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Estimation of Evapotranspiration and Other Water Budget Factors at Glacier Creek Preserve

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Estimation of Evapotranspiration and Other Water Budget Factors at Glacier Creek Preserve

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ABSTRACT

A water budget of a watershed consists of the inputs and outputs of water to and from it, including precipitation, change in water storage, surface water flow, and evapotranspiration. Water budget estimates are of high importance as a result of increasing demand due to population growth and other factors. Improving estimate accuracy and precision of evapotranspiration and runoff to streams allows scientists to better determine the true availability of water for human and conservation use. At Glacier Creek Preserve, 6.5% of the incoming precipitation left the preserve as discharge from the stream and 95.9% of the incoming precipitation was lost back to the atmosphere as evapotranspiration from 12/01/2017 to 11/30/2018. A slight decrease in soil moisture also yielded a small amount of water (2.4% of the annual precipitation). Directly calculating evapotranspiration based on wind speed, solar radiation, humidity, and temperature estimates that 83.3% of incoming precipitation was lost to evapotranspiration from the watershed. Although evapotranspiration from agricultural land use was slightly higher than evapotranspiration from prairie land use, the difference was not statistically significant.

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INTRODUCTION

Obtaining knowledge of hydrologic conditions can be important for a variety of purposes. Water resources are imperative for maintaining ecosystems, providing drinking water for humans and livestock, irrigating crops, and allowing industrial production of various goods. Overuse of water resources has led to legal intervention, such as the Republican River Compact that requires Colorado and Nebraska to allow a certain amount of water to flow downstream from the Republican River (Kansas Department of Agriculture 2016).

Clearly, conserving water is important, and there is more than one approach that can be taken to do so. In 2007, Nebraska legislature brought up the idea of cutting down vegetation near the Republican River to decrease the amount of water lost to evapotranspiration as a solution to consuming too much of the river's water. This was a proposed alternative to turning off nearby irrigation wells (Glennon 2010). However, the Kansas water resource engineers were skeptical that this would be effective. This skepticism may be in part due to the lack of information available on the effectiveness of this strategy. Although there have been studies that sought to estimate transpiration rates, these studies have not covered many of the different types of vegetation and climatic conditions that exist. Therefore, more research on this topic would likely prove useful to water resource engineers, legal entities, conservation groups, and many others.

Glacier Creek Preserve is a 4 km^2 restored prairie preserve located near Bennington, NE, at approximately 1 km to the west of the intersection of 144th and State Streets (Fig. 1). This preserve has been used for numerous research projects due to its ecological importance and proximity to the University of Nebraska at Omaha. Despite this, little analysis has been conducted on the hydrology of the preserve, although a significant amount of data related to this has been collected. (Dere et al., 2019).

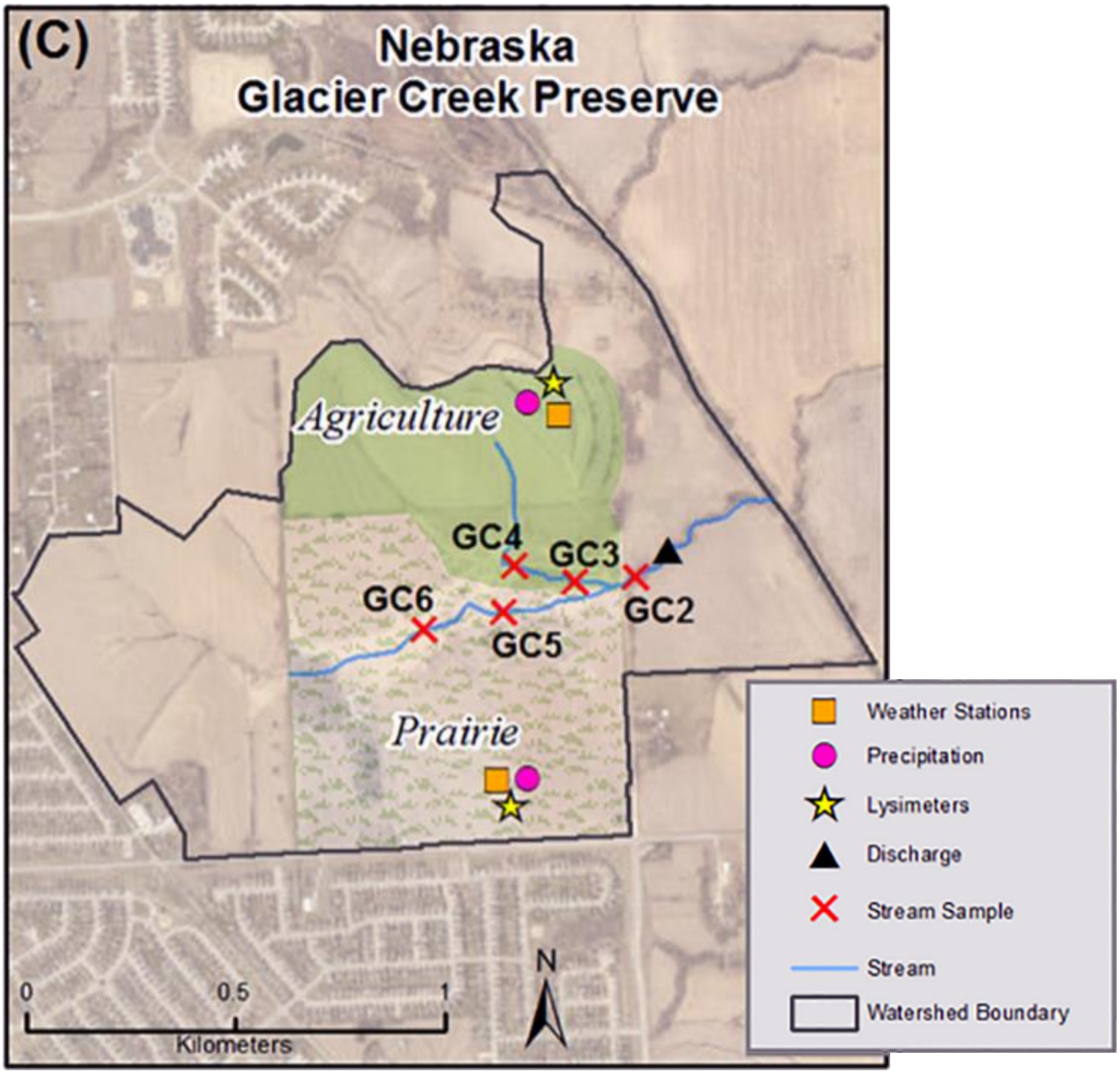

Figure 1. Map of the Glacier Creek Preserve watershed with approximate locations of notable features (Modified from Dere et. al., 2019). Two weather stations are located within the preserve, each of which collect data for precipitation, soil moisture, solar radiation, wind speed, and humidity.

In addition, a better understanding of the hydrologic conditions, specifically evapotranspiration, would be beneficial to promote ongoing research that is taking place at Glacier Creek Preserve. Specifically, a manually calculated estimate of evapotranspiration can be used to help verify automatically calculated estimates from the weather stations at Glacier Creek Preserve. These automatically calculated estimates rely heavily on assumptions based on functions determined using other data sets.

For these reasons, this study was conducted to determine a manually calculated water budget of Glacier Creek Preserve, including evapotranspiration. Evapotranspiration is defined as "the sum of evaporation from the land surface plus transpiration from plants" (USGS). I hypothesize that the American Society of Civil Engineers (ASCE) reference function for evapotranspiration, which is a commonly used function used to estimate evapotranspiration, will not be applicable to Glacier Creek Preserve, and therefore will have a large (more than ±10%) relative error from the evapotranspiration found from the calculation of the water budget by difference.

METHODS

The water budget of Glacier Creek can be summarized in four main components: Q (stream discharge), P (precipitation), ΔS (change in storage), and ET (evapotranspiration) (Fig. 2). All of these values were normalized to the m/yr equivalent for the entire watershed to comply with precipitation measurements. These variables can be summarized using the Eq. 1 (modified from Healy et al. 2007):

$$Q = P - \Delta S - ET \qquad \text{Eq. 1}$$

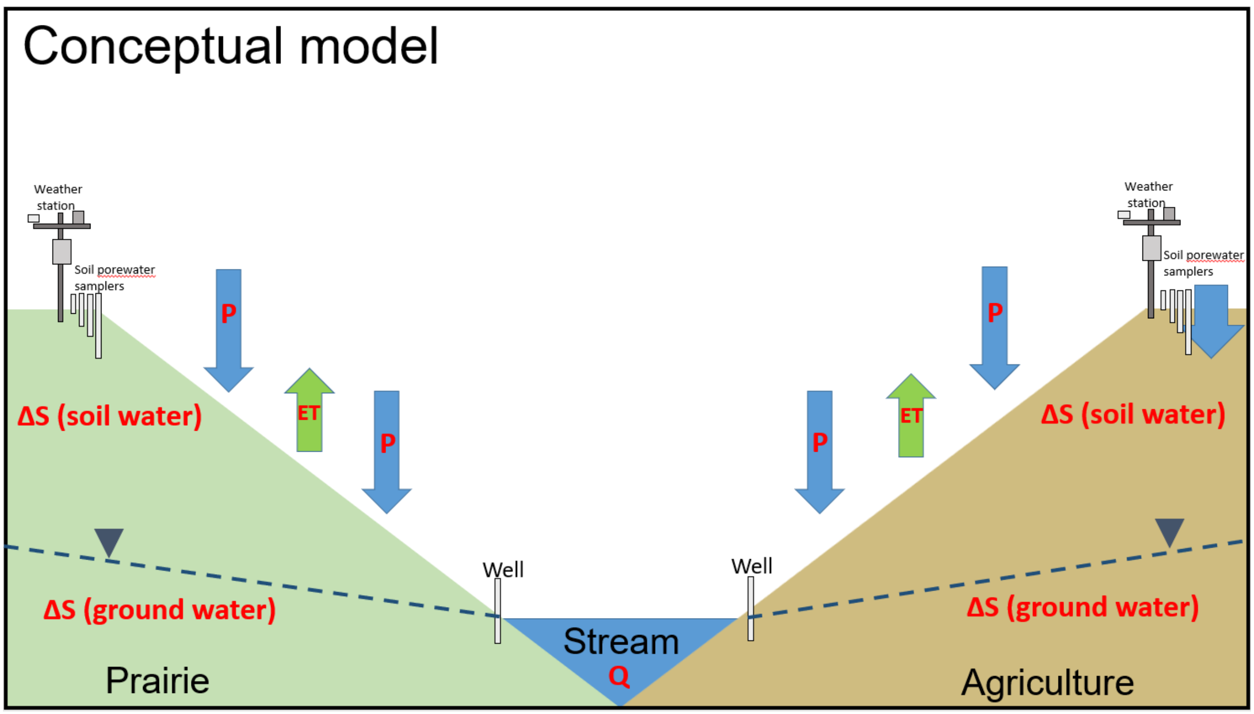

Figure 2. Conceptual model showing the factors of water budget at Glacier Creek (modifed from Dere et al., 2019). "P" represents precipitation, "Q" represents discharge from the Glacier Creek Stream, "ΔS" (soil water) represents change in storage of water in soil moisture, "ET" represents evapotranspiration, and "ΔS" (ground water) represents change in storage of ground water.

P, representing volume of precipitation entering the watershed and the assumed sole input of water to the watershed, was measured using a Texas Electronics Tipping Bucket Rain Gages at each weather station, one on restored prairie land use and one on agricultural (corn/soybean) land use. When data was available, the precipitation of the northern station located in the primarily agriculturally-dominated section of the reserve (denoted as the agricultural station) and the southern station located in the primarily prairie-dominated section of the reserve (denoted as the prairie station) were used to find an average value. When data from one of the stations was not available, the remaining station precipitation measurements alone were used to determine precipitation. These measurements were summed to find the average precipitation rate per square meter over the course of the timeframe considered.

Q represents the flow of water exiting Glacier Creek out of the preserve, and was measured using a SonTek Xylem IQ in situ stream discharge sensor every 15 minutes. This stream gauge is approximately 50 meters upstream from the outflow culvert where the stream flow leaves the preserve. The flow at given time intervals from 11/30/17 00:00:00 to 12/01/18 23:45:00 was averaged and then multiplied by the total number of data points collected to find the annual flow rate of the stream.

ΔS represents change in water storage (final water storage volume – initial water storage volume). ΔS can be separated into two components: change in storage due to soil moisture and change in storage due to a change in the ground water table. Soil moisture sensors (Campbell Scientific) installed at each weather station measured soil moisture once per hour at depths of 10 cm, 25 cm, 50 cm, and 100 cm. To find change in water storage due to soil moisture, the average soil moisture was calculated using data from all depths collected on 12/01/17, the first day of the annual dataset, and 11/30/18, the last year of the annual dataset. Then, the average soil moisture value for 12/01/17 was subtracted from the average for 11/30/18 to find the soil moisture change over the course of the year at -0.000212 m^3 water m^{-3}soil. This soil moisture change was assumed to be representative of all soils in the preserve, and it was multiplied by the watershed area of 4.00 x 10^6 m and by the assumed average depth to water table of 10 m. Water table elevation change was assumed to be negligible, due to the precipitation rate of the study year having less than a 15% relative difference (14.9%) from the average annual precipitation rate of Omaha, NE from 1981 to 2010 of 768.35 mm (0.76835 m) (US climate data 2019).

ET represents rate of water lost to evapotranspiration in m^3 water m^{-2} land yr^{-1}, and was estimated by difference in water budget for the time period of 12/1/17 to 11/30/18 using a modified version of Eq. 1 (Healy et al. 2007):

$$ET = P - Q - \Delta S \qquad \text{Eq. 2}$$

In addition to the estimate by difference in water budget, evapotranspiration was also estimated using a Campbell Scientific CR-1000 data logger and associated software. The function used to make this estimation has no input from the stream gauge in Glacier Creek, and instead estimates evapotranspiration (labeled ET_{sz}) using a standardized reference crop function (ASCE, 2019) which factors in variables collected from the weather stations (Table 1; Table 2). The equation is as follows:

$$ET_{sz} = \frac{0.408\,\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad \text{Eq. 3}$$

where:

ET_{sz} = standardized reference crop evapotranspiration for short (ET_{os}) or tall (ET_{rs}) surfaces (mm d^{-1} for daily time steps or mm h^{-1} for hourly time steps),

R_n = calculated net radiation at the crop surface (MJ m^{-2} d^{-1} for daily time steps or MJ m^{-2} h^{-1} for hourly time steps),

G = soil heat flux density at the soil surface (MJ m^{-2} d^{-1} for daily time steps or MJ m^{-2} h^{-1} for hourly time steps),

T = mean daily or hourly air temperature at 1.5 to 2.5-m height (°C),

u_2 = mean daily or hourly wind speed at 2-m height (m s^{-1}),

e_s = saturation vapor pressure at 1.5 to 2.5-m height (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature,

e_a = mean actual vapor pressure at 1.5 to 2.5-m height (kPa),

Δ = slope of the saturation vapor pressure-temperature curve (kPa °C^{-1}),

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

C_n = numerator constant that changes with reference type and calculation time step, and

C_d = denominator constant that changes with reference type and calculation time step.

(ASCE, 2019)

Vegetation from the "prairie" weather station was assumed to fit the tall reference, ET_{rs}, while vegetation from the "agricultural" weather station was assumed to fit the short reference, ET_{os}. The short reference was used for the agricultural land due to the minimal plant coverage for a significant portion of the year (before planting, for a short time after planting, and after harvesting).

Calculation Time Step	Short Reference, ET_{os}		Tall Reference, ET_{rs}		Units for ET_{os}, ET_{rs}	Units for R_n, G
	C_n	C_d	C_n	C_d		
Daily	900	0.34	1600	0.38	mm d^{-1}	MJ m^{-2} d^{-1}
Hourly during daytime	37	0.24	66	0.25	mm h^{-1}	MJ m^{-2} h^{-1}
Hourly during nighttime	37	0.96	66	1.7	mm h^{-1}	MJ m^{-2} h^{-1}

Table 1. Values for factors of the standardized reference evapotranspiration function, ET_{sz} (ASCE, 2019).

Term	ET_{os}	ET_{rs}
Reference vegetation height, h	0.12 m	0.50 m
Height of air temperature and humidity measurements, z_h	1.5 – 2.5 m	1.5 – 2.5 m
Height corresponding to wind speed, z_w	2.0 m	2.0 m
Zero plane displacement height	0.08 m	0.08 m [a]
Latent heat of vaporization	2.45 MJ kg^{-1}	2.45 MJ kg^{-1}
Surface resistance, r_s, daily	70 s m^{-1}	45 s m^{-1}
Surface resistance, r_s, daytime	50 s m^{-1}	30 s m^{-1}
Surface resistance, r_s, nighttime	200 s m^{-1}	200 s m^{-1}
Value of R_n for predicting daytime	> 0	> 0
Value of R_n for predicting nighttime	≤ 0	≤ 0

Table 2. Values for factors of the standardized reference evapotranspiration function, ET_{sz} (ASCE, 2019).

The value of ET_{sz} was calculated separately for each weather station. The relative error of ET and ET_{sz} was found using the equation:

$$\text{Relative Error} = 100\% * (ET_{sz} - ET) / (ET) \qquad \text{Eq. 4}$$

Despite the relatively low hydraulic conductivities associated with the subsurface in Glacier Creek Preserve (glacial till and loess), it was assumed that the lag time of ground water from water gained by precipitation to the creek was negligible as the time scale of this study (1 year) is relatively long.

RESULTS

The precipitation rate within the watershed was 0.883 m yr^{-1} (883 mm yr^{-1} total precipitation). Total flow (Q) for 2018 was 0.057 m yr^{-1}. The calculated change in storage due to soil moisture was found to be 0.021 m yr^{-1}. ET was 0.847 m yr^{-1} from the watershed (Fig. 3). ET_{sz} at the agriculture weather station was 0.796 m yr^{-1}, and ET_{sz} at the prairie weather station was 0.675 m yr^{-1}. No significant difference in ET_{sz} was found between the weather stations ($p = 0.84$). ET_{sz} averaged across both the agriculture and prairie weather stations was 0.735 m yr^{-1}. The relative error between ET_{sz} calculated from weather station parameters compared to ET calculated by difference (Eq. 2) was -13.2% (Fig. 4).

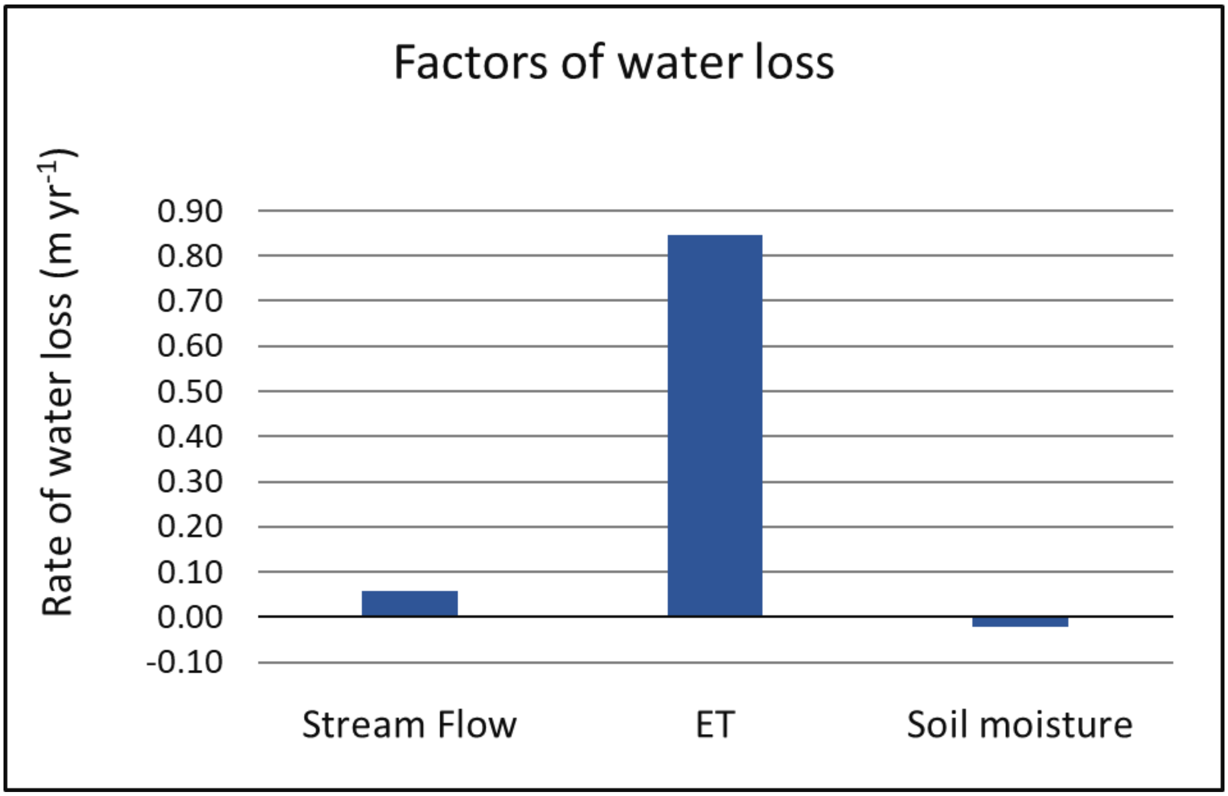

Figure 3. Rate of water loss from stream flow (Q), evapotranspiration (ET), and soil moisture (ΔS) calculated using Eq. 2.

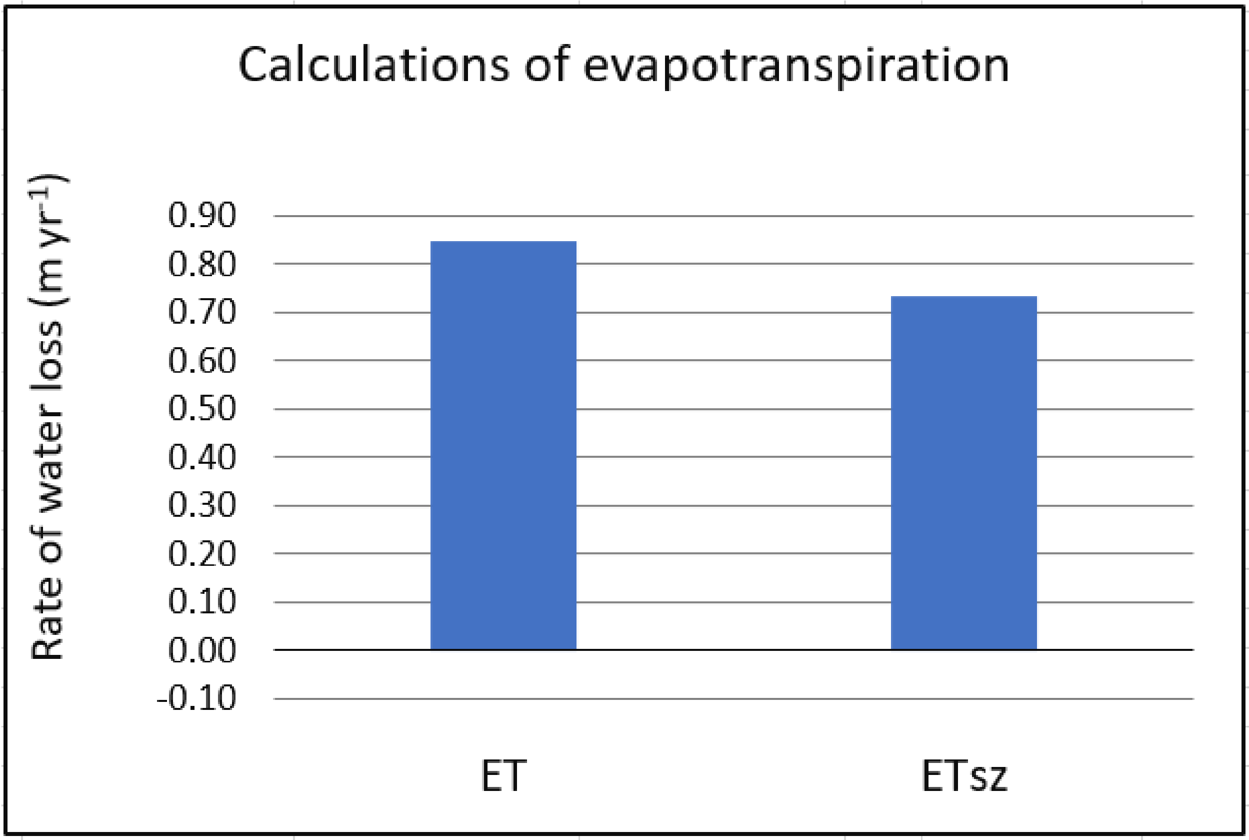

Figure 4. Calculation of evapotranspiration by difference using Eq. 2 (ET) compared to the calculation of evapotranspiration using wind speed, solar radiation, and humidity using Eq. 3 (ET_{sz}).

DISCUSSION

At Glacier Creek Preserve, most (95.9%) of the water entering the preserve as precipitation leaves as evapotranspiration. This high value indicates that plants are major contributors to water loss from mixed grass and corn/soybean environments of similar climatic and geographical conditions experienced at Glacier Creek Preserve. Although the area near the Republican River is dominated by different vegetation, the results of this study imply that the removal of vegetation near the Republican River would likely have a noticeable effect on the river discharge. More broadly, evapotranspiration is an especially important factor to consider within the field of water resource management, and mitigation of evapotranspiration could prove to be a useful tool for water conservation.

While ET calculated by difference (ET, Eq. 2) and the ASCE function (ET_{sz}, Eq. 3) both showed that the majority of water lost from Glacier Creek Preserve is due to evapotranspiration, there is a large (-13.2%) relative difference of ET_{sz} from ET. If ET represents the true value of evapotranspiration, this indicates that there is a noticeable source of error for the ASCE ET_{sz} function. Potential sources of error for this function include inaccurate measurement of daily solar radiation, wind speed, humidity, temperature, and height of the plants. Notably, plant height tends to change over the course of the year, and this function is very limited in its ability to account for plant height with only two options (short at 0.12 m and tall at 0.50 m). It is also notable that this function is intended primarily for estimating evapotranspiration from crops rather than from prairie grasses.

While the calculation of ET by difference relies on direct measurements of the water budget (as opposed to ET_{sz}), a significant amount of skepticism is reserved for this estimate. Most notably, water table elevation was not considered. While the contribution of change in water table was assumed to be negligible due to the typical precipitation rate experienced during the timeframe of study, fluctuations in water table elevation or an unexpected groundwater flow direction away from Glacier Creek could potentially lead to inaccurate results. It is also notable that change in soil moisture is only measured at two locations within the preserve, which may not be representative of the entire watershed. Other sources of error may arise from inaccurate measurements of stream flow and soil moisture. Given the difference between the weather station ET estimates and the estimate from the water budget, it is likely that assumptions about the change in storage (groundwater and/or soil moisture) are incorrect and should be investigated further.

In addition, estimates of evapotranspiration for Glacier Creek Preserve are representative of mixed use between tall grass prairie and cropland. Due to this, the results may not be applicable to locations dominated by prairie only, areas significantly far away from Glacier Creek Preserve, locations with different climatic conditions, or mixed land use with crops and short grass prairie.

CONCLUSIONS

Precipitation accumulated at a rate of 0.883 m yr^{-1}, change in storage increased at a rate of -0.021 m yr^{-1}, surface water flowed from the watershed at a rate of 0.057 m yr^{-1}, and ET was found to be at a rate of 0.847 m yr^{-1}. The relative error of ET_{sz} from ET was found to be large (-13.2%) as defined by the ±10% threshold. This indicates that the ASCE reference function for evapotranspiration is not representative of the mixed tall grass prairie and corn crop conditions found in Glacier Creek Preserve, and that other methods should be used for high-precision estimates of evapotranspiration.

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APPENDIX A – Soil Moisture

	Average soil water content from specified days, depths, and locations (percent volume)								
	Agricultural (10 cm)	Agricultural (25 cm)	Agricultural (50 cm)	Agricultural (100 cm)	Prairie (10 cm)	Prairie (25 cm)	Prairie (50 cm)	Prairie (100 cm)	**Total Averages**
12/1/2017	33.5%	34.3%	34.6%	34.7%	27.5%	30.7%	38.7%	38.0%	**34.0%**
11/30/2018	18.8%	33.8%	33.7%	35.7%	35.9%	34.0%	40.4%	38.0%	**33.8%**

Table A1. Average soil water content from specified days, depths, and locations.

Difference in average soil water content:	-0.00212	
Difference in average soil water content *Watershed area:	-8.48E+03	m^2
Assumed average depth to groundwater table	10	m
Difference in average *watershed area *average depth to water table:	-8.48E+04	m^3

Table A2. Calculations for overall change in water from soil moisture for the watershed.

APPENDIX B – Precipitation

Total Precipitation from specified date ranges (mm)			
	Agricultural	Prairie	Average
12/01/17-12/31/17	0.00	1.78	0.89
01/01/18-03/31/18	Bad data	99.57	99.57
04/01/18-09/19/18	645.94	639.05	642.50
09/20/18-10/24/18	112.27	Bad data	112.27
10/25/18-11/30/18	26.16	29.72	27.94
Total:	784.37	770.12	**883.16**

Table B1. Calculation of precipitation in mm from date ranges. Bolded value represents precipitation rate in mm yr^{-1}.

APPENDIX C – ET_{SZ}

	ET_{sz} calculated using Eq. 3 (mm yr^{-1})				
	Average Agricultural	Average Prairie	Agricultural total (accounting for errors)	Prairie total (accounting for errors)	Average of Agricultural and Prairie
12/01/17-12/31-17	0.64470968	0.725180328	19.986	22.48059016	21.2332951
01/01/18-11/30/18	2.32224299	1.95473871	775.6291589	652.882729	714.255944

Table C1. Calculations of ET_{sz} for specified date ranges and locations.

	Agricultural total (accounting for errors)	Prairie total (accounting for errors)	Average of Agricultural and Prairie
Total ET_{sz} 12/01/17 - 11/30/18 (mm):	795.6151589	675.3633192	735.489239
Percent of precipitation lost to ET_{sz}	90.1%	76.5%	83.3%
ET_{sz} rate (m yr^{-1})	0.796	0.675	0.735
ET_{sz} rate (m^3 yr^{-1})	3.18E+06	2.70E+06	2.94E+06

Table C2. Calculations of ET_{sz} for entire date range from 12/01/17 to 11/30/18.

t-Test: Two-Sample Assuming Unequal Variances		
	Ag mean ET_{sz} (mm/day)	*Prairie ET_{sz} (mm/day)*
Mean	2.017128058	2.000011527
Variance	2.666076316	2.598985434
Observations	695	694
Hypothesized Mean Difference	0	
df	1387	
t Stat	0.197	
P(T<=t) one-tail	0.422	
t Critical one-tail	1.646	
P(T<=t) two-tail	**0.844**	
t Critical two-tail	1.962	

Table C3. T-test between ET_{sz} of the Agricultural weather station and ET_{sz} of the Prairie weather station.

APPENDIX D – Data Summary

Total rainfall 12/01/17 to 11/30/18 (mm yr^{-1}):	883.2
Total rainfall 12/01/17 to 11/30/18 (m yr^{-1}):	0.8832
Surface area of watershed (km^2):	4.00
Surface area of watershed (m^2):	4.00E+06
Total volume of precipitation (m yr^{-1})	0.883
Total flow through Glacier Creek stream (m yr^{-1}):	0.057
Water gained from soil moisture (m^3 m^{-2} land yr^{-1})	0.021
(Volume of rainfall/yr) - (Total flow through stream/yr) + (Water gained from soil moisture/yr) (m^3 yr^{-1}):	0.847
Percent of rainfall lost to ET:	95.9%

Table D1. Various values summarized.

Precip rate (m yr^{-1}):	0.883161
Percent of stream flow/precip:	6.51%
Percent of ET/precip:	95.89%
Percent of soil moisture/precip:	-2.40%

Table D2. Percentage losses of water budget factors relative to precipitation.