



Study on soil moisture distribution of the Gash Delta Spate Irrigation System, Sudan

GHEBREAMLAK, Araya Zeray

田中丸, 治哉

ELAMIN, Khalid Ali Eltaib

多田, 明夫

AHMED ADAM, Bashir Mohammed

(Citation)

土木学会論文集B1(水工学), 74(4):I_817-I_822

(Issue Date)

2018

(Resource Type)

journal article

(Version)

Version of Record

(Rights)

© 2018 公益社団法人 土木学会

(URL)

<https://hdl.handle.net/20.500.14094/90005936>



STUDY ON SOIL MOISTURE DISTRIBUTION OF THE GASH DELTA SPATE IRRIGATION SYSTEM, SUDAN

Araya Zeray GHEBREAMLAK¹, Haruya TANAKAMARU², Khalid Ali Eltaib ELAMIN³,
Akio TADA⁴ and Bashir Mohammed AHMED ADAM⁵

¹ Student Member of JSCE, Doctoral Student, Graduate School of Agricultural Science, Kobe University
(Rokkodai 1-1, Nada, Kobe 657-8501, Japan)
E-mail: araiag4@gmail.com

² Member of JSCE, Professor, Graduate School of Agricultural Science, Kobe University
(Rokkodai 1-1, Nada, Kobe 657-8501, Japan)
E-mail: tanakam@kobe-u.ac.jp

³ Assistant Professor, Agricultural Research Corporation
(Wad Medani, P.O.Box 126, Sudan)
E-mail: khalidaltaib@yahoo.com

⁴ Associate Professor, Graduate School of Agricultural Science, Kobe University
(Rokkodai 1-1, Nada, Kobe 657-8501, Japan)
E-mail: atada@kobe-u.ac.jp

⁵ Associate Professor, Agricultural Research Corporation
(Wad Medani, P.O.Box 126, Sudan)
E-mail: bashir70us@yahoo.com

The Gash Delta spate irrigation system (GDSIS) with a net command area of about 100,000 ha is the largest spate irrigation system in Sudan. Annually one third of the net command area is prepared before the flood season and irrigated during the flood period from July to September. The portion of the irrigated area, which is considered as well irrigated, is allocated to farmers for cultivation of crop and it depends on the moisture stored in the soil from the single irrigation. Classification of the irrigated area as well irrigated and poorly irrigated has been done based on experience. Hence, a scientific approach that can help in estimating the soil moisture is essential. This study deals with the estimation of soil moisture distribution based on remote sensing. A simple single-band and multiband indices at the end of flood period are used to show flooded area and the relationship between the flooded area and soil moisture distribution at the early cultivation period estimated by satellite-based Surface Energy Balance Algorithm for Land (SEBAL) is discussed. The result shows the flooded area can be used as a good index to specify well irrigated area.

Key Words: soil moisture, remote sensing, SEBAL, spate irrigation, Gash Delta

1. INTRODUCTION

In spate irrigation system, which is very common and important in arid and semi-arid environments, flood water from seasonal rivers is diverted to a large deep-soiled field and allowed to spread with minimum control. In conventional irrigation system, water application is done at controlled intervals during the growing period of the crop, whereas in spate irrigation system, water application depends on the occurrence of flash floods. Usually, application of water is done during the flood season and cultivation of crops is done exclusively depending on the resulting soil moisture. The Gash Delta Spate

Irrigation System (GDSIS), which supports about 45,000 farmers¹⁾, is the biggest spate irrigation system in Sudan. Despite its importance, the paucity and unreliability of data such as cultivated areas, evapotranspiration, soil moisture, crop production and others are the main barriers for conducting scientific studies of the irrigation system.

However, a few studies have shown the potential and possibility of using remote sensing to augment the data for irrigation system management and planning. Khalid *et al.*²⁾ have applied SEBAL to estimate actual evapotranspiration, cultivated area and water use efficiency of the GDSIS. SEBAL, which is an acronym for “Surface Energy Balance

Algorithm for Land” developed by Bastiaanssen *et al.*³⁾, is a parametrization of energy balance and surface fluxes based on satellite measurement with main target of estimating actual evapotranspiration.

On the other hand, soil moisture plays an important role in terrestrial water cycle and is used as a key variable in several applications such as drought severity and duration, irrigation scheduling, soil erosion, evapotranspiration, forest fire hazard and forest management. The direct measurement is the most accurate method for estimating soil moisture, however it is expensive, time consuming and only provides point measurements. Technological advances in satellite remote sensing have offered an alternative to field measurements of soil moisture and enabled us to monitor it at higher temporal and spatial resolutions at lower cost and time⁴⁾. Many researchers have developed different methods that vary from purely empirical to more physical based approaches for estimating soil moisture as a function of satellite-derived land surface parameters.

Therefore, this study is an extension of the study by Khalid *et al.*²⁾ and intends to show an additional possible use of remote sensing data in GDSIS with particular interest in soil moisture distribution. A simple single-band and multi-band indices that discriminate wet surface are used to show flooded area and the area is compared with the soil moisture distribution by SEBAL-based approach.

In GDSIS spate water is distributed to an annually prepared area for an effective average period of 60 to 70 days (July–September) to supply the total seasonal irrigation water requirement of the crop. The portion of the prepared area that received water within this period is referred as irrigated area. Out of the total irrigated area, the portion that received sufficient water (stored sufficient moisture) is distributed to farmers for cultivation, in which the cultivated crops grow from October to February without additional irrigation. However, judgment of the irrigated area as sufficiently irrigated (stored sufficient moisture) and insufficiently irrigated has been done by experience. Hence, our study, which provides a methodology to estimates the spatial and temporal distribution of soil moisture, can be an essential tool to increase the accuracy of classifying the irrigated area into sufficiently (well-irrigated) and insufficiently irrigated.

2. STUDY AREA

Gash Delta Spate Irrigation System with a net command area of 100,000 ha is located in Kassala State, Sudan near to the border with Eritrea (**Fig. 1**).

It is an oasis in a surrounding desert with relative humidity ranging from 20 to 50%, annual rainfall from 180 to 280 mm (from Hadaliya in the North to Kassala in the South) and average temperature from 26°C in winter to 42°C in summer.



Fig. 1 Location of the study area

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

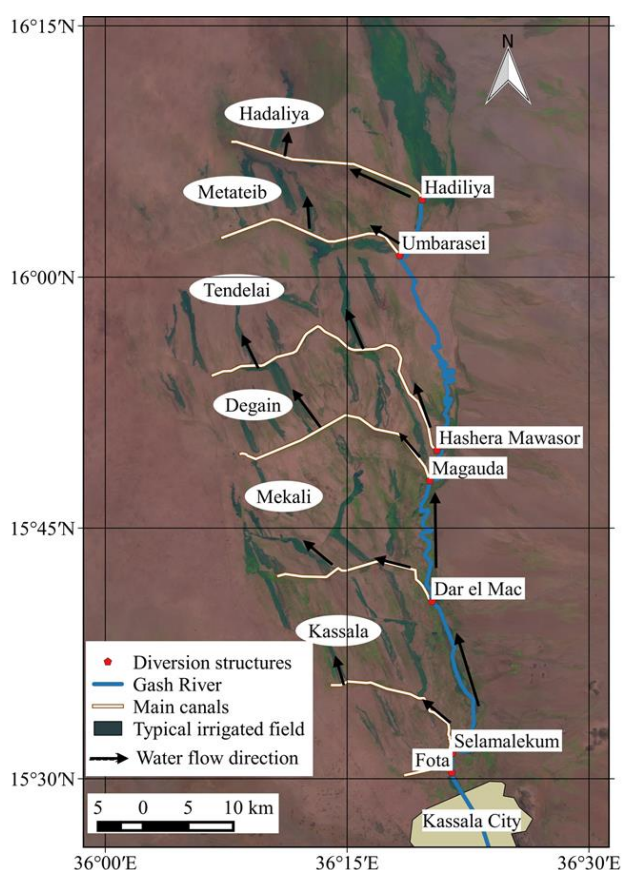


Fig. 2 Layout of Gash Delta Spate Irrigation System (note: typical irrigated area in this figure shows only the area irrigated up to July 28th 2009 of season 2009-2010)

The total command area of GDSIS is divided into six irrigation blocks namely Kassala, Mekali,

Degain, Tendelai, Metataib and Hadaliya (**Fig.2**). Each block is further divided into a number of irrigation units known locally as “Misga”. Flood water from the west bank of the Gash River is diverted through seven diversion structures for an effective period of 60 to 70 days per year. The diverted water is then conveyed by a system of canal network to one third of the net command area, which is prepared before the flood season. The portion of the prepared area that received water as shallow surface flow within this period is referred as irrigated area. Usually about one week after irrigation, when tractors can enter the field, seed sowing is done on the portion of the irrigated area that received sufficient water and is cleaned by removing mesquite infestation. This area actually sown with seed is referred as cultivated area. The dominant crop in GDSIS is sorghum and it is cultivated from October to February.

3. METHOD

In GDSIS, the irrigation (flood water application) period is from July to September. The period of water spreading over the field for irrigation lasts from 10 to 20 days and then the watering is continued for a further 10 to 20 days. This practice leaves the irrigated area covered with water or wet enough to be clearly detected on a satellite image acquired within this period. Band 5, which is the middle infrared (1.547-1.749 μm) in Landsat-7 ETM+, has the capability of discriminating the wet or flooded surface. Hence, Band-5 of Landsat-7 ETM+ and the Modified Normalized Difference Water Index (MNDWI) proposed by Xu⁵⁾ are adopted to identify extent of water spread or wet surface. The MNDWI is calculated by the normalized ratio of green (*Gr*) and middle infrared (*MIR*) bands as:

$$\text{MNDWI} = \frac{Gr - MIR}{Gr + MIR} \quad (1)$$

Moreover, this study also used the results of SEBAL for estimating the soil moisture in GDSIS. The SEBAL developed by Bastiaanssen *et al.*³⁾ computes a complete radiation and energy balance for the surface along with heat fluxes and resistances for momentum, heat and water vapor transport. The land surface energy balance is expressed as:

$$R_n = H + \lambda E + G \quad (2)$$

where, R_n is net radiation heat flux to the surface, H is sensible heat flux to the air, λE is latent heat flux

(energy used for evaporation) and G is soil heat flux.

The SEBAL model comprises of number of computational steps for image processing and produces a number of intermediate variables such as NDVI, surface albedo and surface temperature. Then, different empirical and physical relationships are used to derive the R_n , G , and H as a function of the above intermediate variables. Finally, the daily actual evapotranspiration is estimated as:

$$ET_{24} = \frac{86400 \times \Lambda \times R_{n24}}{\lambda} \quad (3)$$

where, ET_{24} is actual evapotranspiration (mm d^{-1}), R_{n24} is daily net radiation (Wm^{-2}), λ is the latent heat of vaporization and Λ is evaporative fraction (dimensionless).

The evaporative fraction (Λ) is the ratio between the latent heat flux (λE) and the net available energy that is the net radiation (R_n) minus soil heat flux (G).

$$\Lambda = \frac{\lambda E}{R_n - G} \quad (4)$$

Soil wetness is clearly manifested in the surface energy balance by the magnitude of sensible heat (H) and latent heat fluxes (λE)⁶⁾. If a soil is dry, H will be large and λE will be small and the contrary holds true for wet soil. Scott *et al.*⁷⁾ have developed an empirical relationship between the evaporative fraction (Λ) and soil moisture content (θ). The relationship is expressed as:

$$\frac{\theta}{\theta_s} = \exp\left(\frac{\Lambda - 1}{0.421}\right) \quad (5)$$

where, θ_s is saturated soil moisture content and θ/θ_s is relative soil moisture content and ranges from 0 (oven dry soil) to 1 (full saturation).

Equation (5) is denominated as standard relationship and can be applied to a wide range of soils⁶⁾. As a result, it was applied without calibration in many areas such as Mexico, Indus River Basin, and Egypt⁸⁾. Normalizing the soil moisture between 0 and 1 allows the empirical function to be applied to a wider range of soil types as it excludes the soil specific limits such as saturated soil water content and dry bulk density.

The results of SEBAL such as the actual evapotranspiration and the soil moisture content should be validated by comparing them with field measurements. However, in Gash Delta, field measurements related to water balance are either unavailable or unreliable due to unobserved surface water flow. Hence, the actual evapotranspiration estimated by SEBAL was compared with that by a

conventional method (Penman-Monteith method) as a validation²⁾.

Similarly, due to the lack of reliable soil moisture data, observed soil moisture content could not be used in this study. However, the soil moisture distribution estimated by SEBAL can be used as basic data for investigating the applicability of the Band-5 and MNDWI to classify the irrigated area into sufficiently and insufficiently irrigated.

4. APPLICATION RESULTS

(1) Actual evapotranspiration (ET_a)

Fig.3 shows the distribution of actual evapotranspiration (ET_a) on November 9th, 2009. This date is within the crop growing stage of cultivation. As clearly shown in **Fig.3**, the GDSIS has large variation of daily actual evapotranspiration, which ranges from 0.0 to 10.96 mm d⁻¹. The large variation in the ET_a is due to the presence of irrigated/cultivated Misgas with high ET_a and fallow Misgas resulting in low ET_a .

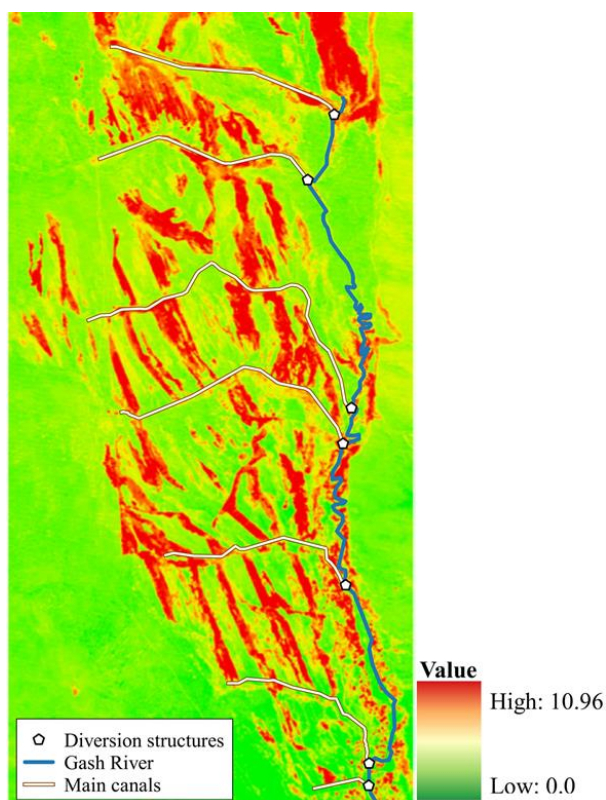


Fig. 3 Actual evapotranspiration (mm d⁻¹) of GDSIS on November 9th, 2009

2) Soil moisture distribution and flooded area

Fig.4a shows the spatial soil moisture distribution on November 9th, 2009 using SEBAL. **Fig.4b** and **Fig.4c** show flooded area on September 30th, 2009 mapped from Band-5 and MNDWI, respectively.

The Band-5 and MNDWI maps use Landsat-7 image. The date, September 30th is just end of irrigation period and start of crop sowing and the maps show the extent of wet surface as a result of the water application. Hence, these indicate the irrigated area. Although both approaches show the distribution of wet surface, but their resulting maps are less shaper than those of ET_a (**Fig. 3**) and relative soil moisture (**Fig. 4a**) maps. This could be due to the difference in image date. Moreover, the Band-5 and MNDWI methods only give the surface moisture information. On the other hand, the SEBAL approach estimates the root zone soil moisture.

The relative soil moisture content of the GDSIS on November 9th 2009 (with in the crop growing period) was calculated using Equation (5) and the resulting distributed value is shown in **Fig.4a**. The relative soil moisture content varied from 0 to 40% indicating the non-uniformity of water distribution.

As expected spatial distribution of the ET_a (**Fig.3**) and relative soil moisture (**Fig.4a**) are similar. Moreover, visual inspections of both maps show that the sharp changes between high and low values follow the Misga boundaries. This implies, in addition to the usual importance of the ET_a and soil moisture content, they can be used to estimate and delineate the cultivated areas in GDSIS.

In order to clearly compare the potential of each approach in mapping the soil moisture distribution, **Fig. 5** was developed. **Fig.5b** and **Fig.5c** depict the Misgas flooded or wet on September 30th 2009. Misgas “A”, “B” and “D” indicate complete spreading of water while Misga “C” indicates incomplete water spreading. Moreover, Misga “B” and “D” show runoff water to outside of Misgas. These phenomena, runoff in some of the Misgas while others experience incomplete advance of irrigation water, calls for attention in the management of the system to increase the irrigation efficiency.

Visual comparison of the maps in **Fig.5** implies that the soil moisture distribution is solely the result of the water spreading. For example, Misga “A” show relatively high uniformity of water spreading and relative soil moisture, whereas Misga “C” shows low uniformity in both cases. Considering Misga “D” one can observe low values of water spreading (**Fig.5b** and **5c**) and relative soil moisture (**Fig.5a**) near to the inlet and high values near to the end of the Misga. Moreover, fields between Misgas “A” and “B” as well as between Misgas “C” and “D” show very low values in all the maps implying un-irrigated and hence uncultivated (Fallow Misga).

Fig.5a, which shows the relative soil moisture content of the root zone is an indication of the cultivated and fallow area.

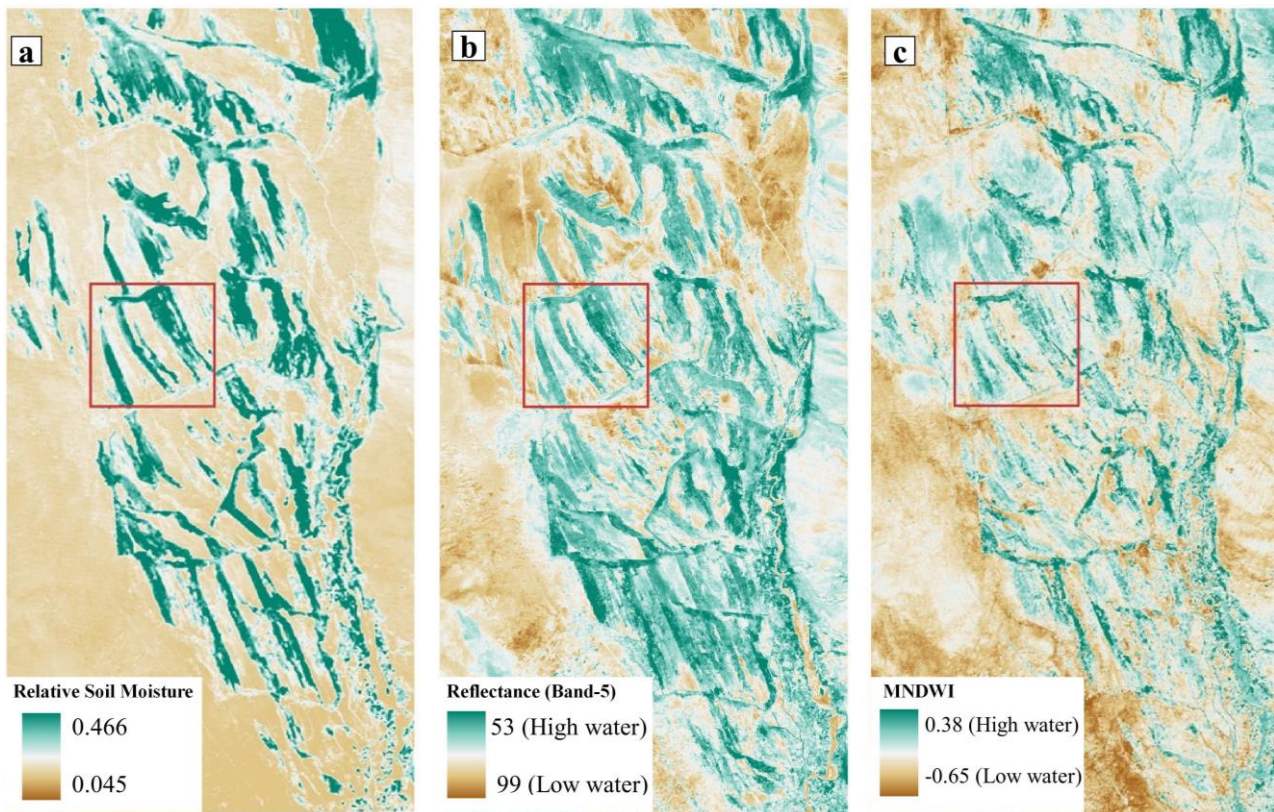


Fig. 4 Spatial distribution maps of (a) relative soil moisture from SEBAL (b) Band-5 in digital number and (c) MNDWI (Image date of (a) is November 9th, 2009, whereas image date of (b) and (c) is September 30th 2009)

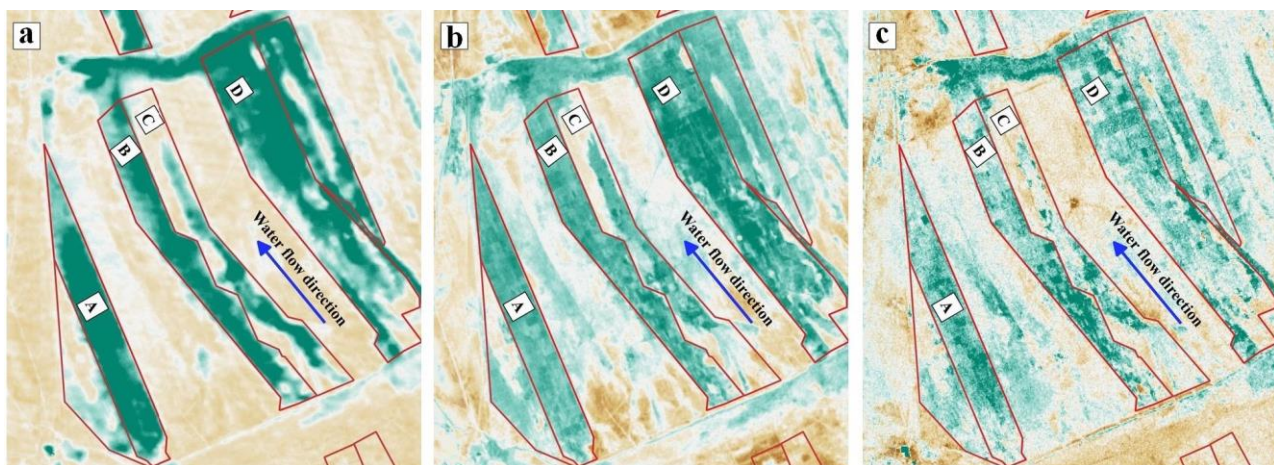


Fig. 5 Magnified view as indicated in Fig 4 of the (a) relative soil moisture (b) Band-5 and (c) MNDWI (Note: Range of values in these images is the same as their corresponding images in Fig.4)

The cultivated area is considered to be that area, which is sufficiently watered. Moreover, **Fig.5a** derived based on SEBAL analysis can be safely assumed as reliable estimate of the soil moisture distribution and hence used as reference for comparing the soil distribution maps (flooded area maps or irrigated area maps) from the other two approaches considered in this study.

Although, as shown in **Fig.5** both the Band-5 and MNDWI maps show similar moisture distribution

patterns, the Band-5 map is more comparable to the SEBAL-based map. In addition, the Band-5 method is the simplest, which do not require any calculation but simple visual enhancement. Hence, Band-5 of the freely available Landsat-7 ETM+ and Landsat-8 OLI can be used by the GDSIS management as a guide to map and evaluate the irrigated area for subsequent distribution to the farmers for cultivation.

5. CONCLUSIONS

This study investigates the possibility of estimating the soil moisture distribution from remote sensing data. Three approaches, first employing single-band index, second multi-band water index and third SABAL-based empirical relationship, were employed to determine the flooded (irrigated) area and soil moisture distribution. The SEBAL-based soil moisture distribution was used as a reference to evaluate the capability of the first two approaches. The single-band (Band-5) based approach was found to produce soil moisture distribution map fairly comparable to the SEBAL approach. Hence, this simple approach can be used by the GDSIS administration for mapping of the moisture distribution at minimum cost. Moreover, visual interpretation of the actual evapotranspiration, relative soil moisture and water spreading (from Band 5 of Landsat 7 ETM+ and MNDWI) suggested the possibility of delineating the cultivated Misgas from remote sensing analysis. The main limitation of this study is the unavailability of field data on soil moisture sampled in situ as well as surveyed map of actual irrigated and cultivated areas, which are necessary for the validation. Hence further study should deal with validation of the methodology using the aforementioned relevant field data.

ACKNOWLEDGMENT: This study was supported by the Grant-in-Aid for Scientific Research (B) from the Japan Society for the

Promotion of Research (No. 16H04996, HT).

REFERENCES

- 1) Ngirazie, L. A.: Assessing the performance of water user associations in the Gash Irrigation Project, Sudan, *Water International*, Vol. 40, No. 4, pp. 635-645, 2015.
- 2) Khalid, A. E., Tanakamaru, H. and Tada, A.: Estimation of actual evapotranspiration in Gash Delta, Sudan using a satellite-based energy balance model, *International Water Technology Journal (IWTJ)*, Vol. 2, No. 1, pp. 47-56, 2012.
- 3) Bastiaanssen, W. G., Menenti, M., Feddes, R. A. and Holtslag, A. A. M.: A remote sensing surface energy balance algorithm for land (SEBAL) 1. Formulation, *J. Hydrol.*, Vol. 212-213, pp. 198-212, 1998.
- 4) Rahimzadeh-Bajgiran, P., Berg, A. B., Champagne, C. and Omasa, K.: Estimating of soil moisture using optical/thermal infrared remote sensing in the Canadian Prairies. *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol. 83, pp. 94-103, 2013.
- 5) Xu, H.: Modification of normalized difference water index to enhance open water features in remotely sensed imagery, *Int. J. Remote Sensing*, Vol. 27, No. 14, pp. 3025-3033, 2006
- 6) Ahmad, M. and Bastiaanssen, W. G.: Retrieving soil moisture storage in the unsaturated zone using satellite imagery and bi-annual phreatic surface fluctuations, *Irrig. Drain. Syst.*, Vol. 17, pp. 141-161, 2003.
- 7) Scott, C. A., Bastiaanssen, W. G. and Ahmad, M. : Mapping Root Zone Soil Moisture Using Remotely Sensed Optical Imagery. *Journal of Irrigation and Drainage Engineering*, Vol. 129, No. 5, pp. 326-335, 2003..
- 8) Bezerra, B. G., dos Santos, C. A. C., da Silva, B. B., Perez-Marin, A. M., Bezerra, M. V. C., Bezerra, J. R. C. and Rao, T. V. R.: Estimation of soil moisture in the root-zone from remote sensing data. *Revista Brasileira de Ciencia do Solo*, Vol. 37, No.3, pp. 596-603, 2013.

(Received September 29, 2017)