PERFORMANCE ASSESSMENT OF LARGE IRRIGATION SYSTEMS USING SATELLITE DATA: THE CASE OF THE GEZIRA SCHEME, SUDAN

EVALUATION DE LA PERFORMANCE DES GRANDS SYSTEMES D'IRRIGATION UTILISANT LES DONNEES SATELLITAIRES : PLAN DE GEZIRA AU SOUDAN

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ABSTRACT

Continuous assessment of irrigation system performance is a pre-requisite for optimal management of land and water resources in irrigated lands. The cost of data collection for monitoring and evaluation can be prohibitively expensive in large systems, such as Gezira Irrigation Scheme in Sudan. In such cases, satellite images can help assessing the spatial and temporal patterns of performance indicators.

This study discusses the experience of using public domain satellite data with limited ground measurements to assess the performance of Gezira Scheme at two spatial scales: (i) Section level (6,000 to 19,000 ha) at four pilot sites, and (ii) the whole Gezira Scheme (882,000 ha). Using unsupervised classification of Landsat-7 ETM+ images (30m x 30m resolution) and ground-truth information, crop type and cultivated area for 2007/2008 season were estimated. The 8-daily actual evapotranspiration (ET) and dry matter production over each pixel of 1km x 1km has been computed with ETLook algorithm of WaterWatch applied to MODIS images.

The performance of the scheme has been assessed using indicators, including irrigation efficiency, relative water supply, and land and water productivity. At section level, the irrigation efficiency varies between 19% and 36%, relative water supply between 2.2 and 4.9. For the whole Gezira scheme, efficiency and relative water supply were 22% and 4.6, respectively. The average land productivity (crop yield divided by area) over the whole Gezira is 1.3, 1.1, 0.9, and 0.85 ton/ha for cotton, wheat, groundnut and sorghum, respectively. The average

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water productivity (crop yield divided by actual ET is 0.28, 0.47, 0.22 and 0.23 kg/m3 for cotton, wheat, groundnut and sorghum, respectively. The Gezira productivity showed relatively lower values compared to the Gezira Agricultural Research Station, as well as to the international yield levels.

The study demonstrated that remote sensing data supplemented with limited ground data, can be very useful to assess the performance of large irrigation systems. The main areas to improve for higher accuracy should include utilizing higher resolution images, employing interpolation algorithms for cloudy conditions and refining satellite data with additional ground points to improve accuracy of crop classification.

Key words: *Large irrigation systems, Satellite data, Ground data, Water productivity, Sudan.*

RESUME

L'évaluation continue de la performance du système d'irrigation est nécessaire pour la gestion optimale de la terre et des ressources en eau des pays irrigués. Le coût de la collecte des données du contrôle et de l'évaluation peut être cher dans les grands systèmes tels que le Plan d'Irrigation de Gezira au Soudan. Dans ce cas, les images satellitaires peuvent aider à l'évaluation des modèles dans l'espace et dans le temps des indicateurs de la performance.

Cette étude discute l'expérience d'utiliser les données satellitaires du domaine public ainsi que les mesures actuelles limitées pour évaluer la performance du Plan de Gezira à deux échelles spatiales : (i) niveau de Section (6,000 à 19,000 ha) à quatre sites pilotes, et (ii) ensemble du plan de Gezira (882,000 ha). Utilisant la classification non surveillée des images Landsat-7 ETM + (de résolution 30m x 30m) et les informations sur le sol, on a évalué le type de culture et le secteur cultivé de la saison 2007/2008. L'évapotranspiration (ET) réelle de 8 jours et la production de matière sèche sur chaque pixel de 1km x 1km ont été calculées avec l'algorithme ETLOOK de WaterWatch appliqué aux images de MODIS.

La performance du plan a été évaluée utilisant les indicateurs, y compris l'efficience d'irrigation, l'approvisionnement en eau relatif et la productivité de l'eau et de la terre. Au niveau de la section, l'efficience d'irrigation varie de 19% à 36%, l'approvisionnement en eau relatif de 2,2 à 4,9. L'efficience d'irrigation et l'approvisionnement en eau relatif étaient de 22% et 4,6 respectivement pour l'ensemble du plan de Gezira. La productivité moyenne de la terre (rendement agricole divisé par secteur) de l'ensemble du plan de Gezira était de 1,3, 1,1, 0,9 et 0,85 tonnes/ha pour le coton, le blé, l'arachide et le sorgho respectivement. La productivité moyenne de l'eau (rendement agricole divisé par ET réelle était de 0,28, 0,47, 0,22 et 0,23 kg/m3 pour le coton, le blé, l'arachide et le sorgho respectivement. La productivité de Gezira a montré des valeurs relativement inférieures aux valeurs de la Station de Recherche Agricole de Gezira, ainsi qu'au niveau international du rendement.

L'étude a montré que les données de télédétection accompagnées des données limitées obtenues sur la terre seront utiles dans l'évaluation de la performance de grands systèmes d'irrigation. Pour obtenir haut niveau de précision, il est nécessaire d'utiliser les images de haute résolution, les algorithmes d'interpolation d'emploi pour les conditions nuageuses et d'améliorer les données satellitaires pour obtenir la classification exacte des cultures.

Mots clés: *Grands systèmes d'irrigation, données satellitaires, données obtenues sur la terre, productivité de l'eau, Soudan.*

1. INTRODUCTION

Irrigation water provides about 40% of the world food, and constitutes around 70% of the fresh water consumption (Seckler et al., 1998; Postel, 2000). Improvements in the performance of irrigation systems has a huge potential to enhance food productivity, and improve water availability for other competing uses (Molden, 2007). However, performance assessment is confronted by requirements of large amount of actual data from the irrigated fields, which can be prohibitively expensive in large irrigation systems. Remotely Sensed (RS) data and Geographic Information Systems (GIS) techniques have emerged as potential tools for assessing performance of medium and large irrigation systems.

Classically, performance indicators are used to assess performance of an irrigation system, including: irrigation efficiency, adequacy of water supply, as well as land and water productivity (Bos et al., 2005; Perry, 2005). However, the challenge always is the monitoring and collection of large amount of raw data on cultivated area; net water supply; water consumption and crop production. This task becomes complex and expensive for medium and large irrigation schemes

Roerink, et al. (1997) computed water efficiency using RS data for the Rio Tunuyan irrigation scheme in Argentina. Bastiaanssen and Bos (1999) summarized the possibilities of using RS data to improve performance diagnosis under data scarce conditions. Santos, et al. (2008) estimated irrigation efficiency of Genil-Cabra irrigation scheme in Spain using evapotranspiration (ET) estimates from satellite data. Zwart & Leclert (2009), studied irrigation performance of the Office du Niger in Mali using RS. Ahmad, et al. (2009) diagnosed irrigation performance of the Rachna Doab system in Pakistan using NOAA-AVHRR satellite images. Hamid et al., (2011) used NOAA-AVHRR images to assess the performance of the Rahad Scheme in Sudan. Bastiaanssen et al. (2003) estimated crop production in the Indus Basin, Pakistan using NOAA-AVHRR satellite images. Limitations of RS data for accurate results have also been discussed in the literature. Bashir et al. (2007) discussed low temporal and spatial resolution as a key limitation for dynamically changing irrigation systems. High cost of high resolution images is one of the constraints for widespread applications of RS data in irrigation water management. The requirements of high technical skills to acquire and process satellite images are also one of the reasons for widespread use of the technique.

The Gezira Scheme (800,000 ha), is located in central Sudan was famous of growing cotton in the old days. It used to be the backbone of the Sudan economy until 1960's and partly 1970's. The scheme consumes annually around 6 to 7 billion m^3 of water, which is about 35% of the Sudan's total share from the Nile water. The performance of the scheme is claimed to be deteriorated during recent decades, though very few studies on water management appeared in the literature (Adeeb 2006, Worldbank, 2000, Eldaw 2004), and even these show no consensus in performance and productivity values. They mostly agree on the declining performance of the system. Lack of appropriate operation and maintenance, limited financial resources, canal siltation, and changing policies and institutional setups are among the reasons of the downfall. Accurate information on the performance of the Gezira system is pre-requisite for planning and management, in particular with dwindling water availability and rising population and food demand in the region.

The objective of this research is to assess the performance of the Gezira irrigation system in Sudan using RS data to inform better water management. Specifically, we determined the irrigation performance indicators: irrigation efficiency, adequacy of water supply, and the productivity of land and water in kg/ha and kg/m^3, respectively. The indicators have been derived at two scales: (i) section (major canal supply), at four study sites; head, middle, tail, and extension of the scheme, and (ii) overall irrigation scheme (882,000 ha). Public domain satellite images of MODIS and Landsat 7 were used to prepare input data, in addition to ground data of canal discharges and actual crop production for verification purposes.

The next section of the paper gives a short description of Gezira scheme. Section 3, presents the material used, which is mainly Landsat 7 and MODIS images as well as ground data on canal discharges and crop production. Section 4 gives the results of performance indicators, and comparison with the literature. Discussion on potentiality and limitation of RS data has been given here as well. The last section summarized key conclusions on indicators values, and suitability of MODIS and Landsat data for performance assessment in medium to large scale irrigation systems.

2. DESCRIPTION OF THE STUDY AREA

The Gezira scheme is the largest irrigation scheme in the world under a single managing body, Sudan Gezira Board (SGB). It is located on the flat plains between the Blue Nile and White Nile, south of Khartoum, Fig. 1. The scheme is supplied from Sennar dam through extensive canal network comprising of two main canals (194 km long), branch and major canals (2300 km), and minor canals (8000 km) that feed tertiary canals (locally called Abu XX), and then through field ditches (Abu VI), to the fields.

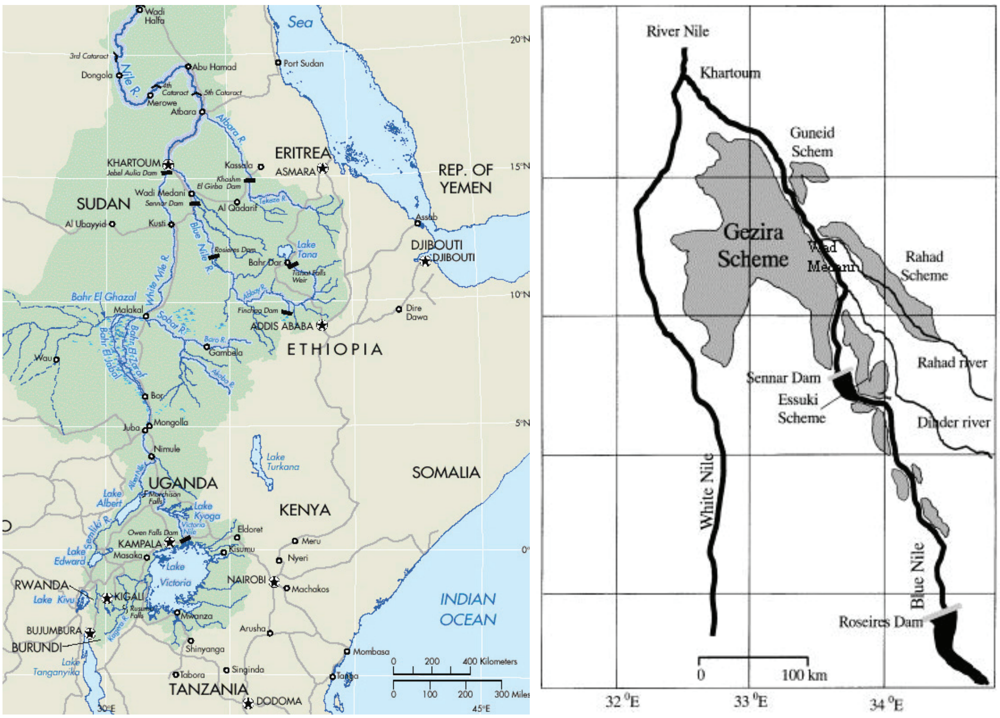

Fig. 1: Location of the Gezira Scheme, Sudan.

The climate of the Gezira area is hot and semi-arid. The rainy season (autumn) last only for 3 month (July to September) and it varies between 400 mm/yr in the southern part to 200 mm/yr in the northern part of the scheme. November to February is the winter season with average temperature of 25 °C, while April to June is the summer season with average temperature of 31 °C at Wad Medani station. The mean daily relative humidity is 18 % in summer, 55 % in autumn, and 28 % in winter. The region experiences long sunshine hours, about 10.5 hours, outside the autumn season. The wind is moderate (about 3.3 m/s), blowing mainly from the north in summer and winter and from the south in autumn.

A new law governing the management structure of the scheme has been introduced in 2005, called 'THE GEZIRA SCHEME ACT OF 2005'. Before the act, the scheme followed a four-course rotation. Each tenancy of 8.4 ha (20 feddans) is divided into 4 plots (locally called Hawasha), grown by cotton, wheat, sorghum/groundnuts and fallow, respectively. However sorghum is considered to be the main staple food in Sudan.

The Sudan Gezira Board (SGB) historically manages the Gezira scheme. Before 2005, the management was based on a tripartite relationship among the Ministry of Irrigation and Water Resources (MoIWR), the SGB and the tenant farmers. However, after the Gezira Act in 2005, farmers are free to choose crops, and can participate in the operation and maintenance of the scheme through their water users associations.

3. MATERIALS AND METHODS

The irrigation performance of the Gezira Scheme has been assessed for 2007/2008 season, i.e., from June 2007 to March 2008 in accordance with the cropping pattern in Gezira. Usually sluice gates are closed during April and May for routine maintenance. Two sets of satellite have been used in the study, (i) Landsat-7 to define crop type and cultivated area, and (ii) Moderate Resolution Imaging Spectroradiometer (MODIS) to estimate ET and biomass production.

3.1 Satellite images

The satellite imagery of Landsat-7 Enhanced Thematic Mapper Plus (ETM+) has been acquired for the months of September 2007 to March 2008 (Table 1). Cloudy condition during June to August obstructs selection of usable images. Images were downloaded from the website of

Table 1: Landsat images acquisition dates for 2007/2008 season.

Month	date in 2007	date in 2008
September	16, 23	-
October	9, 18, 25	-
November	10, 19, 26	-
December	5, 12	-
January	-	6, 29
February	-	7, 14
March	-	1, 10

the United States Geological Survey (USGS) (http://glovis.usgs.gov/). The Landsat-7 ETM+ has 16 day temporal resolution, and spatial resolution of 30 meter for the six (6) visible and near-infrared bands, and 60 meter for the thermal band. Five Landsat scenes were assembled to cover the Gezira scheme.

The actual evapotranspiration ETa and biomass production maps were already produced by WaterWatch for a Nile basin study on water productivity for the year 2007 (IWMI, 2009). The ET_a and biomass maps shown in Fig. 2, were based on the ETLook model, which is a newer version of the SEBAL algorithm. ETLook has been applied to MODIS images at 8-daily time steps (WaterWatch, 2009). Due to no availability of satellite data for January to March 2008, those were assumed to have similar values as the corresponding months in 2007. To verify this assumption, the climatic condition at Wad Medani station of January to March 2007 were compared to the corresponding months of 2008, and negligible differences were found for open water evaporation term.

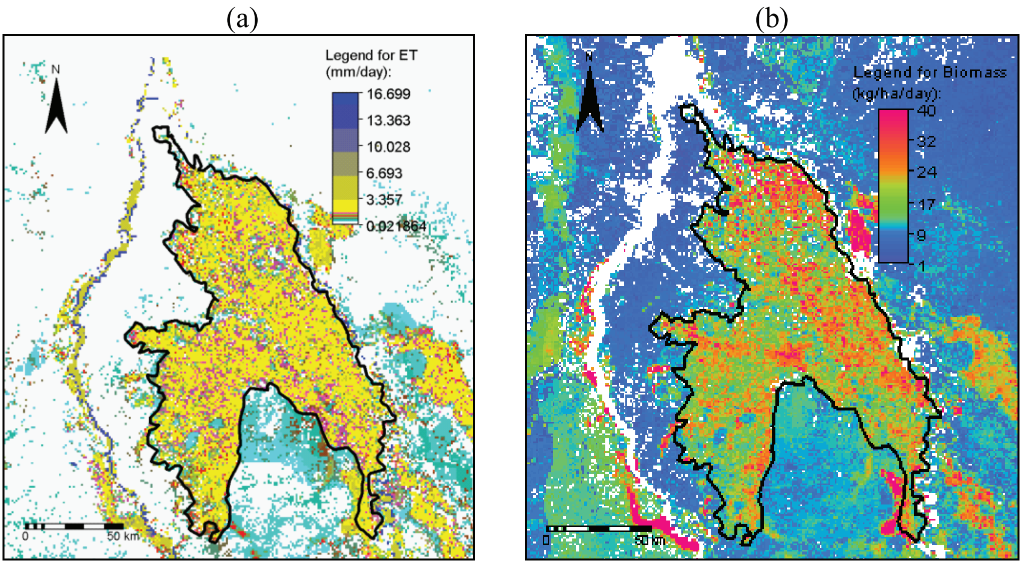

Fig. 2: (a) Actual Evapotranspiration ETa in mm/day, (b) Biomass production (kg/ha/day) for the month December 2007. [Source: Waterwatch (2009)]

3.2 Ground measurements

The climate data and canal discharges for 2007/08 season, as well as ground truth of crop type and cultivated areas were collected during a field visit to the scheme during December 2009. The secondary data comprised monthly climate data of rainfall, temperature, humidity, wind speed, and sunshine hours measured at three ground stations, shown in Fig. 3.

Four study sites at head, middle, tail and extension were selected for ground truth information, in addition the information for the whole scheme. Figure 3, Annex A1, A2 and A3 provide a summary of cultivated area, crop yield and monthly discharge of the Gezira scheme and the selected four major canals. The cultivated area, were obtained from the MoIWR as planned area at the beginning of 2007/2008 season. The crop yields were obtained from the SGB.

It is to be noted that, obtaining field data during a visit to the scheme in December 2009 proved to be very hard coinciding with major changes of the Gezira management system.

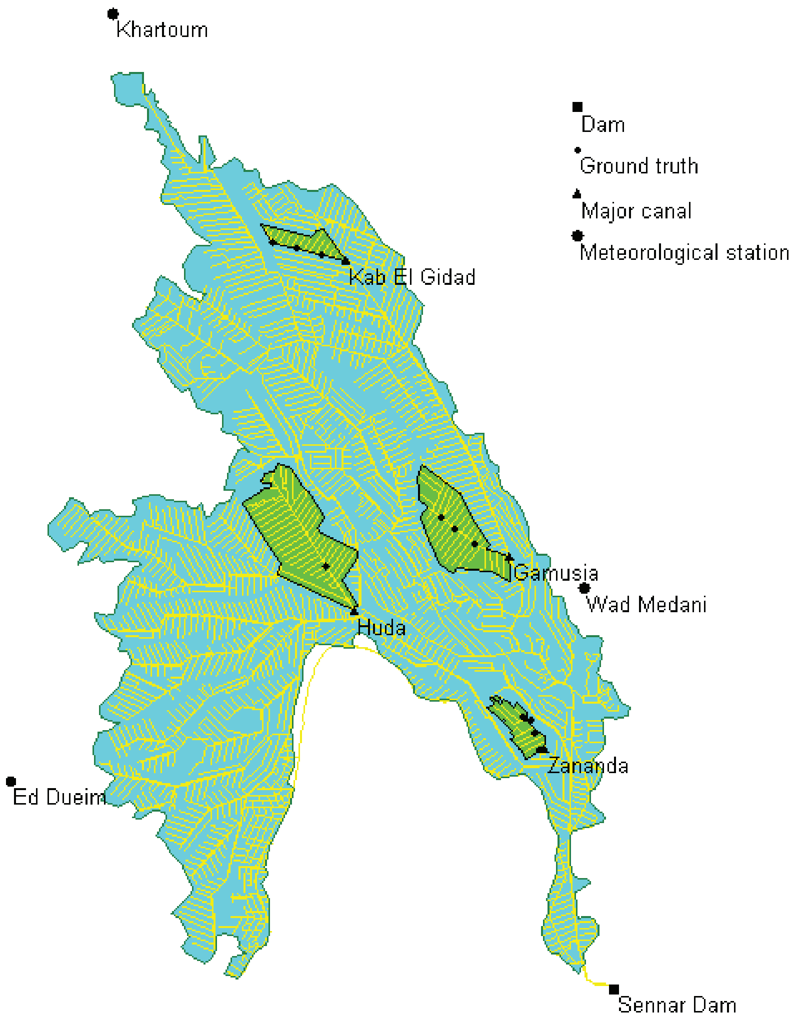

Fig. 3: The Gezira canalization, and location of the four selected study sites (major canals) and the climate stations.

Fifteen ground truth points (crop type) were used to fine tune the land use classification derived from the satellite images (Fig. 3). The points were selected to cover crop area at head, middle and tail end of Gezira Scheme as well as of the major canals.

3.3 Methodology:

The Integrated Land and Water Information System (ILWIS) software has been used for all steps of image processing and analysis. ILWIS has been used to define cultivated area, crop types, and computation of performance indicators.

3.3.1 Crop identification:

Satellite images are commonly used to identify land use classes in particular for cases of limited ground information. The Landsat-7 ETM+ images (30m x 30m) were used for land use classification. First, the physical boundaries of the Gezira scheme were demarcated by visual observation. Minor errors were corrected using the command area layout of the Gezira scheme. The unsupervised classification was used to segregate the (spectral) colour composite images into six classes (CGIS, 2010). The ground truth information was used for crop identification, and accordingly to estimate cultivated area. This includes five main crops in Gezira: cotton, groundnut, sorghum, vegetable and wheat, and fallow land. As a 2nd check, the normalised difference vegetation index (NDVI) maps were computed, as:

$$NDVI = \frac{NIR - R}{NIR + R} \tag{1}$$

NIR is the Near Infra Red which is band 3 for Landsat-7, and R is Red (band 4). The NDVI generally ranges from -1 to +1. The NDVI graphs together with the cropping calendar, and ground truth information were used to identify crop types.

1.3.2 Irrigation Performance indicators

Key indicators were selected to assess the performance of the Gezira Scheme, including: Irrigation efficiency (ζ); Relative Water Supply (ψ); land productivity (Y_{land}), and water productivity (Y_{water}), as:

The Irrigation efficiency ζ is given by Eq. 2 (Bos and Nugteren, 1990):

$$\zeta = \frac{ET_a - P_e}{Q_{AW}} \tag{2}$$

where, ET_a = actual evapotranspiration in mm/month
P_e = effective or net precipitation in mm/ month
Q_{AW} = Applied Water in mm/ month

The ratio of water supply to demand defines the Relative Water Supply (ψ), as originally described by Small et al. (1974), Levine (1982) and Sakthivadivel (1993).

$$\psi = \frac{P_{gross} - Q_{AW}}{ET_p} \tag{3}$$

where, Pgross = Gross precipitation in mm/day
Q_{AW} = Water delivery from the reservoir in mm/day
ET_p = Potential evapotranspiration by irrigated crops in mm/day

ψ is a suitable indicator to inform irrigation managers about sufficiency of water supply to meet total water demand of a cultivated land.

The land productivity Y_{land} is defined as the crop yield per unit area, Eq. 4 (Bos et al., 2005; Zwart and Leclert, 2009).

$$Y_{act} = \frac{Bio * H_i}{1 - \theta_p} \quad (4)$$

where: Y_{act} = actual crop yields (*kg/ha*) = Y_{land}

H_i = crop harvest index (–)

Bio = biomass production (*kg/ha*)

θ_p = plant water content at harvest (–)

The harvest index H_i is the ratio of grain yield to dry matter yield (Donaldson et al., 2001). H_i is affected by the given environment and cultivar, and decreases due to water, nutrient or temperature stress (Zwart and Leclert, 2009). The Biomass is the total dry matter production including roots, stems, leaves, grains, and flowers (Leclert et al., 2009).

The water productivity Y_{water} is defined as the ratio of crop produced to water consumed (Perry et al., 2009). While Molden et al. (2009) defined water productivity as the ratio of the net benefits from crop, forestry, fishery, livestock and mixed agricultural systems to the amount of water used to produce those benefits. Zwart and Leclert (2009) defined water productivity as the total yield divided by water consumption represented by actual evapotranspiration. We have used the later definition as given by Eq. 5:

$$Y_{water} = \frac{Y_{act}}{ET_a} \quad (5)$$

4. RESULTS AND DISCUSSIONS

The result of the irrigation performance assessment using satellite data for the Gezira Scheme during season 2007/2008 is presented in this section. How the performance indicators compared to the literature is discussed as well. The uncertainty of results derived from RS data on cultivated area, crop type, crop production was validated against observed data.

4.1 Cultivated area

The Landsat 7 images have data gaps after May 31, 2003. These gaps were first filled using '*ETM+ Gap Filling Software*' from The National Aeronautics and Space Administration (NASA, 2010). Making use of information from three additional images (before, after, and on the same month) of the given image, the missing values were estimated as the average value.

To estimate the cultivated area during 2007/2008 season, crops types were identified using monthly NDVI values at the 15 ground truth points. These results were then checked against standard crop calendar (Table 2), and field information obtained from farmers in December, 2009. It was found that nine out of fifteen NDVI points match farmers' information on crop types. The mismatch for the other 6 points could be attributed to inaccurate information reported by farmers, or staggered sowing dates not captured by standard NDVI curve. The practice showed that actual sowing dates could be quite different from standard schedule. The relatively large resolution of Landsat images, also adds to uncertainty of crop classification. Obviously this will affect final results of the study, though errors could cancel each other at larger spatial scales.

Next, the cultivated area for season 2007/08 was delineated from the Landsat-7 images as given in Table 3. The data obtained from the MoIWR is also given. In fact the MoIWR record is the planned area at the beginning of the season, which could be slightly different from actually cultivated. As can be seen from the table, sorghum (the staple crop) constitutes about 44% of the total cultivated area. The comparison with MoIWR data shows for groundnut and sorghum a 0% difference. Vegetable and cotton also give a reasonable difference of less than 18%, while wheat shows a 52% difference. The large difference for the wheat area is likely due to inaccuracy of image classification and/or field records. It is possible that grass, weeds or other similar crops have been classified as wheat. Sometimes farmers cultivate more wheat than planned.

Table 2: Crop calendar in the Gezira scheme for 2007/2008 season.

Month	Jun			Jul			Aug			Sep			Oct			Nov			Dec			Jan			Feb			Mar			Days
Date	1-10	11-20	21-30	1-10	11-20	21-30	1-10	11-20	21-30	1-10	11-20	21-30	1-10	11-20	21-30	1-10	11-20	21-30	1-10	11-20	21-30	1-10	11-20	21-30	1-10	11-20	21-30	1-10	11-20	21-30	
Groundnut																															140
Sorghum																															120
Cotton																															180
Wheat																															120
Vegetable																															

[Source: Ministry of Irrigation and Water Resources, Sudan, December, 2009]

Table 3: The cultivated area in the Gezira Scheme for 2007/2008 season.

Crop type	MoIWR ha	Satellite ha	% difference
Cotton	37,474	44,078	18
Groundnut	66,624	66,532	0
Sorghum	199,088	199,887	0
Vegetable	105,000	112,422	7
Wheat	18,900	28,657	52
Total	427,086	451,576	6

The Percentage difference between RS and MoIWR increases for smaller spatial scales of the major canals, and it is 46%, -82%, 26%, and 15% for Zenanda, Gamusia, Kab El Jedad, and El Huda, respectively. Considering, the uncertainty of MoIWR data (planned vs. actual), and non-availability of information from the SGB, results obtained from RS data could be assumed representative. The results are acceptable for the whole scheme, while it can be considered at least qualitatively representative for smaller scales of the major canals. This could be justifiable for comparative analysis between major canals at different locations: head, middle, tail, and extension of the Gezira Scheme.

4.2 Performance indicators

The following section discussed the results of irrigation performance indicators in two parts (i) irrigation water efficiency and relative water supply, and (ii) Land and water productivity in kg/ha and kg/m^3, respectively.

4.2.1 Irrigation efficiency and relative water supply

The results of irrigation efficiencyζ; and relative water supply ψ (Eq. 2 to Eq. 3) for the four study sites, and the whole scheme, is presented in Table 4. The efficiency ζ for the whole Gezira scheme is 22%, i.e., about 78% of the water supply at the headwork is lost before consumed by crops. This includes all losses, conveyance, distribution, and on-farm losses. The Gamusia major canal at the middle of the system shows the highest efficiency (36%), while Zenanda (head) and Kab El Jedad (tail) show the lowest efficiency (19%). These are lower than irrigation efficiency of other irrigation schemes worldwide. Bandara (2003) estimated ζ of three large irrigation systems in Sri Lanka as 48%, 71% and 32%. Perry et al. (2009) cited the work of Postal and Vickers (2001), showing the surface water irrigation efficiency between 25% and 40% in India, Mexico, Pakistan, the Philippines and Thailand; between 40% and 45% in Malaysia and Morocco; and between 50% and 60% in Israel, Japan and Taiwan.

The relative water supply is a suitable indicator to show whether crop water requirements of an area were sufficiently provided. The results of Table 4 show relatively high values of ψ. The Gamusia major canal gives lowest ψ, while Zenanada and Kab El Jedad and the whole scheme gives $\psi>4$. This clearly indicates adequate water supply, independent of the location, even with additional losses, and relatively larger than other schemes of the world. The results of Karatas et al. (2009) in Gediz basin, Turkey, using RS data showed ψ for ten water user associations areas to vary between 0.47 to 1.66. The ψ of three large irrigation systems in Sri Lanka was 1.27, 1.88 and 2.71 (Bandara, 2003). The ψ of 18 irrigation systems located in 11 countries vary between 0.8 and 4.0, with half of these systems have $\psi>2$ (Molden et al., 1998). The ψ of Alto Rio Lerma irrigation district, Mexico ranged between 2.1 and 4.4 during winter of 1995/96 and between 1.9 and 2.0 during summer of 1996 (Kloezen and Restrepo, 1998).

Table 4: The irrigation efficiency and relative water supply in Gezira for seasons 2007/2008

Study Site	Irrigation efficiency %	Relative Water Supply
Zenanada	19	4.9
Gamusia	36	2.2
Kab El Jedad	19	4.4
El Huda	28	3.2
Gezira Scheme	22	4.6

The temporal variability of ζ and ψ as represented by the monthly results is given in Fig. 4a and 4b. For the four major canals, and for the scheme as a whole, the ζ was relatively high at the beginning of the irrigation season, almost double the values of the end of the season. This implies more efficient use of irrigation water during the first three months. The indicators (ζ, ψ) of the four major canals show similar temporal trends, though with considerable difference in magnitude. The ψ showed abundant water delivered during the last 4 month of the irrigation season. These results are attributed to the fact that, the same water supply from the headwork at Sennar dam was continued even for reduced area from December onward, Fig. 4 c. Subsequently, the water supply per unit area in mm/ha shows a sharp increase from December onward, Fig. 4d. The ET_a in mm/ha shows small monthly variability between 50 in December to 80 mm/month in September. The effective rainfall P_e is almost negligible during September to March. This indicates that the water applied to the Gezira scheme during the last four months of the study period is around five times than actually consumed. A similar pattern to the results of Fig. 4d is also shown for the four major canals (results are not given here).

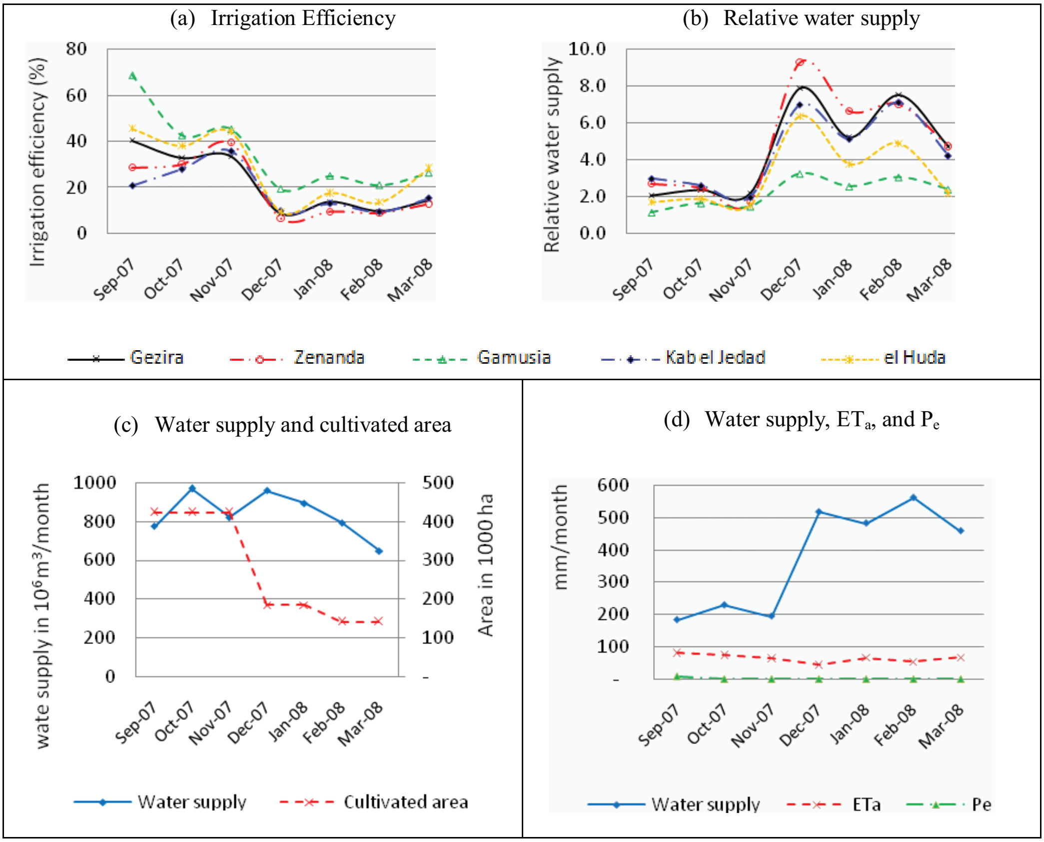

Fig. 4: Irrigation performance assessment (a) irrigation efficiency, (b) relative water supply, (c) total water supply in million m^3/month and cultivated area in 1000 ha, and (d) total water supply, actual evapotranspiration, and effective rainfall in mm/month.

The sorghum and groundnut crops comprising 44% and 15% of the cultivated area (Table A1) were supposed to be harvested during November/December. Even though wheat cultivation started during December it was only 6% of the area. This shows a drastic decrease in cultivated area from 423,000 ha to 185,000 ha, while, water supply from the dam increased slightly from 822 Mm^3/month in November to 959 Mm^3/month in December, though decreased to 648 Mm^3/month in March. Because of this, the water supplied (mm/month) to the Gezira scheme was higher during December – March than during September –November. This directly impacted the temporal variation of the irrigation efficiency and relative water supply in the Gezira Scheme.

4.2.2 Land productivity

The land productivity Y_{land} (Eq. 4) in kg/ha of the four main crops is given in Fig. 5. Although differences are not very large between the four major canals, the summer crops (cotton, groundnut and sorghum) show a declining trend from south to north, highest at Zenanda (head), and lowest at the tail (Kab el Jedad). While, the winter crop (wheat) shows a reverse pattern. This is expected, as winter is relatively cooler in the northern part of the scheme, being a critical factor for wheat growth in the tropics.

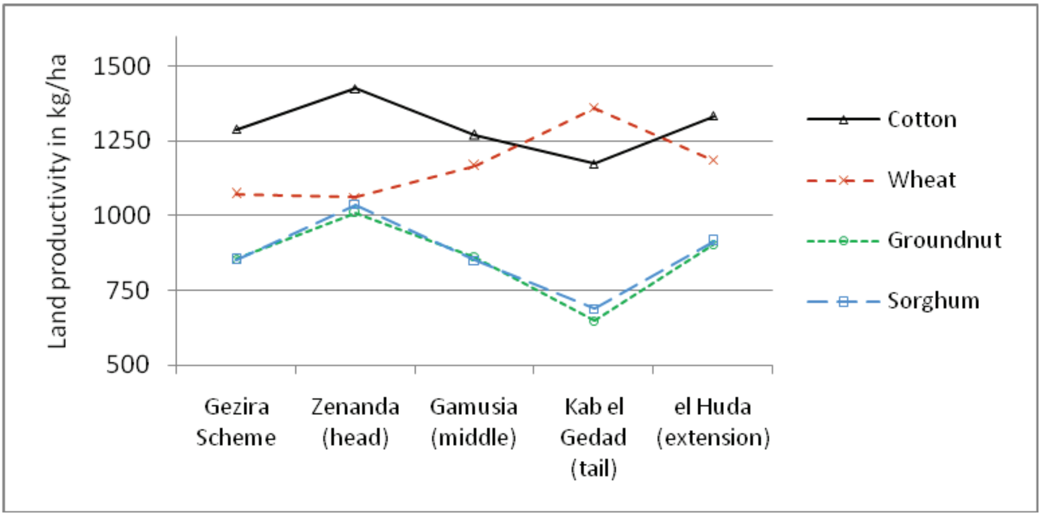

Fig. 5: land productivity in kg/ha of the Gezira Scheme, and the four study sites

The comparison with field data on crop production obtained from the SGB (Table A2) showed variable results, as shown in Fig. 6. For the Gezira Scheme, the differences are -2% for cotton, 29% for wheat and sorghum, and 55% for groundnuts. For the four selected major canals the difference varies between 1% to 64%. Large differences were obtained for Kab el Jedad, and smallest for el Hudda extension. In general, the remote sensing results show lower yield compared to the field data of the SGB. It is to be mentioned that, filed data itself may contain some errors, and this is due to major transition of the Gezira management at the time of field data collection (December 2009). Possibly, the differences are also attributed to underestimation of harvested yield from biomass data derived from satellite images. Except for cotton, the RS results are relatively lower than the literature (e.g., Osman, 2009; 2000).

However, the land productivity level in Gezira (computed or observed) is lower than research figures, and lower compared to worldwide schemes. Bastiaanssen et al. (2003) computed average yields of 2276 kg/ha for wheat and 293 kg/ha for cotton in the Indus basin, Pakistan.

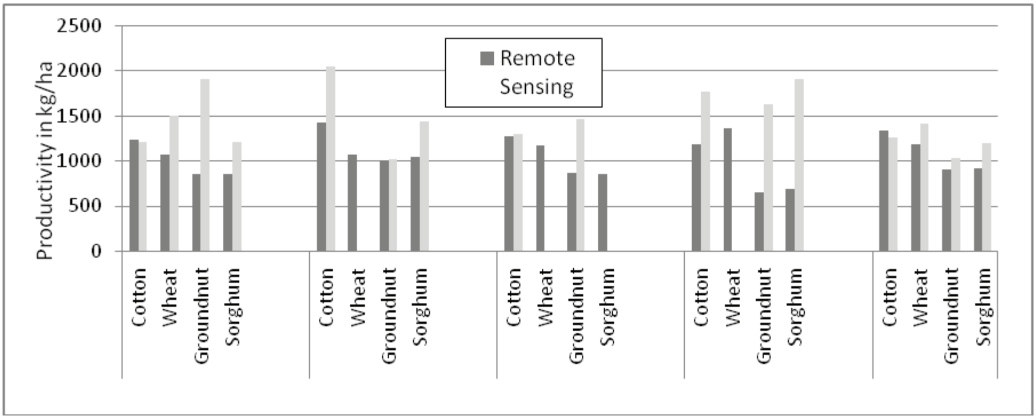

Fig. 6: Comparison of land productivity in kg/ha in Gezira and four study sites, derived from RS data against SGB record.

The water productivity (Eq. 5) of the four major crops is shown by Fig. 7. Similar to land productivity, the summer crops showed a slight decreasing trend from south to north. Unlike land productivity, these showed higher values compared to Gezira literature (Adeeb, 2006; Osman, 2009; Svendsen et al., 2009). The reasons could be attributed to different irrigation season and/or method of calculation. Here we used ET_a as the water consumption, while in those studies total canal water supply was used.

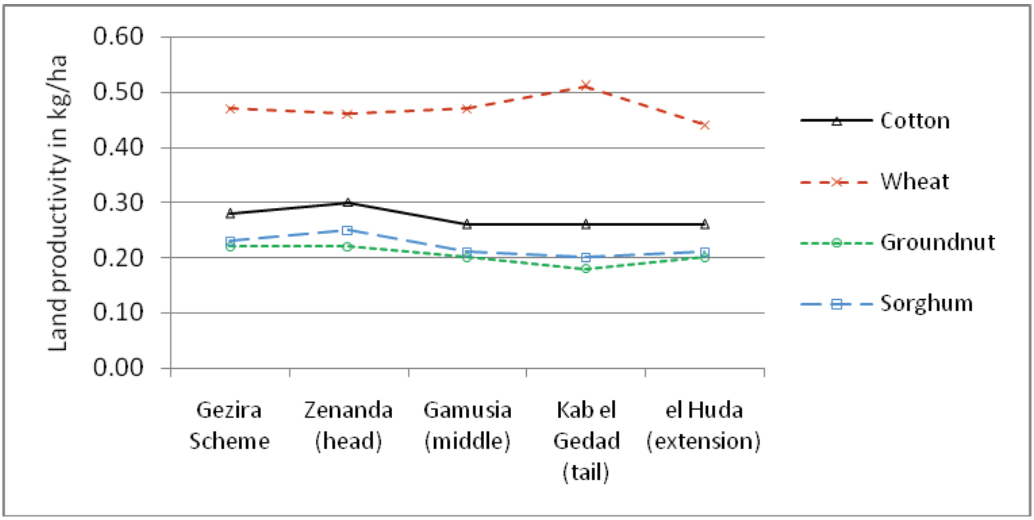

Fig. 7: Water productivity in kg/m³ of the Gezira Scheme, and the four study sites.

Cai et al. (2009) categorized water productivity into three levels, < 0.3 kg/m³ as low; 0.3 to 0.4 moderate and > 0.4 as high. Accordingly, the productivity of the Gezira wheat can be considered high; cotton is moderate; while both groundnut and sorghum are low. In general, water productivity in Gezira showed low values compared to global averages retrieved from 44 publications from 22 countries in the world (Zwart et al., 2004). Bandara (2003) using RS data computed average water productivity for three irrigation schemes in Sri Lanka to be 1.23, 0.99 and 0.76 kg/m^3. The grain productivity in Gezira was also lower compared to global grain average given by Falkenmark et al. (2004). These results indicate a highly significant scope to increase land and water productivity in Gezira.

The above results of irrigation performance in the Gezira scheme during the 2007/2008 season showed lower performance (efficiency, relative water supply and productivity) compared to other schemes of the world. However, the performance of the Gamusia major canal (middle) is comparatively high. Better water management within this major canal could have contributed to higher performance as other factors (facilities, funding etc.) are similar to other areas of the scheme (head and tail). Therefore other areas of the scheme could potentially reach high efficiency as they get similar and adequate amount of water

The analysis given here confirmed the ability of RS data to capture key performance indicators in large irrigation schemes, at least in qualitative manner if not quantitatively. Although the accuracy of results varies with scale (lower for larger scale), still the comparative value of the results is extremely useful. The literature showed, though mentioning some limitations, the potentiality of RS data for performance assessment, e.g., Perry (2005), Zwart and Leclert (2009). Key limitations of using public domain RS data in performance assessment studies could be summarized as coarse spatial and temporal resolution of the current satellite images (MODIS and Landsat). Secondly, limitation of optical satellites during cloudy conditions, almost 3 month in the Gezira case showed very high cloud coverage. The data gaps of Landsat 7 (after May 2003), though worked around through interpolation analysis, adds to the uncertainty of the results. The staggered sowing dates by the Gezira farmers makes crop classification a bit tricky, adds to sources of uncertainty in defining crop type and area cultivated. The inconsistency of ground data itself (farmers, SGB, MoIWR) showed relatively larger differences when compared to RS data.

5. CONCLUSIONS

This study focused on assessment of the performance of the Gezira irrigation scheme for 2007/2008 season using remotely sensed data (Landsat and MODIS). The results showed comparatively low performance of the Gezira Scheme. The irrigation efficiency and relative water supply were 22%, and 4.6 respectively. The land and water productivity in Gezira scheme is 1.3, 1.1, 0.9, 0.85 kg/ha, and 0.28, 0.47, 0.22 and 0.23 kg/m^3, respectively for cotton, wheat, groundnut, and sorghum. These are the four main crops in Gezira. The results over smaller spatial scales (6,000 ha to 19,000 ha) of four selected major canals at different parts of the scheme: Zenanda (head), Gamusia (middle), Kab el Jedad (tail), el Hudda (extension), showed varied performance results, but still lower than world wide irrigation performance estimates. The Gamusia major canal gave better performance compared to other areas. The high relative water supply at the four study sites -except for Gamusia, indicates adequate (even with additional losses) water supply to all parts of the scheme.

The comparison of the satellite results with field observations showed acceptable differences at the scheme level, with relatively larger error for the four study sites. The difference in cultivated area in Gezira found to be 18, 52, 0, and 0%, for cotton, wheat, groundnut, and sorghum. The land productivity results (yield divided by cultivated area) derived from remote sensing data showed slightly smaller values than literature on Gezira Scheme, while water productivity (yield divided by evapotranspiration) showed slightly higher values. This is attributed to different irrigation season, method of calculation, and possible errors in satellite data estimates.

This study confirmed the large scope for improving the performance of the Gezira Scheme, at least obtaining equal efficiency and productivity levels from different areas of the scheme. The study also confirmed the potentiality of (free) satellite data to assess irrigation performance of large irrigation systems. Despite limitations of public domain optical satellites (coarse resolution, missing data during cloudy conditions), the results are extremely useful for comparative purposes. Accuracy of future remote sensing studies can be improved by incorporating more ground truthing as well as better interpolation techniques during cloudy conditions.

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Annex A1: Cultivated area and crop types in Gezira Scheme for 2007/2008 season.

Crop type/area	Zenanda (ha)	Gamusia (ha)	Kab El Gidad (ha)	Huda (ha)	Whole Gezira (ha)
Cotton	46	0	1,037	509	37,474
Groundnut	1,672	951	595	3,652	66,624
Sorghum	1,711	1,247	1,424	5,171	199,088
Vegetable	0	1,346	348	304	105,000
Wheat	2,373	1,655	0	9,175	18,900
Total cultivated	5,802	5,199	3,404	18,811	427,086
Total available	8,520	18,952	5,846	N A	882,000

Source: Ministry of Irrigation and Water Resources, Sudan.

Annex A2: Crop yield estimate collected from the SGB, for 2007/2008 season.

	Cotton	Sorghum	Wheat	Groundnut
	(kg/ha)			
Gezira Scheme	1200	1200	1500	1900
Zenanda (Head)	2043	1429	n.a.	1020
Gamusia (Middle)	1294	n.a.	n.a.	1462
Kabelgidad (Tail)	1770	1905	n.a.	1629
Huda (Managil)	1256	1190	1405	1022

Source: Sudan Gezira Board (December 2009)

Annex A3: Monthly discharge in 1000 m^3/month for 2007/2008 season.

Month/flow in 1000 m^3/month	Zenanda	Gamusia	KabEl Gidad	Huda	Whole Gezira
Jun. 2007	3,452	467	3,279	5,199	345,050
Jul. 2007	3,566	1,988	7,626	13,131	414,800
Aug. 2007	2,207	2,384	5,992	17,875	488,450
Sep. 2007	7,535	8,706	7,865	25,659	774,200
Oct. 2007	7,554	15,441	8,153	29,645	969,000
Nov. 2007	4,906	13,329	6,328	22,389	822,530
Dec. 2007	12,527	14,407	6,970	33,181	959,250
Jan. 2008	12,587	15,757	6,591	30,375	894,500
Feb. 2008	9,170	14,275	6,462	23,386	793,500
Mar. 2008	8,021	14,607	4,946	12,803	648,100
Apr. 2008	0	0	0	0	96,812
May. 2008	0	0	0	0	113,000
Total	71,525	101,361	64,212	213,643	7,319,192

Source: Ministry of Irrigation and Water Resources, Sudan.