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Improving irrigation efficiency will be insufficient to meet future water demand in the Nile Basin

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A R T I C L E I N F O

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A B S T R A C T

The Nile River Basin covers an area of approximately 3.2 million km^2 and is shared by 11 countries. Rapid population growth is expected in the region. The irrigation requirements of Nile riparian countries of existing (6.4 million ha) and additional planned (3.8 million ha, 2050) irrigation schemes were calculated, and the likely water savings through improved irrigation efficiency were evaluated. We applied SPARE:WATER to calculate irrigation demands on the basis of the well-known FAO56 Crop Irrigation Guidelines. Egypt (67 $km^3\ yr^{-1}$) and Sudan (19 $km^3\ yr^{-1}$) consume the highest share of the 84 $km^3\ yr^{-1}$ total (2011). Assuming today's poor irrigation infrastructure, the total consumption was predicted to increase to 123 $km^3\ yr^{-1}$ (2050), an amount far exceeding the total annual yield of the Nile Basin. Therefore, a key challenge for water resources management in the Nile Basin is balancing the increasing irrigation water demand basin-wide with the available water supply. We found that water savings from improved irrigation technology will not be able to meet the additional needs of planned areas. Under a theoretical scenario of maximum possible efficiency, the deficit would still be 5 $km^3\ yr^{-1}$. For more likely efficiency improvement scenarios, the deficit ranged between 23 and 29 $km^3\ yr^{-1}$. Our results suggest that that improving irrigation efficiency may substantially contribute to decreasing water stress on the Nile system but would not completely meet the demand.

Study Region: The Nile River Basin covers an area of approximately 3.2 million km^2 and is shared by 11 countries. Rapid population growth is expected in the region.

Study Focus: Record population growth is expected for the study region. Therefore, the irrigation requirements of Nile riparian countries of existing (6.4 million ha) and additional planned (3.8 million ha, 2050) irrigation schemes were calculated, and likely water savings through improved irrigation efficiency were evaluated. We applied a spatial decision support system (SPARE:WATER) to calculate the irrigation demands on the basis of the well-known FAO56 Crop Irrigation Guidelines.

New Hydrological Insights for the Region: Egypt (67 km^3yr^{-1}) and Sudan (19 km^3yr^{-1}) consume the highest share of 84 km^3yr^{-1} (2011). Assuming today's poor irrigation infrastructure, the total demand were predicted to increase to 123 km^3yr^{-1} (2050), an amount far exceeding the total annual yield of the Nile Basin. Therefore, a key challenge for water resources management in the Nile Basin is balancing the increasing irrigation water demand and available water supply.

We found that water savings from improved irrigation technology will not be able to meet the additional needs of planned areas. Under a theoretical scenario of maximum possible efficiency,

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1. Introduction

1.1. Irrigation efficiency

Water consumption is globally driven by agricultural demand to grow food and feed for people and animals (Rost et al., 2008; Siebert and Döll, 2010; FAO, 2016). Strategies for decreasing water consumption by agriculture include better management of rainfall (Rockström et al., 2009) and irrigation (Pereira et al., 2002). In particular, the latter is important because unsustainable irrigation is globally a major driver of water resource depletion, e.g., of river flows (Döll et al., 2009) and groundwater aquifers (Wada et al., 2012). As a consequence, surface and groundwater resources are under severe pressure worldwide (Gleeson et al., 2012; Hoekstra et al., 2012). Nevertheless, irrigation is indispensable for feeding people (Siebert and Döll, 2010). Hence, the management of irrigated areas was addressed in this study for one of the world's largest river basins, where irrigation has shaped agriculture for thousands of years: the Nile River Basin. In particular, we investigated the likely effects of improved irrigation efficiency for the future, i.e., the ratio between the water made available for plant water uptake and the water taken from the source (surface and groundwater).

Irrigation efficiency has been discussed in great detail (Howell, 2003; Jensen, 2007; Lankford, 2012), and general instructions for the estimation of irrigation efficiency have been provided by the FAO Irrigation and Drainage guidelines (Brouwer et al., 1989). The efficiency of an irrigation scheme is derived from two components. The conveyance efficiency (off-farm, e_c) is calculated according to water losses that occur when water is delivered to farms (e.g., through leakage and evaporation from canals and cracks in canal bunds). The application efficiency (on-farm, e_a) is calculated according to losses on fields, e.g., evaporation from the soil surface and open waters and interception and deep percolation into the groundwater. The scheme efficiency (e) is derived by multiplying both components ($e = e_c \times e_a/100$).

Water savings through improved irrigation efficiency has been discussed for Saudi Arabia, where arid climate and irrigation with fossil groundwater resources are dominant, and the agriculture sector consumes most of the scarce water resources (Multsch et al., 2016b). Multsch et al. (2016b) have shown that national water consumption could potentially be reduced by 32% if no salt sensitive crops are grown and modern irrigation technology is adopted. Hence, irrigation efficiency plays a major role, as shown in a global study (Jägermeyr et al., 2015) highlighting the likely water savings gained by decreasing non-beneficial consumptive use, i.e., by limiting losses through evaporation and interception and decreasing non-recoverable return flow (e.g., water flows to salinized water bodies).

1.2. Objective and approach

We evaluated the water consumption of irrigated agriculture in the riparian countries of the entire Nile River Basin, because a substantial expansion of irrigation schemes is expected in the coming decades (BCEOM, 1999; WREM, 2006; Awulachew et al., 2012). Previous studies have highlighted that the accompanying agriculture water demand cannot be met in the future (Awulachew et al., 2012). This situation is likely to worsen because many dams are being constructed, which will alter river flows, most probably decreasing water resources for downstream users (McCartney et al., 2012). Collaboration between riparian countries is important to solve the current and future water resources demands in the Nile River Basin (Abdelhady et al., 2015). Furthermore, technical approaches, such as improving irrigation efficiency, may be a measure to partly counteract future water scarcity (McCartney et al., 2012), but it is currently unknown to what degree this is feasible.

Three objectives were focused on in this study. First, the water consumption of today's irrigated agriculture (existing areas) was estimated on the basis of current irrigation technology. National plans show considerable increases in the extent of irrigation schemes during the coming decades up to 2050. Therefore, in a second step, we estimated the water consumption for additional planned irrigated areas up to 2050, assuming that the irrigation efficiency remains at today's level. When summing up existing and planned irrigated areas, a prediction of the future water demand in the Nile River Basin can be done.Third, scenarios were assessed that assumed stepwise improvements in irrigation efficiencies as well as a theoretical best technology scenario leading to maximum efficiency. Our key question addressed the problem of whether the quantity of likely water savings through improved irrigation technology might be sufficient to provide for the total water consumption of planned irrigation schemes in the future.

The study relied on existing data obtained primarily from the Nile Basin Initiative (NBI) (such as the Nile Basin Decision Support System (NB DSS), Multi-Sector Investment Studies for the Eastern Nile and the Nile Equatorial Lakes region) and from public data sources. The field level water demand model SPARE:WATER (Multsch et al., 2013), which was integrated into a geographic information system, was set up with site-specific crop parameters and high resolution gridded climate data to assess the water requirements for growing field crops and to evaluate the water savings from improved irrigation efficiency.

2. Methods: SPARE:WATER model

The Site–sPecific Agricultural water Requirement and footprint Estimator (SPARE:WATER, www.uni-giessen.de/cms/hydro/download) (Multsch et al., 2013) is a spatial decision support system for estimating the fate of water consumption in agricultural production systems. SPARE:WATER enables the spatially explicit calculation of crop-specific water requirements, considering all water resources needed, including green (consumed rainfall), blue (consumed irrigation) and gray (salt leaching) water. Equipped with a graphical user interface, SPARE:WATER calculates the crop water requirement according to the Food and Agricultural Organization FAO56 crop water guidelines (Allen et al., 1998). This study focused on the consumption of blue and gray water by irrigation schemes, as calculated as follows:

$$IRR_{gross} = \frac{\overbrace{\max(ET_c - P_{eff}, 0)}^{Blue}}{e_a} + \overbrace{LR_{add}}^{Grey} \tag{1}$$

with gross irrigation IRR_{gross}, crop specific evapotranspiration ET_c, effective rainfall P_{eff} and leaching requirement LR_{add} in (m^3 ha^{-1}) and the application efficiency e_a in (dimensionless). The application efficiency, e_a, refers to on-farm efficiency and accounts for unproductive water losses. In particular, managing salt leaching is an important task (Ayers and Westcot, 1985), because salinization is an increasing issue worldwide (Fischer et al., 2008; Rengasamy, 2010), especially in Egypt and Sudan, where one-third of irrigated

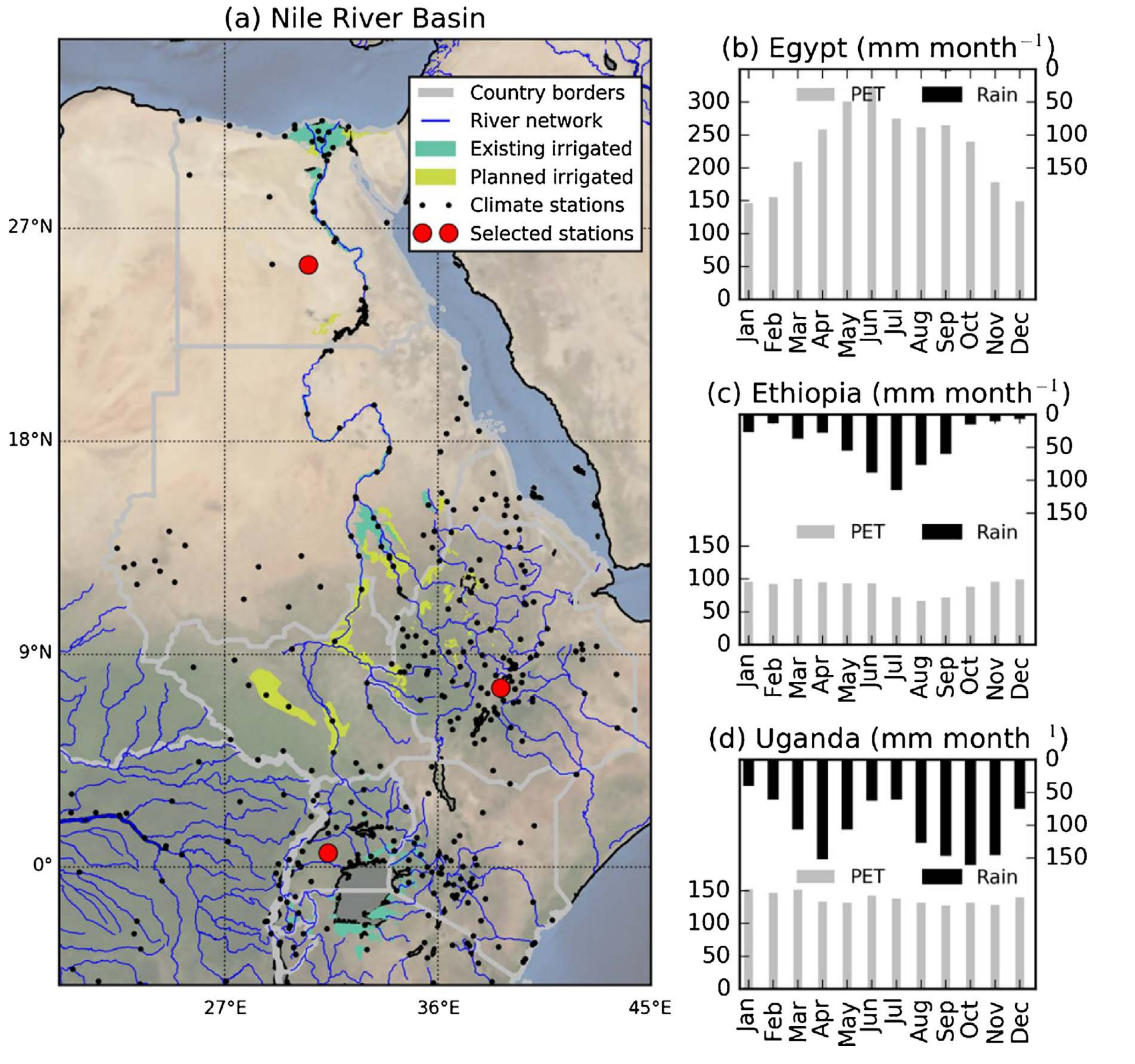

Fig. 1. (a) Map of the Nile River Basin and existing and planned irrigated areas. The black dots indicate climate stations from the Climwat 2.0 database (FAO, 2015), and the red dots highlight the stations from which the reference evapotranspiration (ET_o) and rainfall data shown in b-d were taken.

areas are salinized, comprising 900,000 ha and 500,000 ha, respectively (FAO, 2016). The leaching requirement is the water needed to wash salts from the rooting zone. LR_{add} refers to the additional water requirement when ineffective irrigation losses through percolation are insufficient to cover the potential leaching requirement (Howell, 2003). The leaching requirement was calculated according to Ayers and Westcot (1985) on the basis of a crop salinity response function, in which two parameters describe the salinity tolerance of a field crop, including the maximum value of the electrical conductivity of irrigation water without any yield losses (ECe100%) and the electrical conductivity at which crop growth is fully limited (ECe0%). A linear relationship between crop growth and conductivity is assumed between these values. ET_c is derived by multiplying reference evapotranspiration (ET_o) by a crop-specific parameter (K_c) to adjust ET_o to the crop-specific development, according to the single crop coefficient concept (Allen et al., 1998). The development of a field crop is divided into four development stages (initial stage, growth stage, mid-stage, and late stage). Three crop coefficients are defined for the initial stage, the mid-stage and the last day of the late stage. Values for the development stage, as well as the time during the late stage, are interpolated according to the number of days after sowing. ET_o is calculated by using the FAO56 Penman-Monteith equation, which is based on temperature, humidity, wind speed and radiation derived from sunshine hours. P_{eff} is derived from the difference between rainfall and surface runoff. A detailed overview of the underlying equations is given in Multsch et al. (2013).

IRR_{gross} was derived for each crop for the entire Nile River Basin at a grid cell spatial resolution of ~5 km x 5 km. An average of IRR_{gross} for all grid cells per irrigation scheme ($m^3\ ha^{-1}$) was calculated to derive the annual IRR_{gross} ($km^3\ yr^{-1}$) of the existing and planned irrigation schemes of the Nile River riparian countries. Subsequently, irrigation efficiency scenarios were evaluated on the basis of country-specific assumptions regarding current and future technological improvements. Further details on the underlying meteorological data, irrigated areas and irrigation efficiency and the scenarios are described in the following sections.

3. Data

3.1. The Nile Basin

The Nile is the longest river in the world (6,700 km) (Fig. 1a). The basin covers an area of approximately 3.2 million km^2 and is shared by 11 countries. The total population living within the basin is estimated to be 238 million, whereas the total population of the riparian countries is currently 437 million inhabitants. Further rapid population growth is expected, and the population has been predicted to increase to 648 million inhabitants in the riparian countries in 2030 (NBI, 2012).

Compared with other large rivers worldwide, the Nile has a relatively small annual runoff, with an average discharge between 40 and 150 $km^3\ yr^{-1}$ at the High Aswan Dam (Johnston, 2012) and a long-term average of 84 $km^3\ yr^{-1}$ per year. River flow in the Nile River Basin is generated from an area less than one-third of the total basin area. Approximately 85% of the river flow received at the High Aswan Dam in Egypt is generated in the Ethiopian highlands (Blue Nile, Baro-Akobo, and Tekeze-Atabara), and the remaining flow is delivered from the Equatorial Lakes region and South Sudan (Awulachew et al., 2010) (note that the 85% contribution is at the higher range of published estimates; e.g., Conway (2000) has reported a value of 60%). A strong climate gradient affects the river basin, with almost no rainfall in Egypt (Fig. 1b) and higher rates in Ethiopia (Fig. 1c), particularly around Lake Victoria (Fig. 1d). Further, we found two to three times higher reference evapotranspiration in Egypt than in Ethiopia or Uganda.

The downstream parts of the Nile River Basin in Egypt and Sudan are characterized by relatively high levels of water resource development for agriculture and power generation, whereas the upstream parts largely depend on traditional subsistence level rain-fed agriculture and, as a result, very low levels of water extraction from the river. Concordantly, the current level of dependence on Nile waters for energy and food production is highly skewed, with Egypt being the most Nile-dependent country.

However, national plans show a considerable increase in water resource development over the coming decades (Nedeco, 1998; BCEOM, 1999; WREM, 2006). On the basis of national plans available for this study, the total increase in irrigation areas by 2050 is estimated to be 3.2 million ha (Fig. 1a, light green areas). More than half of this increase is expected to be in upstream countries. Given that the Nile is shared by 11 countries and that agriculture consumes most of the Nile waters, one of the most important questions to address is how the Nile River Basin's water resources will evolve under the anticipated water extractions to meet the growing demands for food production.

3.2. Meteorological data

The FAO Climwat 2.0 database was used for this analysis (FAO, 2015). The dataset includes over 5,000 climate stations worldwide, from which 425 were considered for this analysis (Fig. 1). The climate time series provides long-term averages of at least 15 years (1971–2000) of various variables (minimum and maximum temperature, relative humidity, wind speed, and sunshine hours) as monthly averages. These were used to derive ET_o according to the FAO56 Penman-Monteith method as well as monthly sums of rainfall to estimate P_{eff}. Grid maps were interpolated by using the Inverse Distance Weighted method (Philip and Watson, 1982; Watson and Philip, 1985) to derive maps for the Nile River Basin at a spatial resolution of 0.041° (~5 × 5 km at the equator), by using ArcGIS™ Spatial Analyst (Fig. A1a, b).

3.3. Irrigation technique, efficiency and salinity

Irrigation technologies can generally be divided into two types. In surface (gravity flow) systems, water is transported from the source by a system of (open) canals and ditches. In such systems, there are several different methods for applying the water to irrigation fields, such as basin inundation systems or furrows (small ditches between rows of plants). The degree of maintenance of the canals is an important topic. Well-maintained canals provide little hydraulic resistance to flows and hence decrease the residence time of the water in canal systems, which in turn contributes to decreased evaporation losses. In pressurized systems (sprinkler or drip systems), water is conveyed in closed pipes under pressure and is either 'sprayed' on the crops or provided through a system of flexible pipes with small nozzles, from which 'drips' directly supply water to the plants. Such systems have the highest irrigation efficiencies but also the highest implementation costs. The dominant method in the Nile River Basin is surface irrigation, according to FAO Aquastat (FAO, 2016). Sprinkler irrigation is used in Egypt (5%), Ethiopia (2%), Uganda (25%) and Kenya (60%). An even lower percentage of areas in the Nile River Basin are irrigated by drip irrigation, with, e.g., the highest values in Egypt (6%), Uganda (3%) and Kenya (2%). The data from the FAO were considered in the calculations in this study, except for Egypt, for which regional data were available (Table 1).

A comprehensive list of irrigation efficiencies according to irrigation method has been published by the FAO (Brouwer et al., 1989) and by Howell (2003). Often, values of 60%, 75% and 90% have been reported for surface, sprinkler and drip irrigation, respectively (Brouwer et al., 1989). We used this information along with the expert knowledge of NBI staff members who are familiar with local management and practices. See Table A1 for a detailed description of the irrigation efficiencies for each country and province for gravity and pressurized systems. On average, the values ranged between 60 and 70% for Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania and Uganda. The irrigation efficiency of Egypt was assumed to be slightly higher (between 70 and 80%). The calculations presented in this work are related to application efficiency (on-farm) without considering off-farm losses such as the maintenance conditions of the canals or farmer discipline. In our concept, water quality is related to the salinity concentration in irrigation water, because this is the largest driver of additional water needed to wash salts from the soil. The salinity is commonly measured in terms of total dissolved solids (TDS in mg L^{-1} or ppm) or electric conductivity (EC, dS m^{-1}), whereby an EC of 1 dS m^{-1} equals a TDS of approximately 640 ppm. A detailed map is available for parts of the Nile Delta in Egypt (Abu-Zeid, 1990) and shows a strong downstream increase in Nile River salinity, with values up to 13 dS m^{-1} in the coastal area. Such high salinity water is caused by river water mixing with brackish water from the Mediterranean Sea and is unsuitable for irrigation. Therefore, the total salinity

Table 1
Irrigation technology in the Nile River Basin.

Country	District	Baseline, Sce1, Sce2		Sce3	Sce3
		%Gravity	%Pressurized	%Gravity	%Pressurized
Egypt[a]	Aswan	100%	0%	0%	100%
Egypt[a]	Qina	100%	0%	0%	100%
Egypt[a]	Sohag	100%	0%	0%	100%
Egypt[a]	Asyiut	100%	0%	0%	100%
Egypt[a]	Al Fayyum	100%	0%	0%	100%
Egypt[a]	Al Jizah	44%	56%	0%	100%
Egypt[a]	Al Minya	100%	0%	0%	100%
Egypt[a]	Beni Suwayf	100%	0%	0%	100%
Egypt[a]	Al Bahayrah	66%	34%	0%	100%
Egypt[a]	Al Daqahliyah	97%	3%	0%	100%
Egypt[a]	Al Gharbiyah	100%	0%	0%	100%
Egypt[a]	Al Minufiyah	100%	0%	0%	100%
Egypt[a]	Al Qalyubiyah	80%	20%	0%	100%
Egypt[a]	Ash Sharqiyah	73%	27%	0%	100%
Egypt[a]	As Ismailiyah	39%	61%	0%	100%
Egypt[a]	Dumyat	100%	0%	0%	100%
Egypt[a]	Kafr-El-Sheikh	100%	0%	0%	100%
Egypt[a]	Matruh	0%	100%	0%	100%
Egypt[a]	Al Qahirah	100%	1%	0%	100%
Egypt[a]	Al Iskandariyah	27%	73%	0%	100%
Egypt[a]	Bur Said	0%	100%	0%	100%
Egypt[a]	Shamal Sina	0%	100%	0%	100%
Sudan		95%	5%	0%	100%
South Sudan[b]		100%	0%	0%	100%
Ethiopia[b]		98%	2%	0%	100%
Kenya[b]		38%	62%	0%	100%
Tanzania[b]		100%	0%	0%	100%
Rwanda[b]		100%	0%	0%	100%
Uganda[b]		73%	27%	0%	100%

[a] Information from the Nile Basin Decision Support System (NB DSS).
[b] FAO Aquastat (FAO, 2016).

Table 2
Harvest area of existing irrigation schemes in 2011 and planned in 2050 (including double cropping).

Country	Existing (2011)		Planned (2050)	
	Gravity (million ha)	Pressurized	Gravity (million ha)	Pressurized
Egypt	4.16	0.9	0.58	0
Ethiopia	0.12	0	2.05	0.04
Kenya	0.02	0	0	0
Rwanda	0	0	0	0
South Sudan	0	0	0.27	0
Sudan	1.11	0.06	0.84	0.04
Tanzania	0.01	0	0	0
Uganda	0.01	0	0	0
Sum	5.43	0.96	3.74	0.09
	Sum 2011:	6.4	Sum 2050:	3.82

level is limited to 2.5 dS m^{-1} in the Nile delta and 0.4 dS m^{-1} at the Aswan dam (personal communication with NBI staff). A linearly declining salinity level was assumed for the areas between the Aswan dam and the Nile delta (Fig. A2). Other upstream river parts had a salinity level equal to that of the Aswan dam.

3.4. Irrigated areas and cropping pattern

The study relied on data collected from NBI's previous work, national plans and other published materials. Data on irrigated areas in the Nile Basin were collected from various reports and studies conducted by the Nile Basin Initiative (Bart et al., 2011; NBI-NELSAP, 2012; NBI-ENTRO, 2014). Table 2 provides a summary of existing irrigation areas and those planned for the 2050 time horizon. The existing areas represent the current state in 2011. The planned areas represent additional irrigation areas according to national development plans. To calculate the total amount of irrigated areas in 2050, both values were added. It is important to note that the reported areas include double cropping, i.e., the cropping intensity in Egypt is 136% because some fields are harvested twice per year. Most of the irrigated areas exist in Egypt and Sudan. Other Nile countries depend primarily on rain-fed agriculture and flood recession agriculture. However, this pattern is expected to change because other countries also plan to implement ambitious irrigation schemes, e.g., the Grand Ethiopian Renaissance Dam (GERD) in Ethiopia (Abdelhady et al., 2015). Overall, nearly 90% of the planned expansion in irrigated areas is expected to occur in the Eastern Nile countries of Egypt, Ethiopia, South Sudan and Sudan.

Cropping patterns and crop coefficient (Kc) values for Egypt were taken from FAO F4T (Bart et al., 2011) for the different districts (governorates). Cropping patterns for Sudan (and corresponding crop coefficients) were taken from the EN MSIOA (NBI-ENTRO, 2014) database and those for Ethiopia were taken from the ENIDS CRA2 documents (2009), supplemented by data from the Baro-Akobo-Sobat and Tekeze master plans from Ethiopia. Data for the other Equatorial countries were obtained from NEL MSIOA documents and a GIS database (NBI-NELSAP, 2012).

3.5. Irrigation efficiency scenarios

We estimated plausible irrigation efficiency improvements, taking into account pertinent factors that might influence the performance of irrigated agriculture in the Nile Basin. The extent to which such improvements can be effected for a given irrigation area depends on many factors.

1. Size and ownership types of schemes: Often, the financial resources of owners are small, and irrigation efficiencies tend to be low, with no major improvements expected on a small scale for household-owned irrigation systems. In cases in which individual schemes are part of larger-scale irrigation schemes (e.g., Gezira in Sudan, most of the irrigation areas in Egypt, and the Koga scheme in Ethiopia), the conveyance and distribution system is maintained by the state or Water Users Association. These systems tend to be in good condition, whereas farm-level water applications remain less efficient. Such distinctions need to be made when assigning improvements.
2. Technical and institutional capacities for managing irrigation agriculture: More experienced regions/countries, such as Egypt and Sudan, tend to be aware of the needs for irrigation efficiency improvements. Hence, larger effects of irrigation efficiency improvements can be expected for these regions compared with regions with little experience.
3. Main purpose of irrigation: Irrigation for high value crops tends to be better managed and to have higher efficiencies and higher likelihoods for improvements; often, the intended use is commercial or for own-consumption, with some surplus being marketed.
4. Type of irrigation technology in use: Improvements in irrigation efficiencies are expected to be due to one of the following: (i)

Changes in water application techniques, such as changing from a surface-gravity (e.g., furrow) system to a pressurized system (e.g., drip). (ii) Changes in application efficiency for the same water application technique (e.g., lining of canals or improving land leveling).

We acknowledge that many detailed effects of the various irrigation technologies and practices cannot be incorporated in a large-scale assessment such as the one presented in this study. Thus, three normative scenarios of irrigation efficiency improvements (Sce1, Sce2 and Sce3) were used to evaluate potential water savings on the basis of available reports and the expert knowledge of NBI staff members. In summary, the irrigation efficiency of gravity and pressurized systems in Egypt was raised by 5%, 10% and 15% for scenarios Sce1, Sce2 and Sce3, respectively. Improvements in gravity systems of 5%, 10% and 20% for scenarios Sce1, Sce2 and Sce3 were assumed for the other countries, in addition to enhancements of 15%, 20% and 25% for pressurized systems under each scenario, respectively. Specific values per country and province of irrigation efficiency improvements are given in Table A2. Note that the improvements apply to current and planned irrigation areas.

4. Results

4.1. Gross irrigation of existing and planned irrigation schemes

The IRR_{gross} to grow crops in the Nile River Basin was calculated for existing harvested areas (6.4 mio. ha) under the assumption of the baseline scenario, i.e., most schemes were equipped with gravity irrigation systems (85%), and only a minor fraction of the schemes were equipped with pressurized systems (15%), most of which were located in Egypt (Table 3). The IRR_{gross} totaled 84 km^3 yr^{-1} (Table 3). A further differentiation in relation to irrigation systems showed that 73 km^3 yr^{-1} (87%) and 11 km^3 yr^{-1} (13%) would be consumed in areas equipped with gravity and pressurized systems, respectively. Egypt and Sudan have the largest areas under irrigation, 5.06 mio. ha and 1.17 mio. ha (97%), and were responsible for almost the entire IRR_{gross} (99%), with 65 km^3 yr^{-1} and 19 km^3 yr^{-1}, respectively. The situation slightly changed when the additionally planned irrigation schemes up to 2050 (3.82 mio. ha) were considered, which would lead to a total irrigated area of ~10 million ha in the Nile River Basin. Although most of these schemes are planned for Ethiopia (55%), Egypt will still have most of the irrigated areas (55%). In total, the IRR_{gross} is expected to increase by approximately 46% (39 km^3 yr^{-1}) to 123 km^3 yr^{-1} in 2050 (existing + planned areas). Egypt will be still the largest water consumer, with 61%, followed by Sudan and Ethiopia, with 27% and 9%. An interesting point is the rather low IRR_{gross} of Ethiopia in comparison with that of Sudan, given that both countries will irrigate roughly the same area (~2 mio. ha). The reasons are the less favorable climatic growing conditions in Sudan in comparison with Ethiopia, thus leading to a three times higher IRR_{gross} in Sudan.

A further differentiation of IRR_{gross} can be made for crop categories (Fig. 2a). A more detailed overview per crop and country is given in Appendix A Figs. A3 and A4. Regarding existing areas, grains shared the highest fraction of the IRR_{gross}, with 44% and 38% for existing and planned areas. The second largest group was formed by other crops, dominated by cotton, sugarcane and groundnuts (Fig. A3e). Most of the water is consumed in May to August by grains (Fig. 2b) such as maize, wheat and barley, which are grown in Egypt in particular (Fig. A3a). Other important crops driving the high IRR_{gross} were fruits, vegetables, cotton and sugarcane in Egypt as well as groundnuts in Sudan at that time of year. November to February are dominated by clover in Egypt and cotton in Sudan. Planned irrigation schemes showed a different distribution between months, because the highest IRR_{gross} would occur between December and April, with a maximum in March (Fig. 2c). Cropping patterns would then be mainly driven by the cultivation of wheat and cotton in Sudan as well as by sugarcane and soybean in Ethiopia (Fig. A3). The combined IRR_{gross} of existing and planned areas is expected to lead to more constant and higher water demand throughout the year, which must be provided by the Nile River.

Table 3
Gross irrigation (IRR_{gross}) of Nile River riparian countries for existing and planned schemes.

Country	Existing (2011)		Planned (2050)	
	Gravity (km^3 yr^{-1})	Pressurized	Gravity (km^3 yr^{-1})	Pressurized
Egypt	54.06	10.25	11.26	0.00
Ethiopia	0.47	0.01	10.06	0.18
Kenya	0.08	0.00	0.00	0.00
Rwanda	0.01	0.00	0.00	0.00
South Sudan	0.00	0.00	3.05	0.00
Sudan	18.18	0.89	13.80	0.67
Tanzania	0.13	0.00	0.00	0.00
Uganda	0.04	0.01	0.00	0.00
Sum	72.97	11.16	38.17	0.85
	Sum 2011:	84.12	Sum 2050:	39.02

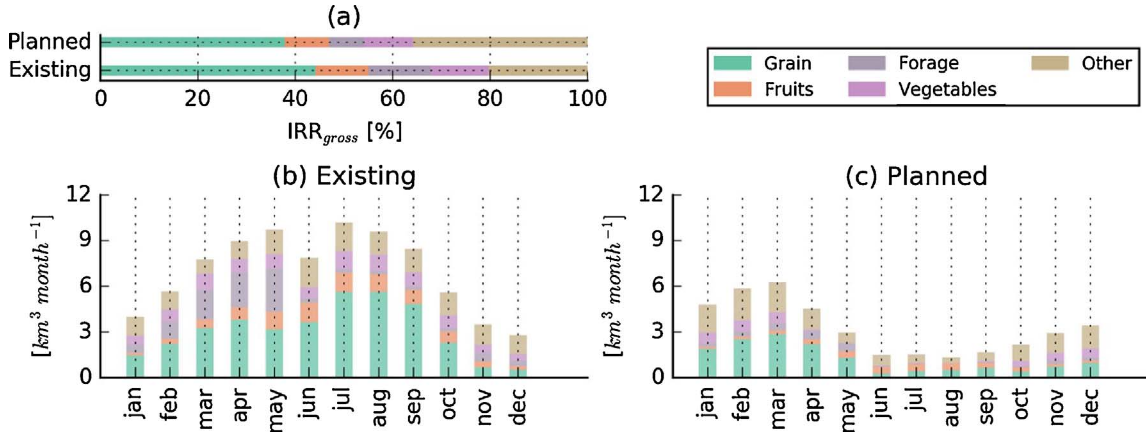

Fig. 2. Comparison of the gross irrigation (IRR$_{gross}$) of existing and planned irrigation schemes grouped by crop categories (a). (b) and (c) show further differentiation of IRR$_{gross}$ per month for existing and planned irrigation schemes.

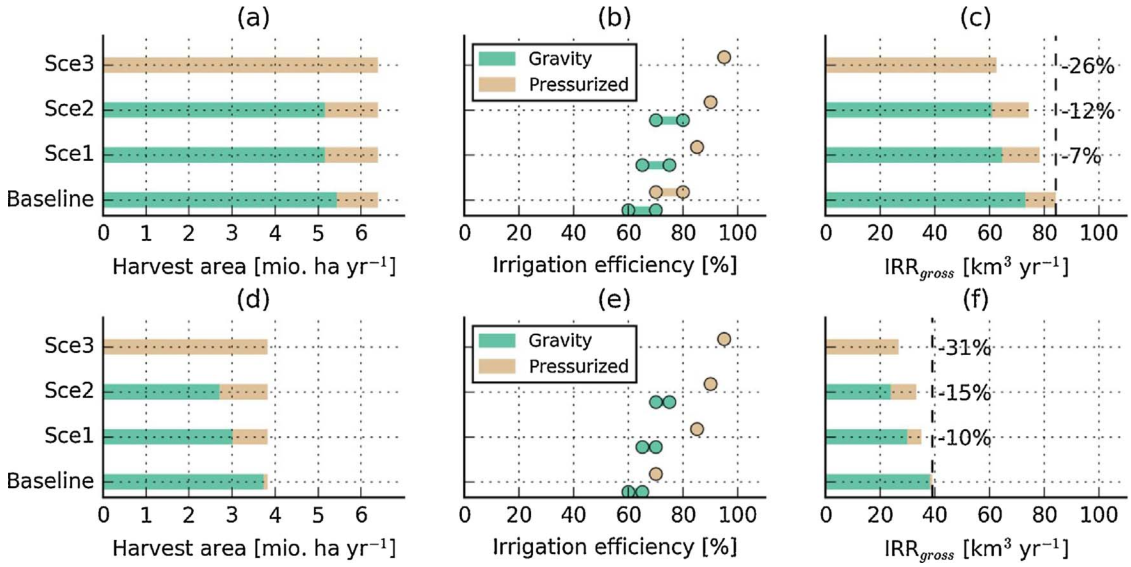

Fig. 3. The evaluation of irrigation technology scenarios Sce1-3 is shown in (a-c) and (d-f) for existing and planned irrigation schemes for Nile River riparian countries.

Table 4
Evaluation of irrigation efficiency scenarios for existing and planned irrigation schemes.

Scenario	Status	Harvest area (ha yr^{-1})		Irrigation efficiency (−)		Gross irrigation (km^3 yr^{-1})	
		Gravity	Pressurized	Gravity	Pressurized	Gravity	Pressurized
Baseline	Existing	5.433	0.964	0.6–0.7	0.7–0.8	73.0	11.2
Baseline	Planned	3.737	0.086	0.6–0.7	0.7–0.8	38.2	0.9
Sce1	Existing	5.158	1.240	0.65–0.75	0.85	64.5	13.8
Sce1	Planned	3.011	0.811	0.65–0.75	0.85	29.8	5.1
Sce2	Existing	5.158	1.240	0.7–0.8	0.90	60.9	13.4
Sce2	Planned	2.711	1.111	0.7– 0.75	0.90	23.8	9.4
Sce3	Existing	0.000	6.397	0.7–0.8	0.95	0.0	62.5
Sce3	Planned	0.000	3.822	0.7–0.8	0.95	0.0	26.8

4.2. Evaluation of irrigation efficiency scenarios

The evaluation of the scenarios of irrigation efficiency improvements is shown in Fig. 3 for existing (a-c) and planned (d-f) irrigation schemes and in Table 4 (see Table A3 for a differentiation according to country). The total area remained constant throughout the scenarios (Fig. 4a, d), whereas the fractions of gravity and pressurized irrigation systems, as well as efficiencies (Fig. 3b, e), were modified. The water savings ranged between 7% and 26%, under Sce1 (slight increase of efficiency) and Sce3 (theoretical possible improvement) for existing areas. The total savings was −6, −9 and −22 $km^3\ yr^{-1}$ for scenarios Sce1, Sce2 and Sce3, as compared with the current consumption of 84 $km^3\ yr^{-1}$.

Relative water savings in the planned irrigation schemes amounted to a reduction of 10%, 15% and 31% for scenarios Sce1, Sce2 and Sce3. The reason for the higher water savings in these planned areas was the higher fraction of schemes located in Ethiopia (~2 mio. ha, 55%, Table 1), where the currently implemented irrigation techniques are of low efficiency and will therefore benefit substantially from improvements. Importantly, when the possible water savings in existing areas was compared with the future water needs of planned areas, even when considering the highest technological improvement (Sce3), the water savings of 22 $km^3\ yr^{-1}$ in the existing areas was predicted to be insufficient to meet the future water demand. This demand of 27 $km^3\ yr^{-1}$ (Sce3) would result in a water deficit of 5 $km^3\ yr^{-1}$. Under the more likely Sce1 and Sce2 scenarios, the deficit would be even larger: 29 and 23 $km^3\ yr^{-1}$, respectively. Hence, water savings via improved irrigation efficiency will not be able to meet the demand of the planned irrigation schemes.

5. Discussion

5.1. Validation of results

The results of this study were compared with results from other studies on a national level and for the entire Nile Basin. However, a detailed comparison is difficult, because manifold model settings, such as irrigation use efficiency (off-site and on-site), the considered spatial model input data, such as the irrigated area, and information on cropping patterns and dates or cropping intensity differ among studies. We therefore note that results between the different studies should explain similar regional patterns and be in the same range rather than providing identical values.

The highest current IRR_{gross} occurred in Egypt, with 64 $km^3\ yr^{-1}$ on 5 mio. ha of harvested irrigated crops. Comparable results have been presented by others, e.g., a total IRR_{gross} of 57 $km^3\ yr^{-1}$ has been simulated with a global water balance and demand model (PCR-GLOBWB) on the basis of the spatial locations of irrigated areas around 2000 (Wada et al., 2014). The total water withdrawal, including on-farm and off-farm water losses, was 67 $km^3\ yr^{-1}$ in 2010, considering 6.3 mio. ha of irrigated land (FAO, 2016). For this area, the authors considered a double cropping intensity of 176%, whereas in our study, an intensity of 136% was assumed (a relative difference of 23%) for Egypt, which is the main reason for the different harvest areas and resulting higher water withdrawal, with a relative difference of 15%.

In the case of Sudan, the IRR_{gross} of the irrigated areas in 2011 and 2050 was 19 and 34 $km^3\ yr^{-1}$ (1.2 mio. ha, 2.1 mio. ha). The FAO (2016) has reported a water withdrawal of 26 $km^3\ yr^{-1}$ for the year 2010, also including off-farm water losses, on the basis of a higher harvested area of 1.6 mio. ha. The difference between the harvested areas and the resulting 27% higher water withdrawal was caused by the different cropping intensities of 68% and 91% (relative difference 25%) used in this study and by the FAO (2016). Others have estimated the irrigation demand (i.e., only consumptive use by crops) of Sudan as being 8.5 $km^3\ yr^{-1}$ and 14 $km^3\ yr^{-1}$ for irrigated areas of 1.3 mio. ha and 2.2 mio. ha in 2008 and 2050 (McCartney et al., 2012). Their irrigation demand (i.e., net irrigation, without assuming likely losses through inefficient irrigation) is somewhat lower than our results, but when an on-farm efficiency of 60% is considered, the values given by McCartney et al. (2012) become closer to our results.

The IRR_{gross} for the entire Nile Basin was calculated to be 84 $km^3\ yr^{-1}$ (6.4 mio. ha) and 123 $km^3\ yr^{-1}$ (10.2 mio. ha) for 2011and 2050. Two other studies (Sulser et al., 2010; Awulachew et al., 2012) have also reported current and future water consumption of the Nile Basin. Awulachew et al. (2012) have calculated an IRR_{gross} of 66 $km^3\ yr^{-1}$ for today (5.6 mio. ha) and 128 $km^3\ yr^{-1}$ for the long term (10.6 mio. ha) with the WEAP model. Our estimate for the current IRR_{gross} is 22% higher, a result that can be partly explained by the higher harvest area of 13% used in our approach. Further reasons for the difference may be varying cropping patterns as well as different assumptions regarding irrigation efficiency. The difference between the future predictions of IRR_{gross} is low (~4%). Sulser et al. (2010) have calculated blue water consumption (consumed irrigation, without losses) for the years 2000 and 2050, obtaining 46 $km^3\ yr^{-1}$ (5.8 mio. ha) and 57 $km^3\ yr^{-1}$ (6.9 mio. ha), by using the IMPACT model. Considering on- and off-farm losses, the total withdrawal of water for irrigation for 2000 is close to our IRR_{gross} estimate. The prediction of the harvest area for 2050 appears to be too low, because we, as well as Awulachew et al. (2012), generated higher predictions for the harvest area of approximately 10 mio. ha in 2050.

As described, the differences between our study and others may have been caused by uncertainties in parameterizations, different model structures or input data (Renard et al., 2010). For example, the models used by others (McCartney et al., 2012; Wada et al., 2014), as well as our approach, are based on the single crop coefficient concept. In this concept, the crop specific evapotranspiration is calculated on the basis of ET_o and crop-specific Kc parameters that are applied to adjust ET_o to specific field crops (Allen et al., 1998). Because ET_o was derived with the Penman-Monteith equation in this study and that by Wada et al. (2014), the observed differences may partly be related to the differences in Kc; we collected site-specific crop parameters for the different irrigation schemes in the region from the literature, whereas the Kc values used by Wada et al. (2014) were based on a global parameter set (Portmann et al., 2010). Moreover, the irrigation efficiency is often not accurately defined or communicated (Howell, 2003; Perry, 2007; Lankford, 2012) and therefore is difficult to compare. This inaccuracy is one of the major reasons for differences in the calculation of IRR_{gross}. For the assessment of the irrigation water requirement in the Nile Basin, we considered the on-farm irrigation efficiency, i.e., the losses that occur during the application of the irrigation water to the plants at the field scale. Values were taken from the literature according to the irrigation system as defined per country (FAO, 2016). Our assumptions may differ from those of other studies. Different input data can also cause tremendous uncertainties, e.g., the extent of irrigated areas and, in particular, the estimate for the planned future irrigation schemes. Wisser et al. (2008) have shown in a global scale analysis that irrigation demands vary by $+/-30\%$ for calculations based on two different datasets for irrigated areas and weather data. Finally, Multsch et al. (2015) have shown that the structural model uncertainty can dominate global model uncertainty. Their study has found that the most important factor driving the estimated irrigation requirement for the Murray Darling Basin is related to the underlying equation for estimating ET_o. Thus, various sources of uncertainty exist that can alter the model predictions. To overcome such uncertainties, our input and output data were carefully revised in cooperation with local experts and compared with other localized simulations of irrigation requirements by the WEAP model, which are unfortunately unpublished.

5.2. Impact of improved irrigation efficiency

Two aspects are important to discuss. First, how does the IRR_{gross} of existing areas compare with the total water volume of the Nile (under current and improved irrigation technology)? Second, can the water savings from improved irrigation efficiency meet the additional water demand of planned irrigation schemes?

Water allocation underlies historical plans that regulate water allocation in accordance with the average Nile River flow at the Aswan dam of 84 $km^3\ yr^{-1}$. Only Egypt and Sudan are part of the agreement, and the two countries agreed on an allocation scheme in which Egypt receives 55.5 $km^3\ yr^{-1}$ of the total flow, and Sudan receives 18.5 $km^3\ yr^{-1}$ (Johnston, 2012), considering additional evaporation losses from the open water surface of 10 $km^3\ yr^{-1}$. The IRR_{gross} of existing irrigation schemes was calculated to be 64 $km^3\ yr^{-1}$ and 19 $km^3\ yr^{-1}$ for Egypt and Sudan in this study. Hence, even the IRR_{gross} of existing irrigation schemes exceeded the average river flows as well as the amount stated in the 1959 agreement between Egypt and Sudan. Similar results have been reported by other researchers (McCartney et al., 2012), who have emphasized that the Nile River Basin cannot meet irrigation needs in the long term. Those authors have concluded that the implementation of water saving measures, such as improved irrigation efficiency, is of high priority. We addressed, in particular, the potential of irrigation efficiency to meet the increased water needs of agriculture. By implementing more efficient irrigation technology, the on-farm water losses can be limited. In the case of Egypt, at least scenario Sce2 (IRR_{gross} = 58 $km^3\ yr^{-1}$) must be implemented to approximately balance water consumption with the guaranteed water extraction. In the case of Sudan, Sce1 (IRR_{gross} = 17 $km^3\ yr^{-1}$) would be sufficient. Thus, improved on-farm irrigation efficiency would aid in keeping the IRR_{gross} of existing schemes within the range of the average river flows currently reaching the Aswan dam.

The expansion of irrigation schemes (1.6 times larger in 2050 compared to 2011) will lead to a large increase in IRR_{gross} in the future (1.5 larger in 2020 compared to 2011), when all plans will be realized. The overall IRR_{gross} of 123 $km^3\ yr^{-1}$ will far exceed today's average river flows. Even under Sce3, with a theoretical implementation of pressurized systems across all irrigation schemes, we estimated a demand of 89 $km^3\ yr^{-1}$. Predictions of future river flows exacerbate the situation because stream flows are expected to decrease in the time period after 2040, because of lower rainfall rates and increases in evaporation (Beyene et al., 2010), as calculated from a multi-model ensemble. The authors of that study have acknowledged the underlying uncertainty related to emission scenarios as well as model projections. Thus, future water flows are not certain. Nevertheless, the assumed decline in river flows is in line with estimates by Elshamy et al. (2009), who have shown that temperature and rainfall will probably increase and decrease, respectively, thereby leading to decreased runoff in the upper Blue Nile Basin.

6. Conclusions

The Nile Basin is expected to undergo expansion in irrigated agriculture in most countries to feed the fast growing population. The populations of most Nile Basin riparian countries double every 20 to 25 years. This expected increase in irrigation water demand exceeds the available water in the Nile Basin. Improved irrigation efficiency would aid in decreasing water resource consumption in the Nile River Basin, in particular to balance the current demand and supply. However, our calculations of gross irrigation with different irrigation technologies showed that the saving potentials are insufficient to meet the demand of planned irrigated schemes in 2050. Hence, other measures are required to further optimize water resource utilization. A better management of green water (consumed rainfall) in combination with supplementary irrigation is a promising opportunity to improve management of irrigation schemes in the Equatorial Lake regions as well as along the Blue Nile in Ethiopia. The implementation of deficit irrigation may further decrease gross irrigation in Egypt, Sudan and South Sudan. Locally, even solar desalination might be a problem-solving strategy in regions where water quality has deteriorated over the past decades because of overuse.

Under current conditions, most of the annual river flows are consumed by irrigation schemes in Egypt and Sudan, which have very little internally generated river flow. This situation will continue when all plans for future irrigations schemes are realized, and the competition among users will be intensified because of the growing water demand of irrigation schemes in Ethiopia in 2050 as well as decreased river runoff in the future. Moreover, the construction of dams for energy production will further increase competition for water in the absence of comprehensive management plans that integrate all types of uses (agriculture, industry, households, and energy) in the whole Nile River Basin, on a detailed temporal and spatial scale, in order to implement a legal framework for all users.

7. Outlook

Improving the utilization of local water resources by improving irrigation technology is only one way to meet future demands for food and feed in Nile riparian countries. Virtual water trading has been highlighted as another useful measure to cope with water scarcity, particularly in the Middle East and North Africa (Allan, 1998). The Nile River Basin countries virtually export 39 $km^3\ yr^{-1}$ and import 11 $km^3\ yr^{-1}$ of water through crop trading, as recently reported by Zeitoun et al. (2010). The possible advantages of virtual water trading are still under discussion. D'Odorico et al. (2010) have reported that virtual water trading is helpful to counteract food scarcity in the short term but decreases the ability of countries to cope with scarcity in the long term, because the capacity of trading additional food in times of extremes, e.g., droughts, may be limited.

Improving irrigation efficiency addresses blue water consumption (i.e., the water consumed from surface and groundwater resources). Rather than focusing on this water component only, others have emphasized the importance of green water (i.e., consumed rainfall) for managing agricultural water use (Rockström et al., 2009). Green and blue water consumption has been calculated to be 135 $km^3\ yr^{-1}$ for the Nile Basin, with a high percentage of green water of 59% (Sulser et al., 2010). Improving crop production through use of only green water would play a key role in improving the basin-wide water productivity of the Nile. Multsch et al. (2016a) have stressed the importance of green water for managing agriculture in the High Plains Aquifer region (USA), one of the largest groundwater aquifers worldwide, where severe groundwater decline is related to irrigation agriculture. The assessment of green and blue water resources under the consideration of different irrigation scenarios, as is also acknowledged in the general guidelines for Integrated Water Resources Management (GWP, 2000), would be a next step for improving agricultural water management, particularly in the Nile River Basin.

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Appendix A

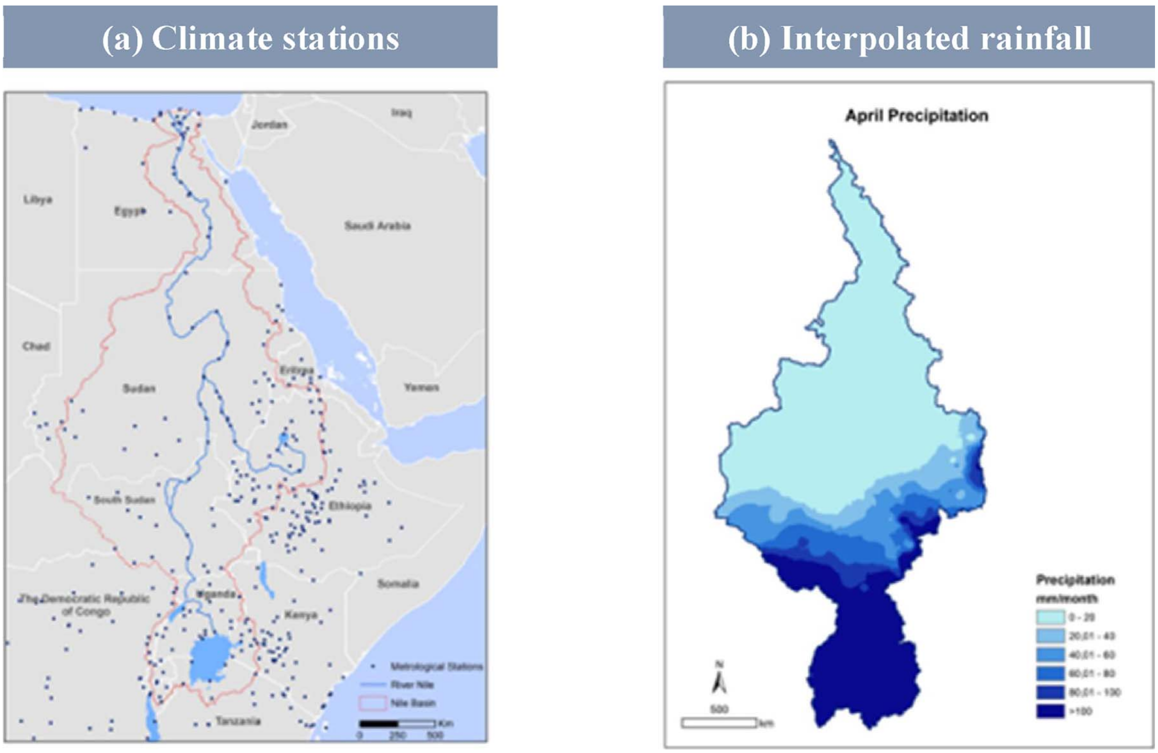

Fig. A1. (a) Climate station from Climwat 2.0 database in North-East Africa and (b) interpolated rainfall in April (mostly average of the years 1971-2000).

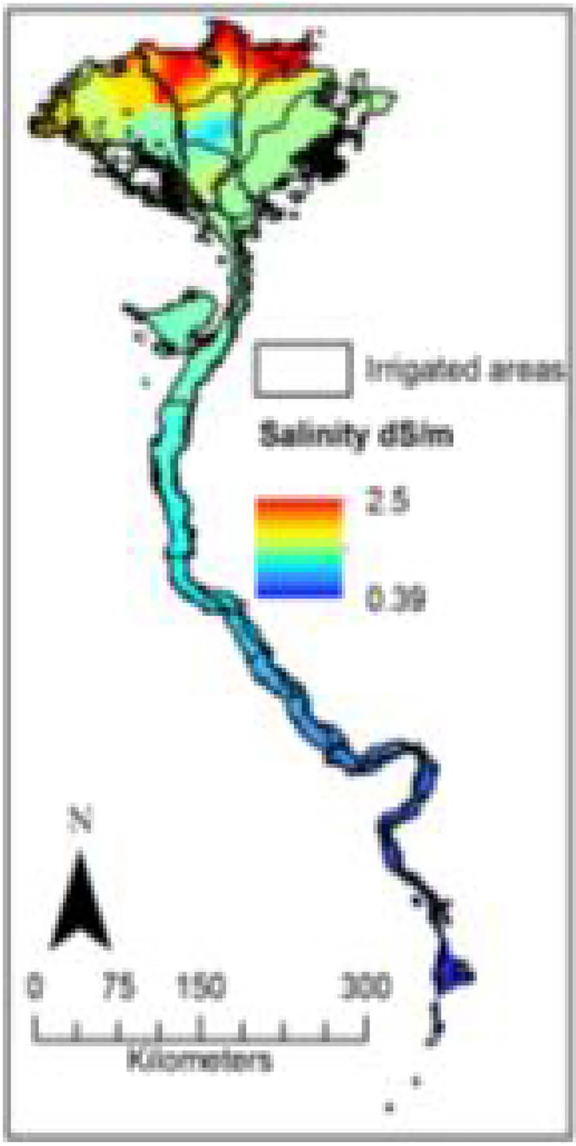

Fig. A2. (a) Stream salinity along irrigated areas in Egypt.

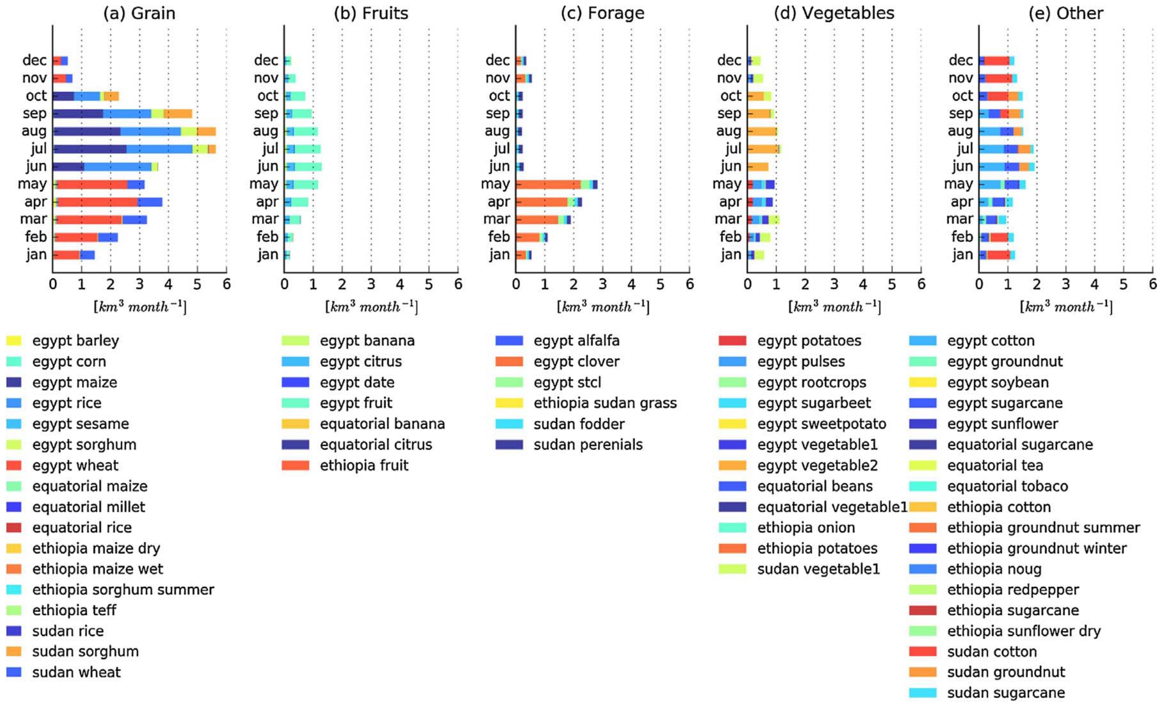

Fig. A3. Monthly gross irrigation of Nile riparian countries for existing irrigation schemes.

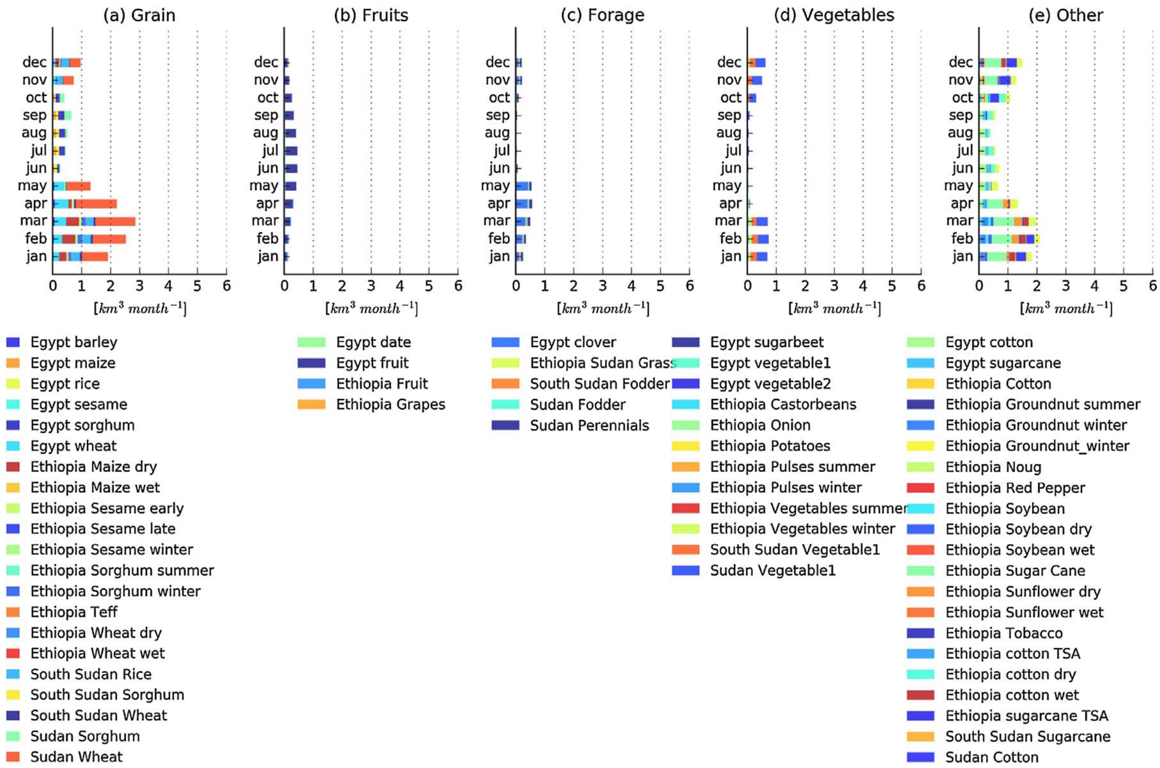

Fig. A4. Monthly gross irrigation of Nile riparian countries for planned irrigation schemes in 2050.

Table A1
Irrigation efficiency per country and province for gravity (Grav.) and pressurized (Press.) irrigation systems for current conditions (baseline) and scenarios (Sce1, Sce2 and Sce3).

		Baseline		Sce1		Sce2		Sce3
Country	Province	Grav .	Press .	Grav .	Press .	Grav .	Press .	Grav .
Egypt	Aswan	70%	80%	75%	85%	80%	90%	95%
Egypt	Qina	70%	80%	75%	85%	80%	90%	95%
Egypt	Sohag	70%	80%	75%	85%	80%	90%	95%
Egypt	Asyiut	70%	80%	75%	85%	80%	90%	95%
Egypt	Al Fayyum	70%	80%	75%	85%	80%	90%	95%
Egypt	Al Jizah	70%	80%	75%	85%	80%	90%	95%
Egypt	Al Minya	70%	80%	75%	85%	80%	90%	95%
Egypt	Beni Suwayf	70%	80%	75%	85%	80%	90%	95%
Egypt	Al Bahayrah	65%	80%	70%	85%	75%	90%	95%
Egypt	Al Daqahliyah	70%	80%	75%	85%	80%	90%	95%
Egypt	Al Gharbiyah	70%	80%	75%	85%	80%	90%	95%
Egypt	Al Minufiyah	70%	80%	75%	85%	80%	90%	95%
Egypt	Al Qalyubiyah	70%	80%	75%	85%	80%	90%	95%
Egypt	Ash Sharqiyah	65%	80%	70%	85%	75%	90%	95%
Egypt	As Ismailiyah	65%	80%	70%	85%	75%	90%	95%
Egypt	Dumyat	65%	80%	70%	85%	75%	90%	95%
Egypt	Kafr-El-Sheikh	65%	80%	70%	85%	75%	90%	95%
Egypt	Matruh	60%	80%	65%	85%	70%	90%	95%
Egypt	Al Qahirah	65%	80%	70%	85%	75%	90%	95%
Egypt	Al Iskandariyah	60%	80%	65%	85%	70%	90%	95%
Egypt	Bur Said	60%	80%	65%	85%	70%	90%	95%
Egypt	Shamal Sina	60%	80%	65%	85%	70%	90%	95%
Ethiopia		60%	70%	65%	85%	70%	90%	95%
Kenya		60%	70%	65%	85%	70%	90%	95%
Tanzania		60%	70%	65%	85%	70%	90%	95%
Rwanda		60%	70%	65%	85%	70%	90%	95%
Uganda		60%	70%	65%	85%	70%	90%	95%
South Sudan		65%	70%	70%	85%	75%	90%	95%
Sudan		65%	70%	70%	85%	75%	90%	95%

Table A2
Irrigation efficiency improvements (difference in comparison to the baseline scenario) for scenarios Sce1, Sce2 and Sce3.

	Sce1		Sce2		Sce3
	Gravity	Pressurized	Gravity	Pressurized	Pressurized
Egypt	5%	5%	10%	10%	15%
Ethiopia	5%	15%	10%	20%	25%
Kenya	5%	15%	10%	20%	25%
Tanzania	5%	15%	10%	20%	25%
Rwanda	5%	15%	10%	20%	25%
Uganda	5%	15%	10%	20%	25%
Sudan	5%	15%	10%	20%	25%
South Sudan	5%	15%	10%	20%	25%

Note: *Pressurized systems for Egypt vary by district − on new land we assume pressurized irrigation techniques and on old land surface irrigation and remain like that in the future.*

Table A3
Gross irrigation (IRR_{gross}) of gravity and pressurized systems in 2011 and 2050 grouped by country and scenario.

Scenario	Country	2011		2050	
		Gravity (km^3 yr^{-1})	Pressurized	Gravity	Pressurized.
baseline	Egypt	54.06	10.25	11.26	0.00
sce1	Egypt	50.67	9.97	10.51	0.00
Sce2	Egypt	47.95	9.81	5.78	4.56
Sce3	Egypt	0.00	48.92	0.00	8.48
baseline	Ethiopia	0.47	0.01	10.06	0.18
sce1	Ethiopia	0.33	0.09	7.11	1.81
Sce2	Ethiopia	0.31	0.08	6.60	1.71
Sce3	Ethiopia	0.00	0.31	0.00	6.49
baseline	Kenya	0.08	0.00	0.00	0.00
sce1	Kenya	0.04	0.03	0.00	0.00
Sce2	Kenya	0.03	0.03	0.00	0.00
Sce3	Kenya	0.00	0.05	0.00	0.00
baseline	Rwanda	0.01	0.00	0.00	0.00
sce1	Rwanda	0.01	0.00	0.00	0.00
Sce2	Rwanda	0.01	0.00	0.00	0.00
Sce3	Rwanda	0.00	0.00	0.00	0.00
baseline	South Sudan	0.00	0.00	3.05	0.00
sce1	South Sudan	0.00	0.00	2.11	0.54
Sce2	South Sudan	0.00	0.00	1.96	0.51
Sce3	South Sudan	0.00	0.00	0.00	1.93
baseline	Sudan	18.18	0.89	13.80	0.67
sce1	Sudan	13.32	3.66	10.12	2.78
Sce2	Sudan	12.44	3.45	9.44	2.62
Sce3	Sudan	0.00	13.09	0.00	9.94
baseline	Tanzania	0.13	0.00	0.00	0.00
sce1	Tanzania	0.09	0.02	0.00	0.00
Sce2	Tanzania	0.08	0.02	0.00	0.00
Sce3	Tanzania	0.00	0.08	0.00	0.00
baseline	Uganda	0.04	0.01	0.00	0.00
sce1	Uganda	0.03	0.01	0.00	0.00
Sce2	Uganda	0.03	0.01	0.00	0.00
Sce3	Uganda	0.00	0.03	0.00	0.00

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