Effects of Rangeland Evapotranspiration on Groundwater Recharge, Discharge, and Flow at the Tuba City, Arizona, Disposal Site – 17159

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ABSTRACT

The US Department of Energy Office of Legacy Management is modeling groundwater flow and contaminant transport at a former uranium mill site near Tuba City, Arizona. A goal is to project groundwater travel times and flow volumes between the former mill site and Moenkopi Wash, a downgradient stream. Aquifer recharge and discharge are sensitive model parameters; however, assigning representative rates is inexact and involves approximations. We applied a remote sensing algorithm to determine spatially variable evapotranspiration (ET), precipitation recharge, and groundwater discharge rates for use in a large scale groundwater flow model for the site. ET is the combination of evaporation and plant transpiration from soil and groundwater. We estimated landscape-scale ET over a 13-year period (2000 to 2012) for distinct plant communities within a 3531-hectare groundwater model domain (GMD), and then evaluated effects of ET on groundwater recharge and discharge within the GMD. Our empirical algorithm was derived from ground ET measurements, multispectral satellite imagery, and temperature data. Groundwater recharge or discharge rates were calculated for each plant community (or ET Zone) as the difference between precipitation (PPT) and ET rates. Recharge occurred in plant communities where PPT exceeded ET; discharge occurred where ET exceeded PPT.

Estimates of groundwater recharge rates for upland plant communities that survive on meteoric water ranged from 0 to 88 mm yr^{-1}. Estimates of groundwater discharge for phreatophyte plant communities ranged from 23 mm yr^{-1} to 150 mm yr^{-1}. Phreatophytes are plants that survive by extracting groundwater. Zero recharge occurred in plant communities where ET rates equaled annual average precipitation. An increase in groundwater recharge (PPT > ET) was associated with past land disturbances and heavy livestock grazing in upland areas. Groundwater discharge (ET > PPT) was highest in riparian phreatophyte communities, but lower than optimal in upland phreatophyte communities impacted by heavy grazing. Protecting phreatophyte communities from grazing at Tuba City could potentially increase ET from 153 mm yr^{-1} to at least 500 mm yr^{-1}. The validity of using the ET algorithm to estimate recharge and discharge was evaluated by comparing the net volumetric outflow rate for the model domain with base flow measurements collected from Moenkopi Wash. Modeled outflow approximated measured flow gains in the Wash, increasing our confidence in the ET algorithm and in the model.

Results suggest that rangeland management practices that reduce groundwater recharge rates and increase groundwater discharge rates should be evaluated as part of an overall groundwater remediation strategy.

INTRODUCTION

The US Department of Energy (DOE) Office of Legacy Management is modeling groundwater flow for a former uranium mill site near Tuba City, Arizona. The model incorporates estimates of evapotranspiration (ET) for different rangeland plant communities within the groundwater model domain (GMD). Some plant species within the GMD, classified as phreatophytes, survive by extracting groundwater. ET within these plant communities can result in a net discharge of groundwater if ET exceeds precipitation (PPT). Upland desert plants within the GMD survive on meteoric water. These plant communities can limit groundwater recharge if annual ET is equivalent to precipitation. For all plant communities within the GMD, excessive livestock grazing or other disturbances can tip the balance to a net groundwater recharge.

This study characterized and mapped rangeland vegetation within a GMD for the Tuba City site, applied remote sensing algorithms to estimate ET for each vegetation zone, and then used ET estimates to model groundwater flow. The study was designed to address four objectives:

1. Characterize and map vegetation types or ET zones within the GMD, focusing on the separation of upland plant communities that are dependent on PPT, and plant communities with phreatophytes that survive by tapping groundwater.
2. Estimate temporal and spatial variability in landscape-scale ET for upland and phreatophyte plant communities within the GMD.
3. For selected vegetation zones, estimate ET that might be achieved given a scenario of improved grazing management.
4. Estimate groundwater recharge and discharge within the GMD, model groundwater flow within the GMD, and then compare model results with field measurements of flow.

BACKGROUND

Recharge in Deserts

Arid and semiarid environments are often considered well-suited for the long-term storage of radioactive and other hazardous wastes due to a presumed low groundwater recharge [1,2]. However, vegetation and soil properties in arid areas can alter the effects of climate on recharge. Deep percolation (or groundwater recharge) can occur in denuded soils, whereas vegetation can eliminate recharge [3]. Vegetation type can also influence net recharge [4,5]. In arid and semiarid rangelands, >95% of PPT is removed as ET [6], and globally, transpiration accounts for 80% to 90% of terrestrial ET [7].

Recharge, Discharge, and Uranium Mill Tailings

Effects of landscape-scale variability in vegetation and ET on groundwater recharge and discharge have implications for waste site management. Under the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978, DOE is responsible for remediating groundwater at several former uranium mill sites. 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 [8,9]. An understanding of effects of vegetation and ET on recharge and discharge of contaminated aquifers may introduce new options to hydraulically control groundwater plumes [10,11,12]. However, disturbances such as overgrazing of rangeland vegetation by livestock can result in lower-than-optimal ET rates [11,13].

Tuba City, Arizona Site History

The Tuba City, Arizona, uranium mill operated from 1956 to 1966 [14]. 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 hectares (ha), and some process water was diverted to adjacent, unlined retention ponds covering another 10 ha. In 1988, tailings, ponds, and soil contaminated from windblown tailings were stabilized in a disposal cell. Groundwater remediation began in 2002 [15] and consists of 37 extraction wells encompassing an area of about 40 ha [16]. Contaminated water was treated by distillation and returned to the aquifer through an infiltration trench. 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.

METHODS

Study Site

Potential ET for the arid Tuba City site is about 1820 millimeters per year (mm yr^{-1}), 11 times mean PPT. Groundwater generally flows south within the Navajo Sandstone Formation from the disposal cell toward Moenkopi Wash. The water table is 12 to 15 m below ground surface at the disposal cell. 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 [16,17]. Up to 7 m of dune sand mantles the Navajo Sandstone; terrace alluvium underlies the disposal cell.

Groundwater Flow Model

DOE developed conceptual and numerical models to understand groundwater flow at the Tuba City, Arizona, Disposal Site [9,16,17]. The overall modeling objective was to simulate groundwater travel times and flow volumes from the former mill to Moenkopi Wash. The conceptual model encompassed the local watershed within which all groundwater originates from precipitation. Groundwater discharge occurs as ET within the 3531 ha GMD, and by aquifer discharge to surface flow in Moenkopi Wash. Boundaries of the GMD included an up-gradient limit that was beyond the influence of site remediation activities, a downgradient limit that encompassed the aquifer discharge boundary along Moenkopi Wash, and an adequate lateral extent to encompass recharge that could influence groundwater flow. Numerical implementation of the conceptual model used MODFLOW [20] to simulate groundwater flow, and the PEST program [21] to calibrate the model [16,17]. ET estimates from this study were used to specify recharge and discharge zones within MODFLOW.

Plant Associations and Vegetation Mapping

We characterized and mapped vegetation zones by (1) identifying plant species within the entire GMD, (2) estimating changes in the abundance of dominant species along a north-south transect through the GMD, (3) defining separate plant associations, and (4) delineating boundaries between plant associations. We used a modified relevé method to estimate species abundance, and then grouped and classified vegetation types [18]. We used a simplified gradient analysis [19] to illustrate changes in species abundance along the north-south transect, and to define 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.

Empirical ET Algorithm

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 [22,23]. 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. We used the MOD13 product, a composite image spanning 16-day periods. We modified the algorithm for rangeland plants using 2 years of sap flux measurements at the Monument Valley UMTRCA site [11,13].

Our analyses used MODIS EVI pixels corresponding to shapefiles for each ET zone. EVI pixels 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 a hypothetical groundwater divide. Our analysis of Zone 9 (the riparian bottomland) was narrower than the width of a MODIS pixel, so we analyzed five pixels in the widest areas of Zone 9, displayed each pixel footprint on a high-resolution Quickbird image, and then divided pixels into riparian and non-riparian areas. We then weighted the EVI value based on proportions of pixels that were riparian phreatophytes, terrace phreatophytes, and upland desert vegetation. We estimated leaf area index (LAI) from MODIS EVI imagery using an algorithm that we developed at the Monument Valley UMTRCA site [13].

Impact of Grazing on ET

Navajo Nation rangeland has historically been heavily grazed [24]. However, temporary but marked reductions in grazing pressure occurred during a 1999–2009 drought period [25]. In 2001, stocking rates were an estimated 41% greater than authorized [26]. In 2003, the Navajo Nation called for ranchers to reduce herd sizes to numbers appropriate for drought conditions [26]. Livestock grazing on rangeland in the vicinity of the Tuba City GMD likely dropped from high levels for 2000 to 2002, to much lower levels for 2005 to 2007 [25], but high again as observed in 2011. We contrasted annual ET within the GMD for 2005 and 2011, representing lower and higher grazing pressure, respectively. Both years had low annual PPT (77 mm yr^{-1} and 80 mm yr^{-1}) but were preceded by years of higher PPT (162 mm yr^{-1} and 186 mm yr^{-1}) (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?aztuba).

Statistical Analyses

We estimated net groundwater recharge or discharge as the difference of PPT and ET, two large numbers subject to error and uncertainty. We conducted an error analysis of the ET estimates in each vegetation zone and for the entire groundwater domain based on standard error (SE) of annual means. Because ET is expected to vary annually in response to PPT, grazing, and other factors, we used the relative standard error (RSE) for each year. RSE, if aggregated over years, can represent the degree of random error in the estimates across years. Analyses included correlation, regression, analyses of variance, and associated tests [27].

RESULTS

Vegetation Types and ET Zone Map

Fig. 1 illustrates (1) changes in the abundance of dominant plant species (which are defined in TABLE I) along a transect between the disposal cell and Moenkopi Wash, as estimated using the relevé method, and (2) the subjective separation of different plant associations along the transect. We named plant associations for their dominant two species. Plant associations became the discrete vegetation or ET zones used to estimate and map ET within the GMD (TABLE II). We delineated and then outlined ET zones as polygons on a Google Earth Image (Fig. 2).

Using this process, we mapped three phreatophytic vegetation zones and six upland vegetation zones (Fig. 2, TABLE II). The disposal cell is a separate zone. 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 interdune areas. The cool season grass *Achnatherum hymenoides* (ACHY) dominates undisturbed sites in this region, with lower cover of EPsp and less evidence of coppice dune formation [28].

Phreatophyte communities potentially accessing groundwater occur at three places within the GMD. Four phreatophyte species were observed: ATCA, SAVE, POFR, and TARA. The desert phreatophytes ATCA and 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). ATCA and SAVE are likely transpiring (discharging) groundwater flowing toward Moenkopi Wash. POFR and TARA are floodplain phreatophytes growing in the riparian bottomland of the incised wash (Zone 9). Common upland desert shrubs and grasses dominate the other vegetation zones. The ATCA/SAVE community in Zone 6 is of special interest. One management concept relies on Zone 6 phreatophytes to hydraulically control groundwater flow that might otherwise reach Moenkopi Wash [12,14].

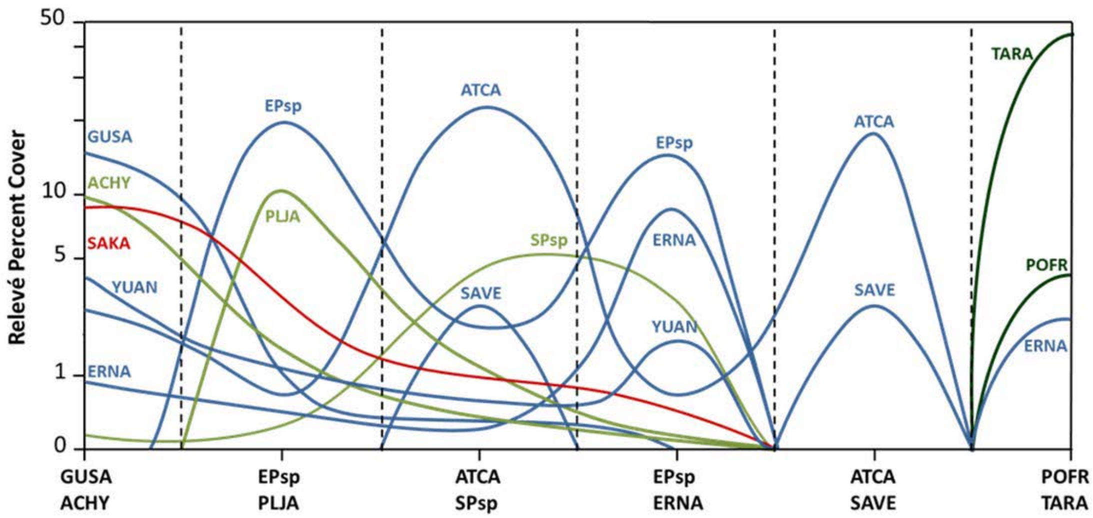

Figure 1. Distributions of dominant plant species and delineation of plant associations along a vegetation gradient (transect) between the Tuba City disposal site (left side) and Moenkopi Wash (right side). Plant acronyms are defined in Table I. Small letters "sp" indicate that more than one species within the genus was observed. Colors designate trees (dark green), shrubs (blue), grasses (light green), and annual weeds (red). Dashed lines mark the subjective separation of plant associations.

ET and LAI by Vegetation Zone

In desert areas, nearly all precipitation is expected to be returned to the atmosphere as either soil evaporation or plant transpiration [34]. Our estimate of mean ET for the overall GMD satisfies this expectation. The mean ET rate for the GMD (weighted by area of each zone) was 129 mm yr^{-1} compared to PPT of 130 mm yr^{-1} from 2000 to 2012 (not significantly different, P = 0.88 by Mann-Whitney Rank Sum Test) (TABLE III). Total annual ET for the GMD was 4.55 million cubic meters per year (Mm^3 yr^{-1}) compared to 4.59 Mm^3 yr^{-1} for PPT. Green LAI within the GMD varied seasonally and annually; peak summer values ranged from 0.32 in 2011 to 0.76 in 2010 (Fig. 3).

Estimates of groundwater recharge rates for upland plant communities (Zones 1, 2, 5, 7, and 10), that survive on meteoric water ranged from 0 to 88 mm yr^{-1}. Estimates of groundwater discharge for phreatophyte plant communities (Zones 6, 8, and 9) ranged from 23 mm yr^{-1} to 150 mm yr^{-1}. Zone 1 contributed the greatest ET due to its large area. However, despite the 13-year balance of ET and PPT, we observed considerable variability in ET across vegetation zones. Mean ET for upland vegetation in Zones 1 (excluding 1d), 2, 7, and 10 did not differ significantly from PPT for the 13-year period (mean = 130 mm yr^{-1}, SE = 4, $P > 0.05$). Mean ET over the 13 years for ATCA/SAVE phreatophyte communities in Zones 6 and 8, although slightly higher,

TABLE I. Dominant plant species identified within the GMD.

Scientific Name[a]	Acronym[b]	Common Name[c]
Trees and Shrubs		
Atriplex canescens (Pursh) Nutt.	ATCA	fourwing saltbush, chamizo, Díwózhii_beii
Ephedra species Coville	EPsp	green joint fir, Mormon tea, T_'oh azihii_ibáhígíí
Ericameria nauseosa (Pall. ex Pursh) G.L. Nesom & Baird	ERNA	rubber rabbitbrush, chamisa, K'iitsoí nitsaaíí
Gutierrezia sarothrae (Pursh) Britton & Rusby	GUSA	broom snakeweed, Ch'il_diilyésiitoh
Populus fremontii S. Watson	POFR	Fremont cottonwood, T'iis bit'ąą' niteelígíí
Sarcobatus vermiculatus (Hook.) Torr.	SAVE	greasewood, chico, chicobush, Díwózhiishzhiin
Tamarix ramosissima Ledeb.	TARA	saltcedar, tamarisk, Gad ni'ee_ii bílátah_ichí'ígíí
Yucca angustissima Engelm	YUAN	narrow leaf yucca, Tsá'ázi'ts'óóz
Grasses		
Achnatherum hymenoides (Roem. & Schult.) Barkworth	ACHY	Indian ricegrass, sand bunchgrass, Nididlídii
Pleuraphis jamesii Torr.	PLJA	galleta, curly grass, T_'oh _ichí'í
Sporobolus sp	SPsp	dropseed
Forbs		
Salsola kali L.	SAIB	Russian thistle, tumbleweed, Ch'il deeníní

[a] The scientific nomenclature for genera, species, and authorities is consistent with the Natural Resource Conservation Service PLANTS database (http://plants.usda.gov/java/).
[b] Acronyms combine the first two letters of the genus and species names.
[c] English and Navajo common names are from a variety of sources (29,30,31,32,33,http://plants.usda.gov/java/).

was also not significantly different from PPT ($P > 0.05$) because of high inter-annual variability. ET for the revegetated area inside the disposal cell fence (Zone 3) was higher than PPT in 2005 and 2011. The southern portion of this zone received an undetermined amount of runoff from the cell (Zone 4), and it is likely that Zones 3 and 4 were in long-term balance with PPT. 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.

Assuming a mean groundwater discharge rate of 150 mm yr^{-1}, based on ET – PPT, riparian phreatophyte vegetation in the 51 ha of Zone 9 discharged 0.0765 Mm^3 yr^{-1} of groundwater from 2000 to 2012. Zones 6 and 8 also support desert phreatophytes and, using ET – PPT, may have discharged an additional 0.034 Mm^3 yr^{-1} of groundwater. A combined estimate of groundwater discharge by phreatophytes is 0.111 Mm^3 yr^{-1}, or about 2.4% of PPT for the 3531 ha GMD. In contrast, for Zones 1d

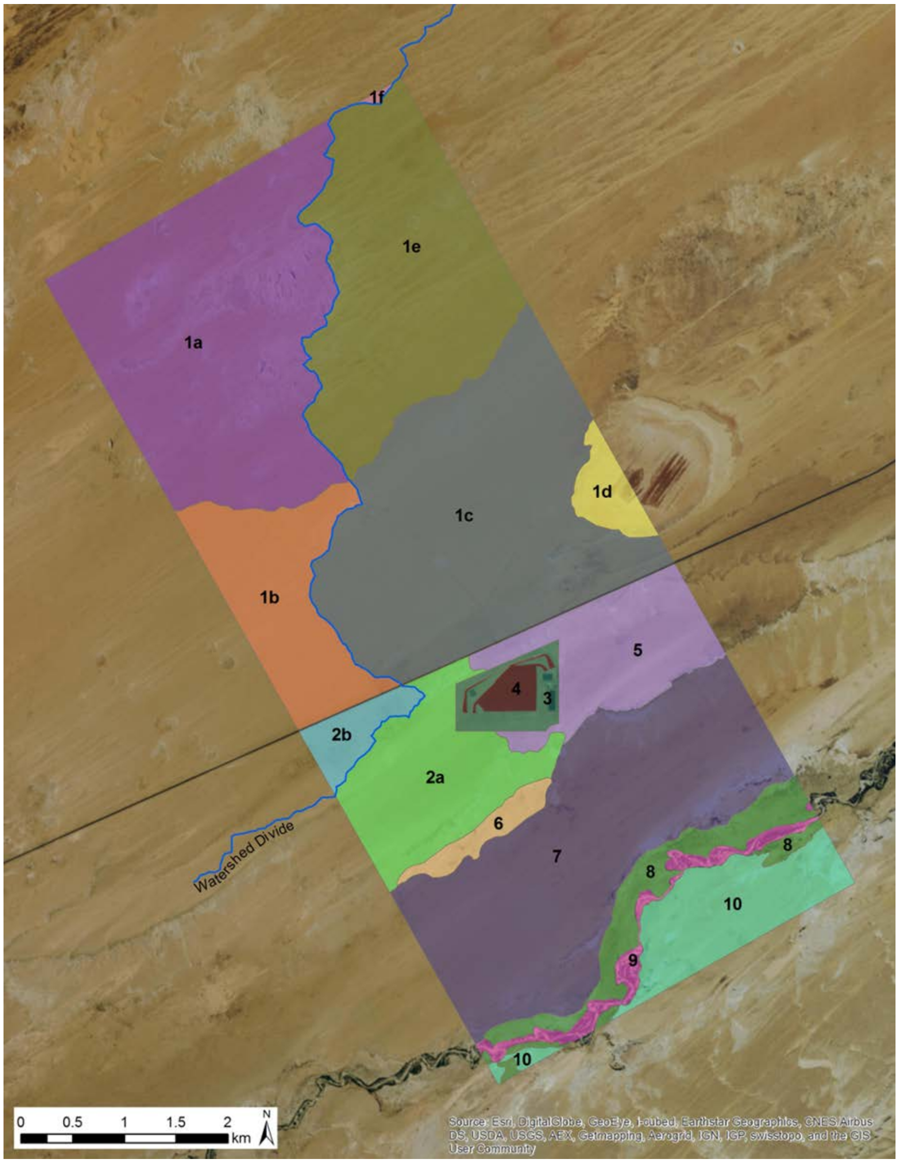

Figure 2. ET zones within the groundwater model domain at the Tuba City UMTRCA site. The blue line is a surface water divide. Zones 8 and 9 are in Moenkopi Wash. Soil was removed from Zone 1d and used for the engineered disposal cell cover (Zone 4).

and 5, with sparse upland vegetation, an estimated 0.132 $Mm^3 yr^{-1}$ of groundwater recharge occurred from 2000 to 2012.

Annual and Seasonal Variability in ET

As with LAI (Fig. 3), ET was also variable across years (Fig. 4). Although year-to-year variability in ET was not significantly correlated with PPT for any zone (r = 0.37, P = 0.21 across zones), except for the riparian Zone 9 (r = 0.57, P = 0.06), annual ET values for upland zones (1, 2, 7, 10) were strongly correlated with each other (r = 0.72–0.99, $P < 0.01$). ET values for these zones exceeded PPT in 2001, 2002, and

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

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

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. 5). 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.

Grazing Effect

ET for the entire GMD was 177 mm yr^{-1} in 2005 (Table III), a year with lower grazing pressure, and 68 mm yr^{-1} in 2011, a year with higher grazing pressure. PPT in 2005 and 2011, and in preceding years (2004 and 2010), were similar, so the difference is not likely a response to PPT. ET was higher for most areas within the GMD in 2005 than in 2011. ET in Zone 6, an ATCA/SAVE zone thought to provide hydraulic control of groundwater, was much higher than PPT in 2005 but lower than PPT in 2011.

Modeled and Measured Flow

We compared modeled inflow and measured surface flows in Moenkopi Wash to test the groundwater model [16,17] and ET estimates. Using our mean annual estimates of ET, the model predicted a contribution of 342 liters per minute (L m^{-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 average increase in surface flows of about 700 L m^{-1} [16,17]. Assuming equivalent

TABLE III. ET estimates (mm) for zones (Figure 2 and TABLE II) within the groundwater model domain at the Tuba City UMTRCA site. Numbers in parentheses are standard errors of means. ET from the cell (Zone 4) was assumed to equal PPT.

	Year													
Zone	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**Mean**
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						193 (2)						175 (1)		184 (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	286 (69)	240 (57)	276 (68)	296 (75)	291 (73)	284 (70)	264 (66)	292 (73)	298 (77)	258 (63)	317 (81)	264 (64)	274 (65)	280 (6)
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	**114**	**157**	**83**	**153**	**93**	**177**	**135**	**160**	**112**	**114**	**166**	**68**	**142**	**129**
PPT	**148**	**113**	**119**	**131**	**162**	**77**	**100**	**159**	**126**	**84**	**186**	**80**	**200**	**130**

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 about 350 L m^{-1}, in good agreement with the model.

DISCUSSION

At the Tuba City UMTRCA site, ET and PPT in the GMD appear to be in balance over long time periods. This is similar to results for the Monument Valley site [11] and supports the accuracy of the ET algorithm. At Tuba City, we assumed that little or no overland flow exits the GMD, except throughflow in Moenkopi Wash, and only a small fraction of PPT falling within the GMD seeps into Moenkopi Wash.

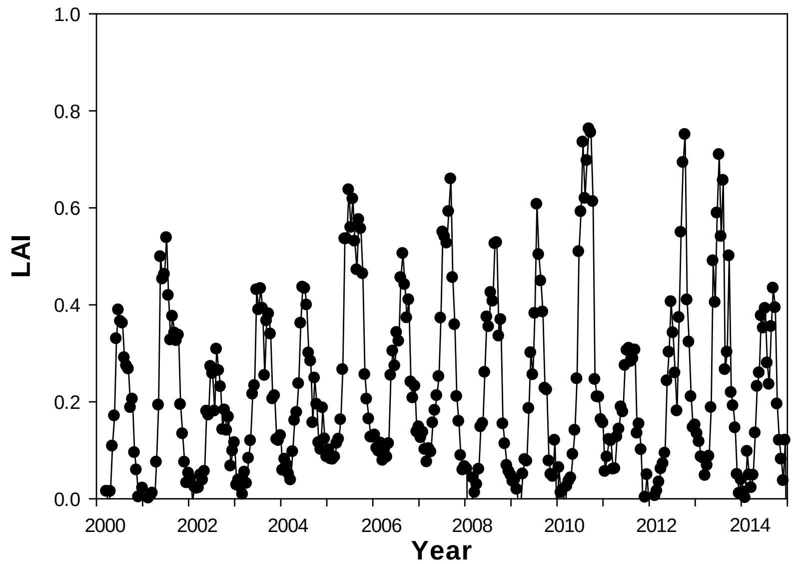

Fig. 3. Green LAI within the Tuba City groundwater model domain as determined using MODIS Enhanced Vegetation Index data.

This study demonstrated the important role that vegetation plays in regulating ET in sparse desert environments. Despite the fact that LAI was under 0.8 [35] 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. For example, in 2005 during the period of reduced grazing pressure, PPT was only 77 mm and ET was 177 mm, but in 2004, PPT was 162 mm and ET was only 93 mm, and over the 2-year period, ET and PPT were more nearly balanced.

The ATCA/SAVE vegetation in Zones 6 and 8, which might otherwise intercept groundwater flow toward the wash, has been heavily overgrazed and does not

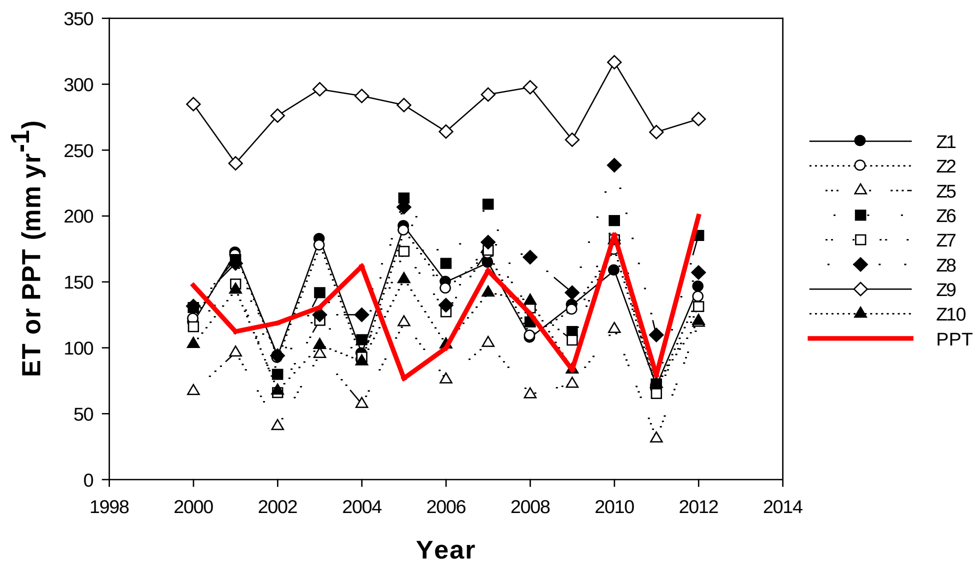

Fig. 4. PPT and ET by vegetation zone within the Tuba City site groundwater model domain. Zone Z3, the disturbed area immediately surrounding the disposal cell, and zone Z4, the rock-covered disposal cell, were excluded because MODIS EVI was not used to estimate ET in these zones.

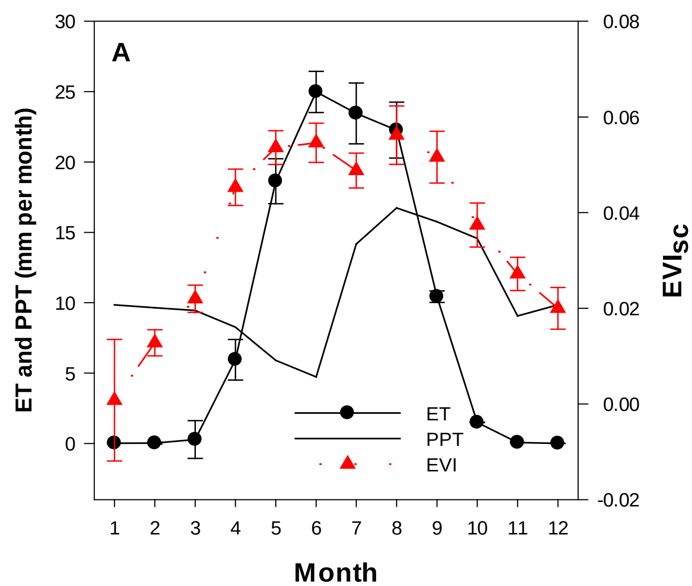

Fig. 5. Mean monthly ET (closed circles), PPT (solid line), and the EVI (red line and symbols) across vegetation zones and years, 2000–2012, within the Tuba City groundwater model domain. Bars are standard errors of means.

currently support ET much above PPT. Enhancing ET through grazing management might be an effective way to tip the water balance toward discharge rather than recharge. For example, at the Monument Valley site, a natural ATCA/SAVE zone protected from grazing for 10 years increased in ET from 2.9 millimeters per day (mm d^{-1}) to 13.1 mm d^{-1} in summer, as compared to a grazed ATCA/SAVE zone outside the livestock fence [11,13]. Hence, fencing ATCA/SAVE Zones 6 and 8 at Tuba City could potentially increase ET from 153 mm yr^{-1} to at least 500 mm yr^{-1}, resulting in a net groundwater discharge of about 370 mm yr^{-1}. Over the 35 ha of Zone 6, this would result in 0.13 Mm^3 yr^{-1} of discharge, similar to groundwater volumes pumped and treated at the site before 2015. Another opportunity to reduce groundwater flow is to more effectively restore Zone 5, for which ET is consistently below PPT. Previous studies show that transplanting of shrubs can enhance plant cover [36,37].

CONCLUSION

Temporal and spatial variability in the type and abundance of vegetation at desert waste disposal sites can influence groundwater recharge and discharge; therefore, land use management should also be factored into efforts to characterize, model, and remediate contaminated groundwater. 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. Episodes of heavy grazing caused groundwater recharge in upland vegetation and reduced discharge in desert phreatophyte vegetation. Grazing management might otherwise preclude recharge in upland areas, enhance discharge by desert phreatophytes and, thereby, potentially help control groundwater flow.

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