Application Of A Remote Sensing Technique In Estimating Evapotranspiration For Nyazvidzi Sub-Catchment., Zimbabwe

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Abstract

The integration of Remote Sensing and ground data into hydrological and cropwater requirement models enables water resources managers to adequately quantify the availability of water for irrigation in space and time. The SEBS algorithm was used to derive actual evapotranspiration estimates using MODIS images to assess cropwater requirements in the Ruti irrigation scheme after validation with ground based evapotranspiration measurements. Results show that actual evapotranspiration computed using SEBS (ET_oS) were comparable to those obtained using Penman Monteith method (**R^2=0.96**). The Kendall's tau test showed that there is significant statistical association (**α = 0.05**) between Pan Coefficient (K_p) values determined using ET_oS and ET_oPM and K_p values from the Snyder equation. In conclusion, the study highlights the potential use of GIS and remote sensed data for catchment management, planning and irrigation scheduling at irrigation scheme level. Welch's ***t*** test showed that there is no evidence to reject H_o: K_p determined from ET_oPM – K_p from ET_oS = 0. The above is crucial in the evaluation and comparison of performance of different irrigation systems in the country for food security and improvement of livelihoods in the light of integrated water resources management.

Keywords: Cropwater Requirements, SEBS, Remote Sensing, Pan Coefficient

Introduction

Evapotranspiration (ET) is one of the most important regulating factors of the atmosphere linking energy between the atmosphere and hydrologic system (Jia *et al*., 2003). ET values are used for determining cropwater requirements for efficient irrigation scheduling and management. ET is usually calculated as either the difference in water balance terms or measured using instruments in-situ (Droogers *et al.*, 2004). This presents a limitation in the spatial coverage as these methods provide point measurements of ET. Installing complex ET measuring systems such as lysimeters to cover large areas is costly. Alternative methods have been developed in recent years which provide rapidly available hydrological data over large areas based on remote sensing techniques (Farg *et al.*, 2002).

Irrigation water management and planning at Ruti irrigation scheme is hinged on the pre-determined average annual water allocation by Zimbabwe National Water Authority (ZINWA) of 15 x 10^3 m^3 per hectare per annum. Continuous repetitive observations are needed to provide the necessary input data to manage irrigation processes and interactions involved. Remote sensing provides a most efficient and reliable tool measure to monitor, and forecast and model the spatial and temporal variations of water in the environment in near real time. GIS allows for the advanced analysis and modeling methods to be implemented (Bandara, 2006). Due to the above mentioned advantages associated with GIS and remote sensing data, an attempt is made in this study to show how the Pan coefficient can be derived from the Surface Energy Balance System (SEBS). Results obtained from SEBS are compared with those obtained from Snyder equation and Penman – Monteith method.

Variations in water abstractions for irrigation depend on irrigation requirements per hectare and the size of the irrigated area (Pieter *et al*., 2008). It is also important to determine the aspects of the water balance for the dam (quantify discharge from the dam through discharge to downstream users, evaporation, and ground flow and irrigation requirements for local irrigation schemes). It is vital that cropwater requirements at the irrigation scheme are estimated and compared against available yields for efficient management of the irrigation. The residual water can be committed to other uses such as expanding the irrigation and more families can benefit in order to improve livelihoods.

Literature review

Methods for determining Irrigation water requirements

Irrigation scheduling is a process used to determine the correct frequency and duration of watering enough water to fully wet the plant's root zone while minimizing overwatering (Droogers *et al*., 2004). Irrigation scheduling is an essential means to achieve better water management (Abdelhadi *etal*., 2000). Most irrigation scheduling techniques are developed for sophisticated management conditions (Aghdasi *et al*., 2010). Akbari and Toomanian (2007) stated that they require frequent observations, close monitoring and maintenance. On a practical scale such techniques can often not be used for small farm holdings. Simple and practical methods need to be developed to achieve better irrigation management practices which take into account not only the water use by the crops but also the field irrigation method and water supply system. Weather-based pan coefficients for the conversion of pan evaporation to evapotranspiration of a tall grass reference crop have been published and equations have been developed to estimate the published coefficients. However, the equations used to estimate pan coefficients are complex (Snyder, 1992).

CropWat for Windows is a decision support system developed by the Land and Water Development Division of FAO, with the assistance of the Institute of Irrigation and development studies of Southampton UK and National Water Research Centre of Egypt (Chen Min *et al*., 2005). The model carries out calculations for reference evapotranspiration, cropwater requirements and irrigation requirements in order to develop irrigation schedules under various management scenarios and scheme water supply using the Penman-Monteith method (Beyazagl *et al*., 2000; Aghdasi *et al*., 2010).

Remote sensing and irrigation management

Estimation of crop water parameters using remote sensing techniques is an expanding research field and development trends have been progressing since 1970s (Jackson and Clark, 1971; Jackson et al., 1977; Seguin and Itier, 1983). The remote sensing algorithms such as SEBAL (Surface Energy Balance Algorithm for Land) by Bastiaanssen *et al*., (2003) and SEBS (Surface Energy Balance System) by Su (2002) are currently used approaches to estimate crop water parameters. In the field of geoinformatics, the software developments provide advanced techniques and modern facilities to the user. The remote sensing technology is slowly being introduced to Zimbabwe, but it has rarely been applied to support irrigation management practices probably because of the associated costs and lack of transferred technology. Prices are decreasing rapidly, and the quality of images is improving. The scale of satellite measurements is a measure of its quality and it is associated with two parameters, namely spatial resolution and temporal resolution. The spatial resolution measures the ability of a sensor to distinguish among closely spaced objects in the terrain. One pixel is the smallest area of the terrain that can be recorded as a unique element by the sensor. Ground objects smaller than the pixel size can be detected but not be resolved.

The Surface Energy Balance System (SEBS) for estimation of actual evapotranspiration

The Surface Energy Balance System (SEBS) is designed for the estimation of atmospheric turbulent fluxes, evaporative fraction and evapotranspiration using satellite earth observation data, in combination with meteorological information at proper scales (Su, 2002; Jia *et al*., 2003; Rwasoka *et al*., 2011). SEBS consists of: a set of tools for the determination of the land surface physical parameters, such as albedo, emissivity, temperature, vegetation coverage from spectral reflectance and radiance measurements; a model for the determination of the roughness length for heat transfer; and a new formulation for the determination of the evaporative fraction on the basis of energy balance at limiting cases (Su, 2002). SEBS requires as inputs three sets of information (Sun *et al*., 2008). The first set of information consists of land surface albedo, emissivity, temperature, and fractional vegetation coverage and leaf area index. Due to the unavailability of vegetation information, the Normalized Difference Vegetation Index (NDVI) is used as a surrogate for the leaf area index. These inputs can be derived from remote sensing data in conjunction with other information about the concerned surface. The second set includes air pressure, temperature, humidity, and wind speed. The third data set includes downward solar radiation, and downward longwave radiation which can either be measured directly.

The Surface Energy Balance System (SEBS) was conceptually developed for local and regional scale application using Landsat images with 30 m spatial resolution and a 16 day temporal resolution to estimate instantaneous surface energy balance (Li *et al*., 2012). However the launch of other sensor systems such as the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor with 250 m, 500 m, 1 km spatial resolutions and a twice a day temporal resolution has given remote sensing methods a new boost (Elhaddad *et al*., 2011).

Rwasoka *et al* (2011) used SEBS to estimate actual evapotranspiration in Upper Manyame catchment in Zimbabwe and he found that it can be used for estimating actual evapotranspiration although it over estimated compared to ground based measurements. Fatemeh (2006) made use of both the ASTER and MODIS images to determine crop coefficients in Iran, he noted differences from the traditional methods such as the FAO methods but the differences were not significant ($\alpha = 0.05$). Evaporation pans [Class A pan, U.S. Weather Bureau (USWB)] are used extensively throughout the world to measure free-water evaporation and to estimate reference evapotranspiration (ET_o) (Irmak *et al*., 2002) However, reliable estimation of ET_o using pan evaporation (Epan) depends on the accurate determination of pan coefficients (Kpan). Thus an attempt is made in this study to apply the SEBS algorithm to estimate Kpan values.

Methods and materials

Description of the study area

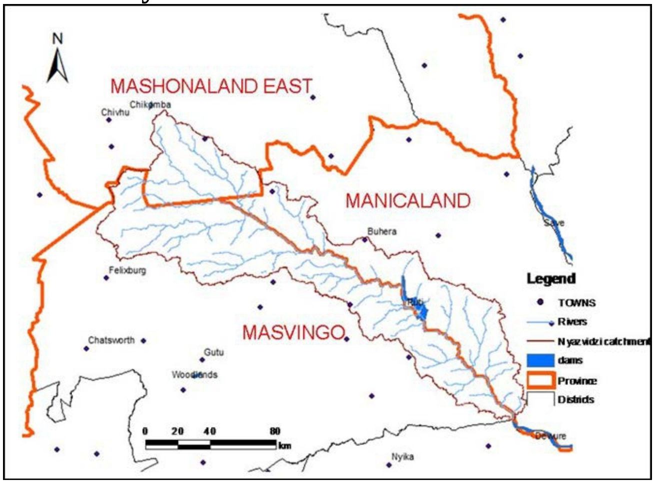


Figure 1: Location of the study area

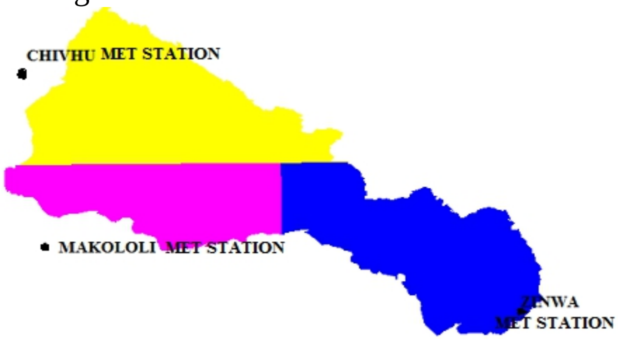
Climate

Climatic conditions are largely sub-tropical, with one rainy season between November and March. Rainfall events over the catchment are fairly scarce, averaging between 600 – 700 mm/year. The mean monthly maximum temperature is about 24^{o}C with a minimum of 14^{o}C and 85 % of rainfall occurs during the same period. The mean monthly actual evaporation is 137 mm. The climate is characterised by a short rainy season from November to April. The Nyazvidzi sub catchment region is subject to periodic seasonal droughts, prolonged midseason dry spells and unreliable commencement of the rainy season. Irrigation plays an important role in sustaining crop production.

Data Analysis

Evaluation of the rainfall distribution using GIS

Precipitation is the major source of inflow into the catchment. Daily precipitation data for three neighbouring stations, Chivhu, Makololi and the ZINWA station located at the dam wall are available for use in the modeling for the Nyazvidzi sub catchment water balance. Rainfall data is available in point measurement for but hydrological modelling requires areal distributed rainfall. The Thiessen polygon method of interpolation was used for this purpose. The approximate zones of influence of each rainfall recording station are shown in figure 2. It can be observed in the table that Makololi and Chivhu station are outside the catchment area and are further away from the Irrigation scheme which is nearer to the ZINWA station.



Station	Thiessen weight
Chivhu	0.42
Makololi	0.24
ZINWA(Ruti Dam)	0.34
	1.00

Figure 2: Approximate zones of influence around stations by Thiessen Polygons and the Thiessen weights.

The daily areal rainfall of Nyazvidzi Sub catchment is estimated for 1992 to 2012 using the Thiessen Polygon by applying the weights of these meteorological stations. Daily rainfall obtained from the Thiessen polygon method is compared to average daily areal rainfall. Station Thiessen weights calculated in ILWIS software; Chivhu 0.42, Makoholi 0.24, ZINWA (Ruti dam) 0.34. Estimates of the Thiessen Polygon method show higher peaks of daily rainfall than the average daily rainfall.

In order to address the main objective of the research, four objectives were identified and the following methods were used to arrive at answers that addressed the main research questions. Table 1 shows the summary of the study materials and data used in this study.

Available climatic elements used were: monthly average values of maximum air temperature (Tmax), mean air temperature (T), minimum air temperature (Tmin), air relative humidity (RH), total sunshine hours (n), wind speed at 2.0 m height (Ws) and class A pan evaporation (ECA). Meteorological data daily rainfall temperature including the above mentioned variables from 1991 to 2012 was provided by the Meteorological Services Department of Zimbabwe.

Reference evapotranspiration (ET_o) was calculated using the Penman-Monteith-FAO model. K_p monthly values were determined based on RH, Ws and fetch distance (F) using the equation by Snyder (1992) and the FAO chart. The equation can be written as follows:

$$K_p = 0.482 + 0.024 \text{ Ln } (F) - 0.000376 * Ws + 0.0045 * RH$$

Table 1 Study Materials and Data

Data needed	Source of data
Ground control coordinates for validation of classification results MODIS images (2003 - 2012)	Global Positioning System(GPS) used to take ground control points MODIS images downloaded from Glovis (www.lads.usgs.gov)
Meteorological data (1974 - 2012)Rainfall, temperature Irrigation scheme area, cropping pattern MODIS reprojection tool	ZINWA, Department of meteorological services (www.lpdaac.usgs.gov/landdaac/tools/mrtswath)

K_p values were obtained considering: a) the annual period; b) the rainy period (November to March); c) the dry period (April to October) when, normally, producers use irrigation more frequently. From the angular coefficients obtained by regression between ET_oPM and ECA and ET_oS and ECA approximate K_p values were fixed for the dry and rainy periods. These were compared to FAO charted (ET_oF) K_p values and those obtained from Snyder (1992) equation (ET_oSn). Linear regression, giving respective determination coefficients (R^2), Kendall's tau test were used for analysing the relationship and statistical association between the K_p values. The ***t*** distribution was used for analysing the difference of mean of K_p values for the two periods were used to test for statistical association (□□□□□□□□).

$$\text{Kendall's } tau = \frac{\sum c - \sum d}{\sum c + \sum d}$$

$$Z_s = \frac{3 \text{ x } tau \text{ x} \sqrt{n(n-1)}}{\sqrt{2(2n+5)}}$$

Where *c = concorded elements*
d = discorded elements
n = number of elements
Z_s *= test statistic*

Remote sensing data acquisition and pre-processing for SEBS

In this study cloud free Terra MODIS 1 km remote sensing satellite image data sets of Nyazvidzi sub catchment in Zimbabwe were used. Downloaded MODIS images used in computing maps required for the SEBS algorithm (Su, 2002) in estimating actual evapotranspiration. Firstly the MODIS images were preprocessed and reprojected from level 1 to level 2 using the MODIS reprojection tool called ModisSwath tool. The preprocessed and reprojected MODIS bands were imported into ILWIS, a GIS and RS software with a built-in SEBS algorithm. SEBS used multispectral remote sensing data complemented with meteorological data. The SEBS was used in this study to highlight the spatial and temporal differences in actual evapotranspiration over the catchment. The actual evapotranspiration computed from SEBS was then used for determining Kpan, a class A pan evaporation dish coefficient used for determine evapotranspiration.

SEBS estimates actual evapotranspiration ET_oS by solving the energy balance equation. Latent heat flux (LE) ($W·m^2$) is estimated as a residual of energy-balance equation that is the difference between net radiation (R_n: $W·m^2$), soil heat flux (G: $W·m^2$) and sensible heat flux (H: $W·m^2$).

$LE = R_n – G – H$

The SEBS algorithm requires a couple of maps when being run and these include: Surface albedo (α_s) which was estimated using MODIS daily surface reflectance, while surface emissivity (ε_s) was estimated using MODIS Normalized Difference Vegetation Index (NDVI) composition.

$$\alpha_s = \sum_{b=1}^{7} \rho\, s, b, \omega_s$$

$$\boldsymbol{\varepsilon}_S = 1.009 + 0.047 \ln(NDVI)$$

in which ρs,b is the at-surface reflectance for band “n” and ω_s is the weighting coefficient representing the fraction of at-surface solar radiation occurring within the spectral range represented by a specific band (Ma *et al*., 2006). The daily ET_oS (ET_{24h}: mm/day) was estimated from the residual in the instantaneous energy-balance equation and the evaporative fraction (EF). EF has an important characteristic which is its regularity and constancy in cloud-free days (Su, 2002). These energy variables are computed in ILWIS. Thus, its instantaneous value can be taken as the daily mean value, so that the spatial variability in daily ET_0S can be predicted over large scales.

$$\mathrm{EF} = \frac{LE}{Rn - G}$$

$$\mathrm{ET_0S} = \frac{86400\mathrm{EFRn}}{\varphi}$$

Where φ = *latent heat of evaporation (Jkg^{-1})*

Estimating cropwater requirements using the FAO Penman Monteith method

The FAO Penman- Monteith method for calculation of reference evapotranspiration (Chiew *et al*., 1995).

$$ET_0 = \frac{0.408(\mathrm{Rn} - \mathrm{G}) + \gamma \frac{900}{\mathrm{T} + 273} \mathrm{u}_2(\mathrm{e_s} - \mathrm{e_a})}{\Delta + \gamma(1 + 0.34\mathrm{u}_2)}$$

Where:

ET_0	= *reference evapotranspiration*	[mmd^{-1}]
R_n	=*net radiation at the crop surface*	[$MJm^{-2}d^{-1}$]
G	=*soil heat flux density*	[$MJm^{-2}d^{-1}$]
T	=*mean daily air temperature at 2 m height*	[^oC]
U_2	=*wind speed at 2m height*	[ms^{-1}]
e_s	=*saturation vapour pressure*	[kPa]
e_a	=*actual vapour pressure*	[kPa]
γ	=*psychometric constant*	[$kPa\ ^oC^{-1}$]
Δ	=*slope vapour pressure curve*	[$kPa\ ^oC^{-1}$]

Crop evapotranspiration calculated using the crop coefficient approach

Evapotranspiration from each specific vegetation type or crop evapotranspiration (ET_c) was calculated using the crop coefficient approach (K_c) from the FAO Irrigation and Drainage Paper No. 56 (Er-Raki *et al*., 2007). In the crop coefficient approach, crop evapotranspiration was calculated by multiplying the reference evapotranspiration (ET_o) by K_c as follows:

$$\mathrm{ET_c} = \mathrm{K_c ET_0}$$
$$\mathrm{ET_o} = \mathrm{k_p ET_p}$$

Where:

ET_c = crop evapotranspiration [$mm\ d^{-1}$]
K_c= crop coefficient [$mm\ d^{-1}$]
K_P = pan coefficient [$mm\ d^{-1}$]
ET_p= Class A pan evaporation [$mm\ d^{-1}$]
ET_o= reference crop evapotranspiration [$mm\ d^{-1}$]

The above equations indicate the intricate relationship between pan evaporation and crop evapotranspiration. It is therefore important to accurately determine the pan coefficient for efficient management of irrigation systems. Crop evapotranspiration differs distinctly from the reference evapotranspiration as the ground cover, canopy properties and aerodynamic resistance of the crop are different from those of grass (Er-Raki *et al*., 2007). The K_c varies predominately with the specific crop characteristics while climatic settings only have marginal effects (Bos *etal*., 2009). This enables the transfer of standard values for K_c between locations and between climates. The reference ET_o is defined and calculated using the FAO Penman-Monteith. The crop coefficient, K_c is basically the ratio of the crop ET_c to the reference ET_o, and it represents an integration of the effects of four primary characteristics that distinguish the crop from reference grass (Abdelhadi *et al*., 2000).

Results and Discussion

Performance of the Surface Energy Balance System

SEBS actual evapotranspiration (ET_oS) values were compared to evapotranspiration determined using Penman- Monteith method (ET_oPM) for the following days January 19, February 09, March 12, April 01, May 16, June 13, July 27, August 17, September 22, October 21, November 04, December 11 all taken in 2012 for the Chivhu meteorological station. ET_oS values under estimate by 10% ET_oPM values for all months except in June and October where it over estimates by 1% and 2% respectively. Figure 4a shows a high determination coefficient (0.962) between ET_oPM and ET_oS. Kendall tau test (Table 2) showed high statistical association between ET_oPM and ET_oS (significance level $\alpha = 0.05$). These results confirm that SEBS can be used for approximating actual evapotranspiration and hence can be used to estimate Kp values. ET_0Sn from the Snyder equation yielded high correlation ($R^2 = 0.853$) which can also be regarded as excellent (figure 4b). Reference evapotranspiration values estimated using (ET_oF) charted FAO Kp coefficients presented the worst performance, with R^2 equal to 0.7503 (Figure 4c). The good performance of Snyder (1992) equation shows that the use of continuous values provided by equations is more suitable than the use of discreet values provided by charts.

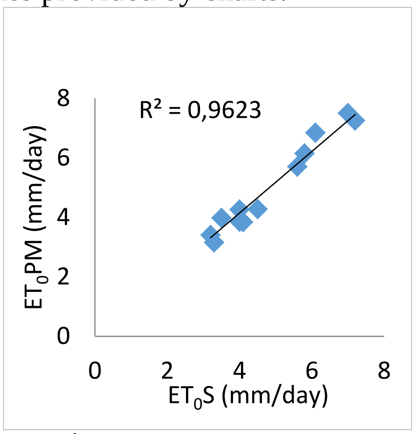


Figure 4a[1]: Comparison of ET_0PM and ET_0S

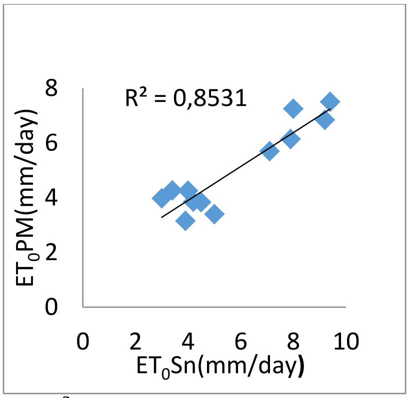


Figure 4b[2]: Comparison of ET_0PM and ET_0Sn

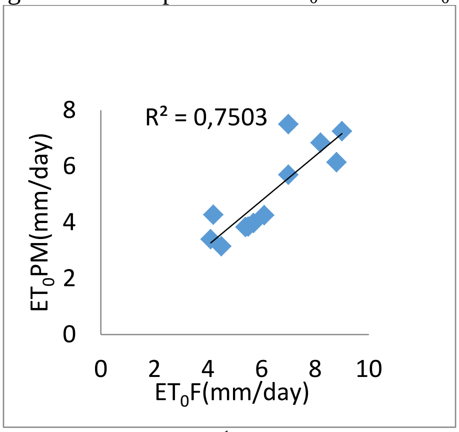


Figure 4c[3]: Comparison of ET_0PM and ET_0F[1]**P-value (0.034**) we accept the null hypothesis [2]**P-value (0.042)** we accept the null hypothesis [3]**P-value (0.054)** we reject the null hypothesis (*significance level 0.05*)

Spatial variation of actual evapotranspiration

It is important to note the differences between values on the irrigation site and those at Chivhu Meteorological station. These values are an indication of the spatial variation of evapotranspiration, which means the use of point measurements results in interpolated values that are not accurate. Therefore SEBS determined ET_oS values are advantageous in that they are determined over large study area at resolution determined by the available sensors.

Figure 5 shows the spatial distribution of ET_oS. Relatively, it can be shown that high values are obtained in the water body (Ruti dam) and relatively low values at the irrigation fields. The differences are mainly due to the land cover types especially when it comes to the water body were water is abundantly available. The irrigation scheme has varying values determined by the crop type, stage and agricultural practices. The differences clearly indicate the need for ET values determined onsite so as get more accurate values for the determination of cropwater requirements.

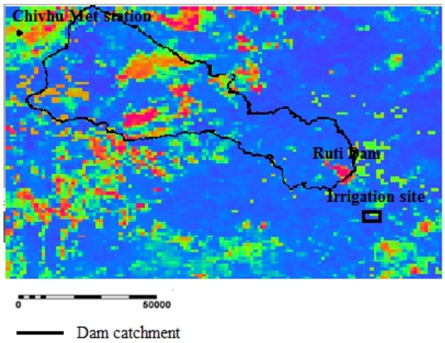


Figure 5: Spatial variation of ET_0S SEBS output map

Difference of mean

The test for difference of mean of angular coefficients (K_P) determined from SEBS and Penman –Monteith method, 0.721 and 0.739 (figure 6) yielded a P-value 0.054 > 0.05, therefore there is no significant evidence to reject H_o: □□□□□□□

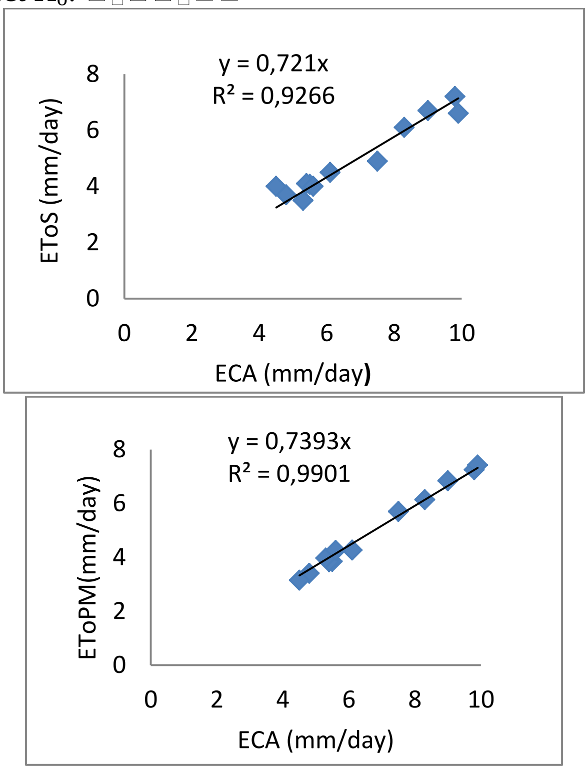


Figure 6: Angular coefficients: a) ECA-ET_0S b) ECA-ET_0PM

Test for the difference of mean for the selected periods April - October and November - March

P–value 0.020 < 0.05, therefore there is enough evidence to reject

H_0:□□□□□□□□at 5 % level of significance. This shows that K_p values are different for the selected periods. Therefore for accurate determination of cropwater requirements different K_p values should be used in estimating cropwater requirements.

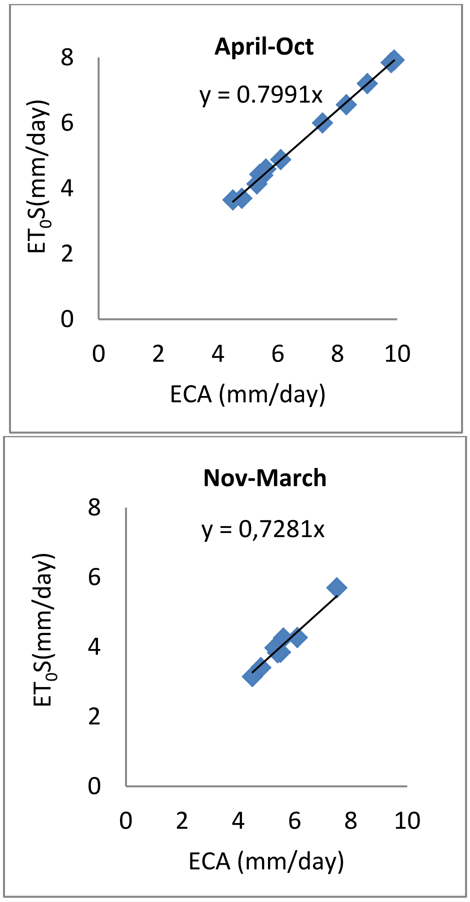


Figure 7: Angular coefficients: ECA-ET_0S April-Oct/Nov-March

Table 2: Statistical coefficients

Coefficient	ET_oSn	ET_oS	ET_oF
R^2	0.85	0.96	0.75
Z_S	3.212	7.551	4.521
p	0.042	0.034	0.054

Conclusion and Recommendations

Conclusion

In this research the following conclusions were drawn

I. Class A pan coefficients (Kp) calculated using the actual ET from SEBS is comparable to Kp determined from Penman-Monteith and Snyder equation.

II. The actual evapotranspiration values determined from The Surface Energy Balance System (SEBS) were comparable to Penman- Monteith equation.

Recommendations

From this study it is very important to consider the following:

Future studies should use higher resolution satellite images such as ASTER and Landsat for ET_oS estimates to monitor actual evapotranspiration at farm holder level (0.5 ha) on Ruti Irrigation scheme.

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