Assessment of Blaney-Criddle Equation for Calculating Reference Evapotranspiration with NOAA/AVHRR Data

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Abstract

Reference evapotranspiration (ET_0) data are desirable for assessing crop water requirements and irrigation needs. A large number of methods have been developed for assessing ET_0 from meteorological data. In several places of the world, the existing network of weather stations is insufficient to capture the spatial heterogeneity of this variable The purpose of this work is to investigate whether it is possible to attain reliable estimation of ET_0 only on the basis of the remote sensing-based surface temperature (T_s) data by Blaney-Criddle (B-C) model under a semi arid environment of Iran. This study has assumed that the daytime surface temperature at the cold pixel obtained from the AVHRR/NOAA sensor can be used instead of air temperature in the Blaney-Criddle (BC) equation for ET_0 estimation in irrigated area. For this purpose, 61 NOAA- AVHRR satellite images acquired between June and September in 2004 and 2005 and weather data measured at two weather located in two irrigation regions with sugar cane located in Khuzestan plain in the southwest of Iran were used to calibrate and test the B-C model. The FAO-56 Penman–Monteith model was used as a reference model for assessing the performance of the calibrated BC model. The results show that calibrated B-C model provided close agreement with the reference values, with an average RMSE of 1.0 mm $d^{-1}$and a R^2 of 0.91.

KEY WORDS: Reference evapotranspiration; Blaney-Criddle model; AVHRR data; Iran

Introduction

Reliable information of evapotranspiration (ET) is essential in studies relating to water resources management, farm irrigation scheduling, and environmental assessment. Although ET can be directly measured, it is laborious, time-consuming and costly, and is therefore estimated in most situations using climatological parameters. The most widely used approach is the one recommended by the Food and Agriculture Organization (FAO), where ET is calculated by a reference crop evapotranspiration (ET_0) multiplied by a crop coefficient (Allen et al., 1998). ET_0 is defined as the evapotranspiration of extensive surface of green grass of uniform height (8 to 15 cm tall), actively growing, completely shading the ground and not short of water (Doorenbos and Pruitt, 1977) and as a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23 (Allen et al., 1998). The crop coefficient accounts for differences between the grass and crop ET. Therefore, the correct estimation of ET_0 is critical to accurately calculate ET.

A large number of equations have been developed for assessing ET_0 from meteorological data. The Penman-Monteith (PM) equation is considered the best method (Allen et al., 1998) across a wide range of climates and is recommended by the FAO as the standard method (hereafter referred to as FAO- PM). ET_0 by FAO-PM equation is estimated using climatic data such as net radiation, air temperature, wind velocity, vapor pressure deficit, and relative humidity obtained from nearest weather stations. However, most weather stations around the globe are located in nonagricultural setting having dry, bare soil surface and/or concrete surfaces. Using weather data from such stations to estimate ET_0 for planning and design of an irrigation system may cause serious errors due to elevated maximum and minimum air temperatures (T_x and T_n) and depressed dew point temperature (TD). Irrigation modifies the microclimate of an area by influencing the partitioning of radiant energy at the surface (De Vries and Birch 1961). Irrigation water causes more energy to be consumed in ET and less energy to be consumed in heating the air and the soil. This reduces the air temperature and increases the humidity of the air.

Recent developments in satellite remote sensing (RS) ET models have enabled us to accurately estimate ET for large cultivated areas and fields. Papadavid et al. (2013) integrated modeling and remote sensing techniques for estimating actual evapotranspiration of groundnuts that is cultivated near Mandria Village in Paphos District of Cyprus. During the last two decades, many energy balance (EB) algorithms have been developed to make use of RS data to estimate ET regionally. These algorithms compute at satellite overpass instantaneous ET as the residual term of energy budget, once net radiation, soil heat flux and sensible heat flux are derived (Bastiaanssen et al., 1998a; Norman et al., 2003; Su, 2002; Caparrini et al., 2003, 2004; French et al., 2005; Crow and Kustas, 2005; Allen et al., 2007; Cleugh et al., 2007). A detailed review of different ET algorithms was presented in Gowda et al. (2008). Some of the commonly used EB-based ET algorithms include Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen et al., 1998a; 1998b), Surface Energy Balance Index (SEBI; Menenti and Choudhury, 1993), Surface Energy Balance System (SEBS; Su, 2002), and most recently the Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC; Allen et al., 2007) method. Elhag et al. (2011) used the SEB System to estimate daily evapotranspiration and evaporative fraction over the Nile Delta. The simulated daily evapotranspiration values were compared against actual ground-truth data taken from 92 points uniformly distributed all over the study area. They showed that SEBS could successfully be employed in the estimation of daily evapotranspiration over agricultural areas.

However, these algorithms are complex to use and they calculate actual ET rather than reference ET (ET_0). The estimate of ET_0 is an important factor to be considered in agricultural planning and has been an objective of studies related to irrigation management and agrometeorology all over the world. It is desirable to have a method that estimates ET_0 from a large irrigated farm surface. The combination of ET_0 models with RS data provides a feasible alternative to obtain temporally and spatially continuous information about biophysical variables (Maeda et al., 2011). Maeda et al. (2011) evaluated three temperature- based ET_0 models by using land surface temperature data from the MODIS sensor that is replaced by air temperature data from ground stations. This evaluation has been conducted in an inter-tropical convergence zone. They showed that Hargreaves model is the most appropriate with an average RMSE of 0.47 mm d^{-1}, and a correlation coefficient of 0.67. In this paper, we have investigated the accuracy of the Blaney-Criddle temperature based ET_0 model to estimate daily ET_0 by adapting this model for its use with satellite's infrared surface temperature (T_s) in a semiarid environment of Iran.

Materials and methods

The originality of this paper is to use cold pixel from large irrigated sugarcane farms surface. The cold pixel was selected as a wet, well-irrigated crop surface having full ground cover by vegetation with maximum ET occurs at this surface. The daily air temperature in the Blaney-Criddle ET_0 model was replaced with the daytime surface temperature obtained by the Advanced Very High Resolution Radiometer (AVHRR). In order to achieve this replacement, the Blaney-Criddle model was calibrated using the Penman Monteith (PM) equation as the reference ET_0 equation.

Study area

The present investigation has been carried out in two irrigated units that cultivate sugar cane. These irrigated sites are the Shoabieh (SH) and Khazae and each of them covers an area of approximately 15 thousand hectares (see fig. 1 and Table 1). These areas are located in the Khuzestan province in the south-west of Iran, borders Iraq and the Persian Gulf. On the basis of the Koppen climate classification, the Khuzestan plain is categorized as having a semi-arid climate. Maximum temperature reach 50^oC in summer and 12^oC in winter and the annual rainfall ranges between 150 and 250 mm. Most of soil in the plain is alluvial. These areas are irrigated by the Karun River.

Satellite and weather data

The National Oceanic and Atmospheric Administration (NOAA) series of meteorological satellites has a significat role in various applications of remote sensing. These satellites are in a sun-synchronous orbit at an average altitude of 833 km, having the advantage of covering the same area twice a day with a spatial resolution of 1.1 km at nadir (Lillesand and Kiefer, 1987). The Advanced Very High Resolution Radiometer (AVHRR) sensor, on board the NOAA satellite series, acquires five spectral channels, consist of visible (0.58–0.68 μm), near infrared (0.725–1.10 μm), middle infrared (3.55–3.98 μm), and two thermal infrareds (10.3–11.3 μm and 11.5–12.5 μm). The main purpose of NOAA–AVHRR satellite is to forecast weather and monitor regional climatic conditions. Numerous algorithms have been developed to derive climatic variables such as air temperature, near-surface water vapour, perceptible water, soil moisture and land surface temperature from the NOAA AVHRR observations (Prince et al., 1998, Chrysoulakis and Cartalis, 2002, Czajkowski et al, 2002, Prihodko and Goward, 1997 and Ulivieri et al. (1994).

A total of 61 daytime images without cloud cover of NOAA-AVHRR level 1b, covering the plain of Khuzestan in Iran were collected from the Satellite Active Archive (SAA) of NOAA. These images were scanned between noon and 3.00 pm (local time) between June and September in 2004 and 2005. The images were corrected radiometrically and geometrically, and the data in the digital counts were converted to reflectance (for channels 1 and 2) and to brightness temperatures (for the thermal channels 4 and 5) using the calibration information given in the documentation for each image. For each image, two polygons were defined around the sugarcane units. As mention above, these units consist of well-vegetated areas, but for ensure the right choice pixels representing the reference evapotranspiration, the pixel with the lowest surface temperature and highest NDVI within each polygon was selected. These pixels were represented as "cold" pixels and their surface temperatures were used as input instead of air temperature for estimating ET_0 by empirical methods.

In this study, the model developed by Ulivieri et al. (1994) was used for retrieving the land surface temperature, which is based on the following split window algorithm:

$$T_s = T_4 + 3.33\,(T_4 - T_5) + 48\,(1-\varepsilon) - 75\,\Delta\varepsilon \qquad (1)$$

where, T_s is infrared surface temperature (^oC), T_4 and T_5 are brightness temperatures (^oC) in AVHRR channels 4 and 5, ε is the average emissivity in AVHRR channels

4 and 5, $\Delta\varepsilon$ is emissivity difference between 4 and 5 channels ($\varepsilon_4 - \varepsilon_5$). The emissivity in each channel has been calculated using the vegetation cover method of Valor and Caselles (1996):

$$\varepsilon_i = \varepsilon_v P_v + \varepsilon_s (1 - P_v) \quad (2)$$

where ε_i is channel emissivity values (channels 4 or 5), ε_v is the vegetation emissivity (0.985 in both channels 4 and 5), ε_s is the soil emissivity (0.949 for channel 4 and 0.967 for channel 5) and P_v is the fraction of vegetation cover, which was estimated from NDVI according to Carlson and Ripley (1997):

$$P_V = \left(\frac{NDVI - NDVI_S}{NDVI_V - NDVI_S}\right)^2 \quad (3)$$

where $NDVI_V$ and $NDVI_S$ are the NDVI values of full vegetation cover (P_V=1) and bare soil (P_V=0), respectively, which can be obtained from the NDVI histogram. Values of NDVIv = 0.5 and NDVIs = 0.2 were proposed by Sobrino and Raissouni (2000) to apply the method in global conditions. In order to obtain consistent values of P_V, for those pixels with $NDVI<NDVI_S$ the P_V has been set to zero, whereas for those pixels with $NDVI > NDVI_V$ it has been set to 1.

During the same time period of collected satellite data, ground weather data were obtained from one weather station installed in each irrigated sugarcane units. These weather data is necessary for the FAO-PM equation and consisted of daily observations of maximum and minimum temperature (Tmax and Tmin), relative humidity (RH), wind speed (U) and bright sunshine hours (n). Daily mean temperature (relative humidity) records by calculating the average of the daily maximum and minimum temperature (relative humidity) records. A linear variation between the daily minimum and maximum temperatures (relative humidity) were assumed. The locations and elevations of the stations are given in Table 1.

Table 1- Weather stations used in the study

Station	Code	Latitude (^{o}N)	Longitude (^{o}E)	Elavation (m)
Shoabieh	SH	31^o 48'	48^o 46'	29
Khazae	KH	31^o 08'	48^o 35'	7.2

The FAO Penman–Monteith equation

In this study, the Blaney–Criddle ET_0 model was calibrated using the conventional FAO Penman–Monteith method as reference. Although in practice, the best way to test the performance of the empirical methods would be to compare their performances against the lysimeter-measured data; this type of data set is not available in the study area. The following equation was applied for the PM (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_a + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (4)$$

where the ET_0 is reference crop evapotanspiration (mm d^{-1}), R_n is the daily net radiation (MJ m^{-2} d^{-1}), G is the daily soil heat flux (MJ m^{-2} d^{-1}), T_a is the mean daily air temperature at a height of 2 m (^{o}C), U_2 is the daily mean wind speed at a height of 2 m (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure versus the air temperature (kPa $^{o}C^{-1}$), and γ is the psychrometric constant (kPa $^{o}C^{-1}$).

In this study, the daily values of Δ, R_n, e_s and e_a were calculated using the equations (for albedo, α=0.23 for green vegetation surface) given by Allen et al. (1998). Since G is very small compared with R_n and is often difficult to measure, it was assumed to be zero over the calculation time step period (daily and monthly) (Allen et al. 1998). The measured RH, T_x and T_n values were used to calculate e_a and e_s. The daily solar or shortwave radiation (R_s) was calculated using the Angstrom formula, which relates solar radiation to extraterrestrial radiation and relative sunshine duration (Allen et al. 1998):

$$R_s = \left(0.25 + 0.5\frac{n}{N}\right)R_a \tag{5}$$

where n and N are, respectively, the actual daily sunshine duration and the daily maximum possible sunshine duration, R_S and R_a are, respectively, the daily global solar radiation (MJ m^{-2} d^{-1}) and the daily extraterrestrial solar radiation (MJ m^{-2} d^{-1}) on a horizontal surface. The extraterrestrial radiation and maximum possible sunshine hours are function of day of year and latitude and were determined by equations proposed by Allen et al. (1998). Equation (39) in Allen et al. (1998) was used to calculate the net outgoing longwave radiation.

Blaney-Criddle equation

The modified Blaney–Criddle equation (Blaney and Criddle, 1962) introduced by Doorenbos and Pruitt (1977) is:

$$ET_0= a+b\,[p(0.46T+8.13)] \tag{6}$$

where, ET_0 is in mm day^{-1}, T is the mean daily air temperature (^{o}C), P is the daily percent of annual daylight hours, and a and b are the parameters of the equation. In this study, air temperature data from ground stations were replaced by T_s obtained from split window algorithm (Ulivieri et al., 1994). Daily percent of annual daylight hours for each day of year is computed using latitude and Julian day information from the following equations (Allen, et al., 1998):

$$\delta(J) = 0.409\,sin\left(\frac{2\pi}{365}J - 1.39\right) \tag{7}$$

$$\omega_S(J) = \arccos\left[-\tan(\varphi)\tan\,(\delta)\right] \tag{8}$$

$$N(J) = \frac{24}{\pi}\omega_S(J) \tag{9}$$

$$NYEAR = \sum_{J=1}^{365} N(J) \tag{10}$$

$$P(J)=(N(J)\;/\;NYEAR)\times 100 \tag{10}$$

where, δ is the declination (radians), J is the Julian day (1-365), ω_S is the sunset angle (radians), φ is the latitude (radians), N is the daily daylight hours, NYEAR is the annual day light and P is the daily percent of annual daytime hours.

The values of a and b were computed using the procedure of Doorenbos and Pruitt (1977), daily wind speed, daily minimum relative humidity and the ratio of daily actual sunshine hours to daily maximum sunshine hours are needed. However, in this study, a linear regression procedure was made for computing the values of a and b. Considering the linear regression between ET_0 and $P(0.46T_s+8.13)$ the slope and intercept of the regression line can be calculated. The values of "b" and "a" are equal to the slope and intercept terms of regression line. In this study in order to calibrate B-C equation, the whole data set of the two stations (122 patterns, 2004 and 2005) was divided into two parts: the first part (58 patterns, 2004) was used for calibration and the second part (64 patterns, 2005) was used for validation. Applying this procedure, the values of a and b were determined for the cold pixels in the study area.

ET_0 estimates from calibrated B-C equation were compared against the FAO-PM estimation with the validation data. For each location, the following parameters were calculated: coefficient of determination (R^2), mean bias error (MBE), root mean square error (RMSE) and the ratio between both average ET_0 estimations (R).

Results and Discussion

A temporal comparison between the mean daily air temperature (T_a) and the Land Surface Temperature (T_s) records for the period between 2004 and 2005 is presented in Fig. 2. T_a data was measured at two weather stations located in the irrigated area and T_s data was obtained by the AVHRR sensor from the pixels that have maximum NDVI value (cold pixel). Clearly, the surface temperature in the middle of the day is more than daily air temperature. The evolutions of daily Ta values were nearly similar to Ts values. Fig. 3 shows a scatter plot of Ts versus Ta values values on all acquisition dates of the AVHRR images for the two meteorological stations. There is a close relationship between T_a and the T_s with a R^2 of 0.93. It should be noted that only data from cold pixels located in irrigated area were used in the analysis between T_a and the T_s, therefore the relationships is only valid for these cold pixels located in these two sugar cane areas and not mandatory for the total area. So it is reasonable to replace the T_a by surface temperature of cold pixels (T_s) in the Blaney–Criddle equation.

To calibrate the Blaney–Criddle equation with T_s as input data for estimating ET_0, a simple linear regression (of the form Y = a + bX) of $P(0.46T_s+8.13)$ *versus* the ET-PM values was made. The regression data is shown in Fig 4. The R^2 of the regression equation was 0.88, which means that approximately 88% of the variations in the ET_0 are linearly related to the $P(0.46T_s+8.13)$. The values of constants a and b are -2.92 and 1.15, respectively. To assess the usefulness of the calibrated Blaney–Criddle model in estimating reference evapotranspiration, we used the dataset from SH and KH weather stations for the year 2005. Fig. 5 shows a scatter plot of the ET_0 values computed by equation 4 and FAO-PM method for the two irrigated area. It shows that, there is a very good correlation between the two methods. The slope of the straight line is nearly close to one. Neither overestimations nor underestimations of values are made in the study range. The high values of R^2 (=0.95 and 0.88) with the calibrated BC model also confirms that this approach works well in estimating reference evapotranspiration for both sites. The root mean square (RMSE) of 1.01 and 0.22 mm d^{-1} provided by the Calibrated B-C model suggests that it can be used to estimate reference evapotranspiration for the sites.

Fig. 6 shows the variation in reference evapotranspiration estimated using the FAO56 method and the calibrated B-C model for the year 2005 for the two irrigated area. It is evident that for the both irrigated area, evolution is similar and one line is practically superimposed over the other.

Conclusions

For irrigated agriculture in a semi-arid environment of Iran, an alternative for estimating ET_0 using NOAA/AVHRR data and Blaney-Criddle (B-C) model has been evaluated in this article. The midday surface temperature of cold pixel from irrigated area was used as inputs to the B-C model to estimate ET_0 obtained using the FAO-56

Penman–Monteith equation. In the first part of the study, the Ts data from cold pixels of irrigated area were compared with mean daily air temperature data. The comparison results indicated that there is a close relationship between the mean daily temperature and the T_s with a R^2 of 0.93. Therefore the parameter of T_a in the B-C equation was replaced by T_s. In the second part of the study, the B-C equation was calibrated using T_s data as inputs instead of T_a. This calibrated model was evaluated with data from irrigated area for estimating daily reference evapotranspiration. The results demonstrated that modelling of reference evapotranspiration is possible through the use of Blaney–Criddle from T_s data of cold pixels from irrigated area. This assessment is practical for estimation of daily ET_0 in the areas where weather data are not available and/or non-representative due to the sparseness of the weather-observing network. However, the operational use of NOAA-AVHRR images can be limited, because images cannot be acquired during cloudy conditions.

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Figs Legend:

Fig. 1- The location of the Shoabieh and Khazae irrigated sites in the south-west of Iran.

Fig 2- Daily means air temperature measured at weather stations and midday surface temperature retrieved from cold pixel of irrigated area. a Shoabieh , b Khazae

Fig 3. Scatter plot of midday surface temperature and daily mean air temperature

Fig. 4- Relationship between $P(0.46T_s+8.13)$ and ET-PM

Fig. 5- ET_0 calculated from the reference method (FAO-PM) and the calibrated Blaneye-Criddle method for two irrigated area. a) Khazae, b) Shoabieh.

Fig. 6- Evolution of the reference evapotranspiration estimated by FAO-PM and those estimated by the calibrated B-C model during the test period, a a) Khazae, b) Shoabieh.