DOI number: 10.5027/jnrd.v1i0.03

JOURNAL OF
NATURAL RESOURCES
AND DEVELOPMENT

Analysis of water footprints of rainfed and irrigated crops in Sudan

Shamseddin Musa Ahmed [a*], Lars Ribbe [b]

[a] Water Management and Irrigation Institute, University of Gezira, Wadmedani, Sudan.

[b] Center of Natural Resources and Development, Cologne University of Applied Sciences. Betzdorfer Straße 2. 50679 Cologne, Germany.

*Corresponding author: shams_id@yahoo.com

Article history

Received 04.08.2011
Accepted 11.10.2011
Published 06.12.2011

Keywords

Water footprint
Virtual water
Rainwater harvesting
Sudan

Abstract

Water rather than land is the limiting factor for crop production in Sudan. This study attempts to use the water footprint (WFP) and virtual water concepts to account for crops water consumption under the Sudanese rainfed and irrigated conditions. The general average of the green WFP of sorghum and millet were found to be about 7700 and 10700 m^3 ton^{-1}, respectively. According to experimental results at three different climates, in-situ rainwater harvesting techniques could reduce the WFP of rainfed sorghum by 56% on the average. The blue component (surface water) shows the highest contribution to the total WFP of irrigated crops: 88% for cotton, 70% for sorghum, 68% for groundnut and 100% for wheat. However, the role of the green water (rainwater) is not marginal since it largely influences the operation and maintenance (silt clearance) of the gravity-fed irrigation system. Under normal conditions, the annual total virtual water demand of sorghum (the dominant food crop in Sudan) is found to be 15 km^3, of which 91% is green water. During a dry year, however, Sudan could experience a deficit of 2.3 km^3 of water, necessitating the adoption of a wise food stocking-exporting policy.

Introduction

The global increase in population and changing consumption patterns undoubtedly will put more pressure on food supply and natural resources. For instance, the worldwide required increase in the cereal production is projected at 55-80% by the year 2050 (De Fraiture et al. 2010). This can be achieved either through increasing the cultivated area (horizontal increasing), increasing yield per unit of cultivated area (vertical increasing) or both. In most cases water availability is the limiting factor rather than the land (Wallace 2000).

Generally, irrigated (blue water) and rainfed (green water) agricultural systems provide most of the food supply. There are discernible reasons why attention should be paid towards rainfed agriculture. It covers 80% of the worldwide agricultural land (Rockström et al. 2003); there is no much remained blue water (surface and groundwater), especially in arid, semi arid and dry sub humid areas, for food production, thus green water (infiltrated rainfall, stored as soil moisture) is the viable alternative (Hoff et al. 2010; Rockström et al. 2009). Rainfed agriculture, especially under arid and semi arid areas, still holds considerable potentiality (De Fraiture and Wichlens 2010; Rockström et al. 2010); in spite of its tremendous brought benefits, irrigation development has high environmental and social costs (Aldaya et al. 2010; De Fraiture et al. 2010; Gleick 2003); and from a water management perspective, two thirds of global rainfalls infiltrate into soils forming the green water; thus, concentration only on blue water gives no sustainable solutions (Hoff et al. 2010); however, irrigated agriculture sustains a significant and reliable share of food production, 22% of the water consumed by crops comes from blue water (De Fraiture et al. 2010). In addition, by increasing the irrigated area by 33%, irrigation water could contribute to 55% of the global total value of food supply by the year 2050 (De Fraiture et al. 2010). Thus, a better field water management for both irrigated and rainfed agriculture is of utmost important.

The quantification of the water use may be a good support for conducting in depth analysis and planning.

Recently, the concept water footprint (WFP) has been introduced as a volumetric measure of water consumption and pollution, in order to obtain explicit spatiotemporal information on how water is appropriated for various human purposes (Hoekstra et al. 2009). Three kinds of WFP (volume/mass) are formulated: (1) the blue WFP: the consumption of surface and groundwater water; (2) the green WFP: the consumption of the infiltrated rainwater in the soil stored as soil moisture, and (3) the grey WFP which is related to the polluted water. These WFP can be used to assess the water use and its sustainability at different spatiotemporal levels, i.e. global, regional, national, provincial, year, and across years (Aldaya et al. 2010; Bulsink et al. 2010; Chapagain and Hoekstra 2010; Ercin et al. 2011; Hoekstra and Hung, 2005; Ma et al. 2006; Mekonnen and Hoekstra 2010).

An alternative term for the WFP of a product is its virtual water content (Hoekstra et al. 2009). While the term virtual water refers to the volume of water embodied in the product alone, the WFP refers not only to this volume but also to the sort of water used, when and where this volume is used (Hoekstra et al. 2009). Therefore, the term WFP has a broader meaning than the term virtual water. Succinctly, WFP of a product is a multi-dimensional indicator, whereas 'virtual-water content' or 'embedded water' refers to a volume alone (Hoekstra et al. 2009). Thus, WFP can be used also to assess the virtual water balance for a given area.

The arable land of Sudan is estimated at 84 million hectare, of which only 2% is under irrigation due to the limited blue water as has been stipulated in the Nile Waters Agreement in 1959. This is coupled with limited storage capacities (Table 1), which are mainly used for generating hydropower and supplying irrigation water for four main gravity-fed irrigation schemes. These are Gezira (established in 1925), New Halfa (1964), Suki (1971) and Rahad (1977). Cotton, sorghum, groundnut and wheat are the main grown crops.
Sudan has almost used its share in the Nile River waters (Abdalla 2001). The Sudanese Ministry of Irrigation and Water Resources has projected that Sudan would experience a deficit of 18 km^3, by the year 2030 as the total need would be 48 km^3, compared to the current available of 30 km^3 (Eldaw 2003). Accordingly, the current capita share (830 m^3) is expected to drop down to be only 530 m^3. Thus, the Sudan agricultural expansion depends entirely on the rainfed sector.

The current rainfed area is roughly estimated at 18% of the Sudan arable land, of which 60% is traditional rainfed agriculture (it depends on traditional technology and usually practices in small areas near to homesteads), which is mainly practiced in the regions of Blue Nile, Sennar, Gezira, White Nile, Kordofan and Darfur. The remaining is cultivated under the mechanized rainfed sub-sector (characterizes by its large areas and a heavy use of agricultural machineries), which is mainly practiced in Gedarif State. Sorghum, cotton, millet, sesame, and groundnuts are the main rainfed crops, where sorghum is the dominant (Food and Agriculture Organization of the United Nations, FAO 2006). The yield of rainfed crops is characterized by its high variability due to the high variability in seasonal rainfall (total annual country average ≈1000 km^3). Accordingly, farmers adopt low-input rainfed agriculture as a risk management option. This reduces the yield per unit of land and water. Shamseddin (2009) found that the low yield of rainfed crops in Sudan is mainly due to rainwater mismanagement, agreeing with Rockström et al. (2010). Generally, the rainfed sector produces around 95% of the pearl millet, 78% of the sorghum, 67% of the groundnut and 100% of the sesame has grown (FAO 2010).

Studies on the quantification of the water footprint for agricultural products are rare or absent in Sudan. To the best of our knowledge, this study represents the first attempt to document the field WFP and virtual water in order to estimate crops water use (irrigated and rainfed), water saving opportunities, sustainability and food security in Sudan. Thus, this study would be a baseline for future studies.

Table 1. Main storage reservoirs capacities (km^3 in Sudan)

Dam	Design capacity	Actual capacity	Establishment
Sennar	0.9	0.4	1925
Rosiers	3.4	1.9	1966
Khashmelgrba	1.3	0.5	1964
Geblawlia	3.0	3.0	1937

Material and Methods

The green and blue WFP of crops

The calculation of the WFP has been done following the approach described in Hoekstra et al. (2009). This approach needs two main inputs, the evapotranspiration and yield. The reference evapotranspiration (ETo) is estimated on the basis of the Penman-Monteith formula using the computerized program CROPWAT 8.0, which needs minimum and maximum temperature, relative humidity, wind speed and sunshine hours that were collected from the Sudanese meteorological authority and the FAO program "CLIMWAT". The crop evapotranspiration (ETc) was calculated by multiplying ETo with a specific crop factor (Kc), taken from Adam (2005) and Allen et al. (1998). Mostly, the crop water requirements can be met either with green water or/and blue water. For the calculation of the green water evapotranspiration (*ETgreen*), the crop water requirement option (optimal conditions) in the CROPWAT 8.0 model has been used as described in (Aldaya et al. 2010; Chapagain and Hoekstra 2010; Hoekstra et al. 2010; Mekonnen and Hoekstra 2010). The *ETgreen* is calculated as the minimum of the total evapotranspiration and effective rainfall, *Peff*, (Hoekstra et al. 2009) using a time step of ten days. The CROPWAT model calculates the effective rainfall on the basis of the USDA Soil Conservation Service. Sorghum and millet rainfed crop were studied as they dominate the Sudanese food supply, especially in rural communities. Sowing dates and yields data were taken from the statistical department of Sudanese Ministry of Agriculture, Mohamed (2003), Mohamed (2005), Elamin (2006) and FAO (2010). For the calculation of the blue water evapotranspiration (*ETblue*), the irrigation schedule option in the CROPWAT 8.0 model was used, following the local farmers' practices, i.e. the irrigation interval and application depth are 14 days and 100 mm, respectively. *ETblue* is calculated as the difference between the total evapotranspiration (*ETc*) and the total effective rainfall. When, within the period considered, *Peff* is greater than *ETc*, the *ETblue* approaches zero (Hoekstra et al. 2009):

$$ETgreen = \min(ETc\ ,\ Peff) \quad (1)$$

$$ETblue = \max(0,\ ETc - Peff) \quad (2)$$

$$ETc = Kc * ETo \quad (3)$$

The green WFP (*WFPgreen*) and blue WFP (*WFPblue*) were calculated as follows:

$$WFPgreen = \frac{CWUgreen}{Y} \quad (4)$$

$$WFPblue = \frac{CWUblue}{Y} \quad (5)$$

Where CWU refers, respectively, to the green and blue components in the crop water use ($m^3\ ha^{-1}$) and Y is the crop yield ($kg\ ha^{-1}$). Virtual water has been defined as "the water used in the production process of agricultural or industrial product consumed in the product (Ma et al. 2006). This study concerns on assessing the virtual water of sorghum crop for selected Sudanese states by multiplying the sorghum trade amount ($t\ year^{-1}$) with their associated volume of water content. This is done following the methodology mentioned in Ma et al. (2006), where the net import of the sorghum into a region (or net export from the region) is a function of regional production, stock changes and domestic utilization:

$$NI\ (n_i\ , t\ , c) = DU\ (n_i\ , t\ , c) - P\ (n_i\ , t\ , c) - \triangle S\ (n_i\ , t\ , c) \quad (6)$$

Where, $NI\ (n_i,\ t,\ c)$ is the net import of an importing region (n_i in year t as a result of trade of product c); DU is the total domestic utilization, P is the production of a product c and ΔS is the change in stock, i.e. no change is assumed. The net virtual water import related to the trade in the product c ($n_i,\ t,\ c$), is equal to the net import volume of the product c multiplied by its virtual water content ($n_e,\ t,\ c$) in the exporting region n_e. Sorghum crop is used because it is the dominant food diet and the dominant cultivated crop in Sudan (FAO 2006). The per capita annual sorghum food supply has been taken from FAO (2007).

Rainwater harvesting experiments

The experiments last for two consecutive seasons, using the 1-factor completely randomize design (tillage factor). The experiment total number of runs was six; each run has a size of 13 x 70 m. Furrow and chisel tillage as in-situ rainwater harvesting techniques (IRWHT) were implemented against control plots at three different climatic zones: arid (Wadmedani station, Gezira state), semi-arid (Sennar station, Sennar state) and semi-humid (Abunaama station, Sennar state). The locations of the three sites are shown in Figure 1. For each IRWHT, three replicates were made. In order to avoid effects of water stagnation, the seeds were placed a little bit higher than the beds of the furrows by a conventional planting method (traditionally known as Saluka) with 0.2 - 0.3 m between holes (3 - 4 seeds per hole). However, for the control treatment plant distances of 0.7 – 0.8 m between holes were used (the widespread practice adopted by local farmers). Dykes at the plots ends were constructed manually in order to collect the in situ surface runoff, i.e. maximizing the infiltrated rainwater volume so as to increase the soil moisture content in the root zone. The experimental sites belong to the central clay plain, where the soil is vertisols (Elias *et al*., 2001; Blokhuis, 1993) with a clay percent of 52-58%. On one hand the soils are characterized by moderate to poor mineral fertility due to low content of nitrogen, available phosphorus, and sometimes potassium (FAO, 2006). In spite of these deficiencies, rainfed farmers, whether in traditional or mechanized sector, do not use fertilizers in order to reduce the cost, i.e. rainfed farmers, especially traditional farmers, receive very low percent of all formal agricultural credit, besides that they receive few support services such as research and extension (FAO, 2006). On the other hand, due to relatively higher cation exchange capacity and percentage base saturation values, these soils have greater ability to retain added nutrients and reduced tendency to lose by leaching (FAO, 2006).

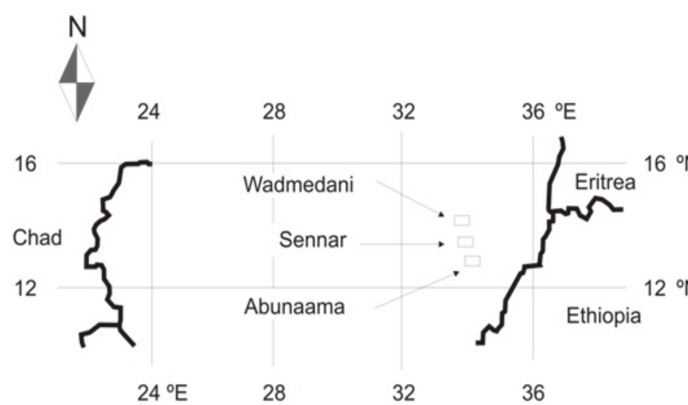


Figure 1. Locations of the three selected experimental sites, central Sudan

In Wadmedani site, soil water contents were determined by the gravimetric sampling method. The gravimetric soil moisture was converted to the volumetric soil moisture (V) using the soil bulk density. Thus, the crop water use (*CWU*) is obtained by a water balance equation, which under heavy clay soil conditions is simplified as follows (Adam 2005):

$$\Delta S = Peff - CWU \quad (7)$$

Where, ΔS stands for the change in soil moisture during the period *t* and *Peff* is the effective rainfall. This simplification is adopted as the ground slope is gentle (10 cm km^{-1}) resulting in a negligible runoff; the deep percolation is zero (heavy clay soil) and zero leaching requirements (no salinity). Therefore, the crop water use can be easily determined from measurements of the soil moisture (Adam 2005). The *CWU* (mm) is converted to m^3 ha^{-1} by multiplying it with the factor 10. Thereafter, the green water footprint of rainwater was calculated as follows:

$$WF_P = \frac{CWU}{Y} \quad (8)$$

Where, WF_p is the water footprint (m^3 kg^{-1}) and Y is the sorghum yield (kg ha^{-1}).

Results and Discussion

Water footprints of rainfed sorghum and millet

Rainfall data of the main producing rainfed regions in Sudan are presented in Table (2). It is obvious that annual rainfalls were associated with a high variability of 25%, on average. In the total term, the green water footprint of sorghum (7700 m^3 t^{-1}) is found lower than that of the millet (10700 m^3 t^{-1}). This is mainly due to the high yield of sorghum compared to that of millet, as there is no large difference found in the ETgreen for both crops. Figure 2 shows the water footprints of sorghum and millet for each region. El Obied region shows the highest water footprints of both sorghum and millet of 21 and 33 m^3 kg^{-1}, respectively. This is caused by the low yields. Moreover, El Obied region (arid climate) is neighboring the boundaries of the semi desert climate zone and this may affect the water consumption. Moreover, there were evidences that desertification is creeping down from the northern part of the Sudan (FAO 2006). In contrast, due to the high yields, Gezira region shows the lowest WFP for both sorghum and millet of 3700 and 4200 m^3 ton^{-1}, respectively. It is probably that the Gezira irrigated scheme affects positively the micro climate of the region, i.e. a long period of cultivation (86 years) coupled with a huge gravity-fed irrigation system (0.15 million km in length). Globally, Mekonnen and Hoekstra (2010) estimated the water footprints of rainfed sorghum at 1300 m^3 t^{-1}. Accordingly, there is a large room for a water saving opportunity in the Sudanese rainfed sector. It is worth mentioning that the grey water footprint is neglected herein as the rainfed agriculture in Sudan is a free-fertilizer practice, i.e. a risk management option taken by farmers and there is no re-use of the irrigation water or waste water.

The differences in climate and agricultural practices lead to a large regional variation in the green WFP for both sorghum and millet i.e. 26% and 29%, respectively, with the exclusion of El Obield region. Due to the lack of supporting services such as agricultural extension, rainfed farmers depend entirely on their own acquired knowledge, traditional technology, traditional varieties and cultural practices. For instance, farmers are used to spread seeds regardless of the rainfall onset (a dry planting) in the Kordufan region (arid climate). While farmers of Gezira (arid climate), Sennar and Gedarif (semi-arid climate) regions are permanently sowing sorghum during the period 20-30th of July so as to ensure adequate accumulation of soil moisture (Shamseddin 2009). Figure 3 shows that proper sowing dates can help in effectively using of rainwater for crop production. For example, during the second experimental season a large amount of rainfall was misuse because the sowing date was late. In addition cultivating on a proper sowing date is one of the ARC recommended strategies for controlling the midge sorghum problems. Rainfed farmers use to cultivate traditional seeds since the improved seeds is too costly (inadequate formal credit), and these seeds are not easily available everywhere. FAO launched a program in order to provide improved seeds; however, this provision is restricted to conflict-affected and post-conflict areas (FAO 2011). In spite of its general low rate, adoption of RWHT by rainfed farmers is different from a region to another in Sudan. Shamseddin et al. (2009) reported that only 0.05% of the farmers is adopted RWHT in Sennar region. However, the adoption rate at western regions of the central Sudan (Kordufan and Darfur) is relatively high since farmers became more willing to adopt RWHT as a direct result of the witnessed historical drought events in the region. Therefore, there is a high need for conducting solid research on proper sowing dates, increasing formal credit to traditional rainfed farmers and an initiation of nation-wide RWHT capacity building programs.

Table 2. Mean annual rainfall and coefficient of variation (CV) for the studied rainfed areas

Station	Mean (mm)	CV
Kadugli	681	0.21
Damazine	698	0.17
Gedarif	612	0.20
Nyala	365	0.23
El Obied	329	0.30
El Renk	495	0.23
Sennar	424	0.25
Wadmedani	281	0.29
El Fasher	193	0.34

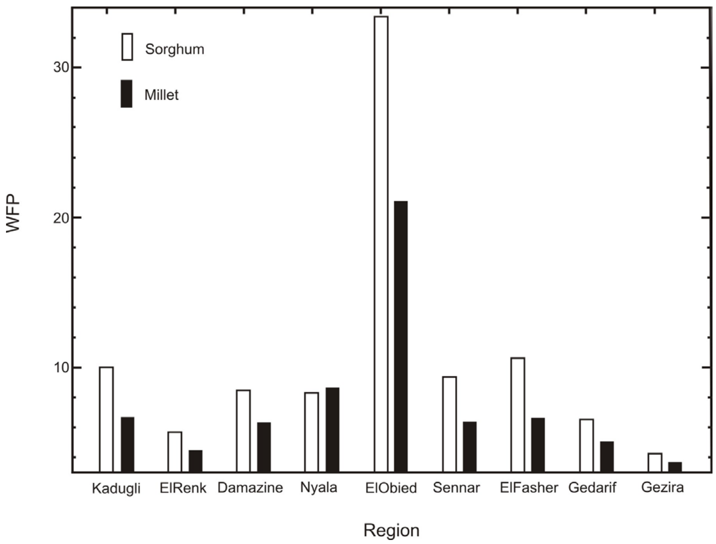


Figure 2. Water footprints (WFP $m^3 kg^{-1}$) of rainfed sorghum and millet crops at selected regions in Sudan.

Table 3 presents the influence of rainwater harvesting techniques (RWHT) on the rainfed sorghum WFP in the arid, semi arid and semi humid climatic zones. The average WFP of sorghum under rainwater harvesting is found to be 3000 $m^3 t^{-1}$. It is obvious that the implementation of RWHTs resulted in reducing the WFP of sorghum (grain) by 80, 72 and 55% compared to controls in arid, semi arid and semi humid climates. Similar influences of RWHTs were observed in the production of dry matter of sorghum, as the average WFP was found to be 800 $m^3 t^{-1}$ (dry matter), compared to 2100 $m^3 t^{-1}$ of the control plot. These are attributed to biophysical effects of RWHTs in increasing the benefits drawn from rainwater through increasing soil moisture and in turn increasing the transpired water ratio to the total evapotranspiration water. Abdelhadi et al. (2002) found that RWHTs have increased the soil moisture in the root zone by 27-46% in the Butana area (semi-arid), central Sudan. In rainfed agriculture the distribution of rainfall is more important than its total amount. For instance, a dry spell (a period of 14 days having rainfall of less than 1.0 mm) at a flowering/mid growth stage (sensitive stage) would harm the crop yield event if the crop receives enough water during the initial or harvesting stage. Therefore, Dry spell mitigation is a common water management practice for minimizing the risk of crop failure due to drought (Rockström et al., 2010). RWHTs, as water management techniques, could bridge the dry spells. For instance, in the semi-arid climatic zone, during the first experimental season a long dry spell of 42 days occurred during the sorghum mid stage i.e. after 63 days of sowing (DAS). And during the second season, a dry spell of 18 days occurred during the development stage i.e. 46 DAS. These dry spells resulted in reducing the yield of the control plots, compared to the yield of the RWHT plots. This is because RWHTs are capable to retain relative more soil moisture content. For instance, the implementation of RWHTs resulted in significant increases in the soil moisture content ($P \approx 0.01$), compared to the control, especially during the period 30-September, which corresponds the mid-growth stage of rainfed sorghum (a sensitive stage for water stress) during the normal hydrological conditions of the first season in Wadmedani site (Figure 4). Accordingly, the adoption of RWHT is a very good viable option for water saving. Noting that, the cost of the tested RWHTs is tolerable for poor farmers. FAO (2011) attributed the failure of RWHT projects during the 1980s and 1990s to the lack of technical knowledge, and to inappropriate approaches of selection with regards to the prevailing socio-economic conditions. Therefore, a technical know -how program is badly needed.

Table 3. Water footprints ($m^3 kg^{-1}$) of the rainfed sorghum under rainwater harvesting techniques (RWHT), compared to control plots in arid, semi-arid and semi-humid areas of Sudan

RWHT	Arid conditions (Wadmedani)		Average
	First season	Second season	
Furrow	1.8	5.3	3.6
Chisel	2.6	3.8	3.2
Control	8.5	26.3	17.4
Semi-arid conditions (Sennar)			
Furrow+Chisel	2.4	3.6	3.0
Control	6.5	14.6	10.6
Semi-humid conditions (Abunaama)			
Furrow+Chisel	6.8	1.3	4.1
Control	13.7	4.5	9.1

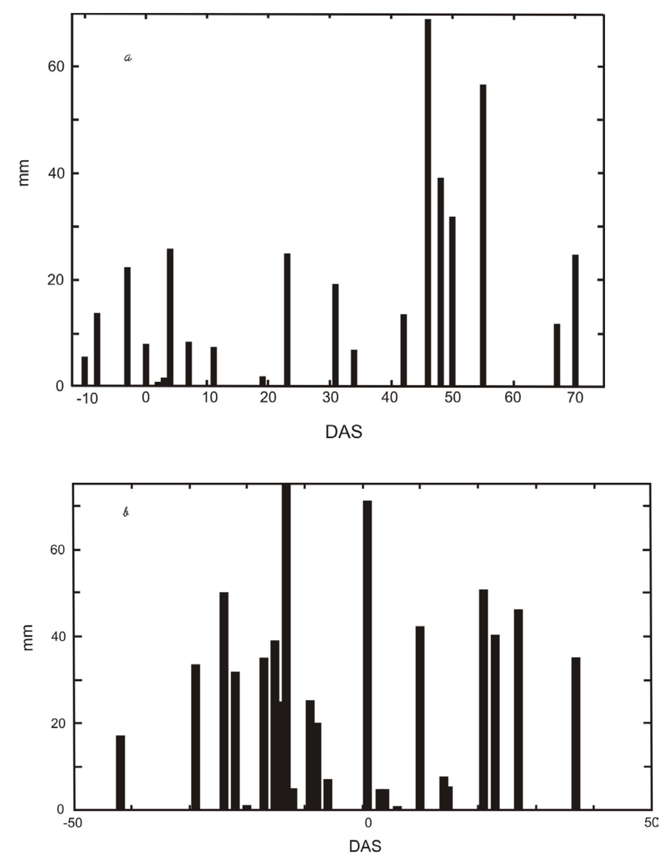


Figure 3. Distribution of rainfall during the first (a) and second (b) seasons in semi-arid climate of the Sennar site. DAS is the days after sowing (positive numbers refer to DAS).

Water footprints of irrigated crops

Figure 5 shows the WFP of the main gravity-fed grown crops (cotton, sorghum, groundnut and wheat), compared to that of the Sudanese Agricultural Research Corporation (ARC). ARC WFPs were the lowest (optimum conditions and practices), revealing that all irrigated crops in Sudan are beyond their potentiality, which gives a room for water saving opportunity. In the average term, cotton shows the highest WFP of 10400 m^3 t^{-1} as it has the longest growing season. Spatially, the highest cotton water consumptions were found in New Halfa, Suki, Rahad and Gezira, respectively. Mekonnen and Hoekstra (2010) estimated the average WFP of cotton at 3800 m^3 t^{-1}. Gezira scheme shows the lowest WFP due to the relative long experiences of farmers, highest governmental attention (the largest and oldest scheme) and to the continuous water management building capacity program conducted by the Water Management and Irrigation Institute, University of Gezira. Generally, there are rooms found for saving about 8, 2, 4 and 4 m^3 from every produced kg of cotton, sorghum, groundnut and wheat, respectively, without impairing the yield. This requires an intensive field water management capacity building program.

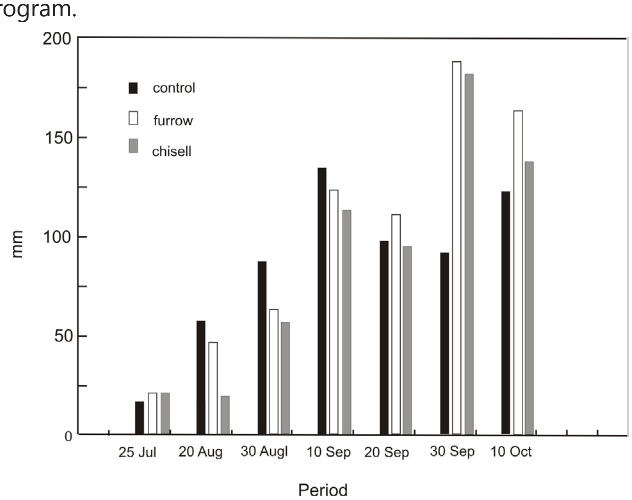


Figure 4. Soil moisture contents of the control, furrow and chisel plots during the first experimental season in Wadmedani site.

Globally, Mekonnen and Hoekstra (2010) estimated the irrigated agriculture WFP at 2230 km^3 yr^{-1} (48% green, 40% blue, and 12% grey). In this study, the averages of the blue and green components for cotton, sorghum, groundnut and wheat are shown in Figure 6. It is clear that the blue water component has the largest contribution to the WFP of irrigated crops. For cotton, the blue water component contributes 88% to the total water footprint, 70% for sorghum, 68% for groundnut and 100% for wheat. This is because most of the irrigated schemes in Sudan are situated in the arid climatic zone where rainfall is not exceeding 300 mm per annum coupled with a high variability and high evapotranspiration. However, the contribution of green water is not marginal as found in groundnut and sorghum (Figure 7). In addition, the operation and maintenance of the surface irrigation systems of the four schemes are highly depended on rainfall. Because, the silt concentration in the Nile waters during July and August are high, thus, during the summer growing season (June-November) the less the water indenting is the less the silt accumulation in the canals and fields. This only can be achieved if rainfall is good, spatially and temporally. Table (4) summarizes the silt accumulation amounts in the canals (main, major and minor) and fields of the Gezira scheme. Moreover, currently due to silt accumulation Sennar and Khasm Elgirba dams have lost more than 50% of their storage capacities, which resulted in reducing the total cultivated areas (Abdalla 2006). Thus, rainfall has indispensable role in water management in the main irrigated schemes of the Sudan.

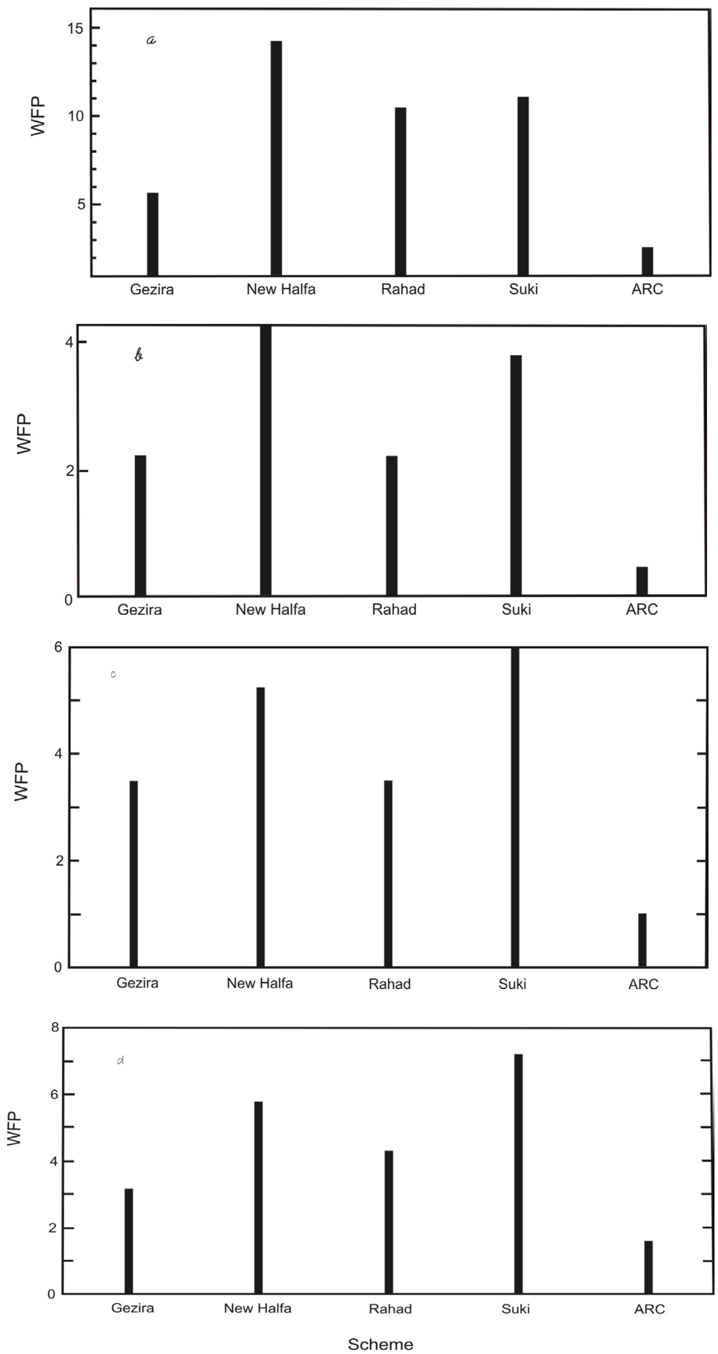


Figure 5. Water footprints (WFP, m^3 kg^{-1}) for cotton (a), sorghum (b), groundnut (d) and wheat (d) grown in the main gravity-fed irrigation schemes, compared with the Agricultural Research Corporation (ARC) in Sudan.

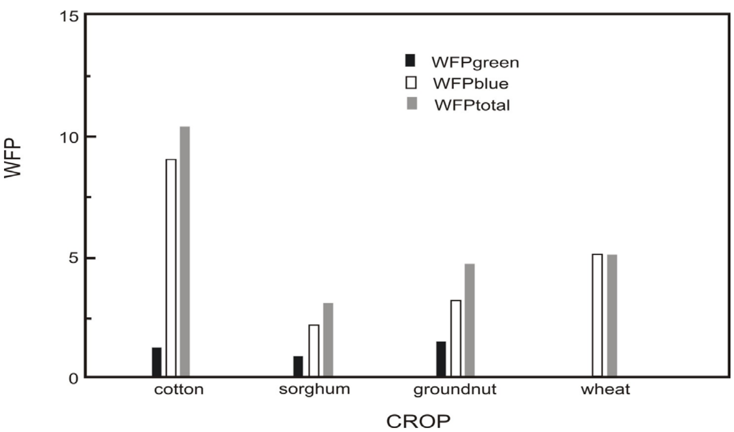


Figure 6. Averages of the green water footprint (WFPgreen, $m^3 kg^{-1}$), the blue water footprint (WFPblue) and the total water footprint of the main irrigated crops, Sudan

Table 4. The annual average of silt accumulation in the Gezira irrigated scheme with a total cultivated area of 0.92 Mha

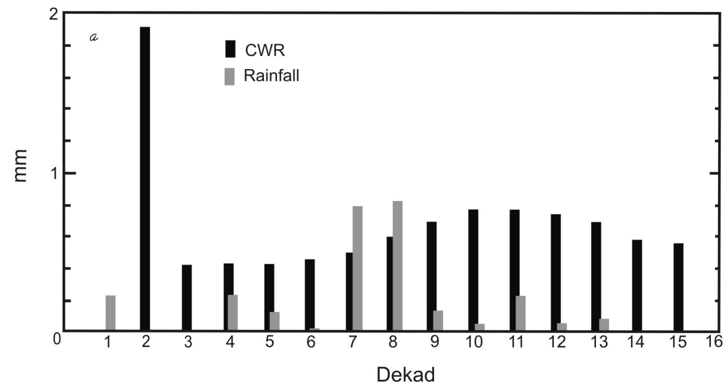
Site	Main canal	Major canal	Minor canal	Field
Sediment (Mm^3)	0.5	2.1	3.0	3.5

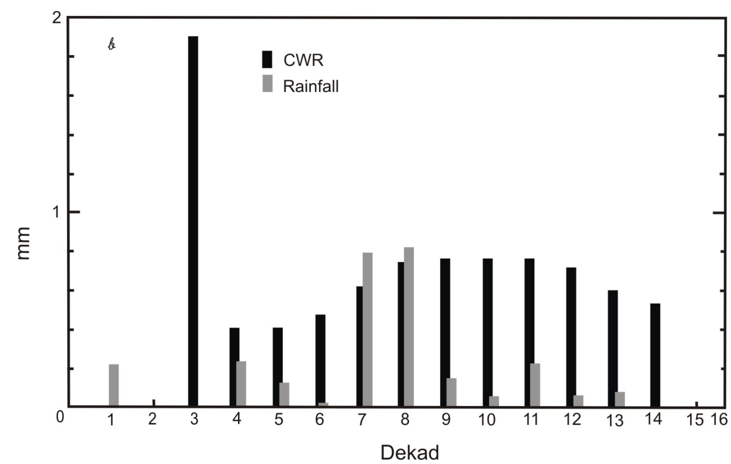
Source: Elamin (2006)

Sorghum's virtual water for selected states

Two seasons were selected. The first represents normal hydrological conditions and normal yield (season 2006/2007). The second represents below normal hydrological conditions and low yield (season 2009/2010). Table (5) shows the obtained results. It is obvious that, during the normal year there is a virtual water surplus of 5 km^3, which can be either stored (strategic stock) or exported. In contrast, during the below normal year the country experiences a water deficit of 2.3 km^3. During the normal hydrological year the total national water used in sorghum production is 18.9 km^3, of which 91% is green water. Thus, rainwater is largely contributed in the Sudan's food security. However, the severe droughts cycles during 1970s and 1980s in the central Sudan jeopardized the dependable rainfed sorghum supplies; it is therefore the government became more willing to tolerate grain production in the Gezira scheme, at the expensive of cotton crop (Guvele 2002).

Among the studied states, Gedarif and South Kordufan produce the highest virtual water; while the states of North Kordufan, North Darfur and South Darfur show negative virtual water. Accordingly, these states experience food supply shortages. Thus, the Sudanese food supply is fragile due to the high dependency on the green water, which in turn shows low-yield boundaries due to rainfall variability, drought and dry spells. Consequently, the Sudanese government needs to be very careful and wise in designing its exportation policy, considering that the irrigated production alone is incapable to meet the shortage without the help of the green water.





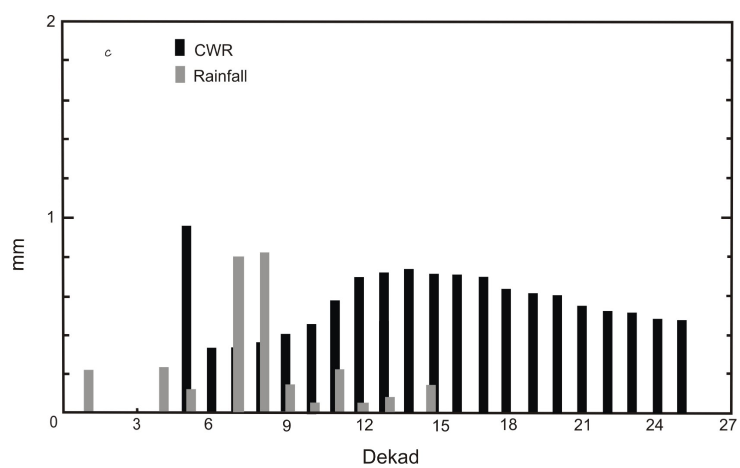


Figure 7. Crop water requirements (CWR $m^3 ha^{-1}$) of groundnut (a), sorghum (b) and cotton (c) and rainwater during normal hydrological conditions of the Gezira irrigated scheme. Data of crop water requirements are obtained from Adam (2005). Rainfalls are in situ data collected during the first experimental season in Wadmedani site. The first CWR data represent pre-irrigation events (added for moistening the soil in order to make it workable), which can be escaped in case that good showers are received

Table 5. Sorghum's virtual water balance (km^3) for selected Sudanese states during a normal year (2006) and a below normal year (2010)

State	Normal year	Dry year
RiverNile	0.07	0.04
Gezira	0.81	0.28
W.Nile	0.63	0.05
Sennar	1.10	0.08
Gedarif	2.48	0.47
Kassala	0.44	-0.15
B.Nile	1.35	0.30
N.Kordufan	-2.12	-3.23
S.Kordufan	2.30	1.80
N.Darfur	-0.94	-1.00
S.Darfur	-1.12	-0.93
Total	5.0	-2.29

Conclusion

The obtained results provide deeper insights into the current field water uses situation in Sudan. The water footprint concept is found easy to apply and less data – demanding while giving useful hints regarding field water uses and water saving opportunities.

The Sudanese food supply is found dependent on the green water contribution. A large variation, however, in the green WFP is found, which may attribute to the variability in rainfall and agricultural practices. Using of rainwater harvesting techniques could reduce this variation as well as water consumptions without impairing yields and sustainability. The blue water has the largest contribution in the total water footprints of the irrigated schemes in Sudan. However, all irrigated crops shown high water consumption compared to that of the Agricultural Research Corporation as well as the global ones. This is suggested a large room for saving water. This study can be used as a baseline for further similar studies.

Acknowledgements

The authors would like to thank Dr. Rui Pedrosa for his valuable comments.

References

Abdalla, H.S., 2001. Long term strategy (2002–2027) of irrigated agriculture in Sudan: The Nile section. Ministry of Irrigation and Water Resources (a report). Khartoum, Sudan.

Abdalla, H.S., 2006. Socio-economic and environmental impacts of sedimentation in Sudan. International Sediment Initiative Conference (ISIC). Khartoum, Sudan.

Abdelhadi, A., Salih, A., Yosif, M., Hata, T., 2002. Effect of water harvesting methods on sorghum (*Sorghum vulgare*) yield in the Butana area, Sudan. ICID, 18th Congress, Montreal, Canada.

Adam, H.S., 2005. Agroclimatology, crop water requirement and water management. Gezira University Publication Company. Wadmedani, Sudan

Aldaya, M., Allan, J., Hoekstra, A., 2010. Strategic importance of green water in international crop trade. J. Ecol. Econ. 69, 887-894.

Allen, R., Pereira, L., Raes, D., Smith, M., 1998. Crop evapotranspiration. Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage paper, vol. 56, Rome, Italy.

Bulsink, F., Hoekstra, A., Booij, M., 2010. The water footprint of Indonesian provinces related to the consumption of crop products. Hydrol. Earth Syst. Sc. 14 (1), 119–128.

Chapagain, A. and Hoekstra, A., 2011. The blue, green and grey water footprint of rice from production and consumption perspectives. J. Ecol. Econ., 70 (4). pp. 749-758

De Fraiture, C., Molden, D., Wichlns, D., 2010. Investing in water for food, ecosystems, and livelihoods: An overview of the comprehensive assessment of water management in agriculture. Agr. Water Manage. 97, 495-501.

De Fraiture, C., and Wichelns, D., 2010. Satisfying future water demands for agriculture. Agr. Water Manage. 97, 502–511.

Elamin, O., 2006. Agriculture and water management in the national irrigated schemes: problems and solutions. Ph. D. thesis, Water Management and Irrigation Institute, University of Gezira, Wadmedani, Sudan.

Eldaw, A.K., 2003. Sudan water resources: challenge and future perspectives. Conference of Water harvesting and the future of development in Sudan. UNESCO Chair in Water Resources, Khartoum, Sudan.

Elias E., Salih, A. Alaily F., 2001. Cracking patterns in the vertisols of the Sudan Gezira at the end of dry season. Int. Agrophys. 15 (3), 151-155.

Ercin, A., Aldaya, M., Hoekstra, A., 2011. Corporate water footprint accounting and impact assessment: The case of the water footprint of a sugar-containing carbonated beverage. Water Resour. Manag. 25(2), 721-741.

Farbrother, H.G., 1996. Water Management options in Sudan Gezira. Natural Resource Institute publication. UK.

FAO, 2011. Fact sheet: Sudan. Available online at: thttp://www.fao.org/nr/water/aquastat/countries_regions/sudan/index.stm (last access on 7th June 2011).

FAO, 2010. Crop production and food security assessment for the northern states of the Sudan. Assessment mission report 2009/2010. Rome, Italy.

FAO, 2007. FAOSTAT-Agriculture. http://faostat.fao.org/site/339/default.aspx. (Accessed on February 25th 2011).

FAO, 2006. Fertilizer use by crop in the Sudan. Land and Plant nutrition and management service. Land and Water development division. Rome, Italy.

Fudl Elmoula, I., 2004. Rainfall analysis and crop yield forecast. M Sc. Thesis. The Institute of Environmental Studies, University of Khartoum. Sudan.

Guvele, C.A., 2002. Gains from crop diversification in the Sudan Gezira scheme. Agri. Syst. 70, 319-333.

Hoekstra, A. and Hung, P., 2005. Globalisation of water resources: international virtual water flows in relation to crop trade. Global Environ. Chang. 15 (1), 45-56

Hoekstra, A., Chapagain, A., Aldaya, M., Mekonnen, M., 2009. Water footprint manual, state of the art. Water Footprint Network t. Netherlands

Hoff, H., Falkenmark, M., Gerten, D., Gordon, L., Karlberg, L., Rockström, J., 2010. Greening the global water system. J. Hydrol. 384, 177–186.

Ma, J., Hoekstra, A., Wang, H., Chapagain, A., Wang, D., 2006. Virtual versus real water transfers within China. Philos. T. Roy. Soc. B. 361, 835-842.

Mekonnen, M. and Hoekstra, A., 2010. The green, blue and grey water footprint of crops and derived crop products. Volume 1: main report. Value of water research report series No. 47. UNESCO-IHE Institute for Water Education. Netherlands

Mohamed, A., 2003. Water management in New Halfa Agricultural Corporation. M. Sc. Water Management and Irrigation Institute, University of Gezira, Wadmedani, Sudan.

Mohamed, I., 2005. Adequacy of irrigation water during the critical period in Suki Agricultural Corporation. Water Management and Irrigation Institute, University of Gezira, Wadmedani, Sudan.

Rockström, J., Barron, J., Fox, P., 2003. Water productivity in rain-fed agriculture: challenges and opportunities for smallholder farmers in drought-prone tropical agroecosystems, in: Kijne J., Barker, R. and Molden, D. (Eds), Water productivity in agriculture: limits and opportunities for improvement. CAB International 2003, 145-162.

Rockström, J., Kaumbutho, P., Mwalley, J., Nzabi, Temesgen, M., Mawenya, L., Barron, J.., Mutua, J., and Damgaard-Larsen, S., 2009. Conservation farming strategies in East and Southern Africa: yields and rain water productivity from on-farm action research. Soil Till. Res. 103 (1), 23-32.

Rockström, J., Louise, K., Wani, S., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J. Qiang, Z., 2010. Managing water in rainfed agriculture—The need for a paradigm shift. Agr. Water Manage. 97, 543–550.

Shamseddin, A.M., 2009. Effect of water harvesting techniques on sustainable rainfed agriculture under the dry and semi dry climate of central Sudan. Ph. D. thesis, WMII, University of Gezira, Wadmedani, Sudan.

Wallace, J.S., 2000. Increasing agricultural water use efficiency to meet future food production. Agr. Ecosyst. Environ. 82, 105–119.