Variability of the Ratio of Alfalfa to Grass Reference Evapotranspiration under Semiarid Climate

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Abstract

Crop evapotranspiration estimation is critical for sustainable water management under the semiarid and arid climate in New Mexico. While irrigation scheduling is based on daily evapotranspiration through the two step approach, reference evapotranspiration and crop coefficients should be determined with accuracy. The utilization of grass reference evapotranspiration (ETo) or alfalfa reference evapotranspiration (ETr) and the conversion from one to the other calls for an understanding of the relationship between ETr and ETo. The objectives of this study were to develop the ratio of ETr to ETo values (Kr) and to determine the variability of Kr during the year for six locations across the State of New Mexico (USA). The results showed long term annual Kr values to vary from 1.28 to 1.45 and the coefficient of determination varied from 0.96 to 0.98. Kr value decreases from January to July and increases from August to December and was at its lowest Kr value at the peak daily reference evapotranspiration. Annual average Kr values were 1.31, 1.38, 1.43, 1.38, 1.38 and 1.48 at Alcalde, Fabian Garcia, Farmington, Leyendecker, Las Cruces and Tucumcari locations and the growing season average Kr values were 1.24, 1.32, 1.38, 1.31, 1.32 and 1.42 at the respective locations. The strong correlation between ETr and ETo allows the conversion of the grass reference evapotranspiration to alfalfa reference evapotranspiration and vice versa however, caution should be taken when using the crop coefficient values to convert either ETo or ETr to actual crop evapotranspiration for irrigation scheduling and water management.

Keywords: Reference evapotranspiration; Grass; Alfalfa; Ratio; New Mexico

Introduction

Crop water use is generally the main source of water losses from the hydrological cycle and is an important parameter in hydrological, agricultural and environmental studies. Accurate crop evapotranspiration estimation is therefore critical for system sustainability. While crop actual evapotranspiration could be measured via lysimeter [1], scintillometer [2,3], Bowen ratio energy balance system [4-7] or eddy covariance [6,8-11], among other methods, it is also estimated through the two step approach by multiplying crop reference evapotranspiration by the crop coefficients [12,13]. Reference evapotranspiration is the rate at which readily available soil water is vaporized from specified vegetated surfaces [12]. Reference evapotranspiration 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 [14]. The reference surface has recently been expressed as a hypothetical crop (vegetative) surface with specific characteristics for convenience and reproducibility [13,15]. Grass and alfalfa are considered as reference crops grown under humid and semiarid/arid climates respectively. Under the same conditions, the ET rate for grass is usually less than for alfalfa, particularly under dry, hot and windy conditions. Part of the reason for this is that the alfalfa crop that is taken as a reference is taller (0.5 m) than a grass-reference crop (0.12 m) and also has a greater leaf area [14]. Irmak et al. [5] stated that there is no consensus on the choice of reference crop for a particular region however, they indicated that alfalfa may be preferable for semiarid or arid climates because alfalfa has a vigorous and deeper root structure and tends to transpire water at potential rates even under adventive environments, and is less likely to suffer water stress while grass has a shallow-rooted system and grass crop is subjected to suffer water stress. Therefore, the grass may be preferable under humid, subtropical climates where alfalfa is not commonly grown [5]. Wright et al. [16] reported that alfalfa has greater aerodynamic and surface conductance.

Weather variables as air temperature, relative humidity, solar radiation and wind speed are used to estimate reference evapotranspiration. Numerous reference evapotranspiration equations have been developed, tested, calibrated and validated under different climatic conditions with varying performance [13,17-30]. The Standardized Penman Montheit equation is generally regarded as the most accurate equation, used worldwide [28-34] and is recommended for reference evapotranspiration estimation under different climates [13,14]. It is critical to always relate the estimated reference evapotranspiration to either grass or alfalfa reference surface as the two step approach combines reference evapotranspiration and crop coefficients. Crop coefficients (Kc) for grass reference surface is smaller than the Kc values for alfalfa reference surface [35,36]. During crop actual evapotranspiration estimation, Kc values for grass-reference and alfalfa-reference cannot be used interchangeably with ETo and ETr without adjustment. The correction factor, the ratio of ETo to ETr (Kr) should be used to adjust ETo to ETr and vice versa when Grass Kc is available with estimated ETr or alfalfa Kc available with estimated ETo. Daily, monthly, seasonal and annual Kr values were developed for some locations. Jensen et al. [12] reported average Kr values range of 1.30-1.38 for the arid locations and 1.12-1.39 for humid locations. A Kr value of 1.15, for example, was suggested for dry climate under light to moderate wind [37], 1.21 for Davis California [38], and 1.20

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for Kimberly, Idaho [39]. Irmak et al. [5] showed variability among developed daily, monthly seasonal Kr values for Bushland (Texas), Clay Center (Nebraska), Davis (California), Gainesville (Florida), Phoenix (Arizona) and Rockport (Missouri).

While the aforementioned Kr values were developed for some locations, very limited information exists for the semiarid and arid climate across the Southwest United States when water resource are the most limiting factor for crop and fiber production. The objectives of this study were to develop the ratio of ETr to ETo values (Kr) and to determine the variability of Kr during the year and during the crop growing season for six locations across the State of New Mexico (USA).

Materials and Methods

This study was conducted at six weather stations across New Mexico (USA) at Alcalde, Fabian Garcia, Farmington, Las Cruces, Leyendecker, Tucumcari for the period of 2009-2017. The geographical coordinates and the long term average climatic variables are summarized in Table 1. Minimum temperature (Tmin), maximum temperature (Tmax), minimum relative humidity (RHmin), maximum relative humidity (RHmax), wind speed (u), and solar radiation (Rs) were collected on the daily basis from automated weather stations installed by the New Mexico Climate Center at the six sites.

Penman-Monteith reference evapotranspiration model: (ASCE-EWRI, 2005)

Daily grass-reference ET was computed using the standardized ASCE form of the Penman-Monteith (PM-ETo) equation [14]:

\[
ETo = \frac{0.408 \Delta (Rn - G) + \gamma (Cn u_1^2 / (T + 273))(e_s - e_a) - \Delta \gamma}{\Delta + \gamma (1 + Cc u_2)}
\]  

where: ETo—the reference evapotranspiration (mm day \(^{-1}\));  
\(\Delta\)—slope of saturation vapor pressure versus air temperature curve (kPa°C\(^{-1}\));  
Rn—net radiation at the crop surface (MJ m\(^{-2}\)day\(^{-1}\));  
G—soil heat flux density at the soil surface (MJ m\(^{-2}\)day\(^{-1}\));  
T—mean daily air temperature at 1.5-2.5 m height (°C);  
u\(_2\)—mean daily wind speed at 2 m height (m s\(^{-1}\));  
e_s—saturation vapor pressure at 1.5-2.5 m height (kPa);  
e_a—actual vapor pressure at 1.5-2.5 m height (kPa);  
Cc—saturation vapor pressure deficit (kPa);  
\(\gamma\)—psychrometric constant (kPa°C\(^{-1}\));  
and Cc and Cd=constants with values of \(900 \div 2 \div 273\) respectively, while the maximum daily ETr was 8.45, 11.13, 12.09, 7.63, and 10.25 mm/day observed in December-January at Alcalde, Fabian Garcia, Farmington, Las Cruces and Tucumcari, respectively. With regard to the weather conditions, the highest magnitude of the reference evapotranspiration at Tucumcari is strongest at Tucumcari (3.30 m/s) and weakest at Alcalde (1.19 m/s). Wind speed is an important water evaporation driving force and the highest magnitude of the reference evapotranspiration at Tucumcari is in good alignment with the highest values of wind speed at that location as compared to other locations.

Comparisons of Kr values between locations were made using the t-test. A paired sample t-test (two-sample for means) was performed to determine any significant difference between Kr values from one location to another at 5% significance level.

Results and Discussion

Climatic conditions at the study sites

The climatic conditions for the study period are summarized in Table 1. The Alcalde and Farmington stations are located at high elevation (1735 and 1720 m, respectively) and showed the greatest solar radiation. The highest maximum temperature (Tmax) was observed at Las Cruces and the lowest Tmin was observed at Farmington (Table 1). The lowest minimum temperature (Tmin) was observed at Alcalde and the highest Tmax was observed at Las Cruces. The lowest annual mean temperature was 11.7°C at Alcalde and highest annual mean temperature was 18.7°C observed at Las Cruces. The annual mean relative humidity was less than 55% at all stations and was at its greatest value at Alcalde with the lowest peak reference evapotranspiration value (Figure 1). Slight variation in solar radiation was observed among the stations and there was large difference between the stations in terms of annual mean wind speed that ranged 1.19 to 3.3 m/s. Wind speed on average was generally strongest at Tucumcari (3.30 m/s) and weakest at Alcalde (1.19 m/s). Wind speed is an important water evaporation driving force and the highest magnitude of the reference evapotranspiration at Tucumcari is in good alignment with the highest values of wind speed at that location as compared to other locations.

Comparisons of Kr values between locations were made using the t-test. A paired sample t-test (two-sample for means) was performed to determine any significant difference between Kr values from one location to another at 5% significance level.

| Parameters | Alcalde | Fabian Garcia | Farmington | Leyendecker | Las Cruces | Tucumcari |
|------------|---------|---------------|------------|-------------|------------|-----------|
| Latitude (Deg. North) | 36.09 | 32.28 | 36.69 | 32.2 | 32.28 | 35.2 |
| Longitude (Deg. West) | -106.06 | -106.77 | -108.31 | -106.74 | -106.76 | -103.69 |
| Elevation (m) | 1735 | 1186 | 1720 | 1176 | 1185.06 | 1246 |
| Wind speed (m/s) | 1.19 | 1.82 | 2.45 | 1.81 | 1.59 | 3.3 |
| Tmax (°C) | 21.09 | 26.5 | 20.94 | 26.12 | 27.14 | 24.07 |
| Tmin (°C) | 2.22 | 9.82 | 4.33 | 7.67 | 10.27 | 7.52 |
| RHmean (%) | 83.86 | 65.21 | 68.63 | 77.34 | 57.42 | 71.78 |
| Rhmin (%) | 22.88 | 18.6 | 19.7 | 19.09 | 15.53 | 22.29 |
| Rs (MJ m\(^{-2}\)) | 17.35 | 21.23 | 19.84 | 19.63 | 19.94 | 19.8 |

Table 1: Weather stations with long term average climatic condition.
Variability of the ratio of Alfalfa to grass reference evapotranspiration (Kr=ETr/ETO)

The Kr values for the study period equivalent to the slopes of the simple regression relationship between the ETr and ETo varied from 1.28 to 1.45 and the coefficient of determination varied from 0.96 to 0.98 (Figure 2). The highest Kr value was obtained at Tucumcari (Kr=1.45) while the lowest Kr value was obtained at Alcalde. There is variability in Kr values during the year and it decreases from January to July and increases thereafter (Table 2 and Figure 2). Kr values decrease with increasing daily reference evapotranspiration and increase with decreasing reference evapotranspiration. Lowest Kr values were obtained at the peak daily reference evapotranspiration. Similar trend in Kr values was observed at all six weather stations. At Alcalde, monthly Kr decreased from 1.43 in January to 1.19 in August and increased thereafter to 1.42 in December. At Fabian Garcia, Kr values were 10.41, 10.81 and 14.77 mm/day at the respective locations, observed late July at all locations (Figure 1).

**Figure 1:** Trends in average daily grass reference evapotranspiration (ETO) and alfalfa reference evapotranspiration (ETr) at the study locations.

**Figure 2:** Relationships between grass reference evapotranspiration (ETO) and alfalfa reference evapotranspiration (ETr) at the study weather stations.
Variability of the Ratio of Alfalfa to Grass Reference Evapotranspiration under Semiarid Climate.

Kr tends to decrease with increasing reference evapotranspiration and increases during winter time. Wright [39] indicated that the seasonal variation in Kr may reflect the relative response of the respective reference surfaces to evaporative demand and changes in general grass or alfalfa morphology during the season. As the relative humidity increases, the Kr values should decrease as stated by Jensen et al. [12]. Ji et al. [41] reported seasonal variation in the ratios of ET\text{r} to ET\text{o} with a mean value slightly lower than the generalized Kr value of 1.35 for arid conditions, due primarily to the differences in responsiveness of both standardized PM equations to the trends and interactions among input parameters. Irmak et al. [5] reported average annual Kr values of 1.46, 1.43, 1.37, 1.21, 1.33, and 1.36 for Bushland, Clay Center (Nebraska), Davis (California), Gainesville (Florida), Phoenix (Arizona), and Rockport (Missouri). Different annual Kr values were reported as 1.15 at Bushland (Texas) [42], 1.21 at Davis (California) [38], 1.20 at Kimberly (Idaho) [39], from 1.30 to 1.38 for arid areas and from 1.12 to 1.39 for humid zones [12]. The strong correlation between ET\text{r} and ET\text{o} allows the conversion of the grass reference evapotranspiration to alfalfa reference evapotranspiration and vice versa however, caution should be taken when using the crop coefficient values to convert either ET\text{o} or ET\text{r} to actual crop evapotranspiration for irrigation scheduling and water management. Ji et al. [41] reported seasonal mean Kr value slightly lower than the generalized Kr value of 1.35 for arid conditions, due primarily to the differences in responsiveness of both standardized PM equations to the trends and interactions among input parameters. There is a need to develop local crop coefficients related to grass (Kco) or alfalfa (Kcr) reference surface [35,36,41] to avoid the

| Month      | Alcalde | Fabian Garcia | Farmington | Leyendecker | Las Cruces | Tucumcari |
|------------|---------|---------------|------------|-------------|------------|-----------|
| January    | 1.43    | 1.47          | 1.51       | 1.50        | 1.48       | 1.58      |
| February   | 1.37    | 1.44          | 1.45       | 1.47        | 1.45       | 1.53      |
| March      | 1.34    | 1.42          | 1.44       | 1.43        | 1.41       | 1.49      |
| April      | 1.31    | 1.40          | 1.41       | 1.40        | 1.40       | 1.46      |
| May        | 1.27    | 1.36          | 1.39       | 1.35        | 1.36       | 1.42      |
| June       | 1.26    | 1.33          | 1.39       | 1.31        | 1.33       | 1.42      |
| July       | 1.20    | 1.28          | 1.32       | 1.26        | 1.29       | 1.38      |
| August     | 1.19    | 1.28          | 1.35       | 1.26        | 1.29       | 1.38      |
| September  | 1.22    | 1.30          | 1.37       | 1.29        | 1.30       | 1.42      |
| October    | 1.29    | 1.37          | 1.47       | 1.36        | 1.36       | 1.50      |
| November   | 1.38    | 1.45          | 1.52       | 1.46        | 1.43       | 1.58      |
| December   | 1.42    | 1.49          | 1.52       | 1.50        | 1.48       | 1.59      |

Table 2: Long term monthly average ET\text{r} to ET\text{o} ratio for the six locations.
conversion process. Failing to adjust the reference evapotranspiration to the corresponding crop coefficient values could be detrimental to crop failure and result in loss of production cost. However, Wright et al. [16] indicated that there is substantial uncertainty in the ratio of ETr to ETo (Kr) to use for conversion and how the ratio changes with location, time of year and with climate. Moreover, the Kr values computed from the standardized equations may not reproduce ratios of ETr/ETo from field measurements because of the characterization of net radiation due to impacts of daytime length, changes in albedo and low sun angle, surface resistance of living reference crops which are not kept as described as reference surface and the incorporation of the impacts of unique diurnal patterns in wind speed profile into daily step calculation [16,43].

Conclusion

The ratio of grass reference evapotranspiration (ETo) to alfalfa reference evapotranspiration (ETr) (Kr) was developed for six locations across the State of New Mexico (USA). Daily weather data for the period of 2009 - 2017 was monitored by automated weather stations. The results showed strong correlation between ETr and ETo with high coefficient of determination that varied from 0.96 to 0.98. There was variation in daily Kr with the lowest Kr values obtained late July. Annual average Kr values ranged from 1.28 to 1.45 and the growing season Kr values varied from 1.24 to 1.42. The strong correlation between ETr and ETo allows the conversion of ETo to ETr and vice versa and the use of appropriate locally developed crop coefficients which could help in improving water management under the semiarid and dry climatic conditions across the State of New Mexico.

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