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Satellite-based measurements for verification of cultivated area and water use efficiency in Gash Delta, Sudan

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ABSTRACT

Three Landsat-5 TM images were analyzed to estimate actual ET of 47 Misgas for irrigated sorghum in Gash Delta, Sudan. Moreover water use efficiency (WUE) was estimated. Surface Energy Balance Algorithm for Land (SEBAL) developed by Bastiaanssen . (1998a, 1998b) was used to estimate land surface variables and actual ET. The results show that highest crop water productivity (CWP) was obtained by Kassala block which was 0.48 Kg m^{-3} followed by Metateib block 0.35 Kg m^{-3} with a bit low evapotranspiration (ET). In contrast, Mekali block obtained the minimum CWP 0.20 Kg m^{-3} and consuming much water (ET ≈ 606 mm) compared with other five blocks. The results show the WUE obtained by SEBAL was 46% compared with 45% in previous study, the difference between both was very small which is about 1%. The cultivated Misga was identified by using binary images of NDVI and actual ET. The boundaries of Misga were compared with that drawn manually in actual ET image and both boundaries were approximately same except for horticulture area. This result shows that the binary images of NDVI and actual ET can be used as a simple method for identifying cultivated area

Keywords: *land surface variables, evapotranspiration, remote sensing, SEBAL, Gash Delta.*

INTRODUCTION

Nowadays, remote sensing techniques are applied intensively in agricultural field and considered as one of the most important approches to provide useful information for land surface management.

Bastiaanssen . (1998a, 1998b) developed a Surface Energy Balance Algorithm for Land (SEBAL). The SEBAL is an energy balance model based on a satellite image-processing, which is comprised of twenty-five computational sub-models that calculate various land surface parameters, such as surface albedo, normalized difference vegetation index (NDVI), surface temperature, and energy balance parameters. Recently, many successful applications of this model have been demonstrated by Bastiaanssen . (1998a, 1998b), Allen . (2001), Chemin . (2004), Kimura . (2007).

The authors applied SEBAL to Gezira scheme, Sudan and estimated the actual ET in irrigated sorghum (Bashir ., 2008), and we also estimated the actual ET of Gash Delta project, Kassala State, eastern Sudan (Eltaib, 2012).

In this study, SEBAL were applied to analyze three Landsat-5 TM satellite images of Gash Delta to estimate land surface variables, actual ET and water use efficiency (WUE). Moreover, the cultivated Misga area was identified by using binary images of NDVI and actual ET.

Study Area and Data

Gash Delta is located between latitudes 15º 15′ – 16º 15′ N and longitudes 36º 05′ – 36º 30′ E, Kassala State, eastern Sudan (Figure 1). Climate is dry and average annual precipitation is 260 mm, it is hot throughout the year with maximum temperature of 42 ℃ in May and minimum temperature of 16 ℃ in January.

Generally it is estimated that the total area of the Gash Delta is about 315, 000 ha from which 168, 000 ha are suitable for agriculture. The cultivated area of 105,000 ha is irrigated. Around 33,600 ha annually planned for irrigation by using rotation. The irrigation system of Gash Delta consists of major intakes and canals. Main canals convey water from Gash River to Misgas (local irrigation unit of 840 – 1050 ha). The width of Misga is from 700 to 1000 m. The length of Misga for flow direction is about 10 km, which is equal to the interval of main canals.

Figure 1. Location of study area

(Source of satellite image: http://www.maplibrary.org/)

In this study, Landsat-5 TM images of November 9th, December 11th, 2009 and January 12th, 2010 were used to calculate land surface variables and daily actual ET for Gash Delta. ERDAS Imagine was used to process the images.

Daily meteorological data (temperature, relative humidity, wind speed and hours of sunshine) of Kassala Metrological Station were used to estimate the reference ET by Penman-Monteith method. Kassala Metrological Station is located in latitude 15º 28′ N and longitude 36º 24′ E and its altitude is 500 m.

Surface Energy Balance Algorithm for Land (SEBAL)

SEBAL developed by (Bastiaanssen, 1998a, 1998b) is an intermediate approach to estimate ET for a horizontal surface using both empirical relationships and physical parameterizations based on the energy balance in the vertical direction, assuming that advection and light energy required for photosynthesis are negligible. This model has been designed to compute energy partitioning at the regional scale from satellite data in conjunction with minimum ground data.

The latent heat flux is computed as the residual of energy balance as follows.

$$\lambda E = R_n - G_0 - H \qquad (1)$$

where λE is latent heat flux (Wm^{-2}), R_n is net radiation flux at the surface (Wm^{-2}), G_0 is soil heat flux (Wm^{-2}) and H is sensible heat flux into the air (Wm^{-2}).

The net radiation (R_n) at the earth's surface is a result of the combination of incoming and outgoing solar radiation. In the SEBAL, The incoming shortwave radiation is computed by solar constant, solar incidence angle, relative earth-sun distance and atmospheric transmissivity. The incoming long wave radiations are computed by the Stefan-Boltzmann equation and surface temperature T_s (K). The outgoing long wave radiation is also computed by the same equation and near surface air temperature of cold pixel (wet surface). The surface temperature is estimated by the modified Plank equation. The surface albedo is calculated by the albedo at the top of atmosphere, the average portion of the incoming solar radiation across all bands and the atmospheric transmissivity.

The soil heat flux is the rate of heat storage into the soil and vegetation due to conduction and it is calculated as an empirical equation of net radiation, normalized difference vegetation index (NDVI), surface temperature and surface albedo (Bastiaanssen, 2000). NDVI is the ratio of the differences in reflectivities for the near-infrared band (ρ_4) and the red band (ρ_3) to their sum. Sensible heat flux is the rate of heat loss to the air by convection and conduction due to a temperature difference. It is computed by the equation for heat transport using air density, air specific heat at constant pressure, temperature difference between two heights and aerodynamic resistance to heat transport.

The evaporative fraction (Λ) describes the partitioning of surface energy balance as the ratio of latent heat to net available energy defined by the difference in net radiation and soil heat flux. The fraction is as follows.

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

where Λ is instantaneous evaporative fraction (dimensionless).
The daily actual ET can be estimated by the daily net radiation and the evaporative fraction as follows.

$$ET_{24h} = \frac{86400 \times \Lambda \times R_{n24h}}{\lambda} \qquad (3)$$

where, ET_{24h} is actual evapotranspiration in mm d^{-1}, R_{n24h} is daily net radiation (Wm^{-2}) and λ is the latent heat of evaporation. The 24-hour evaporative fraction is assumed to be similar to the instantaneous Λ .

Distribution of Surface Parameters and Actual ET

The distribution maps of NDVI, albedo, surface temperature, net radiation, actual ET on December 11th, 2009 are shown in Figures 2(a)-(e), respectively. In these figures, red color shows high value and green color shows low value. These surface parameters and actual ET shows large range. The areas which have low surface albedo and low surface temperature have high NDVI, high net radiation and high actual ET, whereas the other areas which have low NDVI tend to have high surface albedo and high surface temperature.

The leaf density of crop plants (sorghum) becomes the highest in December and a shifting cultivation system is practiced in Gash Delta. Therefore, the high NDVI area with high actual ET is considered to be the cultivated and irrigated area and the low NDVI area with very low actual ET near zero is thought to be the non-cultivated fallow land and non-irrigated area. Figure 2(f) shows the distribution of actual ET and 47 cultivated Misgas with red boundary and it is discussed later.

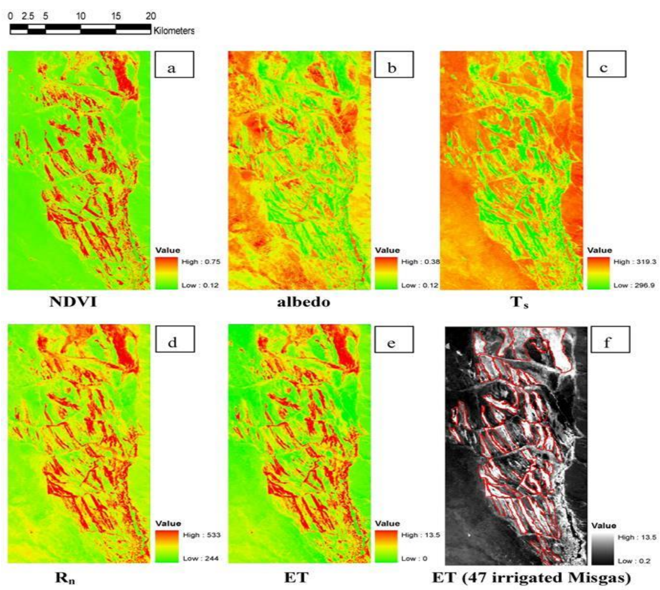

Figure 2. Distribution map of (a) NDVI, (b) albedo, (c) surface temperature, (d) net radiation, (e) ET and (f) ET of 47 irrigated Misga in Gash Delta (December 11th, 2009)

Crop water productivity (CWP)

Table 1 shows the seasonal ET, crop yield and crop water productivity (CWP) for six blocks. Each block divided into a number of Misga which occupies about 840 ha in Gash Delta season 2009/2010. The highest CWP was obtained by Kassala block which was 0.48 Kg m^{-3} followed by Metateib block (0.35 Kg m^{-3}) with a bit low evapotranspiration (ET). In contrast, Mekali block obtained the minimum CWP (0.20 Kg m^{-3}) and consuming much water (ET ≈ 600 mm) compared with other five blocks. It worth to know that, irrigation system in Gash Delta is uncontrolled and the irrigation water flows along the natural gradient of the land, in which, water infiltration takes place in the area covered with water. Therefore, the water distribution in the Misga depends entirely on the topography and operations of land leveling.

Based upon the aforementioned facts, the variation in CWP among the blocks of Gash Delta can be attributed to non-uniformity of water distribution which mostly caused by scheme topography and absence of proper land preparation and leveling. Therefore, areas having high elevation receive a little water and areas having low elevation (e.g., Mekali block) have had received much water. Therefore, the inequity of water distribution has severe impact on crop yield and consequently affected crop water productivity.

According to the specific nature of Gash irrigation system, other factors could also play crucial role in water equity and uniformity such as days of flooding allowed for each Misga, adjacent of Misga to water source, nature/texture of soil, surface characteristics and its covering. Table (6.1) also shows that CWP among different blocks ranges between 0.20 and 0.48 kg m^{-3}, these variations illustrate that a huge scope of improvement still could be achieved through intervention of better irrigation and cultural practices.

Table 1. Seasonal ET, crop yield and crop water productivity for 6 blocks in Gash Delta season 2009/2010

Block	ET_s (mm)	Crop Yield (Kg ha^{-1})	Crop water productivity (Kg m^{-3})
Kassala	500.79	2381	0.48
Mekali	606.65	1190	0.20
Degain	582.63	1548	0.27
Tendelai	533.98	1190	0.22
Metateib	550.65	1905	0.35
Hadaliya	550.09	N/A	N/A

Water use efficiency (WUE)

Figure 3 shows the water use efficiency (WUE) calculated by SEBAL compared to WUE found in previous study. The results show the WUE obtained by SEBAL was 46% while in previous study was 45%, the difference between both was very small which is about 1%. These results clearly explained that the water consumption by the plant was less than 50% and more than 50% loss through infiltration and evapotration. The information gained could be used to improve water management, which may lead to increase irrigated area each season in Gash Delta.

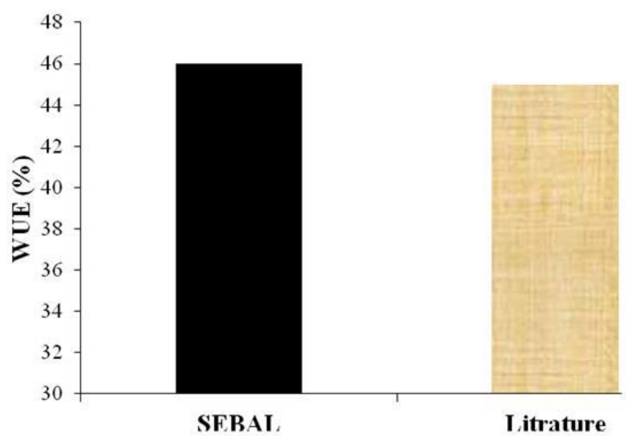

Figure 3. Water use efficiency in Gash Delta

Identification of Cultivated Misga Area

In the previous study (Eltaib, 2012), identified cultivated Misga area in Gash Delta using NDVI and actual ET distribution and the boundary of 47 cultivated Misga was drawn manually. The identified Misgas are shown by red curves in the actual ET map (Figure 2(f)).

In this study, the identification of Misga was attempted by using binary images of NDVI and actual ET. Figures 4 (a) and (b) are binary images of NDVI and actual ET on December 11th, 2009 and existing Misga boundaries drawn manually are overlaid. In these figures, white color shows NDVI larger than 0.36 and actual ET larger than 5.0 mm and black color shows NDVI lower than 0.36 and actual ET lower than 5.0 mm. The threshold values were selected considering size and shape of white area.

Figures 4(a) and (b) shows that white area in binary image is similar with Misga boundary drawn manually. In crop growing season, some Misga are cultivated while others are not by using shifting system. It can be clearly observed that the high value of NDVI and actual ET in the cultivated land appears as white area, while the low value of NDVI and actual ET in the fallow land appears as black area. The method used in this paper is more clear and easy to determine the cultivated area and non-cultivated area in Gash Delta.

Figure 4 shows that small black area appears inside irrigated Misga and this might be due to non-uniform water distribution, vegetation density and water deficit. The white area appears in lower right of binary images and it is outside of Misga boundary. The white area is recognized a horticultural area and excluded from Misga area. It is difficult to distinguish between cultivated Misgas and horticultural area by using binary image. This is a defect of the method using binary image. But, looking overall, this result shows that the binary images of NDVI and actual ET can be used as a simple method for identifying cultivated area.

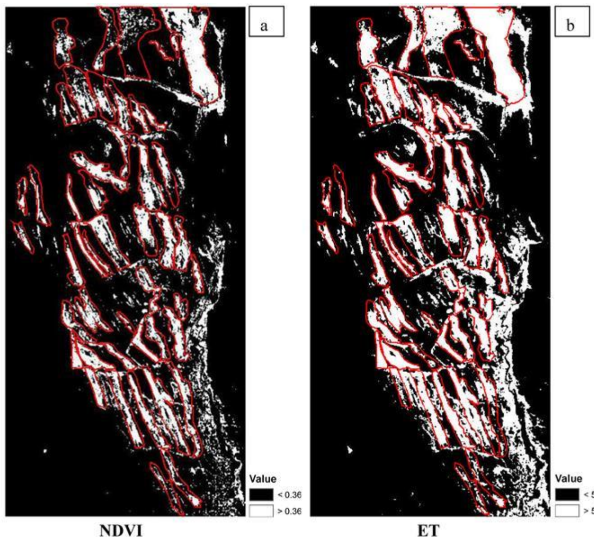

Figure 4. Binary images of (a) NDVI and (b) ET for Gash Delta (December 11th, 2009)

CONCLUSION

In this study, the SEBAL was applied to analyze three Landsat-5 TM satellite images of Gash Delta, estern Sudan and land surface components were estimated. Moreover, the cultivated Misga area was identified by using binary images of NDVI and actual ET. The results obtained can be summarized following.

(1) The highest CWP was obtained by Kassala block compared to other six blocks.
(2) The difference between WUE estimated by SEBAL and WUE in previous study was very small which is about 1%.
(3) The cultivated Misga area identified by binary images of NDVI and actual ET is similar with the Misga boundary drawn manually (Eltaib ., 2012) and this result shows that the binary images of NDVI and actual ET can be used as a simple method for identifying cultivated area.

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