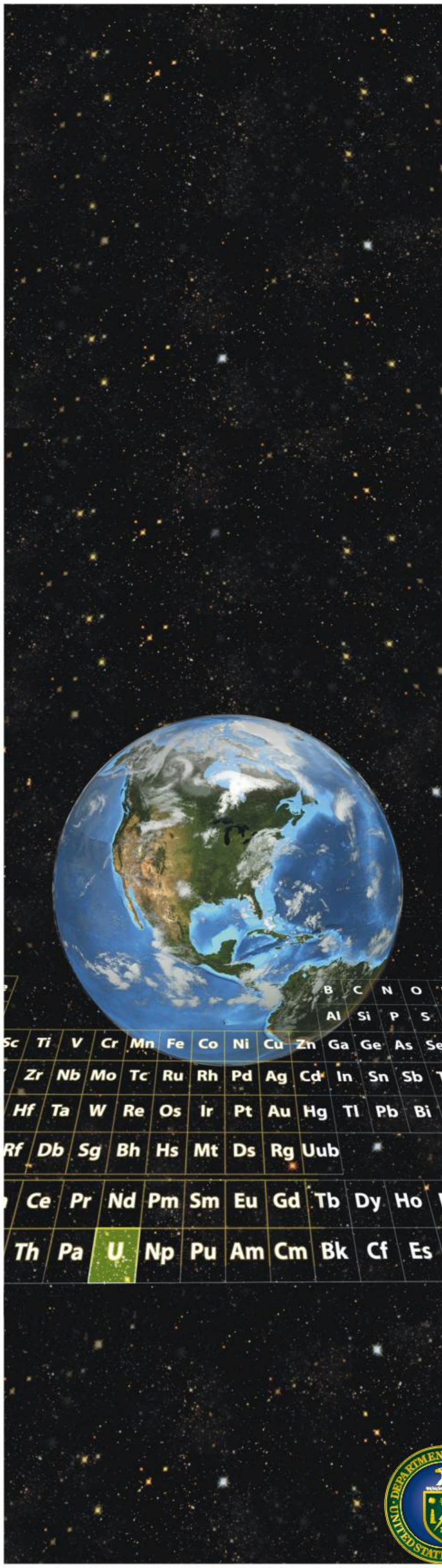
LMS/TUB/S13751
ESL-RPT-2016-02

Environmental Sciences Laboratory



Evapotranspiration Dynamics and Effects on Groundwater Recharge and Discharge at the Tuba City, Arizona, Disposal Site

February 2016

Prepared for
U.S. DEPARTMENT OF ENERGY | Legacy Management

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Abbreviations

ATCA	*Atriplex canescens*
DOE	U.S. Department of Energy
ET	evapotranspiration
ET_o	potential evapotranspiration
EVI	Enhanced Vegetation Index
GMD	groundwater model domain
ha	hectare
LAI	leaf area index
m	meters
mm d^{-1}	millimeters per day
mm yr^{-1}	millimeters per year
Mm^3 yr^{-1}	million cubic meters per year
MODIS	Moderate Resolution Imaging Spectrometer (sensors on the Terra satellite)
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
PPT	precipitation
RSE	relative standard error
SAVE	*Sarcobatus vermiculatus*
SE	standard error
UMTRCA	Uranium Mill Tailings Radiation Control Act of 1978

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Executive Summary

The U.S. Department of Energy Office of Legacy Management is evaluating groundwater flow and contaminant transport at a former uranium mill site near Tuba City, Arizona. We estimated effects of temporal and spatial variability in evapotranspiration (ET) on recharge and discharge within a groundwater model domain (GMD) as part of this evaluation. We used remote sensing algorithms and precipitation (PPT) data to estimate ET and the ET/PPT ratios within the 3531 hectare GMD. For the period from 2000 to 2012, ET and PPT were nearly balanced (129 millimeters per year [mm yr^{-1}] and 130 mm yr^{-1}, respectively; ET/PPT = 0.99). However, seasonal and annual variability in ET and PPT were out of phase, and spatial variability in vegetation differentiated discharge and recharge areas within the GMD. Half of ET occurred during spring and early summer when PPT was low, and about 70% of PPT arriving in fall and winter was discharged as plant transpiration in the spring and summer period. Vegetation type and health had a significant effect on the site water balance. Plant cover and ET were significantly higher (1) during years of lighter compared to years of heavier grazing pressure, and (2) on rangeland protected from grazing compared to rangeland grazed by livestock. Heavy grazing increased groundwater recharge (PPT > ET over the 13-year period). Groundwater discharge (ET > PPT over the 13-year period) was highest in riparian phreatophyte communities but insignificant in desert phreatophyte communities impacted by heavy grazing. Grazing management in desert upland and phreatophyte communities may result in reduced groundwater recharge, increased groundwater discharge, and could be used to influence local groundwater flow.

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1.0 Introduction and Objectives

The revised groundwater flow model for the Tuba City, Arizona, Disposal Site includes estimates of evapotranspiration (ET). The types of vegetation and the influences of ET on groundwater hydrology vary within the model domain. Some plant species within the model domain, classified as phreatophytes, survive by extracting groundwater. ET within these plant communities can result in a net discharge of groundwater if ET exceeds precipitation. Other upland desert plants within the model domain survive on meteoric water, potentially limiting groundwater recharge if ET is equivalent to precipitation. For all plant communities within the model domain, excessive livestock grazing or other disturbances can tip the balance to a net groundwater recharge.

This study characterized and mapped vegetation within the groundwater model domain (GMD) at the Tuba City site, and then applied a remote sensing algorithm to estimate ET for each vegetation zone. The study was designed to address five objectives:

1. Characterize and delineate different vegetation or ET zones within the GMD, focusing on the separation of plant communities with phreatophytes that survive by tapping groundwater and upland plant communities that are dependent on precipitation.
2. Refine a remote sensing method, developed to estimate ET at the Monument Valley, Arizona, Site, for application at the Tuba City site.
3. Estimate recent seasonal and annual ET for all vegetation zones, separating phreatophytic and upland plant communities within the Tuba City GMD.
4. For selected vegetation zones, estimate ET that might be achieved given a scenario of limited livestock grazing.
5. Analyze uncertainty of ET estimates for each vegetation zone and for the entire GMD.

2.0 Literature

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 millimeter per year [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 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 ET to PPT often approaches 1.0, as most 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 U.S. 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 Title 40 *Code of Federal Regulations* Part 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 GMD (DOE 2015a) of an UMTRCA site near Tuba City, Arizona, where uranium, nitrate, and sulfate have migrated in shallow groundwater away from the site (DOE 1998). 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.

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. However, spatial and temporal heterogeneity in terrestrial vegetation creates high variability in ET (Frank and Inouye 1994, Stephenson 1998). 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 to 2012 within the GMD at the Tuba City UMTRCA site.

3.0 Relevant Site History

The uranium ore processing mill operated at the site from 1956 to 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 hectares (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-centimeter-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 consists of 37 recovery wells extracting about 0.3 cubic meter per minute encompassing an area of about 40 ha (DOE 2015b). Contaminated water was treated by distillation and returned to the aquifer through an infiltration trench, with brine piped to an evaporation pond (DOE 2015b). 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 2015b).

4.0 Materials and Methods

4.1 Study Site

The Tuba City climate is arid with mean winter low temperatures of −6 °C and summer highs of 34 °C (Western Regional Climate Center, http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?aztuba). ET_o is about 1820 mm yr^{-1}, 11 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 meters (m) above sea level, about 6 kilometers north of U.S. Highway 160, to Moenkopi Wash at 1425 m above sea level. 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 2015a) where a 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 2015b). For most of the GMD, up to 7 m of dune sand mantles the Navajo Sandstone; terrace alluvium underlies the disposal cell (DOE 2015b).

4.2 Plant Associations and Vegetation Mapping

The composition and abundance of plant communities generally vary across a landscape as a continuum rather than as uniform units, although discrete physical boundaries can occur, such as escarpments or abrupt changes in soil properties. Consequently, delineating plant communities in areas without discrete physical boundaries can be somewhat arbitrary.

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. We used a modified Relevé method to estimate species abundance in selected stands[1], and then grouped and classified stands as plant associations[2] (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.

4.3 Remote Sensing Method

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, (http://daac.ornl.gov/cgi-bin/MODIS/GLBVIZ_1_Glb/modis_subset_order_global_col5.pl), which displays the footprint of MODIS pixels on high-resolution satellite imagery so the user can pinpoint areas of interest in the landscape.

We modified the algorithm for fourwing saltbush (*Atriplex canescens*, acronym ATCA) and black greasewood (*Sarcobatus vermiculatus*, acronym SAVE) using 2 years of sap flux measurements at the Monument Valley UMTRCA site (Glenn et al. 2008, Breshlof et al. 2013) as follows:

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

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

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

[1] A stand is a basic unit for identifying vegetation in a landscape. A stand has compositional and structural integrity. The composition of species is similar throughout the stand and different from the composition in adjacent stands. The relative abundance and horizontal spacing of species are also similar within a stand and different from those of adjacent stands.

[2] A plant association is a class of plant community that is generally a synthesis of stands and has a consistent floristic composition, a uniform appearance, a distribution that reflects a consistent mix of environmental factors (e.g., soils, history of use, habitat), and can be shown to be different from other associations.

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 (°C) for each 16-day period of MODIS data collection. T_{max} was better correlated with ET at the tower sites than any other meteorological variable or combination of variables, including ET_o. T_{max} data are widely available from National Oceanic and Atmospheric Administration (NOAA) Cooperative Observer stations around the United States; hence, this method can be applied to areas without full meteorological stations. The first term in Equation 1, $(1 - e^{-1.63*EVIsc})$, is based on the equation for the absorption of light by a canopy, with EVI_{sc} replacing leaf area index (LAI) 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 Equation 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 millimeters per day (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 does go to zero, and because the sap flux meters used for validation only measure the transpiration component of ET, whereas moisture flux towers measure both transpiration and direct evaporation. 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. For example, mean PPT was 154 mm yr^{-1} (standard error [SE] = 14), and the ET estimate was 149 mm yr^{-1} (SE = 14) from 2000 to 2010 for 200 hectares of sparse ATCA shrubland at the Monument Valley site, indicating that the method produced reasonable ET estimates for that location (Breshlof et al. 2013).

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). Landsat 5–based Normalized Difference Vegetation Index (NDVI) images for July 15, 2005, and July 15, 2011, were obtained from the USGS Land Satellites Data System Science Research and Development website (http://espa.cr.usgs.gov/). 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 $NDVI_{min}$ and $NDVI_{max}$ derived from each image. We then calculated ET as:

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

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). ET_o was 7.6 mm d^{-1} for both image dates, and mean annual ET_o was 1438 mm yr^{-1}.

With three exceptions, our Tuba City ET analyses used MODIS EVI pixels corresponding to shapefiles for each zone in Figure 2 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 a hypothetical groundwater divide. Our analysis of Zone 9 (the riparian bottomland) differed from larger zones because it was narrower than the width of a MODIS pixel. 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 by placing a point-intercept grid over the pixel outline using Adobe Photoshop. We then weighted the EVI value based on proportions of pixels that were riparian phreatophytes, terrace phreatophytes, and upland desert vegetation. Zone 3, the area inside the inner site fence, was analyzed by Landsat imagery because its small size and the presence of buildings and evaporation ponds made it impossible to obtain a representative MODIS pixel. A shapefile encompassing the vegetated area around the cell was prepared, and annual ET for 2005 and 2011 was calculated using Equation 3 and an ET_o value of 1438 mm yr^{-1}. 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):

$$LAI = 3.21EVI_{sc} \tag{4}$$

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.

4.4 Impact of Grazing on ET

Although Navajo Nation rangeland has historically been heavily grazed (Pellant et al. 2004), temporary but marked reductions in grazing pressure occurred during a 1999–2009 drought period (Redsteer et al. 2010). In 2001, stocking rates were an estimated 41% greater than authorized (Navajo Nation Department of Water Resources 2003). Overstocking led to a mass die-off of livestock during the drought—30,000 cattle perished from 2001 to 2002—approximately 50% of the total population (Redsteer et al. 2010). In 2003, a Navajo Nation drought contingency plan called for ranchers to reduce herd sizes to numbers appropriate for drought conditions (Navajo Nation Department of Water Resources 2003). Livestock grazing on rangeland in the vicinity of the GMD likely dropped from high levels for 2000 to 2002, to much lower levels for 2005 to 2007 (Redsteer et al. 2010), 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, using MODIS and Landsat imagery. 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}) (Western Regional Climate Center, http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?aztuba). We also contrasted ET for both years and for two adjacent areas within Zone 5: 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 shapefiles and estimated ET from Landsat NDVI images for both areas using Equation 3.

4.5 Statistical Methods and Other Data

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). We obtained T_{max} and PPT data as monthly means for the period 2000–2012 from the Tuba City NOAA Cooperative station (028792). Data collection at the station ended after 2012, so comparisons of ET and PPT were confined to the period 2000–2012.

Net groundwater recharge or discharge is usually a small number calculated 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 SE of annual means. Annual means of ET are not random samples from a fixed population; rather, ET is expected to vary annually according to PPT, degree of grazing, and other factors. Therefore, the relative standard error (RSE) for each year is a better estimate of the variance among pixel values and, if aggregated over years, can represent the degree of random error in the estimates across years. Equations are:

$$\mathrm{SE} = \mathrm{SD}/N^{0.5} \tag{5}$$

$$\mathrm{RSE} = \mathrm{SE}/\mathrm{Mean\ ET} \tag{6}$$

Where SD is the standard deviation and *N* is the sample size (in this case 13 years). We squared each RSE to convert to variances; added them together over the 13-year period to get total variance over all years; divided by N^2 (169) to get the variance of the mean across years; then took the square root of that variance to get the standard error across years for each zone. We then took mean aggregated SE for all zones, weighted for the area of each site, and determined RSE across zones and years. We multiplied this RSE by mean ET for the entire groundwater domain to get SE as the groundwater domain ET estimate.

5.0 Results

5.1 Plant Species, Associations, and Vegetation Zone Map

Table 1 lists plant species identified within the GMD. The list includes Navajo names in addition to scientific names, common English names, and acronyms. Figure 1 illustrates (1) changes in the abundance of dominant plant species, as estimated using the Relevé method, along a transect between the disposal cell and Moenkopi Wash, and (2) the subjective separation of different plant associations along the transect. We used this approach to classify plant associations named for their dominant two species. These plant associations, combined with other landscape units, became the discrete vegetation zones we used to estimate and map vegetation/ET within the GMD (Table 2). We delineated vegetation zones by visual inspection of a June 11, 2014, QuickBird image, and then outlined the zones as polygons on a Google Earth Image (Figure 2).

Table 1. Plant species identified within the groundwater model domain at the Tuba City site.

Scientific Name[a]	Acronym[b]	Common Name[c]
Trees and Shrubs		
Atriplex canescens (Pursh) Nutt.	ATCA	fourwing saltbush, chamizo, Díwózhii_beii
Atriplex confertifolia (Torr. & Frém.) S. Watson	ATCO	shadscale, spiny saltbush, Dá'ák'óózh deeníní
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'iiłtsoí nitsaaíí
Gutierrezia sarothrae (Pursh) Britton & Rusby	GUSA	broom snakeweed, Ch'il_diilyésiitoh
Opuntia polyacantha Haw.	OPPO	plains prickly pear, Hosh niteelí
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
Agropyron cristatum (L.) Gaertn.	AGCR	crested wheatgrass
Aristida purpurea Nutt.	ARPU	purple threeawn, Dlóóbibé'ézhóó'
Bouteloua barbata Lag.	BOBA	sixweeks grama
Bouteloua eripoda (Torr.) Torr.	BOER	black grama
Bromus rubens L.	BRRU	red brome
Bromus tectorum L.	BRTE	cheatgrass brome, Zéé'iilwo'ii
Muhlenbergia pungens Thurb.	MUPU	sandhill muhly
Munroa squarrosa (Nutt.) Torr.	MUSQ	false buffalograss
Panicum capillare L.	PACA	witchgrass
Pleuraphis jamesii Torr.	PLJA	galleta, curly grass, T_'oh _ichí'í
Sporobolus airoides (Torr.) Torr.	SPAI	alkali sacaton
Sporobolus contractus A.S. Hitchc.	SPCO	spike dropseed
Sporobolus cryptandrus (Torr.) A. Gray	SPCR	sand dropseed
Sporobolus flexuosus (Thurb. ex Vasey) Rydb.	SPFL	mesa dropseed
Vulpia octoflora (Walter) Rydb.	FEOC	sixweeks fescue
Forbs		
Amaranthus albus L. Wats.	AMAL	prostrate pigweed Naazkaadii
Ambrosia confertiflora DC.	AMCO	weakleaf bur ragweed
Astragalus wingatanus S. Watson	ASWI	Fort Wingate milkvetch, Dibéhaich'iidii
Chamaesyce chaetocalyx (Boiss.) Woot. & Standl.	CHCH	bristlecup sandmat
Conyza Less.	CO sp.	horseweed
Cryptantha crassisepala (Torr. & A. Gray) Greene	CRCR	thicksepal cryptantha
Eriogonum subreniforme S. Watson	ERSU	Stoke's buckwheat

Table 1 (continued). Plant species identified within the groundwater model domain at the Tuba City site.

Scientific Name[a]	Acronym[b]	Common Name[c]
Eriogonum wetherilli Eastw.	ERWE	Wetherill's buckwheat
Eriogonum wrightii Torr. ex Benth.	ERWR	Wright's buckwheat
Lupinus L. species	LU sp.	lupine, Azee' bíni'í
Lygodesmia arizonica S. Tomb	LYAR	Arizona skeletonplant
Mentzelia sp. L.	ME sp.	stickleaf Íiłtł'ihii
Pectis angustifolia Torr.	PEAN	lemonscent
Phacelia ivesiana Torr.	PHIV	Ives' phacelia
Plantago patagonica Jacq.	PLPA	wooly plantain
Salsola kali L.	SAIB	Russian thistle, tumbleweed, Ch'il deeníní
Solanum physalifolium Rusby	SOPH	hoe nightshade
Sphaeralcea rusbyi Gray	SPRU	Rusby's globemallow, Azee' nt_'iní
Stephanomeria exigua Nutt.	STEX	wire lettuce

[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 (Mayes and Lacy 1989, Dodge 1985, Elmore and Janish 1976, Dunmire and Tierney 1997, and Whitson et al. 2002 Natural Resource Conservation Service PLANTS database, http://plants.usda.gov/java/).

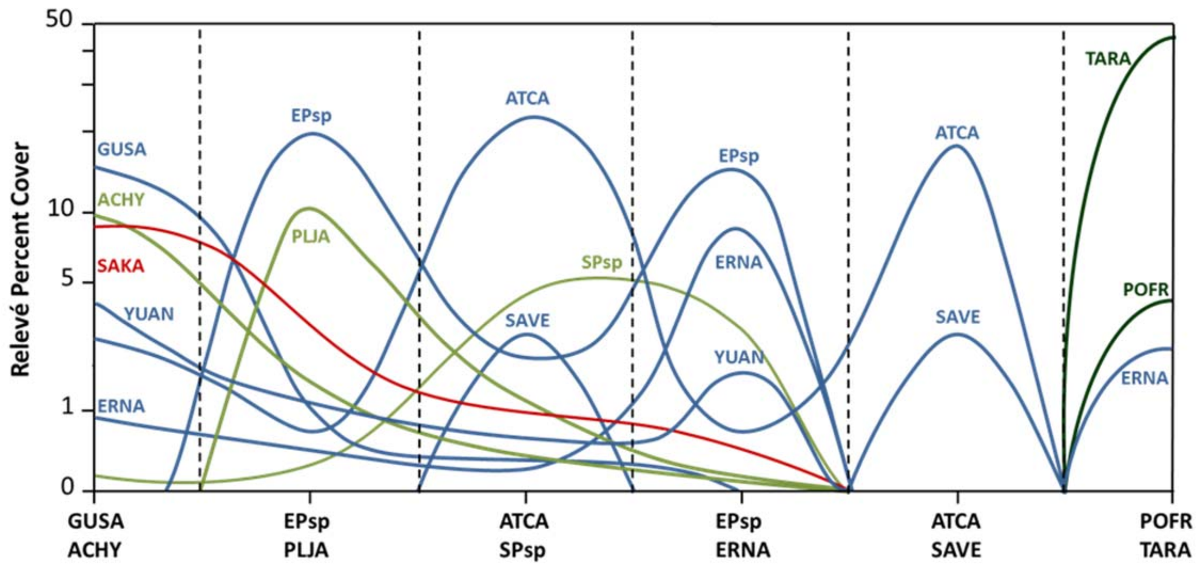


Figure 1. Distributions of dominant plant species and delineation of plant associations along a vegetation gradient (transect) between the Tuba City disposal site (left side) and Moenkopi Wash (right side). Plant acronyms are defined in Table 1. Small letters "sp" indicate that more than one species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

Using this process, we mapped three phreatophytic vegetation zones and six upland vegetation zones (Table 2, Figure 2). 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 inter-dune areas. This pattern is likely an indication of heavy grazing. The cool season grass *Achnatherum hymenoides* dominates undisturbed sites in this region, with lower cover of *Ephedra* species and less evidence of coppice dune formation (Hodgkinson 1983).

Phreatophyte communities potentially accessing groundwater occur at three places within the GMD. Four phreatophyte species were observed: SAVE, ATCA, Fremont cottonwood (*Populus fremontii*, or POFR), and saltcedar (*Tamarix ramosissima*, or 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 Figure 2). ATCA and SAVE also grow on a bench above Moenkopi Wash (Zone 8). ATCA and SAVE may be rooted in and 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 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).

Table 2. 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 inter-dunes.
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**	

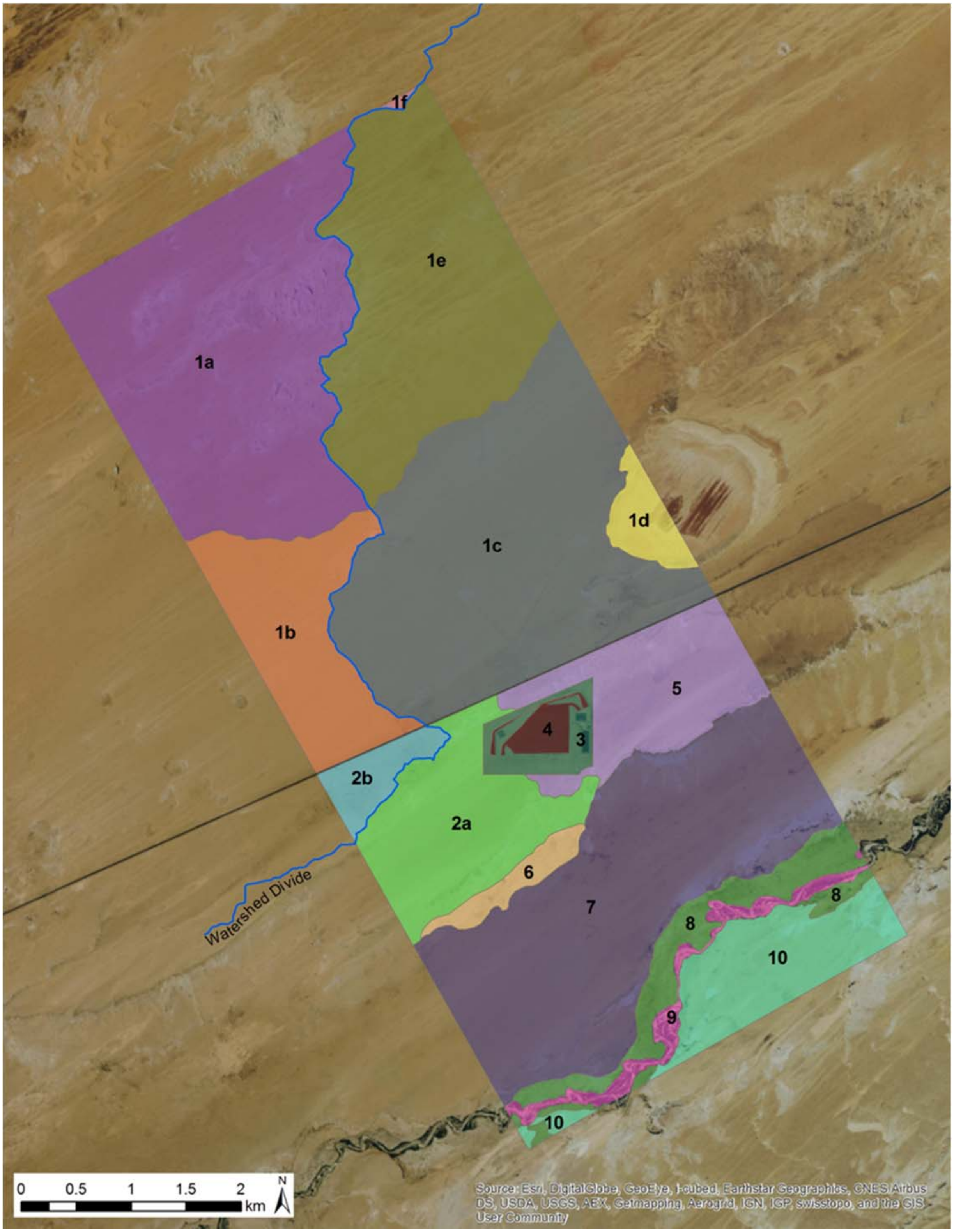


Figure 2. ET zones within the groundwater model domain at the Tuba City UMTRCA site. Blue line is a surface water divide. Zones 8 and 9 are in Moenkopi Wash. Soil was removed from Zone 1d and used for the engineered disposal cell cover (Zone 4).

5.2 LAI and ET by Vegetation Zone

In desert areas, nearly all precipitation is expected to be returned to the atmosphere as either soil evaporation or plant transpiration (Huxman et al. 2004). 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 2). 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, with peak summer values ranging from 0.32 in 2011 to 0.76 in 2010 (Figure 3).

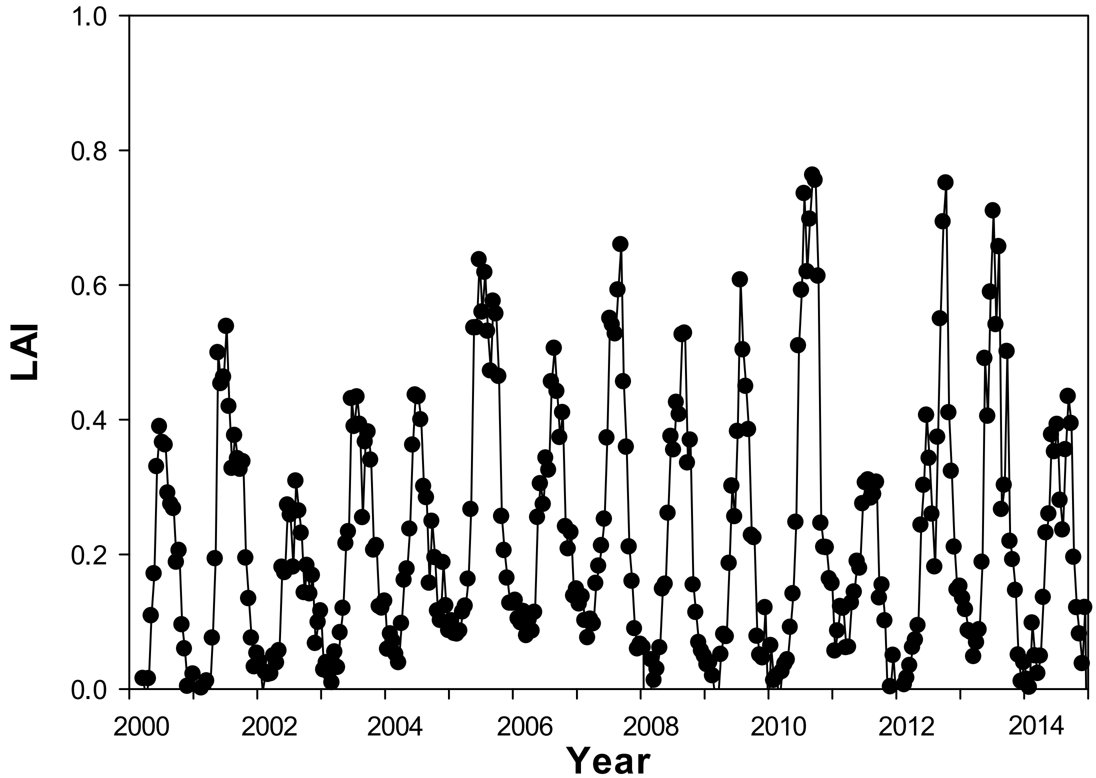


Figure 3. Green LAI within the Tuba City groundwater model domain as determined using MODIS Enhanced Vegetation Index data.

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 (Table 2). 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, 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) was higher than PPT in 2005 and 2011. However, 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 withdrawal rate of 0.15 m 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 and 5, with sparse upland vegetation, an estimated 0.132 $Mm^3\ yr^{-1}$ of groundwater recharge occurred from 2000 to 2012.

5.3 Annual and Seasonal Variability in ET

As with LAI, ET was also variable across years (Figure 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 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 (Figure 5A). 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. Figure 5B 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, with 20.3 mm directly evaporating.

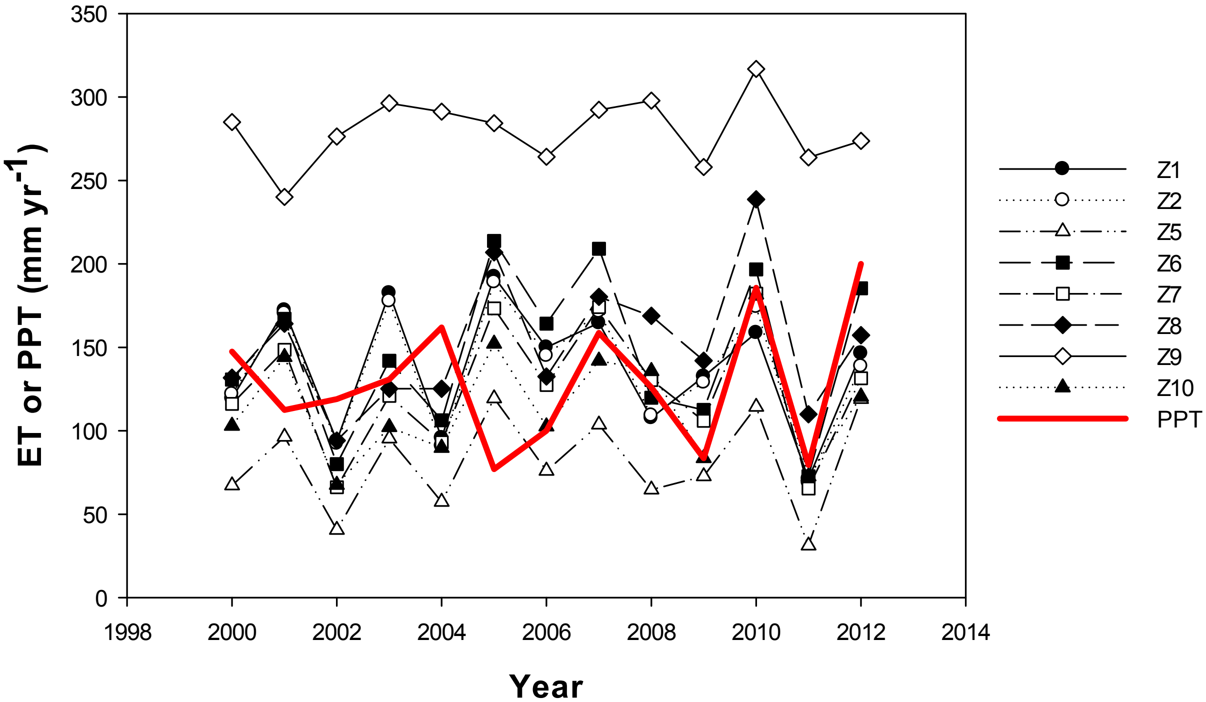
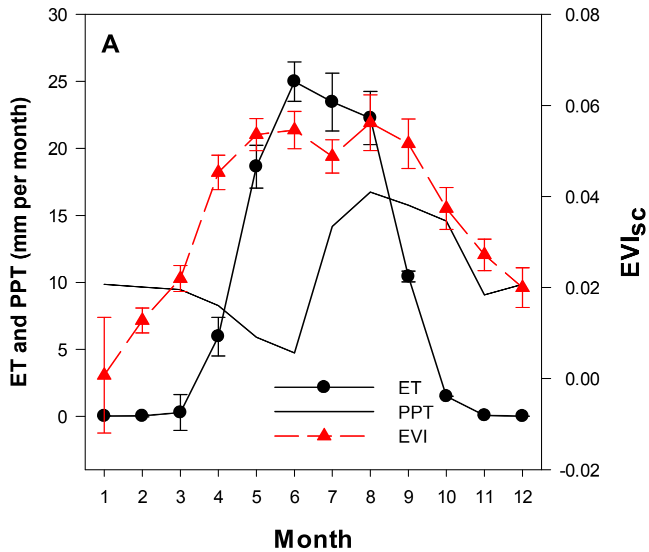


Figure 4. PPT and ET by vegetation zone within the Tuba City site groundwater model domain. Zone Z3, the disturbed area immediately surrounding the disposal cell, and zone Z4, the rock-covered disposal cell, were excluded because MODIS EVI was not used to estimate ET in these zones.

5.4 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. We evaluated the influence of grazing. ET for the entire GMD was 181 mm yr^{-1} in 2005, a year with lower grazing pressure, and 69 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 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 (Table 2). Landsat images also indicate that ET was higher for most areas within the GMD in 2005 than in 2011 (Figure 6). Note the higher ET immediately south of the cell in Zone 3, presumably enhanced by runoff from the cell. Note also the higher ET in the upland areas north and upgradient of the GMD compared to most areas within the GMD.



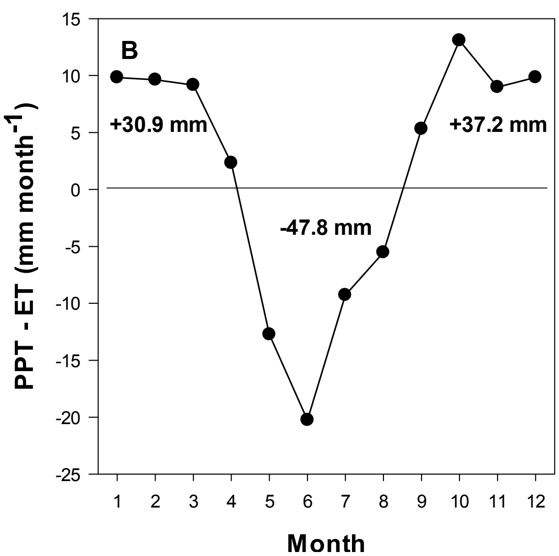


Figure 5. (A) Mean monthly ET (closed circles), precipitation (solid line), and the Enhanced Vegetation Index (red line and symbols) across vegetation zones and years, 2000–2012, within the Tuba City groundwater model domain. Bars are standard errors of means. (B) Difference between monthly PPT and monthly ET.

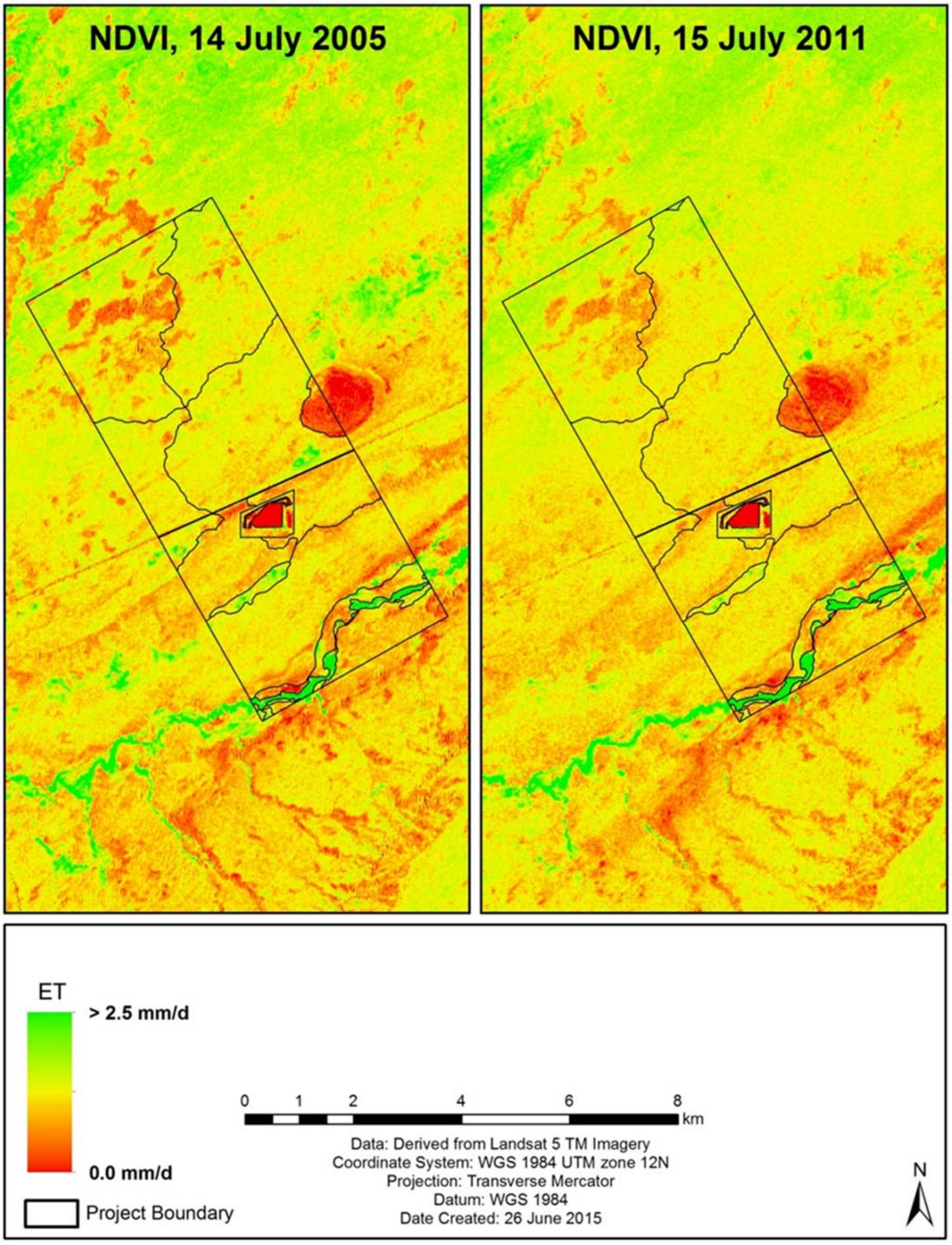


Figure 6. Landsat 5 ET maps contrasting July 2005, a year of relatively light grazing pressure, with July 2011, a year of heavier grazing pressure within the Tuba City groundwater model domain. Soil was removed from the large, circular, low-ET area northeast of the UMTRCA site and used for the engineered disposal cell cover.

We also compared areas within Zone 5 that had been protected from grazing for 30 years inside the site perimeter fence with an adjacent area outside the fence (Table 3, Figure 7). ET in the grazed area outside the site fence was 55% higher in 2005 than in 2011 ($P < 0.001$); however, ET values inside the fence in 2005 and 2011 were not significantly different ($P = 0.46$).

Table 3. ET estimates (mm) for vegetation zones within the groundwater model domain at the Tuba City UMTRCA site. Numbers in parentheses are standard errors of means. 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.

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						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[a]	**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**

[a] Weighted by area per zone

Table 4. Estimated ET of natural vegetation areas east of the Tuba City UMTRCA disposal cell in Zone 5. Grazing occurs in the marked area outside the fence; the area inside the fence has been protected from grazing for 30 years. Means followed by different letters are significantly different (P < 0.05) based on the Tukey post-hoc test with individual pixel values in each area used as replicates.

Year	Treatment	ET (mm d^{-1})	SD
2005	Outside Fence	0.313a	0.0120
2005	Inside Fence	0.287b	0.0117
2011	Outside Fence	0.202c	0.0064
2011	Inside Fence	0.284b	0.0076

SD = standard deviation

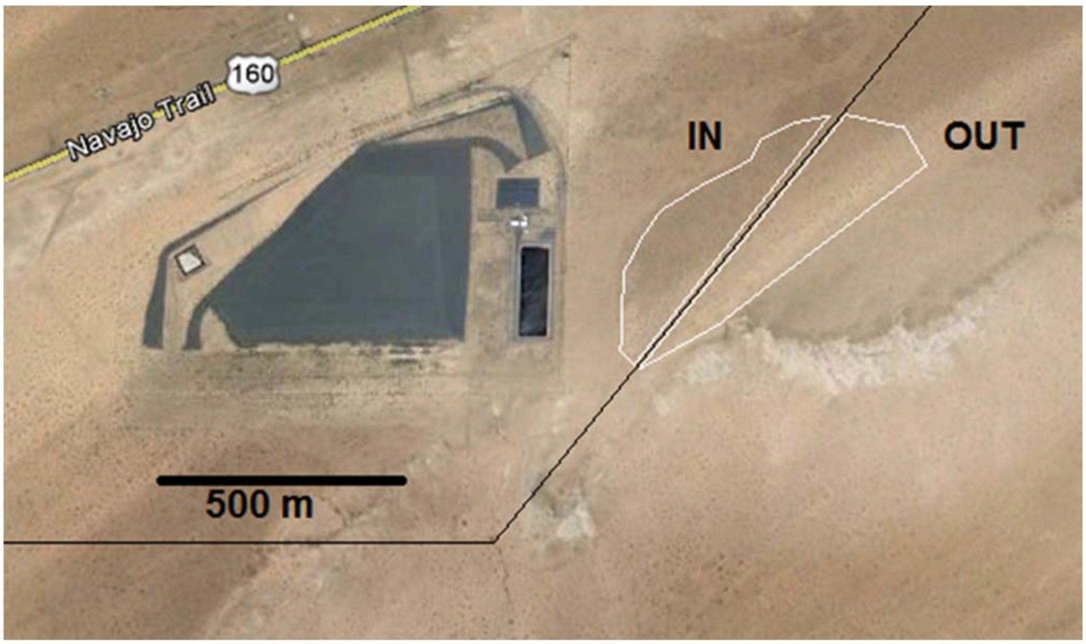


Figure 7. Areas of natural vegetation inside (In) and outside (Out) of a perimeter fence at the Tuba City UMTRCA site.

5.5 Reference Area ET

Discharge of groundwater in vegetation zones with desert phreatophytes might be higher if these areas were protected from livestock grazing. We tested this hypothesis by comparing estimates of ET within the groundwater model domain with ET in reference areas. Phytoremediation test plots with ATCA and SAVE at the Monument Valley UMTRCA site, both grazed plots and plots protected from grazing, and a dense stand of grazed SAVE at Red Lake east of Tuba City, were selected as reference areas. We compared annual ET rates for all vegetation zones between the disposal cell and Moenkopi Wash, including Zones 6 and 8, with ET rates for the reference areas.

Table 5. ET estimates for ET/vegetation zones downgradient of the Tuba City disposal cell and comparison data from Red Lake and Monument Valley reference areas. Values are means and standard errors for years 2000–2012 unless otherwise stated. SAVE at Red Lake is a natural stand; ATCA and SAVE at Monument Valley were natural stands protected from grazing by fencing (Exclosure), planted stands inside protected from grazing within the site boundary fence (Inside), and natural stands outside the site fence and not protected from grazing (Outside). The Whole Site at Monument Valley (MV) refers to the fenced source area (8 ha) plus the natural vegetation outside the site fence (about 200 ha).

Vegetation/ET Zones	Precipitation	ET rate (mm yr^{-1})
Tuba City Data:		
Zone 2a	130 (11)	120 (11)
Zone 6	130 (11)	153 (14)
Zone 7	130 (11)	126 (11)
Zone 8	130 (11)	152 (11)
Zone 9	130 (11)	280 (6)
Comparison Data:		
Red Lake SAVE	129 (11)	176 (15)
MV Exclosure SAVE (2007–2010)	175 (27)	724
MV Exclosure ATCA (2007–2010)	175 (27)	204
MV Outside SAVE (2005–2010)	166 (25)	233 (28)
MV Outside ATCA (2005–2010)	166 (25)	170 (21)
MV Inside Fence, All (2005–2010)	166 (25)	259 (20)
MV Whole Site (2005–2010)	166 (25)	186 (19)

6.0 Discussion

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 (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). We assumed that 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. 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. 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 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.

The GMD is not a closed basin, as an unknown amount of groundwater recharge occurs from the uplands north of the GMD (Jacobs Engineering Group 1994). This groundwater supports phreatophytes in Zones 6, 8, and 9. However, the vegetation in Zones 6 and 8, which might otherwise intercept the flow toward the wash, has been heavily overgrazed and does not currently support ET much above PPT. Enhancing ET through control of grazing might be an effective way to tip the water balance toward discharge rather than recharge, to reduce the movement of water and contaminants toward the wash. For example, at the Monument Valley site, a natural ATCA/SAVE zone protected from grazing for 10 years increased in F_c from 0.15 to 0.75, increased in LAI from 0.58 to 2.88, and increased in ET from 2.9 mm d^{-1} to 13.1 mm d^{-1} in summer, as compared to a grazed ATCA/SAVE zone outside the livestock fence (Glenn et al. 2008, Breshlof et al. 2013). Fencing the ATCA/SAVE stand in Zone 6 in the Tuba City UMTRCA site GMD could potentially increase ET from 153 mm yr^{-1} to at least 500 mm yr^{-1} (about one-third of ET_o) based on results at the Monument Valley site, 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. Controlling grazing and rehabilitating the vegetation in Zone 8 could increase discharge even further. Another opportunity to reduce groundwater flow is to more effectively restore Zone 5, for which ET is consistently below PPT. Studies at the Tuba City and Monument Valley UMTRCA sites show that transplanting of shrubs is more effective than direct seeding for enhancing plant cover (Glenn et al. 2001, McKeon et al. 2006), and Zone 5 is already fenced to exclude grazing.

7.0 Conclusion

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, episodes of heavy grazing caused groundwater recharge in upland range vegetation and reduced discharge in desert phreatophyte stands. Grazing management might otherwise preclude recharge in upland areas and enhance discharge in stands of desert phreatophytes and, thereby, potentially help control groundwater flow.

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9.0 Acknowledgements

This study and report are products of a DOE Office of Legacy Management (LM) collaboration with the University of Arizona (UA) and the U.S. Geological Survey (USGS). The concepts, design, and interpretation of results are largely products of the knowledge, creativity, and leadership of Dr. Edward Glenn, Department of Soil, Water and Environmental Science at UA. Chris Jarchow, USGS, served as the GIS analyst for the project. Richard Bush, DOE LM, serves as UMTRCA Manager for the Tuba City, Arizona, Disposal Site, and as Technical Manager for this study under the LM Applied Studies and Technology Program (AS&T). Jalena Dayvault is the LM director of AS&T.

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