Title: Quantification of wheat crop evapotranspiration and mapping: a case study from Bhiwani District of Haryana, India

Author names and affiliations

- 1). Dr. (Er). Kishan Singh Rawat*
Centre for Remote Sensing and Geo-Informatics,
Sathyabama University, Chennai, India
E-mail: ksr.kishan@gmail.com
- 2). Anju Bala
Department of Civil Engineering,
WCTM, Gurgaon, India
E-mail: anjukathuria@yahoo.com
- 3). Dr. Sudhir Kumar Singh
K. Banerjee Centre of Atmospheric and Ocean Studies
IIDS, Nehru Science Centre, University of Allahabad
Allahabad-211002 (U.P.), India
Email: sudhirinju@gmail.com
- 4). DR. Raj Kumar Pal
Punjab Agricultural University,
Regional Research Station, Bathinda, Punjab, India
E-mail:- rkpal1985@gmail.com

***Corresponding author's email: ksr.kishan@gmail.com & sudhirinju@gmail.com**

Quantification of wheat crop evapotranspiration and mapping: a case study from Bhiwani District of Haryana, India

Abstract

In this study an attempt has been made to estimate the actual wheat crop evapotranspiration (ET_c) by Surface Energy Balance Algorithm (SEBAL) and standardized FAO-Penman-Monteith (FAO-PM). Improved knowledge of evapotranspiration (ET) helps in understanding the water balance of any region. The results obtained through measured lysimeter, SEBAL and PM method were evaluated through statistical performance measure tests. ET_c estimated from SEBAL was found to correlate significantly as r^2 (0.910) with the measured ET_c of lysimeter. ET_c estimated by SEBAL was also compared with PM ET_c with the help of crop coefficient and was found to correlate significantly as r^2 (0.850). The other statistical parameters (RMSE=0.561, nRMSE=0.090, MAE=0.265, NRMSE=0.2033, R-RMSE=0.268, NSE=1, d=0.870 (≈ 1)) were also showing a good agreement between SEBAL ET_c and PM ET_c . The findings of work have suggested that SEBAL model shows a good potential to estimate spatial ET_c for the region. Additionally the validation of models results were performed with the analysis of correlation between models ET_c and district level wheat production and area under crop of five years. The results of this analysis outline that water availability and good amount of rainfall gives higher wheat yield and resulted into more ET_c .

Keywords: Actual evapotranspiration; Lysimeter; Penman-Monteith method; SEBAL model; Wheat

1. Introduction

To understand the process of loss of water from soil and plant to the atmosphere through evapotranspiration (ET) is critical for water resources management. ET is a key and crucial component of hydrologic cycle and defined as loss of water through both plant (transpiration) and surface (evaporation). ET account for 60-90% on an average of rainfall water return back to the atmosphere. The scanty rainfall and rapid declining water table over last few decades is one of the critical problems in many parts of India. The demand of water for industries and agriculture sector in India is continuously growing to meet the demands of 1.2 billion people. The area under agriculture fields is continuously increasing hence more water is required to irrigate the crops. The real-time irrigation management and allocation of water resources needs real-time prediction of daily reference evapotranspiration (ET_0) that will help in understanding the Impact Based Decision Support Service (IBDSS).

ET models using remote sensing data can be categorised as Simplified Empirical Regression Method (Jackson et al., 1977) and Residual Method of Surface Energy Balance. Further, the Residual Method of Surface Energy Balance can be divided into Single Source Models and Dual Source Models (Li et al., 2009). The more details about these models are available in the comprehensive review article on current methodologies for regional evapotranspiration estimation from remotely sensed data by Li et al. (2009). Owing to this, different methods have been developed to retrieve the surface fluxes from remotely sensed data sets. These methods are categorized as Single Source Energy Balance and Two Source Energy Balance model. Single Source Energy Balance Model are as following: Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998; Bastiaanssen 2000), Simplified Surface Energy Balance Index (S-SEBI) (Roerink et al., 2000), Surface Energy Balance System (SEBS) (Jia et al., 2003) and Mapping EvapoTranspiration at high Resolution with Internalized Calibration (METRIC). The Two-Source Energy Balance (TSEB) (French et al., 2003), and Norman et al. (1995) developed a Two-Source (soil+canopy) Model (TSM) and Anderson et al. (1997) examined and tested the Two-Source Time Integrated Model (TSTIM), subsequently was named as Atmosphere-Land Exchange Inverse (ALEXI) (Mecikalski et al., 1999).

Bastiaanssen et al. (1998) have evaluated ET with minimum ground-based measurements using SEBAL and tested at both field and catchment scales under several climatic conditions in more than 30 countries worldwide. They found that seasonal scales accuracy higher (95%) was than daily scale (85%) at field scale. ET estimates for both irrigated and drylands fields using SEBAL (Gowda et al., 2008). SEBAL has been successfully applied for ET estimation, calculation of crop coefficients and evaluation of basin wide irrigation performance under various agro-climatic conditions in several countries including Spain, Sri Lanka, China, and the United States (Bastiaanssen et al., 2005, Singh et al., 2008).

Estimation of SEBAL ET from any region has added advantage as to get spatial distribution of biophysical descriptors namely surface albedo, surface temperature, Normalized Difference Vegetation Index (NDVI, Bala et al., 2015b; Rawat et al. 2012) and Soil Adjusted Vegetation Index (SAVI, Bala et al., 2015b) map and Leaf Area Index (LAI, Bala et al., 2015b) map etc. Zhao-Liang et al. (2009) have reviewed energy balance algorithms and found that if these models employed under clear sky conditions then these ET models can provide relatively more accurate spatial distribution of instantaneous ET. Actual

ET maps can be used with confidence in water accounting and hydrological modelling if they are validated for different agro climatic zones (Karimi and Bastiaanssen, 2014).

Many studies have successfully used FAO-Penman-Monteith (FAO-56) method to calculate reference crop evapotranspiration (ET_o) (Cai et al., 2007; Abdelhadi et al., 2000; Hou et al., 2014; Li et al., 2016; Muniandy et al., 2016; Xu et al., 2017) and estimated crop water requirement (Allen et al., 1998). Jensen (1968) has introduced the concept of crop coefficient (K_c) and later many researchers have further improved (Doorenbos and Pruitt, 1975; 1977; Burman et al., 1980a; Burman et al., 1980b; Allen et al., 1998). However, K_c approach has potential to precisely calculate actual crop evapotranspiration (ET_c). The K_c depends on many factors such as greenness, crop cover and LAI and varies differently in different ecological system with variations in environmental conditions.

Even though SEBAL model is strongly based on theoretical and physical relationship, minimum ground measurements, accurate atmospheric corrections are not needed and its automated internal calibration of empirical coefficients makes it accurate and operational (Allen et al., 2007). It also has few following disadvantages: applied over flat surfaces and uncertainty in the determination of anchor pixels (Li et al., 2007). Owing to all these facts, SEBAL model is extensively being in practice to estimate ET from crop and vegetative ecosystems.

The main objective of the work was to estimate ET_c from wheat crop of Bhiwani district of Haryana (India) through the validated SEBAL model for the same agro-climatic zone (Bala et al., 2015a). Further, validation of spatial estimates of ET_c using FAO guidelines for K_c of wheat crop.

2. Materials and Method

2.1. Geographical conditions and field Data

The study area is Bhiwani district lies between latitudes 28°19' and 29°05' N and longitudes 75°26' and 76°28' E with an average elevation of 225 m above mean sea level (Fig. 1). The climate is mainly dry with very hot summer and cold winter and classified as tropical steppe, semi-arid and hot. The soil is loamy in the north and sandy in the southwest region. The water table in the region is declining at faster rate (Borana, 2012) and saline with few small pockets of fresh water in southwest parts. Very high seasonal differences in the temperature range (2°C-winter to 45°C-summer). The south west monsoon brings rain and contributed to 85% of annual rainfall, however, rest 15% rainfall is received during the non-

monsoon period due to western disturbances and thunder storms. The normal annual rainfall of the district is 420 mm which is unevenly distributed over the area.

Fig. 1 Location map of the study area showing Bhiwani district of state Haryana, country India

2.2. Data sets used (Meteorological, Satellite, Crop Yield and Area Statistic)

The daily meteorological data of atmospheric variables (*viz.* temperature, relative humidity, wind speed, Sunshine hours and rainfall) was collected from India Meteorological Department (IMD). The ET_o data of respective years (2004-2005, 2005-2006, 2007-2008, 2012-2013 and 2013-2014) was collected from Regional Meteorological Station, Chandigarh of common dates of satellite images.

The three cloud free remotely sensed scenes of LANDSAT7-ETM+ (Path/Row as 140/40) of each year were downloaded from portal (<https://earthexplorer.usgs.gov/>). The downloaded images were archived and pre-processed (geometric and radiometric correction and geo-registered). The satellite data scenes have recorded the reflected energy and captured the three different stages of crop growth *viz.* (i) early growth stage (30-Jan-05, 16-Dec-06, 22-Dec-07, 19-Dec-12 and 06-Dec-13), (ii) middle growth stage (14-Feb-05, 06-Mar-06, 23-Jan-08, 09-Mar-13 and 07-Jan-14) and (iii) full growth stage (03-Mar-05, 22-Mar-06, 24-Feb-08, 25-Mar-13 and 12-Mar-14) of wheat crop.

The wheat crop yield and area statistics data of region was collected from Department of Agriculture Cooperation & Farmers Welfare, Haryana (<http://agriharyana.nic.in/cropwisearea1.htm>) in order to correlate with actual ET of respective years of crop.

2.3. Methodology

ET by PM method was estimated through software CROPWAT 8.0, developed by Land and Water Development Division of Food and Agriculture Organization (FAO) of the United Nation. Reliable ET estimate is widely calculated by researchers using eq. (1):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where, ET_o is reference ET (mm day^{-1}), R_n is net radiation at the crop surface ($\text{MJ m}^{-2} \text{day}^{-1}$), G is soil heat flux density ($\text{MJ m}^{-2} \text{day}^{-1}$), T is mean daily air temperature at 2 m height ($^{\circ}\text{C}$), u_2 is wind speed at 2m height (m s^{-1}), e_s is saturation vapour pressure (kPa), e_a is actual vapour

pressure (kPa), $e_s - e_a$ is saturation vapour pressure deficit (kPa), Δ is slope vapour pressure curve (kPa °C⁻¹), and γ is psychrometric constant (kPa °C⁻¹).

2.3.1 Crop Coefficient

K_c is defined as ratio of actual crop evapotranspiration (ET_c) to reference crop evapotranspiration (ET_o). Crop coefficient curve was used to identify K_c value corresponding to development and growth stage of crops (Tarantino and Spano, 2001). The daily value of ET_c was calculated using equation (2):

$$ET_c = ET_o \times K_c \quad (2)$$

where, ET_c is actual crop evapotranspiration (mm), ET_o is reference crop evapotranspiration (mm), K_c is crop coefficient.

The guidelines of FAO were used to calculate K_c value of wheat crop at different growth stage (early, mid and full). The trend of K_c value along with normal dates of sowing has been used for rest of years with actual sowing of crop. Afterwards same K_c value was used to find out the actual ET with multiplying by PM ET_o at particular dates and stages of the crop.

2.3.2 SEBAL model

SEBAL is an intermediate/integral approach based on physical parameters as well empirical relations. Normalized Difference Vegetation Index (NDVI), Leaf Area Index (LAI), surface temperature and albedo data sets were prepared through reflectance and emittance property of visible, infrared and thermal band of satellite data sets and finally fluxes have been calculated (Bastiaanssen et al., 1998; Bala et al., 2015a). The net radiation was calculated by summing up long and shortwave radiation and soil heat flux by empirical equations (Bastiaansen and Robeling, 1993) for all types of vegetation. The sensible heat flux is an important component of SEBAL model but due to its calibration by developing empirical coefficient for each satellite image, it was estimated correctly by iteration procedure.

SEBAL model comprises of more than twenty five computational steps to calculate actual evapotranspiration. However, it calculates the fluxes independently from land cover and handle thermal infrared images at resolution between a few meter to several kilometre (Bastiaanssen et al., 1998), it estimate spatial ET using equation (3):

$$ET = R_n - G_o - H \quad (3)$$

where, ET is the latent heat flux (evapotranspiration) associated with evaporation of water from soil, water and vegetation, R_n is the net radiation absorbed at the land surface, H is the

sensible heat flux to warm or cool the atmosphere, and G_o is the soil heat flux to warm or cool the soil, all expressed in (Wm^{-2}).

For G calculations, the empirical formula proposed by Bastiaanssen (2000) was adopted, which estimates the ratio G/R_n near midday as eqn. (4):

$$\frac{G}{R_n} = \frac{T_s}{\alpha} (0.0038\alpha + 0.0074\alpha^2) * (1 - 0.98 \cdot NDVI^4) \quad (4)$$

where, T_s is the surface temperature (K), α is the surface albedo, and NDVI is the Normalized Difference Vegetation Index.

H is estimated from an aerodynamic function from eqn. (5):

$$H = \frac{(\rho \cdot C_p \cdot dT)}{r_{ah,1,2}} \quad (5)$$

where, ρ is air density (kgm^{-3}), C_p is specific heat of air at constant pressure ($1004Jkg^{-1}K^{-1}$), and $r_{ah,1,2}$ is the aerodynamic resistance (sm^{-1}) between two near-surface heights, z_1 and z_2 (generally 0.1 and 2 m above the zero-plane displacement height) computed as a function of the estimated aerodynamic roughness of the particular pixel. dT (K) is the temperature difference between the two heights z_1 and z_2 .

dT is assumed to be linear in proportion to radiometric T_s as Bastiaanssen (1995) empirically proved as mentioned in eqn. (6)

$$dT = b + a \cdot T_s$$

Since there are two unknown variables in (5), dT and r_{ah} , an internal calibration process is performed. For that purpose, two extreme pixels, representing very dry and very wet agricultural surfaces, are selected. In SEBAL, the cold pixel is a local water body, where $dT = 0$ is assumed, that means air temperature is equal to T_s and H is expected to be zero. The dry end of the dT function is estimated for a selected “hot” pixel in the image where the soil is assumed to be dry enough that LE is 0.

This relationship was used to obtain empirical coefficients on the basis of anchor pixel (hot and cold pixel); they are located within the satellite image. After calculating all the fluxes, ET_c was calculated using energy balance method on a pixel basis.

Bala et al. (2015a) have validated the SEBAL model for wheat crop using measured lysimeter data at farm of Water Technology Centre (WTC), Indian Agriculture Research Institute (IARI), New Delhi, India during 2010-2011. Validated SEBAL model for same agro climatic region was used to estimate wheat crop ET_c of respective years: 2004-2005, 2005-2006, 2007-2008, 2012-2013 and 2013-2014 and generate spatial ET_c products. The readers

can found the detailed procedure of SEBAL model for same agro climate region related information Bala et al. (2015a). For SEBAL detailed methodology and validation procedure see Appendix (1).

2.4. Statistical evaluation

The statistical analysis was performed to determine the statistical differences between measured vs. model ET_c . The following statistics were applied: Root Mean Square Error (RMSE), Relative Root Mean Square Error (R-RMSE, Rawat et al., 2013), Mean Absolute Error (MAE), Mean Bias Error (MBE), Percentage Bias (PBIAS), Normalized Root Mean Square Error (NRMSE), Nash Sutcliffe Efficiency (NSE), Index of Agreement (d), Coefficient of Determination (R^2) to know the significance between measured vs. model and model vs. model. The details of these statistics can be found in any standard statistics book.

3. Results and Discussion

3.1. Response of crop coefficient

Table 1 has coordinates of pure wheat crop dominating areas. Lysimeter based wheat K_c in year 2013-14 is generally varying from 0.41 to 1.24 (Fig. 2). The lower value of K_c (0.41) at the initial stage with lesser growth of the crop, as the wheat crop canopy grows K_c value reached to 1.24. However, with maturity of crop, due to decrease of the LAI, it shows declination to 0.44. Growth-stage-specific K_c values of wheat have been determined based on year 2013-14 lysimeter of K_c curves. These values are representing distribution of K_c over time throughout crop season. Similar results have also been reported by other researchers (Bala et al., 2015a; Jensen et al., 1990). ET_c estimation of remaining years and dates, K_c values were considered from Figure 2. The following K_c values 0.84, 1.11 and 0.71 during 2012-13 (Table 2) and 0.43, 1.24 and 1.04 for 2013-14 (Table 3) have considered for estimation of ET_c from PM method corresponding to early, mid and full growth stages of wheat, respectively. The values of K_c are reflecting the changing rates of crop water use during the growing season. Figure 3 is a graphical representation of wheat statistics for Bhiwani district of Haryana during *Rabi* (winter) season. ET_c differs with crops mainly due to variation in crop canopy and climatic conditions (Tyagi et al. 2000). The peak value of crop coefficients of wheat was 1.42 derived by Penman-Monteith method. They found that the estimated K_c values of wheat by Penman-Monteith method during initial, crop development, reproductive and last growth stages have much higher different values than reported by FAO at respective growth. This could be mainly due to the additional source of stages energy

available from soil heat flux during initial and crop development growth stages of wheat in the climate prevailing in the region (Tyagi et al. 2000). The evapotranspiration varied with crops seasons and duration of crop growth. Tyagi et al. (2000) have suggested the K_c values of wheat 0.50 (stage I), 1.36 (stage II), 1.24 (stage III), and 0.42 (stage IV) with 0.87 (average).

Fig. 2 Crop coefficient (K_c) curve of wheat crop of period 2013-14 at Bhiwani district, study site

Fig. 3 Graphical representation of wheat statistics for Bhiwani district of Haryana during *Rabi* (winter) season

Table 1 Coordinates of pure wheat crop dominating areas

Table 2 SEBAL ET_c and PM ET_c on ground truthing points during crop season 2012-2013

Table 3 SEBAL ET_c and PM ET_c on ground truthing points during crop season 2013-2014

3.2. SEBAL ET_c vs. PM ET_c

Field plots of two or more than two hectares (20,000.00 meter²) was selected to avoid the image resolution issue (Fig. 4). Five in situ measurements (lysimeter ET_c), from SEBAL ET_c and PM ET_c are estimated at fixed points for year 2012-2013 and 2013-2014 and results are presented (Fig. 5) and results are mentioned in Table 2. During the year 2012-13 (Table 2), the average SEBAL ET_c is found higher followed by 2013-14 (Table 3). Similar trend is also observed for PM ET_c . However, the average SEBAL ET_c of five fields have greater than PM ET_c for 2012-13 and 2013-14 (Table 2 and 3). Statistically a significant R^2 of 0.85 is observed between SEBAL ET_c and PM ET_c . The other evaluation statistics results shows that SEBAL ET_c and PM ET_c with RMSE of 0.561 mm day⁻¹, nRMSE of 0.09 mm day⁻¹, MAE of 0.265 mm day⁻¹, NRMSE of 0.2033 mm day⁻¹, R-RMSE of 0.268 mm day⁻¹, NSE of 1 mm day⁻¹, d of 0.87 (≈ 1) mm day⁻¹ are suggesting a good agreement between SEBAL ET_c and PM ET_c (Table 4). Similar results of good ET estimates using SEBAL for both irrigated and drylands fields have been reported by Gowda et al. (2008) and suggested that automated calibration of SEBAL's empirical coefficients makes this model more accurate and operational on practical basis (Allen et al., 2007). Bala et al. (2015a) also reported that RMSE of crop growing period is 0.51 mm d⁻¹ for SEBAL ET_c , means SEBAL ET_c has a good accuracy with respect to lysimeter ET_c . Due to dependency of ET on crop coverage, weather parameters, ET_c has been calculated using both the model and found increasing trend for both years. With this reason, wheat crop is selected; it is a winter dominant crop of region and has maximum area of extent (Sharma et al., 2014). Ground verification was performed using high precision Global Positioning System (GPS), in 2012-13 and 2013-14 for wheat fields located

in different villages. Wheat field's coordinates were superimposed on ET imageries of 2012-2013 and 2013-2014 crop seasons to further identify wheat fields.

Fig. 4 Pure wheat crop dominating points over Landsat satellite image

Fig. 5 SEBAL-ET_c vs. PM-ET_c correlation graph at ground truthing points during crop season 2012-2013 and 2013-2014

Table 4 Comparison of ET_c values between SEBAL and Penman-Monteith (PM) method

3.3. Mapping of actual ET_c using SEBAL model

SEBAL model was applied on LANDSAT7-ETM+ images over 15 different dates/years for ET mapping for study area during wheat crop season. After validation of SEBAL ET_c with measured lysimeter data has showed significant R² of 0.91 and with PM ET_c also have significant R² of 0.85 (Fig. 5). Bala et al. (2015a) found that SEBAL ET_c corresponds to lysimeter ET_c with R-RMSE of crop-growing period of 0.19 mm d⁻¹. However, the other evaluation statistics shows SEBAL ET_c vs. lysimeter ET_c with MAE of 0.19 mm d⁻¹, NRMSE of 0.21 mm d⁻¹ and r² of 0.91. The evaluation statistics suggests that model prediction is significant and model has efficacy for estimation of ET using SEBAL and earth observation data sets as input.

The process of SEBAL ET_c estimation has involved calculation of vegetation indices and other variables viz. NDVI, LAI, SAVI, albedo, net radiation, surface temperature, ground heat flux, latent heat flux and evaporative fraction (Bastiaanssen et al., 1998; Bastiaanssen 2000; Bala et al., 2015a). The standard practice to estimate spatial ET and products are presented in Figure 6(a) to 6(i) of 7 January 2014 images. Based on these above retrieved parameters spatial ET was estimated for the study area of five crop years (Fig. 7 to 11).

Histogram of ET value with maximum number of pixels in the image, the calculated average ET (ET_{avg}), maximum ET (ET_{max}) and minimum ET (ET_{min}) values (Table 5). Maximum area comes under wheat crop; hence, ET_{avg} represents the average ET value of wheat crop of respective date of image. The value of ET_{avg} varied from 1.5 to 2.0, 3 to 4 and 3.5 to 5 mm day⁻¹ at early, middle and full growth stage of crop, respectively (Table 5). ET_{min} means that the lower value of ET which is due to lack of high moisture availability, however, ET_{max} indicates the area in which water bodies are mainly present or field that have well irrigations facility. It means there will also be a difference in ET_a of the same crop under irrigated and non irrigated conditions because irrigation leads to increase ET_a (Singh et al., 2014).

Fig. 6 (a)Normalised Difference Vegetation Index, (b)Soil Adjusted Vegetation Index, (c) Leaf Area Index, (d) Albedo, (e) Surface temperature, (f)Evaporative Fraction, (g) Net

Radiation, (h) Ground heat flux and (i) Latent heat flux for Bhiwani district of Haryana based on Satellite imageries taken of January 07, 2014.

Table 5. ET_{avg} , ET_{min} and ET_{max} for five wheat crop season for study area

3.4. Response of wheat crop to SEBAL ET_c

Wheat crop is sensitive to temperature *i.e.* cold and warm; ET of crop differs from one phenological stage to another. Moreover, the high sensitivity of wheat crop to high temperature (during early and late stages of crop) depends on the variations in ambient temperature and stages of development (Asseng et al., 2011; Modarresi et al., 2010). At sensitive developmental stage extreme temperature is especially detrimental (David et al., 2012), which directly affect the ET of crop. During the study period (2005-06) there was very low ET value was observed for growth of early and mid stage of wheat crop (Fig. 8). Due to availability of optimum soil moisture and favourable weather conditions as indicated in the Figure (9 and 10), the wheat crop yield was recorded higher during 2012-13 and 2013-14 compared to 2007-08 and 2004-05, even though, there was no large differences was observed in the crop sown areas during these years. It suggests that there is low availability of water and higher heat stress. The crop at this stage is very sensitive and stress to water and heat will affect the development growth and it also affects the crop yield. The actual ET varies spatially with vegetation cover and land use practices, even if the climatic conditions are same. This is shown by the range of actual ET at different stages. The SEBAL ET_c was found to be in a medium range (between 2-4 mm day⁻¹) at mid crop growth stage and in high range (between 4-6 mm day⁻¹) indicated by blue colour at the time of maximum growth of the crop during 2012-13 (Fig. 10) and 2013-14 (Fig. 11) followed by 2007-08 and 2004-05.

Fig. 7 Actual SEBAL ET_c images for wheat crop season 2004-05 for Bhiwani district

Fig. 8 Actual SEBAL ET_c images for wheat crop season 2005-06 for Bhiwani district

Fig. 9 Actual SEBAL ET_c images for wheat crop season 2007-08 for Bhiwani district

Fig. 10 Actual SEBAL ET_c images for wheat crop season 2012-13 for Bhiwani district

Fig. 11 Actual SEBAL ET_c images for wheat crop season 2013-14 for Bhiwani district

4. Conclusion

The main purpose of this research was to determine plant water usage or wheat crop evapotranspiration (ET_c) and wheat crop coefficients (K_c) for wheat grown in the Bhiwani district of Haryana, India. The estimated spatial ET for wheat growing areas using SEBAL was also compared with PM ET_c and it shows better agreement. Leaf Area Index (LAI), Normalised Difference Vegetation Index (NDVI), Albedo, Surface temperature and evaporative fraction have been taken as input in validation of SEBAL model for estimation of

actual ET. These input makes SEBAL model more reliable and robust technique for ET computation. The availability of large open access earth observation data sets with validated SEBAL model has promising ways to estimate ET irrespective of knowledge of crops. The model has shown a variation in average ET values estimated using histogram for wheat growing area of Bhiwani District, Haryana during different stages of crop growth. Therefore, this model has huge potential for the region to estimate ET of different stages of wheat crop growth. This might also help in deep understanding of wheat crop water requirement and irrigation scheduling in the region.

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Fig. 1 Location map of the study area (Bhiwani district of Haryana)

Fig. 2 Crop Coefficient curve for year 2013-14 for Bhiwani District

Fig. 3 Graphical representation of wheat statistics for Bhiwani district of Haryana during *Rabi* season

Fig. 4 Pure wheat crop dominating points over Landsat satellite image

Fig. 5 Correlation between SEBAL ET and PM ET_c at ground truthing points during crop season 2012-2013 and 2013-2014

Fig. 6 Normalised Difference Vegetation Index (a), Soil Adjusted Vegetation Index (b), Leaf Area Index (c), Albedo (d), Surface temperature (e), Evaporative Fraction (f), Net Radiation (g), Ground heat flux (h) and Latent heat flux (i) for Bhiwani district of Haryana based on Satellite imageries taken of January 07, 2014.

Fig. 7 Actual SEBAL ET images for wheat crop season 2004-05 for Bhiwani district

Fig. 8 Actual SEBAL ET images for wheat crop season 2005-06 for Bhiwani district

Fig. 9 Actual SEBAL ET images for wheat crop season 2007-08 for Bhiwani district

Fig. 10 Actual SEBAL ET images for wheat crop season 2012-13 for Bhiwani district

Fig. 11 Actual SEBAL ET images for wheat crop season 2013-14 for Bhiwani district

Table 1 Coordinates of pure wheat crop dominating areas

Field	Longitude	Latitude
Field 1	76°15'22.6''	28°37'14.3''
Field 2	76°16'54.93''	28°38'21.88''
Field 3	76°16'57.41''	28°38'17.11''
Field 4	76°16'51.80''	28°38'11.93''
Field 5	76°16'35.43''	28°38'15.91''

Table 2 SEBAL ET_c and PM ET_c on ground truthing points during crop season 2012-2013

Dates	SEBAL ET_c	Reference ET_o (PM)	K_c	PM ET_c (=ET_o x K_c)
19-Dec-12				
Field1	2.8625			
Filed2	2.4000			
Field 3	2.0325			
Filed4	2.4850	2.23	0.84	1.8711
Field5	3.1825			
Average SEBAL ET _c	2.5950			
09-Mar-13				
Field1	3.810			
Filed2	3.710			
Field 3	3.790			
Filed4	3.815	3.49	1.11	3.8688
Field5	3.795			
Average SEBAL ET _c	3.7840			
25-Mar-13				
Field1	4.285			
Filed2	3.600			
Field 3	4.220			
Filed4	4.3025	4.50	0.71	3.1917
Field5	4.2725			
Average SEBAL ET _c	4.1360			

Table 3 SEBAL ET_c and PM ET_c on ground truthing points during crop season 2013-2014

Dates	SEBAL ET_c	Reference ET_o	Kc	PM ET_c
06-Dec-13				
Field1	2.5000			
Filed2	1.8325			
Field 3	1.6500			
Filed4	2.5300	3.63	0.43	1.5592
Field5	2.5725			
Average SEBAL ET_c	2.0970			
07-Jan-14				
Field1	3.9175			
Filed2	2.9525			
Field 3	3.7325			
Filed4	2.9875	2.42	1.24	3.0008
Field5	2.9675			
Average SEBAL ET_c	3.3115			
12-Mar-14				
Field1	3.7550			
Filed2	3.9275			
Field 3	3.9950			
Filed4	3.9125	3.44	1.04	3.5805
Field5	3.6125			
Average SEBAL ET_c	3.8405			

Table 4 Comparison of ET_c values between SEBAL and Penman-Monteith (PM) method

Date	19-Dec-12	09-Mar-13	25-Mar-13	06-Dec-13	07-Jan-14	12-Mar-14
SEBAL ET_c	2.595	3.784	4.136	2.097	3.3115	3.8405
PM ET_c	1.8711	3.8688	3.19176	1.55925	3.0008	3.5805
RMSE			0.561			
nRMSE			0.090			
MAE			0.265			
NRMSE			0.2033			
R-RMSE			0.268			
NSE			1			
d			0.87 (≈ 1)			

Table 5 ET_{avg} , ET_{min} and ET_{max} for five wheat crop season for study area

Date	ET_{avg}	ET_{min}	ET_{max}
30-Jan-05	1.75	1.3	2.07
14-Feb-05	2.95	2.02	4.05
03-Mar-05	3.54	3.41	3.54
16-Dec-05	1.12	1.06	2.37
06-Mar-06	1.63	1.57	1.73
22-Mar-06	3.21	1.46	5.71
22-Dec-07	1.11	1.07	2.39
23-Jan-08	2.17	2.11	2.227
24-Feb-08	3.42	1.64	3.44
19-Dec-12	1.1	1.04	2.47
09-Mar-13	3.74	3.69	3.85
25-Mar-13	4.12	1.99	4.38
06-Dec-13	1.6	1.48	3.43
07-Jan-14	2.98	2.84	6.11
12-Mar-14	4.07	2.91	5.99