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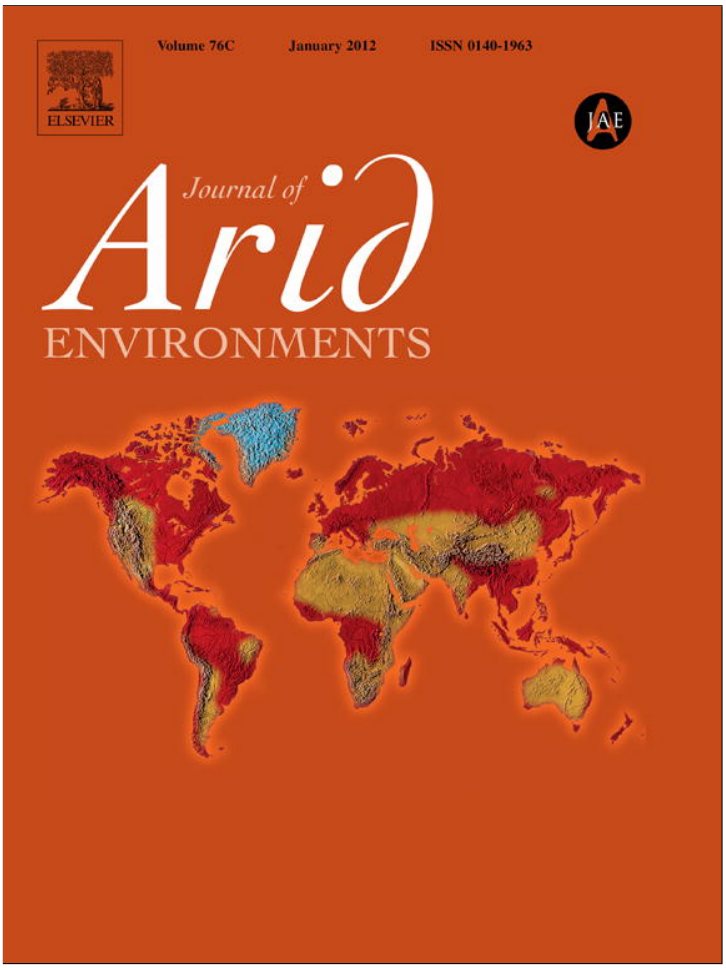

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Journal of Arid Environments 82 (2012) 44–52

Contents lists available at SciVerse ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

A simple method for estimating basin-scale groundwater discharge by vegetation in the basin and range province of Arizona using remote sensing information and geographic information systems

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ARTICLE INFO

Article history:
Received 4 April 2011
Received in revised form
11 January 2012
Accepted 11 February 2012
Available online xxx

Keywords:
Evapotranspiration
Groundwater
Remote sensing
Riparian water use
Semi-arid environments

ABSTRACT

Groundwater is a vital water resource in the arid to semi-arid southwestern United States. Accurate accounting of inflows to and outflows from the groundwater system is necessary to effectively manage this shared resource, including the important outflow component of groundwater discharge by vegetation. A simple method for estimating basin-scale groundwater discharge by vegetation is presented that uses remote sensing data from satellites, geographic information systems (GIS) land cover and stream location information, and a regression equation developed within the Southern Arizona study area relating the Enhanced Vegetation Index from the MODIS sensors on the Terra satellite to measured evapotranspiration. Results computed for 16-day composited satellite passes over the study area during the 2000 through 2007 time period demonstrate a sinusoidal pattern of annual groundwater discharge by vegetation with median values ranging from around 0.3 mm per day in the cooler winter months to around 1.5 mm per day during summer. Maximum estimated annual volume of groundwater discharge by vegetation was between 1.4 and 1.9 billion m^3 per year with an annual average of 1.6 billion m^3. A simplified accounting of the contribution of precipitation to vegetation greenness was developed whereby monthly precipitation data were subtracted from computed vegetation discharge values, resulting in estimates of minimum groundwater discharge by vegetation. Basin-scale estimates of minimum and maximum groundwater discharge by vegetation produced by this simple method are useful bounding values for groundwater budgets and groundwater flow models, and the method may be applicable to other areas with similar vegetation types.

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1. Introduction

The U.S. Geological Survey (USGS) Water Availability and Use Pilot Program – Southwest Alluvial Basins project was established in 2006 to investigate groundwater availability in the basin and range province of the arid to semi-arid southwestern U.S. state of Arizona (Fig. 1). Groundwater conditions and budgets for basins in the study area were a major focus of the project (Tillman and Leake, 2010; Tillman et al., 2011). Estimates of groundwater budgets at the basin scale are important for the development of groundwater flow models that may be used to predict the effects of future management actions (for example, expanded or increased pumping, development of aquifer storage facilities, etc.) and climate change on groundwater availability. Additionally, the 1980 Arizona Groundwater Management Act mandates that the Phoenix, Tucson, and Prescott Active Management Areas achieve a balancing of groundwater withdrawals with recharge by the year 2025 (Colby and Jacobs, 2007). Achieving this "safe yield" will depend upon an accounting of recharge and other inputs and withdrawals from groundwater systems in these basins. Discharge of groundwater by phreatophyte vegetation is a major component of groundwater budgets for basins in the study area (Anderson, 1995; Tillman et al., 2011). This manuscript presents the development of a simple method of determining a bounding estimate of basin-scale groundwater discharge by vegetation in southern and central Arizona.

1.1. Study area

The study area for this investigation covers over 190,000 km^2 and is located in the southwestern United States, in the region of

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0140-1963/$ – see front matter Published by Elsevier Ltd.
doi:10.1016/j.jaridenv.2012.02.010

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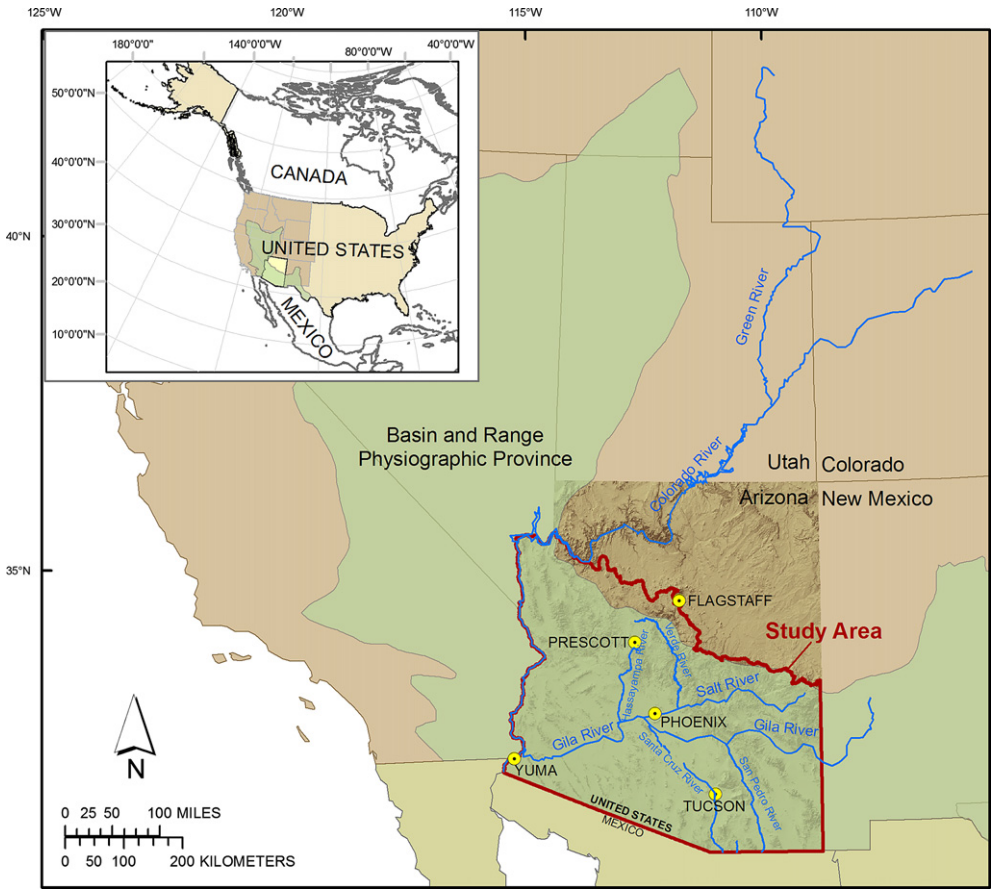

Fig. 1. Study area for the estimation of groundwater discharge by vegetation as part of the USGS Water Availability and Use Pilot Program – Southwest Alluvial Basins project.

the Basin and Range Physiographic Province (Fenneman, 1931) that lies within the state of Arizona (Fig. 1). Tectonic activities associated with the Basin and Range disturbance formed these basins, typified by broad, gently sloping valleys separated by sharply rising mountain ranges (Anderson et al., 1992). Basin fill is composed primarily of erosional material from surrounding mountains. Climate in the area is arid to semi-arid with a range in precipitation conditions that is primarily related to altitude. Mean annual precipitation ranges from less than 75 mm per year near Yuma in the southwestern part of the study area to greater than 1000 mm per year in the high-elevation headwaters of the Salt River (Fig. 2; PRISM Group, 2008). There are two distinct precipitation seasons in the study area: a summer season of high-intensity, short duration thunderstorms covering small areas and a winter season of low intensity, long duration frontal systems covering large areas (Anderson et al., 1992). Owing to greater precipitation at higher elevations, aquifer recharge in the area is generally mountain-block and mountain-front recharge with some focused stream channel recharge along washes that drain mountainous areas (Stonestrom et al., 2007). Groundwater is often located deeper than 50 m below land surface in central areas of alluvial basins in the study area, with some locations that have experienced extensive groundwater pumping having depths greater than 150 m (Tillman et al., 2007). However, near-surface groundwater is often located beneath and adjacent to surface-water drainages in the basins (Fig. 3; Arizona Department of Water Resources, 2009; U.S. Geological Survey, 2010a). Major surface drainages in the study area include the Gila, Salt, and Verde Rivers, with associated perennial and intermittent tributaries (Fig. 1) and ephemeral washes that flow in response to precipitation. Perennial riparian vegetation is located along surface drainages in the study area and provides a critical habitat for many species. Woody and herbaceous plant species in riparian areas of Arizona include saltcedar (*Tamarix* spp.), Fremont Cottonwood (*Populus fremontii*), Arizona Ash (*Fraxinus velutina*), Desert (*Chilopsis linearis*) and Goodding's (*Salix gooddingii*) Willow, Arizona Walnut (*Juglans major*), and sedges (*Carex* spp.), rushes (*Juncus* spp.), spikerushes (*Eleocharis* spp.), and bulrushes (*Scirpus* spp.), among others (University of Arizona, 2006).

1.2. Estimation of evapotranspiration by remote sensing

Several approaches for estimating evapotranspiration (ET) by satellite remote sensing have been developed. The most common approaches have utilized thermal infrared (TIR; ca. 8–14 μm wavelength) sensors on satellites (Kalma et al., 2008; Kustas and Anderson, 2009). These methods are based on solving a simplified form of the surface energy balance (SEB) equation, and estimating the latent heat of evaporation of water in ET as a residual of the equation after estimating sensible heat flux by the difference between air temperature and land surface temperature. Alternatively, vegetation index (VI) methods estimate the plant transpiration component of ET by the amount of green foliage on the land surface as detected by satellite imagery (reviewed in Glenn et al., 2007, 2010; Kalma et al., 2008). Often these methods use time-series imagery from frequent-return satellites to project ET over months and years and over large landscape units, similar to the goals of the present research.

VIs and related products use combinations of visible and near infrared (NIR; ca. 850 nm wavelength) bands (Bannari et al., 1995;

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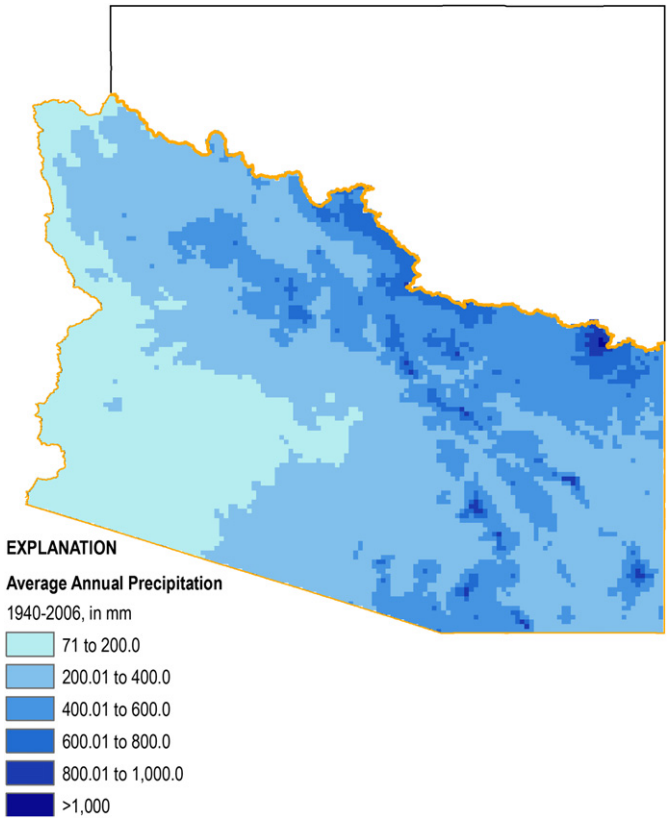

Fig. 2. Mean annual precipitation in the study area for the 1940–2006 time period (PRISM Group, 2008).

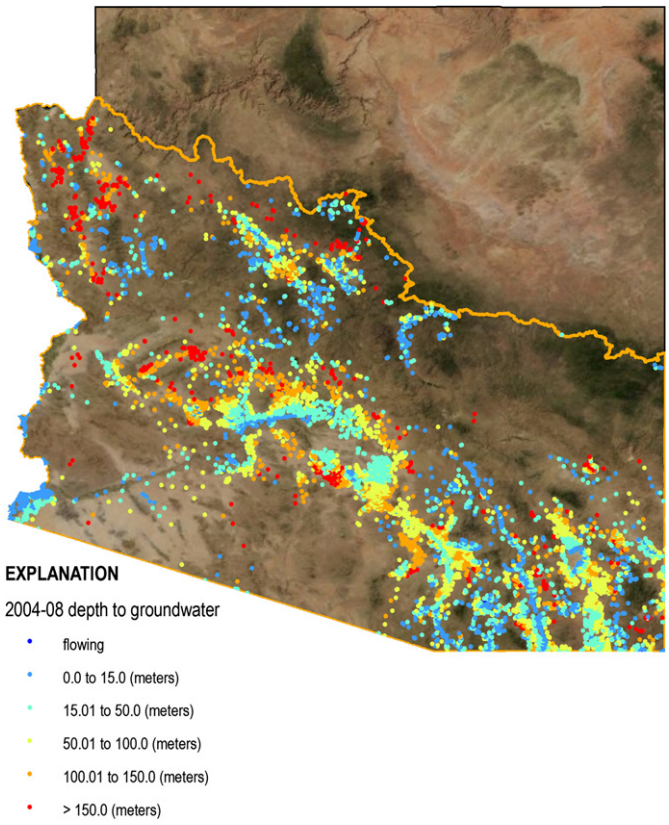

Fig. 3. Depth to groundwater from wells with observations between 1/1/2004 and 12/31/2008 (Arizona Department of Water Resources, 2009; U.S. Geological Survey, 2010a).

Huete et al., 2002). Most VIs ratio the reflectance of light in adjacent Red and NIR bands to provide a measure of absorption of red light by chlorophylls *a* and *b* and reflectance or scattering of NIR by cell wall constituents and the well-structured layers of leaf cells in canopies. Numerous studies (reviewed in Glenn et al., 2007) have reported a strong correlation between VIs and ET over a wide variety of biomes. VI methods require ancillary meteorological data to estimate potential ET (ET_o) over the area of interest, and should be calibrated with ground ET measurements for maximum accuracy. At its simplest, the relationship between ET and a VI is expressed as:

$$ET = ET_o(VI^*) \tag{1}$$

where VI^* is a VI stretched between bare soil (0) and fully transpiring vegetation (1.0) (Groeneveld et al., 2007; Groeneveld and Baugh, 2007). Other methods to evaluate direct evaporation from groundwater include calculating upward soil capillary flux from the water table (for example, Fan and Miguez-Macho, 2010) and performing soil water balance computations on detailed, frequently observed hydrological datasets (for example, Yeh and Famiglietti, 2009). The focus of this project, however, is the development of a simple method of determining a bounding estimate of basin-scale groundwater discharge by vegetation in an area where such detailed soil moisture and water-table depth information is not available. Groundwater ET in this manuscript will, therefore, refer only to ET from groundwater-using plant communities and not to bare-soil groundwater evaporation.

2. Methods

Average annual groundwater discharge by vegetation was estimated for the Southwest Alluvial Basins in Arizona for the period 2000–2007 by first estimating ET throughout the study area, then selecting subset areas where the water for this ET is presumed to be derived primarily from groundwater. 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 groundwater discharge by vegetation.

2.1. Estimation of vegetation ET

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, 2008) in multiple 275 km × 185 km bands and combined using a mosaic tool to cover the study area (Fig. 4). Near-daily satellite passes provided 250 m × 250 m resolution EVI data composited over 16 day intervals over the 2000 through 2007 time period (Fig. 4, Table 1). EVI was used over more traditional indices like Normalized Difference Vegetation Index (NDVI) because it does not saturate at high levels of greenness (Huete et al., 2002), maintains sensitivity over dense vegetation conditions, and uses the 500 m blue band to remove residual atmospheric contamination caused by smoke and thin clouds (U.S. Geological Survey, 2010b). MODIS products are preprocessed to correct for atmospheric, sensor, and sun-angle effects and are calculated from at-surface reflectance values as described in Huete et al. (2011). EVI is calculated from red, blue, and NIR bands:

$$EVI = G\frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + C_1 \times \rho_{red} - C_2 \times \rho_{blue} + L} \tag{2}$$

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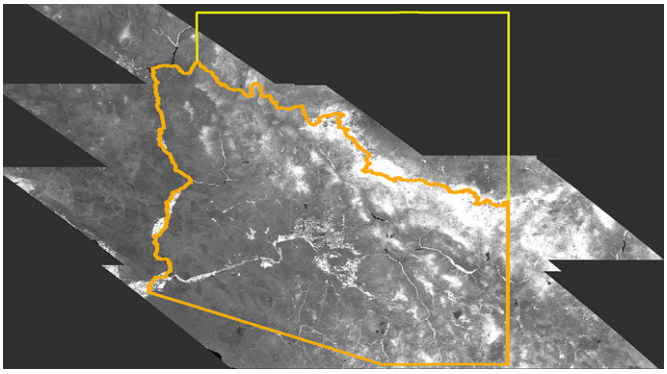

Fig. 4. Example of unprocessed MODIS Enhanced Vegetation Index data from Terra and Aqua satellite passes mosaiced to cover the study area.

where G is a gain factor (set at 2.5); ρ_{NIR}, ρ_{red}, and ρ_{blue} are atmospherically corrected surface reflectances of near infrared, red, and blue bands; L is the canopy background adjustment (set at 1.0); and C_1 and C_2 are the coefficients designed to correct for aerosol resistance in the red band (set at 6 and 7.5, respectively).

ET (mm/day) was calculated in ArcGIS™ on 250 m × 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):

$$ET = 1.22ET_o \times EVI^* \quad (3)$$

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). Plants included in the regression were alfalfa (the most common crop along the river), saltcedar (the most common riparian species), cottonwoods, and arrowweed, all common species throughout the current study area. Eq. (3) had a root mean square error of 20% of the mean across species, within the range of accuracy of the ground methods by which ET was measured.

ET_o was estimated on a monthly basis using a modified Blaney–Criddle relation (Doorenbos and Pruitt, 1977):

$$ET_o = p(0.46T_{mean} + 8) \quad (4)$$

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, 2008). The simplified Blaney–Criddle equation for ET_o was used rather than the more complete Penman–Monteith formulation because it provided a significantly higher coefficient of determination between EVI and measured ET (Nagler and Glenn, 2009; Nagler et al., 2009), and because it can be calculated from temperature data, which is widely available from cooperative weather reporting stations throughout the state, whereas the Penman–Monteith equation requires wind speed, net radiation and relative humidity, available for fewer sites in the state.

EVI is converted to a scaled value (EVI^*) following the relation of Nagler et al. (2005):

$$EVI^* = 1 - (0.542 - EVI)/(0.542 - 0.091) \quad (5)$$

where 0.542 and 0.091 represent maximum and minimum EVI values, respectively, from a large dataset of riparian plant communities in the southwestern U.S. (Dennison et al., 2009; Nagler et al., 2005). These same riparian plant communities are found throughout the current study area. Note that Eq. (3) is the same as Eq. (1), validated by Groeneveld et al. (2007) for phreatophytes in southwestern riparian and upland communities, except for the coefficient 1.22. This coefficient was required because ET_o calculated by Blaney–Criddle is about 10% lower than by the Penman–Monteith equation used in Eq. (1), and because the maximum value of EVI (0.542) was about 10% lower than EVI values for alfalfa, used as the reference crop for ET_o in Groeneveld et al. (2007).

Table 1
Dates of MODIS-EVI data used in groundwater discharge by vegetation analyses.

Dates					
1-Jan-00[a]	9-May-01	14-Sep-02	17-Jan-04	25-May-05	30-Sep-06
17-Jan-00[a]	25-May-01	30-Sep-02	2-Feb-04	10-Jun-05	16-Oct-06
2-Feb-00[a]	10-Jun-01	16-Oct-02	18-Feb-04	26-Jun-05	1-Nov-06
18-Feb-00[a]	26-Jun-01	1-Nov-02	5-Mar-04	12-Jul-05	17-Nov-06
5-Mar-00	12-Jul-01	17-Nov-02	21-Mar-04	28-Jul-05	3-Dec-06
21-Mar-00	28-Jul-01	3-Dec-02	6-Apr-04	13-Aug-05	19-Dec-06
6-Apr-00	13-Aug-01	19-Dec-02	22-Apr-04	29-Aug-05	1-Jan-07
22-Apr-00	29-Aug-01	1-Jan-03	8-May-04	14-Sep-05	17-Jan-07
8-May-00[b]	14-Sep-01	17-Jan-03	24-May-04	30-Sep-05	2-Feb-07
24-May-00	30-Sep-01	2-Feb-03	9-Jun-04	16-Oct-05	18-Feb-07
9-Jun-00	16-Oct-01	18-Feb-03	25-Jun-04	1-Nov-05	6-Mar-07
25-Jun-00	1-Nov-01	6-Mar-03	11-Jul-04	17-Nov-05	22-Mar-07
11-Jul-00	17-Nov-01	22-Mar-03	27-Jul-04	3-Dec-05	7-Apr-07
27-Jul-00	3-Dec-01	7-Apr-03	12-Aug-04	19-Dec-05	23-Apr-07
12-Aug-00[b]	19-Dec-01	23-Apr-03	28-Aug-04	1-Jan-06	9-May-07
28-Aug-00	1-Jan-02	9-May-03	13-Sep-04	17-Jan-06	25-May-07
13-Sep-00	17-Jan-02	25-May-03	29-Sep-04	2-Feb-06	10-Jun-07
29-Sep-00	2-Feb-02	10-Jun-03	15-Oct-04	18-Feb-06	26-Jun-07
15-Oct-00	18-Feb-02	26-Jun-03	31-Oct-04	6-Mar-06	12-Jul-07
31-Oct-00	6-Mar-02	12-Jul-03	16-Nov-04	22-Mar-06	28-Jul-07
16-Nov-00	22-Mar-02	28-Jul-03	2-Dec-04	7-Apr-06	13-Aug-07
2-Dec-00	7-Apr-02	13-Aug-03	18-Dec-04	23-Apr-06	29-Aug-07
18-Dec-00[b]	23-Apr-02	29-Aug-03	1-Jan-05	9-May-06	14-Sep-07
1-Jan-01	9-May-02	14-Sep-03	17-Jan-05	25-May-06	30-Sep-07
17-Jan-01	25-May-02	30-Sep-03	2-Feb-05	10-Jun-06	16-Oct-07
2-Feb-01	10-Jun-02	16-Oct-03	18-Feb-05	26-Jun-06	1-Nov-07
18-Feb-01[b]	26-Jun-02	1-Nov-03[b]	6-Mar-05	12-Jul-06	17-Nov-07
6-Mar-01	12-Jul-02	17-Nov-03	22-Mar-05[b]	28-Jul-06	3-Dec-07
22-Mar-01	28-Jul-02	3-Dec-03	7-Apr-05	13-Aug-06	19-Dec-07[a]
7-Apr-01	13-Aug-02	19-Dec-03	23-Apr-05[b]	29-Aug-06	
23-Apr-01	29-Aug-02	1-Jan-04	9-May-05	14-Sep-06	

[a] MODIS data unavailable. Values used in analyses were averages computed for same day in other available years in date range.
[b] MODIS data unavailable. Values used in analyses were averages of value of MODIS observation before and after unavailable date.

2.2. Areas of groundwater discharge by vegetation

Groundwater discharge by vegetation was estimated from the ET method described above by defining geographic areas of presumed groundwater-using vegetation. For this study, a combination of proximity to surface-water drainages and land cover types was used to define these areas. First, a 50-m buffer was created around all named surface-water drainages in the study area using GIS tools (Fig. 5; Arizona State Land Department, 1993). The 50-m buffer distance was selected based on analyses of satellite and aerial photography of the surface-water drainages in the study area and adequately encompasses riparian vegetative areas in most of the state. The impact of this choice of buffer distance on computed discharge volumes is addressed in the results section below. 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

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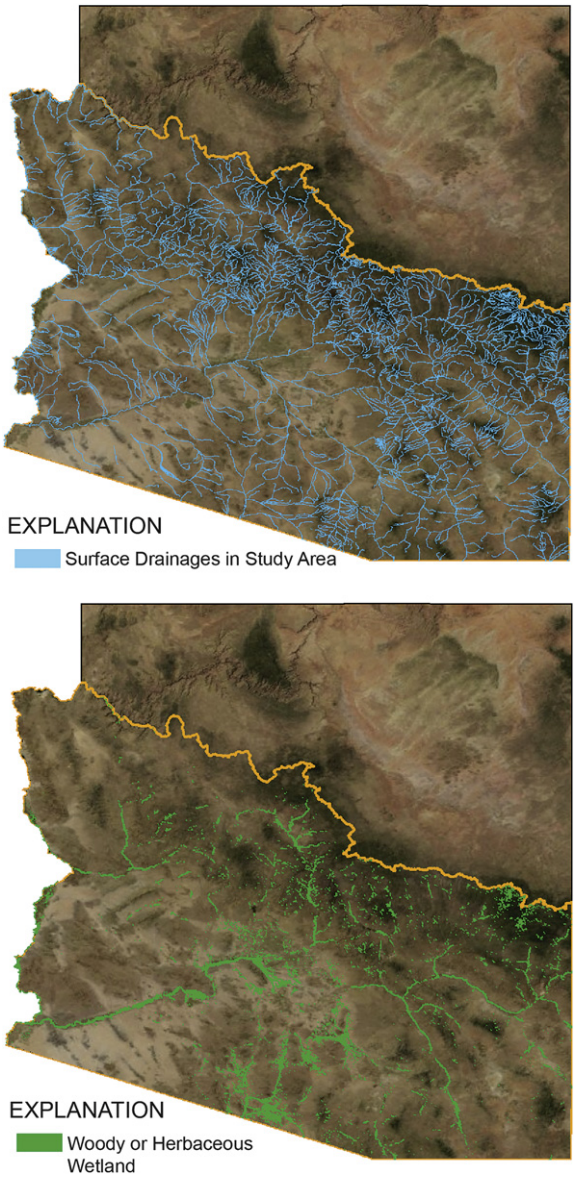

Fig. 5. Location of named surface drainages (upper panel) and woody or herbaceous wetland vegetation types from the 2001 National Land Cover Dataset (lower panel) used to define areas of groundwater discharge by vegetation for this study. Surface drainage and wetland vegetation locations are sized to be visible on these maps and are not to scale.

areas are 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. 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 (Fig. 5). Herbaceous wetland is defined in NCLD as land in which the soil or substrate is periodically saturated or inundated with water and which is covered by more than 80% perennial herbaceous vegetation, and woody wetland is defined as land in which the soil or substrate is periodically saturated or inundated with water and which is covered by more than 20% forest or shrubland. While most of the herbaceous and woody wetland vegetation was located near surface-water drainages, these areas were added to the stream buffer to account for reaches along major rivers where groundwater-using vegetation extends greater than 50 m from the centerline of the river channel, particularly along certain reaches of the Gila and Colorado Rivers (Figs. 1 and 5).

Computed groundwater-discharge-by-vegetation grid cells of 250 m × 250 m using Eqs. (3)–(5) were downsampled in ArcGIS to 50 m × 50 m using nearest neighbor interpolation for further analyses (Fig. 6). The 50 m × 50 m grid values that were spatially associated with the combined stream buffer and land cover areas were extracted for computation of summary statistics. Both the extraction of grid cells and computation of summary statistics were performed using Python scripting in the ArcGIS environment. Negative values of computed groundwater discharge by vegetation using Eq. (5) are the result of EVI values that fall below the scaled range observed by Nagler et al. (2005) in the development of the regression equation, and occur mainly in areas of open water or sparse vegetation. These values, making up only 2.2% of the grid cells for the study area during the 2000–2007 time period, were set to zero for basin-scale summary statistics of discharge.

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 correlation analysis between computed groundwater discharge by vegetation and PRISM precipitation data (PRISM Group, 2008) was performed. A lower bound on estimated groundwater discharge by vegetation for the study area was then developed by subtracting out monthly precipitation from monthly vegetation discharge estimates developed in this study.

3. Results and discussion

Computed annual volume of groundwater discharge by vegetation for the Southwest Alluvial Basins in Arizona ranged from a low of 1.37 billion m^3 to a high of 1.94 billion m^3, with an annual average of 1.59 billion m^3 during the 2000–2007 time period (Table 2). To put this number in perspective, this average groundwater discharge by vegetation value represents 54% of total groundwater pumpage in the study area in 2005 for all water uses including agricultural, municipal, and industrial (Tillman et al., 2011). Computed daily groundwater discharge by vegetation from 16-day MODIS satellite passes follow a cyclical pattern of low discharge volumes in the cooler, winter months and higher discharge volumes in summer months, with intermediate values occurring between these seasons (Fig. 7). Daily computed volumes range from lows of 1.2–2.3 million m^3 to highs of 6.9–9.0 million m^3 (Fig. 7, Table 3). Dates of minimum and maximum daily computed groundwater discharge by vegetation were fairly consistent throughout the 2000–2007 time period, with minimums occurring on January 17th for most years and maximums occurring from mid July through late August (Table 3). The periodicity of daily discharge volumes appears stable during the time period of investigation and no pattern in shifting dates or magnitudes of minimum or maximum daily discharge volumes is evident (Fig. 7). Fairly constant annual volumes of vegetation discharge during the study period supports the premise that groundwater is the primary source of water for vegetation in these areas, as precipitation is much more variable during this time period. Average annual precipitation in the study area ranges from 43% below the 2000–2006 mean in 2002 to 53% above the mean in 2005 (PRISM Group, 2008; Tillman et al., 2011).

The distribution of the rate of groundwater discharge by vegetation in individual 50-m raster cells during low and high discharge times of the year, represented by the 17th and 209th day of the calendar year respectively, remains fairly consistent during the study period (Fig. 8). Median winter rates of computed

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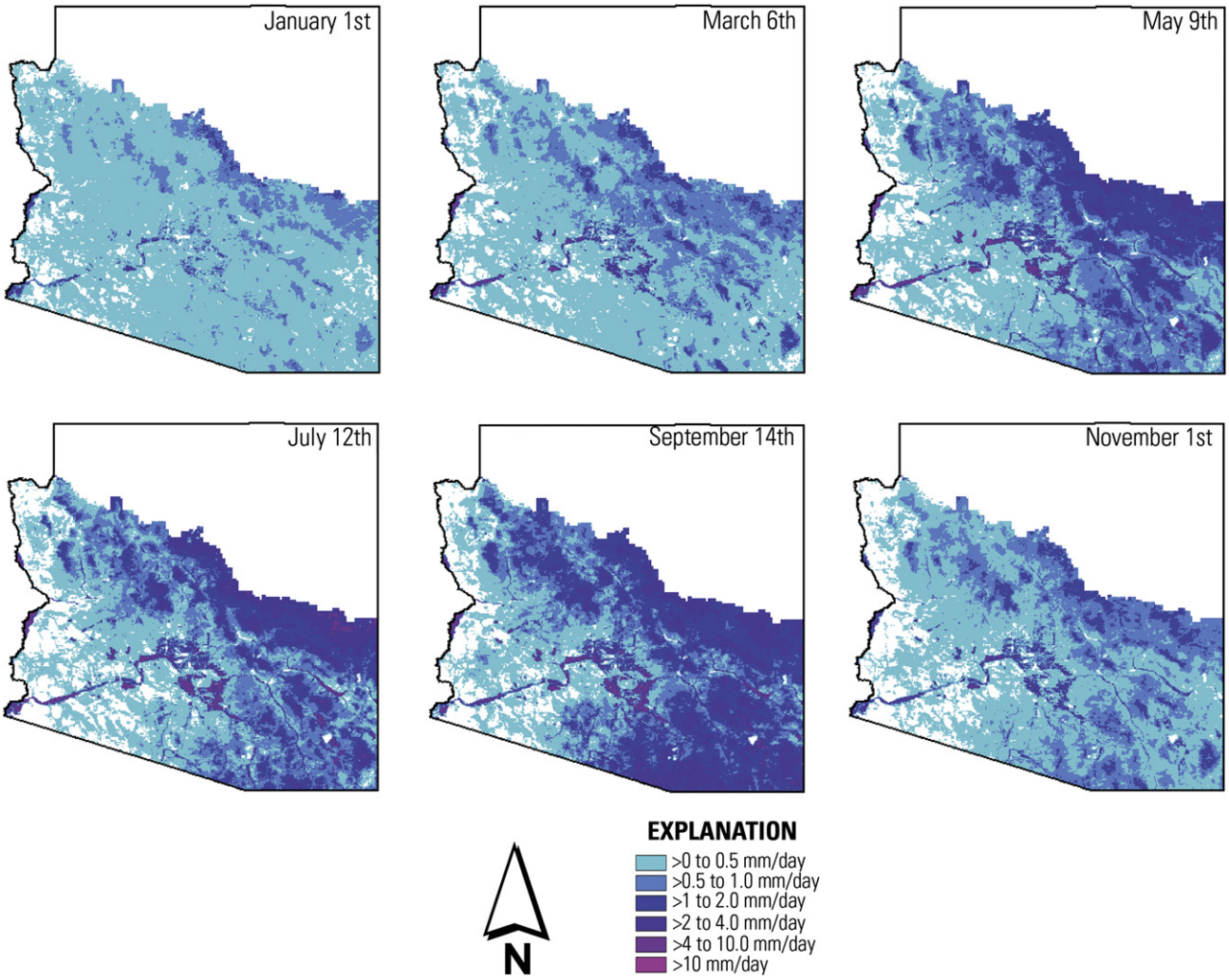

Fig. 6. Example rasters of estimated ET for the entire study area (i.e., not only groundwater ET) for dates shown in 2007.

groundwater discharge by vegetation grid values range from 0.2 to 0.5 mm per day, with somewhat higher median, 25th and 75th percentiles noted during 2001 and 2005 (Fig. 8). Median summer rates of computed discharge are consistently between 1.3 and 1.9 mm per day, 3–5 times the winter median rates.

The impact of the choice of a 50-m surface-drainage buffer area on computed volumes of groundwater discharge by vegetation was investigated by comparing the results with discharge volumes computed with a 75-m buffer. This 50% increase in buffer area around surface drainages produced an increase of groundwater discharge by vegetation of only 33%, indicating a non-linear dropping off of vegetated greenness away from the drainages. Although the 50-m buffer appears adequate for this simple method used to estimate bounding ET values for this study, future refinement of the selected areas of groundwater-using vegetation may include a basin-by-basin delineation of riparian areas from aerial or satellite photos.

Table 2
Computed annual volume of groundwater discharge by vegetation from 2000 through 2007 for the areas indicated.

Year	Study Area [$\times 10^9$ m^3]	Sierra Vista Subwatershed [$\times 10^6$ m^3]
2000	1.542	13.1
2001	1.513	15.3
2002	1.372	11.8
2003	1.666	11.5
2004	1.475	11.3
2005	1.942	12.2
2006	1.652	14.3
2007	1.587	13.9
2000–07 average	1.594	12.9

Volumes of computed groundwater discharge by vegetation were compared with published values for both the study area as a whole and for a smaller-scale subwatershed area within the study area. The 2000–2007 average discharge volume of 1.59 billion m^3 for the study area is comparable to an estimate adapted from Freethey and Anderson (1995) of 1.48 billion m^3 (Tillman et al., 2011). At a smaller scale, estimates were compared with the extensively studied Sierra Vista Subwatershed in the southeastern portion of the State of Arizona (Fig. 9). This area contains the federally protected San Pedro Riparian National Conservation Area, a riparian corridor that is a critically important flyover for migrating bird species. Owing to its protected status and ecological importance, this basin has been extensively investigated, including several studies of riparian ET. Estimates of annual volume of groundwater ET for the Sierra Vista Subwatershed using methods from the current study range from 11.3 to 15.3 million m^3, with an average of 12.9 million m^3 for 2000–2007 (Table 2). These values are comparable with results of annual ET volumes from other studies including 9.89 million m^3 (Corell et al., 1996),

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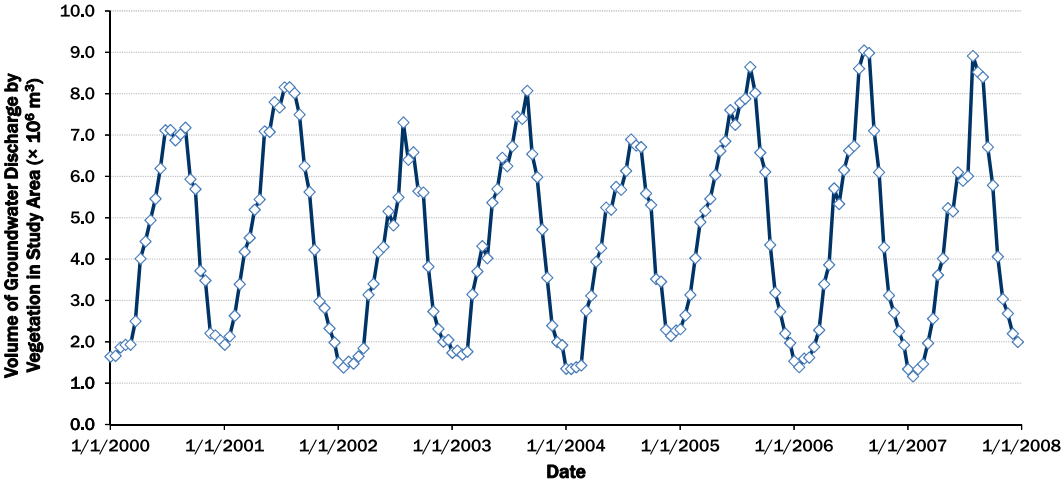

Fig. 7. Volume of estimated groundwater discharge by vegetation for the study area for 16-day composited MODIS satellite passes.

8.13 million m^3 (Goodrich et al., 2000), 11.8–14.9 million m^3 (Scott et al., 2006), and 14.1–16.5 million m^3 (Scott et al., 2008). The Goodrich et al. (2000) estimate only considers ET along the San Pedro River riparian corridor and not in other areas of the Sierra Vista Subwatershed.

3.1. Analysis of the contribution of precipitation

Monthly values of estimated groundwater discharge by vegetation computed in this study and precipitation (PRISM Group, 2008) were analyzed over all basins in the study area. Monthly values of precipitation varied widely, whereas groundwater discharge by vegetation followed a regular seasonal response curve. Correlation coefficients between monthly groundwater discharge by vegetation and precipitation were low and non-significant ($r = 0.182$, $P > 0.05$). The relationship was not improved by correlating groundwater discharge by vegetation with the previous months precipitation ($r = 0.189$, $P > 0.05$). Annual values of groundwater discharge by vegetation exceeded precipitation in all but one year ($P = 0.004$ by Paired *t*-Test). Year-to-year variability in precipitation (Coefficient of Variation = 0.19) was higher than variability in annual groundwater discharge by vegetation (Coefficient of Variability = 0.12), and correlation coefficients between annual groundwater discharge by vegetation and precipitation were low and non-significant ($P > 0.05$). These analyses indicate that vegetation in the areas defined as groundwater-using were at least partially decoupled from the seasonal and annual precipitation cycles, due to consumption of groundwater and effective storage of winter precipitation in the aquifer and vadose zone to support summer greenness.

A lower bound on groundwater discharge by vegetation was estimated by subtracting precipitation from the discharge results presented above, with raster cells resulting in negative values set to zero. This method assumes that all precipitation that falls on the groundwater-using areas is used by vegetation within the month with no losses from runoff or other processes. Lower-bound groundwater discharge by vegetation results for the study area varied from 164 mm yr^{-1} (2004) to 281 mm yr^{-1} (2005), with a mean value for the 2000–2007 time period of 220 mm yr^{-1}. This

Table 3
Dates of maximum and minimum volume of computed groundwater discharge by vegetation for study area.

Year	Date of Minimum ET	Minimum Volume ET [$\times 10^6$ m^3]	Date of Maximum ET	Maximum Volume ET [$\times 10^6$ m^3]
2000	January 1	1.644[a]	August 28	7.180
2001	January 1	1.932	July 28	8.158
2002	January 17	1.380	July 28	7.305
2003	February 2	1.694	August 29	8.070
2004	January 17	1.346	July 27	6.894
2005	January 1	2.305	August 13	8.647
2006	January 17	1.389	August 13	9.044
2007	January 17	1.165	July 28	8.914

[a] MODIS data unavailable. Values used in analyses were averages computed for same day in other available years.

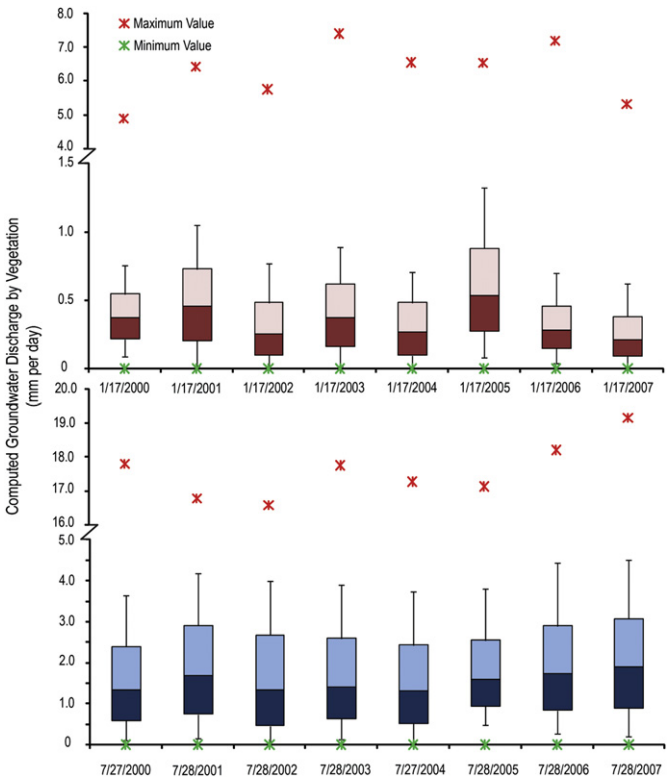

Fig. 8. Comparison of the distribution of computed groundwater discharge by vegetation values during low discharge (upper panel) and high discharge (lower panel) time periods from 2000 through 2007. Upper and lower whiskers represent 90th and 10th percentiles, respectively. Upper, middle, and lower lines on box represent the 75th percentile, median, and 25th percentile, respectively. Note broken vertical axis.

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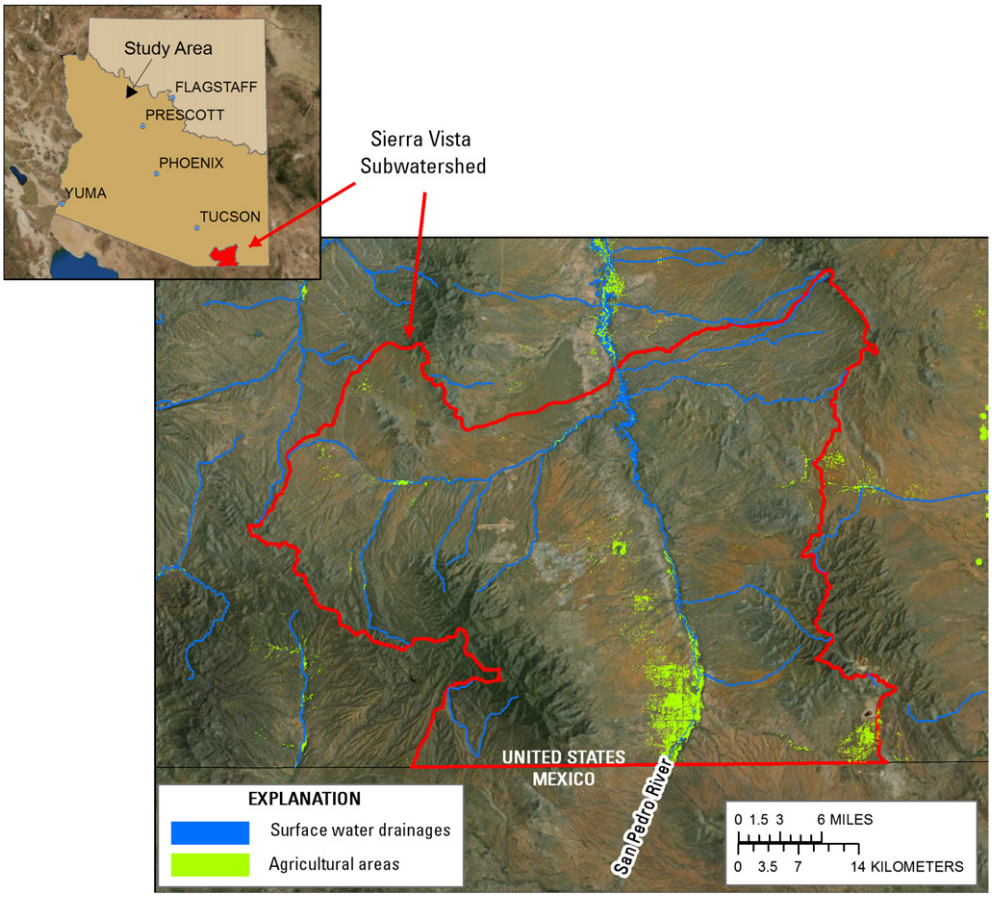

Fig. 9. The Sierra Vista Subwatershed within the study area, location where comparisons are made of estimated groundwater discharge by vegetation with other studies.

value is higher than an estimate of 87 mm yr^{-1} for a shrubby phreatophyte community in Colorado's San Luis Valley when the water table was 2.5 m beneath the soil surface (Cooper et al., 2006). However, it is lower than the 450 mm yr^{-1} estimated for the Upper San Pedro River in Arizona, a perennial river reach with a well-developed community of phreatophytic trees (Scott et al., 2006, 2008). The phreatophyte communities surveyed in the present study represent a wide variety of perennial and ephemeral drainages differing in vegetation density. The estimated lower-bound groundwater discharge by vegetation rate for the study area for 2000–2007 of 220 mm yr^{-1}, or a volume of 906 million m^3, should be considered a minimum estimate.

4. Summary and conclusions

Groundwater discharge by vegetation was estimated for the over 190,000 km^2 area of the Basin and Range Physiographic Province that lies within the state of Arizona, in the southwestern United States. EVI data from the EOS-1 MODIS sensor was acquired for 16-day satellite passes from 2000 through 2007. A relation developed within the study area between ET and EVI, temperature, and mean daytime hours was used to compute vegetation discharge in 250 m grid cells throughout the area. Results were downsampled to 50-m cells and a subset area was selected to represent groundwater-using vegetation with a 50-m buffer from all surface-water drainages minus land cover types of hay/pasture and cultivated crops plus land cover types of woody and herbaceous wetland vegetation. Average annual volume of groundwater discharge by vegetation for the study area was 1.6 billion m^3, a comparable number to previously reported values. A lower-bound estimate of 906 million m^3 was calculated by subtracting monthly precipitation values from the computed discharge estimates. The accuracy of remote sensing estimates of discharge is ultimately limited by the accuracy of the ground-based measurements by which they are validated or calibrated. As more ground data from flux towers becomes available, the accuracy of remote sensing methods can be expected to improve. However, satellite data are useful for basin-scale investigations because they cover large areas of land surface with a repeat sampling rate that is high enough to allow for estimates of seasonal and annual discharge variability, which cannot be easily achieved by point estimates measured on the ground, or by water balance studies of catchment areas. Basin-scale estimates of minimum and maximum groundwater discharge by vegetation produced by this simple method are useful bounding values for groundwater budgets and groundwater flow models, and the method may be applicable to other areas with similar vegetation types.

Acknowledgments

This project was supported by the USGS Water Availability and Use Pilot Program, Southwest Alluvial Basins project.

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