Evapotranspiration and the Wetland Water Budget
Matheson Wetland Preserve,
Moab, Utah

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Introduction

The Scott Matheson Wetland Preserve, in Moab, Utah, is the last intact wetland system along the Colorado River in southern Utah. The Department of Wildlife Resources and the Nature Conservancy jointly manage its 975 acres. With the recent rapid population growth in the town of Moab, more stress has been placed on the Glen Canyon Group Aquifer (GCGA) to supply the drinking water needs of residents and visitors. The Nature Conservancy wishes to ensure that the increased use of GCGA water will not have a detrimental effect on water levels in the wetlands. In order to do this, a detailed hydrologic study needed to be performed.

The first aspects of this project were to ascertain areas of weakness in the understanding of the hydrologic cycle in the Matheson Wetland Preserve, to collect and to analyze data in these weak areas. The components of the wetland water budget are as follows:

Table 1: Components of wetland water budget

INS	*Measured value per year*	*Degree of uncertainty*
1. Precipitation	450 acre-ft/yr (Steigner, et. al, 1997)	Low
2. Spring water: • Skakel • Watercress	430 acre-ft/yr (measured by L. Christy) • 240 gal/min = 390 acre-ft/yr • 30 gal/min = 50 acre-ft/yr	Moderate
3. Flooding	0 acre-ft/yr over the course of this study (2001-2004)	Low
4. Irrigation Runoff	Unmeasured	High
5. Groundwater	Estimated 11,000 acre-ft/yr (Downs, et. al, 2000)	High

OUTS	*Measured value per year*	*Degree of uncertainty*
6. Evapotranspiration	3,000 acre-ft/yr (Sumsion, 1971) to 7000 acre-ft/yr (Blanchard, 1990)	High
5. Groundwater	Unmeasured	High

This project focused on quantifying the overall contribution of evapotranspiration to the wetland water budget. It provides a first-order estimate to water usage by hydrophytes and phreatophytes in the Matheson Wetland Preserve.

Evapotranspiration

For the purpose of estimating evapotranspiration the wetlands have been divided into several vegetation zones. An example of each of these zones is shown in Figure 1.

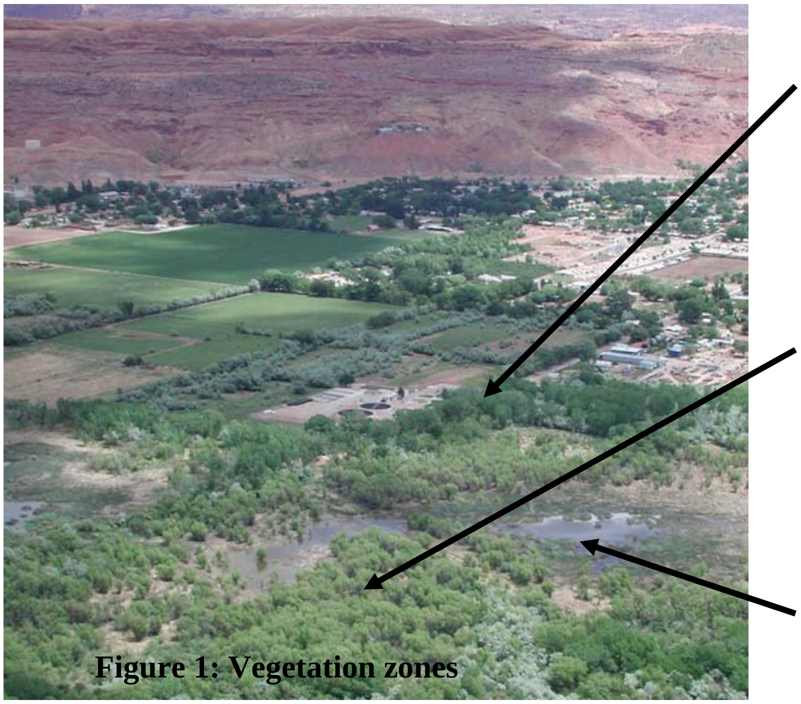


Figure 1: Vegetation zones

1. Native vegetation, dominated by cottonwood meadows, with some Russian olive and willows;
2. Salt cedar (tamarix), a non-native species that has overrun much of the wetland in the past 50 years;
3. Open water plants such as cattails.

Due to the variability of salt content and availability of water, the native vegetation and the tamarix vary regionally in their states of health and subsequent water usage, or transpiration. The wetland can then be divided spatially into five zones, each having a unique evapotranspiration potential:

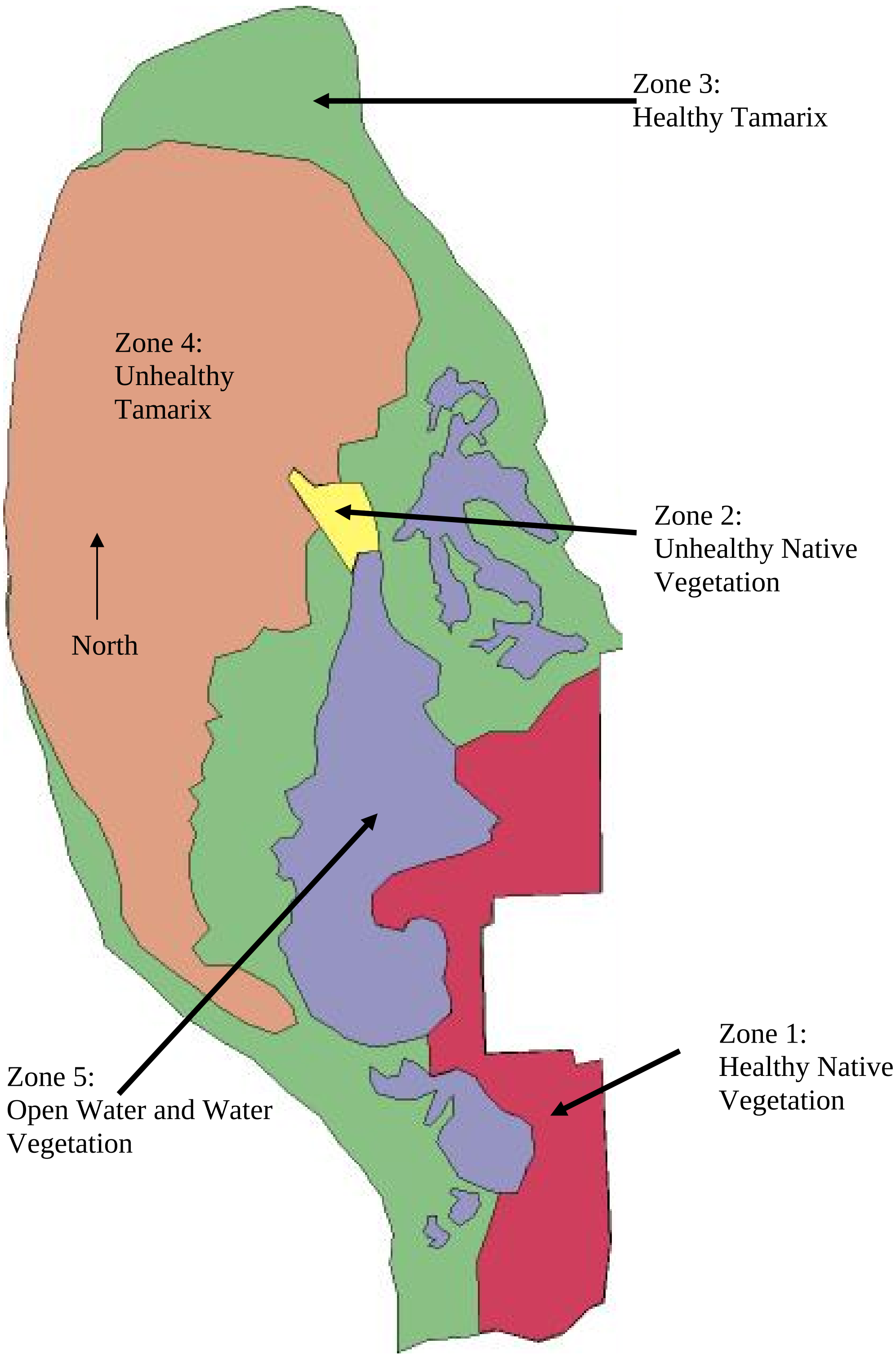
Zone 1: Healthy native vegetation
Zone 2: Unhealthy native vegetation
Zone 3: Healthy tamarisk
Zone 4: Unhealthy tamarisk
Zone 5: Open water and associated plants

These five zones were delineated in map form based on an amalgamation of direct observation and several recent photographs of the wetlands. The primary aerial photograph used was the 1997 black and white aerial photograph obtained from the U.S. Department of Agriculture-Forest Services, as shown in Figure 2.

Figure 2: 1997 Matheson Wetland Preserve aerial photograph

Using this photograph, these five evapotranspiration regions were delineated using Macromedia FreeHand 10. The resulting ET zones are shown in Figure 3.

Figure 3: Evapotranspiration Zones



The ET zone drawing was then imported into Microsoft Visio. The size of each zone was calculated as a percentage of the total area of the wetland. This value was then multiplied by the size of the entire wetlands (875 acres) yielding the total acreage for each zone. The results are shown in Table 2:

Table 2: Vegetation zone acreage

ET Zone	***Percent of total wetland area (%)***	***Total area (acres)***
Zone 1: Healthy native plants	12.4	108.8
Zone 2: Unhealthy native plants	0.9	7.6
Zone 3: Healthy tamarix	31.9	279.3
Zone 4: Unhealthy tamarix	38.5	336.7
Zone 5: Open water/water plants	16.3	142.6
Total	***100***	***875***

The next series of calculations involved computing the evapotranspiration rates for each of theses zones. The following methods were used:

1. Weather data obtained from the CNY weather station located at the Moab Airport was used to empirically estimate reference crop evapotranspiration rates (ET_0) for the region using the Penman-Monteith Equation (Allen et al., 1998).
2. Sap flux measurements were available for both healthy and non-healthy native (i.e. cottonwood) vegetation in the wetlands.
3. A literature search was conducted to determine the potential evapotranspiration rate within each zone.

Penman-Monteith Equation

The Penman-Monteith equation is an empirical equation relating key weather parameters to reference crop evapotranspiration rates (ET_0). ET_0 is the amount of evapotranspiration expected from a reference surface, in this case a well-watered turf. This is related to the actual evapotranspiration of the crop or vegetation zone (ET_C) by a crop factor (k_C) as shown in the following equation:

$$ET_C = k_C \cdot ET_0$$

In Zone 1 for example, the evapotranspiration rate and equivalent water loss would be given by the following equations:

$$ET_1 = k_1 \cdot ET_0$$
$$V_1 = k_1 \cdot ET_0 \cdot A_1$$

where:

ET_1 is the evapotranspiration rate in Zone 1 in feet per year

k_1 is the average crop factor for Zone 1

A_1 is the total area of Zone 1 in acres

V_1 is the total volume of water loss in Zone 1, given in acre-feet per year.

The same equations would apply for Zones 2 through 5, with the appropriate changes in subscripts. The final value we are searching for, V_t, or total volumetric water loss per year, is then given by:

$$V_T = k_1 A_1 ET_0 + k_2 A_2 ET_0 + k_3 A_3 ET_0 + k_4 A_4 ET_0 + k_5 A_5 ET_0$$
$$V_T = ET_0 \left[\sum_{i=1}^{5} k_i A_i \right]$$

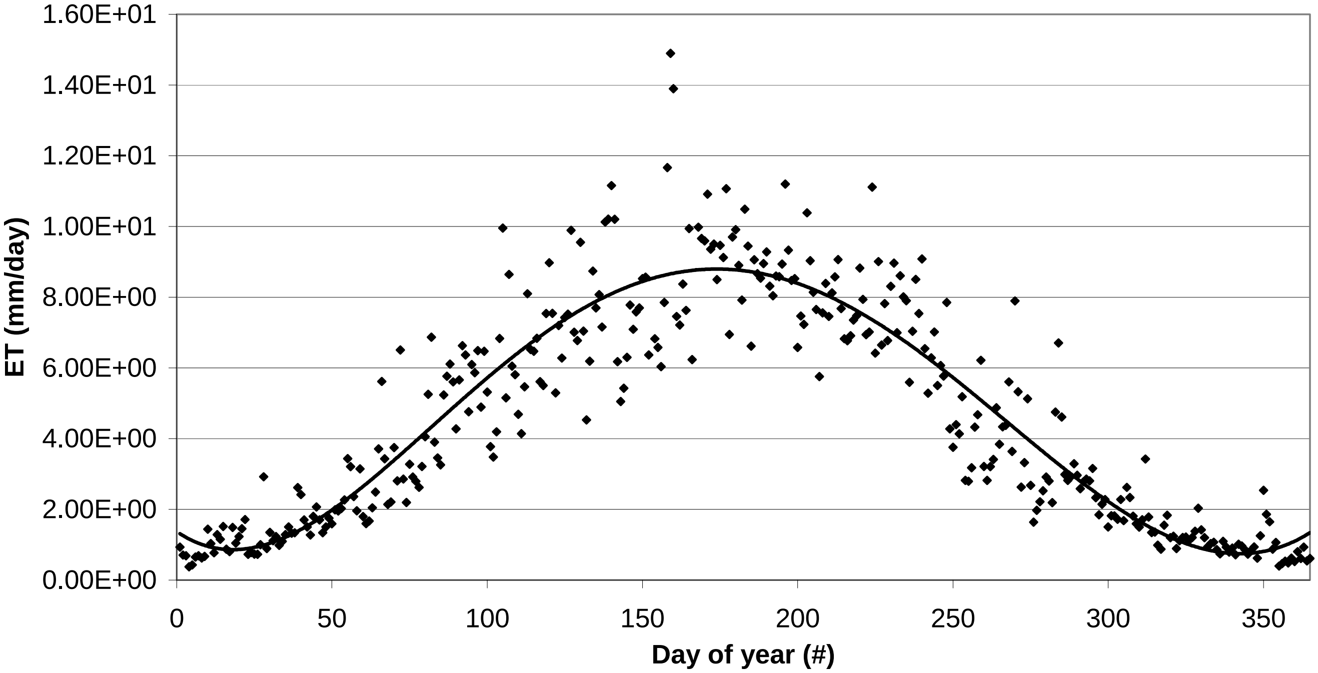
Calculating ET_0

Meteorological data were obtained from the closest operating weather station to the wetlands, the Canyonlands Airport station (with call letters "CNY" on www.mesowest.net), located about 15 miles north of the wetlands on State Route 191. The following daily weather data were collected and used in calculations over the year 2002:

1. Maximum and minimum daily temperature
2. Maximum and minimum relative humidity
3. Average wind speed over the course of the day
4. Total daily rainfall (if applicable)

The methods used for using this data for calculating evapotranspiration using the FAO version of the Penmann-Monteith equation are provided in Appendix A. The total resulting ET_0 for the year 2002 was 1.66 meters, or 65.4 inches. Computed values of Eto for each day in 2002 are shown in Figure 4.

Figure 4:
Reference Crop Evapotranspiration
in the Matheson Wetland Preserve



The next step involved estimating k values for each of the five evapotranspiration zones.

Zones 1 and 2—Native Vegetation

Evapotranspiration in Zones 1 and 2 is dominated by the cottonwoods. In an independent study conducted by Dianne Pitaki, sap flux measurements were taken to yield actual evapotranspiration from individual trees. The measurements were taken from Julian day 197 through 265, a total of 69 days. Among the healthy cottonwoods in Zone 1, Pitaki measured ET_1 values ranging from 5.3 to 12.4 mm/day, averaging 9.72 mm/day. These measured ET_1 values yielded a k_1 value of 1.5. The measurements were likewise taken in unhealthy cottonwoods in Zone 2, with ET_2 values ranging from 1.4 to 6.7 mm/day, yielding a k_2 value of 0.74.

Pitaki's measured values for both Zone 1 and Zone 2 were atypically elevated above predicted reference crop evapotranspiration by significant rain events. Significant rain events are here defined as more than 0.75 cm over a 5 day period. While this may seem insignificant, in the year 2002 over which the study takes place, the wetlands received only 12.8 cm of rain. Only 21 days in 2002 qualify as significant rain events under this definition, and 16 of these 21 days fell within the 69-day period of the Pitaki study. Each time one of these significant rain events occurred, the ET_C measured was significantly higher than the ET_0 calculated using the Penman-Monteith equation, particularly for the subsequent days. This is shown in Figures 5 and 6.

Figure 5: Precipitation dependence of K for healthy native vegetation

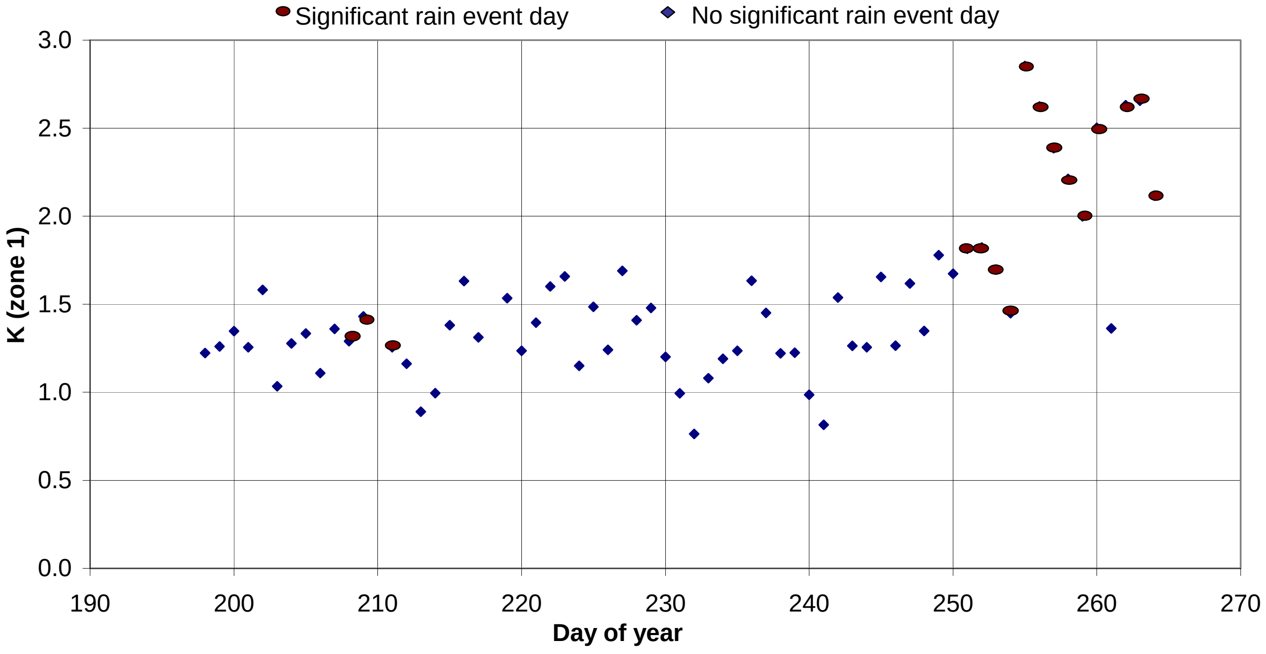
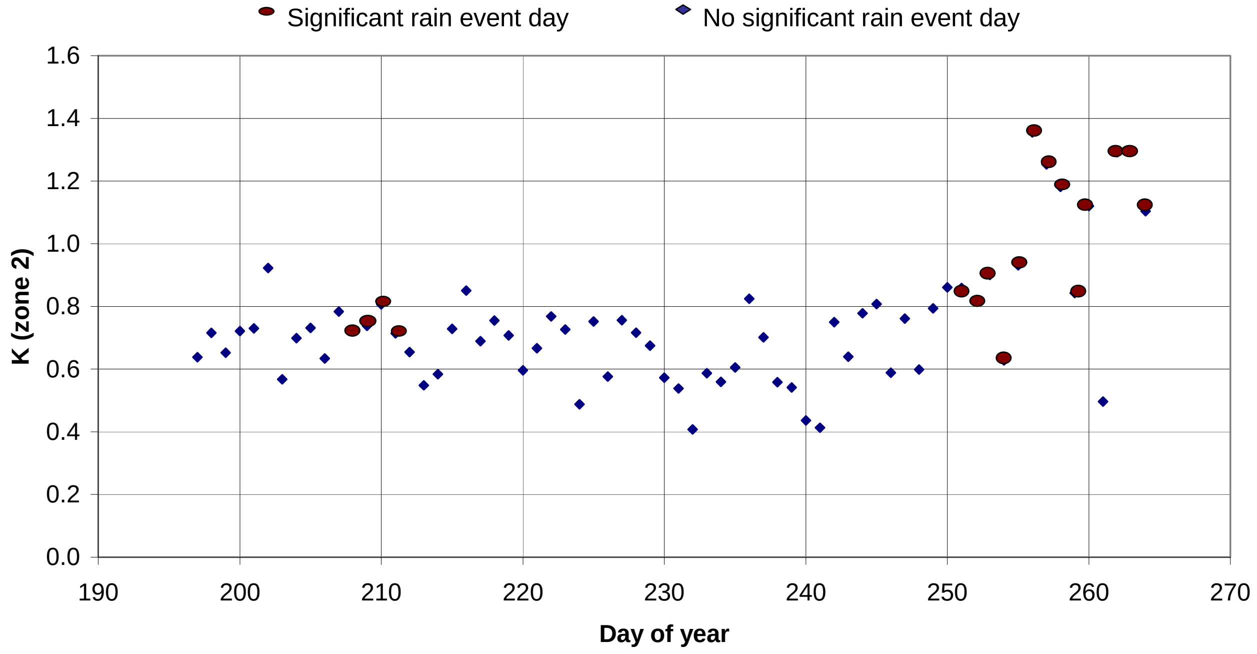


Figure 6: Precipitation dependence of K for unhealthy native vegetation



This problem was corrected manually by removing from k-calculation the days following significant rain; namely those that had greater than 0.75 mm within the last 5 days. This lead to a significant decrease in standard deviation, as is shown in Figures 7 and 8 below.

Figure 7: Spread of K values for healthy cottonwoods

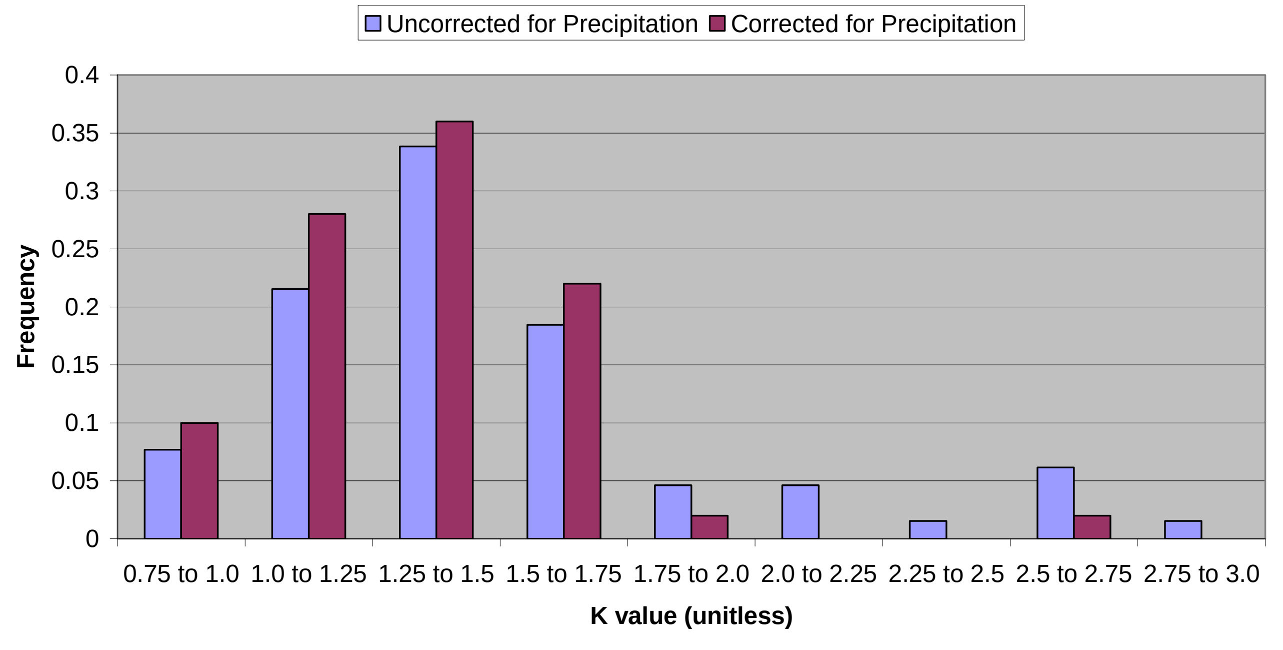
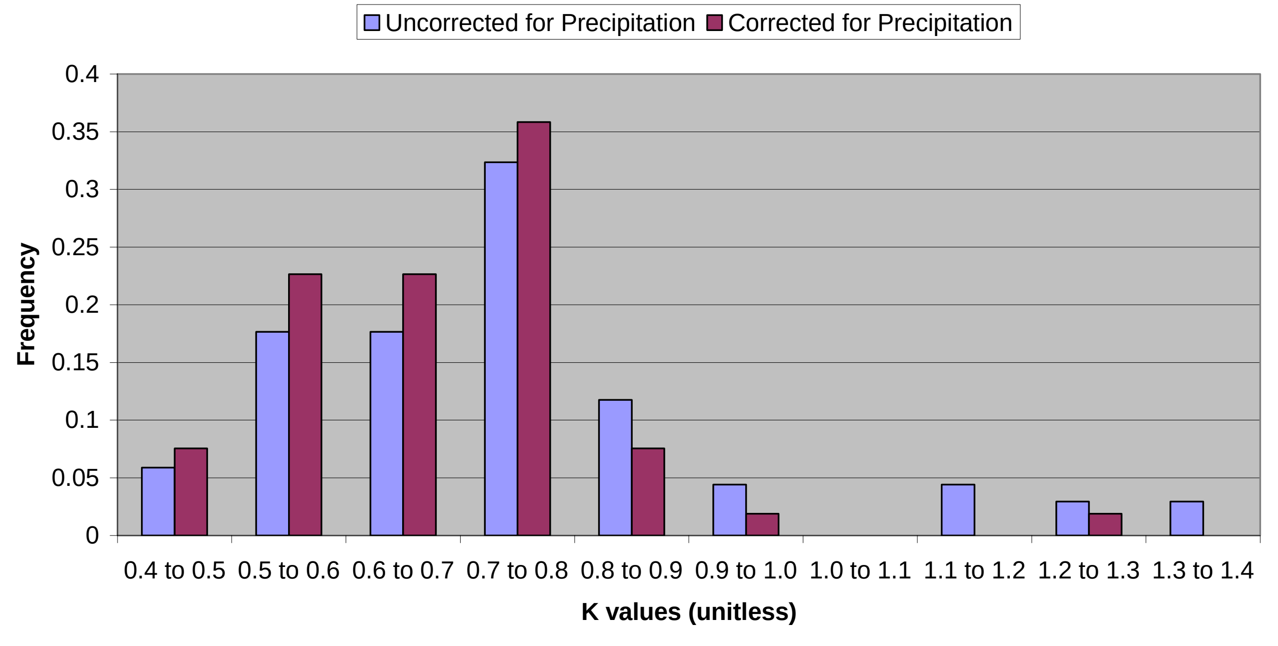


Figure 8: Spread of K values for unhealthy cottonwoods



The final results obtained for cottonwood ET, adjusting Pitaki's data for rain effects, are:

k_1=1.3

k_2=0.67

These values were similar to existing literature values for cottonwood transpiration, as listed in Table 3:

Table 3: Literature values for cottonwood evapotranspiration

Reference	***$ET_{Cottonwood}$ (in/yr)***	***Equivalent $k_{Cottonwood}$***
Meyboom, 1964	40.6	0.62
Muckel and Blaney, 1945 (combined Cottonwood-willow ET rate)	60-92.7	0.92-1.42
Gatewood, et al., 1950	72	1.10

It should be noted, however, that the equivalent $k_{Cottonwood}$s included in the preceding and following tables were back calculated using ET_0 from the Moab site. The directly measured $k_{1,cottonwood}$ in the Moab wetlands was close to the highest literature value for cottonwoods, while the directly measured $k_{2,cottonwood}$ was close to the lowest literature value for cottonwoods.

The actual native vegetation in the wetlands is far more complex, however, including Russian olives, willows and open native meadows. The values in the literature for these types of vegetation are as follows:

Table 4: Literature values for native plant evapotranspiration		
Reference	ET_{Willow} ***(in/yr)***	K_{Willow}
Meyboom, 1964	13.2	0.20
Young and Blaney, 1942	30.5	0.47
Criddle, et al., 1964	35.3	0.54
Robinson, 1970	36.4	0.56
Blaney, et al. 1933	47.8	0.73
Reference	$ET_{Russian\ olive}$ ***(in/yr)***	$K_{Russian\ olive}$
USBR, 1973-1979	18.6-114.6	0.28-1.75
Reference	ET_{Meadow} ***(in/yr)***	K_{Meadow}
Hanson, 1976	6.8-10.5	0.10-0.16
Kruse and Haise, 1974	23.2-27.9	0.35-0.43

Whereas we were able to correlate the literature values for $k_{cottonwood}$ with direct measured values, technical constraints prohibited the explicit measurement of k for the other native vegetation. Consequently, the same pattern recognized in cottonwoods was then applied to the other types of vegetation, in order to determine k_1 and k_2: namely that high literature values were used to represent transpiration rates of healthy vegetation (i.e. in Zone 1) and low literature values were used to represent transpiration rates of unhealthy vegetation (i.e. in Zone 2).

Vegetation in Zones 1 and 2 were estimated and divided as shown in Table 5:

Table 5: Native vegetation calculations for k_1 and k_2

Vegetation Type	***Percentage of Native Vegetation***	$k_{1,ave}$	$k_{2,ave}$
Cottonwood	50%	1.3	0.67
Russian Olive & Willow	25%	0.73	0.20
Meadow	25%	0.43	0.10
Percent-weighted Total	***100%***	***0.94***	***0.41***

Russian olive and willow were grouped together for several reasons:

1. The willow has been more extensively and carefully studied;
2. The highest literature value for russian olive evapotranspiration was disproportionately large in comparison to the cottonwoods in the wetlands;
3. The height and approximate leaf area index for Russian olives and willows are similar in the wetlands.

Therefore, the k values for russian olive were assumed to be similar to those in the willow literature, and the willow values were used.

Zones 3 and 4—Tamarix

Transpiration from the tamarix is arguably one of the most important components in overall wetland evapotranspiration. This single species has overrun more than 70% of the wetlands. Despite its importance, no specific measurements were available for the species in Moab. The determination of k values depended entirely on literature values, which are given in the Table 6:

Table 6: Literature values for Tamarix evapotranspiration		
Reference	**$ET_{Tamarix}$ (in/yr)**	**Equivalent $k_{Tamarix}$**
Grostz, 1972	14.9-29.2	0.23-0.45
USBR 1973-1979	15.6-56.4	0.24-0.86
Culler et al., 1982	25-56	0.38-0.86
Cleverly et al., 1992	29-48	0.45-0.73
Weeks et al., 1987	30-42	0.46-0.64
Criddle et al., 1964	32.6	0.5
VanHylckama, 1974	40-85	0.61-1.3
Turner and Halpenny, 1941	47.9-61.1	0.73-0.93
Gay and Hartman, 1982	68	1.04
Gay, 1986	69-71	1.06-1.09
Gatewood et al., 1950	86	1.31

The k_3 value for healthy tamarix was chosen as the average of all the above literature values, or 0.76. The k_4 value for unhealthy tamarix was arbitrarily chosen at half of that value, 0.38. The justification for this decision lies in the extent to which the tamarisk is dying off on the northern portion of the preserve.

Zone 5—Open Water and Water Plants

Published k values for open water and water plants are extensively studied and well defined. The following k-values are found in Allen, et al., 1998.

Table 7: Literature values for open water and open water plant evapotranspiration		
Vegetation	**k**	**k_{ave}**
Cattails, bulrush	0.6-1.2	0.9
Reed swamp	1.0-1.2	1.1
Open Water <2 m depth	1.05	1.05

The total k_5 value was then determined to be the rounded average, or 1.0.

Total Wetland Evapotranspiration

The values for area, k, and subsequent evapotranspiration calculations are as follows:

Table 8: Total wetland evapotranspiration calculation

Zone	**k_i**	**A_i (acres)**	**V_i (acre-ft/yr)**
1- Healthy native vegetation	0.94	108.8	557
2- Unhealthy native vegetation	0.41	7.6	17
3- Healthy tamarix	0.76	279.3	1156
4- Unhealthy tamarix	0.38	336.7	697
5- Open water and open water plants	1.0	142.6	777
Total			**3204**

Discussion

The final estimated value for wetland evapotranspiration, 3200 acre-ft/yr, closely resembles the value predicted by Sumsion (1971) of 3000 acre-ft/yr. Greater accuracy in evapotranspiration calculations may be possible through using the following methods:

1. An extended leaf area index (LAI) across the wetlands may yield better k values for the Penmann-Monteith equation, since even within an individual plant species there exists a great deal of variation in transpiration.
2. A Class-A pan evaporation study would allow for closer calibration of literature k values for open water evaporation.
3. Using weather data obtained in the wetlands, rather than 10 miles away, would yield a more accurate ET_0.

Ultimately, the most accurate techniques are technically infeasible in the wetlands. Since tamarix represent more than two thirds of vegetation, some sort of check on their transpiration, such as a sap flux measurement, would be ideal. However, sap flux measurements on tamarix are problematic due to relatively small trunk size.

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Appendix A:

Penmann-Monteith Equation

The Penman-Monteith Equation

The FAO form of the Penmann-Monteith Equation as given in Allen, et al., is:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T + 273}\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where:

ET_0 = reference evapotranspiration (mm day^{-1})

Δ = slope of the saturation vapor pressure temperature relationship (kPa ˚C^{-1})

R_n = net radiation at crop surface (MJ m^{-2} day^{-1})

G = soil heat flux (MJ m^{-2} day^{-1})

T = mean daily air temperature at 2 m height (˚C)

u_2 = wind speed at 2 m height (m s^{-1})

e_s = saturation vapor pressure (kPa)

e_a = actual vapor pressure (kPa)

$(e_s - e_a)$ = saturation vapor pressure deficit (kPa)

γ = psychrometric constant (kPa ˚C^{-1})

The site-specific data required include: site location, daily air temperature, humidity, radiation, wind speed, and soil heat flux.

Temperature

Mean temperature data is given by the following equation:

$$T = \frac{T_{\max} + T_{\min}}{2}$$

where:

T = mean daily air temperature

T_{max} = maximum daily air temperature

T_{min} = minimum daily air temperature

Psychrometric constant (γ)

The psychrometric constant is a function of atmospheric pressure (P). Assuming 20˚C for standard atmosphere and applying a simplified form of the ideal gas law, P is approximated by the following equation:

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26}$$

where:

P = atmospheric pressure (kPa)
z = elevation above sea level = 1388 (m)

The psychrometric constant (γ) is given by the following:

$$\gamma = \frac{c_P \cdot P}{\varepsilon \cdot \lambda}$$

where:

γ = psychrometric (kPa ˚C^{-1})
P = atmospheric pressure (kPa)
λ = latent heat of vaporization = 2.45 (MJ kg^{-1})
c_p =specific heat at constant pressure = 1.013 x 10^{-3} (MJ kg^{-1} ˚C^{-1})
ε = ratio molecular weight of water vapor to dry air = 0.622

Saturation vapor pressure

The slope of the saturation vapor pressure curve, Δ, is a function of temperature:

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T + 237.3}\right)\right]}{(T + 237.3)^2}$$

where:

Δ = slope of saturation vapor pressure curve at specific temperature (kPa ˚C^{-1})
T = air temperature (˚C)

The mean saturation vapor pressure (e_s) and actual vapor pressure (e_a) both draw from the following equation:

$$e^{\circ}(T) = 0.6108 \exp\left[\frac{17.27T}{T + 237.3}\right]$$

where:

$e^{\circ}(T)$ = saturation vapor pressure at air temperature T (kPa)

T = air temperature (˚C)

The saturation vapor pressure must be calculated for both the maximum and minimum daily temperatures. The average saturation vapor pressure is then:

$$e_s = \frac{e^{\circ}(T_{\max}) + e^{\circ}(T_{\min})}{2}$$

The actual vapor pressure derived from relative humidity data are given as follows:

$$e_a = \frac{e^{\circ}(T_{\max})\frac{RH_{\min}}{100} + e^{\circ}(T_{\min})\frac{RH_{\max}}{100}}{2}$$

where:

e_a = actual vapor pressure (kPa)

RH_{max} = maximum daily relative humidity (%)

RH_{min} = minimum daily relative humidity (%)

The vapor pressure deficit is simply the difference between e_s and e_a.

Net Radiation (R_n)

$$R_n = R_{ns} - R_{nl}$$

where:

R_n = net radiation (MJ m^{-2} d^{-1})

R_{ns} = net solar radiation (MJ m^{-2} d^{-1})

R_{nl} = net longwave radiation (MJ m^{-2} d^{-1})

The net solar radiation is a function of solar radiation (R_s), which is in turn a function of extraterrestrial radiation (R_a). For a daily period, the equation for calculating extraterrestrial radiation is as follows:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r \left[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)\right]$$

where:

R_a = extraterrestrial radiation (MJ m^{-2} day^{-1})

G_{sc} = solar constant = 0.0820 (MJ m^{-2} day^{-1})

d_r = inverse distance Earth-Sun

ω_s = sunset hour angel (rad)

φ = latitude = 0.6763 (rad)

δ = solar decimation (rad)

The inverse distance Earth-Sun (d_r) is given by:

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365} J\right)$$

where:

J = day of year (from 1 on January 1 through 365 on December 31)

The solar decimation (δ) is given by:

$$\delta = 0.409\sin\left(\frac{2\pi}{365} J - 1.39\right)$$

The sunset hour angle (ω_s) then is:

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)]$$

Solar radiation calculations should ideally include measurements of the actual duration of sunshine (n) in hours. The maximum possible duration of sunshine (N) can be calculated as a function of the sunset hour angle:

$$N = \frac{24}{\pi}\omega_s$$

where:

N = maximum daily sunlight duration (hours day^{-1})

ω_s = sunset hour angle

The actual sunlight reaching the earth would be some fraction of this. In the absence of actual measurements, solar radiation may be approximated with air temperature differences as given in the Hargreaves' radiation formula:

$$R_s = \left[k_{Rs}\sqrt{(T_{\max} - T_{\min})}\right] R_a$$

where:

R_s = solar radiation (MJ m^{-2} day^{-1})

k_{Rs} = adjustment coefficient = 0.16 (°$C^{-0.5}$) for non-coastal regions, far from large water bodies which would influence the air masses

T_{max} = maximum daily temperature (°C)

T_{min} = minimum daily temperature (°C)

R_a = extraterrestrial radiation (MJ m^{-2} day^{-1})

The net solar radiation is then given by:

$$R_{ns} = (1-\alpha)R_s$$

where:

α = albedo or canopy reflection coefficient = 0.23 for the hypothetical reference crop used in the calculation of reference crop evapotranspiration (ET_0)

The net longwave radiation (R_{nl}) is a function, among others, of the clear-sky solar radiation (R_{so}). This is given by:

$$R_{so} = (0.75 + 2_{E-5}\, z)R_a$$

where:

z = elevation = 1388 (m)

R_a = extraterrestrial radiation (MJ m^{-2} day^{-1})

Net longwave radiation (R_{nl}) then is:

$$R_{nl} = \sigma\left[\frac{T_{\max,K} + T_{\min,K}}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right)$$

where:

σ = Stefan-Boltzmann constant = 4.903×10^{-9} (MJ K^{-4} m^{-2} day^{-1})

$T_{max,K}$ = maximum air temperature (K)

$T_{min,K}$ = minimum air temperature (K)

e_a = actual vapour pressure (kPa)

R_s = solar radiation (MJ m^{-2} day^{-1})

R_{so} = clear-sky radiation (MJ m^{-2} day^{-1})

Soil heat flux

In the absence of data, the soil heat flux (G) was approximated to be zero. The soil heat flux is most critical for evapotranspiration calculations spanning a smaller time-frames. Over the course of a full year, however, the overall soil heat flux is negligible.

Wind speed

The average wind velocity at a height of two meters was recorded hourly. An average of these values was used for u_2.