Evapotranspiration Dynamics and Effects on Groundwater Recharge and Discharge at an Arid Waste Disposal Site

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Abstract

Deserts have been used for waste disposal due to presumed low groundwater recharge. The US Department of Energy is evaluating groundwater flow and contaminant transport at a former uranium mill site near Tuba City, Arizona. They developed a groundwater flow model to determine how fast contaminants were moving towards a downgradient stream, Moenkopi Wash, used to irrigate crops. We used remote sensing algorithms and precipitation (PPT) data to estimate ET and the ET/PPT ratios within the 3513 ha groundwater model domain (GMD) from 2000-2012. ET and PPT were nearly balanced (125 mm yr^{-1} and 130 mm yr^{-1} , respectively). However, seasonal and interannual variability in ET and PPT were out of phase. Spatial variability in vegetation differentiated areas where ET was less than PPT (potential recharge areas) from those where ET exceeded PPT (potential discharge areas) within the GMD. ET estimates predicted that 0.2 million cubic meters per year of groundwater contributed to surface flows in Moenkopi Wash, supported by measurements of streamflow at the upstream and downstream boundaries of the GMD. Even small differences between ET and PPT can influence groundwater flow, hence land use practices that enhance discharge through ET can be part of an overall remediation strategy.

Keywords: desert soil, remote sensing, water balance, evapotranspiration, grazing, uranium mill tailings

1. Introduction

Arid and semiarid environments have been considered well suited for long-term isolation of radioactive and other hazardous wastes due to presumed low groundwater recharge (e.g., Winograd, 1981; Reith and Thompson, 1992). Chloride profiles and soil water potentials even suggest a net upward water flux over the past 10,000–15,000 years in deserts of the southwestern

United States (Scanlon et al., 2005). However, vegetation and soil properties can influence effects of climate on percolation and recharge. For example, using a combination of environmental indicators in central New Mexico, Sandvig and Phillips (2006) detected zero percolation past the root zone of creosote shrub communities in the last 20,000 years, but detected episodes of downward flux under juniper-grass communities (0.4 mm yr^{-1}) and ponderosa pine forests (2.3 mm yr^{-1}), and distinct differences in fluxes over short distances across ecotones. Direct measurements in lysimeters demonstrate the critical role of vegetation in controlling percolation in arid environments (Gee et al., 1994; Scanlon et al., 2005). Gee et al. (1994) compared percolation over many years in deep (3-18 m) lysimeters with and without vegetation at three arid sites with varying precipitation (PPT) amounts (100 mm yr^{-1} to 230 mm yr^{-1}) and soil types. Deep percolation, or groundwater recharge, ranged from 10% to >50% of PPT through bare sandy soils, whereas the presence of vegetation greatly reduced or eliminated recharge. Uniquely, lysimeters recorded zero recharge through silt loam soils both with and without plants. A literature survey indicated that as the ratio of potential evapotranspiration (ET_o) to PPT reaches 5 or above, the ratio of actual evapotranspiration (ET) to PPT often approaches 1.0, as any water not transpired by plants readily evaporates (Zhang et al. 2001). In arid and semiarid rangelands, >95% of PPT is removed as ET (Wilcox et al. 2003), and globally, transpiration accounts for 80% to 90% of terrestrial evapotranspiration (Jasechko et al. 2013).

Effects of landscape-scale variability in vegetation and ET on groundwater recharge and discharge have implications for waste site evaluations and management. Under the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA), the US Department of Energy (DOE) is responsible for characterizing and remediating groundwater at several former uranium ore processing sites in the western United States (DOE 1996) where contamination levels exceed regulatory standards in 40 CFR 192. Groundwater contamination at these sites is attributable primarily to the large volumes of processing liquids that seeped from tailings impoundments during the years that mills operated (e.g., DOE 2012, 2014). An understanding of effects of vegetation dynamics on the soil water balance (recharge and discharge) of contaminated aquifers may improve groundwater flow analyses and introduce options to hydraulically control and naturally attenuate groundwater contaminant plumes (Carroll et al., 2009; Breshlof et al., 2013; Looney et al., 2014). Disturbances such as heavy grazing and land clearing can result in lower-

than-optimal ET rates for enhancing contaminant attenuation in groundwater (Glenn et al., 2008, Breshlof et al., 2013).

We estimated changes in landscape-scale ET for the groundwater model domain (GMD) (DOE, 2016) of an UMTRCA site near Tuba City, Arizona, where uranium, nitrate, and sulfate have migrated in shallow groundwater away from the site (DOE, 1998). A MODFLOW groundwater flow model (Harbough, 2005) was developed to estimate the volume of groundwater discharged annually to Moenkope Wash (DOE, 2015), a stream downgradient from the contamination plume that has been used to irrigate crops. The purpose was to estimate how long it would take for contaminants to reach the wash and to evaluate remediation strategies for contaminants in the plume. Mean precipitation is only 163 mm yr⁻¹, and rangeland vegetation has been historically overgrazed (Middleton and Thomas, 1997; Sheridan, 1981). Surrounding rangeland likely converted from shrub steppe and grassland to stabilized coppice dunes (Hodgkinson, 1983) and moving dunes (Draut et al., 2012a,b; Bogle et al., 2015). Our goals were to (1) determine the ET/PPT ratio for vegetation types within the GMD, (2) interpret the role of vegetation in determining the ratio, and (3) identify areas where improving vegetation health may enhance hydraulic control of groundwater movement. Our estimates of site ET were used as input to the groundwater model.

Many water balance studies reported for desert areas have been based on point measurements over relatively short time periods, using lysimeters (e.g., Gee et al., 1994) or soil sampling methods (e.g., Sandvig and Phillips, 2006), to infer groundwater flows over larger areas and longer time spans. ET is often the largest component of the water budget after PPT, but spatial and temporal heterogeneity in terrestrial vegetation creates high variability in ET (Frank and Inouye, 1994; Stephenson, 1998). Furthermore, plants might not use the same pool of water for transpiration that supports recharge (Evaristo et al., 2015), hence an independent estimate of ET is needed to complete the water budget. We used satellite imagery and meteorological data, as applied at a similar site near Monument Valley, Arizona (Glenn et al., 2008; Breshlof et al., 2013), to characterize the spatial and temporal variability of ET from 2000 through 2012 within a 3,513 ha area at the Tuba City UMTRCA site.

2. Materials and methods

2.1. Study site relevant site history

The Tuba City climate is arid with mean winter low temperatures of -6°C and summer highs of 34°C (Western Regional Climate Center, 2012). Potential ET (ET_0) is about 1500 mm yr^{-1} , nine times mean PPT. The 3531 ha GMD included several gently sloping terraces separated by sandstone escarpments, at the southern edge of the Kaibito Plateau, descending from 1630 m above sea level, about 6 km north of U.S. Highway 160, to Moenkopi Wash at 1425 m above sea level.

The uranium ore processing mill operated at the site from 1956 through 1966 (DOE, 1998). About 725,000 tonnes of ore were processed first by acid leaching and then by alkaline leaching. Tailings were conveyed as a slurry into unlined piles covering about 10 ha, and some process water was diverted to three adjacent, unlined retention ponds covering another 10 ha. Contaminants in the piles and ponds included sulfate and nitrate derived from the leaching solutions, and uranium and other heavy metals derived from the ore. Tailings, ponds, and soil contaminated from windblown tailings were stabilized and covered in 1988. The engineered cover relies on a 100 cm thick compacted sandy clay layer to limit radon diffusion and rainwater percolation (DOE, 1989), and rock riprap to control erosion (NRC, 1989). Groundwater remediation began in 2002 (DOE, 2002) and now consists of 37 recovery wells extracting about $0.3\text{ m}^3\text{ min}^{-1}$ encompassing an area of about 40 ha (DOE, 2015). Contaminated water is treated by distillation and returned to the aquifer through an infiltration trench, with brine piped to an evaporation pond (DOE, 2015). After over 10 years of operation, the system extracted approximately a third of the estimated plume pore volume, but with no evident reduction in groundwater contaminant concentrations (DOE, 2015). Therefore, a detailed groundwater investigation with flow modeling was undertaken in 2014 with the goal of developing alternative remediation strategies (DOE, 2014, 2015).

2.2. Groundwater flow model

The Department of Energy (DOE) has developed conceptual and numerical models to understand groundwater flow at the Tuba City, Arizona, Disposal Site (DOE, 2014, 2015). Modeling objectives were to (1) simulate groundwater travel paths from the former mill to the primary discharge boundary approximately 2500 meters downgradient of the mill site at

Moenkopi Wash, (2) estimate groundwater travel times from the site to the Wash, and (3) evaluate capture of contaminated groundwater under multiple remediation scenarios.

To meet these objectives, the modeling process first involved extensive review and evaluation of site characterization data to form a conceptual model of the physical factors that describe the occurrence, movement, and quantity of water within the model domain (DOE, 1998, 2002, 2014, 2015, 2016). The conceptual model encompasses the local watershed within which all groundwater originates from precipitation. Groundwater discharge occurs as ET within the model domain and by aquifer discharge to surface flow in Moenkopi Wash. Overland flow was not considered important due to the lack of surface features indicating surface runoff.

Contamination derived from mill operations (nitrate, sulfate, and uranium) extends downgradient approximately 450 meters and is generally limited to the upper 30 meters of the aquifer.

Boundaries of the groundwater model domain (GMD) included an upgradient limit that was beyond the influence of site remediation activities, a downgradient limit that encompassed the aquifer discharge boundary along Moenkopi Wash, and a lateral extent wide enough to ensure that flow conditions are not influenced by site activities (Figure 1). The GMD encompassed 3,513 ha.

Numerical implementation of the conceptual model used MODFLOW (Harbough, 2005) to simulate groundwater flow in the porous Navajo Sandstone aquifer, and with the PEST program (Doherty, 2004) to calibrate the model (DOE, 2015). The model domain was centered on the mill tailings disposal cell. Model calibration was achieved by automated methods to match steady-state hydraulic heads measured during an extended period before active groundwater remediation began, and to transient hydraulic heads during a following period of active remediation. ET zones and estimates from this study were used to specify recharge and discharge zones within the MODFLOW recharge package. For the initial model, recharge and discharge values were fixed as the difference between mean precipitation and mean ET over the 13-year monitoring period. Seasonal variation in estimated recharge and discharge will be represented in future models.

Groundwater at the site, part of a regionally extensive multiple aquifer system (Cooley et al., 1969), generally flows south within the Navajo Sandstone Formation toward Moenkopi Wash. The water table is 12 to 15 m below ground surface in the middle terrace (DOE, 2015) where the uranium mill tailings disposal cell is located, and as deep as 45 m below the surface at

the northern end of the GMD. The saturated thickness is likely 120–150 m. Groundwater contamination extends approximately 450 m south-southeast downgradient of the disposal cell and approximately 30 m vertically into the Navajo aquifer (DOE, 2015). For most of the GMD, up to 7 m of dune sand mantles the Navajo Sandstone; terrace alluvium underlies the disposal cell (DOE, 2015).

2.3. *Plant communities over the GMD*

We characterized and mapped vegetation zones within the model domain by (1) field-identifying plant species within the domain, (2) estimating changes in the abundance of dominant species along a north-south transect through the domain, (3) defining separate plant associations, and (4) delineating boundaries between plant associations on a satellite image (DOE, 2016). We used a modified Relevé method to estimate species abundance in selected stands, and then grouped and classified stands as plant associations (Barbour et al. 1999). We used a simplified gradient analysis (Bonham 2013) to illustrate how the abundance of dominant species varied along the north-south transect and to define separate plant associations. We then produced a map of discrete vegetation/ET zones by interpreting and field-checking boundaries between plant associations on a QuickBird satellite image (Figure 1). Vegetation is sparse except in areas where plants access groundwater. The most common plant community consists of coppice dunes stabilized by *Ephedra* species (EPsp) with an understory of warm-season grasses and shrubs in the inter-dune areas (Table 1). This pattern is likely an indication of heavy grazing (Hodgkinson, 1963). The cool-season grass *Achnatherum hymenoides* dominates undisturbed sites in this region, with lower cover of EPsp and less evidence of coppice dune formation (Hodgkinson, 1983).

Fig. 1. ET zones within the groundwater model domain at the Tuba City UMTRCA site. Blue line is a hypothetical groundwater divide used in modeling. Zones 8 and 9 are in Moenkopi Wash. Soil was removed from Zone 1d and used for the engineered disposal cell cover (Zone 4).

Table 1

Area and descriptions of ET zones within the groundwater model domain at the Tuba City UMTRCA site.

ET Zone	Area (ha)	Description
1a	659	Mormon tea (<i>Ephedra cutleri</i> , <i>E. torreyana</i> , and <i>E. viridis</i>), sand sagebrush (<i>Artemisia filifolia</i>) and rabbitbrush (<i>Ericameria nauseosa</i>) dominate regional coppice dune topography. Warm-season grasses (<i>Pleuraphis jamesii</i> and <i>Muhlenbergia pungens</i>) dominate the understory. Zone 1a has rocky outcrops, rabbitbrush dominates 1b and 1c, 1d is a mostly bare borrow pit surrounded by black greasewood (<i>Sarcobatus vermiculatus</i>), and sand sagebrush dominates 1e.
1b	221	
1c	647	
1d	46	
1e	479	
1f	2.3	
2a	218	<i>E. cutleri</i> , <i>E. torreyana</i> , and <i>E. viridis</i> coppice dune formations dominate.
2b	47	
3	42	Disturbed area immediately surrounding the disposal cell that has been partially revegetated, primarily with <i>Atriplex canescens</i> . The evaporation ponds and other structures are also in this area.
4	23	Rock-covered disposal cell.
5	188	Most of this area was scraped to remove radioactive soil then reseeded. Native <i>Gutierrezia sarothrae</i> and <i>Achnatherum hymenoides</i> and introduced <i>Salsola kali</i> weeds prevail. Fenced (no grazing).
6	35	Desert phreatophytes (<i>Atriplex canescens</i> and <i>Sarcobatus vermiculatus</i>) on coppice dunes with <i>Sporobolus</i> spp. grasses in understory. All vegetation is in poor condition due to overgrazing.
7	587	Similar to association in Zones 1 and 2 but with sparse grasses and <i>E. nauseosa</i> in inter-dunes.
8	116	Broad floodplain bench above Moenkopi Wash dominated by heavily overgrazed <i>A. canescens</i> and <i>S. vermiculatus</i> .
9	51	Native cottonwood trees (<i>Populus fremontii</i>) and introduced saltcedar (<i>Tamarix ramosissima</i>) dominate the bottom of Moenkopi Wash.
10	170	Similar to association in Zone 1, coppice dunes stabilized by <i>E. cutleri</i> , <i>E. torreyana</i> , and <i>E. viridis</i> .
Total	3531	

Phreatophyte communities potentially accessing groundwater occur at three places within the GMD. The desert phreatophytes *Atriplex canescens* (ATCA) and *Sarcobatus vermiculatus* (SAVE) grow along the toe of an escarpment about 40 m in elevation below the disposal cell terrace (Zone 6 in Fig. 2). ATCA and SAVE also grow on a bench above Moenkopi Wash (Zone 8). *Tamarix ramosissima*, *Populus fremontii*, and other mesic species grow in the riparian bottomland (Zone 9). These phreatophyte communities have also been subjected to heavy grazing. The ATCA/SAVE community in Zone 6 is of special interest. One conceptual management model relies on the native phreatophytes in Zone 6 to hydraulically control groundwater flow that might otherwise reach Moenkopi Wash, a local source of irrigation water for agriculture (DOE, 1998; Looney et al., 2014).

2.4. Remote sensing method for estimating ET and leaf area index (LAI)

We estimated ET rates within the GMD using a remote sensing algorithm originally developed for groundwater-dependent riparian plants as modified and validated for desert phreatophytes. The algorithm empirically relates Enhanced Vegetation Index (EVI) data from the Moderate Resolution Imaging Spectrometer (MODIS) sensors on the Terra satellite with maximum daily air temperatures ($T_{\max}$) and with ET measured at eddy covariance and Bowen ratio moisture flux towers at 13 riparian phreatophyte sites in Arizona and New Mexico (Nagler, 2005a,b). MODIS imagery is acquired at approximately daily satellite overpass intervals, and EVI and other data products are supplied as atmospherically corrected and georectified imagery by the US Geological Survey's EROS Data Center. We used the MOD13 product, a composite image spanning 16-day periods. Each pixel (250 m resolution) within a satellite overpass swath is individually screened to select a day with cloud-free conditions and at as near-nadir a viewing angle as possible. The selected pixels are then composited to form an image representing that 16-day period. We obtained imagery from the Oak Ridge National Laboratory DAAC website, which displays the footprint of MODIS pixels on high-resolution satellite imagery so the user can pinpoint areas of interest in the landscape (ORNL, 2015). Band values are corrected to at-surface reflectances, hence further spectral processing of MODIS data by end-users is not required.

We modified the algorithm for ATCA and SAVE as follows:

$$ET = 11.5 * (1 - e^{-1.63*EVI_{sc}}) * 0.882/[1 + e^{-(T_{\max} - 27.9)/2.57}] \quad (1)$$

EVI_{sc} is MODIS EVI stretched between a maximum value, representing full plant cover, and a minimum value, representing bare soil:

$$EVI_{sc} = 1 - (EVI_{\max} - EVI)/(EVI_{\max} - EVI_{\min}) \quad (2)$$

We set $EVI_{\max}$ at 0.542; $EVI_{\min}$ was 0.091 based on values from the 13 flux tower sites, resulting in an EVI_{sc} of 0.0 for bare soil and an EVI_{sc} of 1.0 for full vegetation. EVI_{sc} values can exceed 1.0, for example, for alfalfa fields. Negative EVI values can also occur for surface water or snow and are excluded from analyses.

$T_{\max}$ is the mean daily maximum temperature ($^{\circ}\text{C}$) for each 16-day period of MODIS data collection. $T_{\max}$ was better correlated with ET at the tower sites ($r = 0.82$, $P < 0.001$) than any other meteorological variable or combination of variables, including ET_o . $T_{\max}$ data are widely available from NOAA Cooperative Observer stations around the United States; hence, this method can be applied to areas without full meteorological stations. The first term in Eq. (1), $(1 - e^{-1.63 \cdot EVI_{sc}})$, is based on the equation for the absorption of light by a canopy, with EVI_{sc} replacing leaf area index in the formula. The second term, $0.882/[1 + e^{-(T_{\max} - 27.9)/2.57}]$, assumes a sigmoidal response of ET to $T_{\max}$, with a center point at 27.9°C . These equations were based on the observed response of phreatophyte ET to EVI and $T_{\max}$ at the tower sites and at the Monument Valley site. Numerical coefficients in Eq. (1) were derived using best-fit regression analysis.

The original equation developed for riparian phreatophytes (Nagler et al., 2005b) included an additional constant, 1.03 mm d^{-1} , to account for the fact that tower ET did not go to zero even when plants were dormant. This term was dropped for the Monument Valley analysis because, given the sparse vegetation, ET frequently probably does go to zero. ET often approaches PPT for large areas and long time periods in deserts (Zhang et al., 2001; Wilcox et al., 2003), and the ratio of ET to PPT can be used as a check on the applicability of ET estimates. Mean PPT at the Monument Valley site was 154 mm yr^{-1} ($SE = 14$) and the ET estimate was 149 mm yr^{-1} ($SE = 14$) from 2000 to 2010 for 200 hectares of sparse ATCA shrubland, indicating that the method produced reasonable ET estimates for that location (Breshlof et al., 2013). Equation (1) also reproduced sap flux measurements of plant transpiration by ATCA and SAVE in plots with dry surface soil for which bare soil evaporation was expected to be very low (Glenn et al., 2008).

MODIS imagery was supplemented with Landsat imagery, which has higher resolution than MODIS imagery (30 m compared to 250 m per pixel) but lower temporal resolution (16 day return time versus daily). Twenty-nine Landsat 5 or Landsat 8 NDVI images for the years 2000 through 2014 were obtained from the USGS LADS Science Research and Development (LSRD) website (<http://espa.cr.usgs.gov/>). As with MODIS, band values are converted to at-surface reflectances by USGS and further spectral processing by end-users is not required. From 1-3 cloud-free images per year (May-September) were collected, except for 2002 and 2012, for which no suitable images were available. We calculated ET from NDVI by an algorithm

developed for Landsat imagery by Groeneveld et al. (2007). NDVI is first scaled between bare soil and full vegetation cover similar to Equation (2) but using values for NDVImin and NDVImax of 0.094 and 0.790, respectively, derived from a sampling of bare soil and dense vegetation areas across images. We then calculated ET as:

$$ET = NDVI_{sc} * ET_o \quad (3)$$

where $NDVI_{sc}$ is scaled NDVI and ET_o was determined from temperature data for Tuba City by the Blaney-Criddle equation (Brouwer and Heibloem 1986). This method uses summer images and assumes that the ratio of ET/ET_o is constant over the year (Groeneveld et al., 2007).

With three exceptions, our Tuba City ET analyses used MODIS EVI pixels corresponding to shapefiles for each zone in Fig.1, and were obtained for February 18, 2000 (the first date of MODIS coverage) to December 31, 2012. For a pixel straddling two zones, the zone making up the majority of the pixel's area was assigned to the pixel. We subdivided Zones 1 and 2 using the hypothetical groundwater divide. Our analysis of Zone 9 (the riparian bottomland) and Zone 3 (the vegetated area inside the containment cell) used the Landsat ET method because the zones were narrower than the width of a MODIS pixel. The disposal cell, covering 23 ha, was unvegetated. Since it was built to be impermeable and to discharge PPT through evaporation, we assumed that annual ET was equal to annual PPT.

We determined LAI from MODIS EVI imagery using an algorithm that we developed at the Monument Valley UMTRCA site (Glenn et al., 2008):

$$LAI = 3.21EVI_{sc} \quad (4)$$

We developed the algorithm by first determining fractional cover (F_c) of individual shrubs on high-resolution (0.3 m) Quickbird image. We then measured LAI of leaves harvested from individual plants within four study areas and calculated landscape-scale LAI as F_c times mean LAI of individual plants. Finally, we measured EVI_{sc} for representative MODIS pixels and calculated the regression for EVI_{sc} and LAI.

2.5. Impact of grazing on ET.

We contrasted ET determined by Landsat imagery for two adjacent areas within Zone 5 that provided a fenceline contrast with respect to grazing: the area outside the fence has been historically grazed; the area inside the fence has been protected from grazing for about 30 years (Lash et al. 1999). The potential natural vegetation in the two areas is similar. We prepared shape files and estimated ET from Landsat NDVI images for both areas using Eq. 3 for the years 2000-2014. We compared interannual patterns of ET for the grazed and ungrazed plots with ET estimates over the entire GMD to see if year-to-year variability could be attributed to different grazing intensity. The Navajo Nation does not keep statistics on livestock stocking rates, hence indirect assessment of grazing effects were used. In addition to the grazed and ungrazed plot study, we used observations of range condition during field surveys of vegetation communities (DOE, 2016).

2.6. Statistical analyses and other data sources.

We performed statistical analyses with SigmaPlot software (Systat, Inc., San Jose, CA) using correlation, regression, analyses of variance, and other tests as described in Montgomery et al. (2012). To compare means, we used the Student's t-test for normally distributed data and the Mann-Whitney Rank Sum Test for data that were not normally distributed. We obtained $T_{\max}$ and PPT data as monthly means for the period 2000–2012 from the Tuba City NOAA Cooperative station (028792) (Western Regional Climate Center, 2012). Data collection at the station ended after 2012, so comparisons of ET and PPT were confined to the period 2000–2012.

3. Results

3.1. LAI, F_c , and ET by vegetation zone

MODIS and Landsat ET estimates were compared across zones and years, excluding zones 3 and 9 for which only Landsat estimates were feasible. The unweighted mean annual ET by the Groeneveld et al. (2007) method for Landsat imagery was 123 (SE = 8.6) mm yr⁻¹ compared to 127 mm yr⁻¹ (SE = 9.2) for the MODIS method (not significantly different, $P = 0.92$) and the correlation coefficient across zones was 0.95 ($P < 0.0012$), indicating good agreement between methods and justifying the use of MODIS for larger zones and Landsat for

the zones too small to encompass a MODIS pixel. MODIS was preferred for the larger areas because it is based on near-daily imagery throughout the year.

Green LAI within the GMD determined on MODIS imagery varied seasonally and annually, with peak summer values ranging from 0.32 in 2011 to 0.76 in 2010 (Fig. 3). The mean ET rate for the GMD (weighted by area of each zone) was 125 mm yr⁻¹ compared to PPT of 130 mm yr⁻¹ from 2000 to 2012 (not significantly different, $P = 0.88$) (Table 2). Total annual ET for the GMD was 4.42 Mm³ yr⁻¹ compared to 4.59 Mm³ yr⁻¹ for PPT. Zone 1 contributed the greatest ET due to its large area. However, despite the 12-year balance of ET and PPT, we observed considerable variability in ET across vegetation zones (Table 2). Mean ET for upland vegetation in Zones 1 (excluding 1d), 2, 7, and 10 did not differ significantly from PPT for the 12-year period (mean = 125 mm yr⁻¹, SE = 4, $P > 0.05$). Mean ET over the 12 years for ATCA/SAVE phreatophyte communities in Zones 6 and 8, although slightly higher, was also not significantly different from PPT ($P > 0.05$) because of high interannual variability. ET for revegetated area inside the inner site fence (Zone 3) started out low due to disturbance of the vegetation when the cell was constructed, then increased after 2004 due to transplanting of ATCA. Mean ET in Zone 5, located east and generally downwind of the disposal cell, was only 81 mm yr⁻¹, 38% less than PPT ($P = 0.002$). Much of Zone 5 had been scraped to remove contaminated topsoil when the site was remediated and continues to have low plant cover. ET for the area excavated to acquire soil for the engineered cover (Zone 1d), was also less than PPT ($P < 0.001$). ET was significantly higher than PPT ($P < 0.001$) only in Zone 9, the riparian phreatophyte community within Moenkopi Wash.

Fig. 2. Green LAI within the Tuba City groundwater model domain as determined using MODIS Enhanced Vegetation Index data.

Table 2. ET estimates (mm) for vegetation zones within the groundwater model domain at the Tuba City UMTRCA site. Zone 3 ET was estimated from 2005 and 2011 Landsat images. ET from the cell (Zone 4) was assumed to equal PPT. All other ET estimates are from MODIS EVI and meteorological data. Numbers in parentheses are standard errors of means. Errors were not available for Landsat ET estimates as they were based on mean NDVI per zone.

Zone	Year													Mean
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	
1 a	109 (27)	149 (34)	88 (23)	168 (39)	105 (28)	180 (41)	145 (39)	164 (41)	113 (28)	131 (33)	152 (40)	76 (20)	129 (32)	132 (9)
1b	118 (29)	172 (41)	84 (21)	173 (43)	89 (23)	193 (45)	158 (42)	163 (44)	100 (26)	118 (32)	162 (43)	63 (17)	151 (41)	134 (11)
1c	114 (28)	171 (40)	92 (23)	173 (41)	87 (23)	178 (42)	148 (38)	153 (41)	87 (23)	123 (38)	151 (39)	60 (16)	159 (45)	118 (13)
1d	21 (8)	70 (23)	22 (9)	63 (16)	28 (16)	65 (21)	37 (12)	42 (16)	20 (9)	57 (24)	54 (17)	7 (0.4)	58 (17)	42 (6)
1e	138 (34)	196 (45)	110 (28)	216 (50)	101 (28)	218 (51)	149 (39)	179 (45)	131 (35)	131 (42)	172 (45)	84 (22)	146 (37)	152 (12)
2a	105 (27)	145 (34)	74 (19)	139 (33)	80 (20)	161 (39)	141 (38)	164 (45)	87 (23)	99 (28)	177 (49)	53 (15)	132 (39)	120 (11)
2b	108 (27)	161 (40)	84 (20)	160 (38)	87 (23)	174 (41)	161 (47)	166 (49)	111 (30)	123 (37)	209 (58)	53 (16)	184 (54)	137 (13)
3	41	97	-	82	65	114	88	125	102	142	188	124	-	106 (13)
4	148	113	119	131	162	77	100	159	126	84	186	80	200	130 (11)
5	67 (18)	96 (24)	40 (10)	95 (22)	57 (16)	119 (27)	76 (18)	103 (26)	65 (18)	73 (22)	114 (30)	31 (10)	119 (36)	81 (8)
6	131 (32)	167 (39)	80 (21)	142 (34)	106 (27)	214 (49)	164 (44)	209 (53)	210 (31)	112 (29)	197 (54)	73 (19)	185 (56)	153 (14)
7	116 (29)	149 (35)	66 (16)	121 (28)	93 (24)	173 (40)	127 (31)	174 (45)	130 (34)	106 (29)	182 (49)	65 (17)	131 (36)	126 (11)

8	132 (33)	164 (38)	94 (24)	125 (31)	125 (34)	207 (48)	132 (33)	180 (46)	169 (45)	142 (39)	239 (65)	110 (30)	157 (38)	152 (11)
9	272	370	-	391	326	372	290	307	307	379	397	324	-	341 (11)
10	103 (26)	144 (33)	68 (18)	102 (26)	90 (28)	152 (37)	103 (26)	142 (36)	136 (36)	84 (46)	182 (50)	73 (21)	120 (31)	115 (9)
Mean^a	114	157	83	153	93	177	135	160	112	114	166	68	142	125
PPT	148	113	119	131	162	77	100	159	126	84	186	80	200	130

^a Weighted by area per zone

ET exceeded PPT by 0.21 m yr^{-1} in Zone 9, therefore the 51 ha of phreatophytes in this zone discharged $0.11 \text{ Mm}^3 \text{ yr}^{-1}$ from groundwater sources. Zones 6 and 8 also support desert phreatophytes and, using $\text{ET} - \text{PPT}$, may have discharged an additional $0.034 \text{ Mm}^3 \text{ yr}^{-1}$ of groundwater. A combined estimate of groundwater discharge by phreatophytes is $0.141 \text{ Mm}^3 \text{ yr}^{-1}$, or about 3% of PPT for the 3531 ha GMD. In contrast, for Zones 1d and 5, with sparse upland vegetation, an estimated $0.132 \text{ Mm}^3 \text{ yr}^{-1}$ of groundwater recharge could have occurred from 2000 to 2012.

The groundwater model required an estimate of groundwater discharge contributing to surface flows in Moenkopi Wash. For all zones outside of Zone 9, mean annual ET was 122 mm yr^{-1} over 3462 ha, equal to $0.28 \text{ Mm}^3 \text{ yr}^{-1}$. Zone 9 discharged 0.11 Mm^3 of this amount in ET, for a potential contribution to surface flows of $0.17 \text{ Mm}^3 \text{ yr}^{-1}$. This estimate was compared to field measurements of flow rates at the upstream and downstream boundaries of Moenkopi Wash (see Discussion).

3.2. Interannual and seasonal variability in ET

As with LAI, ET was also variable across years. Although year-to-year variability in ET was not significantly correlated with PPT for any zone ($r = 0.37$, $P = 0.21$ across zones), annual ET values for upland zones (1, 2, 7, 10) were strongly correlated with each other ($r = 0.72\text{--}0.99$, $P < 0.01$). ET values for these zones exceeded PPT in 2001, 2002, and 2005–2007, but were nearly the same or lower than PPT in other years. Zone 9 ET was consistently higher than PPT, and Zone 5 was consistently lower than PPT across years.

Seasonal patterns of EVI and ET were also out of phase with PPT (Fig. 3A). PPT was biphasic, with winter rains (November–April) accounting for 44% of annual PPT, and monsoon rains (July–October) accounting for 47%. PPT was lowest in May and June. In contrast,

greening, as measured by EVI, peaked first during the dry May-June period, and then again during the monsoon season. ET peaked in June, ahead of the monsoons, and decreased in September and October. Fig. 3B shows monthly differences between PPT and ET. During the May to August period, ET exceeded PPT by 47.8 mm; if this was supplied by water stored in the vadose zone during the wet periods, 47.8 mm of PPT above ET arriving during the wet periods (68.1 mm) was likely removed by plant transpiration during the dry period..

3.3. Effect of grazing on ET

The lack of correlation between annual ET and PPT and the strong correlation of annual ET among zones suggests that factors other than PPT influenced ET.

Fig3. (A) Mean monthly ET (closed circles), precipitation (solid line), and the Enhanced Vegetation Index (red line and symbols) across vegetation zones and years, 2000–2012, within the Tuba City groundwater model domain. Bars are standard errors of means. (B) Difference between monthly PPT and monthly ET.

We compared an area within Zone 5 that had been protected from grazing for 30 years inside the site perimeter fence with an adjacent area outside the fence. Neither area was affected by the soil scraping that had taken place elsewhere in Zone 5. From 2000 to 2014, ET rates were nearly identical, 130 (SE = 9.2) mm yr⁻¹ for the ungrazed plot and 134 (SE = 8.3) mm yr⁻¹ for the grazed plot (not significantly different, $P = 0.75$) and similar to annual PPT (130 mm yr⁻¹). Furthermore, grazed and ungrazed plots as well as the whole GMD exhibited the same variation in annual ET (Figure 4), with r values > 0.97 . Hence, grazing did not appear to be a factor lowering ET and was not able to account for year-to-year variability in annual ET over the whole GMD.

Figure 4. Annual ET estimated by Landsat NDVI for ungrazed (inside fence), grazed (outside fence) plots and for the whole groundwater model domain (whole site) at the Tuba City, AZ, UMTRA site, 2000-2014.

On the other hand, surveys of the ATCA and SAVE phreatophyte communities in Zones 6 and 8 showed plants were damaged by apparent heavy grazing.

Discussion

We compared modeled and measured surface flows in Moenkopi Wash to test the groundwater model (DOE, 2015) and ET estimates. Using on our mean annual estimates of ET, the model predicted a contribution of $0.17 \text{ Mm}^3 \text{ yr}^{-1}$ of groundwater flow from the GMD to surface flows in the wash. Three field surveys in 2015 showed that Moenkopi Wash was a gaining reach within the GMD, with an increase in surface flows of $0.4 \text{ Mm}^3 \text{ yr}^{-1}$ (DOE, 2015). Assuming equivalent groundwater flow rates from both sides of the wash, the contribution from the GMD on the north side of the wash was estimated to be 0.2 mcm yr^{-1} (DOE, 2015), in good agreement with the model.

Overall, ET and PPT within the GMD appear to be in approximate balance over long time periods. This is similar to results for the Monument Valley site (Breshlof et al., 2013) and supports the accuracy of the MODIS ET algorithm: within water-limited arid landscapes, ET/PPT often approaches 1.0 (Zhang et al., 2001; Wilcox, 2003). Little or no overland flow exits the GMD, except throughflow in Moenkopi Wash, and only a small percentage of PPT falling within the GMD supports seeps and vegetation in Moenkopi Wash (DOE, 2015). The main finding of this study was the important role that vegetation plays in regulating ET in this sparse desert environment. Despite the fact that LAI was under 0.8 and F_c is only about 10% (Lash et al., 1999) over the GMD, plant transpiration apparently accounted for most of the water discharged as ET. About 50% of the seasonal ET as estimated by MODIS occurred during the spring and early summer dry period, apparently using water stored in the vadose zone from late monsoon and winter rains. Furthermore, annual ET was not significantly correlated with annual PPT even though they were in balance over longer time periods. This suggests that some excess PPT in wet years is stored in the soil and can support ET in subsequent drier years. Only 3% of PPT was estimated to be discharged as groundwater flow.

The soils in the GMD are deep, unconsolidated sands (Lash et al., 1999) that likely exhibit the "inverse texture effect" (Noy-Meir, 1973; Austin et al., 2004). In wet climates, fine-textured soils such as silts and clays usually support denser plant growth than coarser soils, whereas the opposite is true in dry climates, because water can infiltrate deeper in coarse soils and is less likely to be lost as evaporation. Evaristo et al. (2015) found that plant transpiration is supported by a distinct source of stored vadose zone water rather than groundwater or concurrent PPT in 47 globally distributed sites.

The results did not support the hypothesis that grazing was responsible for reducing ET over the whole GMD. Plots protected from grazing had the same ET as grazed plots, and showed the same annual pattern of ET as the entire GMD, approximately equal to PPT over all years. A ground study conducted in 1996, 10 years after a fence to exclude livestock was placed around the containment cell, reported that plant cover of grazed plots (10.9%) was less than half of that in ungrazed plots (24.4%, $P < 0.05$) but species composition was similar (Lash et al., 1998). However, a more recent study (Q. Bennally, J. Waugh, E. Glenn, University of Arizona Master's thesis, 2016, in review), 30 years after the fence was erected, found that plant cover in grazed and ungrazed plots were now similar, but that cover by less-palatable species ("increasers") was higher in grazed than ungrazed plots ($P < 0.05$). Hence, moderate grazing appears to be impacting species composition but not necessarily cover, NDVI and ET over the GMD.

The situation appears to be different in the two areas where desert phreatophytes are dominant (Zones 6 and 8). These areas are observed to be heavily grazed (DOE, 2016). Enhancing ET through control of grazing in these zones might be an effective way to tip the water balance toward discharge rather than recharge, to reduce the movement of water toward the wash. For example, at the Monument Valley site, a natural ATCA/SAVE zone protected from grazing for 10 years, plant cover increased from 15 to 75%, LAI increased from 0.58 to 2.88, and ET increased from 2.9 mm d^{-1} to 13.1 mm d^{-1} in summer, as compared with a grazed ATCA/SAVE zone outside the livestock fence (Glenn et al., 2008; Breshlof et al., 2013). Based on results at Monument Valley, fencing the ATCA/SAVE stand in Zone 6 in the Tuba City UMRCA site GMD could potentially increase ET from 153 mm yr^{-1} to at least 500 mm yr^{-1} (about one-third of ET_0), resulting in a potential net groundwater discharge of about 370 mm yr^{-1} . Over the 35 ha of zone 6, this would result in $0.13 \text{ Mm}^3 \text{ yr}^{-1}$ of discharge, which could reduce the present estimated discharge rate of 0.17 Mm^3 into the surface flow in Moenkopi Wash. Controlling grazing and rehabilitating the vegetation in Zone 8 could increase discharge even further. The feasibility of grazing control, however, depends on costs and benefits determined by local residents and the Navajo Nation (Redsteer et al., 2010)..

5. Conclusion

This study shows that even a small apparent change in recharge or discharge can have potentially important consequences for the movement of contaminated groundwater. Temporal

and spatial variability in the type and abundance of vegetation at desert waste disposal sites can influence groundwater recharge and discharge and should be factored into site characterization and remediation efforts. Past assumptions of no net recharge at desert sites should be tested using estimates of actual evapotranspiration. At the Tuba City UMTRCA site, fall and winter precipitation was generally removed by evapotranspiration in spring and summer. Also, during years of low precipitation, evapotranspiration removed stored soil water when precipitation was high during the preceding year. Land use management should also be factored into efforts to model and remediate contaminated groundwater. At the Tuba City site, heavy grazing observed in the phreatophyte communities could enhance the groundwater flow towards the discharge area in Moenkopi Wash, even though they represent a small proportion of total plant cover within the GMD.

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