Impact of land-surface elevation and riparian evapotranspiration seasonality on groundwater budget in MODFLOW models

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Abstract Riparian groundwater evapotranspiration (ETg) constitutes a major component of the water balance especially in many arid and semi-arid environments. Although spatial and temporal variability of riparian ETg are controlled by climate, vegetation and subsurface characteristics, depth to water table (DTWT) is often considered the major controlling factor. Relationships between ETg rates and DTWT, referred to as ETg curves, are implemented in MODFLOW ETg packages (EVT, ETS1 and RIP-ET) with different functional forms. Here, the sensitivity of the groundwater budget in MODFLOW groundwater models to ETg parameters (including ETg curves, land-surface elevation and ETg seasonality) are investigated. A MODFLOW model of the hypothetical Dry Alkaline Valley in the Southwestern USA is used to show how spatial representation of riparian vegetation and digital elevation model (DEM) processing methods impact the water budget when RIPGIS-NET (a GIS-based ETg program) is used with MODFLOW's RIP-ET package, and results are compared with the EVT and ETS1 packages. Results show considerable impact on ETg and other groundwater budget components caused by spatial representation of riparian vegetation, vegetation type, fractional coverage areas and land-surface elevation. RIPGIS-NET enhances ETg estimation in MODFLOW by incorporating vegetation and land-surface parameters, providing a tool for ecohydrology studies, riparian ecosystem management and stream restoration.

Keywords Riparian groundwater evapotranspiration · Geographic Information Systems · MODFLOW · Groundwater budget · Ecohydrology

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Introduction

One of the principal mechanisms of groundwater discharge in vegetated soils and shallow groundwater systems of semi-arid basins is evapotranspiration (ET) from phreatophytes (Shah et al. 2007). In many arid and semi-arid environments riparian ET constitutes a major component of the surface and subsurface water balance (Scott et al. 2008). The subsurface component of ET can be further subdivided to unsaturated zone ET and groundwater evapotranspiration (ETg; Shah et al. 2007; Lubczynski 2009). Temporal and spatial variability of ETg is controlled by spatial variability of vegetation types, size and density, seasonal variability in transpiration rates, subsurface hydraulic properties and depth to water table (DTWT; Lubczynski 2009). Regional decline in groundwater levels due to pumping alters riparian vegetation ETg rates and can be detrimental if changes in groundwater levels separate roots from their water source (Naumburg et al. 2005). On the other hand, the ecohydrological impact of riparian land-cover change consists of large-scale effects on groundwater and surface water used by riparian species, and changes in basin-scale carbon and water budgets (Williams et al. 2006).

A review of land surface modeling studies showed that ETg constitutes 5–33% of total ET in shallow aquifers (Yeh and Famiglietti 2009). Despite the importance of ETg in groundwater budgets especially in water-limited

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environments, simplified approaches have been implemented to represent ETg in most groundwater models due to demanding input requirements (Lubczynski and Gurwin 2005). In one of the most widely used groundwater models, the modular three-dimensional finite-difference groundwater flow model (MODFLOW), a piecewise linear relationship between ETg rates and DTWT is used to describe the ETg process in the EVT package (McDonald and Harbaugh 1988). In the ETS1 package, Banta (2000) revised the EVT module by replacing the linear curve with a segmented curve that determines the shape of the function between ETg surface elevation (where ETg rate is maximum at or above this surface) and ETg extinction depth (the depth below which ETg becomes zero). Baird and Maddock (2005) developed a riparian evapotranspiration (RIP-ET) package for use in MODFLOW-2000 (Harbaugh et al. 2000) and MODFLOW-2005 (Harbaugh 2005) using a set of eco-physiologically based ETg curves for plant functional subgroups (PFSGs), which incorporates reductions in ETg due to anoxic conditions by specifying a saturated extinction depth elevation, ie. a water-table elevation corresponding to death of the PFSG (Fig. 1). The RIP-ET package is further modified to incorporate spatial variability of vegetation communities and land-surface elevation in ETg estimation by developing a pre- and post-processor program in a geographic information system (GIS), RIPGIS-NET, used in combination with RIP-ET (Ajami and Maddock 2009; Ajami et al. 2011).

Impacts of land-surface elevation, PFSG ETg curves and spatial representation of riparian vegetation on ETg rates are explored using a MODFLOW model of a hypothetical study site in the Southwestern USA. Specifically this report addresses the following questions: (1) What is the impact of land-surface elevation variability on ETg rates in a given MODFLOW cell for different vegetation types (PFSGs), and (2) what is the sensitivity of the groundwater budget to spatial representation of riparian vegetation and ETg seasonality in MODFLOW groundwater models?

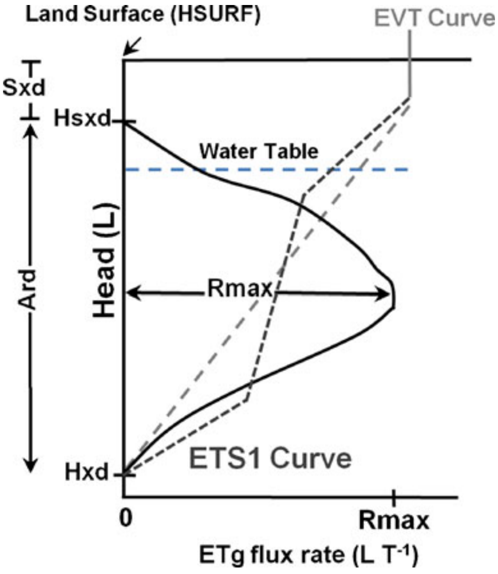

Fig. 1 Generic ETg flux rate in RIP-ET compared with traditional MODFLOW ETg curves (EVT and ETS1 packages). *Sxd* saturated extinction depth (L) measured with respect to the land surface elevation; *Ard* active rooting depth (L); *HSURF* land surface elevation; *Rmax* maximum ETg rate ($L\,T^{-1}$); *Hxd* extinction depth elevation (L); *Hsxd* saturated extinction depth elevation (L) (adopted from Baird et al. 2005)

Overview of RIP-ET and RIPGIS-NET

The Riparian Evapotranspiration package (RIP-ET) simulates riparian and wetland ETg using eco-physiologically based ETg curves for the PFSGs, and separates ground evaporation and vegetation transpiration processes (Maddock and Baird 2003). Plant functional groups are non-phylogenic groupings of plant species with a similar response to environmental conditions such as resource availability, and exert a similar effect on the dominant ecosystem processes (Lavorel et al. 1997). Baird and Maddock (2005) defined four basic plant functional groups (obligate wetlands, shallow and deep-rooted riparian, and transitional riparian) based on plant transpiration rates, vegetation rooting depths, and seasonal ranges of groundwater tolerance. An additional group is added to model evaporation from bare ground or open water. Plant functional groups may be further sub-divided to subgroups (i.e. PFSGs) based on their plant size and density of cover (Baird and Maddock 2005). To compute ETg, PFSGs are arranged in a series of polygons with approximately uniform land-surface elevation. Each MODFLOW cell can contain any number of polygons and each polygon in a MODFLOW cell may have single or multiple PFSGs. RIP-ET requires an ETg curve file for every PFSG in a model, fractional coverage areas of each PFSG and average surface elevation for each polygon to compute ETg at the PFSG level, MODFLOW cell scale and at regional scale (Ajami and Maddock 2009; Ajami et al. 2011).

RIPGIS-NET was developed in Visual Basic 2005 for Environmental System Research Institute (ESRI's) ArcMap 9.2 and 9.3 applications to derive RIP-ET input parameters (PFSG ETg curve parameters (Fig. 1), fractional coverage areas of each PFSG in a MODFLOW cell, and average surface elevation per riparian vegetation polygon). The RIPGIS-NET MODFLOW visualization tool provides an interface to visualize MODFLOW model results (head maps, DTWT maps and DTWT plots for a PFSG in a polygon in relation to the PFSG ETg curve). The tool combines spatial analysis capabilities of GIS with RIP-ET and a MODFLOW groundwater model to provide a spatially explicit estimate of riparian ETg. Several enhancements have been made in RIPGIS-NET compared to other MODFLOW GIS-based processors including (1) inclusion of all the riparian polygons in a MODFLOW cell instead of using proximity to the MODFLOW cell centroid as an inclusion criteria, (2) inclusion of multiple PFSGs in a single MODFLOW cell, (3) calculation of fractional coverage areas of PFSGs per model cell instead

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of using the entire cell as ETg flux area, and (4) calculation of average surface elevation based on a digital elevation model (DEM) for each riparian polygon per cell as a substitute to one elevation value per cell (Ajami and Maddock 2009; Ajami et al. 2011).

Description of the hypothetical study area

Dry Alkaline Valley extends over 518 km^2, and is bounded to the north and south by mountain ranges that act as no-flow boundaries (Fig. 2). The basin is underlain by a single unconfined aquifer with uniform hydraulic conductivity distribution (0.0003 m/s) and specific yield of 10^{-2}. A large lake to the northwest behaves hydrologically as a prescribed head boundary, and is the source of the river that transects the basin from west to east. The basin aquifer and the river both discharge to the east. The stream inflow from the lake is assumed to be the same in both growing and dormant seasons. The growing season extends from April to September, and the dormant season from October to March. The outflow from the eastern boundary is simulated as wells and is assumed to be the same for both seasons.

Riparian habitats exist along portions of the river, and consist of deep-rooted riparian plant functional groups that primarily rely on shallow groundwater for transpiration, growth and establishment (Baird and Maddock 2005). The deep-rooted riparian group was further subdivided to small, medium, and large deep-rooted riparian PFSGs distributed over two terraces mirrored on each side of the 30.5 m wide stream channel. The inner and outer terraces have different surface elevations, and are 30.5 and 70 m wide, respectively (Fig. 2). The outer terrace area is composed of approximately 40% bare ground and 60% canopy. For the canopy transpiration flux area in the outer terraces, 60% are large trees, and 40% are medium trees. The inner terrace areas are composed of 33% bare ground and 67% canopy. The canopy flux area has 40.5% small trees, 24% large trees, 35.5% medium trees. During the dormant season, the terrace polygons are modeled as bare ground.

Methods

Dry Alkaline Valley MODFLOW model

The Dry Alkaline Valley MODFLOW model consists of 12 rows and 20 columns with a uniform cell size of 1.6 km. There are 25 riparian cells in the model domain. Each cell has four polygons, and there are four PFSGs in the model including small, medium and large deep-rooted riparian vegetation with distinct PFSG ETg curves which reflects differences in maximum rooting depth and transpiration rates within a plant functional group. Evaporation from bare ground is simulated as a PFSG with a linear ETg curve. The Dry Alkaline Valley MODFLOW model is used to run five scenarios to evaluate impact of ETg parameters (including PFSG ETg curve, land-surface elevation at MODFLOW cell- or riparian vegetation polygon level, and fractional coverage area) on groundwater budget.

Scenario 1: RIP-ET package

The RIPGIS-NET program is used to create a RIP-ET input file for the MODFLOW model of the site for two seasons. The RIP-ET input file has dimensionless ETg curve segment data for all PFSGs in both seasons, average and standard deviation of land-surface elevation obtained

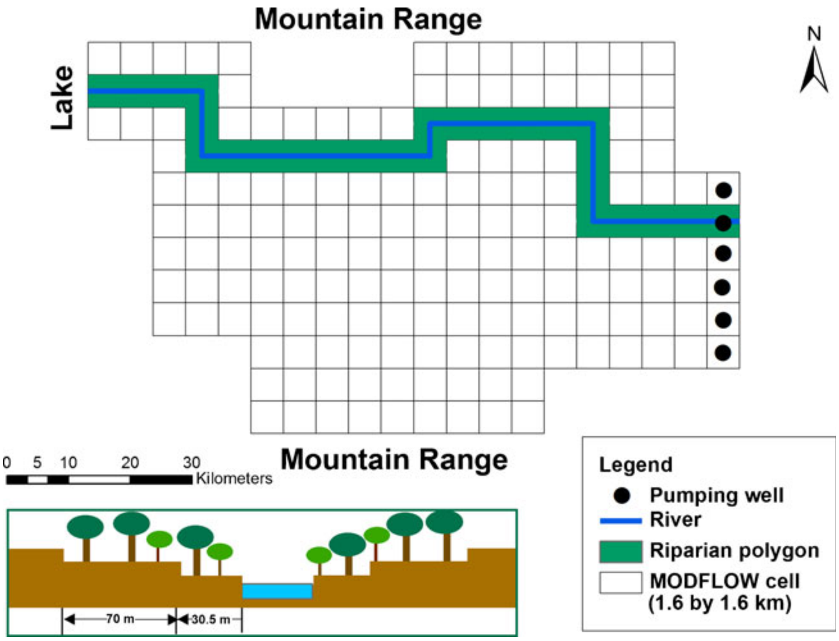

Fig. 2 Aerial view of the hypothetical Dry Alkaline Valley and cross-section of the riparian area

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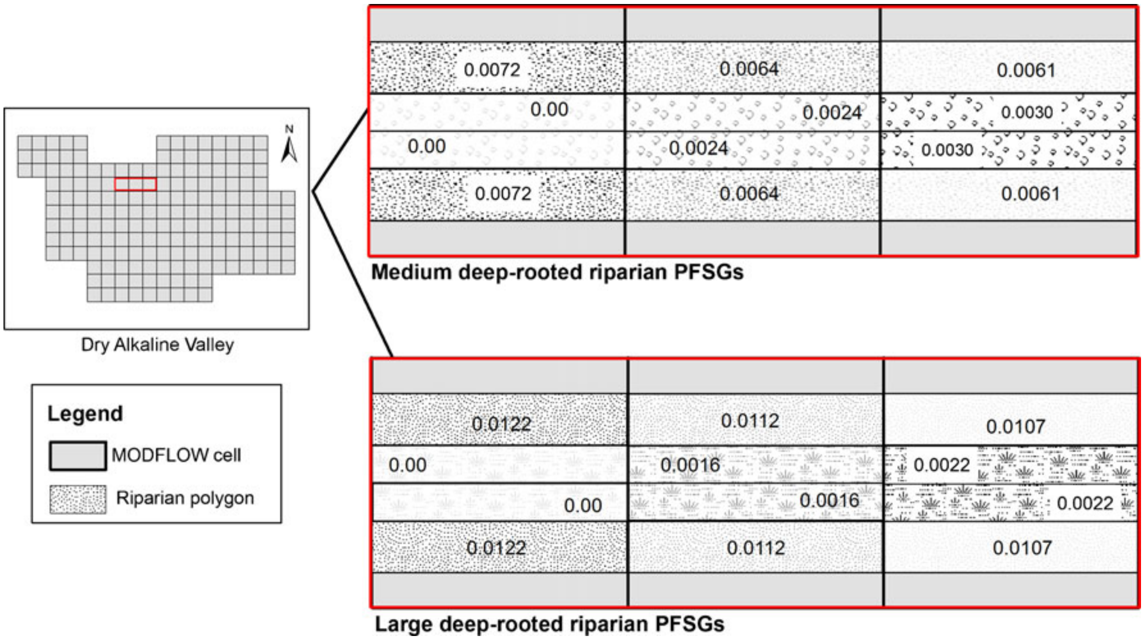

Fig. 3 Spatial variability in ETg rates within and among MODFLOW cells for different PFSGs in each riparian polygon. There are four riparian polygons in each cell and ETg values are in m/day in each polygon for deep-rooted riparian medium and large vegetation only

from the DEM for each riparian polygon, and fractional coverage area of each PFSG. In RIP-ET, each fractional coverage value is then multiplied by the surface area of the cell to provide the cell discharge area for that PFSG. Running the MODFLOW executable file that has the RIP-ET package, head values for both summer and winter seasons are calculated and water budget components are analyzed.

Scenarios 2 and 3: EVT package

To compare the impact of surface elevation and vegetation diversity on ETg and groundwater budget calculations in the EVT package against the RIP-ET package, the Dry Alkaline Valley dataset was modified to be used in the EVT package. The EVT package requires three variables to simulate the effect of evaporation and plant transpiration on groundwater systems, including maximum possible ETg rate (L/T), ETg surface elevation and the extinction depth. To compute the maximum possible ETg rate, fractional coverage area of each PFSG is multiplied by the maximum ETg rate of each PFSG and summed over the entire cell. Multiplication by fractional coverage area removes the impact of cell surface area on ETg estimation. Furthermore, the average extinction depth of all the PFSGs replaces the individual PFSG extinction depth data, and average surface elevation at each cell (scenario 2) or riparian polygons level (scenario 3) replaced individual polygon surface elevation in RIP-ET.

Scenarios 4 and 5: ETS1 package

The Dry Alkaline Valley dataset was modified to be used in the ETS1 package as well. In addition to the EVT parameters, the ETS1 package requires two additional parameters that define proportions of the extinction depth (PXDP) and the maximum ETg rate (PETM) for each ETg curve segment. Because there are multiple PFSGs in a MODFLOW cell, ETg rate for each segment was obtained by multiplying ETg rate of a given PFSG by its fractional coverage area, and adding obtained values for all PFSGs. From these combined ETg rates, PETM was estimated for each segment which is a value between 0 and 1. The largest extinction depth among PFSGs was used to

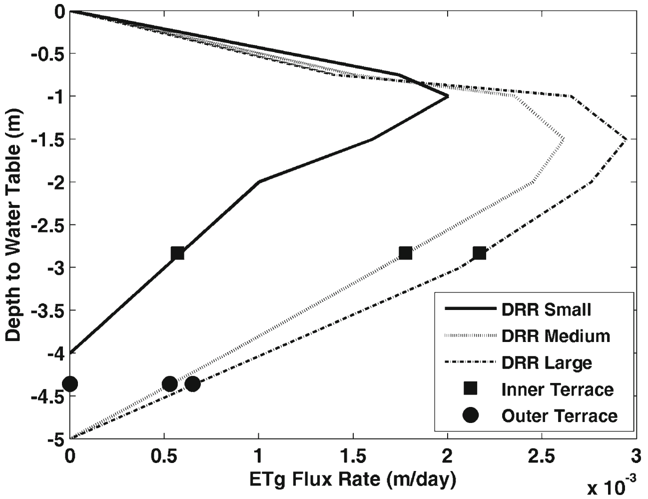

Fig. 4 Differences in average surface elevation in the inner and outer terraces in a single MODFLOW cell impact DTWT calculations and *ETg flux rates* for each PFSG. DTWT is calculated relative to land-surface elevation, and for these three PFSGs saturated extinction depths is at the land surface. These PFSGs belong to deep-rooted riparian (*DRR*) plant functional groups that are subdivided to three subgroups based on their plant size (small, medium and large)

Table 1 Comparison between estimated ETg rate using the traditional MODFLOW approach (single cell elevation) versus the RIP-ET approach (average surface elevation per riparian polygon)

ETg calculation level	MODFLOW estimated head (m)	Average elevation (m)	DTWT (m)	ETg rate (m/day)	Total ETg rate (m^3/day)
Cell level	1,152.7	1,153.07	–0.37	0.0034	8,806
PFSG level					
Inner terrace	1,152.7	1,153.36	–0.67	0.0018	177[a]
Outer terrace	1,152.7	1,154.88	–2.19	0	

[a] Because there are two inner terrace polygons in each cell, the total ETg value for a cell is doubled

represent extinction depth. This is different than the extinction depth that is defined for the EVT package because segmented curves in ETS1 allows adjustment of ETg rate with respect to DTWT. Similar to the EVT package, average surface elevation at each cell (scenario 4) or riparian polygons level (scenario 5) replaced individual polygon surface elevation in RIP-ET.

Results

RIP-ET simulation results

Spatial representation of riparian vegetation in RIP-ET allows spatially distributed ETg rates at a fine resolution (polygon level) in a given MODFLOW cell. Spatial variability of ETg rates in three MODFLOW cells for medium and large deep-rooted riparian vegetation in summer season is presented (Fig. 3). To present the impact of land-surface elevation variability and vegetation types on ETg rates, variations in ETg flux rate among three PFSGs in inner and outer terrace areas for a single MODFLOW cell are shown (Fig. 4). The ETg flux rate at a single depth is different for each PFSG based on plant water requirements. Moreover, the difference in average surface elevation between the inner and outer terrace (1.5 m) impacts calculated DTWT in each polygon despite a uniform head value in a MODFLOW cell.

To remove the ETg curve impact and evaluate the impact of average surface elevation on ETg estimates, evaporation rates in winter season at the Dry Alkaline Valley site were estimated using two approaches. In the first case (cell level), average MODFLOW cell surface elevation was subtracted from the MODFLOW estimated head and by using the evaporation curve for winter season, ETg rate was estimated (Table 1). For the second case (PFSG level), RIPGIS-NET was used to derive average surface elevation per riparian polygon. Following the same procedure, the ETg rate was estimated for each polygon. As shown in Table 1, the estimated ETg in a cell is different between the two approaches. This result is due to the fractional coverage area estimation used in RIPGIS-NET and the difference in DTWT due to surface elevation. In traditional MODFLOW ETg packages, total cell area is used for ETg estimation, whereas in RIPGIS-NET, fractional coverage areas are used for ETg flux area. Similar results have been shown for the South Fork Kern riparian habitat in California, USA and confirmed with field observations (Baird et al. 2005).

Incorporating ETg seasonality in the model resulted in considerable differences in water budget and had a large impact on stream-aquifer interactions. Higher ETg rates in summer resulted in a losing stream condition with 39% increase in stream leakage to aquifer compared to winter (Table 2). Subsequently, distribution of head values for winter and summer seasons are impacted by groundwater dynamics causing lower groundwater heads in summer compared to winter season (Fig. 5).

EVT and RIP-ET comparisons

Summer season water budgets in the EVT package simulations (scenarios 2 and 3) show 65.7% increases in ETg rates when cell surface elevation is used compared to overall polygon average in a MODFLOW cell (Table 3). This result highlights the impact of land-surface elevation on simulating riparian ETg and the groundwater budget. Because RIP-ET allows for incorporating different vegetation types and land-surface elevation variability, results of the EVT package were compared to a more complex

Table 2 Impact of ETg seasonality on groundwater budget between summer and winter seasons in the Dry Alkaline Valley using RIP-ET package

	Percent change between summer and winter
Inflow to aquifer system	
Storage	100.0
Constant head cells	4.5
Stream leakage (losing stream)	39.1
Total inflow	29.7
Outflow from aquifer system	
Storage	39.7
Wells	0.0
Riparian ET	85.4
Stream leakage (gaining stream)	–31.6
Total outflow	29.7

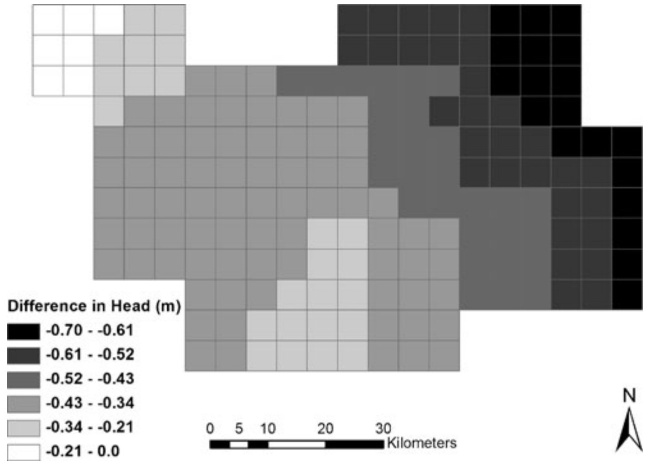

Fig. 5 Difference between estimated head values for winter and summer seasons in Dry Alkaline Valley generated using RIPGIS-NET. Due to riparian ETg, groundwater head is lower in summer

package, RIP-ET. Using average cell elevation in EVT, estimated ETg increased by 48.6% compared to the RIP-ET package. In scenario 3 where polygons average elevation was used, estimated ETg was decreased by 10% compared to the RIP-ET package. These differences in ETg estimation impacted other components of the groundwater budget such as change in storage and stream leakage. Additionally, different estimates of ETg impacted groundwater head distribution (Fig. 6a–b).

ETS1 and RIP-ET comparisons

Estimated summer season riparian ETg in the ETS1 package simulations show 32.8% increases in ETg rate in scenario 4 (cell level) compared to scenario 5 where overall polygon average in a MODFLOW cell was used to represent land-surface elevation. Estimated ETg rates in the ETS1 scenarios 4 and 5 have increased by 43.1 and 7.7% respectively compared to RIP-ET (Table 4). Changes in ETg rates in ETS1 package compared to RIP-ET followed by changes in other components of the groundwater budget and hydraulic head distributions (Fig. 6c–d). However, magnitude of change is smaller in ETS1 compared to EVT especially for scenario 5.

Conclusions

Simulation results highlighted the impact of vegetation types, fractional coverage areas of vegetation, land-surface elevation and ETg seasonality on ETg estimation and groundwater budgets compared to traditional MODFLOW ETg packages. Sensitivity of the groundwater budget to land-surface elevation variation has been shown by Kuniansky et al. (2009) when two DEM processing methods were used to assign cell surface elevation for each MODFLOW cell. Kuniansky et al. (2009) showed, using the mean of the DEM values for each MODFLOW cell compared to the DEM value at the centroid of the model cell, results in a more conservative water budget. Impact of DEM processing on ETg estimation was not considered in their study. Recently, sensitivity of ETg estimates to DEM resolution was examined by modifying the EVT package to estimates ETg at a DEM cell resolution (B.V.N.P. Kambhammettu, New Mexico State University, Personal communications, 2010). Compared to the modified EVT package of the previous study, RIPGIS-NET uses nonlinear PFSG curves of RIP-ET and allows for the presence of multiple riparian polygons in each MODFLOW cell and multiple PFSGs in a single polygon. This study highlights the impact of land-surface elevation parameters in MODFLOW ETg packages, and showed how spatial representation of riparian vegetation impacts water budget. In the evaporation case, ETg rates were increased by 47% when cell level land-surface elevation was used instead of polygon level elevation (Table 1). In addition, incorporating vegetation diversity in each polygon impacted ETg rate considerably (Fig. 4). Comparison between EVT, ETS1 and RIP-ET water budget results highlights impacts of ETg estimation on the stream leakage and groundwater storage (Tables 3 and 4). Moreover, this study demonstrated the power of the RIPGIS-NET program in combination with RIP-ET to include ETg parameters in MODFLOW groundwater models. An example application

Table 3 Summer season groundwater budget from three simulation scenarios using RIP-ET package (scenario 1; S1) and EVT package (scenarios 2 and 3; S2 and S3)

	Percent change S3 and S2	Percent change S1 and S2	Percent change S1 and S3
Inflow to aquifer system			
Storage	–13.1	–8.1	4.5
Constant head cells	–1.1	–3.1	–1.9
Stream leakage (losing stream)	–9.2	–5.7	3.2
Total inflow	–5.9	–4.8	1.1
Outflow from aquifer system			
Storage	6.9	5.1	–2.0
Wells	0.0	0.0	0.0
Riparian ET	–65.7	–48.6	10.3
Stream leakage (gaining stream)	10.6	17.5	7.7
Total outflow	–5.9	–4.8	1.1

S1 RIP-ET package using PFSG curves for all PFSGs and land-surface elevation at polygon level; *S2* EVT package and land-surface elevation at cell level; *S3* EVT package and land-surface elevation at polygon level

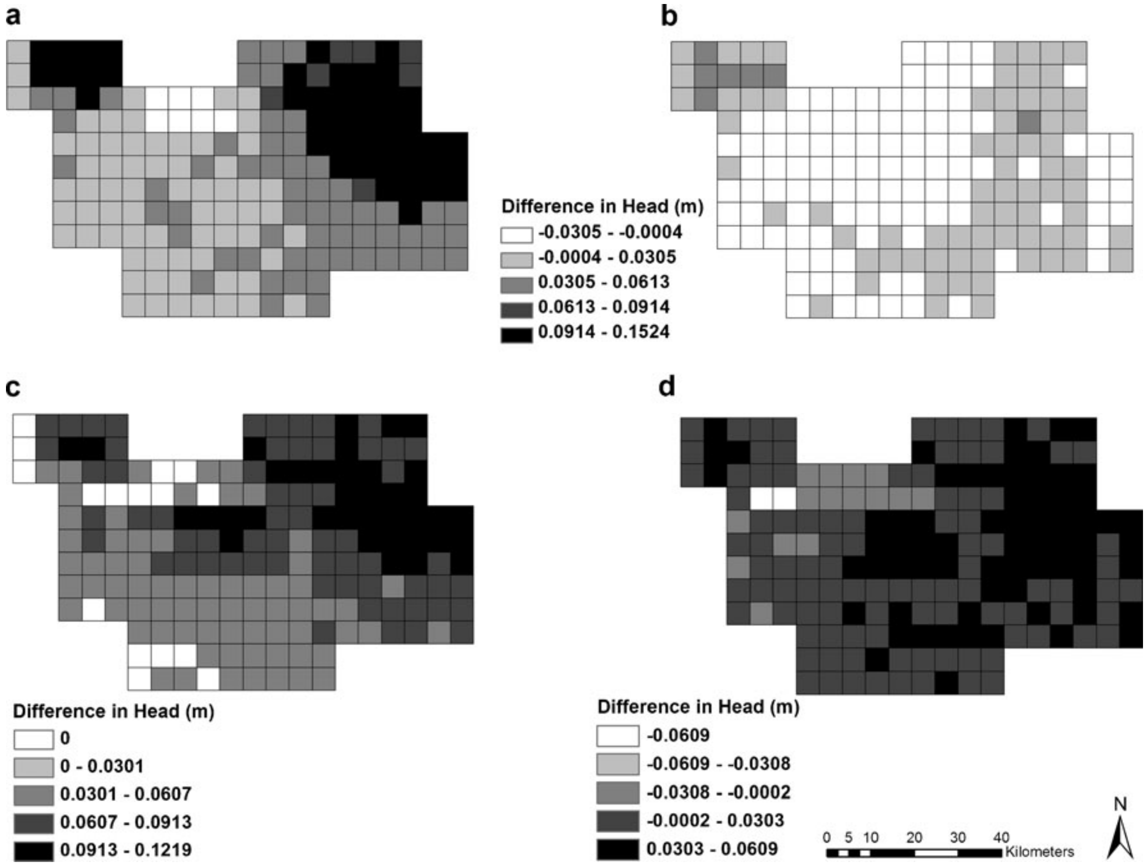

Fig. 6 Difference in estimated head values using EVT (**a** and **b**) and ETS1 (**c** and **d**) packages compared to the RIP-ET. The differences are larger (**a** and **c**) where cell average surface elevation was used compared to average elevation across all polygons (**b** and **d**)

of the program consists of assessing the impact of riparian vegetation change on groundwater resources in a MODFLOW groundwater model for riparian ecosystem restoration. Although RIP-ET allows incorporating spatial and temporal variability of ETg in MODFLOW groundwater models, dynamic vegetation responses such as plant survival, rejuvenation, growth and dispersal in relation to groundwater availability has not been incorporated in this package. Changes in riparian vegetation types, ETg curves, and fractional coverage areas should be updated manually for each stress period if desired.

Results of this study highlight how different ETg estimation methods in MODFLOW impact groundwater budgets. Impact of natural periodic forcings such as ETg in combination with groundwater pumping will ultimately alter seasonal groundwater capture and sustainable pumping rates (Maddock and Vionnet 1998). In groundwater dependent ecosystems capture that results in loss of stream flow and reduction in ETg will cause degradation of riparian habitats and reduction in surface water supplies (Leake et al. 2010). Obviously, sustainable management of groundwater resources requires assessing the impact of

Table 4 Summer season groundwater budget from three simulation scenarios using RIP-ET package (scenario 1; S1) and ETS1 package (scenarios 4 and 5; S4 and S5)

	Percent change S5 and S4	Percent change S1 and S4	Percent change S1 and S5
Inflow to aquifer system			
Storage	–8.0	–9.7	–1.5
Constant head cells	–0.7	–1.7	–1.0
Stream leakage (losing stream)	–5.0	–5.3	–0.2
Total inflow	–3.4	–4.1	–0.7
Outflow from aquifer system			
Storage	4.3	5.2	1.0
Wells	0.0	0.0	0.0
Riparian ET	–32.8	–43.1	–7.7
Stream leakage (gaining stream)	7.4	10.2	2.9
Total outflow	–3.4	–4.1	–0.7

S1 RIP-ET package using PFSG curves for all PFSGs and land-surface elevation at polygon level; *S4* ETS1 package and land-surface elevation at cell level; *S5* ETS1 package and land-surface elevation at polygon level climate variability on recharge, and water supply and demand in a basin (Hanson et al. 2004). Incorporation of spatial and temporal variability of recharge and ET in groundwater models is required to assess impacts of climate variability and vegetation change on groundwater resources.

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