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Comparison of Reference Evapotranspiration Calculations for Southeastern North Dakota

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Abstract

Potential water consumption for irrigation scheduling in North Dakota was typically calculated from a reference Evapotranspiration (ET_{ref}) using the Jensen-Haise method and its associated crop coefficient (K_c) curves developed in the 1970's and 1980's. The ET_{ref} method proposed by the American Society of Civil Engineers, Environmental and Water Research Institute (ASCE-EWRI) reference evapotranspiration task force has shown to be more accurate and therefore more widely used than any other methods. However, to apply the ASCE-EWRI method for irrigation scheduling requires a corresponding change of the K_c curves associated with the Jensen-Haise method. In this paper, a comparison of ET_{ref} estimates for 11 methods, including the ASCE-EWRI and the Jensen-Haise methods, was conducted using 18 years of data collected in southeastern North Dakota. The results show that the annual ET_{ref} by the Jensen-Haise method was nearly the same as the ASCE-EWRI grass ET_{ref}, but with a higher Root Mean Square Deviation (RMSD), 0.903 mm d^{-1}, and a lower coefficient of determination (R^2) 0.8659. The ET_{ref} comparison for the growing season only shows an RMSD of 1.007 mm d^{-1}, R^2 of 0.7996 and 8.13% overestimation. The ET_{ref} by the Jensen-Haisemethod has a higher monthly ET_{ref} than the ASCE-EWRI in June, July, and August, and a lower monthly ET_{ref} for all other months in an 18 year period. The ET_{ref} comparisons also show that the modified Penman method used by the High Plains Regional Climate Center (HPRCC Penman) has the best accuracy and correlation with the ASCE-EWRI ET_{ref} method. Indeed, all alfalfa based ET_{ref} methods, including Kimberly Penman and HPRCC Penman, show better performance than the grass based ET_{ref} methods, including FAO24 Penman, FAO24 Radiation, FAO24 Blaney-Criddle, Priestley-Taylor, Hargreaves, and the Jensen-Haise methods.

Keywords: Reference evapotranspiration; Jensen-Haise; ASCE standardized reference ET

Introduction

Evapotranspiration (ET) is defined as evaporation of water from land and water surfaces [1] and transpiration by vegetation [2]. Knowledge of ET is important for water resource planning, efficient water management, and water permitting application. Direct measurement of ET is time consuming and costly [3]. Therefore, ET is normally determined indirectlyby relating to a reference evapotranspiration (ET_{ref}) to a crop coefficient (K_c), namely, $ET = K_c \times ET_{ref}$ [3]. ET_{ref} is defined as the ET rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation [1]. It represents the evaporative power of the atmosphere at a specific location and time of the year, but does not consider the crop characteristics and soil factors [4]. ET_{ref} can be calculated from weather data collected by weather stations. The K_c curve represents crop growth characteristic for a growing season. Both ET and K_c are influenced by crop characteristics, such as crop variety and cultivar, growth stage, crop height, and surface roughness. ET can also be affected by soil characteristics, including soil salinity, fertility, impenetrable soil layers, and plant residue [4]. The K_c curve for a specific crop is normally developed from research data for a specific region.

Many methods have been developed to estimate ET_{ref}. These can be categorized into four basic groups: combination, radiation, temperature, and pan evaporation methods [3]. The combination method, accounting for radiation (energy balance) and aerodynamic (heat and mass transfer) terms [2], was first proposed in 1948 by Penman [5]. The Penman equation was subsequently modified as the FAO24 Penman method [3], the Kimberly Penman [6], the Penman-Monteith [7], the FAO Penman-Monteith [4] and the American Society of Civil Engineers, Environmental and Water Resources Institute (ASCE-EWRI) Penman-Monteith [1] equation. Radiation based ET_{ref} equations include the Priestley-Taylor [8] and FAO24 radiation methods [3]. Temperature based ET_{ref} equations include the Thornthwaite [9], Jensen-Haise [10], FAO24 Blaney-Criddle [3], and Hargreaves [11]. The pan evaporation methods are termed FAO class-A Pan [3] and Christiansen Pan [12]. While the availability of reliable weather data is limited, temperature methods (e.g. Jensen-Haise method) have been shown to provide reasonable ET_{ref} estimates. Among all the methods, the one that was developed by the ASCE EWRI standardized reference evapotranspiration task committee [1] was recommended as the standardized reference ET method [13-15]. Application of this method requires solar radiation, air temperature, relative humidity and wind speed as the input parameters.

Weather data used for estimating ET_{ref} are normally collected from a reference crop surface, either a tall crop similar to a full-cover alfalfa or a short crop similar to a clipped, cool-season grass. While most ET_{ref} methods are only applicable for one reference surface, the ASCE-EWRI method [1] can be applied to both full cover crops of alfalfa and grass. The ET_{ref} on an alfalfa reference surface is abbreviated as ET_r, and the ET_{ref} on a grass reference surface as ET_o. Most methods, such

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as the FAO24 Penman [3] and the Penman-Monteith [7], are based on the grass reference surface, but some, such as the Kimberly Penman [6] and the modified Penman methods [16] used by the High Plains Regional Climate Center (HPRCC, http://www.HPRCC.unl.edu) are based on an alfalfa reference surface.

In North Dakota, the Jensen-Haise equation is used to calculate the ET_{ref} [17-19]. The Jensen-Haise method only requires temperature and solar radiation as the input parameters. It was originally developed from data collected in the western United States over 35 years using 15 field and orchard crops [10,20].The North Dakota Agricultural Weather Network (NDAWN, http://ndawn.ndsu.nodak.edu/) calculates ET_{ref} values using the Jensen-Haise method and the modified Penman (or HPRCC Penman) method for each weather station on the network. North Dakota is part of the High Plains Regional Climate Center. As indicated by Irmak et al. [21], the HPRCC Penman method applies when vapor pressure deficit (VPD) and wind speed do not exceed 2.3kPa and 5.1 ms^{-1}, respectively. Weather records from the Oakes NDAWN weather station indicate that higher values for wind speeds and VPD are not rare. For the period of record from 1991 to 2008 (6575 days), there are 12 days with VPD over 2.3 kPa, and 724 days (or 40 days per year) with wind speed above 5.1 m s^{-1}. Irmak et al. [21] found that at the higher end of the ET_r values, the HPRCC Penman method provided consistently lower ET_r values than those using the ASCE-EWRI method, which was attributed to the upper limits of applicability by the HPRCC Penman method.

The standardized ET_{ref} method [1] has not been widely used in North Dakota. Most crop coefficient curves were developed using the Jensen-Haise method for this region [22-25]. As indicated by Snyder et al. [26], K_c values are developed specifically for a region, and are highly dependent on the methods used for actual ET measurement and reference ET calculations. This indicates that all K_c curves were bonded specifically to the ET and ET_{ref} methods used to develop them because K_c values were derived as ET/ET_{ref}. The variable ET would only need to be figured initially before ET_{ref} and K_c could be applied. Applications of the ASCE EWRI method will require sequential changes to the K_c curves developed using other methods, such as the Jensen-Haise method.

Most irrigation research studies in North Dakota were conducted near Oakes in the southeast area of the state [17, 27,28]. There hasn't been much research in the west part of the ND state where it's drier and research is needed. Irmak et al. [21] categorized the Jensen-Haise method as an alfalfa reference based method, but Jia et al. [29] found that the ET_{ref} by the Jensen-Haise method is closer to a grass reference based method. Jensen and Haise [10] stated they developed the method based on data collected during the growing season over 35 years from 15 field and orchard crops in different regions of the Western US. The Oakes area does not have the most typical climate to represent the whole state and may not be the best place for irrigation based on its above average precipitation [29], but the sandy soil conditions, available water resources, and financial assistance from Garrison Division Conservancy District made the Oakes area one of the most irrigated areas in ND [30,31].

In this study, using weather data collected at the Oakes NDAWN station from 1991 to 2008, the daily ET_{ref} was calculated using 11 methods. The differences between the ASCE-EWRI ET_o method [1] and the Jensen-Haise ET_o method [10] as well as other 9 methods were compared on a daily, monthly, and yearly basis for the entire year and the growing season for the period of May 1 to September 30.

Material and Methods

Study site

The study site is located in Oakes, North Dakota. The weather station, surrounded by agricultural land, is located south of Oakes at latitude 46.07°N, longitude 98.09°W, and an elevation of 392 m. The soil at the weather station is Embden fine sandy loam (coarse-loamy, mixed Pachic Udic Haploborolls), and Maddock fine sandy loam (sandy, mixed Udorthentic Haploborolls) [32].

Weather conditions

The weather conditions at Oakes are typical continental; cold in the winter and semi-humid in the summer. The weather data recorded during the past 18 years showed that the average annual temperature was about 6°C, with the minimum in January and the maximum in July and August. Rainfall amounts ranged from 346 mm to 637 mm from May to September, with the highest rainfall amounts generally in June. The average ET_r during the growing season was 842 mm, which was 471 mm higher than the average precipitation amount. Wind speed averaged 3.3 m s^{-1} at 2 meter above the ground, with the highest average monthly wind speed of 4.0 m s^{-1} in May, and the lowest monthly average wind speed of 2.4 m s^{-1} in August. The average annual maximal wind speed was 8.8 m s^{-1}. The longest day time at Oakes is 16 hours in June and the shortest day time of 9 hours is in December [3]. There are 137 frost free days at Oakes, with the last killing frost in May and the first killing frost in October [33]. Monthly average, maximum, and minimum daily values for temperature, relative humidity, rainfall, and solar radiation over the 18 years at Oakes are listed in Table 1.

Data quality

"Data quality has the highest priority in the operation of the North Dakota Agricultural Weather Network (NDAWN) because erroneous data are worse than no data" [34]. Two procedures are performed daily for ensuring data quality control: locate missing and erroneous values and provide estimates using data from nearby stations. The data retrieved from NDAWN are further checked following the weather data integrity assessment procedures recommended by Allen [35] and ASCE-EWRI [1] for solar radiation, humidity, temperature, and wind speed to ensure that all data used in the calculation and analysis are good quality.

Weather parameters

Daily weather data, including maximal temperature (T_{max}), minimal temperature (T_{min}), wind speed (U), maximal wind speed (U_{max}), dew point temperature (T_{dew}), and shortwave incoming radiation (R_s) were downloaded from the NDAWN website for the period of 01/01/1991 to 12/31/2008. All the other required information, such as latitude, elevation, height of wind speed measurement and grass height were obtained either from the NDAWN website or from personal communications [34].

NDAWN measures wind speed at a height of 3 m immediately adjacent to the weather station, the grass in an area of about 40 m^2 has been maintained at a height of about 8-10 cm. However, to accommodate the fully mature crop heights typically taller than 0.5 m [34], equation 47 in FAO56 [4] was used to convert the wind speed at 3 m height to 2 m height:

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)} \quad (1)$$

where u_2 is the wind speed at 2 m above the ground surface in m s^{-1},

Month	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)	U_{avg} (m d^{-1})	RH (%)	R_s (MJ m^{-2})	Day time (h)	PET (mm)	Rain (mm)
Jan	-7	-18	-12	3.4	75	5.9	9	18	
Feb	-3	-14	-9	3.6	74	9.4	10	27	
Mar	3	-7	-2	3.7	71	13.4	12	60	
Apr	13	0	6	3.9	57	17.4	14	131	35
May	20	7	14	4.0	56	20.1	15	187	73
Jun	25	13	19	3.4	65	22.1	16	186	102
Jul	28	15	21	2.6	70	23.1	15	183	79
Aug	27	14	20	2.4	68	19.9	14	160	51
Sep	22	8	15	2.8	63	14.9	13	126	66
Oct	14	1	8	3.1	61	9.4	11	84	51
Nov	4	-7	-2	3.3	70	5.8	10	36	
Dec	-3	-14	-8	3.4	75	4.7	9	19	
Annual	**12**	**0**	**6**	**3.3**	**67**	**14**	**12**	**1217**	**457**

Table 1: Monthly average maximal temperature (T_{max}), minimal temperature (T_{min}), daily temperature (T_{avg}), wind speed (U_{avg}) at 2 m height, incoming solar radiation (R_s), day time length (hour), monthly total potential evapotranspiration (PET) by Hprcc Penman method (mm), and monthly total rainfall (Rain) during the study period from 1991 to 2008 at Oakes, North Dakota. All parameters were obtained from the NDAWN website, except day time hours were calculated from Doorenbos and Pruitt (1977) using Oakes' latitude.

u_z is the measured wind speed at z m above ground surface in m s^{-1}, and z is the height of measurement above the ground surface in m, which is 3 m for this study.

The relative humidity is calculated from equation 6 to 8 of ASCE-EWRI method [1] using measured T_{max}, T_{min}, and T_{dew} from NDAWN weather data via saturated (e_s) and actual vapor pressure (e_a):

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

$$e^o(T) = 0.6108\exp\left(\frac{17.27T}{T + 237.3}\right) \quad (3)$$

$$e_a = e^o(T_{dew}) = 0.6108\exp\left(\frac{17.27T_{dew}}{T_{dew} + 237.3}\right) \quad (4)$$

where the T in equation (3) can be either T_{max} in °C or T_{min} in °C to be used in equation (2) to calculate the e_s and e_a in kPa. The relative humidity (RH) is calculated as the ratio of e_a to e_s. Details of sensor types, layout, and data quality control are detailed on the NDAWN website.

Reference ET calculations

The daily Jensen-Haise and HPRCC Penman ET_{ref} values are available on the NDAWN website. The ET_{ref} by these two methods will be directly used in the comparison. The ET_{ref} by the ASCE-EWRI method for grass and alfalfa references were calculated [1] using:

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma C_n (T + 273) \times u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d \times u_2)} \quad (5)$$

Where ET_{ref} is the reference crop evapotranspiration for short grass (ET_o) or tall alfalfa (ET_r) [mm day^{-1}], R_n is net radiation at the crop surface [MJ m^{-2} day^{-1}], G is soil heat flux [MJ m^{-2} day^{-1}], T is mean daily air temperature at 2 m height [°C], u_2 is wind speed at 2 m height [m s^{-1}], Δ is slope vapor pressure curve [kPa °C^{-1}], and γ is the psychrometric constant [kPa °C^{-1}]. For a 24 hour time step, soil heat flux, G, is presumed to be 0. The values of C_n and C_d vary depending on the reference crops, and are 900 and 0.34 for the grass reference and 1600 and 0.38 for the alfalfa reference, respectively.

The downloaded weather data were arranged in the correct format for the REFET software [36], so that daily ET_{ref} by FAO24 Penman, FAO24 Radiation, FAO24 Blaney-Criddle, Priestley-Taylor, Hargreaves ,Kimberly Penman 1982 and Kimberly Penman 1972 methods could be calculated.

A total of eleven methods were used to calculate the ET_{ref}; four methods are alfalfa based methods (ASCE-EWRI ET_r, HPRCC Penman, Kimberly Penman 1982 and Kimberly Penman 1972) and seven methods are grass based reference methods (ASCE-EWRI ET_o, FAO24 Penman, FAO24 Radiation, FAO24 Blaney-Criddle, Priestley-Taylor, Hargreaves, and Jensen-Haise).

Statistics analysis

The daily ET_{ref} values calculated from each method were compared to the ASCE-EWRI ET_r or ET_o values, depending on whether it was grass or alfalfa reference surface method. The root mean square deviation (RMSD) between the ASCE-EWRI ET_{ref} (method x, in Eq. (6)) and the compared method (method y, in Eq. (6)) was used to determine the difference:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}} \quad (6)$$

where x_i is the ET_{ref} calculated by method x on day i; y_i is the ET_{ref} calculated by method y on day i; and n is the total number of days used in the calculation.

Since the ASCE-EWRI ET_{ref} is considered a standard value for comparison, the RMSD values between ET_{ref} values using the ASCE-EWRI and the compared method are considered a quantitative measure of all other methods. A smaller RMSD means a better comparison between the other method and the ASCE-EWRI ET_{ref} method. The slope and coefficient of determination (R^2) values are used to assess the bias of each method. The intercept of the regression line between the ASCE-EWRI ET_{ref} and the compared ET_{ref} values were forced to zero for an equal comparison among all methods. However, when forcing the regression curve to zero, it also assumes that at zero ET values, there is no atmosphere demand for water for all methods and the resulting slope can be used to indicate the error regardless of the magnitude of the readings. It also biases the results by placing heavier weight on points farthest from the origin. The purpose of this paper is to determine how widely the ET_{ref} values were different from the

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standardized ASCE-EWRI ET_{ref} values and the RMSD and R^2 values should be reasonable sufficient.

Results and Discussions

Daily ET_o and ET_r comparison

Comparison of daily ET_o and ET_r values between the ASCE-EWRI ET_o or ET_r method and the targeted method are shown in Figure 1a-1j. The slope of the fitting and coefficient of determination for each pair are also shown in the graph and in Table 2. In addition, the RMSD and the rank of all methods are also shown in Table 2. The rank is made according to the average of the R^2 and the RMSD ranks. For example, the R^2 ranks 9 and the RMSD ranks 7 between the Prestley-Taylor and ASCE-EWRI ET_o methods, the overall rank is the average, 8.

From 1991 to 2008, the HPRCC Penman method results were most similar to the ASCE-EWRI ET_r values using R^2 and RMSD. Even with limitations on high wind speed and high VPD, the HPRCC Penman method performed the best among all methods. It overestimated the ASCE-EWRI ET_r by a mere 1%; much better compared to reports by Irmak et al. [21] with a 5% underestimation. The Jensen-Haise method provided very close ET_o values when compared to the ASCE-EWRI ET_o values with less than 0.2% difference. However, the R^2 was only 0.87 and the RMSD was 0.903 mm d^{-1}. If one argues that forcing the equation to zero has caused the problem, the R^2 was only 0.89 without forcing the equation to zero. This proves that the Jensen-Haise method is not strongly correlated to the ASCE-EWRI ET_o values.

Winter in North Dakota extends from late November to early April. During this time period, average air temperature is normally less than 0 °C, while the ground is frozen, plants are dead or dormant, and most of the state is covered with snow. Under these conditions, no water evaporates from the soil surface or transpired by plants. Thus, these conditions seem to violate the definition of ET. There may be some water loss through sublimation, a phase change from solid ice or snow to vapor [37,38]. The calculation of ET during this time period is for comparison purposed only, and does not represent any actual ET lost. Evaluation of ET values during the growing season in North Dakota is more important.

Growing season ET_o and ET_r

Because the Jensen-Haise method was originally developed using data during the growing season, the ET_{ref} comparisons are performed using weather data from May 1 to September 30 over an 18-year period (Figure 2a-2j).

After changing the comparison days from 6575 days for the 18 years to 2966 days for the growing season only, the relationship between the ET_{ref} by ASCE-EWRI method and other methods did not change significantly. The HPRCC Penman method still performed the best among all the methods with the higher R^2 and smallest RMSD value. The Priestley-Taylor method performed better for the growing season than for the entire year. The FAO24 Blaney-Criddle method had the highest correlation (R^2) with the ASCE-EWRI ET_o values, but with 20.76% overestimation, and therefore, a higher RMSD value than that in Figure 1. The Blaney-Criddle method required mean daily temperature, mean daily percentage of total annual daytime hours, and an adjustment factor depending on minimum relative humidity, sunshine hours, and daytime wind estimates as the input parameters, which are similar to the ASCE-EWRI method, but without considering the crop factors, and thus do not strongly correlated. The Jensen-Haise method remained about the same rank with the ASCE-EWRI ET_o either for the growing season or for the entire year. For the growing

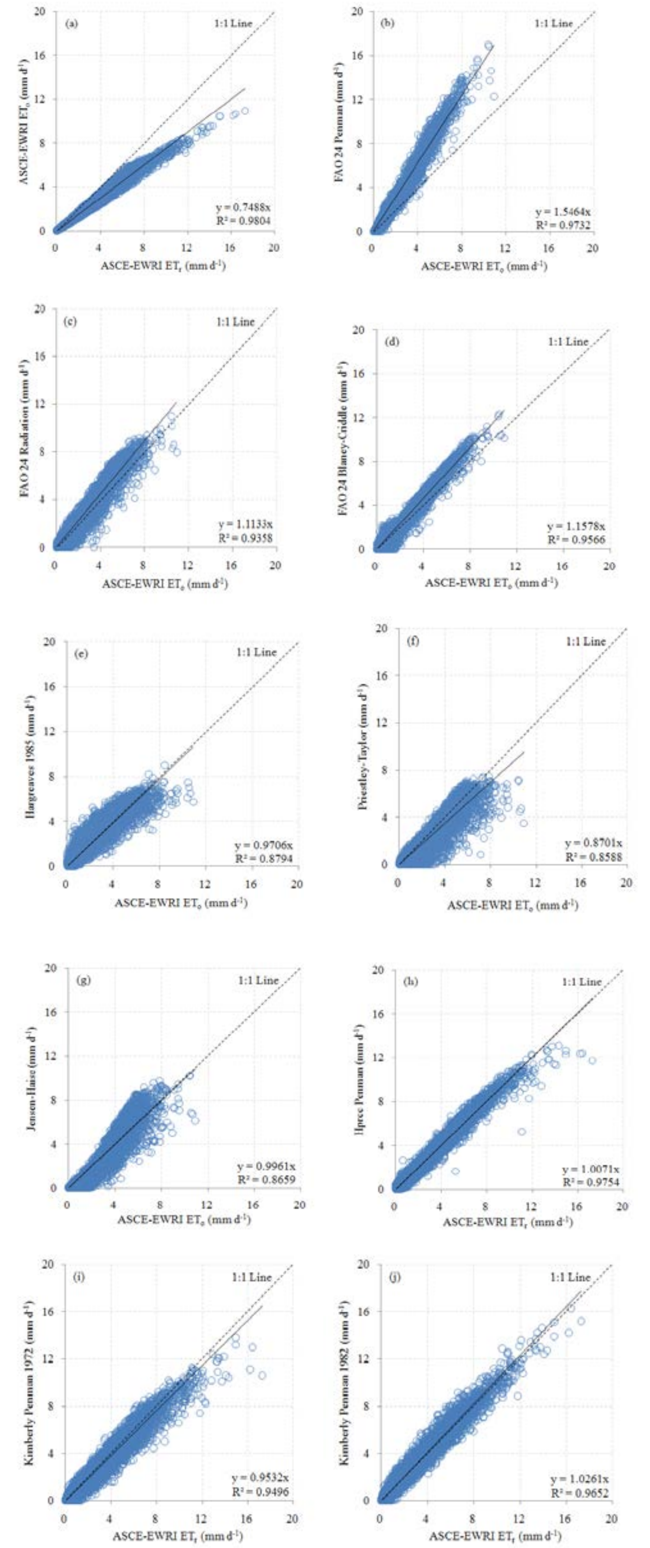

Figure 1: Daily reference evapotranspiration comparisons between (a) ASCE-EWRI ET_o and ASCE-EWRI ET_r; (b) FAO24 Penman and ASCE-EWRI ET_o; (c) FAO24 Radiation and ASCE-EWRI ET_o; (d) FAO24 Blaney-Criddle and ASCE-EWRI ET_o; (e) Hargreaves 1985 and ASCE-EWRI ET_o; (f) Prestley-Taylor and ASCE-EWRI ET_o; (g) Jensen-Haise and ASCE-EWRI ET_o; (h) Hprcc Penman and ASCE-EWRI ET_r; (i) Kimberly Penman 1972 and ASCE-EWRI ET_r; and (j) Kimberly Penman 1982 and ASCE-EWRI ET_r methods for Oakes, North Dakota in 1991-2008.

ID	Method y	Method x	Slope	R^2	Rank-R^2	RMSD	Rank-RMSD	Overall Rank
(a)	ASCE-EWRI ET_o	ASCE-EWRI ET_r	0.7488	0.9804		1.103		
(b)	FAO24 Penman	ASCE-EWRI ET_o	1.5464	0.9735	2	1.827	9	6
(c)	FAO24 Radiation	ASCE-EWRI ET_o	1.1133	0.9358	6	0.717	5	5
(d)	FAO24 Blaney-Criddle	ASCE-EWRI ET_o	1.1578	0.9566	4	0.746	6	4
(e)	Hargreaves 1985	ASCE-EWRI ET_o	0.9706	0.8794	7	0.707	4	5
(f)	Prestley-Taylor	ASCE-EWRI ET_o	0.8701	0.8588	9	0.854	7	7
(g)	Jensen-Haise	ASCE-EWRI ET_o	0.9961	0.8659	8	0.903	8	7
(h)	Hprcc Penman	ASCE-EWRI ET_r	1.0071	0.9754	1	0.429	1	1
(i)	Kimberly Penman 1972	ASCE-EWRI ET_r	0.9532	0.9496	5	0.624	3	3
(j)	Kimberly Penman 1982	ASCE-EWRI ET_r	1.0261	0.9652	3	0.522	2	2

Table 2: Comparison of daily reference evapotranspiration (ET_{ref}), Root Mean Square Deviation (RMSD), and coefficient of determination (R^2) from 1991 to 2008 at Oakes, North Dakota. ET_o is grass based reference surface and ET_r denotes alfalfa based reference surface. The overall rank is based on average ranks from RMSD and R^2 for annual ET_{ref}.

ID	Method y	Method x	Slope	R^2	Rank-R^2	RMSD	Rank-RMSD	Overall Rank
(a)	ASCE-EWRI ET_o	ASCE-EWRI ET_r	0.7671	0.9543		1.395		
(b)	FAO24 Penman	ASCE-EWRI ET_o	1.5697	0.9529	3	2.624	9	6
(c)	FAO24 Radiation	ASCE-EWRI ET_o	1.1387	0.8915	6	0.916	6	5
(d)	FAO24 Blaney-Criddle	ASCE-EWRI ET_o	1.2054	0.9625	1	1.001	8	3
(e)	Hargreaves 1985	ASCE-EWRI ET_o	1.0026	0.4373	9	0.901	5	7
(f)	Prestley-Taylor	ASCE-EWRI ET_o	0.9251	0.7272	8	0.858	4	5
(g)	Jensen-Haise	ASCE-EWRI ET_o	1.0813	0.7996	7	1.007	7	7
(h)	Hprcc Penman	ASCE-EWRI ET_r	1.0108	0.9541	2	0.483	1	1
(i)	Kimberly Penman 1972	ASCE-EWRI ET_r	0.9905	0.9148	5	0.588	2	2
(j)	Kimberly Penman 1982	ASCE-EWRI ET_r	1.0324	0.9316	4	0.586	3	2

Table 3: Comparison of daily reference evapotranspiration (ET_{ref}), Root Mean Square Deviation (RMSD), and coefficient of determination (R^2) from May to September in 1991-2008 at Oakes, North Dakota. ET_o is grass based reference surface and ET_r denotes alfalfa based reference surface. The overall rank is based on average ranks from RMSD and R^2 for seasonal ET_{ref}.

season, it overestimated the ET_o by 8.35% from the ASCE-EWRI ET_o method with a lower R^2 and a higher RMSD value. Considering the relationship between the ASCE-EWRI ET_o and ET_r, this might indicate more than 10% underestimation from the ET_r as others have reported [21,30]. Jensen [20] and Burman et al. [39] stated that the Jensen-Haise method is better suited for time intervals of five days to one month rather than for daily estimates. The daily estimated ET_{ref} by the Jensen-Haise method was used in the analysis for Figures 1 and 2. Therefore, a growing season comparison of ET_{ref} didn't improve the correlation between the Jensen-Haise method to the ASCE-EWRI method than for an entire year.

Monthly ET_{ref}

As shown in Table 3 and Figures 1 and 2, the total ET_{ref} by the Jensen-Haise method was very close to the ASCE-EWRI ET_o values both for annual or seasonal time scale, but with a poor correlation (R^2) and less accuracy (RMSD). Figure 3a-3c shows the monthly average ET_{ref} of the 11 methods over the 18 years. Most methods showed a similar trend as the ASCE-EWRI standardized equation; higher in the summer and lower in the winter. A higher difference was observed between winter and summer, but not between spring and fall. All combination methods showed similar trends for all seasons while comparing the ASCE-EWRI ET_{ref} methods. In Figure 4a, the FAO24 Penman method showed a comparable annual curve to the ASCE-EWRI ET_o method, while in Figure 4c, all the ET_r values were very similar to each other with less than 5% difference and followed the ASCE-EWRI ET_r curve. This is probably due to the fact that the ASCE-EWRI ET_r was developed using data at Kimberly, or originated from the Kimberly Penman methods [2]. The HPRCC Penman method also gave more similar results to the ASCE-EWRI ET_r method for all month. The local-adjusted HPRCC Penman method proved to be the best fit for the Oakes area in southeastern North Dakota. The temperature and radiation based methods were quite different from the monthly ASCE-EWRI ET_o values. The FAO24 Radiation, FAO24 Blaney-Criddle and Prestley-Taylor methods showed underestimation in the winter and overestimation in the summer compared to the ASCE-EWRI ET_o values. The Jensen-Haise method had the greatest deviation from the ASCE-EWRI ET_o method with lower ET_o values from January to May and from September to December, and higher ET_o values from June to August. Though the annual ET_o values were close to the ASCE-EWRI ET_o values, the month to month difference was higher.

Figure 4 shows the average daily ET_{ref} for the ASCE-EWRI ET_r, ASCE-EWRI ET_o, and the Jensen-Haise ET_{ref}. The ASCE-EWRI ET_r peaked on May 21. Actually, the month of May has the highest ET_r, mainly due to the higher wind speed (Table 1). The Jensen-Haise method only accounts for temperature and solar radiation and does not include the effect of wind speed. This may be the reason that non-combination ET_{ref} methods do not have the same ET_{ref} pattern and peaked at different times than the combination methods. Also notice that the higher wind speed shifted the peak of alfalfa based ASCE-EWRI equation, but not the grass based equation. The grass based method peaked at the same time as the Jensen-Haise method. The difference between the grass and alfalfa based equation is the surface resistance, defined by Allen et al. [4] as "the resistance of vapor flow through stomata openings, total leaf area and soil surface". For the alfalfa reference surface, a constant surface resistance of 70 s m^{-1} was used, and for the grass reference surface, 45 s m^{-1} was used as the constant surface resistance for the standardized reference ET calculations [1].

A direct replacement of Jensen-Haise method by the ASCE-EWRI ET_o method may result in underestimation of ET_o during the growing season. Use of ASCE-EWRI ET_o values combined with the

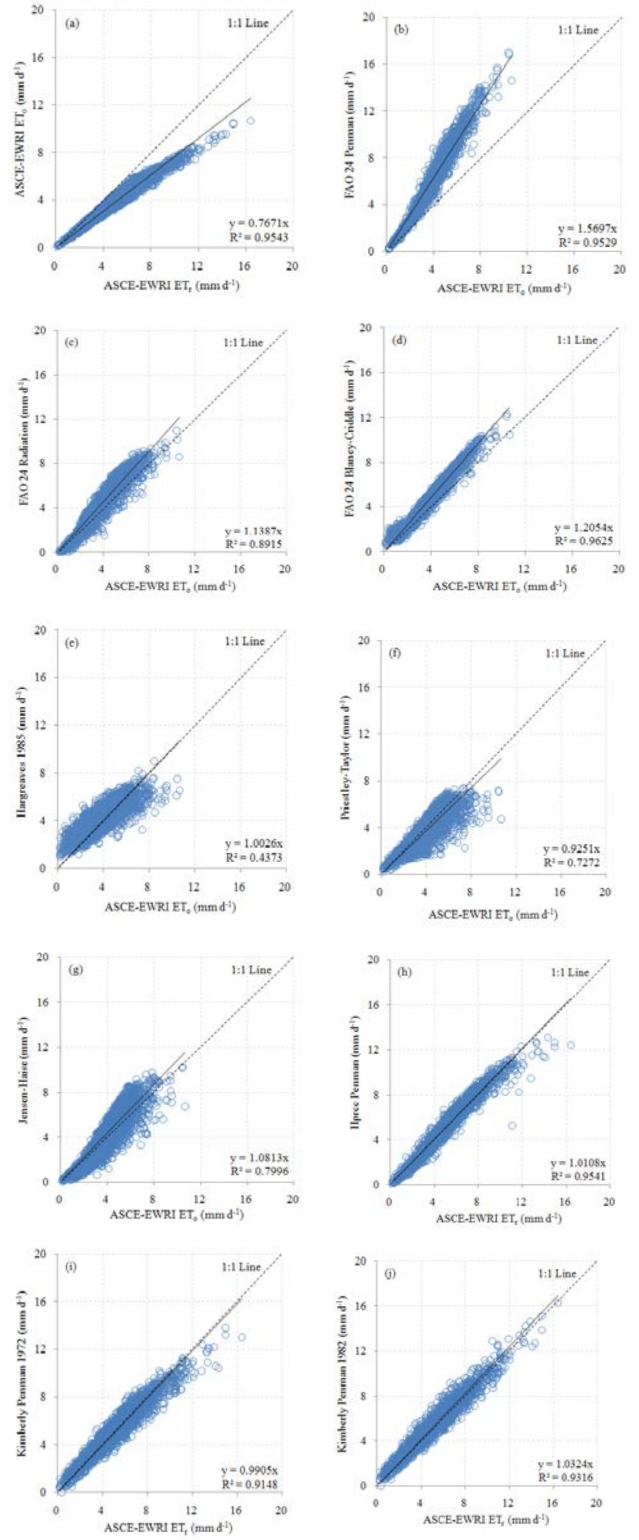

Figure 2: Daily reference evapotranspiration comparisons between (a) ASCE-EWRI ET_o and ASCE-EWRI ET_r; (b) FAO24 Penman and ASCE-EWRI ET_o; (c) FAO24 Radiation and ASCE-EWRI ET_o; (d) FAO24 Blaney-Criddle and ASCE-EWRI ET_o; (e) Hargreaves 1985 and ASCE-EWRI ET_o; (f) Prestley-Taylor and ASCE-EWRI ET_o; (g) Jensen-Haise and ASCE-EWRI ET_o; (h) Hprcc Penman and ASCE-EWRI ET_r; (i) Kimberly 1972 and ASCE-EWRI ET_r; and (j) Kimberly 1982 and ASCE-EWRI ET_r methods for Oakes, North Dakota for the growing season (May 1 – September 30) of 1991-2008.

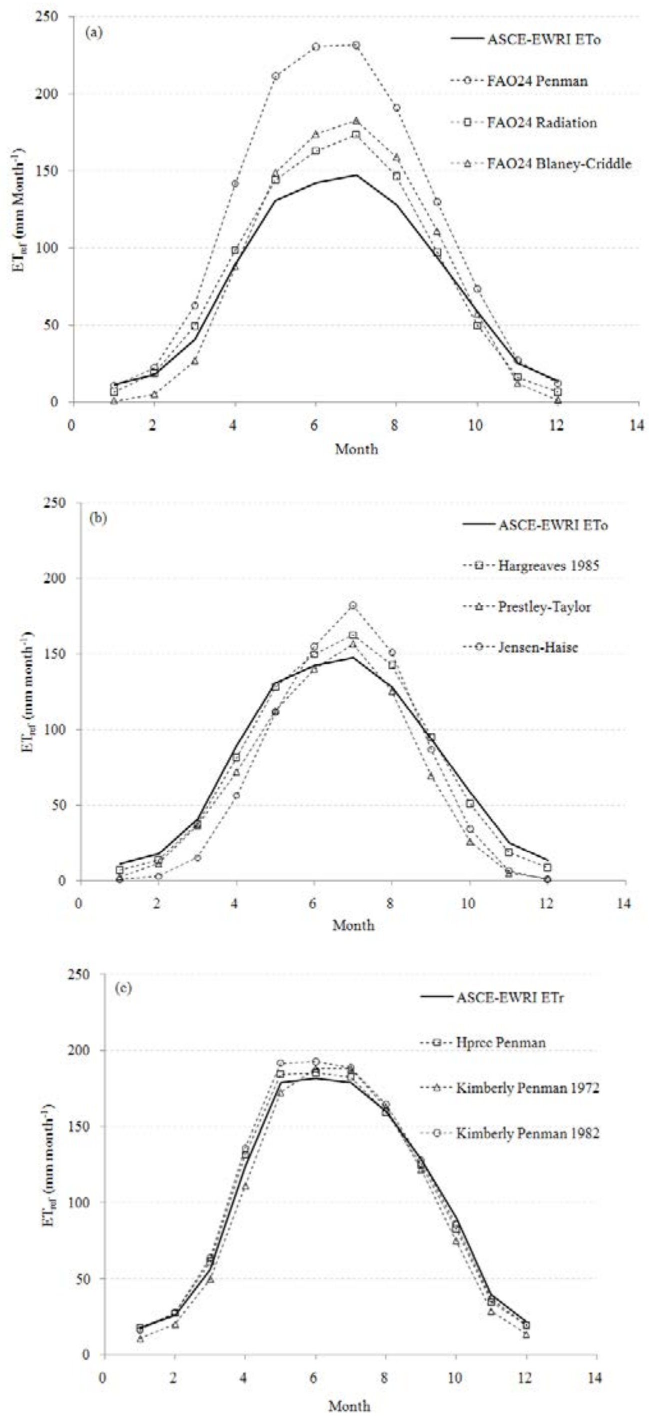

Figure 3: Comparison of monthly total reference evapotranspiration (ET_{ref}) among different methods: (a) ASCE-EWRI ET_o, FAO24 Penman, FAO24 Radiation, and FAO24 Blaney-Criddle methods; (b) ASCE-EWRI ET_o, Hargreaves 1985, Prestley-Taylor, and Jensen-Haise methods; and (c) ASCE-EWRI ET_r, Hprcc Penman, Kimberly Penman 1972, and Kimberly Penman 1982 methods.

K_c curve developed using the Jensen-Haise method would result in lower calculated crop ET, thus applying less irrigation than the crop actually needed. The K_c curve is tied to a particular ET_{ref} method and a replacement of the current ET_{ref} method used for irrigation scheduling will require changes to the K_c curves as well.

Annual ET_{ref}

Average annual ET_{ref} values are shown in Figure 5, with error bars indicating the standard deviation across 18 years of data. Almost all grass based ET_{ref} values showed lower annual ET_{ref} than the alfalfa based methods. However, the FAO24 Penman method showed a similar total ET_o as the alfalfa based method. The ET_o showed lower standard deviation than the ET_r values. Again, the HPRCC Penman method was the closest to the ASCE-EWRI ET_r value, with only 12.4 mm or 1% annual difference. The Hargreaves method has a 0.5 mm, or 0.1% difference from the ASCE-EWRI ET_r method.

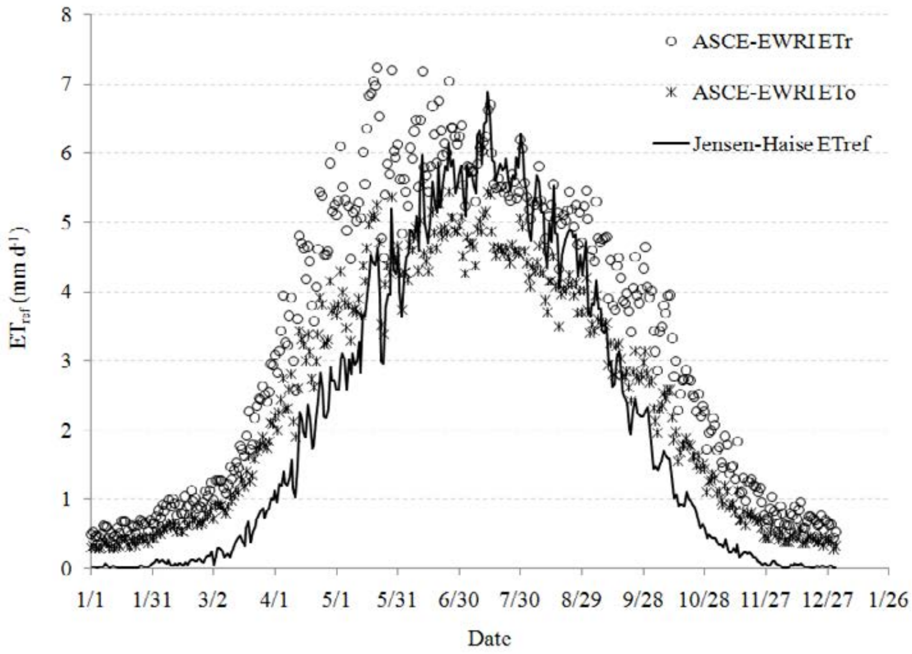

Figure 4: Comparison of average daily reference evapotranspiration (ET_{ref}) for 18 years using ASCE-EWRI ET_r, ASCE-EWRI ET_o and Jensen-Haise ET_{ref} methods at Oakes, North Dakota.

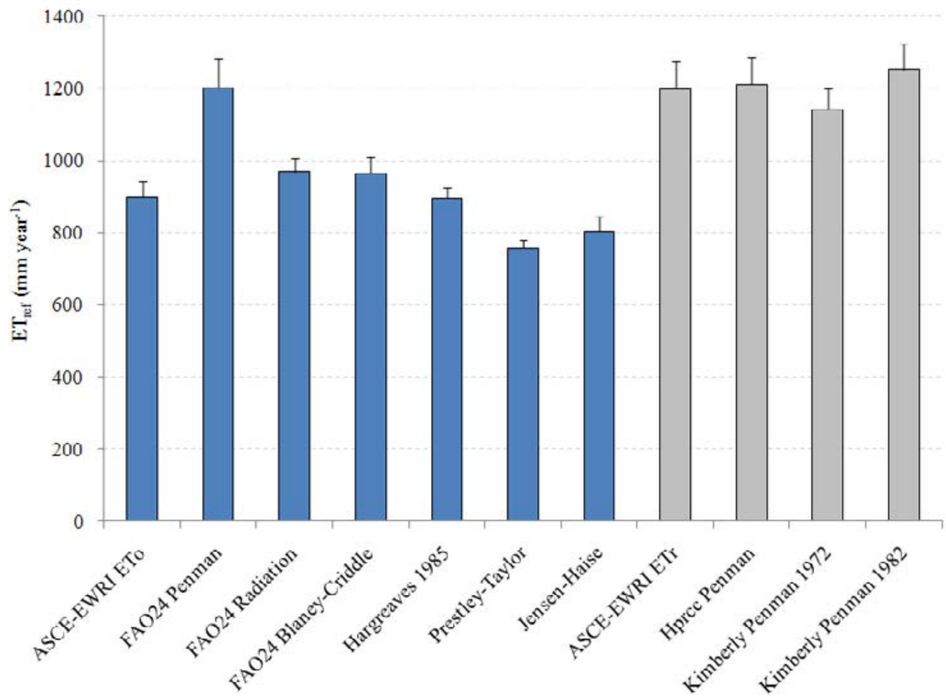

Figure 5: Comparison of annual reference evapotranspiration values (ET_{ref}) for all methods. The dark color bars indicate the grass reference based methods and the light color bars indicate the alfalfa reference based methods. The error bars indicate the standard deviation among the 18 years.

Conclusions

Crop water consumption use for irrigation scheduling in North Dakota is calculated from ET_{ref} by the Jensen-Haise method and the K_c curves developed in the 1970's and 1980's. The standardized ET_{ref} methods by the American Society of Civil Engineers, Environmental and Water Research Institute (ASCE-EWRI) reference evapotranspiration task force [1] has been widely accepted and applied across the world. However, application of the ASCE-EWRI method requires sequential changes to the K_c curves associated with the Jensen-Haise method. This paper compared ET_{ref} estimates for 11 methods, including the ASCE-EWRI and the Jensen-Haise methods using 18 years of data collected in southeast North Dakota. The results showed that the annual ET_o by the Jensen-Haise method was nearly the same (0.39% underestimation) as the ASCE-EWRI grass ET_o, but with a higher RMSD, 0.903 mm d^{-1}, and a lower R^2 0.8659, comparing to the ASCE-EWRI ET_o. Since the Jensen-Haise method was initially developed using growing season data collected from 15 crops, ET_o comparison for the growing season showed an RMSD of 1.007 mm d^{-1}, R^2 of 0.7996 and 8.13% overestimation. The ET_o by the Jensen-Haise method has a higher monthly ET_o than that y the ASCE-EWRI in June, July, and August, and lower monthly ET_o for all other months. The ET_o using the two methods does not show a strong agreement, so direct replacement of the Jensen-Haise method by the ASCE-EWRI method is not recommended. New K_c curves should be developed prior to the application of the ASCE-EWRI ET_{ref} method in southeastern North Dakota. In addition, interest in irrigating alternative crops, development of new crop cultivars of current irrigated crops and climate change will require the development of new K_c curves if ASCE-EWRI ET_{ref} values are used for irrigation scheduling. The ET_{ref} comparison also showed that the HPRCC Penman method has the best accuracy and correlation with the ASCE-EWRI ET_{ref} method overall. Indeed, all alfalfa based ET_{ref} methods, including Penman models, showed a better performance than grass based ET_{ref} methods.

Acknowledgements

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