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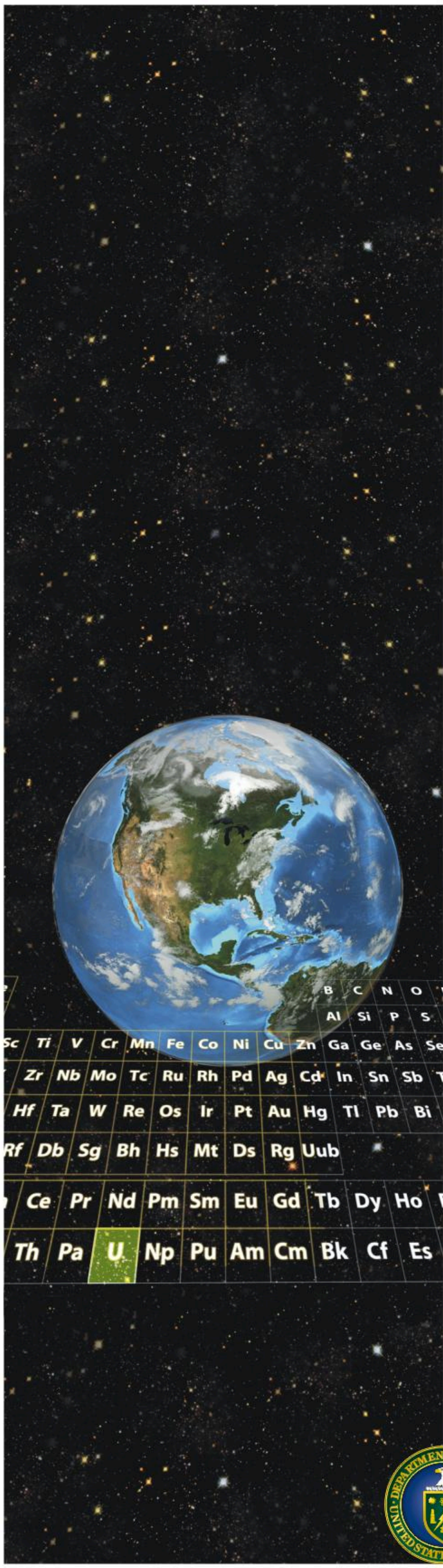

Evapotranspiration Within the Groundwater Model Domain of the Tuba City, Arizona, Disposal Site

Interim Report

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Abbreviations

ATCA	*Atriplex canescens*
ET	evapotranspiration
EVI	Enhanced Vegetation Index
ha	hectare
m	meter
mcm	million cubic meters
mm	millimeter
NDVI	Normalized Difference Vegetation Index
POFR	*Populus fremontii*
PPT	precipitation
RSE	relative standard error
SAVE	*Sarcobatus vermiculatus*
SE	standard errors
TARA	*Tamarix ramosissima*
UMTRCA	Uranium Mill Tailings Radiation Control Act
yr	year

1.0 Objectives

The revised groundwater model 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 task characterized and mapped vegetation within the groundwater model domain at the Tuba City, Arizona, Site, and then applied a remote sensing algorithm to estimate ET for each vegetation type. The task was designed to address five objectives:

1. Characterize and delineate different vegetation or ET zones within the groundwater model domain, 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 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 groundwater model domain.
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 groundwater model domain.

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2.0 Methods

2.1 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.

2.2 Development of the ET Algorithm

ET rates for the Tuba City groundwater model domain were estimated using a remote sensing algorithm developed for groundwater-dependent riparian plants in the southwestern United States (Nagler et al. 2005a,b), as modified and validated for desert plants at the Monument Valley site (Glenn et al. 2008; Bresloff et al. 2013). The algorithm is based on the Enhanced Vegetation Index (EVI) from the MODIS sensors on the Terra satellite. 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 EROS Data Center. We used the MOD13 product, which is a composite image over 16-day periods. Each pixel 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.

Our ET algorithm was developed by empirically relating MODIS EVI with meteorological data and ET measured at eddy covariance and Bowen ratio moisture flux towers at 13 riparian phreatophyte sites in Arizona and New Mexico. The algorithm was then modified for desert plants, *Sarcobatus vermiculatus* (black greasewood, or SAVE) and *Atriplex canescens* (fourwing saltbush, or ATCA), based on 2 years of sap flux measurement at the Monument Valley Uranium Mill Tailings Radiation Control Act (UMTRCA) site.

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[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 that can be shown to be different from other associations.

The equation is

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

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

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

EVI_{max} was set at 0.542, and EVI_{min} was 0.091, based on values from the 13 sites at which the algorithm was developed. The transformation results in bare soil having an EVI_{sc} of 0.0 and full vegetation having an EVI_{sc} of 1.0.

T_{max} is the mean daily maximum temperature (^{o}C) over 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 potential ET (ET_o). T_{max} data are widely available from National Oceanic and Atmospheric Administration (NOAA) Cooperative stations around the United States. The first term in Eq. 1 $(1 - e^{-1.63*EVIsc})$ is based on the equation for the absorption of light by a plant canopy, with EVI_{sc} replacing leaf area index in the formula. The second term, $0.882/[1 + e^{-(Tmax - 27.9)/2.57}]$, assumes a sigmoidal response of ET to T_{max}, with a center point at 27.9 ^{o}C. These equations were based on the observed response of phreatophyte ET to EVI and T_{max} at the tower sites, and numerical coefficients in Eq. 1 were derived from the equation of best fit by regression analysis. The original equation developed for riparian phreatophytes had an additional constant, 1.03 millimeters per day (mm day^{-1}), included 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 site because in that sparse vegetation area ET frequently does go to zero.

2.3 Application of the ET Algorithm at Tuba City

We obtained MODIS EVI pixels for the 13-year period from February 18, 2000 (first date of MODIS coverage), through 2012, and for the nine vegetation zones (Figure 2). For the smaller vegetation zones, 3–5 individual pixels (6.25 hectares [ha] each) located within each zone were acquired from the Oak Ridge National Laboratory (ORNL) DAAC site, which displays the footprint of each MODIS pixel on a high-resolution QuickBird image. Only pixels wholly contained within the zone were selected, and mean values were calculated and assumed to be representative of the entire zone. We followed this procedure to avoid having an “edge effect” when using shape files of the entire zone. For larger zones (i.e., north of U.S. 160 and south of Moenkopi Wash), we obtained 9 × 9 blocks of pixels (506 ha). MODIS pixels were wider than the riparian zone, so we obtained sample pixels in the widest portions of the riparian zone, and divided the pixel footprint as displayed on the high resolution ORNL QuickBird image into riparian and non-riparian areas by placing a point-intercept grid over the pixel outline. Then we corrected (increased) the EVI value according to how much of the pixel was riparian and how much was adjacent terrace or desert vegetation. We obtained T_{max} and precipitation (PPT) data as monthly means for the period 2000–2012 from the Tuba City NOAA Cooperative Station (028792).

MODIS has relatively coarse resolution. In order to compare ET patterns in more detail, we obtained Landsat 5 TM images (30-meter [m] resolution) for July 14, 2005, and July 15, 2011, representing years of relatively low and high grazing pressure, respectively. We converted red and near-infrared bands to at-surface reflectance values, then calculated the Normalized Difference Vegetation Index (NDVI) for each pixel. We calculated ET from NDVI by an algorithm developed for Landsat imagery by Groeneveld et al. (2007). NDVI was first scaled between bare soil and full vegetation cover similar to Eq. 2 but using values for $NDVI_{min}$ and $NDVI_{max}$ derived from each image. $NDVI_{min}$ values were 0.111 and 0.126 and $NDVI_{max}$ values were 0.826 and 0.843 for 2005 and 2011 images, respectively. 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). ET_o was 7.6 mm day^{-1} for both image dates.

2.4 Error Analysis

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 standard errors (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 give a fair representation of the degree of random error in the estimates across years. Equations are:

$$SE = SD/N^{0.5} \quad (4)$$

$$RSE = SE/\text{Mean ET} \quad (5)$$

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. Sites 1, 2, 5, 7, and 10 contributed the most to this analysis.

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3.0 Results and Discussion

3.1 Plant Species, Associations, and Vegetation Zone Map

Table 1 lists plant species identified within the groundwater model domain. The list includes Navajo names in addition to scientific, 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 groundwater model domain (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

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

Scientific Name[a]	Acronym[b]	Common Name[c]
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
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/). Navajo names are from Mayes and Lacy (1989).

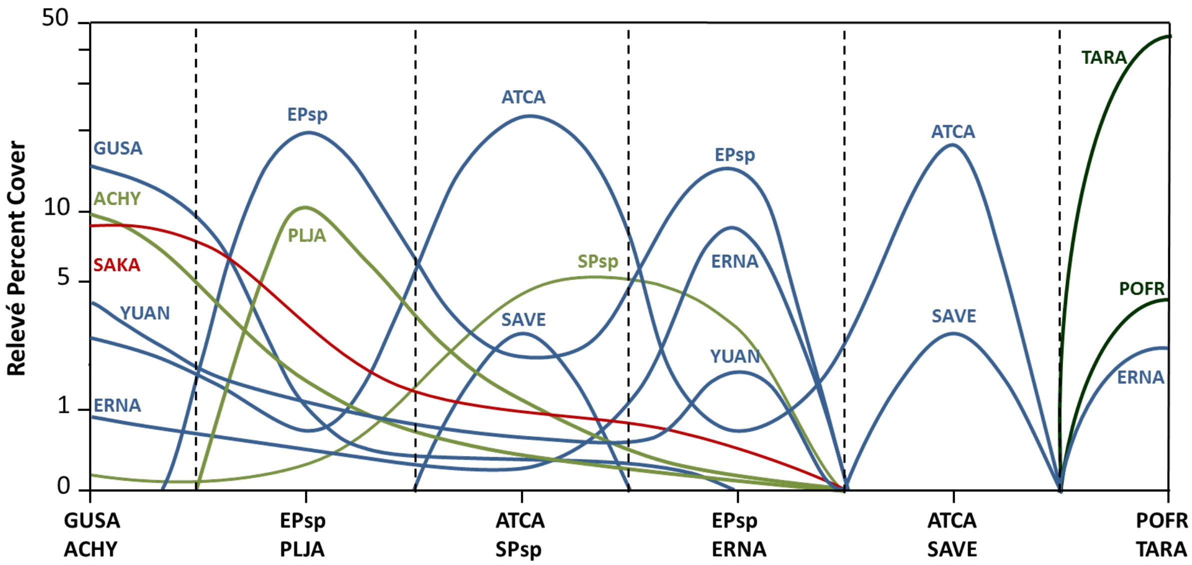

Figure 1. Distributions of dominant plant species and delineation of plant associations along a vegetation gradient (transect) between the Tuba City disposal site (left side) and Moenkopi Wash (right side). Plant acronyms are defined in Table 2. Small letters "sp" indicate that more than one species 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. The disposal cell is a separate zone. Four phreatophyte species were observed: black greasewood (*Sarcobatus vermiculatus*, or SAVE), fourwing saltbush (*Atriplex canescens*, or ATCA), Fremont cottonwood (*Populus fremontii*, or POFR), and saltcedar (*Tamarix ramosissima*, or TARA). Two of the species, the desert shrubs SAVE and ATCA, may be rooted in and transpiring (discharging) groundwater flowing toward Moenkopi Wash. SAVE and ATCA occur in two zones: Zone 6, roughly a third of the way between the disposal cell and Moenkopi Wash; and Zone 8, a terrace within 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 (Table 2).

Table 2. Vegetation/ET zones derived from field plant associations and mapping using QuickBird images

Vegetation/ET Zones	Acronym[a]	Dominant Species	Description
1. Uplands North of Highway160	–	–	This zone is a mixture of upland plant associations that have not been surveyed and delineated.
2. Mormon tea/ Galleta grass	EPsp/ PLJA	*Ephedra* species/ *Pleuraphis jamesii*	Mormon tea (EPsp) dominates regional coppice dune topography (Hodgkinson 1983). A native warm-season grass (PLJA) dominates the understory. Abundant PLJA indicates previous grazing.
3. Revegetated UMTRCA Site	ATCA	*Atriplex canescens*	Disturbed area immediately surrounding the disposal cell that has become revegetated primarily with ATCA.

Table 2 (continued). Vegetation/ET zones derived from field plant associations and mapping using QuickBird images

Vegetation/ET Zones	Acronym[a]	Dominant Species	Description
4. Disposal Cell	–	–	Rock-covered disposal cell. For the purpose of this study, we assumed all precipitation is removed by ET.
5. Snakeweed/Indian ricegrass	GUSA/ ACHY	*Gutierrezia sarothrae/ Achnatherum hymenoides*	Area was disturbed when site was remediated. Native (GUSA) and introduced Russian thistle (*Salsola kali L.,* SAKA) weeds prevail. Erosion gullies and deposition areas are dominated by SAKA. Other native species (ATCA, YUAN, ACHY) likely established from reseeding and dispersal. Fenced (no grazing).
6. Fourwing saltbush/ Dropseed	ATCA/ SPsp	*Atriplex canescens/ Sporobolus* species	Desert phreatophytes (ATCA, SAVE) on coppice dunes. ATCA dominates; SAVE clones are sparse and in clumps. All vegetation is in poor condition due to drought and overgrazing (Redsteer et al. 2013).
7. Mormon tea/ Rabbitbrush	EPsp/ ERNA	*Ephedra* species/ *Ericameria nauseosa*	Similar to Assoc. 2. Mormon tea (EPsp) dominates coppice dune with lace grass (*Eragrostis capillaris* [L.] Nees, ERCA) in interdunes. Grasses are relatively sparse.
8. Fourwing saltbush/ Greasewood	ATCA/ SAVE	*Atriplex canescens/ Sarcobatus vermiculatus*	Broad floodplain bench above Moenkopi Wash dominated by heavily overgrazed desert phreatophytes (ATCA, SAVE).
9. Fremont cottonwood/ Saltcedar	POFR/ TARA	*Populus fremontii/ Tamarix ramosissima*	Bottom of Moenkopi Wash dominated by native (POFR) and introduced (TARA) phreatophyte trees with understory of ERNA.
10. Upland south of Moenkopi Wash	–	–	This zone is a mixture of upland plant associations that have not been surveyed and delineated.

[a] Plant acronyms are formed using capital letters for the first two letters of the genus followed by the first two letters of the species. Lowercase "sp" is used if the plant species has not been confirmed.

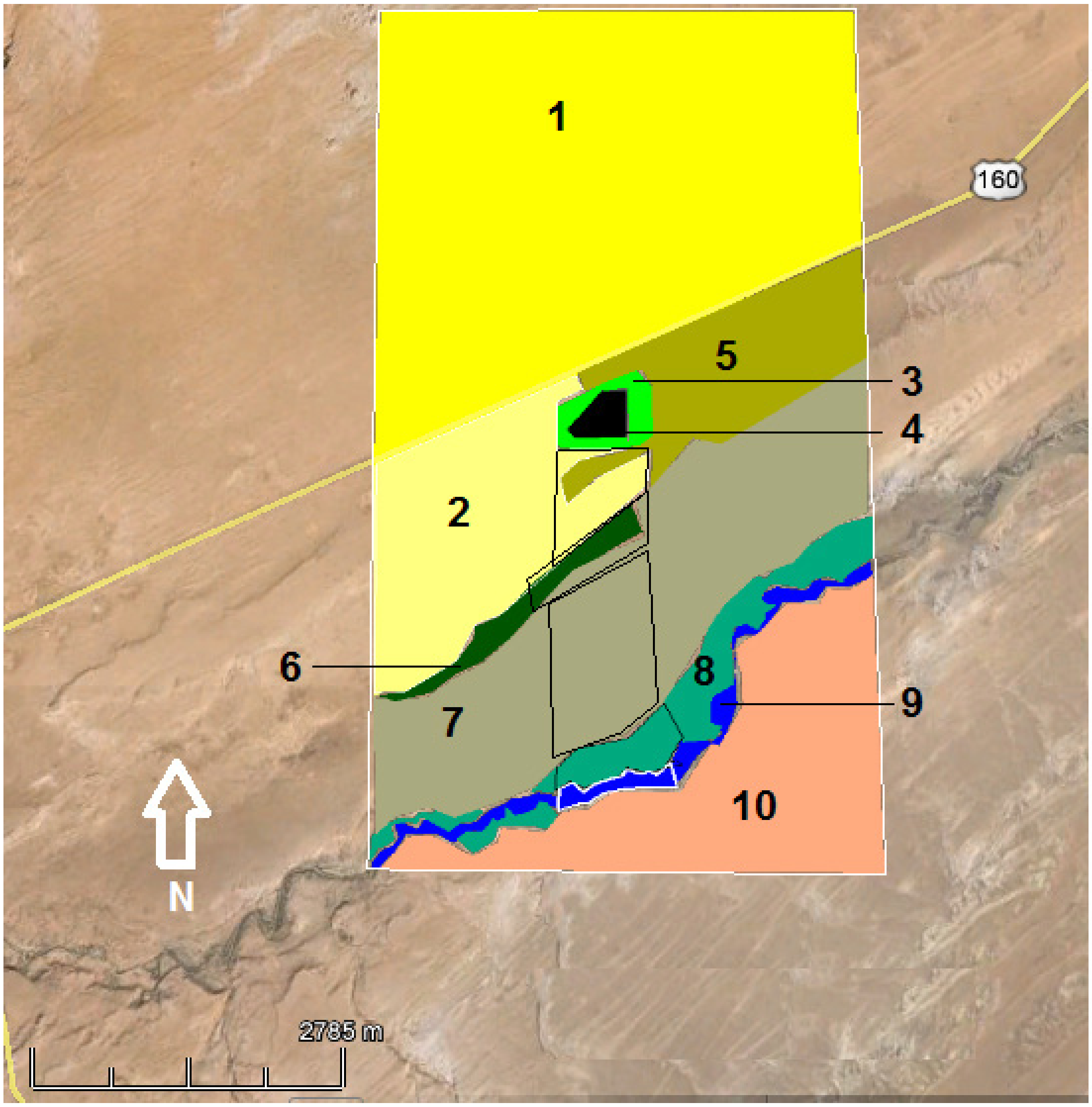

Figure 2. Vegetation/ET zones (defined in Table 2) within groundwater model domain

3.2 ET Rates within the Groundwater Model Domain

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 groundwater model domain satisfies this expectation. Mean ET rates for 2000–2012 and for the entire area within the model domain, weighted by the area of each zone, was 122 mm yr^{-1} (SE = 6.7) (Table 3). The mean annual precipitation rate for the same period was 129 mm yr^{-1}. Because estimated ET and precipitation rates are not significantly different, we can reasonably state that, averaged over the entire model domain, there is little if any net groundwater discharge or recharge.

Table 3. Precipitation and ET rates in millimeters per year and totals in million cubic meters per year (mcm yr^{-1}). Mean and standard errors for years 2000–2012.

Vegetation/ET Zone	Precipitation (mm yr^{-1})	ET Rate (mm yr^{-1})	Area (ha)	Total ET (mcm yr^{-1})
1. Uplands North of Highway160	129	117 (8.7)	1522	1.78
2. Mormon tea/Galleta grass	129	117 (8.7)	383	0.448
3. Revegetated UMTRCA Site	129	204	12.1[a]	0.025
4. Disposal Cell	129	129	27.7 [b]	0.035
5. Snakeweed/Indian ricegrass	129	77.8 (6.1)	256	0.199
6. Fourwing saltbush/ Dropseed	129	127 (9.8)	50.4	0.064
7. Mormon tea/ Rabbitbrush	129	130 (7.2)	697	0.906
8. Fourwing saltbush/ Greasewood	129	153 (11.6)	170	0.260
9. Fremont cottonwood/ Saltcedar	129	280 (19.9)	67.3	0.188
10. Upland south of Moenkopi Wash	129	126 (9.0)	488	0.564
Mean (SE)	129 mm yr^{-1}	122 [b] mm yr^{-1} (6.7)		
Total (SE)	4.43 mcm yr^{-1}		3673	4.47 mcm yr^{-1} (0.25)

[a] ET based on Monument Valley site ATCA exclosure
[b] Includes cell plus buildings and pond (not shown on diagram)
[c] Weighted according to area of each zone

However, comparisons of ET and precipitation rates for individual vegetation zones suggest that areas of net discharge and recharge likely occur within the groundwater model domain (Table 3). ET estimates for Zones 8 and 9, the terrace and riparian bottomland in Moenkopi Wash, exceeded precipitation; these zones are likely areas of net groundwater discharge. In contrast, the ET estimate for Zone 5, an area that DOE scraped in the 1980s to remove windblown contamination, was well below precipitation and, therefore, is likely an area of net groundwater recharge. ET in areas with upland vegetation north of U.S. 160 (Zone 1) and south of Moenkopi Wash (Zone 10) were in approximate balance with precipitation, as were Zones 2, 6, and 7 south of the cell and north of Moenkopi Wash. Zone 6, sometimes called the "greasewood area," was previously thought to be an area of net groundwater discharge.

3.3 ET Water Volumes

Our estimate of mean volume of annual ET for combined upland vegetation zones (1–3, 5, 7, and 10) and Zone 6 was 4.02 million cubic meters per year (mcm yr^{-1}) from 2000 through 2012. Precipitation for the same period was 4.43 mcm yr^{-1} for a net recharge of 0.41 mcm yr^{-1}. (ET volume equals the ET rate multiplied by the area of a zone.) For the two riparian zones (8 and 9), mean net discharge was 0.15 mcm yr^{-1}. That leaves 3.3% of the water budget unaccounted for. Possible sources for the difference include (1) error in ET and precipitation estimates, (2) surface runoff, and (3) downgradient discharge of groundwater in Moenkopi Wash.

3.4 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.

For all comparisons, ET rates in reference areas that have been protected from grazing exceeded precipitation rates and also exceeded ET rates within the groundwater model domain (Table 4). The ET rate for SAVE ranged from 176 mm yr^{-1} at Red Lakes to 724 mm yr^{-1} for a test plot protected from grazing at Monument Valley. The ET rate for ATCA protected from grazing at Monument Valley was about 200 mm yr^{-1}. Based on these estimates, there was a net discharge for all ATCA and SAVE plots at Monument Valley, grazed and protected from grazing, with ET more than 4 times precipitation in protected SAVE plots. These comparisons suggest that protecting Zones 6 and 8 within the model domain at Tuba City may lead to substantially great groundwater discharge.

Table 4. 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 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})	Area (ha)	Total ET (mcm/yr)
Zone 2	129 (11.0)	117 (8.7)	56.0	0.0655
Zone 6	129 (11.0)	127 (9.8)	44.6	0.0566
Zone 7	129 (11.0)	130 (7.2)	131.2	0.171
Zone 8	129 (11.0)	153 (11.6)	37.3	0.0557
Zone 9	129 (11.0)	280 (19.9)	15.6	0.0437
Totals	**0.371 mcm/yr**		**284.7 ha**	**0.393 mcm/yr**
Comparison Data:				
Red Lake SAVE	129 (11.0)	176 (14.7)		
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)		

3.5 Analysis of Annual and Seasonal ET

Analyses of annual and seasonal data indicate that relationships between ET and precipitation can be complicated (Figures 3 and 4). Annual means of ET (means of seasonal estimates) for the different vegetation zones were not significantly correlated ($P > 0.05$) with annual means of precipitation for years 2000 through 2012 (Figure 3). This may be related to rates of livestock grazing. Figure 5 compares Landsat 5 ET maps for 2005 and 2011. Both years had low annual PPT, were preceded by high PPT years (Table 5), but have very different patterns of ET. In 2005, ET was over 2 times greater than PPT in all zones except Zone 5, indicating that plants were using water from previous years stored in the vadose zone or groundwater. Although grazing records for the site are not available, livestock numbers were reduced on the Navajo Nation from 2003 through 2007 due to drought (Bresloff et al. 2013 and citations therein). In 2011, by contrast, ET was below PPT in all nonriparian zones except Zone 10 (Table 3). Livestock grazing reportedly increased in recent years. Note that in Zone 6, a zone with the phreatophytic shrubs ATCA and SAVE, ET rates were much higher in 2005 that in 2011, due presumably to greater livestock grazing in 2011. These analyses (Figures 3, 4, and 5) also show that ET lags precipitation, that plants are likely using water stored in the soil from fall and winter rains and possibly water stored from previous years.

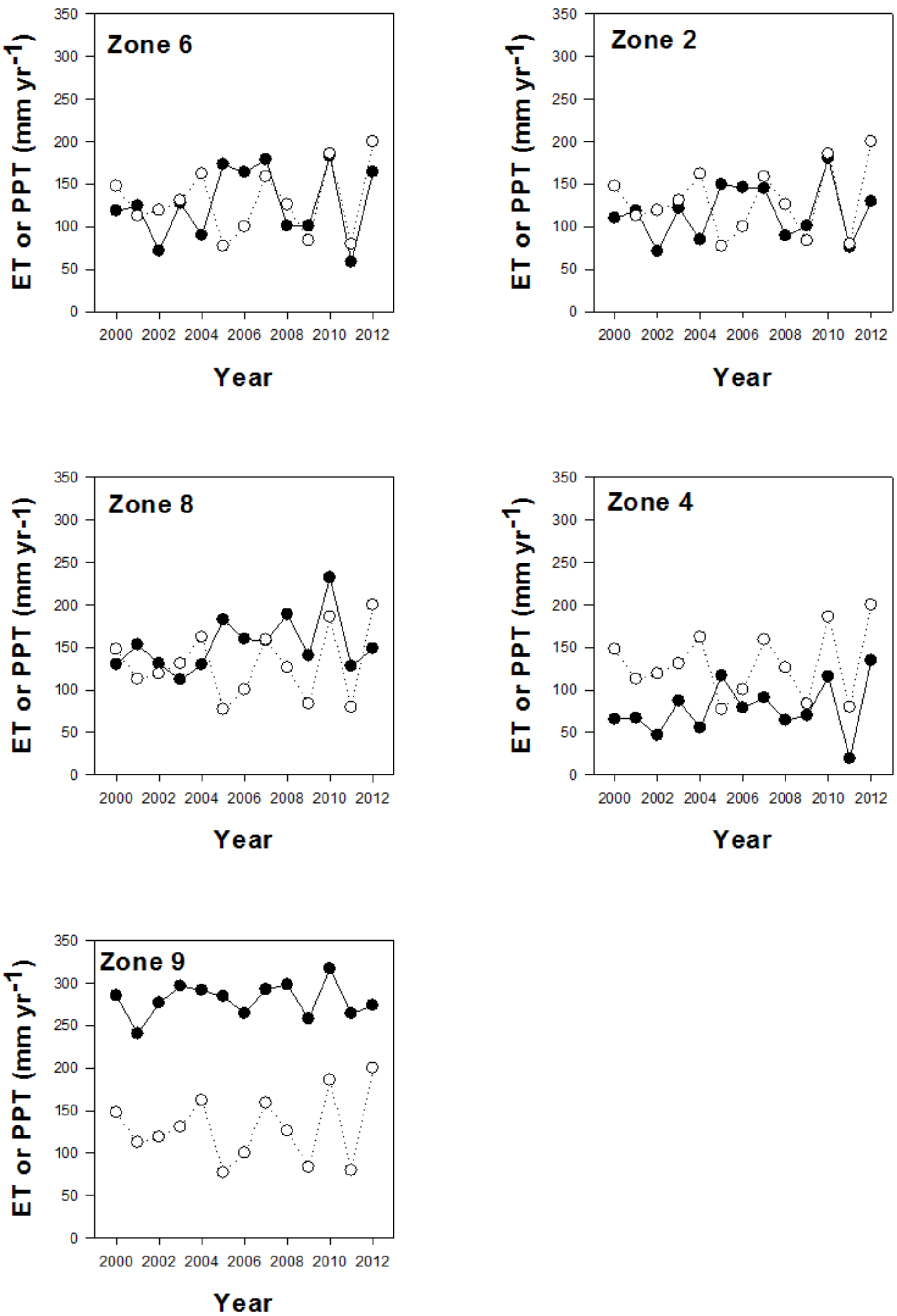

Figure 3. Mean annual ET (closed symbols) in vegetation zones compared with annual precipitation (PPT) (open symbols), 2000–2012.

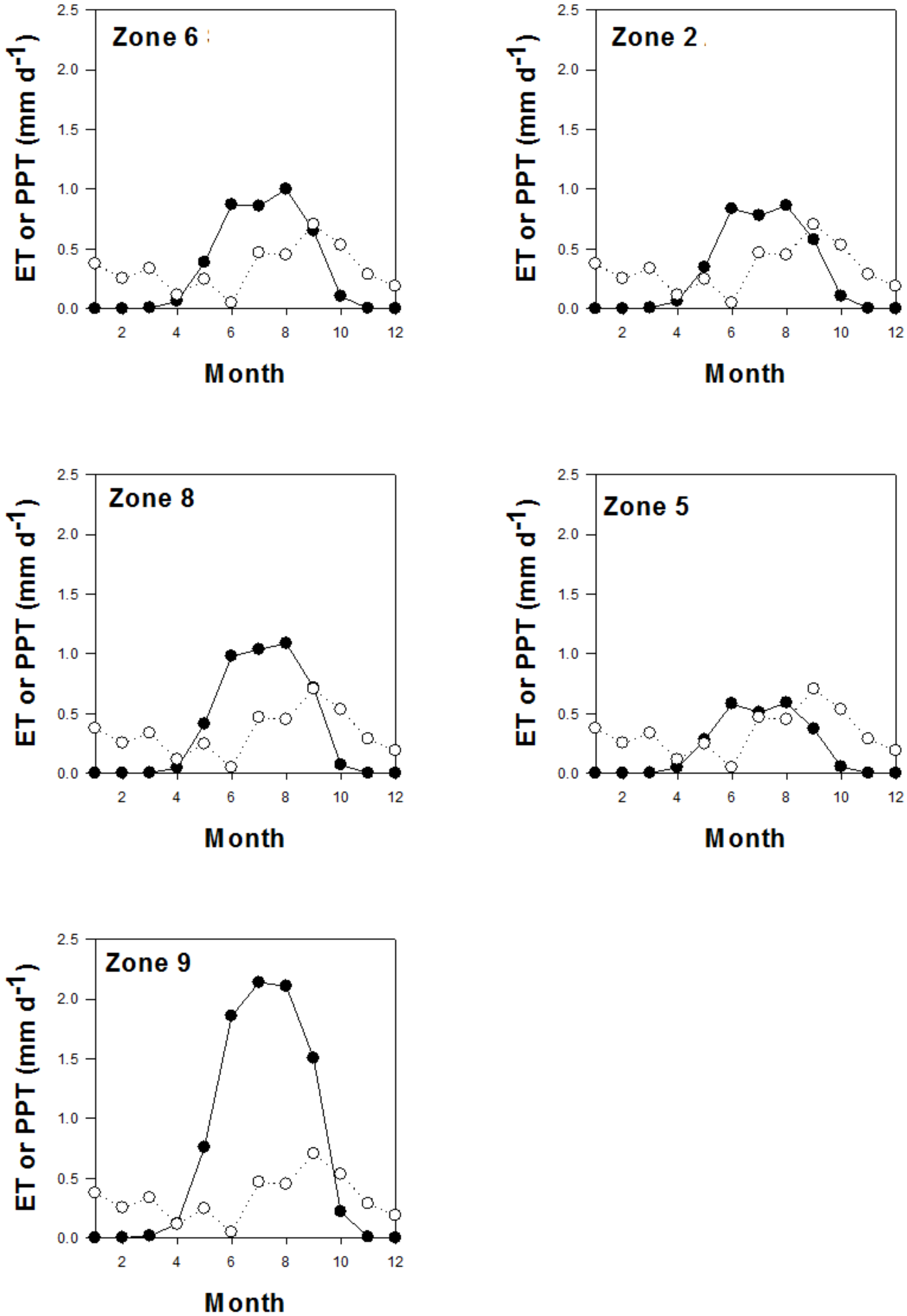

Figure 4. Mean monthly ET (closed symbols) in vegetation zones and precipitation (PPT) (open symbols), 2000–2012.

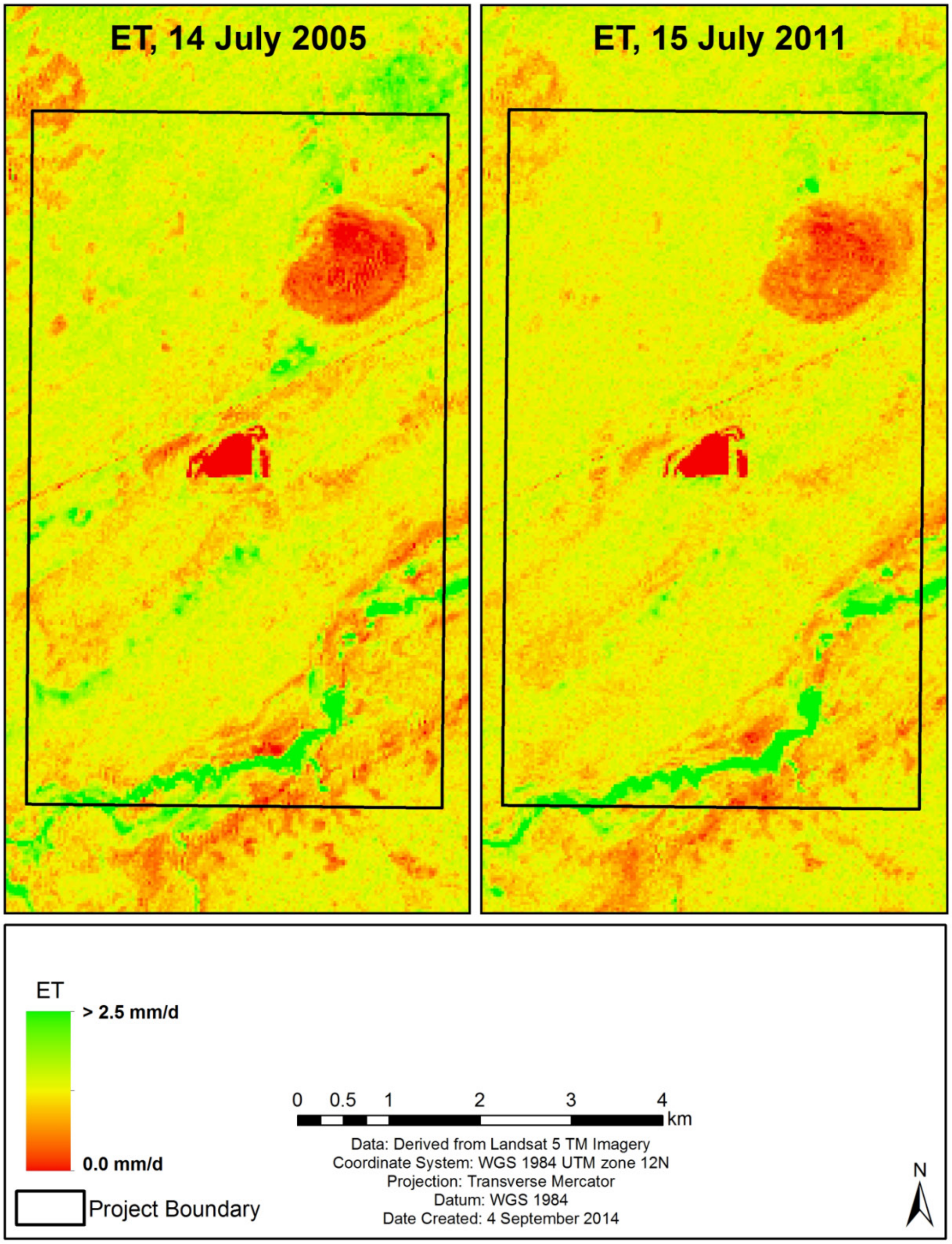

Figure 5. Landsat 5 ET maps contrasting July 2005, a year of relatively light grazing pressure, with July 2011, a year of heavier grazing pressure.Rainfall was low in both years but was above normal in the previous years (i.e., 2004 and 2010). The large, circular low-ET area northeast of the Tuba City disposal cell is where soil was excavated for use in the Tuba City disposal cell cover.

Table 5. Means and standard errors (SE) of PPT and ET in mm yr^{-1} for vegetation/ET zones, 2000-2012. Means across years and standard errors across years are in the last row.

Year	PPT	Z6	SE	Z2	SE	Z7	SE	Z9	SE	Z8	SE	Z1	SE	Z10	SE	Z5	SE
2000	148	119	27	110	26	124	28	285	69	130	31	103	24	107	23	65	18
2001	113	124	31	119	30	128	31	240	57	153	35	128	32	125	30	67	19
2002	119	72	21	71	17	76	18	276	68	131	32	78	20	77	18	47	12
2003	131	128	30	122	29	110	27	296	75	112	30	143	36	127	30	87	22
2004	162	90	22	85	18	101	24	291	73	130	32	81	22	102	25	55	13
2005	77	173	41	150	35	180	43	284	70	182	51	168	40	180	42	117	27
2006	100	164	45	146	39	166	43	264	66	160	41	147	38	119	28	79	20
2007	159	179	50	145	42	189	51	292	73	158	44	132	36	143	36	91	25
2008	126	101	24	89	22	144	36	298	77	189	49	74	19	158	39	64	17
2009	84	101	28	101	29	80	25	258	63	140	41	123	35	107	30	70	22
2010	186	183	55	181	50	194	52	317	81	232	61	141	35	165	41	116	31
2011	80	58	15	76	19	67	16	264	64	128	33	61	15	91	23	19	11
2012	200	164	53	130	40	137	40	274	65	149	34	147	43	141	33	134	41
Mean/SE	**129**	**127**	**9.4**	**117**	**8.4**	**130**	**6.9**	**280**	**19.1**	**153**	**11.1**	**117**	**8.4**	**126**	**8.6**	**78**	**5.9**

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