MAPPING CROP WATER PRODUCTIVITY IN THE NILE BASIN THROUGH COMBINED USE OF REMOTE SENSING AND CENSUS DATA

CARTOGRAPHIE DE LA PRODUCTIVITE DE L'EAU DES CULTURES DANS LE BASSIN DU NIL A L'AIDE COMBINEE DES DONNEES DE TELEDETECTION ET DES DONNEES DE RECENSEMENT

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ABSTRACT

Remote sensed imagery in combination with secondary agricultural statistic was used to map crop water productivity (WP) in the Nile River Basin. Land productivity and crop standardized gross value production (SGVP) were calculated at administrative level using the agricultural census data. Actual evapotranspiration (Eta) generated from remote sensing was used to assess crops consumptive water use. WP was then calculated by dividing SGVP by Eta in the cropped areas. Results show land productivity has a huge variation across the basin. SGVP per hectare in the basin varies from 20 \$/ha to 1833 \$/ha. Likewise SGVP, water productivity in the basin is highly variable. It ranges from 0.01 \$/m^3 to 0.2 \$/m^3. Observed patterns in the water productivity indicate that WP differences in the Nile basin are highly related to crop yield, which varies in different regions and also in irrigated and rainfed systems. Similarly, overall low WP is because of low yields, chiefly rainfed agriculture. This indicates that there is scope for enhancing WP in the Nile Basin through expanding irrigated agriculture and generally increasing yield.

Key words: *Remote sensing, Crop water productivity, Nile basin, Productivity mapping.*

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RESUME ET CONCLUSIONS

Dans ce document, la cartographie de la productivité de l'eau des cultures dans le bassin du Nil se base sur les données de télédétection combinées à des statistiques agricoles secondaires. Pour supporter la demande sans-cesse croissante en nourriture d'une population en augmentation, le secteur agricole doitproduire d'avantage au cours des prochaines décennies. Cependant, cette augmentation de production devra se faire sans augmenter la consommation en eau dans de nombreuses régions où cette ressource se fait rare. La compétition de plus en plus forte pour l'eau entre les secteurs agricoles, industriels et domestiques engendre de plus une prévision à la baisse de la quantité d'eau allouée à l'agriculture. On attend dans le futur par conséquent de l'agriculture qu'elle produise plus en consommant moins d'eau. Cela ne pourra se produire qu'enutilisant de manière plus efficace l'eau en agriculture. Cela nécessitera de plus d'atteindre des niveaux de productivité de l'eau plus élevés en maximisant le rapport des gains de production sur la quantité d'eau consommée. Le terme de productivité de l'eau (PE) est définicomme étant la masse de la production (à l'échelle parcellaire) ou la valeur économique de la production (à l'échelle du bassin) en fonction des flux d'eau entrants bruts, des flux d'eau entrants nets, de l'eau consommée, de l'eau consommée issue d'une gestion artificielle et de la quantité d'eau disponible.

Le bassin versant du Nil est un bassintransfrontalierpartagé par dix pays. Beaucoup d'entre eux dispose d'une faible sécurité alimentaire. A l'exception de l'Egypte, la productivité des terres y est faible et les précipitations y sont la principale source d'eau pour l'agriculture. Améliorer la productivité des différents usages de l'eau en agriculture est d'autant plus important que l'eau est une ressource relativement rare, que cela soit physiquement ou économiquement. Comprendre les tendancesactuelles de productivité de l'utilisation de l'eau dans le bassin est un premier pas vers l'augmentation des PE ainsi que vers l'identification des intervention à envisager.

Le bassin du Nil s'étendant sur plusieurs pays aux systèmes de prix et de marché differents, la Valeur Brute Standardisée de Production (VBSP) a étéutilisé pour calculer les benefices économiques par unité de terre agricoledans le bassin. La VBSP est un index permettant de comparer la valeur économique de certaines cultures sans tenir compteni du pays ni de la région dans lesquelles elles se trouvent. Les statistiques agricoles (comprenant la production par culture, la surface cultivée, ainsi que la valeur de la culture sur le marché pour chaque pays du bassin du Nil) ont été utilisées pour calculer la VBSP au niveau des divisions régionales. L'eau consommée par le secteur agricole est basée sur des données d'évapotranspiration (Eta) estimées par des données de télédétection. L'extraction des donnéesd'Eta en agriculture a été réalisée en utilisant des cartes d'utilisationet de couverture du territoire. La PE a ensuite été calculée grâce au rapport SGVP/Eta.

Les résultats montrent que la productivité des terres varie énormément au sein du bassin. Les VBSP par hectare au sein du bassins ont compris entre 20 à 1833 \$/Ha.De même que la VBSP, la PE au sein du bassin varie énormément. Ses valeurs sont comprises entre 0.01 et 0.2 \$/m^3. L'observation des tendances de la PE montrent que les différences de PE sont fortement liées aux rendements agricoles. Ces derniers varient suivant les pays, les régionsetsuivant les systèmes de culture (irrigué ou dépendant uniquement des précipitations). Une PE plus élevée est principalement due à un rendement plus élevé et à un meilleur revenu par unité de terrain. De la même façon l'ensemble des faibles productivités de l'eau est due à des *rendements faibles, surtout dans des systems dépendant uniquement des précipitations. Cela nous montre qu'il est possible, dans une certaine mesure, d'améliorer la PE dans le bassin du Nil en diffusant les systèmes de culture irriguée et en augmentant de manière générale les rendements. Cela met également en avant l'importance des techniques de conservation de l'eau dans le sol et de l'irrigationcomplémentaireafind'améliorer les performances des cultures dépendants uniquement des précipitations. De manière générale, cette étude montre que l'accessibilité à l'eau et la diffusion des systèmes irrigués sont les facteurs clés afin d'augmenter la productivité des cultures et la PE dans le bassin du Nil.*

***Mots clés :** Télédétection, productivité de l'eau agricole, Bassin du Nil, cartographie de la productivité.*

(Traduction française telle que fournie par les auteurs)

1. INTRODUCTION

To cope with increasing food demands by the growing population, the agricultural sector needs to produce more in coming decades. However, in many water scarce areas this increase in agricultural output must happen in the absence of an increase in water input. Moreover, it is predicted that agricultural sector will get less water allocation due to growing competition for water from other uses (Rosegrant et al., 1997). In fact, in many areas such uses have already reduced water allocation to irrigation systems or have damaged aquatic ecosystems (Ahmad et al, 2009). High producing agriculture with less water in future will be possible only by making a more productive use of water in agriculture and, to maximize the profit out of the consumed water.

The term water productivity (WP) is defined as the physical mass of production (field scale) or the economic value of production (basin scale) measured against gross inflows, net inflow, depleted water, process depleted water, or available water (Molden 1997, Molden and Sakthivadival 1999). The scale of the study defines the nominator and denominator in water productivity assessment. At field level, water productivity often deals with physical production mass per volume of the consumed water and it is expressed in kg/m^3. At a basin scale, where multiple agricultural systems exist, estimates are often based on economic value of agricultural products and actual water depletion. WP index is, also, a parameter to assess the performance of agricultural production systems. It can further help with planning water allocation to different uses and ensure the availability of water for the environmental uses (Loeve et al. 2004, Molden et al. 2007). Thus, having an understanding of current level of WP and its spatial changes across a basin can be helpful in developing future water management plans. WP maps provide such information and help to identify areas with high or low WP in any basin.

Two major components to calculate crop WP are the consumptive water use and yields. At field scale, these factors can be easily monitored by on-site measurements. However at basin scale, other means than field measurements are required to assess water consumption and attained outputs. Remote sensing has shown a high capability for estimating crops yields and water consumption assessments (Courault et al. 2005). Algorithms for calculating evapotranspiration (ET) have improved tremendously over the last 10 years (Kalma et al.

2008) which contribute to improving accuracy of estimating water consumption through satellite imagery. Ahmad et al. (2009) used data generated by remote sensing together with secondary agricultural statistics to map WP in the Karkheh River Basin in Iran. The study concluded that freely available remote sensing data and routine secondary statistics can be used as promising tools to calculate WP at different scales from sub-catchment to river basin. The methodology was further developed and used by Cai et al. (2010) to assess rice yield, water consumption and water productivity in the Indo-Gangetic river basin.

This paper uses combination of agricultural census data and remotely sensed actual ET (ETa) to map WP in the Nile basin. It further advances the methodology described by Ahmad et al (2009) to map WP at basin scale by using standardized gross value production (SGVP) as numerator in WP calculation. SGVP is an index that helps to compare the economic value of different crops regardless of in which country or region they are. Therefore use of SGVP index makes the methodology amenable for mapping WP in transboundary basins.

2. THE STUDY AREA

The Nile basin is one the world's largest basins covering 3.35 million km^2, equal to 10% of Africa's land area. It is shared among 10 countries including Ethiopia, Egypt, Sudan, Burundi, Rwanda, Tanzania, Eritrea, Kenya, Zaire and Uganda (Figure 1.).The 6700 km Nile River, the world's longest, has had a great influence in forming ancient Egypt and Egyptian culture.

Fig. 1. The Nile Basin

The River has two main tributaries, the White Nile, with its sources on the Equatorial Lake Plateau, and the Blue Nile, with its sources in the Ethiopian highlands. The Blue Nile starts at Lake Tana and flows through Ethiopia joins to the White Nile in Sudan. The Blue Nile contributes to 60% of the Nile flow and it is known by its seasonal flow due to monsoon rains. The White Nile starts at Lake Victoria and flows some 3700 km to join the Blue Nile and form the great Nile River. The Nile Basin key character is high variability, mainly caused by its large extent. Annual rainfall varies from over 2000 mm in humid areas to almost 0 in the desert (Table 1). The topography in the Nile basin changes from highland forests and lakes to swamp and to a channel flows through desert. Sudan and Egypt are the main consumers of the Nile water and Ethiopia is the main contributor to the river flow.

Table 1. Nile basin areas and rainfall by country

Country	**Total area of the country**	**Area of the country within the basin**	**As % of total area of basin**	**As % of total area of country**	**Average annual rainfall in the basin area (mm)**		
	(km^2)	(km^2)	(%)	(%)	min	max	mean
Burundi	27 834	13 260	0.4	47.6	895	1 570	1 110
Rwanda	26 340	19 876	0.6	75.5	840	1 935	1 105
Tanzania	945 090	84 200	2.7	8.9	625	1 630	1 015
Kenya	580 370	46 229	1.5	8.0	505	1 790	1 260
Zaire	2 344 860	22 143	0.7	0.9	875	1 915	1 245
Uganda	235 880	231 366	7.4	98.1	395	2 060	1 140
Ethiopia	1 100 010	365 117	11.7	33.2	205	2 010	1 125
Eritrea	121 890	24 921	0.8	20.4	240	665	520
Sudan	2 505 810	1 978 506	63.6	79.0	0	1 610	500
Egypt	1 001 450	326 751	10.5	32.6	0	120	15
Nile basin		3 112 369	100.0		0	2 060	615

Source: FAO (http://www.fao.org/docrep/w4347e/w4347e0k.htm)

3. METHODS AND DATA

3.1 Census data

Secondary crop production statistics and local market prices of crops reported by country's statistic bureau and FAO database in 2005 at administrative units were collected and were used to calculate crops gross standardized gross value of production across the basin. Provincial and District level crops data were only available for Ethiopia and Sudan. For the rest of the countries, authors used country level data. This can affect the accuracy of the results, particularly for Tanzania and Kenya, though it is less of a problem for the other countries as the majority of the country falls within Nile Basin boundary.

3.2 Land use Land cover map

Global Cover Land Cover 2008: The map is produced by European Space Agency. It has 22 land cover global classes, which are defined according to the UN Land Cover Classification System (LCCS). The product pixel size is 300m. Croplands classes in the map are; a)Post-flooding or irrigated croplands (or aquatic), b)Rainfed croplands, c) Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50), and d) Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%).

Spatially Aggregated Multipurpose Landcover database (*Africover*): The land cover map has been formed based on visual interpretation of digitally enhanced LANDSAT TM images acquired mainly in the year 1999. The land cover classes are developed using the FAO/UNEP international standard LCCS classification system. The product pixel size is 1km.

3.3 Water inflow and consumption

Tropical Rainfall Measuring Mission (TRMM) products of 2007 were used to extract rainfall amount and pattern in the Nile Basin. To estimate water consumption in agricultural lands actual transpiration and actual evpotranspiration maps of the Nile produced by "Waterwatch" were used. The Maps have been created by application of the Soil Energy Balance Algorithm for Land model (SEBAL). SEBAL is an image-processing model, which uses satellite images together with DEM and climate data and calculates ETa based on the concept of energy balance at the land surface (Bastiaanssen et al, 1998). The Eta (Fig. 2) and Ta (actual transpiration) maps of the Nile cover 2007 year from January to December based on MODIS images at 8-days intervals with 1km*1km pixel size.

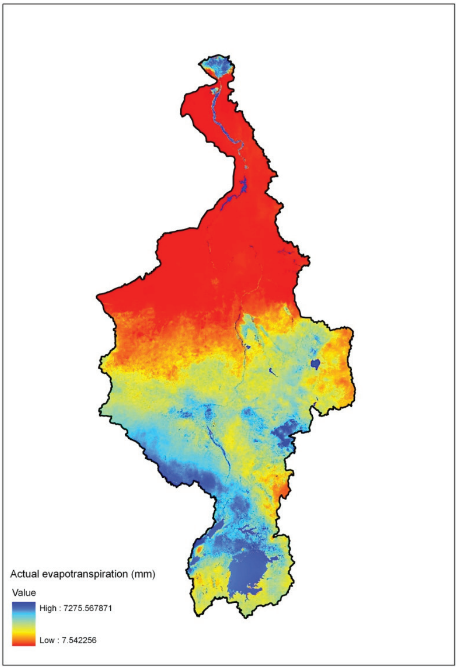

Fig. 2. Actual evapotranspiration (ETa) in the Nile basin (Waterwatch, 2007)

3.4 Water productivity mapping

Water productivity in the Nile River Basin was assessed using agricultural statistics together with remote sensing imagery products. Agricultural statistics including crop production, cropped area, and crops market value in different countries in the Nile Basin were used to calculate standardized gross value of agricultural production at administrative compartments. To cover annual farm water management, pre harvest and post-harvest, in WP analysis depleted water by agricultural section in each compartment was estimated based on annual actual evapotranspiration from cropped lands. Agricultural ETafor each land cover class was extracted from land use land cover maps and the basin ETa map. Then, water productivity was computed based on SGVP/Eta and SGVP/Ta at administrative level boundaries in the basin. Fig. 3 shows the schematic view of computing WP. It is important to note that the calculated WP by this method allows us to compare relative differences among countries and regions, but should not be considered as exact value for water productivity in each country or region.

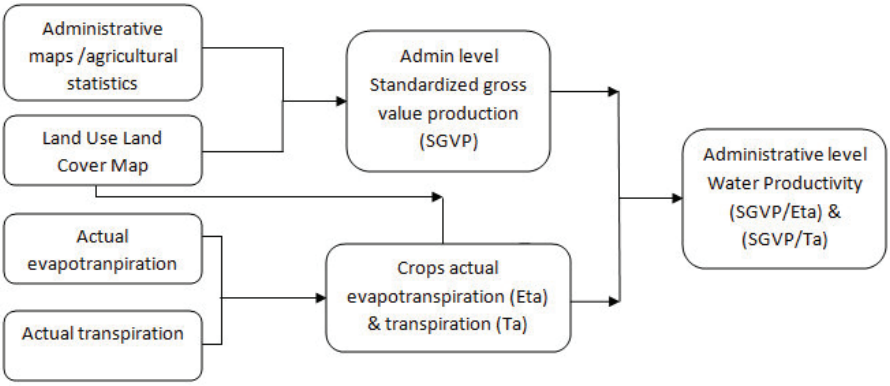

Fig. 3. Schematic view of steps to assess water productivity through combined use of agricultural statistics and remote sensed ETa

3.1.1 Standardized gross value production

Different pricing systems for agricultural goods and local market fluctuations are seen to be challenging WP assessment in transboudary basins. A way to overcome this issue and make WP comparison across a basin is to use standardized gross value of production (SGVP). SGVP is an index which helps to compare the economic value of different crops regardless of in which country or region they are (Molden et al 1998). This index converts value of different crops into an equivalent value of a dominant crop and uses international price of the dominant crop to evaluate the gross value of production. Generally, SGVP formula is presented as below:

$$SGVP_{crops} = \sum_{i=1}^{i}\left[\left(\frac{local\ price_{\ crop\ i}}{local\ price_{\ base\ crop}} \times production_{\ crop\ i}\right) \times International\ price_{\ base\ crop}\right] \qquad (1)$$

In the above formula, variables and base crop must be defined and adjusted according to characteristics of the study area. For the Nile River Basin wheat was chosen as base crop, and variable are year-to-year actual local price of different crops and their production amount in each country. International price of wheat has been taken into account as a fixed value and it is estimated by taking average of inflation corrected (2005 base year) international prices of wheat over the period of 1990 to 2005 (estimated value is 212.5 US$/ ton). Therefore, the formula is defined as follows:

$$SGVP_{crops} = \sum_{i=1}^{i}\left[\left(\frac{local\ price_{\ crop\ i}}{local\ price_{\ wheat}} \times production_{\ crop\ i}\right) \times 212.5\right] \qquad (2)$$

4. RESULTS AND DISCUSSION

4.1 Land productivity

The land productivity of the main crops in the Nile basin is shown in Figure 4. The major crop in the Nile basin in terms of cultivated area is sorghum. Areas under sorghum alone counts for almost 20% of total cropped area in the Nile Basin. About 94% of the total 8 million hectares of sorghum are rainfed. The average land productivity of sorghum in the rainfed system in the Nile is about 0.65 tons/ha, ranging from 2 tons/ha in southeastern part of the Basin, Tanzania, where annual rainfall is about 1000 mm, to less than 0.2 tons/ha in the dry regions of Sudan. Irrigated sorghum is cultivated in parts of Egypt and some Sudanese states namely White Nile, Sennar, Kassala and Gadaref. The average land productivity of irrigated sorghum is about 3.1 tons/ha. It ranges from 6.3 tons/ha in Asyiut state in Egypt to 1.2 tons/ha in Blue Nile state in Sudan.

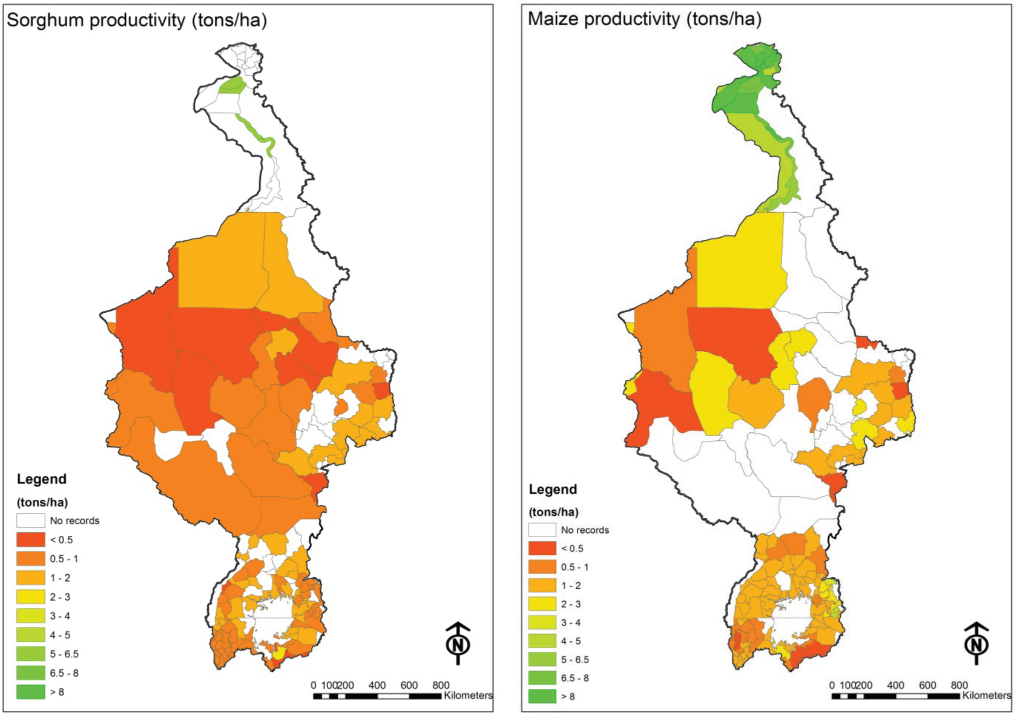

Fig. 4. Sorghum and maize and productivity in the Nile Basin (FAO statistics)

Covering nearly 10% of cropped area, maize is the second major crop in terms of the area in the Nile basin.Likewise sorghum, maize is dominantly rainfed in the Basin. The average yield of rainfed maize in the basin is near 1.3 tons/ha, ranging from 2.7 tons/ha in East Wellega in Ethiopia to less than 0.3 tons/ha in Southern Darfur in Sudan. There is huge gap between yields of irrigated and rainfed. Almost all the irrigated maize in the Basin is being cultivated in Egypt with the average yield of 8.3 tons/ha.This shows from productivity point of view the important role of irrigation, especially in the case of the water intensive crops like maize.

The economic land productivity, SGVP/ha, in the basin show a huge variation (Fig. 5). It ranges from 1833 $/ha in high performing areas in Egypt where croplands are predominantly irrigated to as low as 20 $/ha in the dry zones of Sudan where rainfall is not sufficient for rainfed agriculture and irrigated agriculture is not practiced. The gap between the economic land productivity between Egypt and the rest of the countries in the basin can also be attributed to the fact that irrigation makes it possible for farmers to grow high value crops like wheat and maize in Egypt, hence, their revenue of unit of land is higher compared to those who grow other crops in chiefly rainfed lands in the rest of the basin.

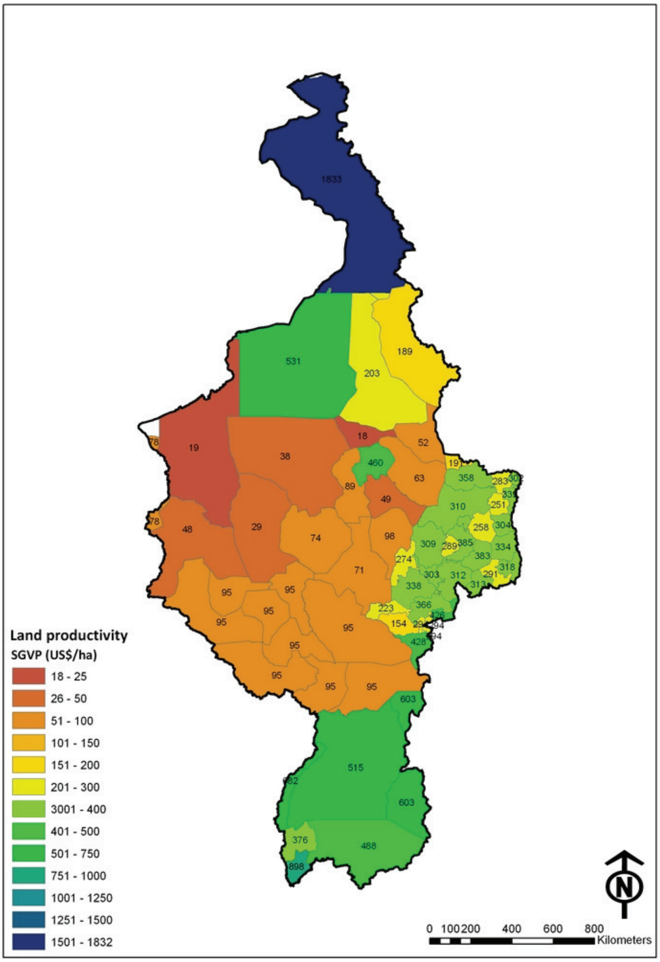

Fig. 5. Standardized gross value of production (SGVP) in the Nile Basin

4.1.2 Water productivity

The average water productivity for theNile basin is 0.045 $/ha. The minimum, maximum, and standard deviation of WP are respectively 0.006, 0.177, and 0.039. Similar to the land productivity, WP shows a huge variation across the Nile basin (Figure 6). The lowest water productivity is observed atthe western parts of Sudan. In the Ethiopian part of the Nile overall WP of crops is higher than Sudan but in general, the Ethiopian part has the second lowest WP in the Basin.

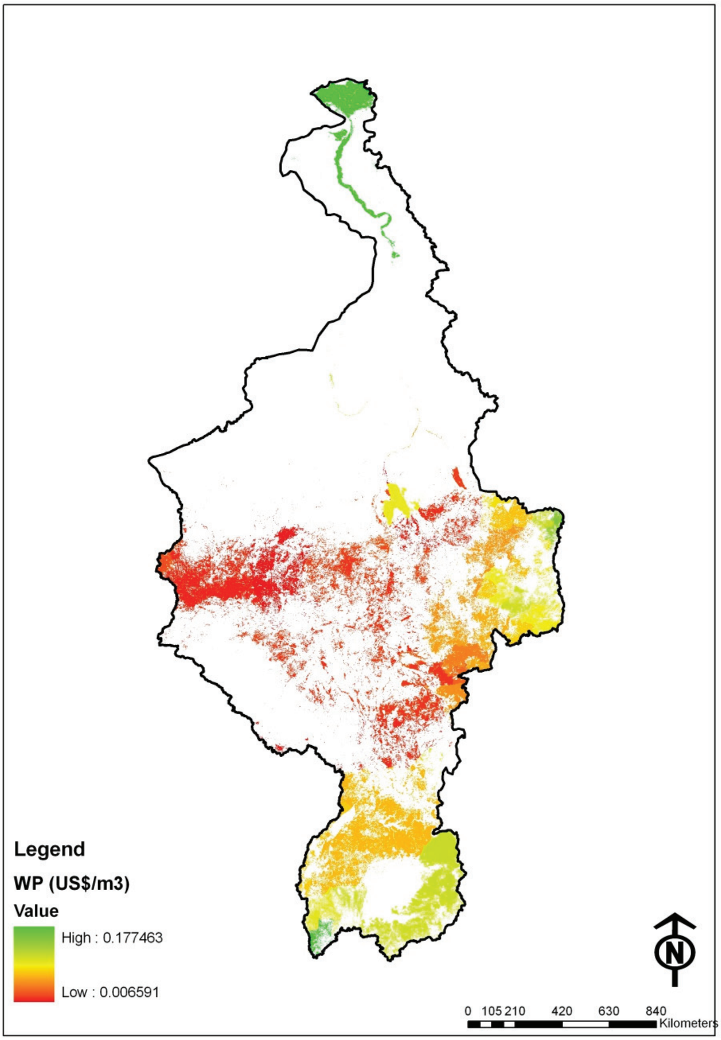

Fig. 6. Water productivity based on SGVP/ETa in the Nile basin

In general, the WP variation follows the same pattern as the land productivity which shows the main driving factor in WP changes in the Nile basin is crop yield. Higher WP in Egypt is mainly due to higher yield and the higher income from unit of land due to growing high value irrigated crops. Similarly, overall low WP in Sudan is because of low yields in its chiefly rainfed agriculture. This indicate that how important is the role of irrigation in increasing WP for the Nile Basin, where in more than two third of areas received rainfall is not enough to meet crop water demand. The real opportunity to improve overall water productivity in the basin lies in the low productivity areas where small improvements in farm water management (like supplemental irrigation, rainwater harvesting and application of soil water conservation techniques) can drastically improve land productivity and subsequently water productivity.

5. CONCLUSIONS

With the exception of Egypt, the Nile Basin's agriculture is predominantly rainfed. Therefore, crop production and land productivity are highly influenced by spatial and temporal variations of rainfall. The results of this study show that in general land and water productivity are low in the basin. However, Egypt's irrigated farming has high crop yields and WP. Variation remains the key characteristic of the basin in the case of land and water productivity, which are strongly linked to variations in resources. WP variation in the basin closely follows the land productivity variation pattern which highlights the facts that improving WP is contingent on improving yields.

Different reasons can be attributed to low agricultural performances in different countries of the Nile. In the case of Sudan the main reason for low productivity is low water availability and low rainfall. Sudan's chiefly rainfed farming suffers from water stress and the fact that crop water demands cannot be met through rainfall alone. For the very same reason, Sudan's irrigated areas like Al-Jazeera state show higher productivity of land and water. Low productivity in Ethiopia is primarily due to low water accessibility. While Ethiopia receives high amount of rainfall, and so has high water availability. However, water accessibility in Ethiopia is very lowdue to lack of water control and storage infrastructure.Therefore, majority of generated run-off leaves the country without being utilized. In effect, the country's agriculture is dominantly rainfed which, in general, has low productivity due to large spatial and temporal variations in rainfall. In general, this study shows increasing water accessibility, expanding irrigated areas, and use of water harvesting techniques are the key factors for improving productivity of crops and productivity of water in the Nile Basin.

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