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Literature-Reviewed Estimates of Riparian Consumptive Water Use in the Drylands of Northeast Arizona, USA

Open-File Report 2020–1129

U.S. Department of the Interior
U.S. Geological Survey

Cover. Riparian trees along Comb Ridge, Navajo Nation. USGS photograph by Pamela L. Nagler.

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DAVID BERNHARDT, Secretary

U.S. Geological Survey
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Abbreviations

ATCA2	*Atriplex canescens* (Pursh) Nutt
ECOSTRESS	The ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
ET	evapotranspiration
ETa	actual evapotranspiration
ETo	potential evapotranspiration
EVI	enhanced vegetation index
METRIC	mapping evapotranspiration with internalized calibration
MODIS	Moderate Resolution Imaging Spectroradiometer
SAVE4	*Sarcobatus vermiculatus* (Hook.) Torr.
SSEBop	operational Simplified Surface Energy Balance
USGS	U.S. Geological Survey

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m^3/s)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Literature-Reviewed Estimates of Riparian Consumptive Water Use in the Drylands of Northeast Arizona, USA

By Pamela L. Nagler[1]

Abstract

This report provides the best estimates of riparian area evapotranspiration (ET) on the rivers and streams of the Navajo Nation by (1) quantifying the natural riparian vegetation water use within the Little Colorado River watershed using a literature search for comparable riparian ET estimates, and (2) in conjunction with the given area of stream-side plant cover on the Navajo Nation, provides the best estimate of consumptive use, the total water requirement (in acre-feet). This report includes riparian water use information only from the literature for riparian areas that are in similar dryland ecosystems in the Southwest, and not specific to the perennial tributaries and springs on the Navajo Nation within the Little Colorado River watershed. The report also includes any information found regarding the location of Navajo Nation weather station variables, such as where we can derive required data inputs from the Navajo Nation to estimate actual ET rates (in millimeters per day or millimeters per year). We provide estimates of annual riparian plant water use and calculations that include reference ET (potential ET or ETo), precipitation (in millimeters), and the calculations of consumptive water requirements of riparian vegetation. We cite our data sources and provide references used to determine the consumptive water requirement (acre-feet).

Introduction

This U.S. Geological Survey (USGS) report provides an estimate of river and stream vegetation (riparian) water use within the Little Colorado River watershed in Arizona, and specifically provides an estimate of riparian plant area evapotranspiration (ET) using newly presented data and literature reported estimates of ET in similar dryland ecosystems such as those from other parts of Arizona as well as the Four Corners region of the southwestern United States.

Accurate estimates of natural plant area water use (ET, in millimeters per day [mm/day] and in millimeters per year [mm/year]) are important to acquire so that surface water, in-stream use can be partitioned for human and natural environments. The grasses, shrubs, and trees that grow alongside rivers and streams are collectively called riparian vegetation and their leaves transpire water that is considered a loss to the ecosystem. Bare soil also loses water through evaporation. In the landscape, we quantify both losses as one variable, ET. A variety of users (land managers, water managers, water rights attorneys, research scientists, and so on) are interested not only in riparian plant ET, but also net water requirements or how much water is left after precipitation is subtracted from ET. To quantify the water requirement for a given area or the consumptive use in terms of acre-feet, the water requirement (after precipitation and soil moisture are subtracted from ET) is multiplied by the number of acres of the given riparian vegetation. This is normally quantified using an area measured by vectors on high-resolution, remotely sensed imagery and provides a measurement of acres of riparian zone vegetation. The riparian zone area multiplied by the net water requirement (ET minus precipitation and soil moisture storage) is the average annual total water requirement for an acre-foot.

Literature Review

Evapotranspiration in drylands consumes between 70 and 90 percent of precipitation (Sun and others, 2019; Wilcox and others, 2017). Accurately measured riparian ET has rarely been included in water budgets because more accessible agricultural estimates have been used instead, such as crop coefficients. These thermal methods also include agricultural-centered methods such as the Actual ET (ETa) that is produced using the operational Simplified Surface Energy Balance (SSEBop) model (USGS, 2015; Senay and others, 2011), mapping evapotranspiration with internalized calibration (METRIC; Allen and others, 2007), and more recently, the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS; National Aeronautics and Space Administration, 2020). Water-use data describe (1) water that is withdrawn from a source (for example, groundwater or surface water and fresh or saline), (2) water that is delivered (for example, domestic homes), (3) water that is unavailable (for example, consumptive use and ET), and (4) water that is returned to a water resource (via for example, wastewater

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returns; Maupin and others, 2018). Along the Colorado River, water withdrawals are mainly for agriculture (78 percent), but other uses exist, such as public supply, domestic use, commercial use, industrial use, livestock and mining, aquaculture, wastewater returns, and power. The portion taken by agriculture is in fact larger than 78 percent because much of the water withdrawal for crop irrigation is consumed via ET, and crops are not able to consume the entire portion of water applied. As a result, some form of return flow is provided, either as surface flow or groundwater recharge, which is then used by other downstream users.

All riparian plant water use is in reference and compared to potential ET (ETo), which is measured as a one-acre area completely covered by a foot-high, full-cover alfalfa or grass (Allen and others, 1998; Jensen, 1990). Weather stations report ETo because it is the maximum amount of water used by vegetation given the area's weather conditions, which include temperature, vapor pressure deficit, and so on. These daily reports are the updated standard condition in near realtime. Based on the general definition surrounding consumptive use and measurement metrics (Water Education Foundation, 2020), it is important to state some general findings from the literature that give values to alfalfa, grass, crops. and riparian areas. Remotely sensed optical data combined with weather station data has been a good method for estimating actual riparian ET (Nagler and others 2005a, b; Glenn and others 2007, 2008a, 2010). We provide a list of water use estimates for the Lower Colorado River and delta (see Figure 1, the border between California and Arizona and Mexico) in table 1 (Murray and others, 2009; Nagler and others, 2020).

The difficulty with providing natural plant ET estimates is that for decades, agricultural methods, such as crop coefficients were used for riparian species and areas, but this method over-estimated riparian water use (Nagler and others, 2005a, b; Westenberg and others, 2006; Hunsaker and others 2007; Khand and others, 2017). Crop-coefficients were established in 1998 based on the best evidence available at the time (Allen and others, 1998; Jensen and others, 1990). However, subsequent ground and remotely sensed measurements of riparian ET have produced lower riparian water-use results compared to that from crop-coefficient estimations (Nagler and others, 2005a, b). From these remotely sensed measurements of actual ET that were validated with ground-based measurements in the Lower Colorado River riparian reaches, we produced the first accurate riparian water-use estimates for the Lower Colorado River (Nagler and others, 2005a, b, 2007, 2008a, b, 2009a, b; Murray and others, 2009). Based on a mean annual flow of 1.8 million cubic meters (m^3) in the river, riparian vegetation consumes about 2.1 percent of the flow (Nagler and others, 2009b). *Tamarix* spp. L. (saltcedar) dominated associations consume 1.0 percent of the flow, much lower than earlier estimates of riparian ET (Nagler and others, 2009b). The best estimates for ETo, Agricultural ET, and Riparian ET are provided in tables 2 and 3 (Murray and others, 2009).

Figure 1. Riparian river reaches (R) on the lower Colorado River and its delta. Data for reaches in Mexico (R1–R7) are described in table 4. Data for reaches the United States (R3–R7) are described in table 5.

Table 1. Tabulated potential and actual evapotranspiration, in millimeters per year (mm/year), for reference land cover types.

[Land Cover Source column lists general location and date of data. Values are from Murray and others (2009), Nagler and others (2020), and this study (for the Lower Colorado River, 2020)]

Land Cover Type	Land Cover Source	Potential and Actual ET (mm/year)
Alfalfa	HayDay Farms, 2009	2,146
Grass	Lower Colorado River, 2009	2,036
Crops	Lower Colorado River, 2009	1,300–1,900
Riparian All Species	Lower Colorado River, 2009	447–1,155
Riparian Gallery Trees	Lower Colorado River, 2009	1,123
Riparian All Species	Lower Colorado River, 2020	777–1,163
Riparian All Species	Colorado River Delta, 2020	654–1,130

Data from table 2 shows that ETo mean use is approximately 2,146–2,036 mm/year and uses three-times more water than riparian species, and ET from crops (mean use 1,486 mm/year) uses two-times more water than riparian estimates (mean of 854 mm/year). Recent findings in Nagler and others (2020) show ETo from the Arizona Meteorological Network (AZMET) Yuma Valley station to be 1,994.36 mm/year average over the past 20 years, with range of 1,854 to 2,142 mm/year (AZMET, 2020). Our estimates are based on an ET algorithm that incorporates Enhanced Vegetation Index (EVI) from the MODerate Resolution Imaging Spectrometer (MODIS) from Nagler and others (2005; 2013):

$$ET\ (MODIS) = ETo\ (daily) \times 1.65\ (1\text{-}e^{-2.25EVI}) - 0.169 \quad (1)$$

where

ETo potential evapotranspiration (ET) from Yuma AZMET; and

EVI enhanced vegetation index.

The enhanced vegetation index (EVI) was calculated as follows (Huete and others, 2002, 2010):

Table 2. Evapotranspiration (ET) estimates (in millimeters per year) for agricultural areas on the Lower Colorado River based on Moderate Resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index from satellite sensors and ground measurements of potential evapotranspiration (ETo) (Murray and others, 2009).

[ETo estimates are listed from three irrigation districts Mohave (MID), Palo Verde (PVID), Yuma (YID), and a privately owned farm (HayDay) along the Colorado River. Crops refer to ET estimates for specific irrigation districts. Mean and Standard Error (SE) are provided in the last row]

Year	MID ETo	PVID ETo	YID ETo	HayDay Farms	MID crops	PVID crops	YID crops
2000	2,177	2,217	2,118	2,495	1,238	1,842	1,242
2001	2,062	2,062	1,920	2,234	1,172	1,888	1,327
2002	2,060	2,060	2,045	1,713	1,187	2,024	1,327
2003	1,885	1,877	1,941	1,580	1,317	1,803	1,333
2004	1,930	1,930	1,887	1,588	1,208	1,844	1,246
2005	2,019	1,951	1,854	omitted	1,347	1,622	1,286
2006	2,019	2,019	2,035	2,593	1,479	1,566	1,329
2007	2,108	2,108	1,999	2,612	1,373	1,886	1,300
2008	2,096	2,096	2,096	2,353	1,484	1,962	1,316
Mean (SE)	2,040 (30)	2,036 (35)	1,988 (31)	2,146 (159)	1,312 (40)	1,846 (29)	1,301 (12)

Table 3. Evapotranspiration (ET) estimates (in millimeters per year) for agricultural areas on the Lower Colorado River based on Moderate Resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index from satellite sensors and ground measurements of potential evapotranspiration (ETo) (Murray and others, 2009).

[Table headings represent ET values of riparian vegetation for the referenced year north of the Mojave Irrigation District riparian vegetation (MID-Rip); Havasu National Wildlife Refuge (HNWR), Bill Williams National Wildlife Refuge (BWNWR), Cibola National Wildlife Refuge (CNWR), Imperial National Wildlife Refuge (INWR), Mittry Lake Wildlife Area (MLWA) and the confluence of the Colorado and Gila rivers at Yuma, Arizona (CRG). Mean and Standard Error (SE) are provided in the last row]

Year	MID_Rip	HNWR	BWNWR	CNWR	INWR	MLWA	CRG
2000	324	1,036	1,447	1,005	1,305	1,083	1,048
2001	437	1,019	1,172	961	1,211	969	953
2002	391	1,005	1,197	834	1,120	902	912
2003	448	1,004	1,056	876	1,141	901	941
2004	415	962	645	833	1,042	806	840
2005	619	963	943	904	1,060	713	778
2006	458	951	1,053	699	1,144	848	632
2007	446	1,002	1,120	608	1,129	801	542
2008	483	1,016	1,173	710	1,242	857	686
Mean (SE)	447 (26)	741 (16)	1,123 (51)	825 (43)	1,155 (28)	875 (36)	815 (56)

$$EVI = G\ (pNIR - pRed) / (pNIR + C1 \times pRed - C2 \times pBlue + L) \quad (2)$$

where

G	the gain factor (set at 2.5);
C1	correction for aerosol resistance (set at 6);
C2	correction for aerosol resistance (set at 7.5);
L	adjusts for canopy background (set at 1);
pNIR	reflectance in the near infrared wavelength;
pRED	reflectance in the red wavelength; and
pBlue	reflectance in the blue wavelength.

Equations 1 and 2 were used by Jarchow and others (2017a, b) to estimate water use in the Lower Colorado River with values of ETo ranging from 1,996 to 2,036 mm/year and actual ET (ETa) from two different vegetation indices ranging from 75 mm to 108 mm/year for 2013, before additional surface water was added in 2014. After adding water, ET increased to 89–112 mm/year in 2014 (Jarchow and others, 2017a). For this same region, they report ET between 10 and 34 million m^3 per year (Jarchow and others, 2017b). Jarchow and others (2018) adapted an algorithm based on eqs. 1 and 2 for use with high-resolution (30 meter pixel size) Landsat data because riparian corridors are often very narrow, and MODIS lacks the ability to accurately predict ET for riparian areas based on its pixel size of 250 meters (m). Using this modified equation, recent work by Nagler and others (2020) show annualized differences in ET in mm/year (using Landsat EVI for the delta [table 4] and the Lower Colorado River between Hoover and Morelos Dams [table 5]) for 20 years covering seven reaches on the lower Colorado River delta and five reaches on the U.S. side of the river (fig. 1). Before the recent drought, water use for the riparian zone was about 1 mm/day or 1,130 mm/year (year 2000), however, it is now as low as 0.8 mm/day or 654 mm/year (year 2019)—a loss in 20-years of 476 mm/year or 1.61 mm/day in the delta (Nagler and others, 2020). The peak or growing season ET (mm/day) has also dropped over the 20-year period from 4.11 mm/day (2000) to 2.53 mm/day (2019) in the delta. The values for ET over the same 20-year period on the U.S. side of the river were similar to the findings in the delta. The annualized ET for the riparian zone on the U.S. side of the Lower Colorado River was 1,163 mm/year (year 2000) and is now 777 mm/year (year 2019), a loss in 20-years of 386 mm/year or 1.59 mm/day

Table 4. Phenology assessment metric evapotranspiration (ET) using Landsat-enhanced vegetation index (in millimeters per year) depicting year to year change from 2000 to 2019 in seven riparian reaches and for the total riparian area (All) of the Lower Colorado River delta (from Nagler and others, 2020).

[Average (AVE) and standard deviation (STDEV) are shown in the final two rows]

Year	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6	Reach 7	All
2000	1,041.2	975.5	1,058.3	1,220.4	1,379.2	1,178.9	1,058.1	1,130.2
2001	979.6	899.3	925.9	1,184.5	1,195.2	1,059.3	971.4	1,030.7
2002	1,015.8	936.2	979.9	1,255.3	1,231.6	1,082.0	947.1	1,064.0
2003	840.0	779.5	799.2	1,065.0	1,062.4	915.4	811.9	896.2
2004	780.3	700.5	719.2	953.0	937.7	813.2	741.8	806.5
2005	869.1	766.7	813.6	1,070.1	1,000.9	795.4	786.7	871.8
2006	915.3	781.2	804.6	1,109.0	1,041.2	849.9	781.3	897.5
2007	818.5	692.5	676.9	1,039.1	939.7	778.2	696.7	805.9
2008	886.4	705.1	680.0	1,173.6	1,059.5	897.3	792.5	884.9
2009	876.1	706.2	671.9	1,121.8	1,026.0	860.4	772.7	862.1
2010	988.2	790.0	778.1	1,154.7	1,132.6	939.2	834.7	945.4
2011	992.5	786.4	759.9	1,080.4	1,006.0	904.1	814.9	906.3
2012	835.0	602.5	588.9	1,056.6	929.5	768.5	685.1	780.9
2013	818.2	602.6	559.7	997.7	879.7	710.1	588.3	736.6
2014	999.8	770.1	674.3	1,117.9	1,000.6	833.9	643.5	862.9
2015	885.5	689.5	575.1	1,051.1	895.6	783.3	540.8	774.4
2016	816.9	666.3	549.2	1,035.8	787.9	702.7	454.0	716.1
2017	733.6	565.9	514.6	1,044.9	799.5	702.4	484.8	692.3
2018	691.5	539.1	493.5	945.5	734.4	643.6	444.7	641.7
2019	655.7	523.2	505.2	970.1	755.6	660.0	509.5	654.2
AVE	**872.0**	**723.9**	**706.4**	**1,082.3**	**989.7**	**843.9**	**718.0**	**848.0**
STDEV	**109.0**	**124.2**	**160.3**	**85.6**	**164.5**	**142.4**	**174.7**	**131.2**

Table 5. Phenology assessment metric evapotranspiration using Landsat-enhanced vegetation index (in millimeters per year) depicting year to year change from the year 2000 to 2019 in five riparian reaches and for the total riparian area (All) of the Lower Colorado River from Hoover Dam to Morelos Dam in the United States.

[Average (AVE) and standard deviation (STDEV) are shown in the final two rows]

Year	Reach 3	Reach 4	Reach 5	Reach 6	Reach 7	All
2000	1,152.46	1,039.13	1,042.15	1,362.09	1,219.39	1,163.04
2001	1,060.54	969.88	1,010.93	,1251.79	1,040.44	1,066.72
2002	1,204.82	1192.94	1,100.23	1,312.58	1,205.28	1,203.17
2003	1,065.54	969.64	884.77	1,178.69	964.01	1,012.53
2004	961.94	862.80	818.60	1,117.92	959.40	944.13
2005	1,144.67	1,122.55	1,022.95	1,277.23	1,015.84	1,116.65
2006	1,045.21	935.57	879.69	1,143.42	994.26	999.63
2007	914.14	775.63	771.07	950.22	873.05	856.82
2008	1,078.36	969.70	937.36	1,178.98	897.21	1,012.32
2009	1,105.82	979.64	916.57	1,067.73	984.99	1,010.95
2010	981.73	905.81	876.41	990.97	937.36	938.46
2011	897.96	859.10	776.81	932.31	838.39	860.92
2012	805.86	771.81	719.66	868.10	810.37	795.16
2013	919.02	918.44	820.68	914.67	867.51	888.06
2014	1,107.57	1,011.68	929.98	1,143.68	1,038.86	1,046.36
2015	896.62	868.28	781.72	1,005.67	886.24	887.70
2016	732.20	760.42	700.62	886.75	796.73	775.35
2017	797.89	925.15	891.19	1,029.75	922.12	913.22
2018	743.43	838.78	768.16	897.36	889.70	827.49
2019	742.09	797.36	737.58	787.73	819.20	776.79
AVE	**967.89**	**923.72**	**869.36**	**1,064.88**	**948.02**	**954.77**
STDEV	**149.36**	**114.45**	**114.14**	**163.79**	**116.58**	**125.45**

(table 1). The peak or growing season ET (mm/day) has also dropped on the U.S. side over the 20-year period, from 4.79 mm/day (2000) to 3.18 mm/day (2019). These ET estmates are in line with the results (1,100 mm/year) found a decade earlier for the same region (Nagler and others, 2008).

Jarchow and others (2020) produced estimates of ET for a riparian river reach on the San Juan River in New Mexico and showed ET ranged from 280 and 620 mm/year between 2000 and 2018. These values are slightly lower than those in the delta of the Lower Colorado River because the dominant riparian species, saltcedar has been affected somewhat by *Diorhabda* Spp. (leaf beetle), whereas in the delta, the leaf beetle has not yet been found and therefore does not yet affect the water use of the riparian zone which contains saltcedar.

Also on the Navajo Nation, near Monument Valley, projected measured transpiration from sap flow of two main dryland species, *Atriplex canescens* (Pursh) Nutt (ATCA2) and *Sarcobatus vermiculatus* (Hook.) Torr (SAVE4), was projected over the area for a site of 318 hectares (ha) near Comb Ridge by Glenn and others (2008). The average transpiration was 1.54 mm/day, ranging between 1.0 and 1.9 mm/day and 116 mm/year, and ranged between 73 and 163 mm/year for years between 2000 and 2007 (Glenn and others, 2008b).Bresloff and others (2013) reported ETo, precipitation, and ET (in mm/year) for the same site and dryland species in Monument Valley (table 6). Their study reported that mean ET was 137 mm/year between 2000 and 2004 and 186 mm/year be-tween 2005 and 2010, mean precipitation was 139 to 166 mm/year, and ETo was between 1,504 mm/year (2000–2004) and 1,442 mm/year (2005–2010) (Bresloff and others, 2013). They reported peak ET of native species was observed in July and ranged between approximately 1.18 and 1.52 mm/day. Values of ET over 10 years ranged from 75 mm/year in 2002 to 240 mm/year in 2010 and somewhat followed precipitation patterns (Bresloff and others, 2013).

ET for upland species on the Navajo Nation was much lower than riparian ET, which was approximately 150 mm/year (Bresloff and others, 2013). We are citing this range between 137 and 186 mm/year from Bresloff and others (2013) as notable but we are not using it in our estimates as this was not based on riparian species, but upland species. For riparian species on Navajo Nation at Shiprock, New Mexico, estimates of actual ET ranged between 280 and 620 mm/year (Jarchow and others, 2020). Estimates from the literature for the riparian

Table 6. Potential evapotranspiration (ETo), precipitation and actual evapotranspiration (ETa) for natural vegetation, *Atriplex canescens* (Pursh) Nutt (ATCA2) and *Sarcobatus vermiculatus* (Hook.) Torr (SAVE4), for a 318 hectare (ha) region on the Navajo Nation near Monument Valley for ten years between 2000 and 2010, with mean and (standard error [SE]) provided after five and six years.

[Data from Bresloff and others, 2013. Abbreviations: ha, hectare; mm/yr, millimeter per year]

Year	ETo (mm/year)	Precipitation (mm/year)	ETa Natural Vegetation Inside Fence	ETa Natural Vegetation Outside SAVE4	ETa Natural Vegetation Outside ATCA2	ETa Natural Whole Site, 318 ha (mm/year)
2000	1573	144 (29)	189	146	123	144
2001	1499	142 (39)	145	149	122	136
2002	1482	148 (8)	13	99	99	90
2003	1508	112 (27)	183	191	147	169
2004	1461	151 (42)	185	159	129	146
Mean (SE)	**1504(19)**	**139 (7)**	**161 (17)**	**148 (15)**	**124 (8)**	**137 (13)**
2005	1463	217 (37)	282	220	196	195
2006	1452	78 (39)	206	157	110	143
2007	1465	167	306	235	199	200
2008	1421	193	259	248	160	162
2009	1432	107	193	184	114	150
2010	1419	234	310	356	242	268
Mean (SE)	**1442(8)**	**166 (25)**	**259 (20)**	**233 (28)**	**170 (21)**	**186 (19)**

vegetation on the Lower Colorado River (this study) and delta (Nagler and others, 2020) have a mean of 777 mm/year and 654 mm/year, respectively, in the most recent year of 2019. The average 20-year mean values for the Lower Colorado River (this study) and delta (Nagler and others, 2020) were slightly higher, 955 mm/year and 848 mm/year, respectively. However, due to the declining trends in riparian vegetation, we used the most current year in our estimates. Thus, to calculate consumptive water use, we use the upper range values from Jarchow and others (2020) for the San Juan riparian vegetation, 620 mm/year, as well as the entire region of riparian vegetation from 2019 using the Lower Colorado River value of 777 mm/year (this study) and delta value of 654 mm/year (Nagler and others, 2020). An average of 684 mm/year was used as the mean value in our literature-based estimates from the Lower Colorado River data. This value converted to inches is 26.93 inches or 2.24 feet; whereas Natural Resources Consulting Engineers (2017) reported 52.2 inches or 4.35 feet of actual ET for riparian vegetation cover and nearly 82 inches or 6.83 feet for ETo. We then subtract 6.06 inches (average effective precipitation from Bresloff and others, 2013) from our value of 26.93 inches of actual plant ET, which results in a net water requirement value of 20.87 inches (1.74 feet). We multiply this by the total area of 14,598 acres, the region of interest within the Little Colorado River watershed on the Navajo Nation, to estimate the average annual total water requirement in acre-feet (and assuming negligible soil moisture change, this will also estimate the average annual depletion in acre-feet). We then multiply this area by 1.74 feet to determine the net water requirement, which is 25,387—the average annual depletion in acre-feet for the region of interest within the Little Colorado River watershed.

Bresloff and others (2013) reported an ETo in this region of 1,473 mm/year or 58 inches or 4.83 feet/year as maximum water use. After this research and the reported 6 inches in rainfall over 11 years, we calculate 52 inches or 4.33 feet/year as the maximum net water requirement. Using an area of 14,598 acres multiplied by 4.33 feet for average riparian vegetation water use yields a maximum consumptive water use (using ETo), for the site on the Colorado Plateau that is near Comb Ridge on the Navajo Nation, equal to 63,258 acre-feet. This value is a literature-based estimate that reflects large averages across river reaches on the Lower Colorado River (Murray and others, 2009) containing a range of riparian species and cover by species. If the region of interest on the Navajo Nation was entire gallery tree species of cottonwoods and willows, for the entire 14,598 acreage, ET would be 1,123 mm/year for these gallery trees or 44.20 inches. Subtracting mean rainfall of 6.06 inches yields a net water requirement of 38.14 inches or 3.18 feet. These calculations result in an estimation from the literature values of a consumptive water use of 14,598 acres times 3.18 feet of gallery forest water use yield a consumptive water use for trees of 46,397 acre-feet. Potential ET using data from Bresloff and others (2013) results in an ETo of only 1,473 mm/year, about 75 percent of the Murray and others (2009) estimate of 2,036 mm/year from the study on the Lower Colorado River. Using Murray and others (2009), we applied the average of the three irrigation districts that reported ETo of 2,021 mm/year. This is reported as ETo Lower Colorado River (table 7).

Table 7. The estimates of evapotranspiration (ET), rainfall, net water requirement, area, and consumptive water use (acre-feet) as reported for varying riparian vegetation density and potential ET from various sites in Arizona as reported in the literature (Murray and others, 2009; Jarchow and others, 2017a, b, 2020; Natural Resources Consulting Engineers [NRCE], 2017; Nagler and others, 2020).

[Abbreviations: AVG, average; ETo, potential evapotranspiration; ft, feet; ft/year, feet per year; in/year, inch per year; mm/year, millimeter per year]

ET (mm/year)	ET (in/ year)	Rainfall (in/year)* Bresloff and others (2013)	Net Water Requirement (in/year) (no soil moisture change)	ET (ft/ year)	Net Water Requirement (ft)	Area: 14,598 acres	Consumptive water use (acre-ft)
AVG 2019 Cover San Juan River and Lower Colorado and Delta Reach Level							
684	26.93	6.06	20.87	2.24	1.74	14,598	25,387
AVG 2000–2019 Cover Lower Colorado and Delta Reach Level							
808	31.81	6.06	25.75	2.65	2.15	14,598	31,325
Riparian Gallery Trees Only							
1,123	44.21	6.06	38.14	3.68	3.18	14,598	46,397
Navajo Nation ETo							
1,473	57.99	6.06	51.93	4.83	4.33	14,598	63,258
Lower Colorado River ETo							
2,021	79.57	6.06	73.51	6.63	6.13	14,598	89,486
NRCE Report							
1,273	50.1	5.10	45.0	4.18	3.75	26.2	98.4
NRCE ETo							
2,080	81.9	8.1	73.8	6.83	6.15	---	108.2

Conclusion

Using literature estimates and newly presented data from this study, we calculate the net water requirements based on an ET for riparian vegetation between average species cover and entirely gallery trees between 20.87 and 38.14 inches or 1.74 and 3.18 feet. We project consumptive water use to be between 25,387 and 46,397 acre-feet for the riparian vegetation along the streams in the area of interest within the Little Colorado River watershed on Navajo Nation. We report a range of potential ET as well. The estimates from a study done on the Navajo Nation by Bresloff and others (2013), Jarchow and others (2020) and Natural Resources Consulting Engineers (2017) were the closest in geographical proximity. Several studies with values for both ET and ETo that were larger than in Bresloff and others (2013) were not in the region (see the Lower Colorado River studies by Murray and others, 2009; Jarchow and others, 2017a, b; Nagler and others, 2020). The range reported for ETo is between 1,473 and 2,080 mm/year, and a reported net water requirement is between 4.33 and 6.15 feet.

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