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 (Kc) 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 Kc 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-Haise method 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 indirectly by relating to a reference evapotranspiration (ET_{ref}) to a crop coefficient (Kc), namely, ET = Kc x 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 Kc curve represents crop growth characteristic for a growing season. Both ET and Kc 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, impermeable soil layers, and plant residue [4]. The Kc 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_{ref}^A, and the ET_{ref} on a grass reference surface as ET_{ref}^G. Most methods, such...
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
\[ u_2 = \frac{H - u_1}{\ln(67.8 - 5.42)} \]
where \( u_1 \) is the wind speed at 2 m above the ground surface in m s\(^{-1}\).

The standardized ET\(_{\text{ref}}\) 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\(_{\text{ref}}\) methods used to develop them because \( K_c \) values were derived as ET/ET\(_{\text{ref}}\). The variable ET would only need to be figured initially before ET\(_{\text{ref}}\) and \( K_c \) could be applied. Applications of the ASCE-EWRI ET\(_{\text{EFRI}}\) 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\(_{\text{r}}\) 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 [10,20]. The North Dakota Agricultural Weather Network (NDAWN, http://ndawn.ndsu.nodak.edu/) calculates ET\(_{\text{ref}}\) 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 ms\(^{-1}\). Irmak et al. [21] found that at the higher end of the ET, the Jensen-Haise Penman method provided consistently lower ET\(_{\text{r}}\) 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\(_{\text{ref}}\) 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\(_{\text{ref}}\) methods used to develop them because \( K_c \) values were derived as ET/ET\(_{\text{ref}}\). The variable ET would only need to be figured initially before ET\(_{\text{ref}}\) and \( K_c \) could be applied. Applications of the ASCE-EWRI ET\(_{\text{EFRI}}\) method will require sequential changes to the \( K_c \) curves developed using other methods, such as the Jensen-Haise method.

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 (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, 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 (Tmax), minimal temperature (Tmin), wind speed (U), maximal wind speed (U2m), dew point temperature (Tdew), and shortwave incoming radiation (R) 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:

\[ u_2 = \frac{4.87}{H - \ln(67.8 - 5.42)} \]

where \( u_2 \) is the wind speed at 2 m above the ground surface in m s\(^{-1}\).
The relative humidity is calculated from equation 6 to 8 of ASCE-EWRI method [1] using measured T\textsubscript{max}, T\textsubscript{min} and T\textsubscript{dew} from NDAWN weather data via saturated (e\textsubscript{s}) and actual vapor pressure (e\textsubscript{a}): 

\[
e_T = e^\prime(T_{\text{max}}) + e^\prime(T_{\text{min}})
\]

(2)

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

(3)

\[
e_a = e^\prime(T_{\text{dew}}) = 0.6108\exp\left(\frac{17.27T_{\text{dew}}}{T_{\text{dew}} + 237.3}\right)
\]

(4)

where the T in equation (3) can be either T\textsubscript{max} in °C or T\textsubscript{min} in °C to be used in equation (2) to calculate the e\textsubscript{a} and e\textsubscript{s} in kPa. The relative humidity (RH) is calculated as the ratio of e\textsubscript{a} to e\textsubscript{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\textsubscript{ref} values are available on the NDAWN website. The ET\textsubscript{ref} by these two methods are to be used in equation (2) to calculate the e\textsubscript{a} and e\textsubscript{s} in kPa. The relative humidity (RH) is calculated as the ratio of e\textsubscript{a} to e\textsubscript{s}. Details of sensor types, layout, and data quality control are detailed on the NDAWN website.

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

\[
\text{RMSD} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}}
\]

(6)

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

The purpose of this paper is to determine how widely the ET\textsubscript{ref} values were different from the ASCE-EWRI ET\textsubscript{ref} or ET\textsubscript{v} values, depending on whether it was grass or alfalfa reference surface method. The root mean square deviation (RMSD) between the ASCE-EWRI ET\textsubscript{ref} and the compared ET\textsubscript{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\textsubscript{ref} values, there is no atmosphere demand for water for all methods and thus the interception of the regression line between the ASCE-EWRI ET\textsubscript{ref} and the compared ET\textsubscript{ref} values were forced to zero for an equal comparison among all methods.

### Table 1: Monthly average maximum temperature (T\textsubscript{max}), minimal temperature (T\textsubscript{min}), daily temperature (T\textsubscript{dew}), wind speed (U\textsubscript{dew}) at 2 m height, incoming solar radiation (R\textsubscript{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.

| Month | T\textsubscript{max} (°C) | T\textsubscript{min} (°C) | T\textsubscript{dew} (°C) | U\textsubscript{dew} (m s\textsuperscript{-1}) | RH (%) | R\textsubscript{s} (MJ m\textsuperscript{-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    | 14.3             | 12          | 60        |          |
| Apr   | 13              | 6               | 3.9             | 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      |

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

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

Statistics analysis

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

\[
\text{RMSD} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}}
\]

where x\textsubscript{i} is the ET\textsubscript{ref} calculated by method x on day i; y\textsubscript{i} is the ET\textsubscript{ref} calculated by method y on day i; and n is the total number of days used in the calculation.
Results and Discussions

Daily ET₀ and ETₜ comparison

Comparison of daily ET₀ and ETₜ values between the ASCE-EWRI ET₀ or ETₜ 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 R² and the RMSD ranks. For example, the R² ranks 9 and the RMSD ranks 7 between the Prestley-Taylor and ASCE-EWRI ET₀ methods, the overall rank is the average, 8.

From 1991 to 2008, the HPRCC Penman method results were most similar to the ASCE-EWRI ET₀ values using R² 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 ET₀ 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 ET₀ values when compared to the ASCE-EWRI ET₀ values with less than 0.2% difference. However, the R² 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 R² 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 ET₀ 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 purposes 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 ET₀ and ETₜ

Because the Jensen-Haise method was originally developed using data during the growing season, the ET₀ref 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 ET₀ref 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 R² 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 (R²) with the ASCE-EWRI ET₀ 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 ET₀ either for the growing season or for the entire year. For the growing
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$_r$ | 0.7488  | 0.9804 | 1.103      |        |            |              |
| (b) | FAO24 Penman | ASCE-EWRI ET$_r$ | 1.5464  | 0.9735 | 2          | 1.827  | 9          | 6            |
| (c) | FAO24 Radiation | ASCE-EWRI ET$_r$ | 1.1133  | 0.9358 | 6          | 0.717  | 5          | 5            |
| (d) | FAO24 Blaney-Criddle | ASCE-EWRI ET$_r$ | 1.1578  | 0.9566 | 4          | 0.746  | 6          | 4            |
| (e) | Hargreaves 1985 | ASCE-EWRI ET$_r$ | 0.9706  | 0.8794 | 7          | 0.707  | 4          | 5            |
| (f) | Prestley-Taylor | ASCE-EWRI ET$_r$ | 0.8701  | 0.8588 | 9          | 0.854  | 7          | 7            |
| (g) | Jensen-Haise | ASCE-EWRI ET$_r$ | 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 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$_{ref}$.

| 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$_r$ | 1.5697  | 0.9529 | 3          | 2.624  | 9          | 6            |
| (c) | FAO24 Radiation | ASCE-EWRI ET$_r$ | 1.1387  | 0.8915 | 6          | 0.916  | 6          | 5            |
| (d) | FAO24 Blaney-Criddle | ASCE-EWRI ET$_r$ | 1.2054  | 0.9625 | 1          | 1.001  | 8          | 3            |
| (e) | Hargreaves 1985 | ASCE-EWRI ET$_r$ | 1.0026  | 0.4373 | 8          | 0.901  | 5          | 7            |
| (f) | Prestley-Taylor | ASCE-EWRI ET$_r$ | 0.9251  | 0.7272 | 8          | 0.858  | 4          | 5            |
| (g) | Jensen-Haise | ASCE-EWRI ET$_r$ | 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            |

season, it overestimated the ET 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, 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 relationship 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$_{ref}$ 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$_{ref}$ method, while in Figure 4c, all the ET values were very similar to each other with less than 5% difference and followed the ASCE-EWRI ET$_{ref}$ curve. This is probably due to the fact that the ASCE-EWRI ET$_{ref}$ 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$_{ref}$ 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$_{ref}$ 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$_{ref}$ values. The Jensen-Haise method had the greatest deviation from the ASCE-EWRI ET$_{ref}$ method with lower ET$_{ref}$ values from January to May and from September to December, and higher ET$_{ref}$ values from June to August. Though the annual ET$_{ref}$ values were close to the ASCE-EWRI ET$_{ref}$ values, the month to month difference was higher.

Figure 4 shows the average daily ET$_{ref}$ for the ASCE-EWRI ET$_{o}$, ASCE-EWRI ET$_{r}$, and the Jensen-Haise ET$_{ref}$ values. The ASCE-EWRI ET$_{ref}$ peaked on May 21. Actually, the month of May has the highest ET, 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$_{ref}$ method may result in underestimation of ET during the growing season. Use of ASCE-EWRI ET$_{ref}$ values combined with the
Kc curve developed using the Jensen-Haise method would result in lower calculated crop ET, thus applying less irrigation than the crop actually needed. The Kc curve is tied to a particular ETref method and a replacement of the current ETref method used for irrigation scheduling will require changes to the Kc curves as well.
Annual $ET_{\text{ref}}$

Average annual $ET_{\text{ref}}$ values are shown in Figure 5, with error bars indicating the standard deviation across 18 years of data. Almost all grass based $ET_{\text{ref}}$ values showed lower annual $ET_{\text{ref}}$ 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 $ET_{\text{ref}}$ values. Again, the HPRCC Penman method was the closest to the ASCE-EWRI $ET_{\text{ref}}$ 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 $ET_{\text{ref}}$ method.

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

Figure 5: Comparison of annual reference evapotranspiration values ($ET_{\text{ref}}$) 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 Kc 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 Kc 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{ref} by the Jensen-Haise method was nearly the same (0.39% underestimation) as the ASCE-EWRI grass ET{ref}, but with a higher RMSD, 0.903 mm d{−1}, and a lower R² 0.8659, comparing to the ASCE-EWRI ET{ref}. Since the Jensen-Haise method was initially developed using growing season data collected from 15 crops, ET{ref} comparison for the growing season showed an RMSD of 1.007 mm d{−1}, R² of 0.7996 and 8.13% overestimation. The ET{ref} by the Jensen-Haise method has a higher monthly ET than that the ASCE-EWRI in June, July, and August, and lower monthly ET for all other months. The ET{ref} 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 Kc 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 Kc 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.

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