Field Evapotranspiration Estimation in Central Luzon, Philippines, Using Different Sensors: Landsat 7 ETM+, Terra Modis and Aster

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ABSTRACT

Satellite derived estimates of actual evapotranspiration over large areas has become popular in water balance studies since 1990. It is practically impossible to get well-distributed cloud free images over the entire cropping season from one sensor in the tropical countries like the Philippine. This limitation can be overcome with the combination of high-spatial resolution of Landsat, and Terra/Aster images with the high temporal resolution of Terra/Modis images in the tropical climate. This study aimed to test the feasibility of using SEBAL with multi sensors data at different processing levels: ASTER L1A, Landsat 7 ETM+ L1G, and MODIS L1B for the different periods of dry season 2001.

The Surface Energy Balance Algorithm for Land (SEBAL) has been applied to ASTER (February 02, 2001), Landsat 7 ETM+ (April 16, 2001), and MODIS (May 18, 2001) sensors for the estimation of evapotranspiration in the District 1 of the Upper Pumapanga River Integrated Irrigation System (UPRIIS), in Central Luzon, of Philippine. All pre-processing and processing steps of all three sensors were discussed in details for SEBAL. Actual evapotranspiration was computed during satellite overpass and integrated for 24-hours on pixel-by-pixel basis.

This paper showed a unique combination and inter-relationship of ASTER and Landsat images with the Modis images for the water consumption studies in District 1. The results were compared with the evapotranspiration calculations at two meteorological stations in District 1 and data showed a non-significant variation. Comparison with other meteorological data found close relationship with daily evapotranspiration estimated by different sensors as predicted by SEBAL. From the finding presented, it can be concluded that results from all three remote sensing platforms can be used for the computation of actual evapotranspiration studies in the tropical climate but with necessary precautions.

Keywords: ASTER, Landsat 7ETM+, MODIS, field evapotranspiration, SEBAL, Central Luzon, UPRIIS, The Philippines

1. Introduction

Water is increasingly becoming a scarce natural resource. The population increase puts a great demand on water resources for domestic, industrial and agricultural use. In Asia, more than 80 % of fresh water resources are used for irrigation, and 50% of this is used to irrigate rice (Tabbal et al., 2002). Rice is major staple food in Asia where 92% of the world rice is produced and consumed (IRRI, 1997). To keep up with the population growth and income-induced demand for food, rice production needs to keep increasing in the next decades. Since about 75% of all rice produced is irrigated, rice production is threatened by the "looming water crisis" and ways must be sought to grow more rice using less water (Guerra et al., 1998). An understanding of the water balance of irrigation systems is crucial developing alternative management strategies that are more efficient. An important component of the water balance of any irrigation system is the evapotranspiration (ET). However, the quantification of ET at the spatial scale of irrigation systems is not a simply task. There are many methods to estimate ET (reference) using meteorological data: FAO-24 (Doorenbos et. al., 1977), FAO-56 (Allen, 1998). Most of these methods are based on point data, which do not provide good estimation of ET for larger areas. Scintillometer instrument can be used to overcome problem of ET computation for larger areas because it provides well-distributed actual ET over 1-5km (De Bruin et al., 1996). Hydrological modeling like SWAP is another method for computation of actual ET that can be distributed (Droogers, 2000).

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The problem of actual ET estimation over a large area can be solved using remote sensing methods that provide ET on pixel-by-pixel basis. Many researchers (Vidal and Perrier, 1989; Bastiaanssen 1995; Granger, 1997) have already developed various methodologies by combination of satellite images and meteorological data for large areas since the 90s. This study focuses on the estimation of actual ET using Surface Energy balance Algorithm for Land (SEBAL) by Bastiaanssen (1995). SEBAL is a thermodynamically based model, which partitions between sensible heat flux and latent heat of vaporization flux.

Bastiaanssen (1995) has developed originally SEBAL in Spain and Egypt using Landsat 5TM. Further, Roerink et al. (1997) also applied the same sensor for monitoring irrigation performance in Argentina. Water consumption of large irrigation systems has been addressed also with NOAA AVHRR in Pakistan (Bastiaanssen et al., 1999; validation in Bastiaanssen et al., 2001). Farah (2001) has studied modeling of evaporation under various weather conditions in the Navaisha Basin, Kenya. His results are extending SEBAL calculations of NOAA AVHRR under clouds with a Penman-Monteith approach supported by a Jarvis-Stewart type model. Combinations of Landsat and NOAA are found in Timmermans and Meijerink (1999) where Landsat 5TM was used, and in Chemin and Alexandridis (2001) who used Landsat 7ETM+. Later on, Hafeez and Chemin (2002) applied SEBAL using TERRA/ASTER sensor in the Upper Pumpanga River Integrated Irrigation System (UPRIIS), Philippines. The combination of high-spatial resolution of Landsat 7 ETM+/Aster with the high-temporal resolution of NOAA AVHRR/MODIS gives a higher accuracy for water balance type studies.

The cloud coverage is a prominent phenomenon in many parts of the world. The mean cloud cover per day may exceed 60% in the humid tropics (Bussieres and Goita, 1997). It is practically impossible to get well-distributed cloud free images over the entire cropping season from one sensor in the tropical countries like the Philippines. This limitation can be overcome with the combination of high-spatial resolution of Landsat, and Terra/Aster images with the high temporal resolution of Terra/Modis images in the tropical climate. In this study, only 1 cloud free image out of 92 for ASTER L1A, 3 cloud free images out of 12 for Landsat 7 ETM + and 7 cloud free images out of 110 MODIS L1B were available over the entire dry season 2001. This paper deals with the 3 images of different sensors of different processing levels for different time period of dry season 2001: ASTER L1A (February 02, 2001), Landsat 7 ETM + (April 16, 2001) and MODIS L1B (May 18, 2001).

The Philippines is an agricultural country with a total land area of 13 million hectares under crop cultivation. Irrigated rice is about 61 % of the 3.4 million hectares present in Philippines. The majority of the production is coming from the Central Luzon. Upper Pampanga River Integrated Irrigation system (UPRIIS), with a total area of 102,591 hectares is an important rice producing areas in the Nueva Ecija province, Central Luzon, the Philippines. The study area, "District 1" is found in the UPRIIS, taking its water from the Panatabangan Dam. District 1 is about 25,000 ha and is divided into northern (San Jose city) and southern part (main cities like Santo Domingo, Quezon and Licab). Talavera and Ilog Bliwag rivers bound both sides of the District 1 of UPRIIS. Most common land use in District 1 is double cropping of rice, with the transplanting method, while direct wet seeding is becoming increasingly popular. The climate in UPRIIS is characterized by two pronounced seasons, dry from November to April with an average rainfall of 193 mm and wet from May to October with an average rainfall of 1654 mm. This study concentrates on the dry season, from late November to mid May, having average yields of 3 to 4.1 $t.ha^{-1}$.

2. Objectives

The main objective of this paper is to study the feasibility of using SEBAL with different sensors of different processing levels: L1A Terra Aster, L1B Terra Modis and L1G Landsat 7 ETM+ data, in order to compute spatially distributed actual evapotranspiration by remote sensing.

It is proposed to validate the results of actual ET with meteorological data collected in the Upper Pampanga River Integrated Irrigation System of Philippines.

3. Methods

Description of the sensors

ASTER stands for Advanced Space borne Thermal Emission and Reflection Radiometer, which started monitoring global environment changes in March 2000 and it provides image free of charge. Sensor on-board Terra is having 14 spectral bands ranging from 15 to 90 m spatial resolution. A fifteenth band is a backward view of the NIR (15 x 15 m in the 0.76 to 0.86 μm) for stereoscopic imaging. L1A image was acquired by ftppull from the EROS Data Center Redhook Internet website. Extraction of the binary file was performed for band 2 and 3N as visible bands and bands 13 and 14 for thermal bands. The data were not calibrated, nor georeferenced, but information were made available in the metadata of the HDF file itself. Rotation, pixel coordinate and size were provided to the image after HDF file information was gathered for georeferencing. The georeferencing of the Aster Image was done in UTM/WGS84/Zone 51.

LANDSAT 7 ETM+ was launched on April 15, 1999 to provide high-resolution image information of the Earth surface, where ETM+ stands for the Enhanced Thematic Mapper Plus instrument. Landsat ETM+ instrument is having 8 multi spectral bands from 15 m (Panchromatic), 30 m (Visible and Short-wave infrared) and 60 m (Thermal). Level 1G products are radiometrically and geometrically corrected to the user-specified parameters including output map projection, image orientation, pixel grid-cell size, and resampling kernel. The gain and offset values for Landsat 7 ETM+ satellite images are extracted from the header file available with original CD-Rom provided by USGS. The georeferencing of Landsat 7 ETM+ was done using the coordinates provided in header file in UTM/WGS84/Zone 51.

MODIS (Moderate Resolution Imaging Spectroradiometer) is the key instrument aboard the Terra (EOS AM-1) satellite, which also started functioning in March 2000. Terra MODIS is viewing the entire Earth's surface every to 2 days, acquiring data in 36 spectral bands, or groups of wavelengths. Modis sensor on TERRA platform has a spectral resolution featuring 36 bands ranging from 250 to 1000 meters spatial resolution. Acquisition of L1B image was done through the Redhook Eros Data Center Internet web site using ftppull protocol. Extraction of the binary file was performed for band 1 & 2 as visible bands and bands 31& 32 for thermal bands. A subset image for Philippine was created from the whole image for better visualization and georeferencing. The L1B data was already calibrated for radiometric variations, while georeferencing parameterization was not feasible through the current software used. Therefore, georeferencing was done manually by selecting many well-distributed Ground control points on the entire image, especially on the coastal features of the Central Luzon Island. The georeferencing was done in UTM/WGS/84/Zone 51 because all the other available images for this study were provided in the same georeference.

Table 1: Overview of the different sensors

Sensor	Sub-Systems	Number of bands	Spectral range (μm)	Spatial resolution (m)
Terra Aster	VNIR	3 (+ 1 backward)	0.52 up to 0.86	15x15
	SWIR	6	1.60 up to 2.43	30x30
	TIR	5	8.125 up to 11.65	90x90
Landsat 7 ETM+	VNIR	4	0.45 up to 0.90	30x30
	SWIR	2	1.55 up to 2.35	30x30
	TIR	1	10.4 to 12.5	60x60
	PAN	1	0.50 to 0.90	15x15
Terra Modis	VNIR	2	0.62 up to 0.876	250x250
	SWIR	5	0.459 up to 2.155	500x500
	SWIR	11	0.405 up to 0.965	1000x1000
	TIR	16	3.66 up to 14.385	1000x1000

Specificity of porting SEBAL to different sensors

The pre-processing parameters required for SEBAL include Normalized Difference Vegetation Index (NDVI), emissivity, broadband surface albedo, and surface temperature for all above-mentioned sensors. NDVI was calculated from band 1 & 2 for Aster, and band 3 & 4 for Landsat. In case of Modis, 16 days composite image of NDVI (level 3) was available in Modis data products and level 3 NDVI was transformed using software Modis Reprojection Tools (MRT) into geotiff files in UTM/WGS 84/zone 51 projection system. Surface emissivity of every sensor was calculated from NDVI of the respective sensors and the broadband surface albedo of every sensor was computed using respective weighing factors of that sensors. Surface temperature of ASTER and Modis sensors was calculated from band 13 & 14 and band 31 & 32 using split-window technique found in Chandrapala and Wimalasuria (2001). While, surface temperature from Band 6L of Landsat 7 was computed using inverse plank function.

Calculation of the Net incoming radiation and the soil heat flux were done after Bastiaanssen (1995), while the determination of the sensible heat flux incorporated the later development of Tasumi et al. (2000) for each sensor. However, to calculate the first temperature difference between air and soil for the “hot” pixel (i.e. where the latent heat flux is assumed null), a first estimation of the air density was done generalizing meteorological data of relative humidity and maximum air temperature from two meteorological stations at the time of satellite overpass in District 1 for every sensor. Iterations of sensible heat flux were conducted 5 times, and it has been observed by the operator that this method is not stabilizing the air-soil temperature difference as fast as the earlier method found in Bastiaanssen (1995). In SEBAL, manual sampling of hot pixel values of the previous iterations output image files are required before the next iteration can be done which is a practical constraint in operationalization. This constraint can be resolved by automation (after hot pixel identify) in the data collection of the results. Although, the iteration of 5 times improve sensible heat flux but it is also time & space consuming.

The Evapotranspiration is calculated in SEBAL (Tasumi et al., 2000; Hafeez and Chemin, 2002) from the instantaneous evaporative fraction, Λ, and the daily averaged net radiation, R_{n24}. The later has to be transformed from W/m^2 to mm/day by the T_0 dependent latent heat of vaporization equation inserted in the main equation (Eq. 1).

$$ET_{24} = \Lambda \times \left[R_{n24} \times \left((2.501 - 0.002361 \times T_0) \times 10^6 \right) \right] \qquad \textit{(mm/day)} \qquad (1)$$

where ET_{24} is the Daily ET actual (mm/day), R_{n24} is the average daily net radiation (W/m^2) and T_0 the surface temperature (°C). The evaporative fraction, Λ, is computed from the instantaneous surface energy balance at the moment of satellite overpass for each pixel (Eq. 2):

$$\Lambda = \frac{\lambda E}{R_n - G_0} = \frac{\lambda E}{\lambda E + H_0} \qquad \textit{(-)} \qquad (2)$$

where λE is the latent heat flux (the energy allocated for water evaporation), R_n is the net radiation absorbed or emitted from the earth's surface (radiative heat), G_0 is the soil heat flux (conduction) and H_0 is the sensible heat flux (convection). λ can be interpreted in irrigated areas as the ratio of actual to crop evaporative potential, it is dependent on the atmospheric and soil moisture conditions equilibrium.

4. Results

The main output of SEBAL is the partitioning of energy balance, and can be visualized as the actual over the potential ET mentioned as the evaporative fraction. A straight derived product is the actual daily ET, shown in figure 1 for Aster, Landsat and Modis images. Range of ET values for Aster Image of February 02, 2001 is (figure 1, left) from 0.35 to 5.35 mm/day, while range of ET for Landsat 7 on April 16 (figure 1, middle) and Modis on May 18, 2001 (figure 1, right) varies from 0.10 to 8.20 mm/day and 0.25 to 9.85 mm/day respectively.

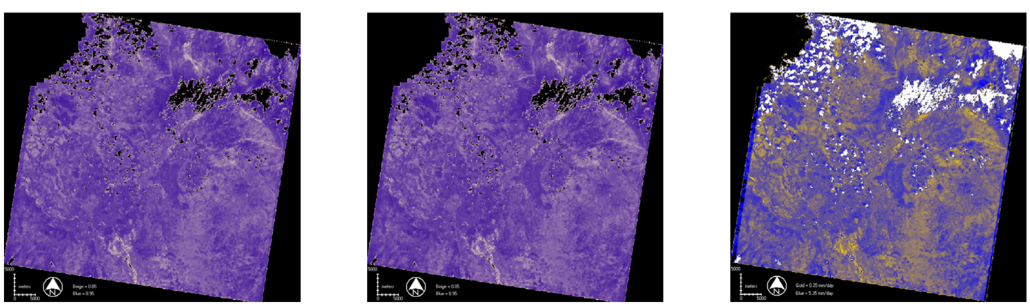

Figure 1: Daily Actual Evapotranspiration for subsets of Aster, Landsat 7 and Modis (mm/day) respectively.

The comparison of the histograms of ET actual for every sensor over an irrigation system of District 1 is shown in figure 2. The histogram of actual ET for Aster image shows a mode around 3.2 mm/day, with main peak feature on covered area is 4.11 mm/day @ 11.25 Ha. Aster histogram shows the water consumption pattern in mono-model because the land cover in the early part of dry season (February 02, 2001) in District 1, were found in 3 major types i.e., flooded rice fields (nurseries), different types of vegetable fields (less water) and few fishponds. For Landsat histogram (April 16, 2001), water consumption pattern shows bi-modal because the land cover was again found in 3 different types i.e., rice fields without irrigation (near to harvest), rice fields with standing water, and few fishponds in District 1. In case of Landsat 7

ETM, histogram of actual ET versus area covered shows peak features in 3.81 mm/day @ 14.75 Ha, and 6.17 mm/day @ 14.4 Ha respectively.

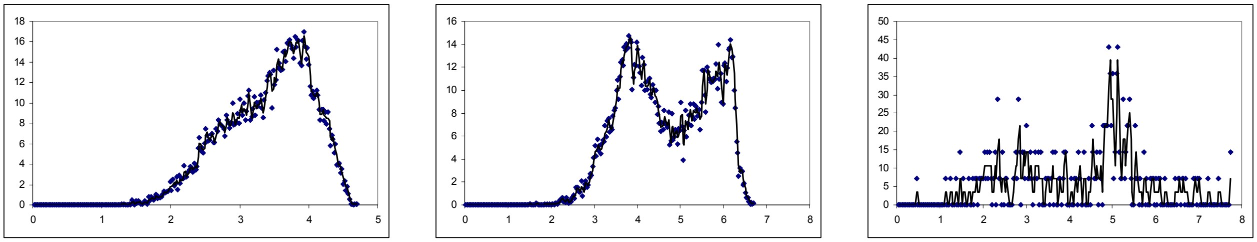

Figure 2: Sensors histograms of Daily ET actual (mm/day) per area covered (hectares) of Aster (left), Landsat (middle) and Modis (right).

The histogram of actual ET versus area covered for Modis image (May 18, 2001) is multi modal (with reminiscence of the bimodal histogram of Landsat) which shows peak features in 2.28 mm/day @ 14.40 Ha, 3.05 mm/day @ 21.50Ha, 5.13 mm/day @ 43 Ha, 5.53 mm/day @ 21.50 Ha and 6.65 mm/day @ 7.18 Ha. Modis histogram shows water consumption pattern in multi-model because land cover were found in many types i.e., 10% under rice fields (near to harvest within 3-4 days), flooded fields without any crop (rainy season starts in May), vegetable fields (some farmers just planted water melons) and few fish ponds. The shortage of water in the lower part of District 1 for dry season forced farmers to grow other crops besides rice and it also affects the cropping calendar. The major reason of different types of land use in the lower part of District 1 is shortage of water. Despite the fact that actual ET is computed from different sensors, it shows a good continuity of reliable information. This, considering the spatial resolutions range from 15-90 m of Aster, 30-60 m of Landsat 7 ETM+, and 250-1000 m of Modis for different stages of cropping season in an irrigation system of District 1.

An average from samples of rice pixels for every sensor was taken over an irrigation systems belonging to the southern part of the District 1. An average value of daily actual ET of these fields, ET_o, and ET_c and ET pan of 2 meteorological stations located within 10 km distance are shown in Table 3.

Table 3: Comparison of ET pan, ET_o, ET_c and Daily ET actual, (mm/day)

Location of Meteorological Stations		PAGASA, Munoz (15° 43' N, 120° 54' E)	PhilRice, Maligaya (15° 39'N, 120° 53' E)
2-Feb-01	ET pan (Met. Stations)	5.3	4.7
	ETo (Penman Monteith)	4.25	3.57
	ETc (Kc=1.05)	4.46	3.75
	ASTER	4.2	
16-Apr-01	ET pan (Met. Stations)	6.8	6.8
	ETo (Penman Monteith)	5.83	5.84
	ETc (Kc=0.9)	5.24	5.26
	Landsat 7 ETM+	5.11	
18-May-01	ET pan (Met. Stations)	7	6.9
	ETo (Penman Monteith)	6.83	6.8
	ETc (Kc=0.8)	5.46	5.44
	Modis	6.19	

Hafeez and Chemin (2002) validated the results of daily actual ET by SEBAL with ETpan, ET_o, and ET_c and found the results of daily actual ET by SEBAL with in a good accuracy for Aster sensor. The ETpan results of both meteorological stations are almost equal on the acquisition days of Landsat and Modis image, while there is 11% difference of ETpan reading of 1 meteorological station to the 2nd in case of ASTER sensor. The possible reasons of this variation in ET pan readings can be attributed to the lack of accurate measurement and the poor maintenance of pan, which was observed by the author during the visits of these meteorological stations. The actual ET values found are 20.7 % & 10.5 % (Aster), 25 % &

25 % (Landsat) and 11.5 % & 10% (Modis) respectively less than the meteorological data of water evaporation. These results match very well the expectations on the difference of ET values between open water bodies and rice crops.
In case of the Penman-Monteith (Allen et al, 1998) method, the results of the estimated reference ET (ETo) from the meteorological stations data gave a difference from the remote sensing data of +1% & -15% (Aster), +12 % & +12.5 % (Landsat), and +9.2 % & +8.9 % (Modis) respectively. Adjustment for the crop coefficient (K_c) of rice in its different growth stages with a corresponding K_c factor of 1.05 (mid), 0.9 (end) and 0.80 (end) for general rice crops from the same author gives also significant results. The crop stages data were monitored continuously of 50 rice fields in District 1 for the entire dry season 2001. The differences of ET_c observed from remote sensing are +6% & -11% (Aster), +2.5 % & +3 % (Landsat), and -13 % & -13.8 % (Modis) respectively. It can be concluded that the results are confirmed by the ET_o and ET_c calculations from ground data within an acceptable range for all sensors.

5. Conclusion

It was proven possible to use simultaneously SEBAL for different sensors with the combination of high spatial and temporal resolution in tropical countries like the Philippines, where the cloud coverage is a big constraint in getting satellite images from one sensor. The interchangeability between Landsat 7 and Aster images was explored, as well as the early study of the Convergence of Modis data to the high-resolution accuracy in terms of water consumption.

Field level spatially distributed actual evapotranspiration can be achieved using Aster, Landsat ETM+ and Modis sensors with a deviation of 9 %, 3% and 13.5 % from ET_c (Penman-Monteith). The possible reason of a large deviation of actual ET estimation using Modis sensor is pixel size for such a small area (District 1 = 25,000 ha) because the thermal bands of Modis provides surface temperature information over 1 Km pixel size.

Comparison shows that high spatial resolution sensors (Aster vs. Landsat) can be used for evapotranspiration studies even at smaller scale irrigation system like District 1 in the tropical climate of the Philippines. The use of Modis in combination of higher resolution satellites is found encouraging, supporting the earlier work of Chemin and Alexandridis (2001). More extensive work on Modis operationalization at field/farm and tertiary/secondary canal command areas is required. It is of paramount importance for future end-user applications, since Modis is freely available through Internet download and its processing levels are well standardized.

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