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# A comparison of estimates of basin-scale soil-moisture evapotranspiration and estimates of riparian groundwater evapotranspiration with implications for water budgets in the Verde Valley, Central Arizona, USA

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A B S T R A C T

Population growth in the Verde Valley in Arizona has led to efforts to better understand water availability in the watershed. Evapotranspiration (ET) is a critical factor in estimating groundwater recharge in the area and a substantial component of the groundwater budget. In this study, two estimates of soil-moisture ET and two estimates of groundwater ET in the Verde Valley are presented and discussed. Basin-scale soil-moisture potential ET (PET) estimates from the soil-water balance (SWB) and basin characteristics model (BCM) groundwater recharge models are compared. Separately, riparian groundwater ET estimated from a method that uses MODIS-EVI remote sensing data and geospatial information, and from the MODFLOW-EVT ET package as part of a regional groundwater-flow model that includes the study area, are also discussed. Somewhat higher PET rates from the SWB recharge model resulted in an average annual ET volume about 17% greater than for PET from the BCM recharge model. For groundwater ET estimates, annual ET volumes were about the same for upper-bound MODIS-EVI ET for perennial reaches of streams as for the MODFLOW ET estimates, with the small differences between the two methods having minimal impact on annual or longer groundwater budgets for the study area.

## 1. Introduction

Population growth in the semiarid to arid Verde Valley in central Arizona (Fig. 1A) has led to increased water demand in the area. Projected growth in Verde Valley (Arizona Department of Administration, 2014), along with plans by adjacent-basin cities to develop groundwater resources near the headwaters of the Verde River to provide for their growing populations (Barks, 2009, 2010) will place further stress on limited surface and groundwater resources in the sub-basin. To assist resource managers and policymakers concerned about water availability in the Verde River watershed, several investigations of the Verde Valley hydrologic system have been performed. Blasch et al. (2006) present results from a study of surface water and groundwater in the area. A groundwater-flow model was developed for the area by Pool et al. (2011), which was then used by Garner et al. (2013) to explore water budgets for the Verde Valley area. The Pool et al. (2011) model was also used to simulate the effects of groundwater pumping on the flow in and riparian vegetation along the Verde River (Leake and Pool, 2010). More recently, Hawkins et al. (2015) published a climate change assessment using a watershed model applied to Beaver Creek, one of the Verde River tributaries. Wyatt et al. (2015) used the Pool et al. (2011) model to examine how tree basal area reductions may impact future groundwater recharge. A number of ET studies in the Verde Valley region have been published, mostly from ponderosa pine forests in the Flagstaff, Arizona area (Dore et al., 2008, 2010, 2012). Ha et al. (2014) compare measured actual ET (eddy covariance method) for ponderosa pine forests near Flagstaff with results from 5 models. The authors found that the simplistic Priestley–Taylor model performed well at the natural vegetation site, but over and under predicted measured ET at two fire-disturbed sites. They found that MODIS ET under predicted eddy covariance ET at all forest sites.

ET is a form of water consumption by vegetation and evaporation of water from soil that is both a critical component in determining physically reasonable estimates of groundwater recharge

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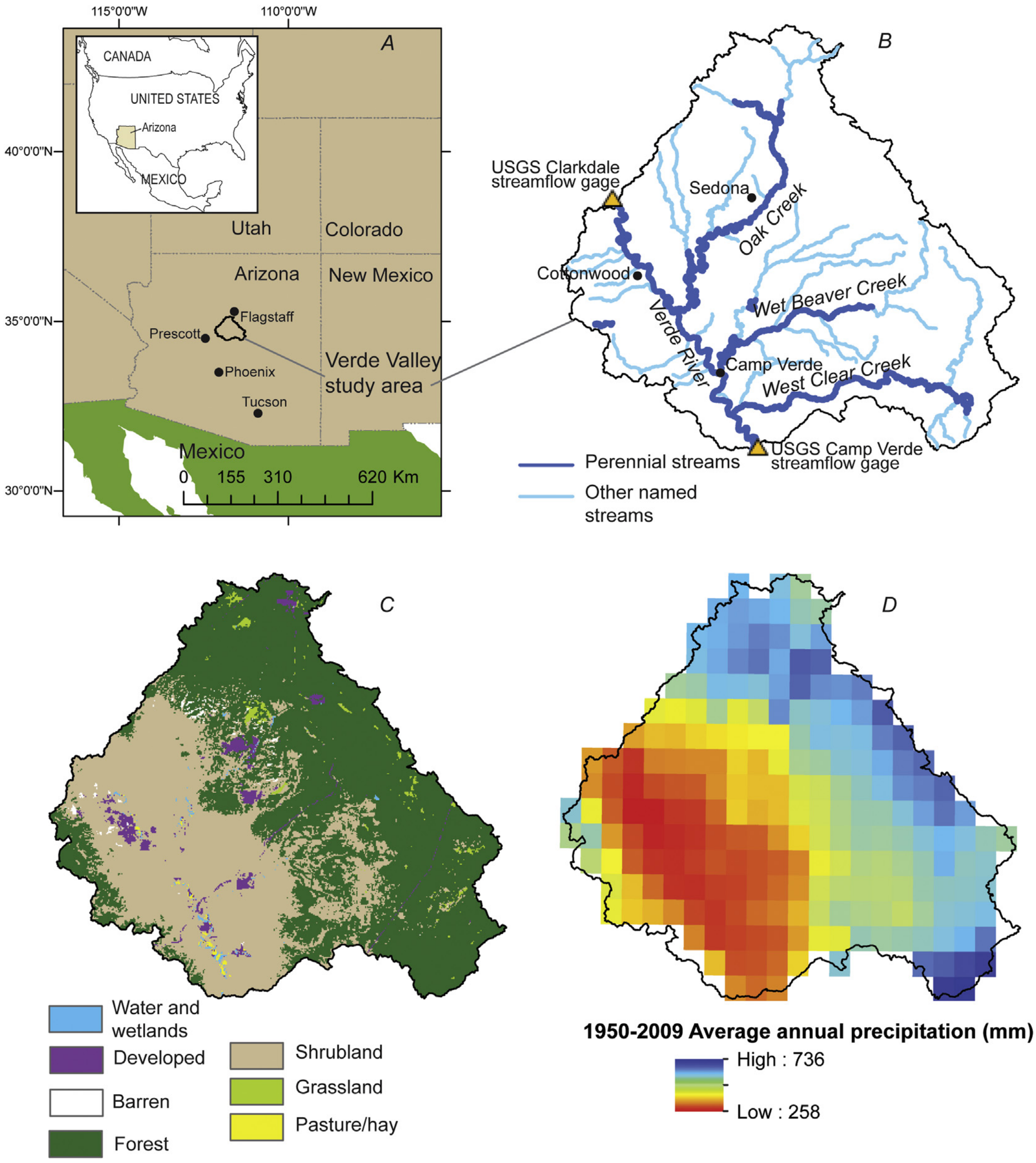


**Fig. 1.** (A) Location of Verde Valley, Arizona, study area, (B) surface water features (Arizona State Land Department, 1993), (C) major land-cover classifications (Fry et al., 2011), and (D) average annual precipitation (PRISM Group, 2011).

and a substantial part of most groundwater budgets. Groundwater recharge models that use a water-balance approach generally subtract sinks of water (e.g., interception, outflow, ET, increasing soil storage) from sources of water (e.g., precipitation, snowmelt, inflow) to estimate groundwater recharge (Fig. 2A). Therefore, ET in the accounting of a water-balance recharge model is presumed to occur before the infiltrating water becomes recharge and part of the saturated groundwater system. ET from this domain is referred to as soil-moisture ET in this manuscript. In contrast, ET in a groundwater budget is presumed to be derived from subsurface water that has already become part of the saturated groundwater system (Fig. 2B). Groundwater ET, as it is referred to in this manuscript, occurs in parts of a basin where vegetation like phreatophytes can access the capillary fringe of the saturated zone through deep roots and/or shallow groundwater tables, which is commonly in riparian areas in the arid southwestern U.S. Soil-moisture ET, by contrast, can occur anywhere in the basin where there is vegetation and is not limited to areas where vegetation must access the saturated zone. The distinction between soil-moisture ET in a water-balance recharge model and groundwater ET is important because they are components of different water budget domains (Fig. 2). Similar rates may be estimated for soil-moisture and groundwater ET, but the volume of water consumption could differ substantially between the two because soil-moisture ET can potentially cover a much larger area than groundwater ET.

In this study, two methods of estimating basin-scale soil-moisture ET are discussed and compared, and two methods of estimating riparian ET are discussed and compared. Basin-scale rates and volumes are presented for soil-moisture ET estimates from the basin characteristics model (BCM) and soil-water balance (SWB) groundwater recharge models. The BCM model uses potential ET (PET) in a water-balance equation to estimate groundwater recharge while the SWB model uses actual ET (AET) to estimate

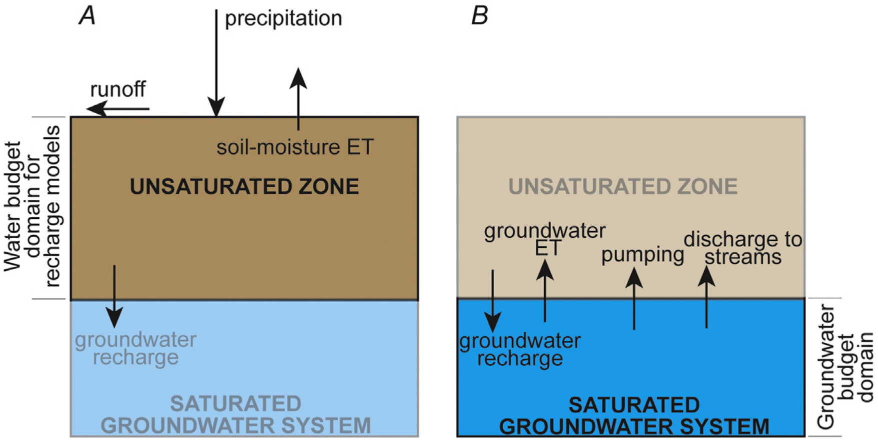


**Fig. 2.** Different accounting domains for (A) water budgets used in groundwater recharge models and (B) groundwater budgets. Soil-moisture ET is presumed to consume subsurface water that has not yet become part of the saturated groundwater system (A), while groundwater ET is accounted for as one of several possible discharge components from the saturated groundwater system (B). Not all budget components are shown.

recharge. PET is the amount of ET that would occur if water were unlimited, while AET limits the amount of ET to the available water in soil. Riparian groundwater ET rates and volume estimates also are presented from two methods. The first method uses remotely-sensed vegetation indices and geospatial data (MODIS-EVI method), and the second uses the ET package in a MODFLOW regional groundwater-flow model of the area.

### 1.1. Study area

The Verde Valley study area is defined by the contributing area to the Verde River between the Clarkdale and Camp Verde streamflow-gaging stations operated by the U.S. Geological Survey (USGS; Fig. 1B). Verde River, Oak Creek, Wet Beaver Creek, and West Clear Creek are all perennial streams in the study area. Population centers in the Verde Valley include Cottonwood (2013 population of 11,424), Camp Verde (11,018) and Sedona (10,111, Fig. 1B, http://quickfacts.census.gov/cgi-bin/qfd/lookup?state=04000). The Verde Valley is in the transition zone of Arizona between the Colorado Plateau to the north and the Basin and Range physiographic province to the south (Fenneman, 1931). Higher altitudes (>2000 m) occur in the northwestern portion of the study area, decreasing towards the southwest along the Verde River floodplain (<1000 m). Land cover in the Verde Valley is primarily forest (55%) in the higher altitude areas and shrubland (40%) in lower altitudes of the floodplain, with a small amount of agriculture and few developed areas (Fig. 1C). Precipitation in the study area averages about 450 mm/year (Fig. 1D) with most of the annual precipitation occurring during the summer monsoon season or winter frontal storms (Blasch et al., 2006). The Verde Valley groundwater system is comprised by the Redwall, Coconino, Verde Formation, and Quaternary alluvium aquifers. The groundwater system is recharged from precipitation that occurs mainly in higher altitude areas (Fig. 1D) and discharges as base flow to streams, through riparian ET, or by pumping from wells (Garner et al., 2013). Depth to groundwater in wells in the Verde Valley ranges from flowing or a few meters below land surface along some stretches of perennial streams to 200 m or more in upland areas (Arizona Department of Water Resources, (2014)).

## 2. Methods

Basin-scale rate and volume of soil-moisture ET in the Verde Valley, Arizona, study area was estimated in two water-balance groundwater recharge models. Additionally, riparian groundwater ET was estimated for the study area using two methods: one incorporating remotely-sensed vegetation indices and geospatial data (MODIS-EVI method), and the second using the ET package in a MODFLOW regional groundwater-flow model of the area.

### 2.1. Soil-moisture ET estimates

#### 2.1.1. Basin characteristics model groundwater recharge model

In general, groundwater recharge models that use a water-balance approach estimate recharge as the difference between sources and sinks of water and the change in storage (Westenbroek et al., 2010):

$$\text{recharge} = (\text{rainfall} + \text{snowmelt} + \text{inflow})^{\text{sources}} - (\text{interception} + \text{outflow} + \text{ET})^{\text{sink}} - \Delta\ \text{soil storage} \quad (1)$$

The basin characteristics model (BCM; Flint et al., 2004; Flint and Flint, 2007a,b), estimates combined runoff and groundwater recharge in 270-m by 270-m grid cells using a water-balance equation that includes rainfall, snowmelt, soil-water storage, snow accumulation, and potential evapotranspiration (PET). Potential evapotranspiration is computed on a daily basis and averaged into monthly values for use in the water-balance recharge Eq. (1). PET is estimated from solar radiation that is modeled using topographic shading and a correction for clouds (Flint and Flint, 2007a,b). Modeled solar radiation is combined with air temperature and converted to net radiation and soil heat flux, which are then used in the Priestley–Taylor equation to estimate PET (Priestley and Taylor, 1972):

$$\lambda PET = \alpha \frac{s}{s+\gamma}(R_n - G) \quad (2)$$

where $\lambda$ is the latent heat of vaporization, $\alpha$ is a model coefficient for drying conditions, $s$ is the slope of the saturation vapor density curve, $\gamma$ is the psychrometric constant, $R_n$ is net radiation, and $G$ is soil heat flux (Flint and Childs, 1991). An $\alpha$ value of 1.26 was used throughout the study area for all time periods (Flint and Childs, 1991). Required precipitation and temperature data for Eqs. (1) and (2) were obtained from PRISM (PRISM Group, 2011). PET from the BCM recharge model was estimated for the study area for monthly time steps from 1980 through 2009.

#### 2.1.2. Soil-water balance groundwater recharge model

The SWB recharge model (Westenbroek et al., 2010) estimates groundwater recharge in grid cells (measuring 200-m by 200-m for this study) based on a modified Thornthwaite-Mather (Thornthwaite, 1948; Thornthwaite and Mather, 1957) soil-water-accounting approach. The SWB model calculates soil-water balance equation components (Eq. (1)) on a daily time step from gridded geospatial data. Sources and sinks of water within gridded cells are calculated based on climate data and landscape characteristics. In contrast with the BCM groundwater recharge model, the SWB model uses actual ET (AET) as the ET term in Eq. (1). AET is calculated in different ways, depending on the amount of precipitation, the rate of potential ET (PET), and the accumulated potential water loss of the soil (Westenbroek et al., 2010). In a particular day, if the amount of precipitation in a cell is greater than PET for that cell, then a potential surplus of water exits and AET is equal to PET. If PET is greater than precipitation, AET is equal to the amount of water that can be extracted from available soil water. Soil water is accounted for through a running daily sum of the differences between precipitation and PET and is bounded on the low end by the soils' wilting capacity and on the high end by maximum soil water capacity, computed as the product of available soil-water capacity and vegetation root-zone depth (Westenbroek et al., 2010). For this study, the Hargreaves and Samani (1985) method of estimating PET was used in the SWB model because it allowed for estimation of PET from spatially distributed climate data. The Hargreaves and Samani method of estimating ET is

$$\mathrm{PET} = 0.0135 \times \mathrm{RS} \times (\mathrm{T} + 17.8) \text{with } \mathrm{RS} = \mathrm{K_{RS}} \times \mathrm{RA} \times \mathrm{TD}^{0.5} \tag{3}$$

where PET is potential ET, RS is incoming solar radiation, T is mean temperature in °C, $K_{RS}$ is a calibration coefficient, RA is extraterrestrial radiation, and TD is the measured temperature range (Hargreaves and Samani, 1985). Extraterrestial radiation is estimated as a function of the day of year and latitude following the method of Allen et al. (2006). Required daily climate data was obtained from Oak Ridge National Laboratory, (2009) (http://daymet.ornl.gov/gridded). These data, known as Daymet, are produced by interpolating spatially referenced ground observations. Vegetation root-zone depth information, required for computation of soil-water capacity and AET, was obtained from the average maximum vegetation root depths published in Canadell et al. (1996). For this study, results for PET and three different cases of AET were analyzed. The three AET cases comprise a base case with published average maximum root-zone depths from Canadell et al. (1996), a high soil-water capacity case with root-zone depths of the base case multiplied by 1.5, and a low soil-water-capacity case with root-zone depths of the base case multiplied by 0.5. Daily values of PET and AET were summarized on a monthly basis for the study area for 1980 through 2010.

Although the BCM and SWB groundwater recharge models are similar water-balance type models, there are fundamental differences in approach between the two in how ET is used to estimate recharge. Both models estimate PET, either from the Priestley–Taylor equation (BCM) or the Hargreaves and Samani equation (SWB). However, the SWB model uses an estimate of AET in computing recharge (Eq. (1)), while BCM uses PET. Additionally, the SWB model calculates the water balance on a daily time step, while the BCM model uses a monthly time step.

### 2.2. Groundwater ET estimates

#### 2.2.1. The MODIS-EVI method

A method for estimating ET using remote sensing and geospatial datasets (Fig. 3) was developed by extending the work of Nagler and Glenn (2009). Further details and explanation of the method are provided in Tillman et al. (2011, 2012) and Garner et al. (2013). Groundwater discharge by riparian vegetation was estimated for the study area for the period 2000 through 2010 by first estimating ET throughout the entire sub-basin, then selecting subset areas along surface water drainages and by land cover where the water for ET is presumed to be derived primarily from groundwater (Fig. 3). A subsequent accounting of the potential contribution of direct precipitation to vegetation greenness in these subset areas was also performed to provide a minimum bounding estimate of riparian ET of groundwater.

Enhanced Vegetation Index (EVI) is a measure of vegetation greenness to which evapotranspiration is directly correlated (Nagler and Glenn, 2009; Nagler et al., 2009). EVI raster data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrumentation aboard the Terra and Aqua satellites operated by the National Aeronautics and Space Administration (NASA) were obtained from the Oak Ridge National Laboratory (Oak Ridge National Laboratory Distributed Active Archive Center, 2009). Near-daily satellite passes provided 250 m × 250 m resolution EVI data composited over 16-day intervals over the 2000 through 2010 time period. ET (mm/day) was calculated in ArcGIS™ on 250-m by 250-m individual grid cells for the entire study area from EVI data using a relation developed previously by researchers with the USGS Southwest Biological Science Center and the University of Arizona (Nagler and Glenn, 2009; Nagler et al., 2009):

$$\mathrm{ET} = 1.22\mathrm{ET_o} \times \mathrm{EVI}^* \tag{5}$$

where $ET_o$ is the reference crop evapotranspiration (mm/day), and $EVI^*$ is scaled EVI. This relation between ET, $ET_o$, and $EVI^*$ was developed by regressing actual ET data measured by sap flux sensors, moisture flux towers, and neutron hydroprobe water balance measurements, in riparian and agricultural areas along the Lower Colorado River in Arizona, and is validated in other publications (Nagler and Glenn, 2009; Nagler et al., 2009).

$ET_o$ was estimated on a monthly basis using a modified Blaney–Criddle relation (Brouwer and Heibloem, 1986):

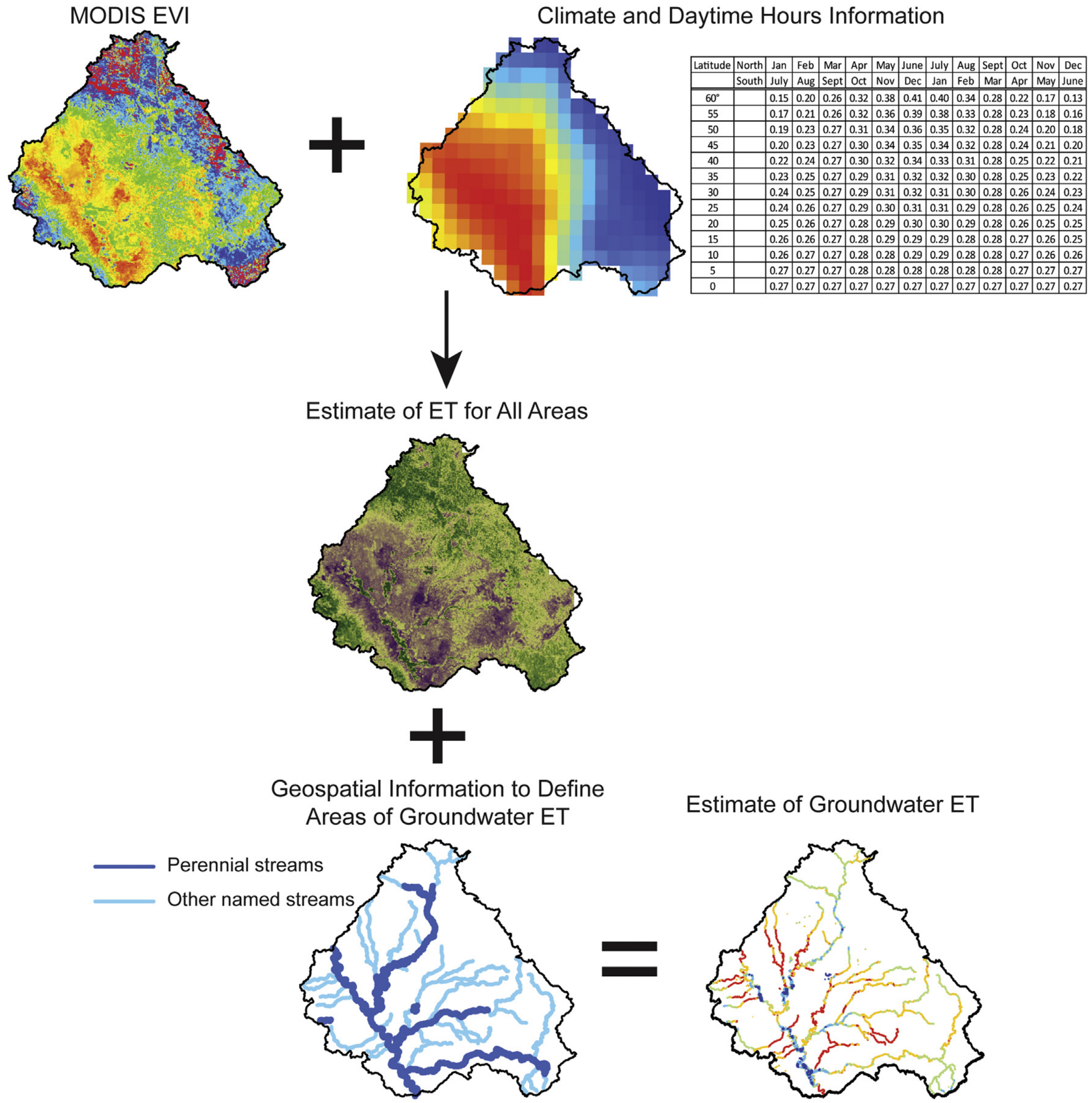
$$\mathrm{ET_o} = \mathrm{p}(0.46\,\mathrm{T_{mean}} + 8) \tag{6}$$

where p is mean daily percentage of annual daytime hours (percent) obtained from published values for the study area (Brouwer and Heibloem, 1986) and $T_{mean}$ is mean daily temperature. $T_{mean}$ was calculated on a monthly basis from daily minimum and maximum temperature data (PRISM Group, 2011). EVI is converted to a scaled value ($EVI^*$) following the relation of Nagler et al. (2005):

$$\mathrm{EVI}^* = 1 - (0.542 - \mathrm{EVI})/(0.542 - 0.091) \tag{7}$$

where 0.542 and 0.091 represent maximum and minimum EVI values, respectively, from a large data set of riparian plant communities in the southwestern U.S. (Nagler et al., 2005; Dennison et al., 2009). These same riparian plant communities are found throughout the current study area.

ET computed on grid cells of 250 m × 250 m using Eqs. (5)–(7) was downscaled in ArcGIS to 50 m × 50 m cells using nearest neighbor interpolation for further analyses. Although the downscaled 50-m cells do not contain higher resolution information that



| Latitude | North | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | South | July | Aug | Sept | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | June |
| 60° | | 0.15 | 0.20 | 0.26 | 0.32 | 0.38 | 0.41 | 0.40 | 0.34 | 0.28 | 0.22 | 0.17 | 0.13 |
| 55 | | 0.17 | 0.21 | 0.26 | 0.32 | 0.36 | 0.39 | 0.38 | 0.33 | 0.28 | 0.23 | 0.18 | 0.16 |
| 50 | | 0.19 | 0.23 | 0.27 | 0.31 | 0.34 | 0.36 | 0.35 | 0.32 | 0.28 | 0.24 | 0.20 | 0.18 |
| 45 | | 0.20 | 0.23 | 0.27 | 0.30 | 0.34 | 0.35 | 0.34 | 0.32 | 0.28 | 0.24 | 0.21 | 0.20 |
| 40 | | 0.22 | 0.24 | 0.27 | 0.30 | 0.32 | 0.34 | 0.33 | 0.31 | 0.28 | 0.25 | 0.22 | 0.21 |
| 35 | | 0.23 | 0.25 | 0.27 | 0.29 | 0.31 | 0.32 | 0.32 | 0.30 | 0.28 | 0.25 | 0.23 | 0.22 |
| 30 | | 0.24 | 0.25 | 0.27 | 0.29 | 0.31 | 0.32 | 0.31 | 0.30 | 0.28 | 0.26 | 0.24 | 0.23 |
| 25 | | 0.24 | 0.26 | 0.27 | 0.29 | 0.30 | 0.31 | 0.31 | 0.29 | 0.28 | 0.26 | 0.25 | 0.24 |
| 20 | | 0.25 | 0.26 | 0.27 | 0.28 | 0.29 | 0.30 | 0.30 | 0.29 | 0.28 | 0.26 | 0.25 | 0.25 |
| 15 | | 0.26 | 0.26 | 0.27 | 0.28 | 0.29 | 0.29 | 0.29 | 0.28 | 0.28 | 0.27 | 0.26 | 0.25 |
| 10 | | 0.26 | 0.27 | 0.27 | 0.28 | 0.28 | 0.29 | 0.29 | 0.28 | 0.28 | 0.27 | 0.26 | 0.26 |
| 5 | | 0.27 | 0.27 | 0.27 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.27 | 0.27 | 0.27 |
| 0 | | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 |

**Fig. 3.** Schematic of datasets required for estimating groundwater ET in the Verde Valley, Arizona, study area from MODIS remote-sensing information and geospatial data.

the original 250-m cells, the smaller size allows for better selection of cells within the riparian buffer, described below. Groundwater discharge by vegetation was estimated from the ET method described above by defining geographic areas of presumed groundwater-using vegetation. Because this study was originally performed to estimate groundwater ET for the Basin and Range province for the entire state (Tillman et al., 2011), a combination of proximity to surface-water drainages and landcover types was used to define the areas of groundwater-using vegetation. Other methods to define the riparian area including digitizing riparian vegetation from aerial photos or digitizing areas of shallow groundwater, would probably result in a more accurate riparian buffer. First, a 50-m buffer was created around all named surface-water drainages in the study area using GIS tools (Arizona State Land Department, 1993). The 50-m buffer distance was selected to adequately encompass riparian vegetative areas based on analyses of satellite and aerial photography of the surface-water drainages in the study area. Areas within the 50-m surface-drainage buffer that were defined in the 2001 National Land Cover Dataset (NLCD; Homer et al., 2004) as “Hay/Pasture” or “Cultivated Crops” were removed, because these areas are normally irrigated in the study area and do not use groundwater directly. All remaining vegetation within the buffer was presumed to be using primarily groundwater for growth and maintenance. Specific land coverages within the NLCD were used to define additional areas of groundwater-using vegetation in the study area that were outside the 50-m surface-drainage buffer. NLCD land classifications of “Herbaceous Wetland” and “Woody Wetland” were selected to represent locations at which all or nearly all water extracted by plants comes from groundwater.

Acknowledging the potential for direct precipitation to be at least a partial source of water for vegetation greenness and associated EVI in the subset areas defined above, a lower bound on estimated groundwater discharge by vegetation for the study area was developed by subtracting monthly precipitation (PRISM Group, 2011) from monthly groundwater ET estimates developed in this study. Groundwater ET was estimated using the method described above both for all named streams in the Verde Valley study area and separately for only perennial reaches of those streams (Fig. 1B). Perennial reaches of streams have groundwater levels that are shallow enough to intercept the stream bed, and vegetation along these reaches is presumed to access groundwater throughout the year. Ephemeral reaches of streams are, at least during some period of time, disconnected from groundwater, and vegetation along these reaches may be utilizing soil-water and not groundwater for growth and maintenance.

### 2.2.2. Groundwater ET estimated with the MODFLOW ET package

A regional groundwater-flow model of the primary aquifers in northern Arizona, including the Verde Valley study area, was developed to investigate interaction between aquifers, perennial streams, and springs (Pool et al., 2011). The three-dimensional finite-difference modular groundwater-flow model code MODFLOW-2005 (Harbaugh, 2005) was used to simulate the regional groundwater-flow system. Outflow components of the groundwater budget simulated in the model included spring discharge, base flow, pumping, and groundwater ET by phreatophytes. ET by phreatophytes was simulated along perennial stream reaches of the Verde River using the Evapotranspiration (EVT) Package (Harbaugh, 2005, Fig. 4). The Evapotranspiration (EVT) Package calculated ET rates in the 1000-m by 1000-m cells of the groundwater-flow model on the basis of a linear depth and rate relation (Fig. 5). Although cells this large would not be ideal if the purpose of the model were to accurately simulate ET along riparian corridors, cells of this size are not uncommon for simulating groundwater flow in large-scale regional models such as this (>200,000 km$^2$ modeled area in this case). ET rates in a model cell are at a maximum when the water table is at or above the evapotranspiration surface and decrease linearly with depth to a rate of zero at the extinction depth below the ET surface (Fig. 5). Requirements for simulating groundwater ET rates in the numerical groundwater-flow model include spatial extent of phreatophytes, depths to groundwater, type of phreatophyte, maximum rates of water use for each type of phreatophyte, and maximum depths of groundwater withdrawal for each type of phreatophyte. Maps and GIS data describing phreatophyte type were generally unavailable for the model area, so the primary vegetation type was assumed to be deciduous trees that may include various species of cottonwood, willow, sycamore, and saltcedar. Published values of maximum water-use rate of 2 mm/d and maximum depth to groundwater for cottonwood trees of 5.0 m (Leenhouts et al., 2005) were initially assumed to apply to groundwater use by phreatophytes in the study area, although calibration of the groundwater-flow model, and large model cell size, necessitated a final maximum water-use rate of 0.2 mm/d (Pool et al., 2011; Blasch et al., 2006). The ET surface was estimated as 1 m below the minimum altitude of land-surface elevation in each model cell. Depths to groundwater were calculated by the groundwater-flow model.

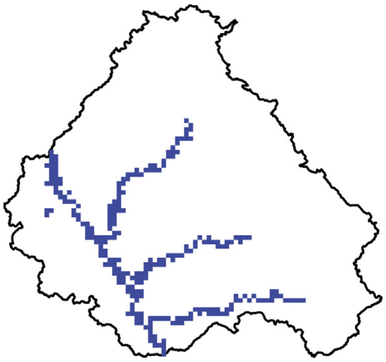


Fig. 4. Groundwater-flow model cells in the Verde Valley, Arizona, study area in which ET by phreatophytes is simulated in the Northern Arizona Regional Groundwater Flow Model (Pool et al., 2011).

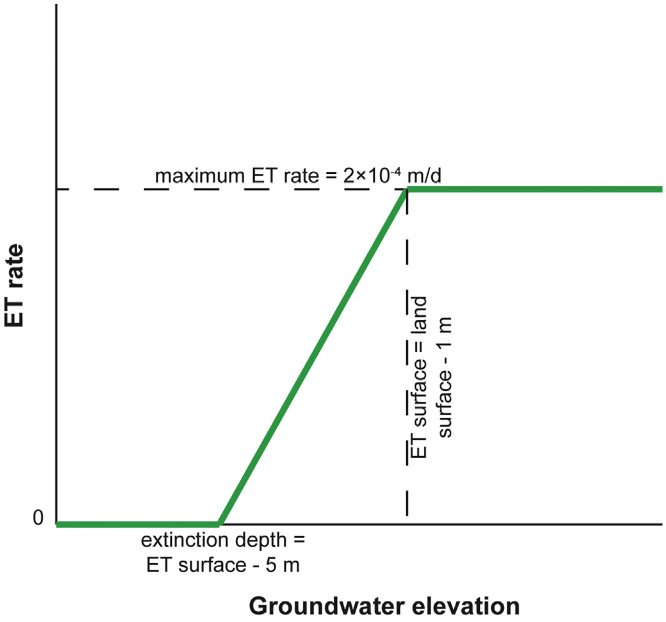


Fig. 5. Diagram showing relation between MODFLOW-simulated ET rate and required simulation parameters of maximum ET rate, ET surface, and extinction depth. (Modified from Harbaugh, 2005).

## 3. Results and discussion

Basin-scale monthly rates and monthly and annual volumes of soil-moisture ET were estimated by the BCM (PET only) and SWB (PET and AET) recharge models for 1980–2009 (BCM) and 1980–2010 (SWB). Daily and annual volumes of riparian groundwater ET were computed by the MODIS-EVI method for 2000–2010 and by the MODFLOW EVT package for 1980–2010.

### 3.1. Soil-moisture ET results

Average monthly rates of PET estimated in the BCM recharge model by the Priestley–Taylor equation follow a sinusoidal seasonal pattern with lowest rates about 40–50 mm/month in the November–February winter months and highest rates about 130–170 mm/month in the May–August summer months (Fig. 6 upper panel). Values of average monthly PET rates computed in the BCM model have a fairly narrow range of values, with a maximum difference between the 90th percentile rate and the median rate of 16 mm/month in both May and July in the over 53,400 cells in the study area in which average monthly PET was computed. Monthly soil-moisture PET estimated in the SWB recharge model using the Hargreaves–Samani relation follow a similar seasonal pattern, with higher rates about 180–220 mm/month in June and July and lower rates about 33–50 mm/month in December and January (Fig. 6 lower panel). The range of monthly PET rates from the SWB model is somewhat broader than for BCM-model rates, probably owing to the finer spatial resolution in the SWB model (97,500 cells in the study area) and the daily time step of PET calculations. In the SWB, the maximum difference between the 90th percentile rate and the median rate is 33 mm/month and occurs in May and June (Fig. 6 lower panel). PET rates in the cooler months of October–April are similar between the BCM and SWB-model estimates (medians within 8 mm/month). PET rates in the

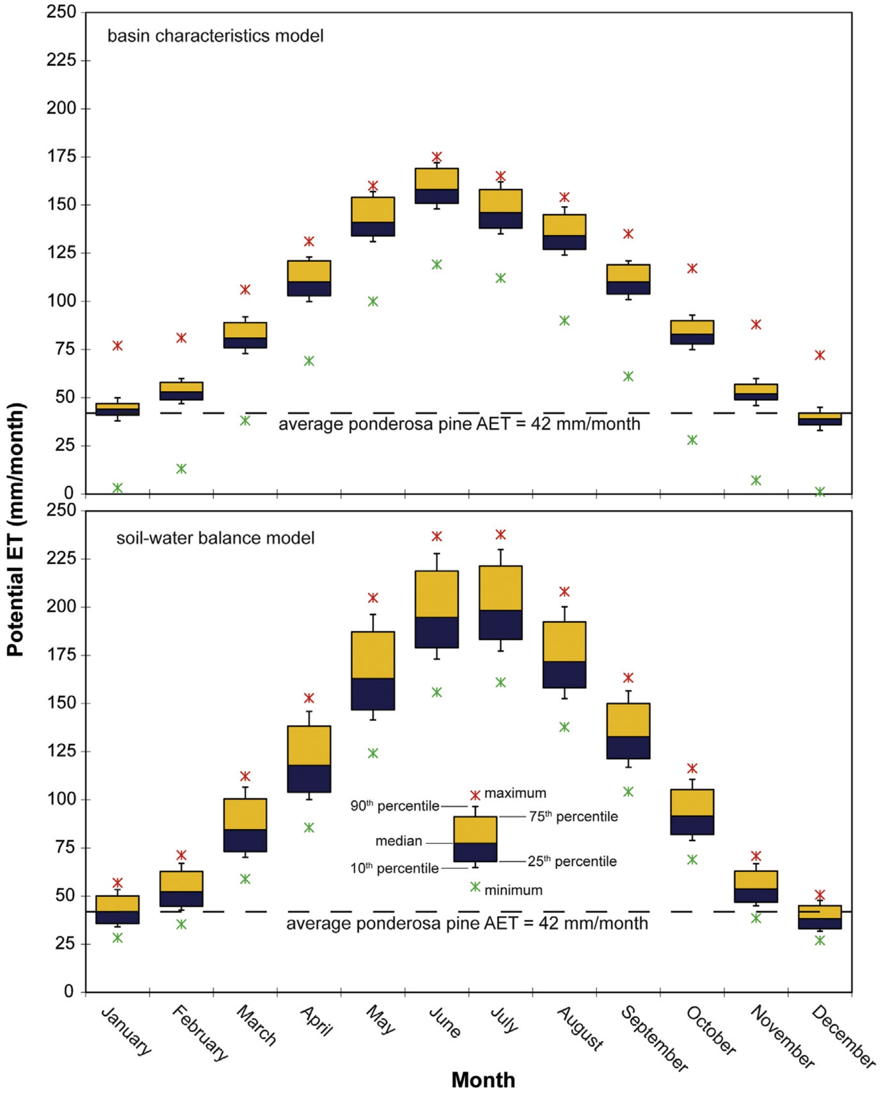


**Fig. 6.** Distribution of average monthly rates of potential ET (PET) in the Verde Valley, Arizona, study area estimated by the basin characteristics recharge model for 1980–2009 (top panel) and the soil-water balance recharge model for 1980–2010 (bottom panel). Average measured AET rate for undisturbed ponderosa pine forest from Dore et al. (2012) and Ha et al. (2014) is presented for comparison.

warmer months of May–September are higher in the SWB model than the BCM model, with median rates from 22 to 52 mm/month higher in SWB-model estimates than in BCM-model estimates (Fig. 6). PET rates from both the BCM and SWB recharge models are substantially higher than published average AET rates from ponderosa pine forests near Flagstaff, Arizona in Dore et al. (2012) and Ha et al. (2014) (Fig. 6).

As discussed in the introduction, the SWB recharge model uses AET in the development of recharge estimates which is, as expected, much less than PET in the study area during certain time periods. Median AET rates in the SWB model are as much as 150 mm/month lower than PET rates in June and July (Fig. 7). During warmer months of the year, PET values are high but AET is limited by the availability of soil water. Cooler months have sufficient soil-moisture conditions to satisfy the reduced PET requirements, so AET and PET rates are more similar during November–March. Little variation is seen in AET monthly rates between the high, base case, and low soil-moisture capacity estimations, except somewhat lower median rates in May and June (Fig. 7), indicating that root-zone depth is not a highly sensitive parameter in the estimation of SWB AET over the range of depths considered. AET rates from the SWB recharge model are similar to published ponderosa pine rates (Fig. 7).

The monthly volume of PET estimated in the BCM recharge model, the sum of the product of rate and area of each cell in the study area, follows the seasonal rate pattern with little variation from year to year during the 1980 through 2009 time period of BCM simulations (Fig. 8 upper panel). Low estimates of about 175 × $10^6$ $m^3$ per month in winter months and highs about 600 × $10^6$ $m^3$ per month in summer months are seen for the entire simulation period. The average annual volume of BCM-estimated PET is 4548 × $10^6$ $m^3$ for 1980–2009 and also shows little variability year to year (Table 1). Average annual BCM-estimated PET is more than double the average annual precipitation in the study area of 2155 × $10^6$ $m^3$ for 1980–2010 (Table 1). The BCM performs water-balance calculations on a monthly basis, and only during months when PET is less than precipitation would there be sufficient available water to produce groundwater recharge. The volume of PET estimated by the SWB recharge model using the Hargreaves–Samani relation also follows the seasonal rate pattern,

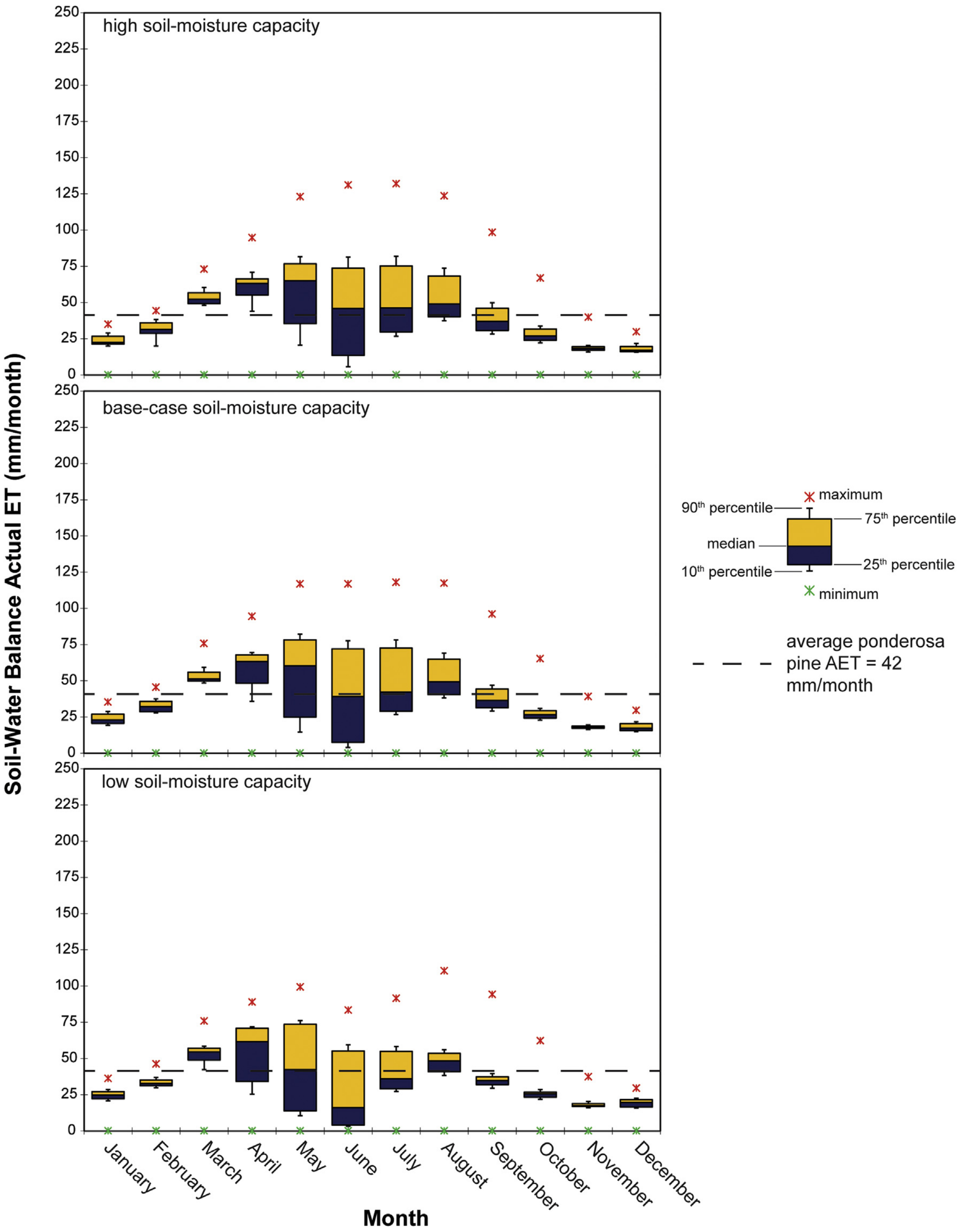


**Fig. 7.** Distribution of average 1980–2010 monthly rates of actual ET (AET) in the Verde Valley, Arizona, study area estimated by the soil-water balance recharge model using high (top panel), base-case (middle panel), and low (bottom panel) soil-moisture capacity scenarios. Average measured AET rate for undisturbed ponderosa pine forest from Dore et al. (2012) and Ha et al. (2014) is presented for comparison.

and, as was seen in the monthly rates (Fig. 6), exhibits significantly higher summer ET volumes than those produced by the BCM recharge model (Fig. 8 middle panel). SWB PET estimates range from lows of about 125 × $10^6$ $m^3$ per month in winter months to highs of over 800 × $10^6$ $m^3$ per month in many summer months for the 1980 through 2010 time period of SWB simulations (Fig. 8 middle panel). The average annual SWB-estimated PET is 5339 × $10^6$ $m^3$ and is somewhat more variable year to year than BCM PET, probably owing to variability resulting from the daily time step of SWB water-balance calculations (Table 1). As a result of the expected lower rates described above, AET volume estimates from the SWB recharge model are lower than both BCM and SWB PET estimates (Fig. 8 bottom panel, Table 1). Changes in the soil-water capacity parameter over the range of changes in vegetation

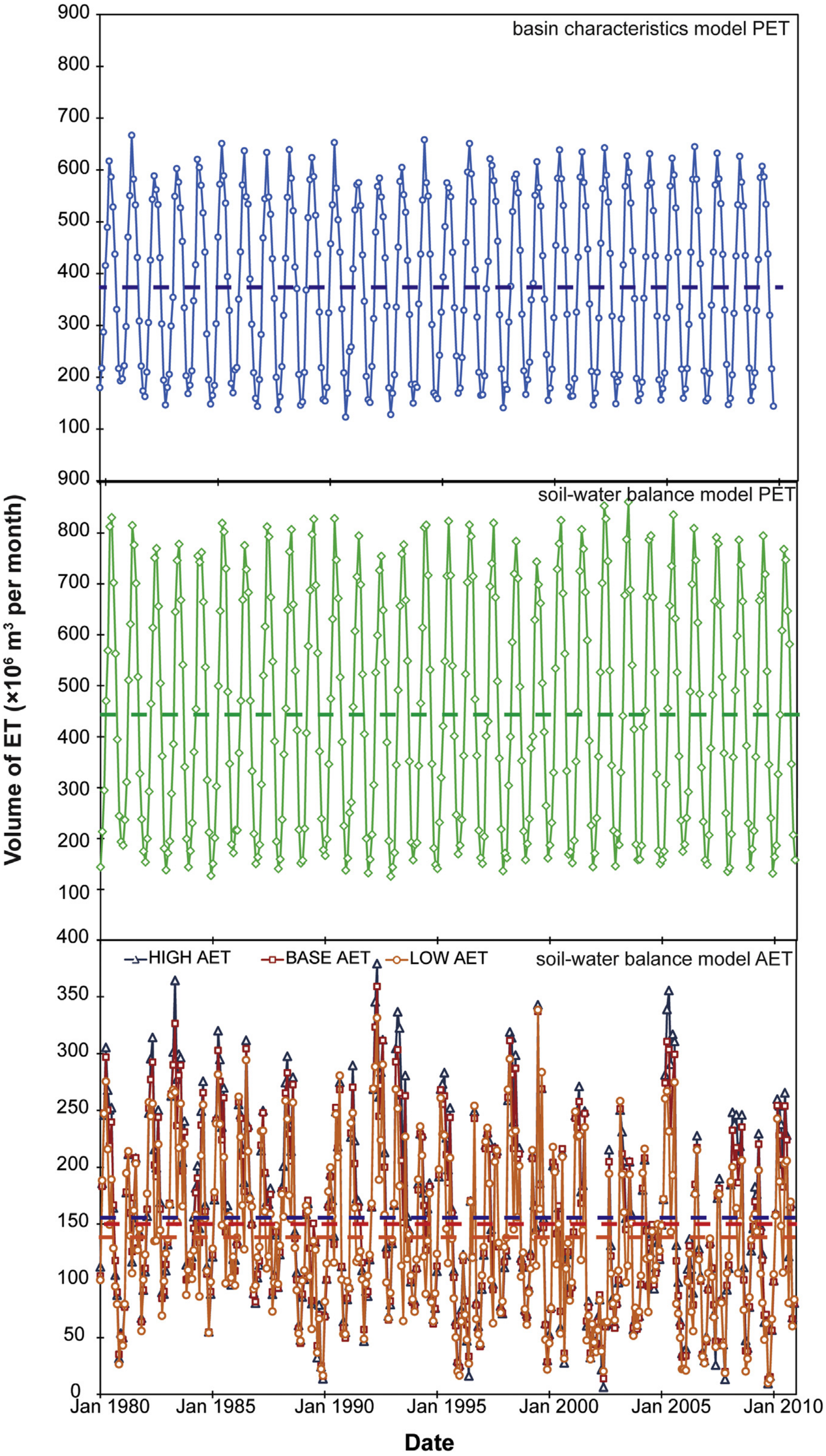


**Fig. 8.** Estimated monthly volume for the basin characteristics recharge model potential ET (PET, top), the soil-water balance recharge model PET (middle), and the soil-water balance recharge model actual ET (AET) for high soil-moisture capacity, base-case capacity, and low capacity (bottom). Period of record means are shown as dashed lines. Note different y-axis scale in bottom panel.

root-zone depth investigated does not appear to have a large effect on either monthly or annual SWB AET estimates as evidenced by substantial consistency between high AET, base-case AET, and low AET estimates (Fig. 8 bottom panel, Table 1). Volume of AET in summer months is somewhat higher for the high soil-water capacity case than the base and low soil-moisture cases (Fig. 8 bottom panel), but average annual volumes of AET are similar with $1863 \times 10^6$ m$^3$, $1804 \times 10^6$ m$^3$, and $1647 \times 10^6$ m$^3$ for the high soil-

**Table 1**
Annual volume of evapotranspiration (ET) in the Verde Valley, Arizona, study area estimated by the BCM and SWB recharge models, along with precipitation.

| Year | BCM PET[a] $(\times 10^6\ m^3)$ | SWB | | | | |
|---|---|---|---|---|---|---|
| | | PET[b] $(\times 10^6\ m^3)$ | AET[c] high soil-water capacity[d] $(\times 10^6\ m^3)$ | AET[c] base case[e] $(\times 10^6\ m^3)$ | AET[c] low soil-water capacity[f] $(\times 10^6\ m^3)$ | PRISM[g] precipitation $(\times 10^6\ m^3)$ |
| 1980 | 4500 | 5432 | 2062 | 2002 | 1747 | 2651 |
| 1981 | 4654 | 5416 | 1585 | 1605 | 1573 | 2139 |
| 1982 | 4406 | 5085 | 2244 | 2186 | 1985 | 3040 |
| 1983 | 4461 | 5102 | 2763 | 2621 | 2309 | 3139 |
| 1984 | 4542 | 5344 | 1871 | 1792 | 1617 | 2064 |
| 1985 | 4553 | 5347 | 2342 | 2270 | 2052 | 2251 |
| 1986 | 4576 | 5289 | 2202 | 2158 | 2052 | 2268 |
| 1987 | 4449 | 5344 | 1823 | 1816 | 1683 | 2182 |
| 1988 | 4558 | 5406 | 2168 | 2081 | 1873 | 1898 |
| 1989 | 4681 | 5721 | 1141 | 1170 | 1103 | 1898 |
| 1990 | 4475 | 5332 | 1818 | 1783 | 1792 | 2067 |
| 1991 | 4428 | 5215 | 1748 | 1716 | 1559 | 2285 |
| 1992 | 4449 | 5182 | 2626 | 2535 | 2296 | 3000 |
| 1993 | 4495 | 5262 | 2480 | 2246 | 1861 | 2855 |
| 1994 | 4544 | 5352 | 1735 | 1676 | 1584 | 1834 |
| 1995 | 4485 | 5272 | 2167 | 2084 | 1801 | 2075 |
| 1996 | 4683 | 5550 | 1098 | 1098 | 1056 | 1371 |
| 1997 | 4652 | 5334 | 1843 | 1814 | 1747 | 2254 |
| 1998 | 4440 | 5059 | 2406 | 2322 | 2099 | 2625 |
| 1999 | 4601 | 5278 | 1858 | 1821 | 1719 | 2625 |
| 2000 | 4612 | 5533 | 1474 | 1487 | 1420 | 1928 |
| 2001 | 4592 | 5483 | 1853 | 1801 | 1663 | 1770 |
| 2002 | 4597 | 5660 | 889 | 880 | 854 | 1148 |
| 2003 | 4600 | 5482 | 1721 | 1676 | 1551 | 1849 |
| 2004 | 4545 | 5324 | 1522 | 1539 | 1535 | 2210 |
| 2005 | 4593 | 5252 | 2546 | 2311 | 1913 | 2321 |
| 2006 | 4572 | 5300 | 1230 | 1162 | 1068 | 1372 |
| 2007 | 4607 | 5378 | 1083 | 1107 | 1108 | 1760 |
| 2008 | 4528 | 5270 | 1979 | 1834 | 1502 | 2150 |
| 2009 | 4576 | 5317 | 1342 | 1315 | 1178 | 1189 |
| 2010 | not available | 5182 | 2146 | 2027 | 1751 | 2584 |
| Average | 4548 | 5339 | 1863 | 1804 | 1647 | 2155 |

[a] BCM uses the Priestley–Taylor (1972) equation to estimate PET.
[b] SWB uses the Hargreaves–Samani (1985) equation to estimate PET.
[c] SWB estimates daily AET as PET when precipitation is more than PET or as the amount of available soil moisture when precipitation is less than PET.
[d] High soil-water capacity case uses base-case vegetation root-zone depths multiplied by 1.5.
[e] Base case uses vegetation root-zone depths from Canadell et al. (1996).
[f] Low soil-water capacity case uses base-case vegetation root-zone depths multiplied by 0.5.
[g] Precipitation estimates from PRISM Group (2011).

water capacity, base-case, and low soil-water capacity simulations, respectively (Table 1). Annual AET for all three cases is less than annual precipitation for nearly all years (Table 1), although SWB computes recharge from a water balance on a daily time step. All SWB AET estimates are significantly less than the BCM PET estimates, both on a monthly (Fig. 8) and annual basis (Table 1). All other sources and sinks being equal in their respective water-balance equations, more recharge would be expected from the SWB recharge model than the BCM model for these ET estimates.

The PET methods used in this study are similar in that they estimate ET based on climate information and presume an unlimited supply of water. The unlimited-water assumption may be valid in more humid or tropical climates, but in the arid to semi-arid southwestern U.S., the availability of water severely limits the amount of ET by vegetation (compare Figs. 6 and 7). Not accounting for the water-limiting effects on ET rates and volumes would appear to substantially overestimate ET discharge, and thus underestimate the amount of groundwater recharge in a water-balance approach. The use of AET instead of PET for the ET term in Eq. (1), as is done by the SWB recharge model, would likely result in a more physically realistic estimate of groundwater recharge.

### 3.2. Groundwater ET results

Average monthly rates of upper-bound ET estimated using the MODIS-EVI method also follow a seasonal pattern with lower ET rates in winter months and higher ET rates in summer months (Fig. 9). Lower bound ET rates are close to zero from December through February, when winter precipitation is sufficient to supply nearly all required water for cool-weather reduced ET. Upper bound ET rates are similar between estimates for all named streams and for estimates from only perennial reaches of streams (Fig. 9). Lower bound ET rates are also similar for the estimates from all streams and the estimates for only perennial reaches, with maximum differences between median rates of only about 14 mm/month in June (Fig. 9). There is a substantial difference between upper and lower-bound monthly rates, both for all streams and perennial reaches, during late-summer months. Median upper and lower bound ET rates differ by over 55 mm/month in August for ET estimates for all Verde Valley streams and for only perennial reaches of the streams (Fig. 9). This difference is a result of precipitation supplying a greater amount of increased summer ET requirements, reducing the amount of water required from groundwater. Ha et al. (2014) found that MODIS ET under predicted annual eddy-covariance ET measurements by at least 51%. The Ha et al. (2014) comparison, however, was performed at high-elevation ponderosa-pine forest sites. Tillman et al. (2012) found comparable results between MODIS estimates and published estimates for the riparian corridor in the Sierra Vista subwatershed in southeastern Arizona, which contained similar phreatophyte vegetation as the Verde Valley

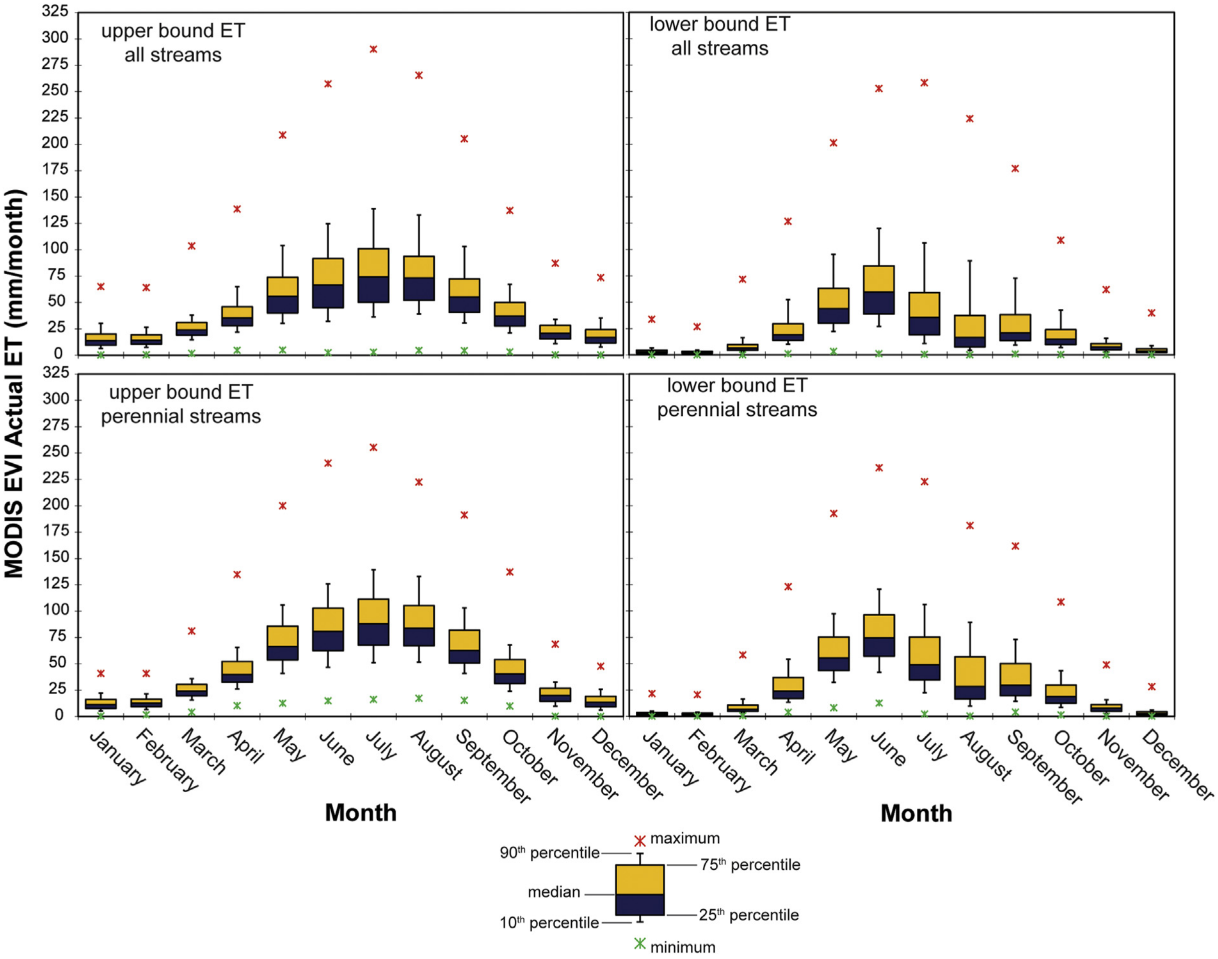


**Fig. 9.** Distribution of average 2000–2010 monthly rates of actual ET (AET) in the Verde Valley, Arizona, study area estimated by the MODIS-EVI method for riparian areas near all named streams in the study area (top panels) and for riparian areas near only perennial streams in the study area (bottom panels). All ET demand is satisfied by groundwater in upper bound ET estimates while ET demand is first satisfied by precipitation and then by groundwater in lower bound ET estimates.

riparian areas in the current study.

The northern Arizona regional groundwater MODFLOW model was not designed to address seasonal changes in system stresses, and model output was only available at time steps ranging from about 300 to over 1000 days between 1980 and 2010. Therefore, monthly ET rates from MODFLOW-EVT estimates were unavailable for analysis. Maximum MODFLOW-EVT rates are constrained by input parameters to 0.2 mm/d or about 6 mm/month. The final calibrated ET rate of 0.2 mm/d for the MODFLOW-EVT package is substantially lower than the rate reported for cottonwood trees (2 mm/d). This low rate is a result of large model cells (1000 m by 1000 m), and may reflect an average rate of all vegetation in the ET-simulated area. Alternatively, groundwater recharge in the model area may be too low or other (non-ET) groundwater discharge rates in the model may be too high.

Estimated daily volume of MODIS-EVI ET follows the seasonal rate pattern, with higher daily volumes in summer months and lower volumes in winter months, for upper and lower bound estimates from all streams and from perennial reaches of streams (Fig. 10). Upper bound perennial-reach daily volumes are consistent in both high and low ET time periods, while all-stream upper-bound estimates vary somewhat from year to year during the summer months (Fig. 10). More variability in daily volumes is seen in the lower-bound MODIS-EVI estimates, owing to variability in study-area rainfall (both temporally and spatially). While the rates of groundwater ET from all named streams in the study area are similar to rates from perennial reaches of streams (Fig. 9), the volume estimates are substantially different (Fig. 10), underscoring the necessity of accurately defining areas where groundwater ET is expected to occur in order to accurately estimate groundwater budgets. ET estimated by the MODFLOW-EVT package is constant during the several-months stress periods of the regional groundwater-flow model, and thus does not reveal a seasonal pattern. The average daily volume of MODFLOW-estimated ET of about 31,318 $m^3$/d is similar to the mean upper-bound MODIS-EVI daily rate for perennial reaches of streams of 31,257 $m^3$/d.

Annual volumes of MODIS-EVI ET are about a factor of 3 higher for all streams versus only perennial reaches of streams for both upper and lower-bound estimates, reflecting the increased ET-area in the all-streams estimate (Table 2). MODIS-EVI annual ET volumes do not differ much from the 2000–2010 mean. All annual volumes are within 12% of the overall mean, except for the 2004 lower-bound estimates which are 20% and 17% lower for all streams and perennial streams, respectively, probably reflecting increased precipitation during high ET time periods. Average annual ET of $11.38 \times 10^6$ $m^3$ for MODFLOW-simulated ET is comparable to the average annual estimate of $11.41 \times 10^6$ $m^3$ for upper-bound MODIS-EVI ET for perennial streams (Table 2).

An important benefit of a groundwater-flow model is that all groundwater budget components must balance during simulations; thus the MODFLOW-EVT estimate, while unverifiable in its absolute accuracy, is at least constrained by other budget inputs

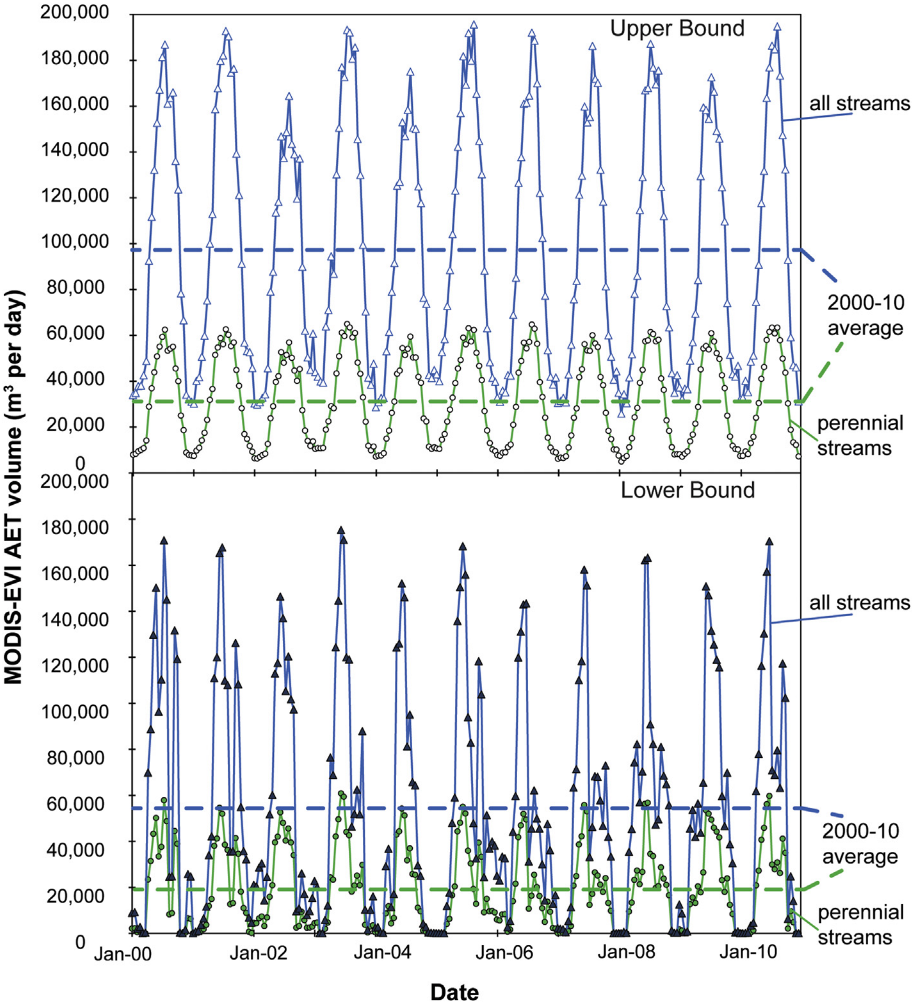


**Fig. 10.** Daily volume and 2000–10 average daily volume of actual ET (AET) in the Verde Valley, Arizona, study area estimated by the MODIS-EVI method for riparian areas near all named streams in the study area (all streams) and for riparian areas near only perennial streams in the study area (perennial streams). All ET demand is satisfied by groundwater in upper bound ET estimates while ET demand is first satisfied by precipitation and then by groundwater in lower bound ET estimates.

**Table 2**
Annual volume of evapotranspiration (ET) in the Verde Valley, Arizona, study area estimated by the MODIS-EVI method and simulated by the MODFLOW EVT ET package.

| Year | Upper-bound ET | | Lower-bound ET | | Simulated |
|---|---|---|---|---|---|
| | All streams ( $\times 10^6$ m$^3$) | Perennial streams ( $\times 10^6$ m$^3$) | All streams ( $\times 10^6$ m$^3$) | Perennial streams ( $\times 10^6$ m$^3$) | MODFLOW ET ( $\times 10^6$ m$^3$) |
| 2000 | 35.8 | 11.3 | 21.2 | 7.1 | 11.44 |
| 2001 | 39.6 | 12.2 | 21.0 | 6.9 | 11.42 |
| 2002 | 32.5 | 10.4 | 20.4 | 7.0 | 11.38 |
| 2003 | 38.7 | 12.5 | 22.2 | 7.7 | 11.40 |
| 2004 | 33.6 | 10.9 | 16.1 | 5.8 | 11.39 |
| 2005 | 40.0 | 12.5 | 22.5 | 7.5 | 11.39 |
| 2006 | 34.2 | 11.0 | 18.3 | 6.2 | 11.34 |
| 2007 | 34.3 | 10.9 | 18.5 | 6.5 | 11.33 |
| 2008 | 34.5 | 10.9 | 19.6 | 6.9 | 11.35 |
| 2009 | 33.9 | 11.0 | 21.7 | 7.6 | 11.35 |
| 2010 | 36.5 | 11.8 | 20.2 | 7.3 | 11.34 |
| 2000–10 average | 35.8 | 11.4 | 20.2 | 7.0 | 11.38 |

and outputs that were deemed reasonable by the modelers. Use of the upper-bound MODIS-EVI ET estimate for perennial streams of 11.41 × $10^6$ m$^3$ in place of the MODFLOW-simulated ET would have minimal impacts on the overall groundwater budget of the area. However, using other MODIS-EVI average annual values instead of the ~11.4 × $10^6$ m$^3$ MODFLOW-EVT and MODIS-EVI upper-bound, perennial streams estimate in groundwater budgets of the area would require net changes from 4.4 × $10^6$ m$^3$ (lower-bound, perennial stream estimate) to over 24.4 × $10^6$ m$^3$ (upper-bound, all streams estimate) in other groundwater-budget components to balance groundwater inputs and outputs.

The accuracy of MODIS-based estimates of ET in the study area is limited by the resolution of the remote sensing data. In this study, EVI was available at a resolution of 250 m × 250 m, which is coarse relative to the narrow riparian corridors along the Verde River and tributaries; non-riparian areas are typically included in the 250 m × 250 m gridded data. Because isolation of target environments is important for accuracy, ET estimates could be improved by using aerial or satellite imagery to accurately delineate riparian ET areas that consume groundwater. In the absence of a finer resolution of riparian areas, the MODFLOW-EVT and the perennial streams MODIS-EVI methods tend to produce similar ET results. The accuracy of the two methods cannot currently be determined owing to the difficulty of scaling up ET measurements from ground methods to the basin scale (Glenn et al., 2007), although the agreement of two independent methods may lend some credence to both and may be an indication of their suitability for the study area.

## 4. Summary and conclusions

Two methods for estimating basin-scale soil-moisture ET and two methods for estimating riparian groundwater ET in the Verde Valley, Arizona, study area were described and results compared. ET estimates were produced in the basin characteristics (BCM) and soil-water balance (SWB) groundwater recharge models. In the BCM estimation of ET, modeled solar radiation is combined with air temperature and converted to net radiation and soil heat flux, which are then used in the Priestley–Taylor relation to estimate PET. The SWB estimates PET from incoming solar radiation, mean temperature, extraterrestrial radiation, and measured temperature range using the Hargreaves–Samani relation. SWB also estimates AET by accounting for the amount of PET that can be satisfied by soil-water capacity. A base-case SWB AET estimate was bounded by low and high estimates that evaluate the effect of root-zone depth on soil-water capacity. Soil-moisture PET results indicated higher monthly rates and greater variability, particularly in warmer months, in SWB PET estimates than in BCM estimates. Higher rates in SWB PET estimates resulted in an average annual PET volume about 17% greater than for the BCM over the 1980–2009 time period of comparison. PET rates from both methods are substantially greater than published actual ET values. BCM PET, which is used in the estimation of groundwater recharge in the BCM model, was, as expected, substantially higher than SWB AET, which is used in the estimation of groundwater recharge in the SWB model. SWB AET rates are similar to published rates for ponderosa pine forests near the study area (Dore et al., 2012; Ha et al., 2014). Annual BCM PET volume was greater by about a factor of 2 or more than SWB AET estimates. All other inputs and outputs being equal, greater ET in a water-balance recharge model would result in lower estimates of groundwater recharge.

Riparian groundwater ET was estimated in the study area using a method that combines MODIS-EVI remote sensing data and geospatial information. A lower bound on the MODIS-EVI ET estimate was developed by assuming that ET demand was first satisfied by precipitation before groundwater was used. Upper and lower bound groundwater ET from the MODIS-EVI method was estimated for riparian areas along all streams in the study area and separately for only perennial reaches of these streams. Riparian groundwater ET also was estimated by the MODFLOW-EVT ET package as part of a regional groundwater-flow model that includes the study area. The every-16-day MODIS-EVI ET method produced monthly rates that demonstrate a seasonal pattern, while MODFLOW ET remained unchanged during the months long stress periods of the groundwater-flow model. Lower-bound monthly ET rates from the MODIS-EVI method were near zero during cooler months when sufficient precipitation satisfied all of the reduced ET demand. Lower-bound rates in warmer summer months were less than upper-bound rates, with greater differences seen during summer months when rainfall satisfied more of the ET demand. Annual ET volumes were about same for the upper-bound MODIS-EVI ET for perennial streams as for the MODFLOW ET estimates, with the small differences between the two methods probably having minimal impact on annual or longer groundwater budgets for the study area. Groundwater budgets using other MODIS-EVI ET estimates would require net changes from 4.4 × $10^6$ $m^3$ to over 24.4 × $10^6$ $m^3$ in other groundwater-budget components to balance groundwater inputs and outputs.

## Acknowledgments

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