell sizes, statistical representations of the land surface can be used within a single cell. Petheram et al. (2003) used a sub-grid representation of the land surface to calculate groundwater discharge using the 1-D flow model FLOWTUBE. Peeters et al. (2013) used hypsometric curves to more accurately represent the land surface within the continental scale Australian Water Resources Assessment (AWRA) model. To the authors' knowledge, this process has not yet been formally included in groundwater flow model codes.

Spatial and temporal scale

The spatial and temporal scale of the problem being investigated will dictate how recharge and ET are conceptualised in groundwater models. Seasonal and long-term average estimates of recharge may have to consider other water inputs, such as ponded runoff which later infiltrates into the soil and

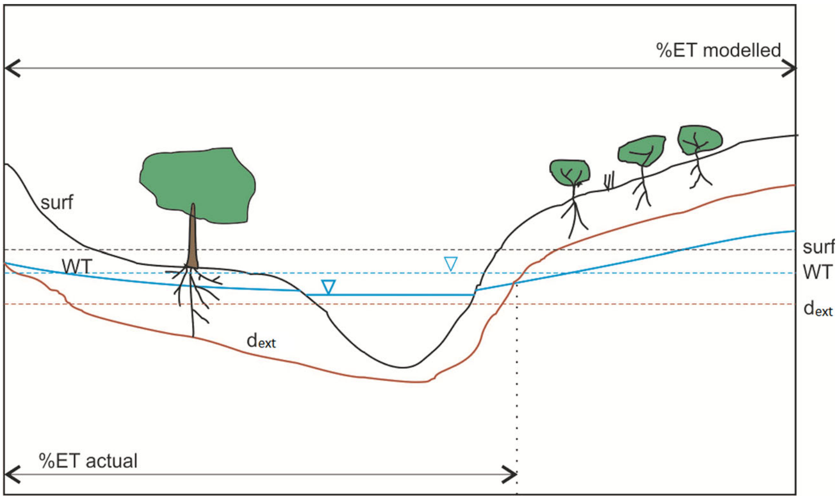

Fig. 6 Representing *ET* extinction depth in a regional groundwater model: schematic of a single model cell. When cell dimensions are large, the proportion of cell undergoing ET will not represent the proportion of cell undergoing ET at a fine scale. In this example, approximately 2/3 of the cell has the water table (*WT*) above the extinction depth (d_{ext}). When the average land-surface elevation (*surf*), water table and extinction depth are used, 100 % of the cell has the water table above the extinction depth, therefore is experiencing ET

recharges groundwater. Courser model discretisation may require runoff to be added to the infiltration term in the water budget for the same reason. More finely discretised models, however, may require the routing of runoff from one cell into an adjacent cell as recharge, and the coupling of a surface-water model with the groundwater model or use of a fully coupled model is justified. For deeper groundwater, there is also a significant lag time between infiltration at the surface and recharge at the water table (Hvorslev 1951).

Seasonal changes are reflected in recharge rates, soil evaporation and vegetation transpiration. Season impacts the antecedent soil-moisture conditions, therefore altering the proportion of infiltration that becomes recharge at the water table (Castillo et al. 2003). For longer timescales, such as calculating an annual average recharge for 10 or more years of continuous data, the impact of assuming no change in soil-moisture storage from the start to end dates is low. This assumption, however, is not valid for monthly or seasonal estimations of recharge. For shorter temporal intervals, soil moisture also has a greater influence on estimates of recharge using water balance methods with remotely sensed ET.

Season governs whether precipitation is in the form of rainfall or snow, and recharge from snowmelt will be delayed from the original precipitation. Long-term climatic change will not only affect the annual average precipitation rate, but may also change the intensity of precipitation events, influencing the proportion of precipitation that is recharged (Barron et al. 2012; Crosbie et al. 2012).

Physically based recharge estimation methods are likely to provide more accurate predictions of daily–monthly variations in recharge and enable prediction of climate change impacts on the seasonality of recharge (Assefa and Woodbury 2013). They will also be more likely to provide adequate predictions for different climate conditions than those under which the model was calibrated. This may not be the case for simple, empirical models such as recharge as a percentage of rainfall.

The rate of change of DTWT will affect the plant response and plant water use. In water-limited environments, when groundwater is drawn down slowly, vegetation may grow deeper roots and continue to use groundwater as the major water source. When drawdown is rapid and sustained such as from the commencement of pumping from a bore, vegetation root growth may not be rapid enough, causing plants to die and groundwater transpiration to cease (Froend and Sommer 2010).

Remote sensing data

Two major growth areas in groundwater modelling recently are the use of uncertainty modelling and risk analysis, and the incorporation of remote sensing data into spatially variable estimations of recharge and evapotranspiration (ET). Field-derived ET data from flux towers should be used where possible for groundwater model calibration or inverse uncertainty analysis; however, this information is at a point scale, and due to the expense associated with obtaining it, coverage can be limited. In data-poor regions, remote sensing may provide a source of data for model calibration (Carroll et al. 2015), through pilot point calibration techniques (Doherty et al. 2010), as an estimate of uncertainty in recharge and ET model inputs, or as a source of data for assimilation into groundwater models (Pauwels and De Lannoy 2009). Assimilation of remote sensing data into land surface models is an active area of research (Pauwels et al. 2001), but there is very little information on assimilating remote sensing estimates of ET and recharge into groundwater models. Use of remote sensing data in groundwater models include the aforementioned work in Botswana and China (Brunner et al. 2007) and Nebraska (Szilagyi et al. 2011).

Estimates of ET are available through a number of independent data sources, including reflectance data (Nagler et al. 2005) and land surface temperature (Kalma et al. 2008). Remote sensing derived information may be used for predicting antecedent soil-moisture conditions used in recharge estimation or detecting shallow groundwater (Jackson 2002). At a global scale, estimating changes in the groundwater store, and therefore inferring groundwater recharge, can be made using information from the NASA GRACE satellite (Reager and Famiglietti 2013), although there is still work required to improve estimates at a sub-continental scale.

Remotely sensed ET still needs to be calibrated against point–scale field data (Nagler et al. 2015), and the errors and uncertainty in field based methods such as eddy covariance towers and sap flow sensors range from 5 to 30 % (Glenn et al. 2011). This is similar to the error and uncertainty estimations from remotely sensed ET data derived using thermal and vegetation index methods, of around 10–30 % (Glenn et al. 2011). Aggregation of remotely sensed ET data to monthly or longer averages improves its accuracy compared with field estimates, but development of improved spatial scaling methods are required (Kalma et al. 2008).

Vegetation index-based estimates of ET usually only reflect the transpiration component, and evaporation from the soil surface is not included. Improvements in remotely sensed soil-moisture estimates will potentially improve estimates of ET by improving the algorithms used to convert potential ET (PET) to actual ET (AET). Thermal–based estimates of ET (Kalma et al. 2008) include both vegetation transpiration and soil evaporation components of ET and is independent of the PET to AET conversion process; however the spatial resolution of thermal estimates of ET are generally coarser than reflectance data.

Uncertainty analysis

Including measures of uncertainty for recharge and ET estimations reflect the confidence in both a model's ability to predict these parts of the water balance, and in the currently available input data used to produce these predictions. Sources of uncertainty include local and global climate models (GCMs; Crosbie et al. 2011), landuse mapping and classification (Eckhardt et al. 2003), soil mapping and classification (Schaap et al. 1998), accurate water table and land surface estimations, functional vegetation responses and the conceptual groundwater model itself. A systematic analysis of the contribution of groundwater conceptual models to uncertainty is presented in Rojas et al. (2010, 2008).

Where field observations of groundwater head or flux are available, inverse uncertainty estimation may be used to determine a range for each recharge and ET parameter that will produce the observed outputs. This can decrease the parameter space required for an emulator model to reproduce the outputs of a more complex model and provide probability distributions or likely ranges for each input parameter. Where observations of groundwater model outputs are not available, expert elicitation or multiple observations of recharge and ET input data may be used to define feasible parameter spaces to use in forward uncertainty propagation to predict probablility distributions for groundwater model outputs.

Presentation of recharge and ET data as probability distributions for groundwater model inputs provides significantly more information to the model user or client and enables model outputs to be easily incorporated into risk analysis and water management planning (Merrick 2000; Raiber et al. 2015). The large number of data points provided by remote sensing data has the potential to assist in this process.

Summary and future research opportunities

Simple representations of recharge and ET in groundwater models have been appropriate in the past, particularly in data poor regions; however, the availability of continuously improving, remotely sensed estimates of ET and recharge mean that a more physically based conceptualisation of recharge and ET may be warranted and potentially lead to improvements in model outputs and confidence. This paper has shown that recharge and ET can both be depth dependent and that this depth dependence can result in additional calibration requirements, particularly estimates of groundwater fluxes such as baseflow to streams. It is critical that recharge and ET are explicitly defined (gross recharge vs net recharge, groundwater ET vs total ET) in the reporting of modelling results to avoid double accounting in the water balance.

There are many options for representing recharge and ET processes in groundwater models, ranging from the basic boundary condition functions to complex fully coupled surface-unsaturated–saturated models. Model emulators enable the behaviour of recharge and ET from complex models to be preserved, while reducing computational effort and model run times. This is particularly important for risk or uncertainty analysis, which is becoming a standard aspect of groundwater modelling.

In whichever manner recharge and ET are modelled, representation of the land surface is critical for accurate estimations of ET. The spatial and temporal scale of the questions being addressed by the model will influence the way in which recharge and ET are represented, through vegetation responses, initial soil-moisture conditions, lag times and interactions between model cells. The use of remote sensing in model parameterisation and calibration is critical for improving recharge and ET in data-poor regions, particularly with respect to the spatial and temporal distributions of these fluxes. Use of risk or uncertainty analysis for estimating recharge and ET or using them as groundwater model inputs is justifiably becoming standard practice. Forward uncertainty analysis to estimate probability bounds for predictive estimates and inverse uncertainty analysis to estimate likely bounds for parameter inputs provide far more information and are more scientifically robust than single predictions and parameter estimations.

Future research opportunities to improve the representation of recharge and ET in groundwater models include:

- Improvements in constraining estimates of recharge and ET using remote sensing of ET and soil moisture. This field of research is likely to grow and evolve as new remote sensing products become available and improve in accuracy and in temporal and spatial scales.
- Inclusion of remote sensing estimates of recharge and ET directly into groundwater models, through calibration processes or direct assimilation. This is a growing area of research for land surface models, but there are very few examples in the groundwater modelling literature.
- Better representation of recharge and ET in terms of risk and uncertainty. While uncertainty analysis is common for hydrological model outputs such as streamflow forecasting and conceptual uncertainty estimates of ET from ensemble global climate models, this has not often translated to recharge and ET estimates in groundwater models. This may be particularly useful for understanding risks for groundwater dependent communities and ecosystems.
- Using uncertainty analysis to prioritise data acquisition and improvement. Analysis of model and remote sensing estimates may give insight into the most effective locations to calibrate model (and remote sensing algorithm) predictions with field-based measurements, gaining the largest model confidence benefit from further field data collection.

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References

Ajami H, Meixner T, Maddock T III, Hogan J, Guertin DP (2011) Impact of land-surface elevation and riparian evapotranspiration seasonality on groundwater budget in MODFLOW models. Hydrogeol J 19: 1181–1188. doi:10.1007/s10040-011-0743-0

Ajami H, Maddock T, Meixner T, Hogan JF, Guertin DP (2012) RIPGIS-NET: a GIS tool for riparian groundwater evapotranspiration in MODFLOW. Ground Water 50:154–158

Alaghmand S, Beecham S, Jolly ID, Holland K, Woods J, Hassanli A (2014) Modelling the impacts of river stage manipulation on a complex river-floodplain system in a semi-arid region. Environ Model Softw 59:109–126

Ali R, McFarlane D, Varma S, Dawes W, Emelyanova I, Hodgson G (2012) Potential climate change impacts on the water balance of regional unconfined aquifer systems in south-western Australia. Hydrol Earth Syst Sci 16:4581–4601

Amlin NA, Rood SB (2001) Inundation tolerances of riparian willows and cottonwoods. Wiley Online Library. doi:10.1111/j.1752-1688.2001.tb03671.x

Anderson VG (1945) Some effects of atmospheric evaporation and transpiration on the composition of natural water in Australia (continued): 4. underground waters in riverless areas. J Aust Chem Inst 12:83–98

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Large area hydrologic modelling and assessment, part 1: model development. J Am Water Resour Assoc 34:73–89

Asher M, Croke B, Jakeman A, Peeters L (2015) A review of surrogate models and their application to groundwater modeling. Water Resour Res 51:5957–5973

Assefa KA, Woodbury AD (2013) Transient, spatially varied groundwater recharge modeling. Water Resour Res 49:4593–4606

Atchley AL, Maxwell RM (2011) Influences of subsurface heterogeneity and vegetation cover on soil moisture, surface temperature and evapotranspiration at hillslope scales. Hydrogeol J 19:289–305

Baird KJ, Maddock T III (2005) Simulating riparian evapotranspiration: a new methodology and application for groundwater models. J Hydrol 312:176–190

Baird K, Stromberg J, Maddock T (2005) Linking riparian dynamics and groundwater: an ecohydrologic approach to modeling groundwater and riparian vegetation. Environ Manag 36:551–564

Banta ER (2000) MODFLOW-2000, the U.S. Geological Survey modular ground-water model-documentation of packages for simulating evapotranspiration with a segmented function (ETS1) and drains with return flow (DRT1). US Geol Surv Open-File Rep 00-466

Barron O, Crosbie R, Dawes W, Charles S, Pickett T, Donn M (2012) Climatic controls on diffuse groundwater recharge across Australia. Hydrol Earth Syst Sci 16:4557–4570

Bauer P, Held RJ, Zimmermann S, Linn F, Kinzelbach W (2006) Coupled flow and salinity transport modelling in semi-arid environments: the Shashe River Valley, Botswana. J Hydrol 316:163–183

Bedekar V, Niswonger RG, Kipp K, Panday S, Tonkin M (2012) Approaches to the simulation of unconfined flow and perched groundwater flow in MODFLOW. Ground Water 50:187–198

Bell DT (1999) Australian trees for the rehabilitation of waterlogged and salinity-damaged landscapes. Aust J Bot 47:697–716

Benoit G, Kirkham D (1963) The effect of soil surface conditions on evaporation of soil water. Soil Sci Soc Am J 27:495–498

Benyon RG, Theiveyanathan S, Doody TM (2006) Impacts of tree plantations on groundwater in south-eastern Australia. Aust J Bot 54: 181–192

Bonython CW (1958) The influence of salinity upon the rate of natural evaporation. Proceedings of a symposium on arid zone recharge, climatology and microclimatology, Canberra, October 1986, UNESCO, Paris

Brooks RH, Corey AT (1964) Hydraulic properties of porous media. Hydrology Paper no. 3, Colorado State University, Fort Collins, CO, 27 pp

Brown A, Kuczera G, Cui L, Xu C, Milligan N, Canci M, Jeeveraj C, Donnelly M (2014) Monthly recharge modelling for the Gnangara Mound. Paper presented at the Hydrology and Water Resources Symposium 2014, Perth, Australia, 24–27 Feb 2014

Brunner P, Simmons CT (2011) HydroGeoSphere: a fully integrated, physically based hydrological model. Ground Water 50:170–176. doi:10.1111/j.1745-6584.2011.00882.x

Brunner P, Franssen H-JH, Kgotlhang L, Bauer-Gottwein P, Kinzelbach W (2007) How can remote sensing contribute in groundwater modeling? Hydrogeol J 15:5–18

Brunner P, Cook PG, Simmons CT (2009) Hydrogeologic controls on disconnection between surface water and groundwater. Water Resour Res 45, W01422. doi:10.1029/2008wr006953

Brunner P, Cook PG, Simmons CT (2011) Disconnected surface water and groundwater: from theory to practice. Ground Water 49:460–467. doi:10.1111/j.1745-6584.2010.00752.x

Caldwell MM, Richards JH (1989) Hydraulic lift: water efflux from upper roots improves effectiveness of water uptake by deep roots. Oecologia 79:1–5

Campbell GS (1974) A simple method for determining unsaturated conductivity from moisture retention data. Soil Sci 117:311–314

Canadell J, Jackson RB, Ehleringer JB, Mooney HA, Sala OE, Schulze ED (1996) Maximum rooting depth of vegetation types at the global scale. Oecologia 108:583–595. doi:10.1007/bf00329030

Carrera-Hernández J, Mendoza C, Devito K, Petrone R, Smerdon B (2011) Effects of aspen harvesting on groundwater recharge and water table dynamics in a subhumid climate. Water Resour Res 47. doi:10.1029/2010WR009684

Carroll RWH, Pohll GM, Morton CG, Huntington JL (2015) Calibrating a basin-scale groundwater model to remotely sensed estimates of groundwater evapotranspiration. JAWRA J Am Water Resour Assoc. doi:10.1111/jawr.12285

Carsel RF, Parrish RS (1988) Developing joint probability distributions of soil water retention characteristics. Water Resour Res 24:755–769

Castelletti A, Galelli S, Ratto M, Soncini-Sessa R, Young PC (2012) A general framework for dynamic emulation modelling in environmental problems. Environ Model Softw 34:5–18. doi:10.1016/j.envsoft.2012.01.002

Castillo V, Gomez-Plaza A, Martınez-Mena M (2003) The role of antecedent soil water content in the runoff response of semiarid catchments: a simulation approach. J Hydrol 284:114–130

Cooper DJ, Wolf EC, Ronayne MJ, Roche JW (2015) Effects of groundwater pumping on the sustainability of a mountain wetland complex, Yosemite National Park, California. J Hydrol Region Stud 3:87–105

Cornelissen T, Diekkrüger B, Bogena H (2013) Using HydroGeoSphere in a forested catchment: how does spatial resolution influence the simulation of spatio-temporal soil moisture variability? Proc Environ Sci 19:198–207

Crosbie RS (2003) The regional scaling of groundwater recharge. PhD Thesis, University of Newcastle, UK

Crosbie RS, Davies P (2013) Recharge estimation. In: Harrington N, Lamontagne S (eds) Framework for a regional water balance model for the South Australian Limestone Coast region. Goyder Institute for Water Research Technical Report Series no. 13/14, GIWR, Adelaide, South Australia

Crosbie RS, Binning P, Kalma JD (2005) A time series approach to inferring groundwater recharge using the water table fluctuation method. Water Resour Res 41, W01008. doi:10.1029/2004WR003077

Crosbie RS, Wilson B, Hughes JD, McCulloch C, King WM (2008) A comparison of the water use of tree belts and pasture in recharge and discharge zones in a saline catchment in the Central West of NSW, Australia. Agric Water Manag 95:211–223

Crosbie RS, Jolly ID, Leaney FW, Petheram C (2010) Can the dataset of field based recharge estimates in Australia be used to predict recharge in data-poor areas? Hydrol Earth Syst Sci 14:2023–2038

Crosbie RS, Dawes WR, Charles SP, Mpelasoka FS, Aryal S, Barron O, Summerell GK (2011) Differences in future recharge estimates due to GCMs, downscaling methods and hydrological models. Geophys Res Lett 38, L11406

Crosbie RS, McCallum JL, Walker GR, Chiew FH (2012) Episodic recharge and climate change in the Murray-Darling Basin, Australia. Hydrogeol J 20:245–261

Crosbie RS, Pickett T, Mpelasoka FS, Hodgson G, Charles SP, Barron OV (2013) An assessment of the climate change impacts on groundwater recharge at a continental scale using a probabilistic approach with an ensemble of GCMs. Clim Chang 117:41–53

Crosbie R, Davies P, Harrington N, Lamontagne S (2015) Ground truthing groundwater-recharge estimates derived from remotely sensed evapotranspiration: a case in South Australia. Hydrogeol J 23:335–350. doi:10.1007/s10040-014-1200-7

Dawes W, Ali R, Varma S, Emelyanova I, Hodgson G, McFarlane D (2012) Modelling the effects of climate and land cover change on groundwater recharge in south-west Western Australia. Hydrol Earth Syst Sci 16:2709–2722

Dawson TE (1996) Determining water use by trees and forests from isotopic, energy balance and transpiration analyses: the roles of tree size and hydraulic lift. Tree Physiol 16:263–272

De Luis M, Gričar J, Čufar K, Raventós J (2007) Seasonal dynamics of wood formation in *Pinus halepensis* from dry and semi-arid ecosystems in Spain. IAWA J 28:389–404

Delin GN, Healy RW, Landon MK, Bohlke JK (2000) Effects of topography and soil properties on recharge at two sites in an agricultural field. J Am Water Resour Assoc 36:1401–1416

Delleur JW (2006) The handbook of groundwater engineering. CRC, Boca Raton, FL

Diersch H (2005) FEFLOW finite element subsurface flow and transport simulation system. Reference manual. WASY, Berlin, pp 20–102

Doble R, Simmons C, Jolly I, Walker G (2006) Spatial relationships between vegetation cover and irrigation-induced groundwater discharge on a semi-arid floodplain, Australia. J Hydrol 329:75–97

Doble RC, Crosbie RS, Smerdon BD, Peeters L, Cook FJ (2012) Groundwater recharge from overbank floods. Water Resour Res 48, W09522. doi:10.1029/2011wr011441

Doble RC, Pickett T, Crosbie RS, Morgan LK (2015) Emulation of recharge and evapotranspiration processes in shallow groundwater environments for improved MODFLOW representation. Paper presented at MODFLOW and More 2015: Modeling a Complex World, Golden, CO, 31 May–3 June 2015

Doherty JE, Fienen MN, Hunt RJ (2010) Approaches to highly parameterized inversion: pilot-point theory, guidelines, and research directions. US Geol Surv Sci Invest Rep 5168:36

Donohue RJ, McVicar TR, Roderick ML (2010) Assessing the ability of potential evaporation formulations to capture the dynamics in evaporative demand within a changing climate. J Hydrol 386:186–197

Doody TM, Colloff MJ, Davies M, Koul V, Benyon RG, Nagler PL (2015) Quantifying water requirements of riparian river red gum (*Eucalyptus camaldulensis*) in the Murray–Darling Basin, Australia: implications for the management of environmental flows. Ecohydrology 8:1471–1487

Doummar J, Sauter M, Geyer T (2012) Simulation of flow processes in a large scale karst system with an integrated catchment model (Mike She): identification of relevant parameters influencing spring discharge. J Hydrol 426–427:112–123. doi:10.1016/j.jhydrol.2012.01.021

Eamus D, Froend R, Loomes R, Hose G, Murray B (2006) A functional methodology for determining the groundwater regime needed to maintain the health of groundwater-dependent vegetation. Aust J Bot 54:97–114. doi:10.1071/BT05031

Eckhardt K, Ulbrich U (2003) Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range. J Hydrol 284:244–252

Eckhardt K, Breuer L, Frede H-G (2003) Parameter uncertainty and the significance of simulated land use change effects. J Hydrol 273:164–176

Ellis T, Hatton T, Nuberg I (2005) An ecological optimality approach for predicting deep drainage from tree belts of alley farms in water-limited environments. Agric Water Manag 75:92–116

Ewers B, Gower S, Bond-Lamberty B, Wang C (2005) Effects of stand age and tree species on canopy transpiration and average stomatal conductance of boreal forests. Plant Cell Environ 28:660–678

Froend R, Sommer B (2010) Phreatophytic vegetation response to climatic and abstraction-induced groundwater drawdown: examples of long-term spatial and temporal variability in community response. Ecol Eng 36:1191–1200. doi:10.1016/j.ecoleng.2009.11.029

Gardner WR (1958) Some steady state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Sci 85:228–232

Gardner WR, Fireman M (1958) Laboratory studies of evaporation from soil columns in the presence of a water table. Soil Sci 85:244–249

Gardner W, Pierre W (1966) Soil water movement and root absorption. Plant environment and efficient water use. Am. Soc. of Agron. and Soil Sci. Soc. of Am., Madison, WI

Gee GW, Hillel D (1998) Groundwater recharge in arid regions: review and critique of estimation records. Hydrol Process 2:255–266

Glenn E, Tanner R, Mendez S, Kehret T, Moore D, Garcia J, Valdes C (1998) Growth rates, salt tolerance and water use characteristics of native and invasive riparian plants from the delta of the Colorado River, Mexico. J Arid Environ 40:281–294

Glenn EP, Doody TM, Guerschman JP, Huete AR, King EA, McVicar TR, Van Dijk AIJM, Van Niel TG, Yebra M, Zhang Y (2011) Actual evapotranspiration estimation by ground and remote sensing methods: the Australian experience. Hydrol Process 25:4103–4116. doi:10.1002/hyp.8391

Goodrich DC, Scott R, Qi J, Goff B, Unkrich CL, Moran MS, Williams D, Schaeffer S, Snyder K, MacNish R, Maddock T, Pool D, Chehbouni A, Cooper DI, We E, Shuttleworth WJ, Kerr Y, Ni W (2000) Seasonal estimates of riparian evapotranspiration using remote and in situ measurements. Agric For Meteorol 105:281–309

Gray D, Norum D (1967) The effect of soil moisture on infiltration as related to runoff and recharge. In: Proceedings of hydrology symposium no. 6, Soil Moisture National Research Council of Canada Associate Committee on Geodesy and Geophysics Subcommittee on Hydrology, Ottawa

Guerschman JP, Van Dijk AIJM, Mattersdorf G, Beringer J, Hutley LB, Leuning R, Pipunic RC, Sherman BS (2009) Scaling of potential evapotranspiration with MODIS data reproduces flux observations and catchment water balance observations across Australia. J Hydrol 369:107–119

Hanson R, Schmid W, Faunt C, Lockwood B (2010) Simulation and analysis of conjunctive use with MODFLOW's farm process. Ground Water 48:674–689

Hanson RT, Boyce SE, Schmid W, Hughes JD, Mehl SW, Leake SA, Maddock Iii T, Niswonger RG (2014) One-water hydrologic flow model (MODFLOW-OWHM) techniques and methods, Reston, VA, 134 pp

Harbaugh AW (2005) MODFLOW-2005, the US Geological Survey modular ground-water model: the ground-water flow process. US Geological Survey, Reston, VA

Harbaugh AW, Banta ER, Hill MC, McDonald MG (2000) MODFLOW-2000, the US Geological Survey modular ground-water model: user guide to modularization concepts and the ground-water flow process. US Geological Society, Reston, VA

Healy RW (2010) Estimating groundwater recharge. Cambridge University Press, Cambridge, MA

Healy R, Cook P (2002) Using groundwater levels to estimate recharge. Hydrogeol J 10:91–109. doi:10.1007/s10040-001-0178-0

Holland KL, Tyerman SD, Mensforth LJ, Walker GR (2006) Tree water sources over shallow, saline groundwater in the lower River Murray, south-eastern Australia: implications for groundwater recharge mechanisms. Aust J Bot 54:193–205

Hughes J, Petrone K, Silberstein R (2012) Drought, groundwater storage and stream flow decline in southwestern Australia. Geophys Res Lett 39. doi:10.1029/2011GL050797

Hunt RJ, Prudic DE, Walker JF, Anderson MP (2008) Importance of unsaturated zone flow for simulating recharge in a humid climate. Ground Water 46:551–560

Hvorslev MJ (1951) Time lag and soil permeability in ground-water observations. US Army Waterways Experiment Station, Vicksburg, MI

HydroGeoLogic (2006) MODHMS: a comprehensive MODFLOW-based hydrologic modeling system, version 3.0. HydroGeoLogic, Herndon, VA

Ireson A, Butler A (2013) A critical assessment of simple recharge models: application to the UK Chalk. Hydrol Earth Syst Sci 17: 2083–2096

Jackson TJ (2002) Remote sensing of soil moisture: implications for groundwater recharge. Hydrogeol J 10:40–51

Jackson RB, Canadell J, Ehleringer JR, Mooney HA, Sala OE, Schulze ED (1996) A global analysis of root distributions for terrestrial biomes. Oecologia 108:389–411. doi:10.1007/bf00333714

Jackson RB, Schenk HJ, Jobbagy EG, Canadell J, Colello GD, Dickinson RE, Field CB, Friedlingstein P, Heimann M, Hibbard K, Kicklighter DW, Kleidon A, Neilson RP, Parton WJ, Sala OE, Sykes MT (2000a) Below ground consequences of vegetation change and their treatment in models. Ecol Appl 10:470–483

Jackson RB, Sperry JS, Dawson TE (2000b) Root water uptake and transport: using physiological processes in global predictions. Trends Plant Sci 5:482–488

Jolly ID, Walker GR, Thorburn PJ (1993) Salt accumulation in semi-arid floodplain soils with implications for forest health. J Hydrol 150: 589–614

Jolly ID, McEwan KL, Holland KL (2008) A review of groundwater: surface water interactions in arid/semi-arid wetlands and the consequences of salinity for wetland ecology. Ecohydrology 1:43–58

Kalma J, McVicar T, McCabe M (2008) Estimating land surface evaporation: a review of methods using remotely sensed surface temperature data. Surv Geophys 29:421–469. doi:10.1007/s10712-008-9037-z

Kambhammettu B, King J, Schmid W (2014) Grid-size dependency of evapotranspiration simulations in shallow aquifers: an optimal approach. J Hydrol Eng 19:04014018. doi:10.1061/(ASCE)HE.1943-5584.0000957

Keating EH, Doherty J, Vrugt JA, Kang Q (2010) Optimization and uncertainty assessment of strongly nonlinear groundwater models with high parameter dimensionality. Water Resour Res 46. doi:10.1029/2009WR008584

Kim JH, Jackson RB (2012) A global analysis of groundwater recharge for vegetation, climate, and soils. Vadose Zone J 11. doi:10.2136/vzj2011.0021RA

Kim NW, Chung IM, Won YS, Arnold JG (2008) Development and application of the integrated SWAT–MODFLOW model. J Hydrol 356:1–16

Kristensen K, Jensen S (1975) A model for estimating actual evapotranspiration from potential evapotranspiration. Nord Hydrol 6:170–188

Kuniansky EL, Lowery MA, Campbell BG (2009) How processing digital elevation models can affect simulated water budgets. Ground Water 47:97–107. doi:10.1111/j.1745-6584.2008.00497.x

Kurtzman D, Scanlon BR (2011) Groundwater recharge through vertisols: irrigated cropland vs. natural land, Israel. Vadose Zone J 10:662–674

Lamontagne S, Cook PG, O'Grady A, Eamus D (2005) Groundwater use by vegetation in a tropical savanna riparian zone (Daly River, Australia). J Hydrol 310:280–293

Lamontagne S, Taylor AR, Cook PG, Crosbie RS, Brownbill R, Williams RM, Brunner P (2014) Field assessment of surface water–groundwater connectivity in a semi-arid river basin (Murray–Darling, Australia). Hydrol Process 28:1561–1572. doi:10.1002/hyp.9691

Larcher W (2003) Physiological plant ecology: ecophysiology and stress physiology of functional groups Springer, Heidelberg, Germany

Leaney F, Christen E (2000) Basin leakage: site studies at Girgarre, Victoria and Griffith, NSW: on-farm and community-scale salt disposal basins on the riverine plain. CRC Catchment Hydrology, CSIRO Land and Water Tech Rep 16/00, CSIRO, Canberra, Australia

Li Z-L, Tang B-H, Wu H, Ren H, Yan G, Wan Z, Trigo IF, Sobrino JA (2013) Satellite-derived land surface temperature: current status and perspectives. Remote Sens Environ 131:14–37

Lu X, Jin M, van Genuchten MT, Wang B (2011) Groundwater recharge at five representative sites in the Hebei Plain, China. Ground Water 49:286–294

Maddock T, III, Baird KJ, Hanson RT, Schmid W, Ajami H (2012) RIP-ET: a riparian evapotranspiration package for MODFLOW-2005. US Geol Surv Tech Methods 6-A39, 76 pp

Maddock TI, Baird KJ (2002) A riparian evapotranspiration package. University of Arizona Research Laboratory for Riparian Studies, Tucson, AZ

Markstrom SL, Niswonger RG, Regan RS, Prudic DE, Barlow PM (2008) GSFLOW: coupled ground-water and surface-water flow model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005). US Geol Surv Tech Methods 6-D1, 240 pp

Maxwell RM, Kollet SJ (2008) Interdependence of groundwater dynamics and land-energy feedbacks under climate change. Nat Geosci 1: 665–669

Maxwell RM, Miller NL (2005) Development of a coupled land surface and groundwater model. J Hydrometeorol 6:233–247. doi:10.1175/jhm422.1

McDonald MG, Harbaugh AG, McDonald MG, Harbaugh AG (1988) A modular three-dimensional finite-difference ground-water flow model. US Geol Surv Tech Water Resour Invest, 6-A1

McLaren R (2004) GRID BUILDER, a pre-processor for 2-D, triangular element, finite-element programs. Groundwater Simulation Group, University of Waterloo, Waterloo, ON

Meinzer OE, Stearns ND (1929) A study of groundwater in the Pomperaug Basin, Connecticut: with special reference to intake and discharge. US Geol Surv Water Supply Pap 597B

Merrick N (2000) Probabilistic estimation of aquifer sustainable yield. Paper presented at the 10th World Water Congress: Water, the Worlds Most Important Resource, Melbourne, Australia, 2000, CSIRO Land and Water, Canberra, Australia

Merrick D (2015) AlgoMesh: a new software tool for building unstructured grid models. Paper presented at Modflow and More 2015: Modeling a Complex World, Colorado School of Mines, Golden, CO, May 31–June 3 2015

Miller MR, Brown PL, Donovan JJ, Bergatino RN, Sonderegger JL, Schmidt FA (1981) Land and stream salinity seminar and workshop Saline seep development and control in the North American Great

Plains: hydrogeological aspects. Agric Water Manag 4:115–141. doi:10.1016/0378-3774(81)90047-0

Morway ED, Gates TK, Niswonger RG (2013) Appraising options to reduce shallow groundwater tables and enhance flow conditions over regional scales in an irrigated alluvial aquifer system. J Hydrol 495:216–237. doi:10.1016/j.jhydrol.2013.04.047

Munns R (2002) Comparative physiology of salt and water stress. Plant Cell Environ 25:239–250

Nagler PL, Cleverly J, Glenn E, Lampkin D, Huete A, Wan Z (2005) Predicting riparian evapotranspiration from MODIS vegetation indices and meteorological data. Remote Sens Environ 94:17–30. doi:10.1016/j.rse.2004.08.009

Nagler PL, Doody TM, Glenn EP, Jarchow CJ, Barreto-Muñoz A, Didan K (2015) Wide-area estimates of evapotranspiration by red gum (*Eucalyptus camaldulensis*) and associated vegetation in the Murray–Darling River Basin, Australia. Hydrol Process. doi:10.1002/hyp.10734

Naylor S, Letsinger S, Ficklin D, Ellett K, Olyphant G (2015) A hydropedological approach to quantifying groundwater recharge in various glacial settings of the mid-continental USA. Hydrol Process. doi:10.1002/hyp.10718

Neitsch SL, Arnold JG, Kiniry JR, Williams JR (2011) Soil and water assessment tool theoretical documentation version 2009. Texas Water Resources Institute, College Station, TX

Niceno B (2002) EasyMesh: a two-dimensional quality mesh generator. http://web.mit.edu/easymesh_v1.4/www/easymesh.html. Accessed August 2016

Nichols WD (1994) Groundwater discharge by phreatophyte shrubs in the Great Basin as related to depth to groundwater. Water Resour Res 30:3265–3274

Niknam SR, McComb J (2000) Salt tolerance screening of selected Australian woody species: a review. For Ecol Manag 139:1–19

Niswonger RG, Prudic DE, Regan RS (2006) Documentation of the Unsaturated-Zone Flow (UZF1) Package for modeling unsaturated flow between the land surface and the water table with MODFLOW-2005. US Geol Surv Tech Methods 6-A19, 62 pp

O'Hagan A (2006) Bayesian analysis of computer code outputs: a tutorial. Reliab Eng Syst Saf 91:1290–1300

O'Grady A, Eamus D, Hutley L (1999) Transpiration increases during the dry season: patterns of tree water use in eucalypt open-forests of northern Australia. Tree Physiol 19:591–597

O'Grady A, Carter J, Bruce J (2011) Can we predict groundwater discharge from terrestrial ecosystems using existing eco-hydrological concepts? Hydrol Earth Syst Sci 15:3731–3739

Panday S, Huyakorn PS (2004) A fully coupled physically-based spatially-distributed model for evaluating surface/subsurface flow. Adv Water Resour 27:361–382

Panday S, Huyakorn PS (2008) MODFLOW SURFACT: a state-of-the-art use of vadose zone flow and transport equations and numerical techniques for environmental evaluations. Vadose Zone J 7:610–631. doi:10.2136/vzj2007.0052

Panday S, Langevin CD, Niswonger RG, Ibaraki M, Hughes JD (2013) MODFLOW–USG version 1: an unstructured grid version of MODFLOW for simulating groundwater flow and tightly coupled processes using a control volume finite-difference formulation. US Geol Surv Tech Methods 6-A45, 78 pp

Pannell DJ, Ewing MA (2006) Managing secondary dryland salinity: options and challenges. Agric Water Manag 80(1–3):41–56

Pauwels VRN, De Lannoy GJM (2009) Ensemble-based assimilation of discharge into rainfall–runoff models: a comparison of approaches to mapping observational information to state space. Water Resour Res 45. doi:10.1029/2008wr007590

Pauwels VRN, Hoeben R, Verhoest NEC, De Troch FP (2001) The importance of the spatial patterns of remotely sensed soil moisture in the improvement of discharge predictions for small-scale basins through data assimilation. J Hydrol 251:88–102. doi:10.1016/S0022-1694(01)00440-1

Peck AJ (1978a) Note on the role of a shallow aquifer in dryland salinity. Aust J Soil Res 16:237–240

Peck AJ (1978b) Salinization of non-irrigated soils and associated streams: a review. Aust J Soil Res 16:157–168

Peck AJ, Hatton T (2003) Salinity and the discharge of salts from catchments in Australia. J Hydrol 272:191–202

Peeters LJM, Crosbie RS, Doble RC, Van Dijk AIJM (2013) Conceptual evaluation of continental land-surface model behaviour. Environ Model Softw 43:49–59. doi:10.1016/j.envsoft.2013.01.007

Peeters L, Podger G, Smith T, Pickett T, Bark R, Cuddy S (2014) Robust global sensitivity analysis of a river management model to assess nonlinear and interaction effects. Hydrol Earth Syst Sci 18:3777–3785

Petheram C, Walker G, Grayson R, Thierfelder T, Zhang L (2002) Towards a framework for predicting impacts of land-use on recharge: 1. a review of recharge studies in Australia. Aust J Soil Res 40:397–417

Petheram C, Dawes W, Grayson R, Bradford A, Walker G (2003) A subgrid representation of groundwater discharge using a one-dimensional groundwater model. Hydrol Process 17:2279–2295

Petheram C, Potter N, Vaze J, Chiew F, Zhang L (2011) Towards better understanding of changes in rainfall–runoff relationships during the recent drought in south-eastern Australia. 19th International Congress on Modelling and Simulation, Perth, Australia, 12–16 Dec. 2011, pp 3622–3628

Petrone KC, Hughes JD, Van Niel TG, Silberstein RP (2010) Streamflow decline in southwestern Australia, 1950–2008. Geophys Res Lett 37. doi:10.1029/2010GL043102

Philip JR (1957) Evaporation, and moisture and heat fields in the soil. J Meteorol 14:354–366. doi:10.1175/1520-0469(1957)014<0354:eamahf>2.0.co;2

Raiber M CT, Pagendam D, Rassam D, Gilfedder M, Crossbie R, Marvanek S and Hartcher M (2015) Observations analysis, statistical analysis and interpolation for the Clarence-Moreton bioregion. Product 2.1-2.2 from the Clarence-Moreton Bioregional Assessment. CSIRO, Canberra and Geoscience Australia, Symonston, Australia. http://data.bioregionalassessments.gov.au/product/CLM/CLM/2.1-2.2. Accessed Ausgust 2016

Razavi S, Tolson BA, Burn DH (2012) Review of surrogate modeling in water resources. Water Resour Res 48. doi:10.1029/2011WR011527

Reager JT, Famiglietti JS (2013) Characteristic mega-basin water storage behavior using GRACE. Water Resour Res 49:3314–3329. doi:10.1002/wrcr.20264

Refsgaard JC, Storm B (1995) MIKE SHE. In: Singh VP (ed) Computer models of watershed hydrology. Water Resources Publ., Littleton, CO, pp 809–846

Reynolds J, Kemp P, Tenhunen J (2000) Effects of long-term rainfall variability on evapotranspiration and soil water distribution in the Chihuahuan Desert: a modeling analysis. Plant Ecol 150:145–159. doi:10.1023/a:1026530522612

Rodriguez-Iturbe I, D'odorico P, Porporato A, Ridolfi L (1999) On the spatial and temporal links between vegetation, climate, and soil moisture. Water Resour Res 35:3709–3722

Rojas R, Feyen L, Dassargues A (2008) Conceptual model uncertainty in groundwater modeling: combining generalized likelihood uncertainty estimation and Bayesian model averaging. Water Resour Res 44. doi:10.1029/2008WR006908

Rojas R, Kahunde S, Peeters L, Batelaan O, Feyen L, Dassargues A (2010) Application of a multimodel approach to account for conceptual model and scenario uncertainties in groundwater modelling. J Hydrol 394:416–435

Sanford WE (2002) Recharge and groundwater models: an overview. Hydrogeol J 10:110–120

Scanlon BR, Keese KE, Flint AL, Flint LE, Gaye CB, Edmunds WM, Simmers I (2006) Global synthesis of groundwater recharge in semiarid and arid regions. Hydrol Process 20:3335–3370

Schaap MG, Leij FJ, van Genuchten MT (1998) Neural network analysis for hierarchical prediction of soil hydraulic properties. Soil Sci Soc Am J 62:847–855

Schmid W, Hanson RT (2009) The farm process version 2 (FMP2) for MODFLOW-2005: modifications and upgrades to FMP1. US Geol Surv Tech Methods 6–A-32

Schmid W, Hanson RT, Madodock T III, Leake SA (2006) User guide for the farm process (FMP1) for the U.S. Geological Survey's modular three-dimensional finite-difference ground-water flow model, MODFLOW 2000. US Geol Surv Tech Methods 6-A17

Sciuto G, Diekkrüger B (2010) Influence of soil heterogeneity and spatial discretization on catchment water balance modeling. Vadose Zone J 9:955–969

Shah N, Nachabe M, Ross M (2007) Extinction depth and evapotranspiration from ground water under selected land covers. Ground Water 45:329–338

Shewchuk JR (1996) Triangle: engineering a 2D quality mesh generator and Delaunay triangulator. In: Applied computational geometry towards geometric engineering, vol 1148. Springer, Berlin, pp 203–222

Shewchuk JR (2002) Delaunay refinement algorithms for triangular mesh generation. Comput Geom 22:21–74

Šimůnek J, Jarvis NJ, van Genuchten MT, Gärdenäs A (2003) Review and comparison of models for describing non-equilibrium and preferential flow and transport in the vadose zone. J Hydrol 272(1):14–35. doi:10.1016/S0022-1694(02)00252-4

Šimůnek J, Sejna M, Genuchten. MTv (1988) The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat and multiple solutes in variably-saturated media, version 2.0. International Ground Water Modeling Centre, Colorado School of Mines, Golden, CO, 202 pp

Slavich PG (1997) Modelling groundwater use, salt accumulation and vegetation growth in areas of shallow saline watertables. PhD Thesis, Flinders University of South Australia, Adelaide, Australia

Smerdon B, Mendoza C, Devito K (2008) Influence of subhumid climate and water table depth on groundwater recharge in shallow outwash aquifers. Water Resour Res 44. doi:10.1029/2007WR005950

Smerdon B, Allen D, Neilsen D (2010) Evaluating the use of a gridded climate surface for modelling groundwater recharge in a semi-arid region (Okanagan Basin, Canada). Hydrol Process 24:3087–3100

Smith SD, Devitt DA, Sala A, Cleverly JR, Busch DE (1998) Water relations of riparian plants from warm desert regions. Wetlands 18:687–696

Sophocleous M (1992) Groundwater recharge estimation and regionalization: the Great Bend Prairie of central Kansas and its recharge statistics. J Hydrol 137:113–140

Sophocleous M, Perkins SP (2000) Methodology and application of combined watershed and ground-water models in Kansas. J Hydrol 236:185–201

Soylu M, Istanbulluoglu E, Lenters J, Wang T (2011) Quantifying the impact of groundwater depth on evapotranspiration in a semi-arid grassland region. Hydrol Earth Syst Sci 15:787–806

Sun T, Pan S-B, J-R Li, H-Y Den (2004) Analysis on the exploitation of water and land resources and its environmental effects in the Shule River Watershed. Arid Zone Res 4:001

Szilagyi J, Zlotnik VA, Gates JB, Jozsa J (2011) Mapping mean annual groundwater recharge in the Nebraska Sand Hills, USA. Hydrogeol J 19:1503–1513

Szilagyi J, Zlotnik VA, Jozsa J (2013) Net recharge vs. depth to groundwater relationship in the Platte River Valley of Nebraska, United States. Groundwater 51:945–951. doi:10.1111/gwat.12007

Talsma T (1963) The control of saline groundwater. Mededelingen Landbouwhogeschool, Wageningen 63(10):1–68. http://edepot.wur.nl/185086. Accessed August 2016

Therrien R, McLaren RG, Sudicky EA, Panday SM (2006) Hydrogeosphere: a three-dimensional numerical model describing fully-integrated subsurface and surface flow and solute transport. Groundwater Simul. Group, Waterloo, ON, 275 pp

Thompson J, Sørenson H, Gavin H, Refsgaard A (2004) Application of the coupled MIKE SHE/MIKE 11 modelling system to a lowland wet grassland in southeast England. J Hydrol 293:151–179

Thorburn PJ, Walker GR, Jolly ID (1995) Uptake of saline groundwater by plants: an analytical model for semi-arid and arid areas. Plant Soil 175:1–11

Tian Y, Zheng Y, Wu B, Wu X, Liu J, Zheng C (2015) Modeling surface water-groundwater interaction in arid and semi-arid regions with intensive agriculture. Environ Model Softw 63:170–184

Turk LJ (1970) Evaporation of brine: a field study on the Bonneville salt flats, Utah. Water Resour Res 6:1209–1215

Turnadge C, Lamontagne S (2015) A MODFLOW-based approach to simulating wetland–groundwater interactions in the Lower Limestone Coast Prescribed Wells area. Technical Report Series, Goyder Institute for Water Research, CSIRO, Canberra, Australia

Twarakavi NKC, Šimůnek J, Seo S (2008) Evaluating interactions between groundwater and vadose zone using the HYDRUS-based flow package for MODFLOW. Vadose Zone J 7:757–768

van Genuchten MT (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44:892–898

Vázquez R (2003) Effect of potential evapotranspiration estimates on effective parameters and performance of the MIKE SHE-code applied to a medium-size catchment. J Hydrol 270:309–327

Vogel T, van Genuchten MT, Cislerova M (2000) Effect of the shape of the soil hydraulic functions near saturation on variably-saturated flow predictions. Adv Water Resour 24:133–144. doi:10.1016/S0309-1708(00)00037-3

Walker GR, Jarwal SD, Jolly ID (1994) Salt and water movement in a saline semi arid floodplain of the River Murray. CSIRO, Adelaide, Australia

Walker GR, Jolly ID, Williamson DR, Gilfedder M, Morton R, Zhang L, Dowling T, Dyce P, Nathan R, Nandakumar N, Gates GWB, Linke GK, Seker MP, Robinson G, Jones H, Clarke R, McNeill V, Evans WR (1998) Historical stream salinity trends and catchment salt balances in the Murray-Darling Basin. CSIRO Land and Water, Canberra, Australia

Wang S, Shao J, Song X, Zhang Y, Huo Z, Zhou X (2008) Application of MODFLOW and geographic information system to groundwater flow simulation in North China Plain, China. Environ Geol 55:1449–1462

Wen X-H, Gómez-Hernández JJ (1996) Upscaling hydraulic conductivities in heterogeneous media: an overview. J Hydrol 183:ix–xxxii

Werner AD, Gallagher MR, Weeks SW (2006) Regional-scale, fully coupled modelling of stream–aquifer interaction in a tropical catchment. J Hydrol 328:497–510

Wohling D, Leaney F, Crosbie R (2012) Deep drainage estimates using multiple linear regression with percent clay content and rainfall. Hydrol Earth Syst Sci 16:563–572

Wood WE (1924) Increase of salt in soils and streams following the destruction of the native vegetation. J R Soc West Aust 10:35–47

Wood WW (1999) Use and misuse of the chloride-mass balance method in estimating ground water recharge. Ground Water 37:2–3

Young C, Wallender W, Schoups G, Fogg G, Hanson B, Harter T, Hopmans J, Howitt R, Hsiao T, Panday S (2007) Modeling shallow water table evaporation in irrigated regions. Irrig Drain Syst 21:119–132

Zhang L, Dawes W (1998) WAVES: an integrated energy and water balance model. CSIRO Land and Water, Canberra, Australia

Zhao C, Wang Y, Chen X, Li B (2005) Simulation of the effects of groundwater level on vegetation change by combining FEFLOW software. Ecol Model 187:341–351