Chapter 8
Evapotranspiration Modeling Using Remote Sensing and Empirical Models in the Fogera Floodplain, Ethiopia

Temesgen Enku, Christiaan van der Tol, Ambro S.M. Gieske, and Tom H.M. Rientjes

Abstract Conventional methods and remote sensing were applied for the estimation of reference evapotranspiration and actual evapotranspiration over the Fogera floodplain. Reference evapotranspiration (ET_0) by Modified Makkink (MM), Priestly-Taylor (PT) and Abtew (A) simple equations was compared to the Penman-Monteith (PM) estimations, in order to decide which method for ET_0 is the most suitable alternative to PM in data scarce conditions. A comparison was also made to a satellite based energy balance approach that estimated actual evapotranspiration. For the remote sensing approach, images from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor were selected. For the study, data has been used from Bahir Dar meteorological station at a distance of 50 km from the floodplain and from Woreta weather station that is located in the floodplain. The comparison of results from the conventional methods indicated that the MM method performed best over the floodplain as compared to the PM approach while the PT and Abtew (A) simple equations only produced fair results. The latter two approaches required calibration of site specific coefficients that may have affected the estimation results. Accumulated actual evapotranspiration from the satellite based approach for the year 2008 was about 1,519 mm for rice, while the reference evapotranspiration by the PM approach was 1,498 mm. A comparison of these results with literature values of the crop coefficient of rice indicated that rice transpired at a potential rate.

Keywords Evapotranspiration · MODIS · SEBS · Remote sensing · Penman-Monteith · Makkink · Priestley-Taylor · Abtew model · Fogera

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8.1 Introduction

Population growth over the past decades in the Lake Tana basin caused the demand for fresh water to increase. Water supply has to meet requirements not only for irrigation and agricultural production but also for domestic uses. Hence, in the area well planned and adequate water resources management is required at local and regional scales. For such management, first quantitative assessments need to be made for meteorological processes of precipitation and evapotranspiration that affect the water balance of the basin at large. This study aims to estimate actual evapotranspiration on the Fogera floodplain, Lake Tana basin, Ethiopia, that probably is the most productive agricultural area in the Lake Tana basin. Also, large scale irrigation is scheduled in the near future.

In the literature, many approaches are available to estimate actual evapotranspiration. Approaches commonly rely on estimated potential evapotranspiration that is estimated from meteorological data. Empirical coefficients in the various conventional methods estimations are usually not transferable to other regions and only have validity for the areas and the period over which estimations are made. As such use of conventional methods results in estimation errors of different magnitude and selecting the most reliable method requires comparison of estimates to select the method that gives best results with preferably minimum data requirement.

8.1.1 Background and Literature Review

Evapotranspiration is a general term that includes all the processes that water in the liquid state or solid state change into gaseous state. Hence the term includes evaporation from open water surface and from bare soil, transpiration through plant leaves and sublimation from snow and ice surfaces. This phase change is mainly influenced by the availability of solar energy at the evaporating and transpiring surfaces. Both processes occur simultaneously and quantifying these processes separately is complex.

Conventional reference ET estimation methods are commonly applied in specific climatic conditions. For instance, Penman Monteith (PM), Priestly-Taylor (PT), Modified Makkink (MM), and Abtew (A) simple methods were developed for humid areas. In Allen et al. (1998), the Penman-Monteith (PM) method is discussed as a standard method for reference evapotranspiration estimation and is globally most widely used. Conventional methods are ground based and estimate ET using weather station data that is collected at a point scale. Spatial variation of the turbulent fluxes as caused by differences in land cover and topography constrains the translation of ground based methods for ET_0 into ET_a for larger spatial areas. To overcome the issue of the observation scale, remote sensing is often advocated since an entire area such as a catchment can be covered by satellite images. Nowadays there are a number of satellite based approaches developed for the estimation of actual evapotranspiration that are all based on solving the land surface energy balance equation. Examples are the Surface Energy Balance Systems (SEBS) (Su, 2002), the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen, 1998), and the Two Source Energy Balance approach (TSEB) (Norman et al., 1995).

In this chapter, the SEBS approach is selected. In this approach, the latent heat flux is estimated as a residual of net radiation from sensible and soil heat flux estimations. SEBS has applications in various climatic zones with good performance when estimating the surface energy fluxes. In central Arizona, it was tested by Su (2002) and good results were reported. McCabe and Wood (2006) in their study in central Iowa, USA showed that SEBS based latent heat fluxes agree well with the flux tower measurements.

SMEC (2007) reported in a hydrological study of the Tana-Beles sub-basins and estimated ET over the floodplain to be 140, 117, 116 mm, and 129 mm for the months of June, July, August and September, respectively. Water Watch (2005) reports on a satellite based energy balance approach of Tana-Beles sub basins and reported an average ET_a of 672 mm/year over the entire lake basin area. Hence, this study will be valuable for estimation of the reference and actual ET over the floodplain using both conventional methods and the SEBS approach.

The effects of characteristics that distinguish field crops from the reference grass are integrated in to the crop coefficient (Kc). The Kc of a crop varies with the crop growing stages (Allen et al., 1998). The rice crop coefficient (Kc) is estimated here as the ratio of actual evapotranspiration (ET_a) to PM reference ET of the rice field in the floodplain.

8.1.2 Objectives

The main objective of this study is to analyze ET estimations by different conventional methods and estimation of spatiotemporal distribution of actual ET over the Fogera floodplain. The specific objectives are (1) estimation of reference ET using Penman-Monteith (PM), Priestley-Taylor (PT), Modified Makkink (MM) and Abtew (A) equation and (2) the application of Surface Energy Balance Systems (SEBS) for the estimation of actual ET from satellite data.

8.2 Study Area

The Fogera floodplain is located in northwestern Ethiopia, about 625 km from the capital Addis Ababa along the shores of Lake Tana. The Ribb and Gumara Rivers with catchment areas of 1,283 and 1,302 km^2 respectively (Abeyou, 2008), pass through the plain and both drain to Lake Tana (Fig. 8.1).

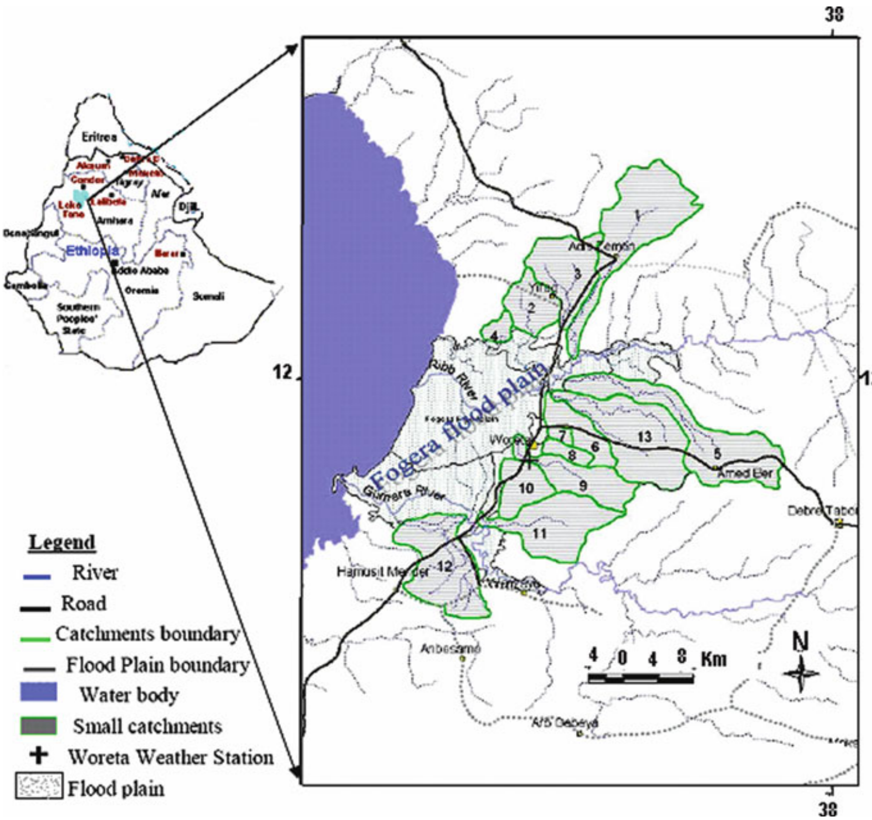


Fig. 8.1 Location map of the Fogera floodplain

The floodplain is bounded by Lake Tana in the west, the Gumara River in south, the Ribb River in the north, and the Bahir Dar-Gondar road in the east. Its latitude ranges from 11°45′ N to 12°03′ N while its longitude lies between 37°29′ E and 37°49′ E. It stretches about 15 km east-west and 34 km north-south, with an elevation of about 1,800 m amsl, having an inundation area of about 490 km^2.

8.2.1 Climate

Total annual rainfall in the floodplain ranges from about 1,100–1,530 mm. The mean monthly rainfall in the floodplain ranges from 0.4 mm in January to 414 mm in August. The mean monthly temperature of the area is about 19°C, monthly mean maximum temperature of about 27.3°C, and monthly mean minimum temperature is 11.5°C (Dagnachew and Woubet, 2008). The rainy season in the area starts in June and ends in October. About 56% of the Fogera floodplain is covered by rice fields (Temesgen, 2009).

8.3 Materials and Data

8.3.1 Station Data

For this study, weather station data is collected from Woreta weather station and from Bahir Dar (BD) station that is part of the National Ethiopian Meteorological Network. Woreta weather station (WWS) is located at 11°54′ N and 37°41′ E. Four months data of temperature, relative humidity, atmospheric pressure, incoming solar radiation, and wind speed were collected from this station. These variables were observed at frequency of 1 Hz and automatically recorded at 5-min interval. Bahir Dar station is located at 11°04′ N and 37°25′ E and was used in this study, although its location is some 50 km from the study area. The station was selected to allow for better estimation of ET. Extraterrestrial solar radiation differences computed at the both stations was found less than 1 W/m^2 (Temesgen, 2009). Also daily temperature and relative humidity were compared and a relation was established between these two stations. The comparison showed that the Bahir Dar station data could be used without significant error in the estimation of ET in the floodplain.

8.3.2 Remote Sensing Data

The Moderate Resolution Imaging Spectroradiometer (MODIS) on board of Terra products were collected which were processed in SEBS. Products used include land surface temperature, surface reflectance and leaf area index. The detailed description of the MODIS products are shown in Temesgen (2009).

8.4 Theory and Methods

8.4.1 Ground Based Evapotranspiration Estimation Models

8.4.1.1 Penman-Monteith Method

The Penman-Monteith equation (Monteith, 1965; Penman, 1948) is a physically based combination approach that incorporates energy and aerodynamic considerations. The Penman-Monteith (PM) equation produces direct estimates of actual ET (ET_a), but requires knowledge of the PM canopy resistance (Sumner and Jacobs, 2005). Generally, the PM equation gives acceptable ET estimates for practical applications (Widmoser, 2009), which require measurement of net radiation, soil heat flux, air temperature, relative humidity, and wind speed. The calculation of the net radiation and the assumption of soil heat flux were according to the FAO-56 version. Reference evapotranspiration (ET_0) is the potential ET from a hypothetical green grass of uniform height, 0.12 m, well watered, and a constant albedo of 0.23 with fixed surface resistance of 70 s/m (Allen et al., 1998). After the aerodynamic resistance, $r_a = 208/u_2$ and the surface resistance $r_s = 70$ s/m are estimated; for the reference crop, the PM equation can be rewritten as:

$$ET_0 = \frac{0.408\Delta\,(R_n - G) + \gamma\,\frac{900}{T+273}u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34u_2)} \tag{8.1}$$

where

ET_0 = reference evapotranspiration (mm/day),
R_n = the net radiation at the crop surface (MJ m^{-2}/day),
G = soil heat flux density (MJ m^{-2}/day), assumed zero on daily basis,
T = mean daily air temperature at 2 m height (°C),
u_2 = wind speed at 2 m height (m/s),
e_s = saturation vapour pressure (kPa),
e_a = actual vapour pressure (kPa),
e_s = ea saturation vapour pressure deficit (kPa),
Δ = slope vapour pressure curve (kPa/°C),
γ = psychrometric constant (kPa/°C).

8.4.1.2 Priestley-Taylor Method

The PT equation (Priestley and Taylor, 1972) was developed for open water and wet land surfaces, so the PT method gives better results (Brutsaert, 2005) when soil moisture is not a limiting factor for ET. The Fogera plain is wet for a long period in the year. ET_0 estimation with the PT method will be compared with the standard PM ET_0 and a locally calibrated coefficient will be proposed for the study area. The PT equation is expressed as:

$$ET_0 = \alpha\left(\frac{\Delta}{\Delta + \gamma}\right)\left(\frac{R_n - G}{\lambda}\right) \tag{8.2}$$

where ET_0 is in mm/day, and the other input parameters as defined in equation (8.1). It was reported that, the coefficient α varies in the range of 1.3±0.03 for wetland surfaces (Priestley and Taylor, 1972). For this study, α value of 1.3 was used.

8.4.1.3 Modified Makkink Method

The Modified Makkink (MM) method is widely used in western Europe. This method is one of the simplest radiation models. The result from this will be compared with PM method and a calibrated coefficient will be proposed. The MM method is defined as (De Bruin, 1981):

$$ET_0 = 0.65\frac{\Delta}{\lambda(\Delta + \gamma)}R_s \tag{8.3}$$

where R_s is the incoming solar radiation (MJ m^{-2}/day).

8.4.1.4 Simple Abtew Equation

This method requires only solar radiation for estimation of ET. This simple method gives actual ET when soil moisture is not a limiting factor for ET and in drier conditions it gives potential ET (Abtew, 1996). It is formulated as:

$$ET = k\frac{R_s}{\lambda} \tag{8.4}$$

where ET (mm/day) is the daily evapotranspiration, k is taken as 0.53, this coefficient could be calibrated locally (Abtew and Obeysekera, 1995). A locally calibrated coefficient will be proposed, after comparing with the P-M reference ET.

8.4.2 Surface Energy Balance Systems (SEBS)

The SEBS method developed by Su (2002) is one of the remote sensing methods to estimate turbulent surface energy fluxes. MODIS spectral products and meteorological data were used for the estimation of energy fluxes in SEBS. Actual ET (ET_a) is estimated as a residual of mass balance and energy balance equations, which is written as:

$$ET_a = \frac{R_n - G - H}{\lambda} \tag{8.5}$$

where R_n is the net radiation, G is the soil heat flux, H is the sensible heat flux and λ is the latent heat of evaporation (J/kg). Parameterizations of the inputs for the SEBS algorithm are explained in detail in Su (2002) and Temesgen (2009). The instantaneous values obtained with Eq. (8.5) are first extrapolated to daily values using the assumption that the evaporative fraction is constant during the day. Secondly, the daily values are extrapolated to monthly estimates, using the monthly PM estimates based on sunshine hours. All pixels of the floodplain are then averaged to obtain a single monthly ET_a value.

8.5 Results and Discussion

In this section, first, the performance of conventional methods of reference ET estimations are compared to the Penman-Monteith PM equation. Second, the results of the calculation of actual ET with the SEBS approach are discussed. Finally, the results are combined to yield the local crop coefficient of rice.

8.5.1 Reference Evapotranspiration

8.5.1.1 Priestley Taylor

Figure 8.2 shows scatter plots of PT versus PM reference ET for two stations: Woreta (left panel) and Bahir Dar (right panel), using an a priori coefficient of $\alpha = 1.3$. Table 8.1 shows the statistics of the comparison: the R^2, the root mean square error (RMSE), the average mean error (AME) and the bias (in mm/day). The table includes both the results for the a priori value of $\alpha = 1.3$ and a (least square error) calibrated coefficient of $\alpha = 1.14$. Calibration obviously improved the results significantly for both the stations: the RMSE, AME and bias are reduced by a factor 2 or more.

8.5.1.2 Modified Makkink

A similar comparison between PM and MM shows that the Makkink method performs very well (Fig. 8.3 and Table 8.1). Even though the Makkink method was

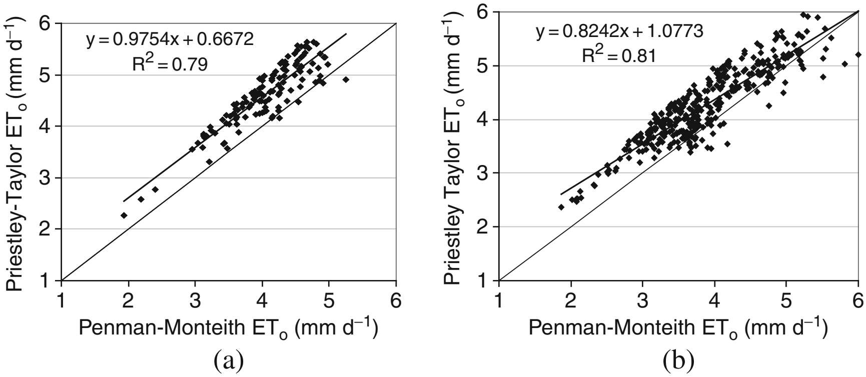


Fig. 8.2 Scatter plot of PT vs PM ET_0 at stations (**a**) Woreta (**b**) Bahir Dar

Table 8.1 Comparison of different methods (PT, MM and A) with PM

Methods	R^2		RMSE (mm day^{-1})		AME (mm day^{-1})		Bias (mm day^{-1})	
PT	WWS	BD	WWS	BD	WWS	BD	WWS	BD
$\alpha = 1.30$	0.79	0.81	0.77	0.63	0.72	0.56	0.71	0.53
$\alpha = 1.14$	0.79	0.81	0.29	0.34	0.25	0.27	0.13	0.01
MM	0.93	0.88	0.19	0.25	0.16	0.19	0.00	0.01
A								
$k = 0.53$	0.90	0.81	0.60	0.63	0.55	0.55	0.54	0.53
$k = 0.48$	0.90	0.81	0.25	0.34	0.21	0.21	0.11	0.11

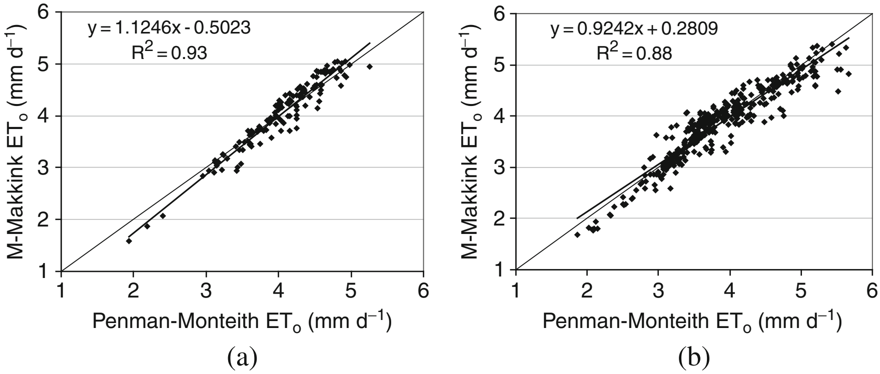


Fig. 8.3 Scatter plot of MM vs PM ET_0 at stations (**a**) Woreta (**b**) Bahir Dar

developed for well-watered grassland in The Netherlands (De Bruin, 1981), the MM equation performs well for both stations without the need for calibration of the coefficient to obtain better matching ET_0 estimations.

8.5.1.3 Abtew Equation

Figure 8.4 and Table 8.1 show the analysis for Abtew's equation. Abtew simple method also requires local calibration of the coefficient. After local calibration with coefficient $k = 0.48$, the result improved (Table 8.1). The MM method appears to be slightly better than Abtew's method because it does not require much calibration and hence it would be more generally valid in Ethiopian conditions.

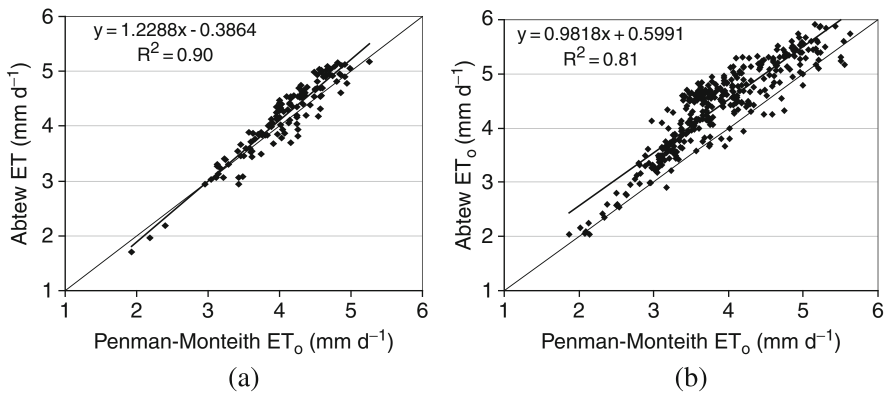


Fig. 8.4 Scatter plot A vs PM equation at stations (**a**) Woreta (**b**) Bahir Dar

8.5.2 Actual Evapotranspiration with SEBS

8.5.2.1 Comparison of Remote Sensing (RS) Actual ET to PM ET_0

Reference evapotranspiration is a climatologic variable characterizing the evaporative demand of the surface, whereas actual evapotranspiration (ET_a) represents the effects of soil moisture, land cover heterogeneity and the variability of climatic conditions. Comparing actual to reference evapotranspiration gives insight in the spatial variability of land cover and stress conditions. Differences between time series of actual evapotranspiration and reference evapotranspiration for specific crops indicate the seasonal cycle for the crop coefficient. It is noted that differences also are due to possible effects of water stress that is unaccounted for. We assume that water is sufficiently available not to constrain evapotranspiration. We note that ET estimations are for the wet season where rainfall commonly occurs in heavy daily showers. When comparing remote sensing based ET_a with ground based ET_0, one should realize that ET_0 estimates are spatially limited and computed on daily basis, whereas the remote sensing technique estimates of ET_a are spatially distributed, but they are only valid for the instantaneous time of the satellite overpasses.

Time series of ET_0 and ET_a are shown in Fig. 8.5. One day per month was analysed. The instantaneous RS ET_a values were extrapolated to daily and monthly values.

The annual ET_a estimated from this approach was 1,519 mm, while PM ET_0 was 1,498 mm in the year 2008 (Nov 2007–Oct 2008). The mean annual rainfall over the last 5 years in the Fogera floodplain was 1,296 mm (Temesgen, 2009). This indicates that the annual actual ET was 17% higher than the mean annual rainfall over the area. This is probably due to the spate irrigation practices in the area during the dry seasons, which use water from upstream areas.

In Fig. 8.5, both the remote sensing daily and monthly actual ET and the PM ET_0 daily and monthly estimations follow a similar trend. In the wet season (July to October) the daily estimations from SEBS were larger than the respective PM ET_0, whereas in dry seasons, the PM ET_0 was larger than SEBS estimations.

This could be explained by the drying out of the top soil layers leading to a reduction of moisture available for evapotranspiration.

April is the driest month in the floodplain and soil moisture is then the limiting factor for ET_a and reduction in ET_a is then observed. ET_a is limited by the available net radiation during the rainy season.

8.5.2.2 Spatiotemporal Distribution of ET_a over the Entire Floodplain

The spatial and temporal variation of ET over the plain was analyzed using three selected images. The spatial variation over the entire area was more pronounced in the dry seasons. The spatial and temporal variation of ET for some selected months is shown in Fig. 8.6.

On January 1st 2008, the actual ET over the plain ranges from 2 mm in a day in bare lands to 4.6 mm a day on wet surfaces, with mean value of 3.3 mm and standard

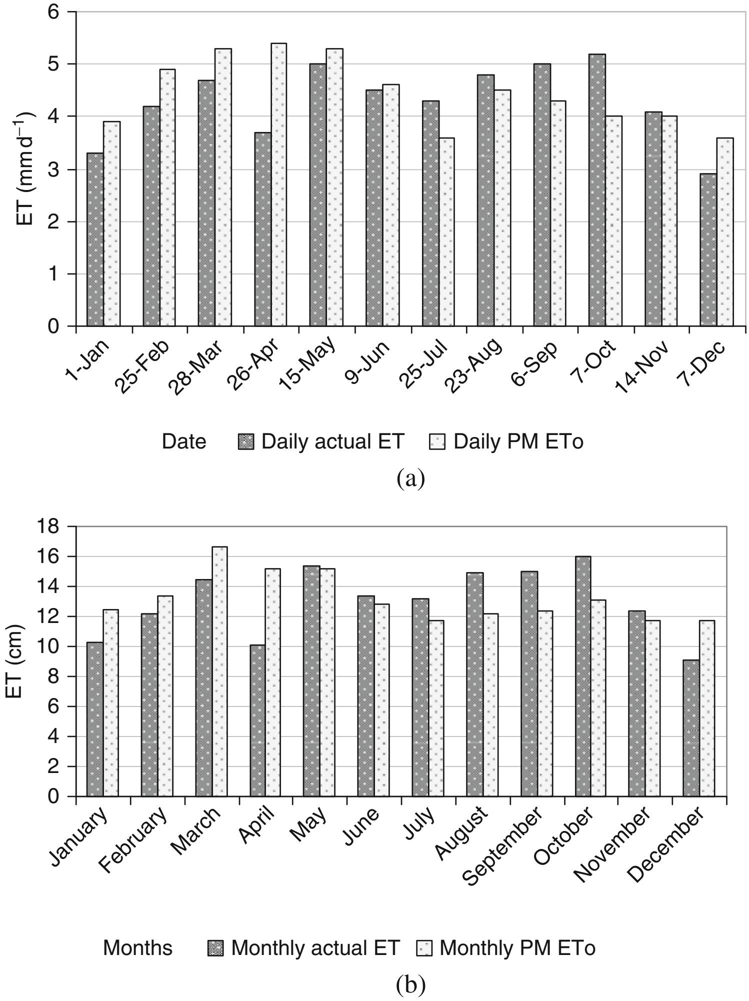


Fig. 8.5 (**a**) Daily actual ET and daily PM ET_0 (**b**) monthly actual ET and PM ET_0

deviation of 0.59 mm. The evaporative fraction for this day ranges from 0.4 to 0.95, with mean of 0.71 and standard deviation of 0.11.

In the same way, on 26 April 2008 the spatial distribution of ET follows similar pattern as of January 1st 2008, except here more pixels become drier. The minimum and maximum ET was 1.5 and 5 mm a day respectively, with mean value of 3.25 mm and standard deviation of 0.61 mm. The evaporative fraction ranges from 0.3 to 0.9 with mean of 0.55 and standard deviation of 0.11.

On 6 September 2008, daily ET ranges from 4 to 6 mm with mean value of 4.95 mm and standard deviation of 0.37 mm. The evaporative fraction ranges from 0.74 to 0.95 with mean value of 0.83 and standard deviation of 0.05. The lower

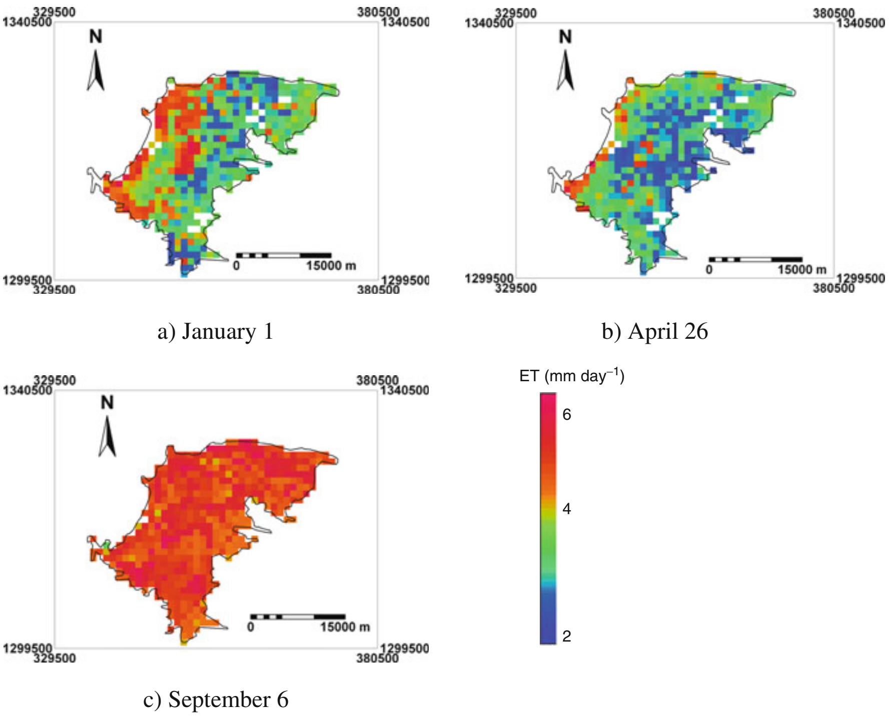


Fig. 8.6 Spatio-temporal distribution of ET over the floodplain (Projection: UTM, WGS 84)

standard deviation here clearly shows that the spatial variation in wet months is less pronounced.

The high ET_a values in September clearly show the abundant vegetation growth in the area at the end of the rainy season. The ET_a values are lowest in April when fields are being ploughed, and conditions are dry. The January values show that vegetation is still growing vigorously near the lake shore, i.e. the lowest part of the floodplain where spate irrigation can be maintained for the longest period of time.

8.5.2.3 Spatiotemporal Distributions of Actual ET over Rice Fields

The spatiotemporal distribution of ET over the rice field in the floodplain was analyzed using three selected images. On July 7, the actual ET over the rice field ranges from 2.7 to 4.7 mm/day, with mean and standard deviation of 3.6 mm and 0.27 mm respectively. Similarly, on September 6, ET varies from 3.5 to 5.9 mm in a day, with mean and standard deviation of 4.95–0.37 mm respectively, whereas on December 7 ET varies from 1.5 to 4.7 mm/day with mean 2.88 mm and standard deviation of 0.79 mm. The lower value of standard deviation in July and September indicate that spatial variation in rice field was less pronounced; whereas in December as majority of the rice has been harvested and the spatial variation was more pronounced.

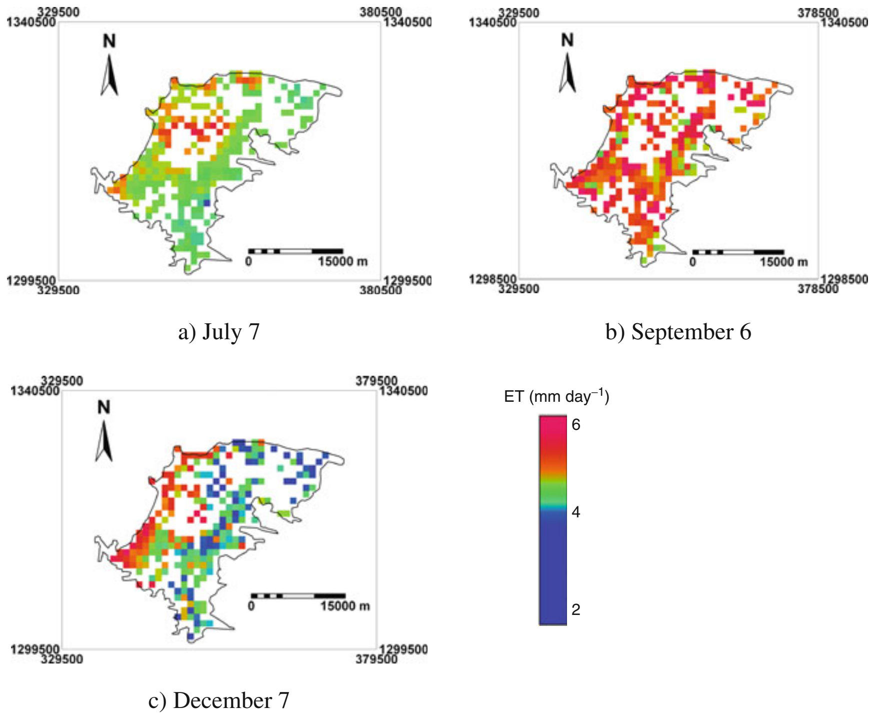
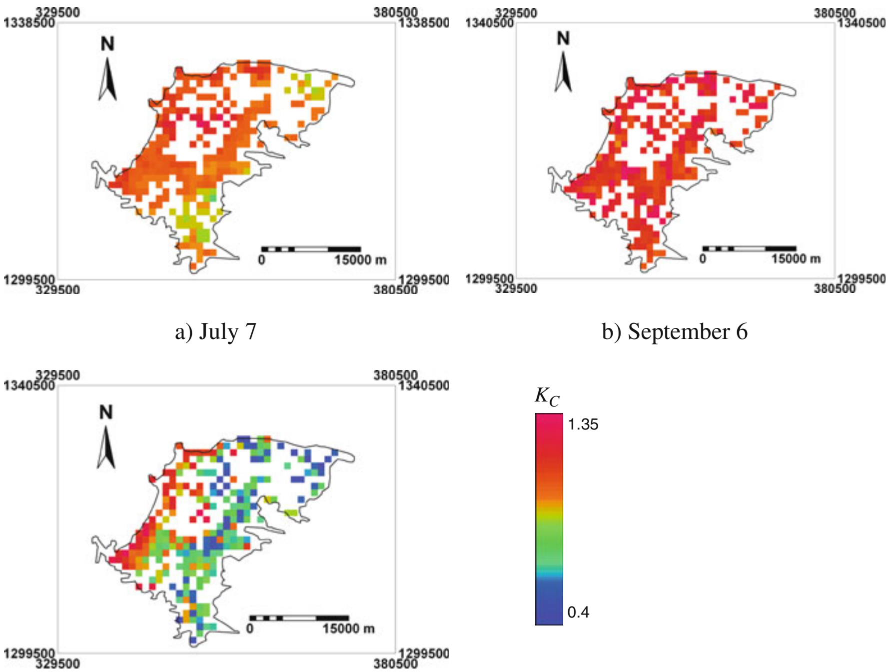


Fig. 8.7 Spatiotemporal distribution of ET on rice field (**a**) July7 (**b**) September 6 (**c**) December 7 (Projection UTM, WGS84)

In summary, the spatial variation of ET over the rice field during the seedling and the fully growing seasons was not pronounced; whereas the temporal variation of ET in the rice field was larger. During early and harvesting stage of rice, ET was relatively low compared to its fully growing season. The images of the three selected days are shown in the Fig. 8.7.

8.5.2.4 Single Crop Coefficient (Kc) for Rice Field

The spatial and temporal variation of Kc is shown in selected images of Fig. 8.8. In July, where the rice was in seedling stage, the Kc had an average value of 0.9 with standard deviation of 0.12. In September, when the rice was in its mid growing stage, the Kc value had increased to an average value of 1.16, with standard deviation of 0.13 and during harvesting period, Kc reduced to an average of 0.81 and standard deviation of 0.30. These values agree well with the literature values of 1.0, 1.15 and 0.7–0.45 for initial, mid and harvesting seasons of the cropping period respectively (Allen et al., 1998). It is assumed that, there is no water stress during this period and therefore Ks can be taken as 1. This seems to be realistic because rains are usually



c) December 7

Fig. 8.8 Spatiotemporal distribution of Kc on rice field (**a**) July 7 (**b**) September 6 (**c**) December 7 (projection UTM, WGS84)

abundant during the rainy season and surface water is also flowing in from upstream areas. The length of the rice growing season appears to be normal (120–150 days) (Allen et al., 1998).

8.6 Conclusions and Recommendations

The two objectives of this study were to compare different ET_0 methods to the (more complete) PM estimate, and to derive remotely sensed based actual ET relative to ET_0 over the Fogera floodplain. MODIS products were used in SEBS. The Woreta and the Bahir Dar weather station data were also used.

Ground based estimations of ET_0 for the year 2008 were carried out using different methods. The different empirical methods were compared to the standard PM reference ET_0. From the different conventional methods used, the MM method was the only method which does not require local calibration of the coefficient. This method performed the best among the models tested, with a coefficient of determination R^2 of 0.93, RMSE of 0.19 mm, and AME of 0.16 mm. The PT method overestimated ET_0 when the a priori coefficient, $\alpha = 1.3$ was used. Better estimates were found when the coefficient α was reduced to 1.14. The simple Abtew equation also performed well in the area. However it proved necessary to calibrate the coefficient which then gives R^2 of 0.9, an RMSE of 0.25 mm/day, and AME of 0.21 mm/day. The advantage of Abtew's method is that ET_0 can be estimated using radiation data only.

The spatial average of actual ET estimated from remote sensing over the floodplain was smaller than the PM reference ET_0 in relatively drier periods, whereas in wet season the actual ET was larger than the PM reference ET_0. The annual actual ET_a over the floodplain was found about 1,519 mm whereas the annual PM reference ET_0 was 1,498 mm. In wet seasons, the spatial variation of actual ET_a was not well pronounced, whereas in relatively dry months the spatial variation was clearly pronounced.

The crop coefficient (Kc) of the rice field was estimated in the three growing stages in 2008. The estimations of Kc in the seedling, fully grown, and harvesting periods were 0.9, 1.16, and 0.81 respectively, where these values agree well with the literature values. The length of the growing season lies between 120 and 150 days which appear to be in line with values reported by Allen et al. (1998). The crop stress coefficient K_s has been taken as 1 because rains are usually quite good during the rainy season.

The preliminary results obtained with the MM and A methods appear to be promising. However, further validation and calibration work is required before these simple methods can be routinely applied in the area.

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