Creating Flexibility in Freshwater Availability for the Eastern Nile Basin

A thesis submitted by

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in partial fulfillment of the requirements for the degree of

Master of Science
in
Civil and Environmental Engineering

Tufts University

February 2017

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ABSTRACT

Water is an important resource for socio-economic development in the Eastern Nile Basin. Current water withdrawals are at the limits of available renewable water resources. Competing demands on water use and allocation include population increase, climate change uncertainty, and the socio-economic and political situation prevailing in the region. Scrutiny of the water balance shows this resource is not a binding constraint for development and that perceived water problems are the result of naturally occurring uneven distribution and inadequacies related to water resources mismanagement. This research aims at finding paths to create flexibility in water availability for the basin. Focus is set on agriculture, the largest land- and water-demanding sector. Examining irrigation efficiency, agriculture practices, rainwater harvesting, and cropping patterns several strategies are proposed and assessed. Results show there is potential to increase the annual water availability up to 11 billion cubic meters, a value representing 13% of the Nile Waters Agreement flow. The largest impact stems from strategies that have little or nothing to do with infrastructure for or policy on water resources, at least from a traditional standpoint. This work aims at shifting the current conversation - in a region where riparian countries struggle to allocate water framing it as a limited resource – to exploratory and collaborative efforts towards sustainable solutions by reframing water as a flexible resource.

Keywords: *Nile Basin, water availability, agriculture, efficiency, flexibility*

LIST OF ACRONYMS

BCM: Billion cubic meter

ENB: Eastern Nile Basin

ET: Evapotranspiration

FAO: Food and Agriculture Organization of the United Nations

GERD: Grand Ethiopian Renaissance Dam

GDP: Gross Domestic Product

MWRI: Egypt’s Ministry of Water Resources and Irrigation

NBI: Nile Basin Initiative

RDI: Regulated deficit irrigation

RWH: Rainwater Harvesting

WP: Water productivity

WUE: Water use efficiency

INTRODUCTION

Concerns have arisen in the international community and among local stakeholders in terms of water resources availability and scenarios of potential water crises in the Eastern Nile Basin, North Africa. Such concerns are primarily based on pressures such as climate change, population increase, political instability, and socio-economic constraints, among others.

A recent study on climate change scenarios indicate Ethiopia and Sudan are at high risk in terms of seasonal water variability and flood occurrence, while Egypt might suffer from severe drought. At a regional scale, water stress is not an issue within the Nile Basin, but there are high risks in terms of seasonal variability, flood occurrence, and drought severity (Gassert, Reig, Luo, & Maddocks, 2013).

The total population in the Eastern Nile Basin (ENB) countries increased by 44% between 2000 and 2015. The annual population growth rate, at 2.4%, doubles the world average. The Food and Agriculture Organization estimates that 209 million people will be living within the Eastern Nile Basin in 2030 (FAO, N.D.). On top of demographic pressures, these countries are either low or lower-middle income countries undergoing serious development constraints and are subject to political instability (Table 1).

Table 1. Relevant statistics for Eastern Nile countries, year 2015. Data on population and income from World Bank Databank. [1]Human Development Index (United Nations); best value for Norway (0.944). [2]Fragile State Index (Fund for Peace); best value for Finland (17.8).

Country	Population		Income		HDI[1]	FSI[2]
	Total (million)	Growth rate (%)	GDP per capita (current US$)	Level		
Egypt	91.5	2.18	3615	Lower middle income	0.69	90.0
Ethiopia	99.4	2.53	619	Low income	0.442	97.5
South Sudan	12.3	4.09	731	Low income	0.467	114.5
Sudan	40.2	2.16	2089	Lower middle income	0.479	110.8

A large amount of research exists on the Nile River Basin. Hydrology, land use, and agriculture are some of the most-addressed topics. Riparian countries, however, struggle on how to split water resources, primarily the Nile River flow. In addition to this, collaborative efforts towards sustainable solutions are meager among the stakeholders.

This research addresses water scarcity in the Eastern Nile Basin by considering water as a flexible resource instead of a finite one. Water allocations and withdrawals in the region have already surpassed the available renewable water resources (FAO-AQUASTAT, 2015; MWRI, 2014). Water is found to be consistently seen a limited resource in the bibliography, and concrete actions to increase water availability[1] to meet current and future have not been fully explored nor summarized into an actionable deliverable.

Focus is given to agriculture in this study for two reasons: it is the largest water-demanding sector and it shapes land use in the region, something tightly related to food production and rainfall exploitation. Strategies on irrigation efficiency, agriculture practices, rainwater collection, and cropping patterns are evaluated, summarized in terms of their potential water savings and gains, and discussed briefly in terms of feasibility for implementation in the region.

Study area

Located on the Northeast corner of the African continent, the Nile River basin encompasses eleven countries, covers about 3.2 million km2, and hosts one of the world’s longest river. The Nile River traverses 6,695 km from its origin in Central Africa to its delta on the Mediterranean Sea (Nile Basin Initiative, N.D.). The Nile Basin can be divided into eight major sub-basins based on catchment drainage divides, sub-basin characteristics and the location of river gauging. Four of the basins contribute over 90% of the main Nile discharge, namely Blue Nile, Lake Victoria, Sobat, and Atbara (Conway & Hulme, 1993). Heavy bimodal and monomodal rainfall prevail in the Lake Victoria area and other parts of the East African highlands, with peaks between March and December and a short dry season. Rainfall in the Ethiopian highlands, conversely, is concentrated during a shorter monomodal period between June and September.

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[1] An increase in water availability stems from considering water as a flexible resource. In this research, two concepts, namely ‘creating flexibility in water availability’ and ‘increasing water availability’ should be understood as the same by the reader. Water availability is increased by either reducing current demand (better manage available water resources) or identifying new or underutilized water sources. See Appendix 1 for a graphic representation of the rationale.

Rainfall declines progressively northward through Ethiopia, Eritrea, Sudan and becomes rare in Egypt (Kloos & Legesse, 2010; Sutcliffe & Parks, 1999).The Blue Nile provides the greater part of the flow of the Main Nile, but its contribution is more seasonal than that of the White Nile, being the residual of seasonal rainfall on the Ethiopian highlands (Conway & Hulme, 1993; Sutcliffe, 2009). Right at the southern border of the ENB, the Sudd is a hydrologically complex region of swamps and seasonal grasslands in South Sudan that conveys the discharge of the Equatorial Lakes to the White Nile. The outflow of this complex wetland are estimated as half of the inflow due to evaporation losses (Sutcliffe & Parks, 1999).

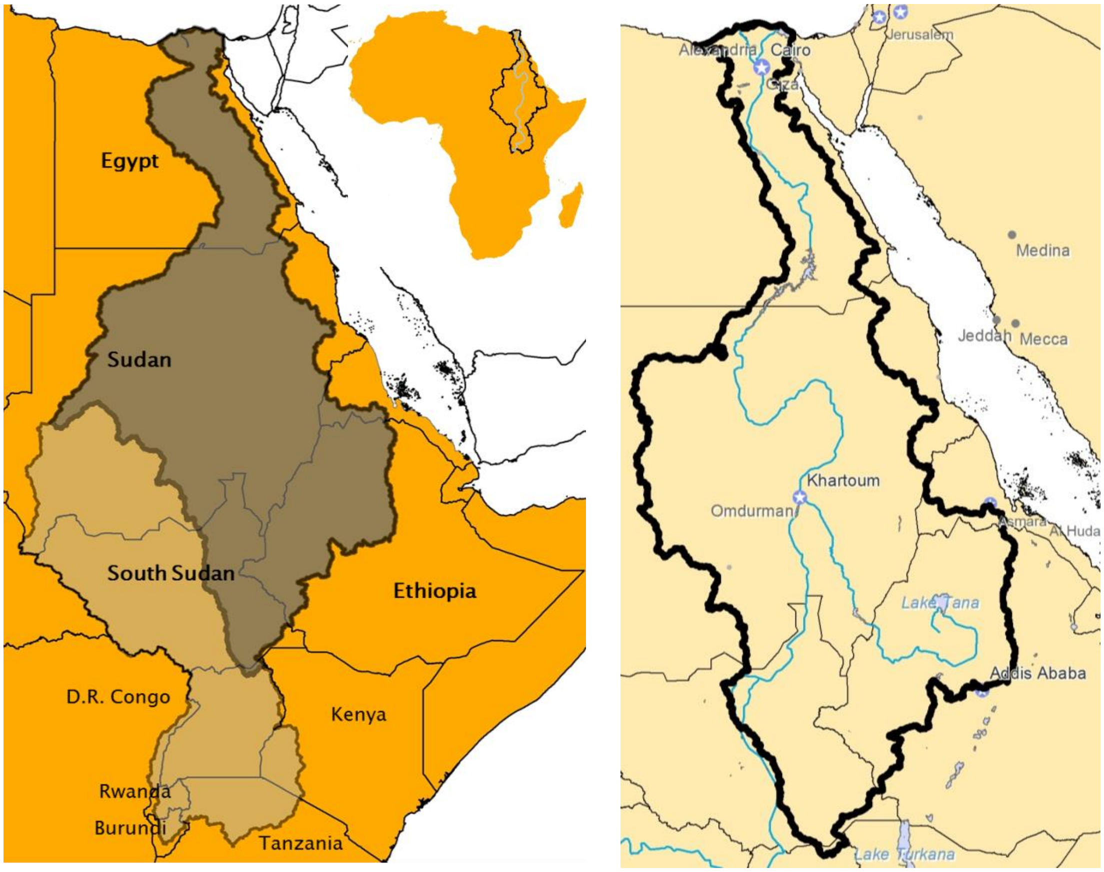


Figure 1: Study area. Left: Nile Basin (all shades) and Eastern Nile Basin (darker shade). Right: Nile River and major cities

The Nile Basin Initiative, an intergovernmental organization fostering development in the region, subdivides the basin into two regions in order to better promote and set out projects. The Eastern Nile subsidiary program spans Ethiopia, Sudan, South Sudan, and Egypt, while the Equatorial Lakes subsidiary program covers the rest of the region. The study area for this research is the Eastern Nile Basin (Figure 1), covering 2 million km^2 (60% of Nile River Basin). The area is of relevance for three reasons: i) more than 80% of the Main Nile streamflow originates from this area within three to four months and is characterized by seasonal and inter-annual variability, ii) the Ethiopian Highlands offer hydropower generation and water saving potential, and iii) the geographical layout of the countries allows interconnecting infrastructure such as power, roads and canals (Nile Basin Initiative, N.D.).

Water resources

Freshwater in the region is available from rainfall, rivers, and aquifers. However, not all the countries benefit from these sources to the same degree. The relationship between water supplies (amount and location) and water withdrawals reveals issues of sustainability and equity (Figure 2). Precipitation is insignificant in Egypt and, thus, 98% of freshwater withdrawals come from outside its national borders (Abdin & Gaafar, 2009). The Nile River is the main source of water with an annual allocation of 55.5 BCM under the Nile Waters Agreement of 1959 with Sudan (Egypt and Sudan, 1959; FAO-AQUASTAT, 2015). On the other hand, Ethiopia is rich in renewable water resources, mainly on the country´s western highlands where annual rainfall average ranges from 1,600 to 2,122 mm (Awulachew et al., 2007). Most of the water, nonetheless, either evaporates or becomes run-off without proper exploitation. Groundwater is not significantly tapped in the region but it is crucial as the only water source for some isolated communities. Egypt and Sudan lie partially above the Nubian Sandstone Aquifer System, a fossil aquifer believed to be the largest reserve of freshwater in the world. So far, this water body has undergone limited development only in Libya and Egypt’s major oases in the New Valley (Thorweihe & Heinl, 2002).

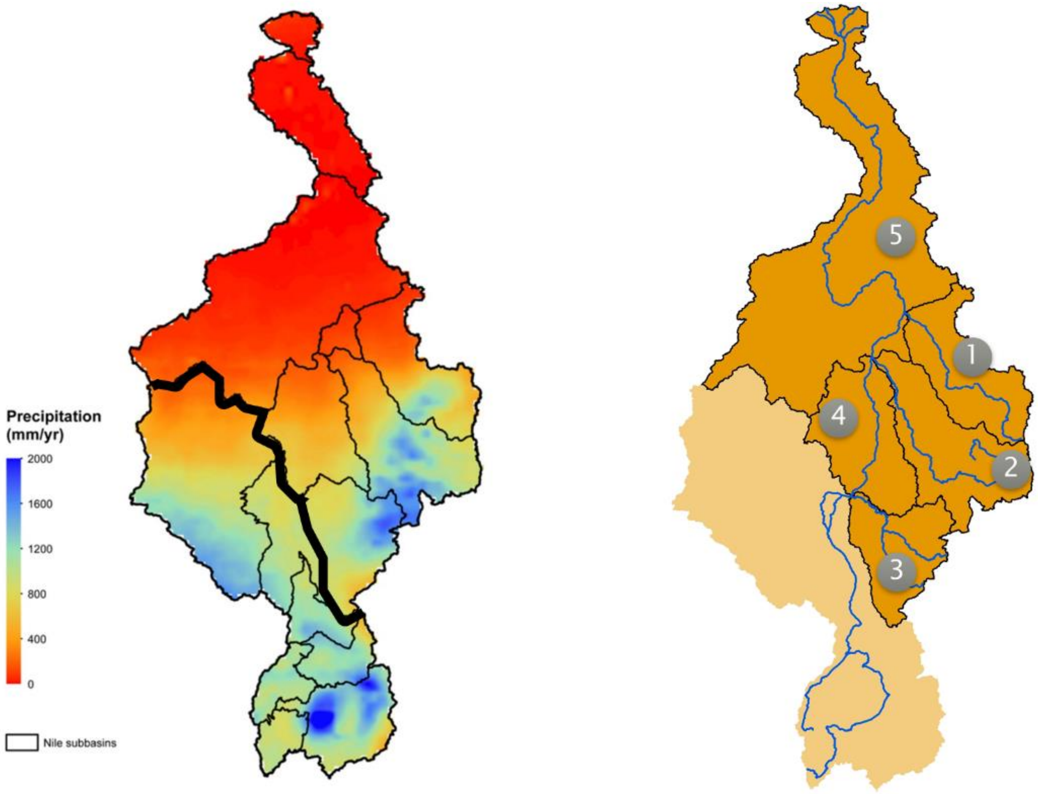
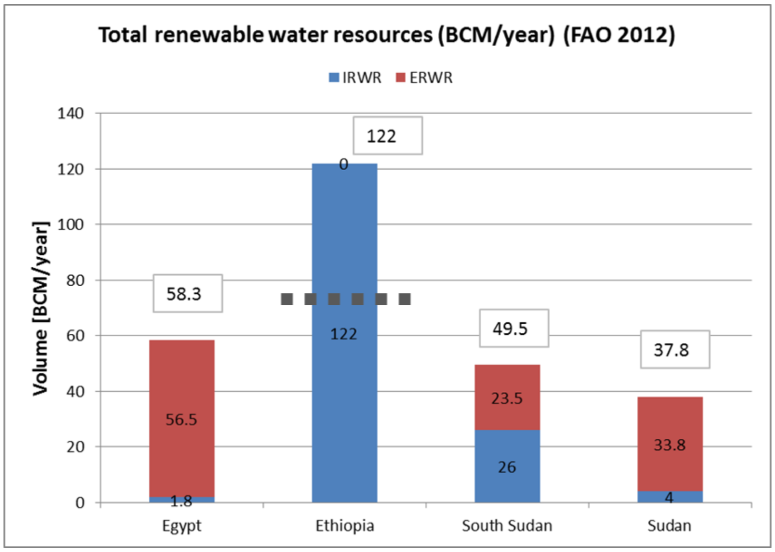


Figure 2. Precipitation distribution (Awulachew et al., 2007) (left); Major drainage system (right). Sub-basins: 1) Tekeze-Atbara, 2) Blue Nile; 3) Baro-Akobo-Sobat, 4) Lower White Nile; 5) Main Nile.

It is claimed North Africa ran out of renewable freshwater decades ago (Qadir, Sharma, Bruggeman, Choukr-Allah, & Karajeh, 2007) and climate change projections indicate the region might become hotter and drier (Conway, 2005; Islam & Susskind, 2015). It seems reasonable then, that riparian countries struggle to re-allocate the limited river flows. However, the annual rainfall in the region is largely superior to those flows but only a small amount is utilized in cities or irrigated agriculture. Most of precipitation is consumed through landscape evapotranspiration. The estimated total water inflow for the Eastern Nile Basin is around 895 BCM/year (Table 2). However, current debates among the riparian countries are about how to manage 84 BCM/year, a volume agreed upon more than half a century ago between Egypt and Sudan, only two of the riparian countries.



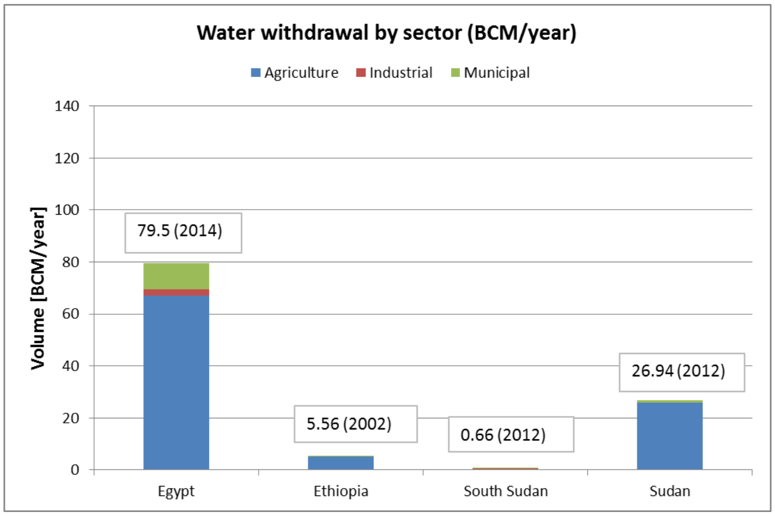


Figure 3. Renewable water resources (above) and water withdrawals by sectors (below) in the Eastern Nile countries. Values at country level. Approximately 60% of Ethiopian renewable water resources correspond to the Eastern Nile Basin (FAO-AQUASTAT, 2015).

Table 2. Water balance in Eastern Nile Basin. Reconstruction based on data by Water Accounting. Values in BCM/year for period 2005 – 2010. Utilized flow is defined as "part of available water that is depleted for uses" (glossary by Water Accounting).

Total Inflow	Total Outflow
895	870
Precipitation	Consumed water*
	828
841	Outflow (Mediterranean Sea)
	24
Surface water and Groundwater inflow	Losses to Groundwater
54	18
Closure error (3% of total inflow)	
25	

* Landscape ET (784) and Utilized flow (44)

There seems to be a gap between supply and demand in the region that needs to be addressed. Reasons behind the gap may be summarized with the following quote. "Water is clearly a major factor in socio-economic recovery and development in Africa. The continent appears to be blessed with substantial rainfall and water resources. Yet, it has severe and complex natural and man-made problems that constrain the exploitation and proper development of its water resources potential" (UN Water/Africa, N.D.).

The water gap is intertwined with social, political, and economical aspects. Higher populations increase the demand for food and drinking water. Higher food production demands more water and energy. In addition to this, the political stability of the region was compromised in recent years by two facts. First, the secession of South Sudan in 2011 and second, the beginning of the construction of the Grand Ethiopian Renaissance Dam (GERD). As a new country South Sudan is requesting revisions to the water agreements with Sudan in order to develop its agricultural sector (Salman, 2011). On the other hand, the construction of a large dam on the Blue Nile river will transform the hydro-political map in the Nile Basin (Abdelhady et al., 2015). Major concerns about the dam construction and operation were addressed in the Declaration of Principles signed recently by Egypt, Sudan and Ethiopia but the issue has not yet been settled.

Research questions

Water problems in the Eastern Nile Basin are surmountable but current water management practices will not succeed (UN Water/Africa, N.D.). According to Islam and Susskind (2015), the water crisis in North Africa will not be solved by incorporating more technical information. What needs to be done is to reframe the problem, build consensus and work cooperatively. It is possible to shift the conversation focus, moving the spotlight from the current approach of ‘how to split what we have’ to ‘how to increase the pie and then how to redistribute’. To do that it is necessary to look at the region as a whole to explore regional water savings and gains through the promotion of water conservation and the implementation of non-conventional water resources, as suggested by Qadir et al. (2007), to cope with water issues in water-scarce countries.

This study addresses the following questions: Can water be seen as a flexible resource? Is there a way to increase water availability in the region? Is it possible to address the supply-demand gap through different feasible and sustainable strategies with different levels of complexity? It is hypothesized that there is significant potential to either save or gain water in the Eastern Nile Basin, and that, so far, this potential has not been comprehensively explored.

This work aims at shifting the current conversation - in a region where riparian countries struggle to allocate water framing it as a limited resource – to exploratory and collaborative efforts towards sustainable solutions by reframing water as a flexible resource. To do this, creative ideas not yet addressed in the literature about the region are evaluated and summarized into actionable strategies.

Methodology

This work was divided into three major components: 1) comprehensive literature review, 2) context-based definition of assumptions, 3) formulation and evaluation of strategies.

The literature review was carried-out at two levels and consisted of searches in major engines and repositories focusing on recent sources (years 2000 – 2016). The first literature assessment was wide and shallow. It addressed water-related issues such as hydrology, water resources management and climate change. It also involved topics not visibly linked to the water problem to provide context to help understand the region’s problems. Those topics are food, energy, political agreements, socio-economic development, investment and trade. Information provided by international organizations like the Food and Agriculture Organization (FAO) and the UN Development Program, the World Bank, and the Nile Basin Initiative set a solid and reliable foundation for our research.

The second level of literature review was narrow and deep. It consisted of a detailed assessment on the specific topic of increasing water availability. The research spectrum involved irrigation efficiency, rainwater harvesting, crop yield improvement, changes in cropping patterns and international trade.

The literature review showed that basic information is missing or hard to find in English. To overcome this values and assumptions were taken from a collection of sources and documented accordingly. As an example, Brouwer and Heibloem (1986) was used for crop water requirements whereas Steduto, Hsiao, Fereres, and Raes (2012) provided figures on yields and water productivity. The data repositories FAOSTAT and AQUASTAT were central to this research. Both references and databases allowed the generation of a baseline upon which the strategies are founded and the corresponding increases in water availability (water savings and gains) are computed.

The final step in this work deals with the formulation and evaluation of strategies in the agriculture sector. Such strategies aim at increasing water availability in the region and respond to either actions being taken already within the basin, successful experiences in other parts of the world that might be translated into the study area, or international standards for best practices in agriculture. For example, actions in the region are reported in Simons, Terink, Badawy, van den Eertwegh, and Bastiaanssen (2012) and Karrou, Oweis, El Enein, and Sherif (2012); actions likely to be translated into the region are found in Basán Nickisch, Lahitte, Sosa, Sánchez, and Tosolini (2016); and best practices in the agriculture sector are found in Kirda (2002) and Steduto et al. (2012).

Specific software was used to complete the research. For numeric data management and processing, as well as for computations, spreadsheets in Microsoft Excel 2010 were developed. Each strategy has its own methodology and formulation, detailed in both sections ‘Strategies

Implementation' and Appendix 1. In addition, some spatial processing and computations were carried out using ArcGIS. Sources for the shapefiles are the GlobCover Land Cover Maps 2009 (www.esa.int) and the Nile Basin Initiative.

THE AGRICULTURE SECTOR

Below is a short background on the Nile Basin’s agriculture sector, with special details for Egypt and Sudan, being the two countries this research focuses on. Reasons for focusing on this sector are founded on its impact on water demand and land use, as addressed later. Secondly, the current agriculture baseline for this study is provided, and finally the rationale behind each evaluated strategy is presented.

Agriculture in the Nile Basin

Agriculture is central for the countries in the Nile Basin in terms of socio-economics and food production. It generates between 32% and 94% of employment, and contributes between 12% and 43% of countries’ GDP (NBI & GIZ, 2012). Average values for the Nile Basin are 75% and 33%, respectively (OECD 2006 in Karimi, Molden, Notenbaert & Peden, 2012).

The Nile Basin Initiative identifies 15 production systems based on available natural resources and dominant patterns of farm activities. They are broadly classified into four categories, namely rainfed and irrigated farming systems, and livestock and fish-related production systems (NBI & GIZ, 2012). Their relevance and extension varies regionally (Figure 3). Rainfed systems encompass 87% of cultivated land. Irrigated agriculture utilizes most of renewable water resources. Livestock and fisheries-related systems are the only livelihood available for some communities (NBI & GIZ, 2012).

Major food crops grown in the Nile Basin are cereals, pulses, tubers, oil seeds, fruits, and vegetables. In turn, major cash crops are coffee, tea, sugarcane, cotton, and tobacco. Sugarcane is the most important cash crop. In terms of food crops, wheat and maize lead cereal production followed by rice and sorghum. Cassava and potato prevail among non-cereal products (NBI & GIZ, 2012).

Agriculture in the Eastern Nile Basin (ENB) is shaped by both cultivated land and irrigation. Sudan and Ethiopia dominate in terms of cultivated land, whereas Egypt dominates regarding irrigation (Figure 3). On the other hand, Egypt and Sudan are responsible for most of the water consumption in the Eastern Nile Basin (recall Figure 2, lower chart).

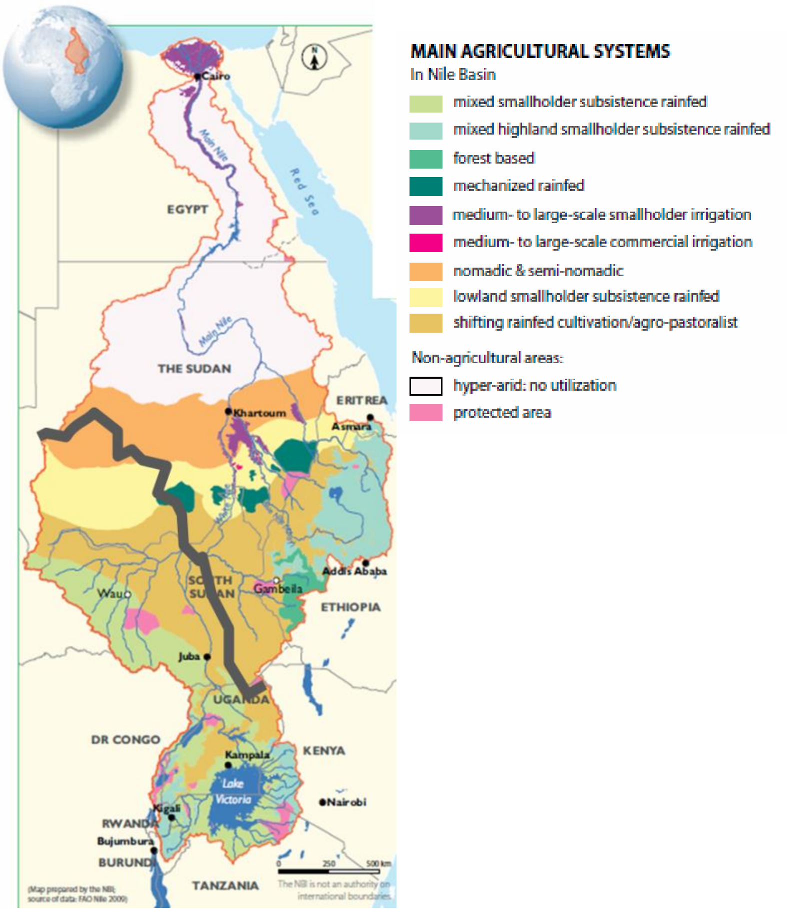
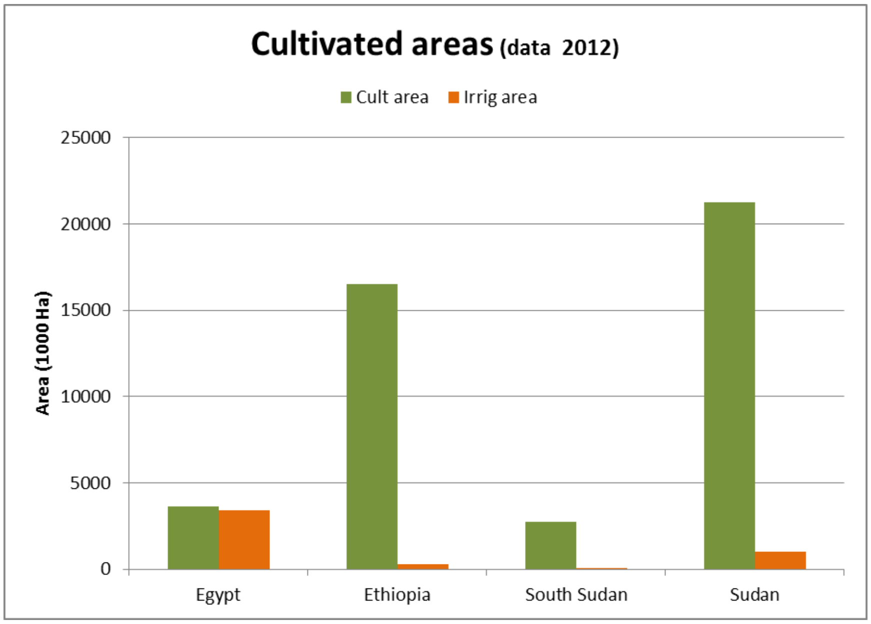


Figure 4. Main production systems in the Nile River Basin. The bold grey line indicates the Southweast border of the Eastern Nile Basin. Source: NBI & GIZ, 2012

More than 90% of irrigation is performed through surface techniques such as flood and furrow irrigation (Figure 3, lower chart). Thus, one might be tempted to claim that water saving efforts should be placed where most of the water is utilized, hence, through efficiency improvements in Egypt and Sudan’s irrigation. That is, nonetheless, partially true and somewhat unfair. An insightful statement by Robyn Johnston found in Awulachew (2012) sheds some light on the issue. “Rain-fed agriculture dominates water use in the Nile Basin outside Egypt, with more than 70% of the total basin rainfall depleted as evapotranspiration from natural systems partially utilized for pastoral activities, and 10% from rain-fed cropping, compared with less than 1% depleted through irrigation […] There is potential to considerably expand and intensify rain-fed production in upstream areas of the basin without significantly reducing downstream water availability”.



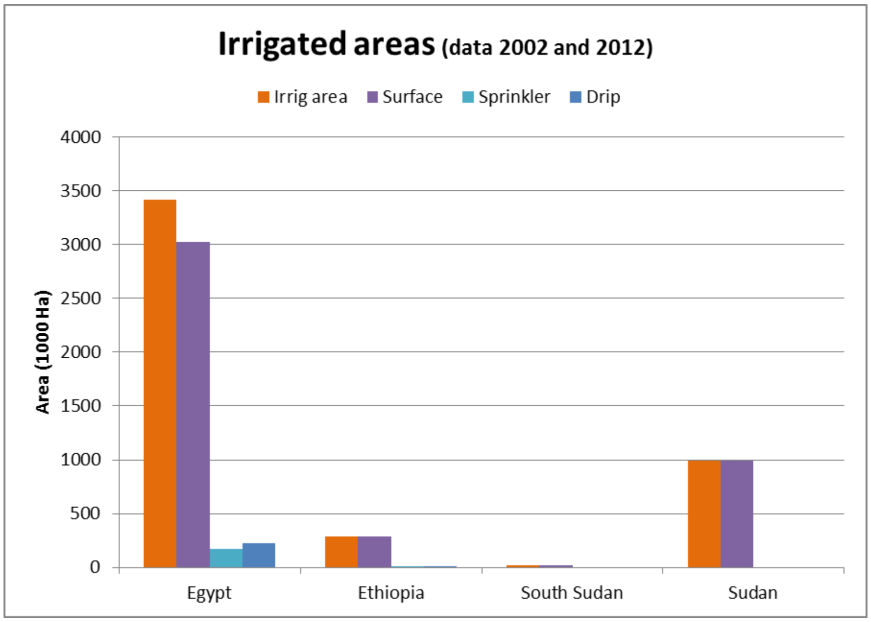


Figure 5. Cultivated (above) and irrigated (below) areas in the Eastern Nile countries. Figures represent country values. Source: AQUASTAT, consulted 2016.

Fears of possible regional crisis are founded in both signs of water stress and staggering food demand. More food is needed for today's people and future generations but the question as to whether it should be produced nationally or imported has not been explicitly addressed. Food production has increased over the years but population pressures have been strong enough to make countries fall short of local demand and become net food importers. Egypt ‘leads’ the negative figures in cereal trade balance with -9 million tones, being distantly followed Sudan with -1.8 million tones. Some trade corridors are identified in the region but traded volumes show they are weak. Intra-basin exchange between the upper and the lower Nile countries is practically non-existent, something likely due to the presence of the Sudd wetland and the Sahara desert as barriers for people and goods (NBI & GIZ, 2012). Such a lack of inner trade is overcome through stronger links with the rest of the world. Egypt is the world’s biggest importer of wheat, with an import estimate of 11 million tones for the 2015/2016 marketing year (GIEWS, 2016; Knecht, 2016). Besides wheat[2], Egypt imports large amounts of maize seed and soya bean.

Based on both cultivated and irrigated land figures and irrigation water withdrawals, this research focuses on both irrigated and rainfed agriculture only in Egypt and Sudan for the implementation of water saving/gaining strategies.

Agriculture in Egypt

Agriculture represented 11% of Egypt’s economy in 2014, a value that has kept below 15% for the last 10 years. The sector, in turn, employed 30% of total labor force in the last 5 years (World Bank, 2016). Water constraints and desert climate have made Egypt master agriculture. The totality of the country’s potential arable land is under production. The most important crops are wheat and maize, accounting for 41% of the total harvested area (FAO-AQUASTAT, 2015). Egypt covers its demand in all agricultural products except oil, sugar, and wheat (MWRI, 2014). The case of wheat draws special attention. This cereal is staple food in Egypt, and even though the country produces large amounts domestically at very high yields, the demand is so remarkable that Egypt has ranked the world’s leading importer for decades. Such reliance on wheat, and cereals in general, renders the country vulnerable to economic ups and downs in the commodities market (Al-Riffai, 2015).

Population increase, urbanization, and food security have mobilized Egypt towards horizontal expansion. The current inhabited area in the country is only 5% and the government is undergoing an ambitious program to stretch it to about 25% (MWRI, 2005). Land needs to be

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[2] Wheat usually implies both wheat and meslin

reclaimed from the desert to both compensate for agriculture land lost to urbanization and to augment land area for food production. Plans include reclaiming about 400 thousand hectares (1 million acres) of land to increase agricultural area (Al-Riffai, 2015), above 10% of the current cultivated land.

Not only agriculture has been mastered in Egypt, but irrigation practices as well. The irrigation network includes more than 30,300 kilometers of channels and large canals. (El Gamal, 1999 in Awulachev 2012). From an engineering and management perspective the irrigation system is as interesting as it is complex. The water conveyance network features five levels of hierarchy. *Rayah* is the name for the principal canals; these usually originate on the Nile River right upstream of the multiple barrages that dam the river and provide potential energy for gravity flow (Figure 2). The second and third level canals do not feature any special name other than Main and Branch canals, respectively. The fourth and fifth level, in turn, namely *mesqas* and *marwas*[3], are highly important because they are closer to the final user (farmer) and are the center of recent irrigation improvement efforts in the country (e.g. Irrigation Improvement Project by the World Bank). Despite such a sophisticated irrigation system water application at a farm-level remains inefficient. Farmers implement surface irrigation techniques over 90% of Egypt's total irrigated area. For wheat and maize, among the most-cultivated crops, basin irrigation is performed, a technique that requires large amounts of water (Karrou et al., 2012) with a significant portion of it being lost to non-productive means.

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[3] Also, known as *merwas*

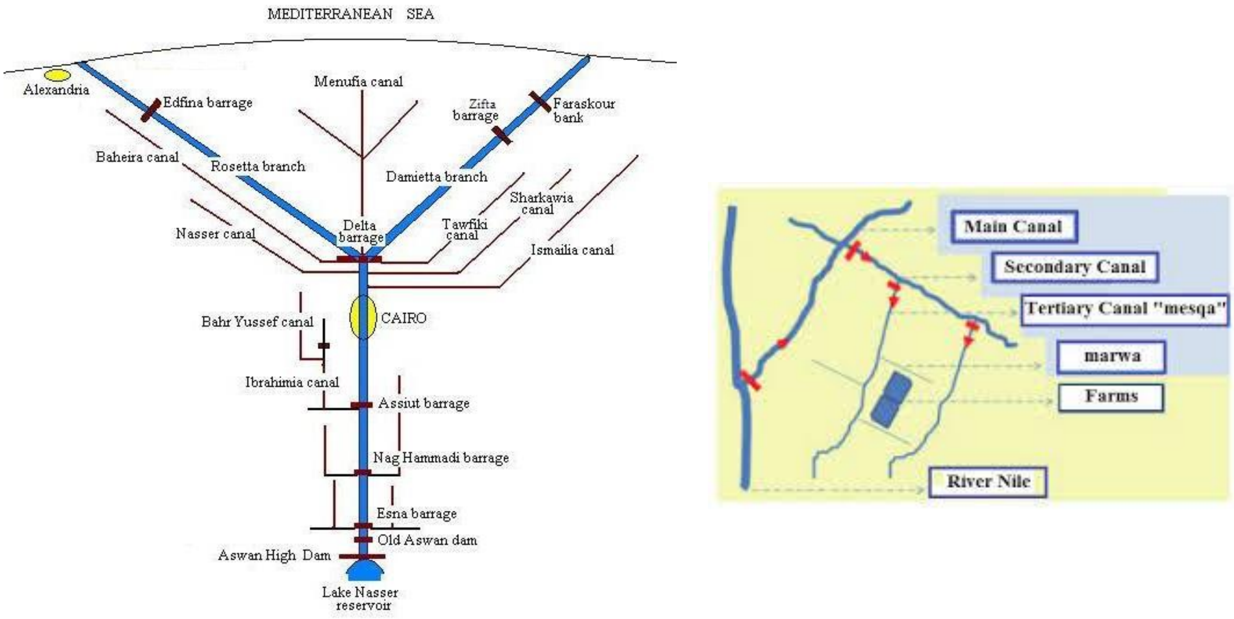

Figure 6. Diagram of Egypt's irrigation system. Left: Barrages and Rayahs along the Nile. Source: Wikipedia. Right: Hierarchy of canals network below the Rayahs. Source: Mostafa and Fujimoto (2015)

Water over-allocation is the cause of waterlogging and salinity. To cope with this increasing issue in the densely cultivated Nile Valley and Delta, a National Drainage Program has been carried out during the last four decades, and surface irrigation has been prohibited in the new reclaimed areas (FAO-AQUASTAT, 2015). New reclaimed desert lands are being used to grow fruits, vegetables, nuts, and vineyards under drip irrigation techniques (Awulachew, 2012). The drainage canals collect a significant amount of water which is used as main water supply for farmers located at the tails of the r*ayahs*. Related to this, aquaculture is being developed in the Nile Delta as an alternative source of protein for Egyptian diet. This also helps mitigate pollution problems that come from using irrigation runoff and sewage from the drains (Awulachew, 2012).

The current Egyptian agriculture is dominated by small farms. 95% of the farms have less than 2.1 hectares (5 feddan[4]), the average size being 0.84 hectares (2 feddan). However, Egyptian and international investors are becoming relevant in the agriculture industry mainly in the new reclaimed expansion areas in the desert, where large farms are irrigated using modern irrigation technologies such as drip and sprinkler (Barnes, 2014).

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[4] Area unit used in Egypt, Sudan and other countries in the region. 1 feddan = 0.42 hectares

Water use in Egypt has defied the economics of common goods. Despite international awareness that pricing water contributes to a more efficient use the country has denied the implementation of tariffs for agriculture water. Most of the cost associated with this activity falls in the government´s hands. Agriculture is inefficient, full of subsidies, and characterized by post-harvest losses and water misuse (Barnes, 2014).

Agriculture in Sudan

Agriculture in Sudan is highly relevant for both the economy and the country's social development. It represents 35 – 40% of the national GDP and 80% of exports. In addition, the sector employs about 65% of the workforce and supplies the industries with 50% of raw materials (Mahgoub, 2014). The country has the largest cultivated area in the Nile Basin (Figure 3). Most of this land is located between the Atbara, Blue Nile, and White Nile rivers (Mahgoub, 2014). The most important crop in Sudan is sorghum which covers 43% and 49% of the irrigated and rainfed harvested area, respectively (FAOSTAT database 2014). The arable land is divided into irrigated agriculture, traditional rain-fed cultivation, and mechanized farming[5] (Mahgoub, 2014). The coverage area of each farming system is 9%, 58% and 33%, respectively (Table 3).

Table 3. Agricultural sub-sector in Sudan. Calculated from the Economic Survey 2006, Ministry of Finance and national Economy (Hamid Faki, 2012, found in Mahgoub, 2014).

Sub-sector	Area [millon Ha]	Share of area (%)	Share of GDP (%)
Irrigated farming	1.5	9.0	11.3
Traditional rainfed	9.8	58.0	6.3
Mechanized farming	5.5	33.0	1.4
Total	16.9	100.0	19.0

Irrigation is crucial for Sudan's economy. Most cash crops are produced in irrigation schemes (FAO, 1997) with sugar being the most relevant. According to Mahgoub (2014) the irrigation schemes are "the center piece of Sudan's agricultural development strategy". These large-scale gravity-irrigated areas are located in the desert, semi-desert, and low-rainfall savannah zones.

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[5] Mechanized farming: rainfed agriculture practiced in a broad belt running from the northeastern portion of the country to the south-southwest (Britannica, 2016) characterized using machinery for certain tasks to improve farm worker productivity.

The largest schemes are Gezira, New Haifa, and White Nile Agricultural Corporations, covering about 1.2 million Ha (65% of total irrigated land). The Gezira Scheme is the oldest and largest gravity irrigation system in the country. It covers 870 thousand hectares and withdraws over one-third of Sudan's share of Nile water (FAO-AQUASTAT, 2015). The impact of Gezira's surface irrigation is such that regional climate, specifically precipitation patterns, might be changing as suggested by recent evidence (Alter, Im, & Eltahir, 2015). Even though of remarkable relevance, irrigation is not fully implemented. Sudan uses only 40% of the irrigation potential.

Different land sizes are found, according to regions and farming system. The tenancy size in the two largest schemes, Gezira and Haifa, is about 12 and 6 Ha respectively. In smaller schemes, tenancy ranges from less than 0.5 Ha to a few hectares. With respect to non-irrigated areas, the holding size is around 400 Ha in traditional rainfed areas, and 2 – 30 Ha in the mechanized farming systems (Craig, 1991 in Mahgoub 2014). Mechanized farming holds the largest share in cultivated land. Nonetheless, planners have given more attention to irrigation schemes because of the ease of organization (Spaulding, Al-Shahi, & Others, 2016).

Agriculture baseline

A baseline of agriculture production in both Egypt and Sudan was built using multiple sources. Both databases by United Nations Food and Agriculture Organization (FAO), namely FAOSTAT and AQUASTAT were key for this analysis. Harvested areas, yields and production for crops constitute the most important information (see Tables 5 to 8). Complementary values for yield and water productivity were found in Steduto et al. (2012) and Simons et al. (2012). Water demand and water productivity were either computed or taken from different sources, as indicated. Data from the ENB was used when available otherwise general worldwide values were used. Appendix 1 provides details on assumptions and formulas utilized along the baseline delineation.

Efficiency plays an important role along this paper´s aims. Efficiency in Egypt is far from uniform. By contrasting water demands in Keith, Hussein, and Mahdy (1998) and Simons et al. (2012), it comes to light that efficiency in the Delta is higher than in the other two regions. For simplicity, Egypt´s efficiency was computed at one sole value of 68%. Details on this country´s special features around irrigation efficiency are discussed later in this paper. On the other hand, Sudanese efficiency was assumed at 65%, a value found by using data for the Gezira Scheme as calibration[6].

Table 4. Breakdown of Egypt's agriculture water use. Depletion is equal to total withdrawal minus return flow. Source: AQUASTAT, 2016

Agriculture water withdrawal			Return Flow	Depletion
Total	Breakdown			
59.0	Surface water	44.7	18.0	41.0
	Reuse of surface water	5.0		
	Groundwater	1.0		
	Reuse of groundwater	6.0		
	Fossil groundwater	0.8		
	Treated wastewater	1.5		

Table 5. Harvested area and irrigation requirement in Egypt's irrigated agriculture. Most relevant crops in terms of both harvested area and water demand. Source: several (see Appendix 1).

Crop production			Estimated annual water demand (ETa)	
Crop	Harvested area			
	[1000 Ha]	[% of total]	Total [BCM]	% of total
Wheat	1418.7	22	5.6	14
Maize	1030.3	16	5.4	13
Sugarcane	138.2	2	2.7	7
Total irrigated area	6333.0	*	Total agriculture Eta	
			41.0	
			Total agriculture withdrawal	
			59.0	

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[6] Crop areas of sorghum at 60%, cotton at 17% and wheat at 6% were considered as demanding 100% of Gezira's water withdrawal (Bastiaanssen & Perry, 2009), reported as one-third of Sudan's Nile share of 18.5 BCM (scheme area of 870 750 Ha) (FAO-AQUASTAT, 2015).

Table 6. Harvested area and irrigation requirement in Sudan's irrigated agriculture. Most relevant crops in terms of both harvested area and water demand. Source: several (see Appendix 1).

Crop production			Estimated annual water demand (ETa)	
Crop	Harvested area			
	[1000 Ha]	[% of total]	Total [BCM]	% of total
Sorghum	678.7	43	3.7	22
Wheat	254.6	16	1.3	8
Sugarcane	70.7	5	1.4	8
Total irrigated area	1563.0	*	Total agriculture withdrawal 25.9	

Table 7. Harvested area and water requirement in Sudan's rainfed agriculture. Most relevant crops in terms of both harvested area and water demand. Source: several (see Appendix 1).

Crop production			Estimated annual water demand (ETa)	
Crop	Harvested area			
	[1000 Ha]	[% of total]	Total [BCM]	% of total
Sorghum	7698.9	49.0	34.65	43.0
Total non-irrigated area (fodder area N/A)	15720.6	*	Total agriculture use in rainfed areas 80.64	

Table 8. Yield and water productivity values for Egypt and Sudan. Source: several (see Appendix 1).

Crop	Yield [tons/Ha]		Water productivity [Kg/m3(Eta)]	
	Egypt	Sudan	Egypt	Sudan
Wheat	6,7	2,1	1,53	0,35
Maize	7,7	-	1,30	-
Sorghum	-	Average 0.7 Irrigated 1.5 Gezira 2.2	-	0,40
Sugarcane	114,1	92,7	5,88	4,23

INCREASING WATER AVAILABILITY

A collection of strategies has been identified to increase water availability by either saving or gaining water in the Eastern Nile Basin's agriculture sector. They are the result of a comprehensive assessment on agriculture water in the region where questions about what water is used for, how much, when and by whom were tacitly addressed. Strategies encompass practices in irrigation, rainfall exploitation, improvement in crop yields, and crop patterns modifications (Table 9).

Interesting claims have shaped this section, for instance those in Abdin and Gaafar (2009) in terms of irrigation practices and crop changes in Egypt, and the ones by the Pacific Institute and the Natural Resources Council about irrigation scheduling and regulated deficit irrigation in California (PI & NRDC, 2014). The bulk of the ideas discussed along the strategies delineation and implementation is not new in the study area. Increasing water and land productivity in Egypt's old lands was addressed by the World Bank, the German Development Bank (KfW), and the Dutch Government in the Irrigation Improvement Project (IIP) (Simons et al., 2012). The implementation of rainwater harvesting techniques and/or measures on soil-water conservation (SWC) are reported by Herweg and Ludi (1999) and Mekuria et al. (2015). The utilization of drought-tolerant and higher-yielding crop, e.g. wheat varieties, has been reported as well by the World Bank ("Egypt: Irrigation Innovations in the Nile Delta," 2009) and Egypt's Global Watch Country Brief (GIEWS, 2016). However, concrete actions to be implemented and their expected impact in water availability are still lacking.

Focus is given to the major cereal crops: wheat, maize, sorghum and sugarcane. Together they represent 48% of the harvested area (11.3 million hectares) and 46% of the irrigated area (3.6 million hectares). Fodder and cotton, even though they are among the most water-demanding crops, were left out for multiple reasons. Cotton is relevant in Sudan and most of it is grown in the Gezira Scheme. Its production, however, fluctuates. Official reports indicate cotton production has declined, giving place to other activities such as livestock (Mahgoub, 2014), something confirmed by the low value of total harvested area in 2014 at about only 65 [1000 Ha] (FAOSTAT database) compared to 158 [1000 Ha] in 2011 (AQUASTAT database).

Fodder crops such as berseem, clover and alfalfa are major water consumers as well but informality in their production and the use they are given makes this type of crop unactionable to save/gain water. According to Simons (2012), in Egypt "berseem is mainly grown as fodder for grazing cattle and for enrichment of the soil […] Farmers seldom sell their harvested berseem crop or seeds, and they do not keep track of harvested amounts". In addition, "the area planted to fodder crops decreased from about 28% in 1970/74 to around 19% of the cropped area in 2007 (SADS, 2009 in El-Nahrawy, 2011). This decrease is due to the high competition between wheat and berseem during the winter season on the available cultivated area" (El-Nahrawy, 2011).

Finally, rice in Egypt is not a target because, on the one hand, its water demand at 555 mm (Simons, Bastiaanssen, & Immerzeel, 2015) is on the lower side of the spectrum 450 – 700 mm (Steduto et al., 2012); the harvested area is about one-fourth the combined area of wheat and maize; rice is among the top-ten of Egypt's exports.

Table 9. Strategies to increase water availability

No.	Name
1	Irrigation efficiency
2	Regulated deficit irrigation
3	Evaporation component
4	Rainfall exploitation
5	Yield improvements
6	Minor changes in cropping pattern
7	Major changes in cropping patterns

Irrigation strategies

Irrigation efficiency

Irrigation is crucial for food production to meet current and future demands (Maliva & Missimer, 2012). It allows water to reach the root zone of plants more efficiently, enabling more transpiration and biomass generation, thus increasing crop yield. Five types of irrigation techniques are widely used in agriculture: flood, furrow, sprinkler, sub-irrigation, and localized irrigation (Pescod, 1992 in Maliva & Missimer, 2012). Surface methods, such as flood and furrow, are the least efficient, whereas localized irrigation techniques are the most efficient (Maliva & Missimer, 2012).

Agriculture water is classified according to management targets. A first approach divides it into consumptive and non-consumptive use (PI & NRDC, 2014). A second approach looks at water either used or lost (Maliva & Missimer, 2012) (Table 10).

Table 10. Classification of agriculture water according to PI & NRDC (2014) and Maliva & Missimer (2012)

Approach	Agriculture water classification	Description
PI & NRDC (2014)	Consumptive use (irrecoverable loss)	Plant transpiration and biomass incorporation, evaporation from soils and water bodies, and water lost to pollution.
	Non-consumptive use (recoverable loss)	Water available to reuse
Maliva & Missimer (2012)	Water used	Plant transpiration
	Water loss	‘Wasted water’ through conveyance and storage losses, evaporation from soil, runoff from farm fields, and drainage from plant root zone

Water conservation in irrigation systems typically involves increasing efficiency in conveyance network and field application addressing non-consumptive use or water losses, depending on the approach being followed. Conveyance efficiency deals with water lost to evaporation, seepage, and spills over canal embankments. Field application efficiency refers to the amount of water consumptively used by crops with respect the total amount applied, something highly relevant in this study (Figure 3). Reference values for application efficiency are 60%, 70% and 90% for surface, sprinkler, and drip irrigation, respectively (Brouwer, Prins, & Heibloem, 1989).

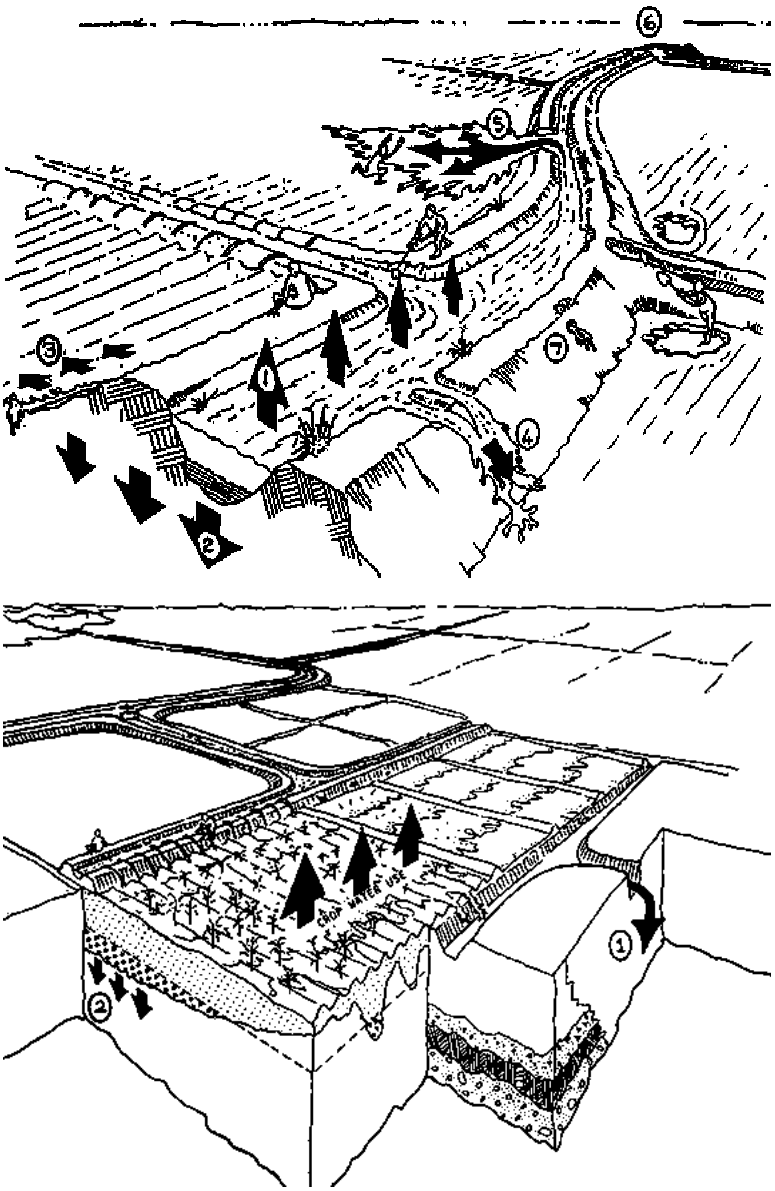


Figure 7. Water losses in agriculture. Losses in conveyance system (upper mosaic) and losses at farm-level (lower mosaic). Source: Brouwer, Prins, & Heibloem (1989)

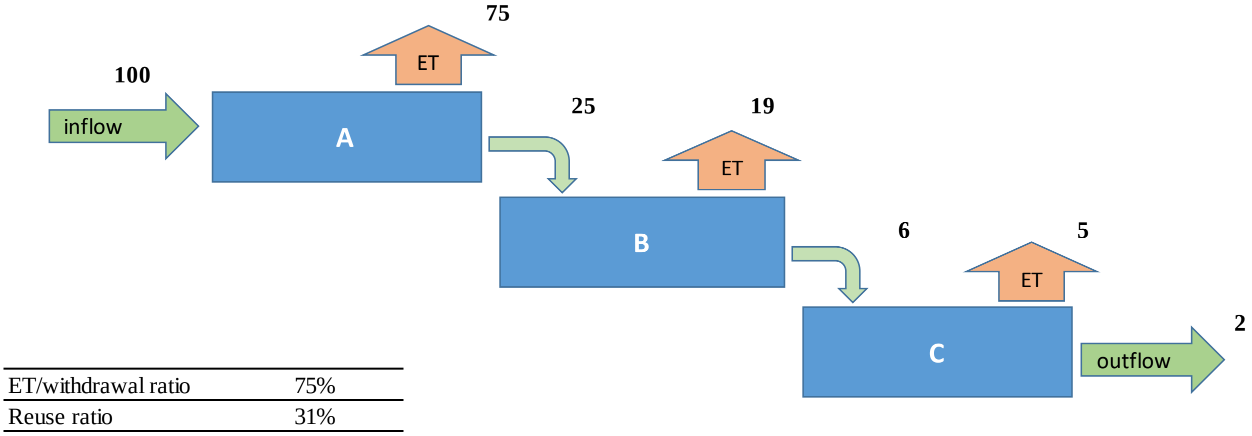
Egyptian context

Water losses are almost inevitable in irrigation systems. Finding and reducing them to increase efficiency is critical because agriculture is the largest water demanding sector and, in many regions, the most inefficient one (Maliva & Missimer, 2012). About 88% of Egypt's irrigation is implemented through surface techniques. A 'traditional' approach dictates upgrading the field water application techniques towards more efficient ones. However, the effects of changes in agricultural irrigation practices need to be considered in the context of the total water balance

(Foster and Perry, 2010 in Maliva & Missimer, 2012). In other words, looking at both the individual farming lot and the entire irrigated region. One user's inefficiency may supply water for another user (Keller & Keller, 1995) and any improvement in water use efficiency can adversely impact downstream users (Maliva & Missimer, 2012; Simons et al., 2015; Simons et al., 2012). Modernization in the Nile Delta may reduce the available amount of drainage water for reuse (Simons et al., 2012).

Keller and Keller (1995) challenged the classical paradigm of water use efficiency and worked out the concept of 'effective water use efficiency' (WUEe) which contemplates that the overall basin-wide efficiency increases when the water is reused. In other words, "the irrigation system as a whole can be much more efficient than any of its parts" (Keller & Keller, 1995). Simons et al. (2015) touch on this in a comprehensive literature review on water reuse in basins with multiple users.

Egypt's Nile Valley provides an example of multiple use-cycle system, where there is low efficiency at farm level but high global efficiency at regional/national level (Allen, 2000; Keller & Keller, 1995). A rotation system is implemented, where branch canals are switched on and off for several days for farmers to water their lands. Large amounts of water are applied in a relative short time to account for those days when the system will be shut down. Part of the applied water is consumed (evapotranspiration) and the rest is lost either to percolation to the aquifer or runoff from the field (Figure 4).



ET/withdrawal ratio	75%
Reuse ratio	31%

Figure 8. ‘Cascade’ of water users (A, B, C) in Egypt. Exemplification with 3 users based on Simons et al. (2015). Numbers are made up for illustration purposes. In this cascade, water is utilized several times. The first green arrow represents the irrigation water in the conveyance system that is withdrawn by the farmer A. The smaller curved arrows represent the sum of runoff out of each field and percolation, captured by the drainage system. The drainage system works as water source for downstream users. The green arrow on the right-hand extreme of the diagram stands for the outflow of the drainage system into the Mediterranean Sea. In this model, the farm-level ratio between evapotranspiration and withdrawal is 75%. On the other hand, water losses to infiltration and runoff are entirely reused downstream. As result, the total withdrawal is 131 (100+25+6), but the actual inflow is 100. There is, hence, a 31% reuse. This cascade has implications on efficiency computations, as addressed in the section Implementation of Strategies

Water lost due to irrigation inefficiency is not necessarily lost for overall use as it may recharge an underlying unconfined aquifer (Postel, 1992, in Maliva & Missimer, 2012) or be caught by the well-developed drainage system. Both the aquifer and the drainage canals are water sources in Egypt’s irrigation system. Government and farmers pump up water from drainage ditches and direct it back into the irrigation canals for reuse in agriculture (Barnes, 2014b).

According to Maliva and Missimer (2012), the efficiency estimate under the classical approach is around 41%, whereas the WUEe is about 91%, and such a high level of efficiency is rarely achieved elsewhere. Conforming to Keller and Keller (1995), potential extra water savings from efficiency are small and real savings should come from reducing either the cropland losses to evaporation or the losses to phreatophytes, both of them being costly. In other words, water saving opportunities should be carefully identified (Allen et al, 2005; Seckler et al, 2003 in Simons et al, 2015). Differences arise depending on what is accounted for in the WUEe computation. After check computations were performed, results were found to not agree with the estimates by Maliva and Missimer (2012). The rationale behind this is explained in the section Implementation of Strategies/Strategies on irrigation (Also see Tables 4 and 15).

As part of the Irrigation Improvement Project (IIP), Egypt has focused on modernizing irrigation in the old farms. Some of the main actions pursued are converting *mesqas* (distribution canals) from ditches to pipes or lined canals, reducing the number of water abstraction points, and setting out water user associations for better water management (Barnes, 2014a). A first study in the period 2011-2012 assessed the impact of such modernization on water availability and crop yields in the Nile Delta. Crops considered are rice, cotton, maize, wheat and berseem, and the results fluctuate regarding the project aims. Water demand for rice shows no change after modernization, and water consumption for wheat was found even higher in modernized areas, something counterintuitive for the study´s authors. According to them, it is not possible to assert that modernization led to positive results in terms of the project, and more research is needed for example in terms of farmer’s behavior (Simons et al., 2012). Barnes (2014a) reinforces this by saying that “irrigation improvement measures do not always achieve what their architects hoped”, some reasons being malfunction of technology or farmers’ misuse of it.

Even though results like these contradict donors’ expectations towards water conservation (i.e. World Bank, JICA, KfW), some authors believe there still are benefits in shifting around magnitudes in the in-field water balance. Interventions in the IIP make the water flow more efficiently to and through the fields (Barnes, 2014a). Water arrives to downstream users’ fields through the irrigation canals (*mesqas* or *marwas*) instead of flowing through the ground, something that shortens time (residence time through soil) and improves water quality (less contact with fertilizer and pesticides). A study in California addressing similar conservation issues (irrigation and vulnerable delta ecosystem) pushes even harder by calling to leave water in the sources longer (source refers to natural water bodies such as rivers and aquifers). Hence, improvements in water use efficiency are encouraged because they foster benefits to downstream water quality, environment, recreation, and even upstream use (PI & NRDC, 2014).

The modernization implemented by IIP does not include changes in the field application technology. The introduction of such technologies, even though it might render less runoff and percolation, which is an obstacle for the Egyptian irrigation layout, might also reduce the non-productive component of consumptive water use, namely the soil evaporation losses. This brings immediate increase in water availability as discussed later on in this report (see Evaporation Fraction section). In addition, losses in higher levels of the conveyance network are not addressed either. Estimates of evaporation losses for the whole irrigation network were 2.4 BCM/year in 2005 (MWRI, 2005) and, given the size of the canals, the bulk of such loss might occur before getting to the *mesqas*. Conveyance evaporation losses are likely greater in present times, as the irrigation system has grown.

Efficiency in Sudan

Efficiency improvements in the Sudanese irrigated territory might follow the traditional approach, by addressing both water conveyance and field application. Less than 60% of the area equipped for irrigation is actually irrigated (FAO-AQUASTAT, 2015). This is likely due to deterioration in supply and drainage infrastructure. The literature consulted does not suggest the existence of farmers' withdrawals from the drainage system. It does not discriminate the irrigated area into different methods either (surface, sprinkler, drip irrigation) and some statements indicate that current irrigation is primarily, almost exclusively, surface-based (FAO-AQUASTAT, 2015). There are three irrigation systems (Zaroug & Reynolds, 2006):

- Spate irrigation (diversion of Nile water during flood periods)
- Water pumped from the Nile and conveyed by canals to irrigate fields (major crops such as cotton, wheat and sorghum);
- Water pumped from ground aquifers and conveyed by canals or modern irrigation systems (sprinkler or drip) for fruit trees, vegetables and field crops.

The Sudanese government reports some irrigation projects accounting for more modern irrigation methods to be in the pipeline. Examples are the projects West El-Goled and El-Khoy on the Main Nile River in the area of Dongola ("Agriculture," N.D.).

Regulated deficit irrigation

Plants need certain amount of water along the different growth stages. In irrigated areas, the timing and amount of water should be tied to maintaining soil moisture at levels sufficient to allow plants to meet their water requirements for optimal growth (Maliva & Missimer, 2012). Nonetheless, the understanding of 'sufficient water levels' and 'optimal crop growth' may vary contextually. When water is scarce, farmers should maximize net income per unit of water rather unit of land (Fereres & Soriano, 2007). Hence, it is necessary to develop new irrigation scheduling approaches, not necessarily based on full crop water requirement, but designed to ensure the optimal use of allocated water (Kirda, 2002).

At the end of the 70s, the Food and Agriculture Organization (FAO United Nations) developed a procedure to estimate yield response to deficit in evapotranspiration (Kirda, 2002; Smith & Steduto, 1998). Such irrigation planning, known as ‘deficit irrigation’, implies the application of water below full crop-water requirements, causing stress to the plants. Cases of deficit irrigation are: i) a natural environmental constraint that keeps from providing sufficient water to plants to cover full evapotranspiration needs; ii) intentional under-allocation of water to provide irrigation service to more users/land. When deficit irrigation is controlled, the procedure is renamed into Regulated Deficit Irrigation (RDI).

The literature addresses RDI using the crop Yield Response Factor *Ky*. This factor indicates the crop’s degree of tolerance to water stress. As found in Smith and Steduto (1998), “it captures the essence of the complex linkages between production and water use by a crop, where many biological, physical and chemical processes are involved […] and its use has shown validity along time”.

The general interpretation of the response factor for water conservation aims is simple. It represents the relative expected yield decrease for a relative evapotranspiration deficit. The factor can be greater, equal or lower than one (negative, neutral or positive, respectively for water-saving purposes). A factor greater than one (Ky>1) indicates that the expected decrease in relative yield is larger than the relative evapotranspiration deficit. On the other hand, a crop with factor less than one (Ky <1) is more tolerant to water deficit and exhibits less than proportional reductions in yield with reduced water use” (Smith & Steduto, 1998). A factor equal to one (K=1) indicates that the yield decrease is equally proportional to evapotranspiration reduction (For details refer to FAO Irrigation and Drainage Paper No. 33 by Doorenbos and Kassam, 1979). Seasonal values of crop yield response Ky for different field crops are shown in Table 11. At seasonal scale, banana is highly sensitive to deficit, whereas groundnuts are tolerant. Crop response to water deficit, however, depends on how stress is imposed (Dorenboos and Kassam, 1979 in Fereres & Soriano, 2007). Yield may vary significantly depending on which stage of the growing cycle the deficit occurs in. A study on maize showed that *flowering* and *yield-formation* stages are sensitive to stress, while the impact of deficit in the *ripening* and *vegetative* phases is limited (Smith & Steduto, 1998). The same occurs with many fruit trees, where yield is not sensitive to water depravation at some developmental stages, and thus are more suitable for RDI through managed high-frequency micro-irrigation (Fereres & Soriano, 2007).

Table 11. Seasonal values for crop response factor Ky from FAO Irrigation and Drainage Paper No. 33. Source Smith & Steduto (1998).

Crop	Ky	Crop	Ky	Crop	Ky
Alfalfa	1.1	Onion	1.1	Spring wheat	1.15
Banana	1.2 - 1.35	Peas	1.15	Sugar beet	1
Beans	1.15	Pepper	1.15	Sugarcane	1.2
Cabbage	0.95	Potato	1.1	Sunflower	0.95
Cotton	0.85	Safflower	0.8	Tomato	1.05
Groundnuts	0.7	Sorghum	0.9	Watermelon	1.1
Maize	1.25	Soybean	0.85	Winter wheat	1.05

Computations at seasonal level are easier and provide a good starting point for RDI. Nonetheless, knowing the impact water stress at a specific growth stage is necessary if better results in water saving are sought. The Yield Response Factor varies not only with crop and growth stage, but also with the field-application technique. Table 12 is the result of a long-term study conducted over a wide range of field crops (Kirda, 2002). The numbers in the table correspond, specifically, to an evapotranspiration deficit of 25% carried out either seasonally or at a certain stage in the growth cycle (refer to Kirda, 2002 for details). Cotton grown under drip irrigation is 5% more water-efficient when subjected to a 25% deficit along the whole season. For maize and wheat under sprinkler irrigation, the improvements in water use efficiency (WUE) were 9% and 8% respectively. Water savings are possible through RDI as long as the value of Ky is less than one. In addition, some crops and growth stages offer significant water savings, for instance sugarcane at tillering, where Ky is much lower than one (Ky<<1).

Deficit irrigation renders lower yield, something not convenient for regions compromised in terms of food security. However, saved water can be diverted to irrigate new lands more efficiently and, so, compensate for such yield drop.

Table 12. Crop response factors (Ky) where yield reduction is proportionally less than relative evapotranspiration deficit. Deficit at 25%. Water Use Efficiency = Expected Relative Yield / 0.75. Source Kirda (2002).

Crop	Stage when ET deficit occurred	Ky	Irrigation method	Expected relative yield	Relative water use efficiency
Common bean	Vegetative; Yield formation	0.57 0.87	Furrow	0.86 0.78	1.14 1.04
Cotton	Whole season; Boll formation and flowering	0.86 0.48	Drip Furrow	0.79 0.88	1.05 1.17
Groundnut	Flowering	0.74	Furrow	0.82	1.09
Maize	Whole season	0.74	Sprinkler	0.82	1.09
Potato	Whole season; Vegetative	0.83 0.40	Drip Furrow	0.79 0.90	1.06 1.20
Soybean	Vegetative	0.58	Furrow	0.86	1.14
Sugar beet	Whole season; Mid-season	0.86 0.64	Furrow	0.79 0.84	1.05 1.12
Sugar cane	Tillering	0.40	Furrow	0.90	1.20
Sunflower	Whole season; Vegetative yielding	0.91 0.83	Furrow	0.77 0.79	1.03 1.06
Wheat	Whole season; Flowering and grain filling	0.76 0.39	Sprinkler Basin	0.81 0.90	1.08 1.20

Worldwide experiences on deficit irrigation

Deficit irrigation techniques have shown good results in grapevine and fruit tree crops. Fereres and Soriano (2007) reviewed different methods for reducing water use in biomass production of both annual and perennial crops. They found that the levels of irrigation for optimal results are between 60 and 100% of full evapotranspiration requirements. In addition, deficit irrigation has shown more suitability for tree crops (e.g. almonds) and vines than for field crops. Horticultural crops represent a special case where the implementation of RDI showed not only better water productivity (WP) but also an increase in farmer’s net income. Costa, Ortuño, and Chaves (2007) agree in term of vine and tree fruits, but state some caveats for horticultural crops because, under deficit, they render lower yield and quality. At the same time, both references coincide on the idea of further research needed with regards to the impact of long-term deficit irrigation in long-life commercial crops (e.g. fruit trees and grapevines).

Two studies bring insights about wheat and maize, two of the most-cultivated crops in the study area. Sivamani et al. (2000) investigated the response of transgenic wheat under both well-watered and 'moderated' water deficit conditions. They found most transgenic types yielded more biomass and used water more efficiently than the non-transgenic versions. For deficit conditions, water use efficiency ratios for transgenic and non-transgenic wheat are approx. 0.67 and 0.55, respectively (Kg dry matter/m3 water used). Kang, Shi, and Zhang (2000) studied the impact of RDI on maize in a semi-arid area of northwest China. They kept soil water content between 65 and 85% of field capacity during the season, except for the seedling and stem-elongation stages, where different depths were assessed. They found that drying the soil at the seedling stage (40 – 60% of field capacity) in addition to a mild soil water deficit at the stem-elongation stage (55 – 65% of field capacity) could maintain the grain yield and reduce water use. Their results show water savings between 79 and 83% by increasing WUE (see Table 4 in the reference)

Deficit irrigation in the Nile region

A search in the major academic engines (Web of Science, Scopus and Google Scholar) produced only a handful of results of deficit irrigation (DI) in the Nile. This suggests that, even though the technique is promising, it remains unresearched in the region. Karrou et al. (2012) carried out in-field studies on maize and wheat during 2005-2006 in the Middle Delta of Egypt (Menoufia Governorate). The performance of four different irrigation techniques was evaluated (Table 13): traditional (basin) irrigation, full irrigation, deficit irrigation (DI), and raised bed techniques (RB). The results indicate that DI, characterized at 70% of full water requirement, leads to substantial water savings with no significant reduction yields, especially in wheat. In addition, raised bed techniques (RB) show better results for both crops. The impactful water savings are visible when comparing water productivity values of less-water demanding irrigation techniques against the traditional farmer's practice. Water savings for maize are about 8 – 23%, whereas for wheat they are about 6 – 30%.

Table 13. Results of regulated deficit irrigation implementation in maize and wheat by Karrou et al. (2012).

Treatment	Description	Relative yield		WP [Kg/m3]		Water savings [%]	
		Maize	Wheat	Maize	Wheat	Maize	Wheat
FT	Farmer's practice (basin irrigation)	1.00	1.00	1.53	1.3	0.0	0.0
FWR	Full water requirements (20% leaching requirements included)	1.00	1.02	1.66	1.38	7.8	5.8
DI	Deficit irrigation (70% water requirements)	0.91	0.99	1.83	1.86	16.4	30.1
RB	Slightly raised beds for crops and furrows for water	1.00	1.05	1.99	1.88	23.1	30.9

Vegetables are relevant in Egypt because of both areal coverage and impact in the global trade. Tomatoes are grown in three seasons: winter, summer and autumn, (Maqbool & Kerry, 1997), and occupy about 3.5% of Egypt's total cultivated area and 28% of total area of vegetables (FAOSTAT, 2014). According to the company Bayer, the crop is “by far the largest vegetable crop in Egypt”, and in 2008 the country “ranked 5th in the world with 9.2 million tons of tomatoes produced” ("Tomato," 2016). Abuarab, Shahien, and Hassan (2013) studied RDI in tomato and they found the highest fruit yield is met at full irrigation levels (100% of ETc), what suggests there is no room for water savings in current tomato production.

Water savings in Sudanese sorghum would be largely valuable, if possible. Several studies show that sorghum is resistant to drought conditions. However, sorghum yield decreases almost linearly with water deficit, a phenomenon aligned with the crop response factor Ky=0.9 (Table 11 above). Therefore, the implementation of RDI would lead to a drop in the sorghum production (Farré & Faci, 2006; Klocke, Currie, Tomsicek, & Koehn, 2012).

Evaporation component of evapotranspiration

The efficiency of the Egypt´s irrigation system was addressed previously in this paper (see Figure 4). Keller & Keller’s work supports the claim that Egypt’s irrigated area behaves as ‘a big farm’ under drip irrigation, with a more-than-acceptable field application efficiency at 91%. The reminder 9% for ‘perfect water utilization’ can be addressed through different strategies, such as improvements in the conveyance network and better in-field application techniques. However, aims in this section are at pointing out an issue that seems to be disregarded in the efforts towards increasing efficiency in the Nile.

Crop evapotranspiration (ETc) combines soil evaporation and crop transpiration. This dual hydrology-relevant component of the water cycle is usually computed as a whole because of the complexity to do it separately. The evaporation component, referred to as 'non-process depletion' in Molden and Sakthivadivel (1999), does not contribute to the plant growth. Such depletion occurs not by the process water was diverted for, i.e. biomass formation. Its existence is related to solar radiation, soil coverage and, of course, the irrigation methods at the farm level. Within an irrigation system such as the Egyptian, water could be saved by plunging the evaporation component of ETc.

A procedure to splitting ETc into its two components is found in the document *FAO -56 dual crop coefficient method* (Allen, Pereira, Raes, & Smith, 1998). The soil evaporation component is determined through Ke, nomenclature for 'soil evaporation coefficient'. Three generic examples are given for cotton under different irrigation techniques, and the evaporation component is computed between 22 and 30%. An additional example is provided for a generic crop under a 10-days irrigation schedule. This case might well be considered analogous to a farm within the Egyptian irrigation system, where rotational turns are in place, forcing farmers to allocate large amounts of water in a short time. The crop is irrigated at day No. 1 and receives rainfall at day No. 6 (Figure 5). The evaporation fraction increases rapidly in days where water is applied to the crop, and remains high for several days afterwards. For this example, total evaporation is calculated at 54% of total ETc.

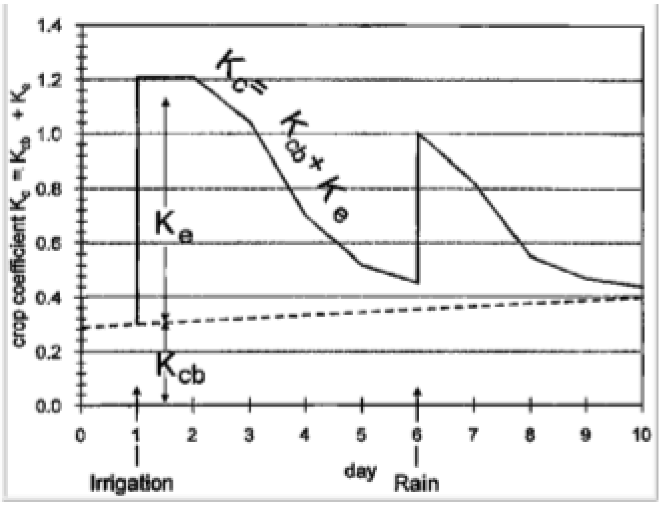


Figure 9. Evaporation component of ETc for a generic crop under a 10-days irrigation schedule. Source R. Allen, Pereira, Raes, & Smith (1998).

Worldwide experiences on evaporation component

Back in the 90s, the influence of early sowing in rainfed-grown wheat under Mediterranean climate was studied in Australia (Eastham, Gregory, Williamson, & Watson, 1999). The authors found that "larger canopies, associated with early sowing, reduced evaporation during the energy-dependent first stage". Drop values are reported at 27% and 48% for 1990, and 1991, respectively. Similar results are reported by Ding et al. (2013), who studied the evaporation component in maize grown on an experimental area in China. In addition to canopy consideration, soil exposure to radiation was controlled with different fractions of mulching. The study shows the evaporation component declines with the increase in both mulching coverage and canopy area (Figure 6). As an example, for no-stress condition, the overall evaporation component drops by 50% when mulching coverage increases from 0 to 50% (compare two upper curves on Figure 6). This study also confirms previous claims about deficit irrigation. For a ground-mulching of 50%, the evaporation drops by about 50% when introducing a water stress of 50% (compare second and third upper curves). Both studies suggest that reducing soils exposure to solar radiation (mulching or canopy) and subjecting crops to an extent of water stress help save irrigation water.

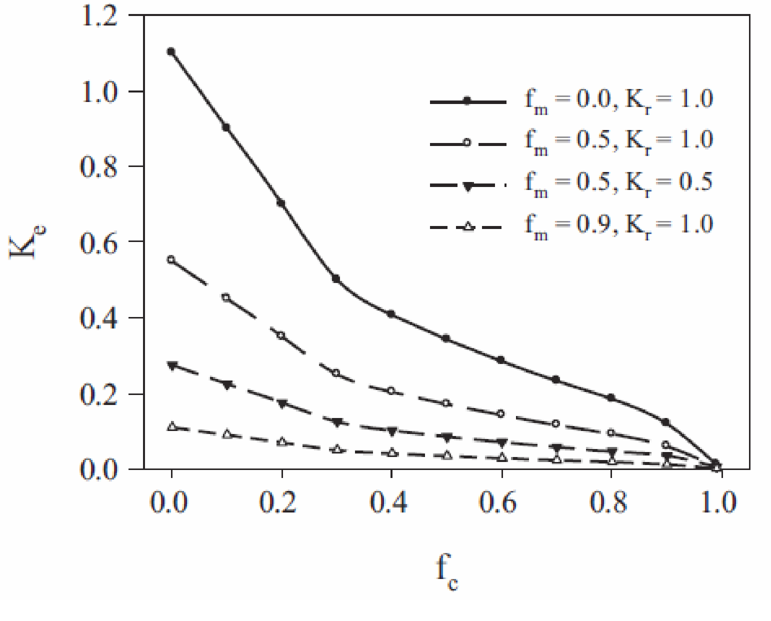


Figure 10. Relationship between soil evaporation coefficient (Ke) and fraction of canopy cover (fc). Different curves are drawn for different ground-mulching fractions (fm) under different water stress conditions (Kr=1 and 0.5 for wet and dry soil respectively). Source Ding et al (2013).

A comprehensive metadata analysis on wheat and maize confirms that soil mulching, either straw or plastic, can significantly increase yields, as well as water use efficiency (WUE). Qin, Hu, and Oenema (2015) used information from 1310 yield observations from 74 studies in 19 countries and found that for well-watered conditions, average water savings for wheat and maize are about 20% and 30% respectively (Figure 7).

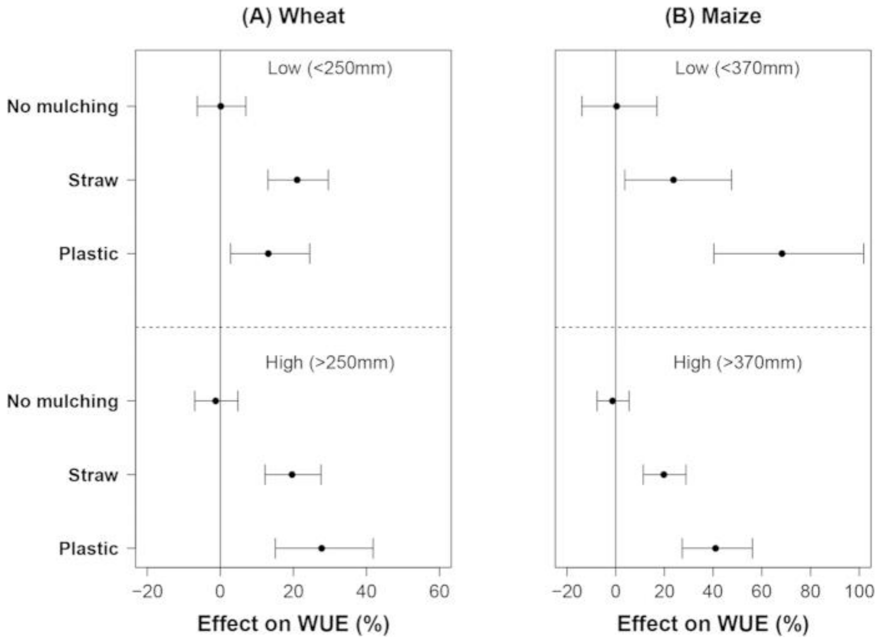


Figure 11. Effect of mulching on WUE of wheat (A) and maize (B) at different water input levels. Source Qin et al. (2015).

Two studies shed some light on opportunities for water savings in sugarcane. Sandhu, Prihar, and Khera (1980) studied the response of sugarcane to irrigation and straw mulch in a subtropical region in India during three years between 1974 and 1978. They conclude that “for the same yield, irrigation under mulching averaged 340 mm less than under no mulch”. From their findings is to see that a mulched areas render the same yields as non-mulched areas, but using a total amount of water at 55% of water needs (measured using the pan-evaporation value). Millard (1974), in turn, studied plastic mulching for rainfed sugarcane in South Africa. The paper concluded, among other things, that the use of mulch over the cane row increased yield by 25 tons of cane per hectare, on average (yields at 158 and 133 tones/Ha for mulched and control areas, respectively). Average yields in Sandhu et al. (1980) are between 56 and 75 ton/Ha, and their results and conclusions indicate there is opportunity for an increase in Water Productivity

(WP) by 81%. In turn, yields in Millard (1974) are higher between 129 and 158 tons/ha and the increase in WP is at 19%.

Evaporation component in the Nile

Simons et al. (2012) studied the impact of modernizations at farm level in the Nile Delta in the period 2010 – 2011. Water efficiency and crop yield were at the center of the Irrigation Improvement Project (IIP). Modernization implied modifications in the tertiary channels, but in-farm application technology was not contemplated. Modernization, in turn, allowed continuous flow (compared to the typical rotational turn system), being farmers able to irrigate at a continuous pace. Insightful values of the evaporation component were found for rice, cotton, maize, wheat, and berseem (Table 14). For rice, 80 and 20% are typical values for transpiration and evaporation, respectively, and the modernization had no impact in water consumption. For cotton, water productive use is between 90 and 80% for modernized and non-modernized areas, respectively. For maize, soil evaporation is reported at about 30%, something that might have to do with the fact that maize is a summer crop. Finally, evaporation in wheat was found between 12 and 20%, whereas for berseem the figure is 10%.

Table 14. Evaporation component for different crops grown in the Nile Delta. Source Simons et al. (2012).

Crop	Evaporation component of ETc [%]	
	Pre-modernization	Post-modernization
Rice	20	20
Cotton	10 - 13	19 - 21
Maize[1]	29 - 32	17 - 18
Wheat	12	20[2]
Berseem	16	19 - 22

[1] Uncertain results; [2] Higher due to lower Leaf Area Index

Rainfall exploitation strategy

According to Falkenmark and Rockström (2005), rainfall is the only actual natural input of water to a watershed. However, it is usually neglected as resource. Hydrologists and planners pay more attention at secondary water supplies such as rivers and aquifers, disregarding the fact that is the rain what recharges other water bodies. In addition, the authors claim that such a narrow focus on blue water[7] has led humans to believe that agriculture uses about 70% of the world's freshwater, when actually only 4% of the global terrestrial precipitation is linked to human activities, and more than 50% of rainfall is lost to the atmosphere as non-productive green water[8] flows (Falkenmark & Rockström, 2005) (Figure 8)

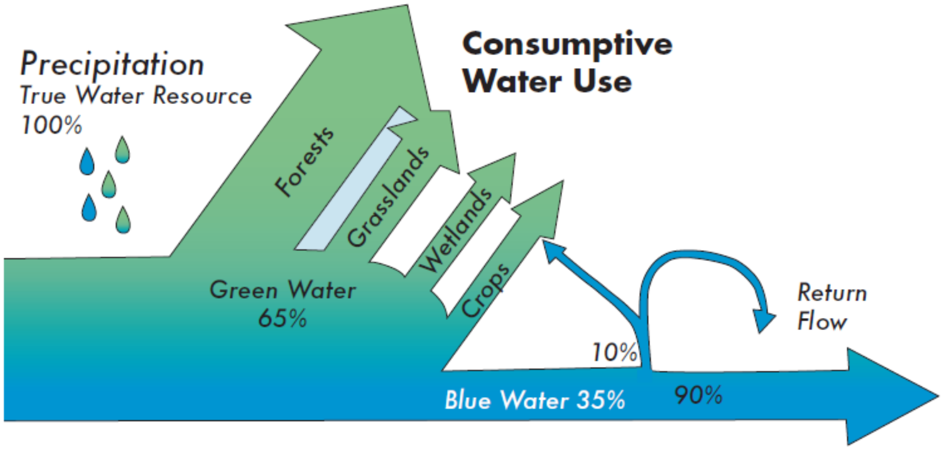


Figure 12. Representation of global green and blue water flows. Two-thirds of the rainfall is consumed in plant production, manly forests. Crops use only 6% of total precipitation as a combination of both blue and green water. Source: Falkenmark & Rockström (2005)

Precipitation in ENB occurs primarily in upstream savannahs, forests and rainfed agriculture lands. A small amount is utilized by humans, while the bulk of water evaporates at low or no beneficial use. Recent estimates of the water cycle confirm that more than 90% of the water input (rainfall) is depleted through landscape evapotranspiration (ET) in areas of limited land use, such as modified land use, utilized land use, and protected land use [9] (Own computations based on Water Accounting, 2016).

The average consumed water for the period 2005 – 2010 amounts to 824 BCM/year. Only 5% of it is managed and the rest is depleted as landscape evapotranspiration (44 and 784 BCM/year,

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[7] Blue water: water in water in freshwater lakes, rivers and aquifers (waterfootprint.org)

[8] Green water: precipitation on land that does not run off or recharge the groundwater (waterfootprint.org)

[9] Modified land use (MLU) is "land where vegetation is replaced with the intention to increase the utilization of land resources. Examples are plantation forests, pastures and rainfed crops, among others". Utilized land use (ULU) is "land use classes with a low to moderate utilization of natural resources, such as savannah, woodland and mixed pastures". Protected land use (PLU) is "environmentally sensitive land uses and natural ecosystem that cannot be modified due to protective measure" (Water Accounting, 2016)

respectively). Most of the evapotranspiration corresponds to the sub-basins Baro-Akobo-Sobat, Blue Nile, and Lower White Nile. Values are 233; 224, and 142 BCM/year, respectively. The basins Blue Nile and Baro-Akobo-Sobat (BAS) account for 58% of landscape evapotranspiration, and the share rises to 76% (600 BCM) when adding the Lower White Nile.

Two facts come up when scrutinizing this source. Firstly, two land uses, namely MLU and ULU, are responsible for the largest share of evapotranspiration, specifically the area called ‘shrubland’. Secondly, the non-beneficial evaporation[10] accounts for 36% (220 BCM) of total evapotranspiration in the three most relevant sub-basins. Significant amount of water might be gained by implementing rainwater harvesting and aquifer recharge throughout the shrublands of these sub-basins. Doing that would allow harnessing rainfall and contribute to the solution of perceived water scarcity in the region.

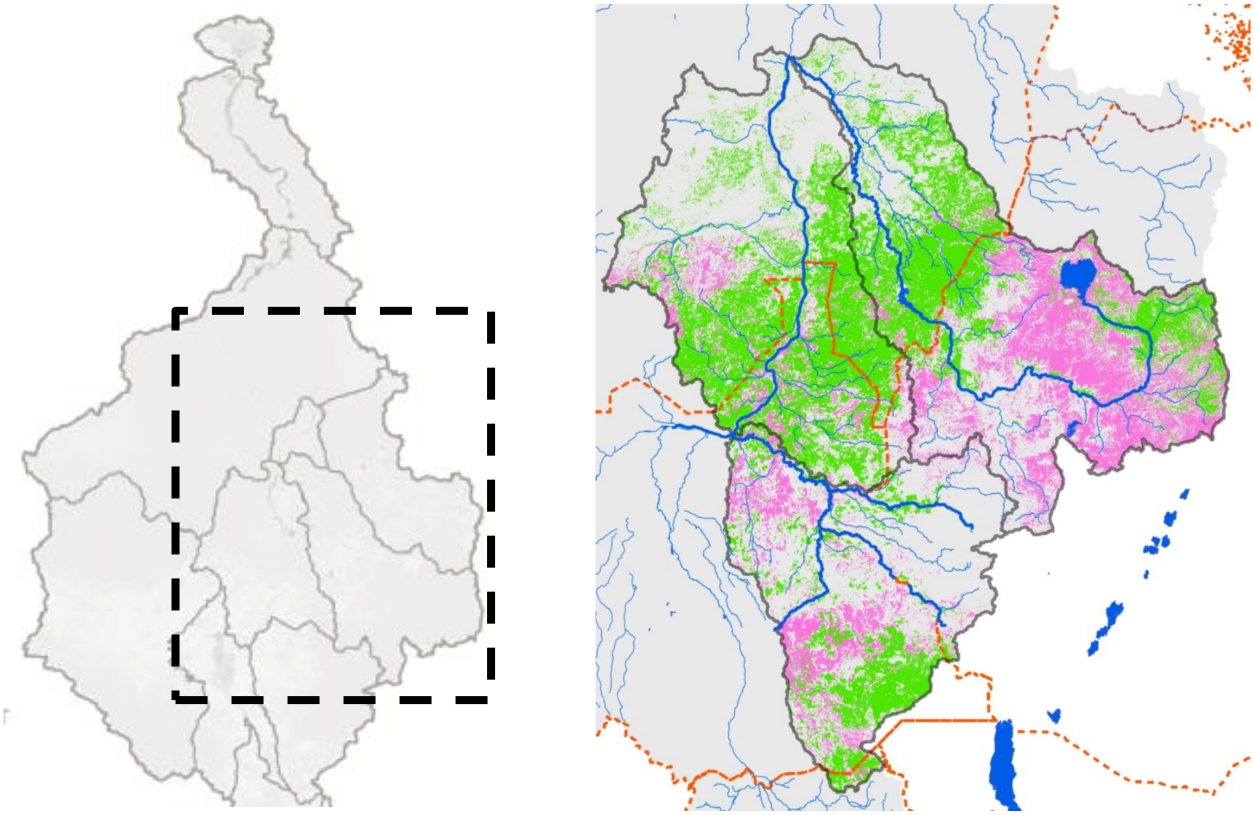

Figure 13. Eastern Nile Sub-basins and major Modified Land Uses in the sub-basins Blue Nile, BAS and Lower White Nile (green: mosaic forest/shrubland/grassland; magenta: mosaic cropland/vegetation. Source: GlobCover Land Cover Maps).

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[10] Non-beneficial evaporation: evaporation for non-intended use, for instance from soil and leaves.

Worldwide experiences rainfall exploitation

A comprehensive review on non-conventional water resources in water-scarce regions is presented in Qadir et al. (2007). Water harvesting either directly from rainfall or from runoff is among the opportunities reported. The use of soil bunds or small dikes on the lower parts of hillsides can help capture runoff with multiple positive side-effects, for example sediment retention, groundwater recharge, and storage for later slow release for downhill uses. The use of *wadi-beds* to capture both water and sediment can benefit adjacent croplands and enable infiltration to increase aquifer storage. *Wadis* have been long time utilized in North Africa and the Horn of Africa for spate irrigation, a technique to capture water from seasonal streams and redirect it to flood arable land. In 2011, Sudan had more than 126 thousand hectares under spate irrigation (FAO-AQUASTAT, 2015). Qadir et al. (2007) mention the implementation of micro-catchment systems for low rainfall regions, where catchment areas are less than 100 meters long. Examples are contour bunds, where there is an alternation between crop and catchment land, and the *meskat* system, where the field is divided into one clean catchment area (uphill) and cultivated area a use (downhill). Olives are grown in Tunisia using the *meskat* system (Qadir et al., 2007).

An interesting experience for rainwater harvesting is found in Argentina. The national institute for agriculture (INTA is the acronym in Spanish) developed a system in the Bajos Submeridionales region that is able to capture more than 60% of precipitation for recharging local aquifers (Basán Nickisch et al., 2016).

Local experiences on rainfall exploitation

Herweg and Ludi (1999) investigated the performance of level and graded structures for soil and water conservation (SWC) in the highlands of Ethiopia and Eritrea. Experiments were developed on-site and at small scale (plots 6m x 36m for each SWC). Most experiments brought along reductions in runoff and soil losses. The success of runoff control structures, however, is design–dependent. For instance, some cases of waterlogging were reported, what may affect crops negatively. The best results of runoff reduction were found in the semi-arid region Afdeyu (Eritrea). A drop between 46 and 60% was achieved through grass strips and level structures.

On the same lines, SWCs were implemented in Ethiopia in 2010 as part of a land restoration program aimed at doubling agriculture productivity (Mekuria et al., 2015). Bunds and infiltration ditches were built in farms within the Debre Mawi watershed. Results of a 5-year study (2010-2014) show runoff reductions between 26 to 71%; at the same time the existence of SWCs enabled water infiltration and helped raise aquifer levels.

Crops strategies

Egypt's crop production matrix is richer than Sudan's. FAO reports 76 products for Egypt and only 22 for Sudan, the difference being mainly in treenuts, vegetables, fruits, and citrus (FAOSTAT, 2016). Egypt produces both temporary and permanent crops, whereas Sudan grows temporary crops only. Wheat, maize, and clover account for about 60% of the total harvested area in Egypt, and they use about 30% of the total agriculture water withdrawal. Following down the list of most water-demanding crops are rice (paddy), tomatoes and sugarcane. The Sudanese irrigated harvested area is occupied at 60% by sorghum and wheat, which in turn demand 50% of the total agriculture water withdrawal. In addition, cotton, fodder and sugarcane demand another 40%, but only in 23% of the irrigated land, bringing up the higher intensity these crops are grown under. Beyond the relevance of sorghum in the irrigated agriculture, the harvested area represents only 8% of the country's total cultivated area. FAO (2014) reports about 8.4 million hectares of sorghum in Sudan, the bulk of it being rainfed-cultivated in both traditional and mechanized farming systems.

Egypt' agriculture follows a multi-cropping system under three irrigation seasons, namely winter (November-May), summer (May-September) and nili (Nile flood from September to November). The cropping calendar shows wheat and berseem in winter, cotton and rice in summer, and maize and millet as flood crops (Ferrari, Osman, & Campus, 2013). On the other hand, Sudan grows sorghum and millet in one main season, the summer, and complementary wheat in the winter. Cropping intensity in the irrigated areas are 176% and 157% for Egypt and Sudan, respectively (FAO-AQUASTAT, 2015).

Yields and water productivity

One of the main concerns in the Nile region is the food production under a scenario of water scarcity. According to Viala (2008), three-quarters of additional food demand in the world could be met by improving water productivity on existing irrigated lands. This is the case of South Asia, for instance, where irrigated areas have low productivity, and might well be valid in the

Sudanese schemes. However, it is not the case of Egypt, where crop yields are quite high and range from double to six times the values in other upstream Nile countries (NBI & GIZ, 2012). According to Viala (2008), the scope for further improvements in both yield and water productivity are limited. However, when looking at the best-performing international values of yield and water productivity, possibilities for improvement in both countries come to light (Table 8).

Cropping pattern changes

From the paragraphs above, it is possible to claim there is room for increasing water availability by focusing on yields and water productivity. Fedoroff et al (2010) in Maliva and Missimer (2012) state “meeting future water demand involves a radical rethinking of agriculture […] both land and water productivity will have to be substantially improved”. Improvements in breeding techniques and genetic modifications are needed as well to increase productivity and favor crops adaptation to changing climatic conditions (Maliva & Missimer, 2012).

To render water gains in the rainfed agriculture areas, other contextual specificities should be considered besides crop replacement. Smallholder rainfed subsistence farming dominates in upper riparian countries, a situation expected to continue to 2030 and beyond, according to the Nile Basin Initiative. Appropriate agriculture technology and best practices lack in those areas, and agriculture changes should be linked to boosting life quality. Improvements in this farming system require water and soil conservation, the provision of appropriate seeds, and encouragement in use of fertilizers (NBI & GIZ, 2012).

Crops adjustments

Some actions have been made with regards to crop pattern changes. The use of short-age crop varieties in Egypt is mentioned in Abdin and Gaafar (2009), for example a 150-days rice instead the traditional species of 180 – 210 days. In addition to shortening the growing season a few weeks, the new variety render higher yields (Bastiaanssen & Perry, 2009). Regarding maize, experiences of short-season cultivar in Africa are reported by Seed Co., a public company in Zimbabwe aimed at developing crop seeds. A recent article states the company is about to release the 200 series of maize that is “water-use efficient and mature in less than 90 days” (Zindi, 2015). Yields for the new hybrids are not found in the article, but the company’s website reports yields around 6 tons/Ha for a the hybrid SC_403, a drought-tolerant ‘very early maturing hybrid’ recommended for irrigation schemes ("Maize," N.D.).

Wheat in Egypt is grown in the winter, from December to April, and the total harvest time ranges between 120 and 135 days (GIEWS, 2016; Gowayed, 2009). Climate in Egypt is considered temperate, thus both winter and spring wheat varieties are possible to be grown. Short –season wheat types allow later sowing (early January) while keeping high yields, something that might render water savings and/or enable expansion in production area. An example of this is the winter wheat ‘Botticelli’, developed by the seed company Nickerson. It has shown good adaptation in irrigated areas and temperate regions, for instance Castile and Leon (Spain). Reported yields found are about 8.0 and 5.1 tons/Ha for irrigated areas and arid and semi-arid rainfed areas, respectively (*Botticelli*, 2008). Official reports in Egypt indicate “efforts are underway to increase water and land productivity as well as to utilize drought-tolerant, higher-yielding wheat varieties” (GIEWS, 2016).

Crops replacement

Water-scarce regions need to use water efficiently. This is particularly important where water is needed for food production and livelihoods support. An assessment on water management in agriculture indicated that “increasing agriculture productivity is the greatest opportunity for reducing poverty in countries with GDP largely dependent on agriculture” (Maliva & Missimer, 2012). This might be true in Ethiopia, where agriculture share on GDP is 45%, and even in Sudan where it is between 35 – 40%. In Egypt, nonetheless, even though agriculture is responsible for about 86% of the water withdrawals, the sector contributes to less than 15% of GDP, largely behind the industrial and service sectors (FAO-AQUASTAT, 2015).

A recent article in on ‘How to feed Egypt’ argues that making the most efficient use of water resources implies focusing on high-value, high-quality crops and livestock, rather than staple crops like wheat and maize (Al-Riffai, 2015). Such claim raises the question of why wheat is both extensively produced and largely imported in Egypt. Cereals in general, and wheat in particular, are essential in the Egyptian diet. Wheat alone accounts for one-third of the daily calories intake. Such significant consumption steams from cultural factors as well as governmental subsidies in bread prices. Consumption has been increasing in past years, but nowadays is “fairly stable and independent from income growth”, provided households feel attracted to other products, such as meat and milk, when economic position improves (McGill, Prikhodko, Sterk, & Talks, 2015). Wheat is so important for people as it is for the Egyptian government, which purchases 40% of total Egyptian wheat (domestically produced plus imports) to produce 82% of the flour for the subsided bread *baladi*.

Wheat is to Egypt as sorghum and millets are to Sudan. Sorghum represents 70% of cereal production in Sudan, playing both roles as fodder and subsistence crop (FAO-AQUASTAT, 2015). It is a staple food for most of the Sudanese population, representing about 70% of food needs ("Sorghum," 2016). Sorghum and millet have been essential in semi-arid regions in Africa and Asia for long time (Lupien, 1990). These crops represent about half the total cereal production in the African continent, being a major source of protein for the population (Belton & Taylor, 2004), especially the poorest. Despite the relevance of sorghum and millet in African people, they are under-researched compared to other cereals (Belton & Taylor, 2004). Yields in Sub-Saharan Africa are low. In most years, sorghum, as well as wheat, are imported to cover domestic demand in Sudan.

Any ‘radical thinking’ regarding changes in cropping patterns imply at least three different, but likely complementary, scenarios. The first one is using less water-demanding varieties of current grown crops, something already discussed in previous lines. A second alternative is replacing current food crops with new ones that, either requiring same or less water, provide same or more nutritional quality (e.g. nutritional density). Fruits and vegetables offer more nutrients per calorie than cereals. Onions, cabbage, and melons, for instance, have lower water needs and, at the same time, as orchards crops can be irrigated through more efficient techniques that require less water and enable higher yields. Among cereals, oatmeal (oat) offers better nutritional value than bread (wheat). The third alternative involves virtual water. Qadir et al. (2007) offer good insight on this topic and its relevance for water-scarce countries. “Food items have been traded among countries since international trade began; by importing food in this way, water – scarce countries avoid having to use their own water to produce the same amount of food domestically under water-deficit conditions”. Egypt, for instance, imported 8 million metric tons of grain from the United States in 2000, an amount that would have required 8.5 BCM of irrigation water” (FAO 2007).

It is not clear whether Egypt imported water explicitly. What is clear, though, is that by seizing the concept, both Egypt and Sudan could step forward and radically change cropping patterns in order to get maximum benefits from their limited water resources. According to Qadir et al, “the opportunity cost is a key component of the virtual water perspective, and it is particularly important to consider such costs when seeking to allocate scarce water resources”. Nonetheless in the Eastern Nile, water is not properly priced, something that prevents from proper water resources policy implementation.

STRATEGIES IMPLEMENTATION

The focus of the strategies is on the agriculture sector of Egypt and Sudan, with a specific target on wheat, maize, sorghum, and sugarcane. Strategies consider cultivated and irrigated areas for these crops only. However, some strategies fall partially apart from these four crops and two countries, but not from the aim of this study. This is the case, for instance, of the strategy for rainfall exploitation that aims at rendering water gains by capturing water in areas of limited use, such as sparse rainfed agriculture or pastoral activities.

Irrigation strategies

Irrigation efficiency

The implementation of efficiency measures contributes to an increase in water availability by using less water. This strategy considers an upgrade in the irrigation technology at the farm level in irrigated areas of Egypt and Sudan. The goal is reducing water losses to soil evaporation, runoff and deep percolation without affecting plants transpiration.

Irrigation in both countries is primarily surface-wise (flood and furrow irrigation), hence linked to heavy local water losses. The irrigation efficiency for Sudan is assumed at 65%, meaning 35% of irrigation water is lost to non-productive use. Egypt has been considered as a large farm, with overall system efficiency higher than the farm-level efficiency. Addressing efficiency in Egypt's irrigation system is complicated because of the intertwined water reuse in place. The Table 15 presents a reconstruction of two scenarios in Egypt's agriculture. The values for the current situation were extracted from FAO AQUASTAT (2016) and are different to those by MWRI (2014). The aim of the table, however, is at allowing to draw conclusions about relative changes between a current and a hypothetically future scenario. Details on the calculation procedure are present in the Appendix 1.

For the current situation, water withdrawal and return flow are reported at 59.0 and 18 BCM/year, respectively, meaning the overall evapotranspiration is 41.0 BCM/year. The evapotranspiration was assumed consisting of 20% soil evaporation and 80% plant transpiration (coordinates B5 and D5 on the table). These are average shares based on values for wheat and maize in the Nile Delta, found in Simons et al. (2012). Hence, in the current situation there is a local (in-farm) application efficiency at 56% and an overall efficiency at 68% (B6 and D6). The overall efficiency is the ratio between the transpiration (D5) and the share of withdrawal that is not reused, i.e. 48 BCM/year (equals to E1-G6). Differences regarding the claims by Keller and Keller (1995) might stem from the use of Evapotranspiration to compute efficiency, instead of Transpiration only.

In the future scenario, it is assumed that efficient irrigation has been implemented through an upgrade in the irrigation techniques at farm level. The new application efficiency is considered at 80%, meaning 20% of the water diverted into the farm is lost to non-productive use (i.e. evaporation, seepage from furrows, or percolation beneath the root zone). An attainable efficiency value of 80% was assumed, considering sprinkler irrigation method, namely center pivot, as found in Howell (2003). The evaporation component of the evapotranspiration was assumed at half the current value, as something likely to be achieved by using irrigation techniques that apply less water and closer to the plant. The return flow was calculated by keeping the crop transpiration constant for both scenarios (shaded cell D5 for both tables). The same proportion for water reuse) was considered for the future situation (61% of the return flow formed by both groundwater and surface water).

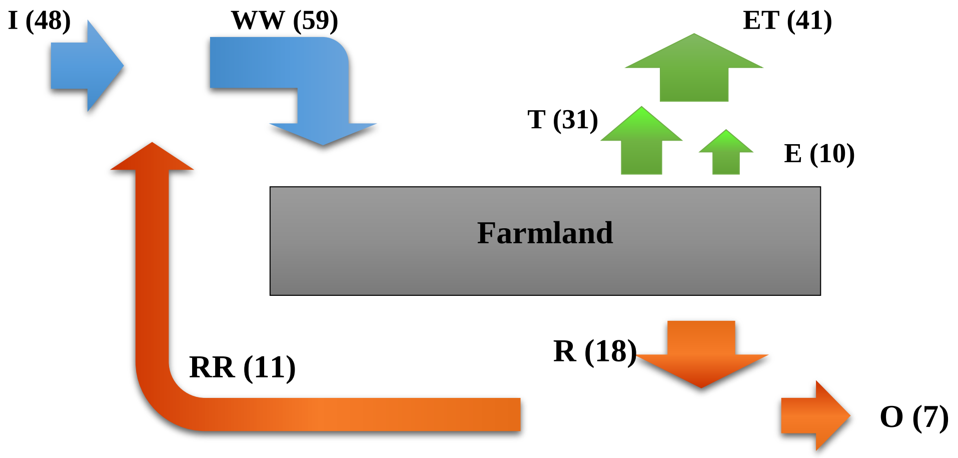

Figure 14. Simplified diagram for Egypt's irrigation system, considered as a big farmland. I: inflow; WW: total water withdrawal; ET: evapotranspiration; E: evaporation; T: transpiration; R: total reflow; RR: reflow reuse; O: outflow (non-reused reflow)

Table 15. Characteristics of Egypt's agriculture water use. Values for years 2000 and 2001. Units at BCM/year. SW and GW stand for surface water and groundwater, respectively. Letters on the left-hand side and numbers under the headlines work as coordinates for the discussion in the text body. Evaporation and Transpiration components of ET assumed at 20% and 80% for the current situation and 10% and 90% for the future situation. The figures in the Current Situation respond to information from FAO AQUASTAT (2016).

				Current situation		
	1	2	3	4	5	6
A	Agriculture withdrawal	Source		Evapotranspiration	Evaporation (20%)	Local efficiency
B		SW	44.7		8.2	56%
C		SW reuse	5.0	41.0	Transpiration (80%)	Overall efficiency
D		GW	1.0		32.8	68%
E	59.0	GW reuse	6.0	Return flow to SW and GW	Reuse agric SW	Total reuse
F		fossil GW	0.8		5.0	
G				18.0	Reuse agric GW	11.0
H		Treated WW	1.5		6.0	
				Hypothetical future situation		
	1	2	3	4	5	6
a	Agriculture withdrawal	Source		Evapotranspiration	Evaporation (10%)	Local efficiency
b		SW	34.9		3.6	80%
c		SW reuse	1.3	36.4	Transpiration (90%)	Overall efficiency
d		GW	1.0		32.8	86%
e	41.0	GW reuse	1.5	Return flow to SW and GW	Reuse agric SW	Total reuse
f		fossil GW	0.8		1.3	
g				4.6	Reuse agric GW	2.8
h		Treated WW	1.5		1.5	

A drop in the evapotranspiration (ET) is achieved by upgrading from current inefficient surface-wise irrigation methods to more efficient ones. The evapotranspiration in the new scenario is 81% of the current one. The implementation of modern irrigation might also bring along a reduction in the total agriculture withdrawal. However, the convolution between agriculture, drainage, outflows, and environmental flows is complex. It requires further scrutiny and was, hence, not taken into account.

The strategy feasibility was evaluated by considering both total areas of efficient irrigation and the percentage of efficient irrigation established in other countries worldwide (see Tables 35 to 37 in Appendix 1). Current areas equipped of modern irrigation were assumed at 10% and 0% for Egypt and Sudan, respectively (FAO-AQUASTAT, 2015). An increase in the coverage of efficient irrigation to a value around 28% might be reasonable, using Morocco as reference country. A total area of efficient irrigation at 2024 [1000 Ha] could be assumed considering the case of India, an area that represents 56% of the irrigated land. The same figures are taken for Sudan, provided it is comparable with Egypt and India in terms of GDP per capita.

Therefore, two scenarios of improvements in irrigation efficiency were assessed. They differ on the coverage of efficient irrigation. The first one assumes a value at 28%, and the second one, a value at 56%, using Morocco and India as reference, respectively. Details on the formulas utilized to compute the water savings are presented on the Appendix 1. The implementation this strategy renders an increase in water availability (water savings) between 1.3 and 3.0 BCM/year.

Table 16. Annual water savings by the implementation of the strategy on irrigation efficiency

Efficiency - Coverage at 28% (reference Morocco)

Implementation region			Efficiency		Water increase [BCM]	
Country	Irrigation area	Crops	Current	New		
Egypt	All irrigated areas	Wheat	68%	86%	0.3	0.8
		Maize			0.3	
		Sugarcane			0.2	
Sudan	All irrigated areas	Sorghum	65%	80%	0.3	0.5
		Wheat			0.1	
		Sugarcane			0.1	
Total values					**1.3**	

Efficient irrigation coverage at 56% (reference India)

Implementation region			Efficiency		Water increase [BCM]	
Country	Irrigation area		Current	New		
Egypt	All irrigated areas	Wheat	63%	80%	0.8	1.9
		Maize			0.8	
		Sugarcane			0.4	
Sudan	All irrigated areas	Sorghum	65%	80%	0.6	1.0
		Wheat			0.2	
		Sugarcane			0.2	
Total values					**3.0**	

Regulated deficit irrigation

The implementation of Regulated Deficit Irrigation (RDI) contributes to an increase in water availability. Such impact is achieved by either using less water to irrigate a fixed area (same crop amount) or using the same water to irrigate more land (more crops). Both water savings and extra land area were computed to see the impact of this strategy. The values of water productivity (WP) and yield for the improved situation were taken from two sources: Kirda (2002) for wheat and maize, and Karrou et al. (2012) for sugarcane.

The area of implementation for this strategy corresponds to all irrigated areas of wheat, maize, and sugarcane in Egypt, and areas of wheat and sugarcane in Sudan. The implementation of Regulated Deficit Irrigation (RDI) demands changes in agriculture practices, as well as some degree of technology upgrading at the farm level. The strategy was given flexibility by assuming the implementation coverage of RDI between 28% and 56%, aligned with assumptions taken for the Strategy 1 on Irrigation Efficiency.

The values of Water Productivity (WP) for wheat and maize in Egypt for both current and improved situations are taken from the work by Karrou et al. (2012). Current WP corresponds to present farmers' practice (basin irrigation), whereas the future situation corresponds to Deficit Irrigation at 70% (see Table 13). Sugarcane WP was calculated using total production and consumed water. For Sudan, the value of wheat WP stems from a yield at 2.2 Kg/m3(Eta) (Table 8), whereas the value for sugarcane was computed based on total production and consumed water. Drops in yield after RDI implementation are taken from the references as indicated in Table 17. For details on methodology for calculations see Appendix I.

The implementation of this strategy renders an increase in water availability (water savings) between 1.8 and 3.6 BCM/year. The land required to keep the current total crop production ranges between 81 and 163 thousand hectares.

Table 17. Water increase by the implementation of strategies on regulated deficit irrigation

Regulated Deficit Irrigation. Implementation coverage at 28% (reference Morocco)

Implementation region		Current Performance		Improved performance			Water increase [BCM]
Country	Crop	Yield [tons/Ha]	WP [Kg/m3 ETa]	Action	Yield [tons/Ha]	WP [Kg/m3 ETa]	
Egypt	Wheat	6.7	1.53	Irrigation at 70% (Karrou et al. 2012)	6.1	1.86	0.4
	Maize	7.7	1.30		7.0	1.83	0.6
	Sugarcane	114.1	5.88	Irrigation at 75% at tillering plus furrow irrigation (Kirda, 2002)	102.7	7.06	0.2
Sudan	Wheat	2.1	0.35	Irrigation at 70% (Karrou et al. 2012)	1.9	1.86	0.5
	Sugarcane	92.7	4.23	Irrigation at 75% at tillering plus furrow irrigation (Kirda, 2002)	83.4	5.08	0.1
							1.8

Regulated Deficit Irrigation. Implementation coverage at 56% (refence India)

Implementation region				Improved performance			Water increase [BCM]
Country	Crop	Yield [tons/Ha]	WP [Kg/m3 ETa]	Action	Yield [tons/Ha]	WP [Kg/m3 ETa]	
Egypt	Wheat	6.7	1.53	Irrigation at 70% (Karrou et al. 2012)	6.1	1.86	0.8
	Maize	7.7	1.30		7.0	1.83	1.3
	Sugarcane	114.1	5.88	Irrigation at 75% at tillering plus furrow irrigation (Kirda, 2002)	102.7	7.06	0.4
Sudan	Wheat	2.1	0.35	Irrigation at 70% (Karrou et al. 2012)	1.9	1.86	0.9
	Sugarcane	92.7	4.23	Irrigation at 75% at tillering plus furrow irrigation (Kirda, 2002)	83.4	5.08	0.2
							3.6

Evaporation component of evapotranspiration

The implementation of measures to reduce the evaporation component of the evapotranspiration increases water availability by reducing the water consumption for non-beneficial use. The evaporation fraction arises due to solar radiation, excessive watering and uncovered soil. Watering methods were addressed previously through efficiency measures, whereas solar radiation is not actionable. Soil exposure, however, can be reduced by either premature canopy or mulching use. Early sowing in wheat is already practiced in both Egypt and Sudan (November), therefore there is no room for savings in water through earlier canopy development. Mulching, either straw or plastic, seems to be barely used in the region. It is, thus, an opportunity.

The value of current evaporation fraction for maize was extracted from Simons et al. (2012). This study provides updated performance indicators of irrigation for the Egyptian Delta. For wheat, a weighted average at 28% was computed using 16% from Simons et al. (2012) for the Delta and 50% from Keith et al. (1998) for the Middle and Upper Egypt. The Delta represents 65% of the irrigation area in Egypt, proportion assumed for the weighing. For sorghum, the evaporation fraction was assumed the same as maize. In terms of the improved performance, the references utilized are Ding et al. (2013) and Qin et al. (2015). The implementation of mulching in Egypt at a 50% of coverage area might reduce the evaporation fraction by 50% for both wheat and maize. In Sudan, an achievable improvement in water productivity (WP) by 25% was considered for wheat and sorghum. For sugarcane, and based on results by Millard (1974) and Sandhu et al. (1980), improvements in WP by 36% and 60% were computed for Egypt and Sudan, respectively. They are the result of linear interpolation for yields of 114 and 93 tons/Ha according to Table 8 in the baseline (for details on the calculation methodology see Appendix I).

The area of implementation for this strategy corresponds to all irrigated areas of wheat, maize, and sugarcane in Egypt, and areas of sorghum, wheat and sugarcane in Sudan. The implementation of measures to reduce the evaporation fraction of evapotranspiration demands changes in agriculture practices, as well as some degree of technology upgrading at the farm level. The strategy was given flexibility by assuming the implementation at a scale between 28% and 56% of the irrigated land, aligned with assumptions taken for the strategies 1 and 2.

The implementation of measures to reduce the evaporation fraction of evapotranspiration renders a water availability increase between 1.0 and 2.1 BCM/year.

Table 18. Water increase by the implementation of strategies on evaporation fraction of ETc

Reduction in Evaporation Fraction. Implementation coverage at 28% (reference Morocco)						
Implementation region		Current performance		Improved performance		Water increase [BCM]
Country	Crop	ETa [BCM]	Evap fraction	Action	ETa [BCM]	
Egypt	Wheat	5.6	28%	50% mulching coverage reduces evaporation fraction by 50% (Ding et al, 2013, and Qin, Hu & Oenema, 2015)	5.4	0.2
	Maize	5.4	30%		5.2	0.2
	Sugarcane	2.7	-	WP improved by 36% (Sandhu, Prihar, and Khera, 1980, and Millard, 1974)	2.5	0.2
Sudan	Sorghum	3.7	30%	WUE improved by 25% for sorghum and wheat (Qin, Hu, & Oenema, 2015)	3.5	0.4
	Wheat	1.3	30%		1.3	0.1
	Sugarcane	1.4	-	WP improved by 60% (Sandhu, Prihar, and Khera, 1980, and Millard, 1974)	1.3	0.1
						1.0

Reduction in Evaporation Fraction. Implementation coverage at 56% (reference India)						
Implementation region		Current performance		Improved performance		Water increase [BCM]
Country	Crop	ETa [BCM]	Evap fraction	Action	ETa [BCM]	
Egypt	Wheat	5.6	28%	50% mulching reduces evaporation fraction by 50% (Ding et al, 2013, and by Qin, Hu & Oenema, 2015)	5.2	0.4
	Maize	5.4	30%		5.0	0.5
	Sugarcane	2.7	-	WP improved by 20% (Sandhu, Prihar, and Khera, 1980, and Millard, 1974)	2.4	0.3
Sudan	Sorghum	3.7	30%	WUE improved by 25% for sorghum and wheat (Qin, Hu, & Oenema, 2015)	3.3	0.5
	Wheat	1.3	30%		1.2	0.2
	Sugarcane	1.4	-	WP improved by 60% (Sandhu, Prihar, and Khera, 1980, and Millard, 1974)	1.1	0.3
						2.1

Rainfall Exploitation strategy

The implementation of measures to harness rainfall increases water availability by bringing more water into the managed water resources. No additional water is physically brought into the system. Green water is not considered in the exploitable water resources assessment within the study area. Thus, collecting rainwater and using it to recharge aquifers might be a valuable water gain.

The three most-relevant sub-basins in terms of rainwater harvesting (RWH) are Baro-Akobo-Sobat, Blue Nile, and White Nile. There is plenty of land under the Utilized Land Use (ULU) of shrubland with low to no human use, where different systems for macro- or micro-rainwater harvesting and groundwater recharge could be placed (See Land Use map in wateraccounting.org for Nile Basin for details on the land use shrubland). This strategy foresees the implementation of RWH schemes, with an area between 100 and 200 thousand hectares, an extension comparable to the five largest irrigation schemes (except Gezira) as reported by FAO-AQUASTAT (2015). The shrubland area in these sub-basins represents between 34% and 58%. The largest RWH scheme size, in turn, represents less than 2% the shrubland land use coverage for all sub-basins. The schemes would be distributed in the three mentioned sub-basins, covering areas in Sudan, South Sudan and Ethiopia with different precipitation regimes ranging between 300 and 1000 mm. Six schemes were considered: three in the Blue Nile, two in the Baro-Akobo-Sobat, and one in the Lower White Nile.

Certain amount of rainfall that is always lost to local infiltration. To take account of this, a rainwater harvesting ratio was introduced based on the literature. The factor is the relationship between precipitation and water captured for exploitation. The difference between these two quantities is the infiltration share. Such amount tends to be fixed, thus the higher the precipitation regime the higher the collection ratio. The values of RWH ratio were set as follows, according to total annual precipitation (TAP): for TAP ≥ 700mm, RWHR = 60%; for TAP ≤ 300mm, RWHR = 40%; and a RWHR = 50% for TAP in between.

The implementation of the strategy on rainfall exploitation under the assumptions stated renders a water availability increase between 2.4 and 4.9 BCM/year, according to scheme sizes of 100 and 200 thousand hectares, respectively (Table 19)

Table 19. Water gain by the implementation of strategies on Rainfall Exploitation. Precipitation values from maps in Awulachew (2012) and NBI & GIZ (2012). Rainwater Harvesting Scheme size set at 200 thousand hectares. Water gains for schemes at 100 thousand hectares would be half (linear behavior assumed).

Sub-Basin	Improved performance				Water increase [BCM]
	Action	Country	Precip. [mm]	RWH ratio	
Blue Nile	New 'schemes' in flat areas for rainwater harvesting system and groundwater recharge (INTA 2014 and Mekuria et al, 2015). Schemes size at 200 thousand hectares according to the White Nile pumping schemes in Sudan, found in FAO-AQUASTAT, 2015	Sudan	300	40%	0.24
		Ethiopia	800	60%	0.96
		Ethiopia	1000	60%	1.20
Baro-Akobo-Sobat		South Sudan	1000	60%	1.20
		South Sudan	700	60%	0.84
Lower White Nile		Sudan	500	50%	0.50
				Total values	**4.9**

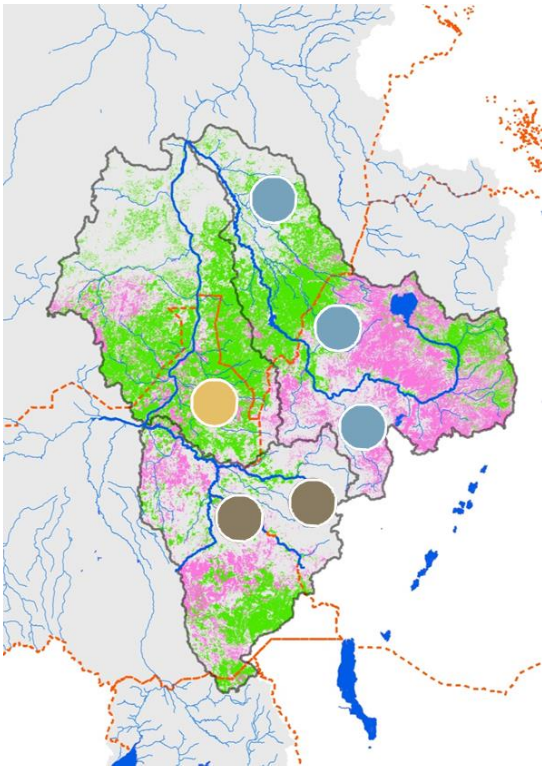

Figure 15. Distribution of six Rainwater Harvesting Schemes (circles) within the sub-basins Blue Nile (blue shade), Baro-Akobo-Sobat (brown shade), and Lower White Nile (orange shade).

Crops strategies

Yield improvements

Actions to improve yields increase water availability by using less water. The implementation of non-water-related agriculture best practices (e.g. better seeds, land leveling, correct use of fertilizers, or reduction in soil compaction) and water-related measures that imply using same or less water (e.g. scheduled irrigation or sprinkler/drip irrigation) can increase yields in the irrigation areas of both Egypt and Sudan.

For this strategy, it was assumed that water demand for a specific crop varies linearly with the land area under production (i.e. one hectare demands same amount of water before and after improvements implementation). Thus, improving yields allows producing the same amount of crops using less land (land savings).

Different scenarios of yield improvement have been considered for Egypt and Sudan. Egypt's yields for wheat and maize are high for the region, but still low compared to international best values. Egypt is an emergent middle-income country and represents a leading economy in the region. It has been assumed, thus, that improvements can be achieved in yields up to international best values. For wheat, yield would change from current 6.7 tons/Ha up to 10 tons/Ha (average of maximum values by Steduto et al., 2012). For maize, a USA's reference value at 10.0 tons/Ha was taken.

Sudan´s yields are low, some being at the lower extreme of the spectrum. This is the case of sorghum, with an overall country average value of 0.7 tons/Ha. The average for irrigated areas exclusively is 1.5 tons/Ha, widely below global averages between 5 and 7 tons/Ha (Table 8). Sudan is a lower middle-income country undergoing processes of pacification and stabilization. Considering this, a comparison with similar countries was performed, in order to estimate possible yield improvements. The new yield for sorghum was assumed at 4 tons/Ha, a level between the cases of Moldova, the Syrian Arabic Republic, and Egypt. Wheat, in turn, is assumed at 5.5 tons/Ha, a value between the cases of Uzbekistan and Egypt. Finally, the sugarcane yield was assumed at 108 tons/Ha, a value in between the cases for Zambia and Egypt. Provided Sudanese sugarcane is entirely irrigated, differences in precipitation regimes between the reference countries were neglected. Yields are found in Table 8 and Tables 29, 30 and 37 Appendix 1.

The strategy is given flexibility by assuming the implementation at a scale between 28% and 56% of the irrigated land, aligned with assumptions taken for the strategies 1, 2 and 3.

The implementation of measures to improve yield under the assumptions stated renders a water availability increase between 2.3 and 4.5 billion cubic meters/year. A complementary reduction in cropland between 301 and 602 thousand hectares is associated to such yield improvements.

Table 20. Water increase by the implementation of strategies on yield improvements.

Yield improvements. Implementation coverage at 28% (reference Morocco)

Implementation region		Current performance		Improved performance			Water savings [BCM]
Country	Crop	ETa [BCM]	Yield [tons/Ha]	Action	Yield [tons/Ha]	ETa [BCM]	
Egypt	wheat	5.6	6.7	Maximum average of 9 tons/Ha (Steduto, Hsiao, Fereres, and Raes, 2012)	9.0	5.2	0.6
	maize	5.4	7.7	Maximum in USA (Steduto, Hsiao, Fereres, and Raes, 2012)	10.0	5.1	0.5
Sudan	sorghum	3.7	2.2	Intermediate yield between values of Moldova, Syrian Arabic Republic (FAOSTAT, 2014) and Egypt	4.0	3.3	0.7
	wheat	1.3	2.1	Intermediate yield between levels of Uzbekistan (FAOSTAT, 2014) and Egypt	5.5	1.1	0.4
	sugarcane	1.4	92.7	Intermediate yield between levels of Zambia (FAOSTAT, 2014) and Egypt	108.0	1.3	0.1
							2.3

Yield improvements. Implementation coverage at 56% (reference India)

Implementation region				Improved performance			Water savings [BCM]
Country	Crop	ETa [BCM]	Yield [tons/Ha]	Action	Yield [tons/Ha]	ETa [BCM]	
Egypt	wheat	5.6	6.7	Maximum average of 9 tons/Ha (Steduto, Hsiao, Fereres, and Raes, 2012)	9.0	4.8	1.2
	maize	5.4	7.7	Maximum in USA (Steduto, Hsiao, Fereres, and Raes, 2012)	10.0	4.7	1.0
Sudan	sorghum	3.7	2.2	Intermediate yield between values of Moldova, Syrian Arabic Republic (FAOSTAT, 2014) and Egypt	4.0	2.8	1.4
	wheat	1.3	2.1	Intermediate yield between levels of Uzbekistan (FAOSTAT, 2014) and Egypt	5.5	0.9	0.7
	sugarcane	1.4	92.7	Intermediate yield between levels of Zambia (FAOSTAT, 2014) and Egypt	108.0	1.3	0.2
							4.5

Minor changes in cropping pattern

The implementation of minor changes in cropping pattern increases water availability by using less water. The rationale behind this alternative is plunging agriculture water demand, while keeping the crop types that exist currently in the production matrix. Short-cycle cultivars for wheat and maize allow shortening the irrigation season without losing yield. A hybrid late-sowing wheat variety was considered in Egypt and Sudan, which is sowed in January and has a 4-months growing cycle. Wheat yield is at 8 tons/Ha, according to the cultivar Botticelli (*Botticelli*, 2008). For maize, a short-season 90-days cultivar was considered in Egypt. Based on information from the seed-producer company Seed Co., the maize yield was assumed at the same current value. Water gains in maize production stem solely from a shorter irrigation cycle, compared to wheat which features both shorter cycle and higher yield. For sorghum in Sudan, the same criteria as in the strategy 5 was assumed, i.e. yield improvements with no special considerations on the growing cycle length. An improved performance at an intermediate value of 4 tons/Ha was assumed.

The strategy was given flexibility by assuming the implementation at a scale between 28% and 56% of the irrigated land, aligned with assumptions taken for the strategies 1, 2, 3 and 5. The implementation of measures to improve yield under the assumptions stated renders a water availability increase between 4.7 and 7.0 BCM/year. A complementary reduction in cropland between 435 and 582 thousand hectares is associated to such yield improvements.

Table 21. Water increase by the implementation of strategies on minor changes in cropping patterns.

Minor changes in crop patterns. Implementation coverage at 28% (reference Morocco)

Implementation region		Current performance		Improved performance			Water increase [BCM]
Country	Crop	ETa [BCM]	Yield [tons/Ha]	Action	Yield [tons/Ha]	ETa [BCM]	
Egypt	wheat	5.6	6.7	Short-season wheat (e.g. Botticelli). Sowing January	8.0	4.9	1.0
	maize	5.4	7.7	90-days maize, same yield (e.g. hybrid by Seed Co)	7.7	5.1	0,6
Sudan	sorghum	3.7	2.2	Average under irrigation (Steduto, Hsiao, Fereres, and Raes, 2012)	4.0	2.9	1.3
	wheat	1.3	2.1	Short-season wheat (e.g. Botticelli). Sowing January	8.0	0,2	1.8
							4.7

Minor changes in crop patterns. Implementation coverage at 56% (reference India)

Implementation region		Current performance		Improved performance			Water increase [BCM]
Country	Crop	ETa [BCM]	Yield [tons/Ha]	Action	Yield [tons/Ha]	ETa [BCM]	
Egypt	wheat	5.6	6.7	Short-season wheat (e.g. Botticelli). Sowing January	8.0	4.2	2.1
	maize	5.4	7.7	90-days maize, same yield (e.g. hybrid by Seed Co)	7.7	4.7	1.1
Sudan	sorghum	3.7	2.2	Average under irrigation (Steduto, Hsiao, Fereres, and Raes, 2012)	4.0	2.0	2.6
	wheat	1.3	2.1	Short-season wheat (e.g. Botticelli). Sowing January	8.0	0.6	1.2
							7.0

Major changes in cropping pattern

The implementation of major changes in cropping pattern are bound to the idea of a radical rethinking in agriculture, presented by Maliva and Missimer (2012). This strategy increases water availability by both introducing more water into the system, namely virtual water, and supporting production in areas where water consumption is not currently accounted for, e.g. rainfed areas. The rationale is plunging agriculture water demand by changing the production matrix in Egypt and Sudan in a way that impacts agriculture and economy, not only at a regional but also a global scale. As the production matrix and the international trade in both countries differ, actions laid out for each country differ as well.

Major changes in Egypt

Egypt's participation in global market is remarkable, being the world's largest wheat importer and one of the world's major producer and exporter of tomatoes. The aim of this strategy is, thus, at the intersection of crops production and produces exports and imports. Table 22 shows Egypt's top-ten major crops in terms of harvested area. Wheat and maize dominates in terms of land use and agriculture water demand. Their production, however, falls short on domestic demand, a reason why these products show up at the top of the imports list (Table 23). Table 24 shows Egypt's exports, oranges being at the top of the list in terms of merchandise trade.

Embedded within imports and exports, Egypt has been buying and selling water, respectively. A rearrangement of virtual water flows has been proposed as an effort to introduce creativity in the strategy. Several aspects are to consider, such as harvested area, yield, total production, transaction costs, and water footprint associated to each produce. The main goal is finding a new cropping pattern in terms of water consumption, while fulfilling two premises: i) satisfying domestic demand of crops and produces, ii) not jeopardizing Egypt's trade balance (currently negative).

The water footprint has been used as a metric to assess water flows. To allow proper comparisons among produces, values have been drawn, only, from Chapagain and Hoekstra (2003). Water footprint values for produces in Tables 22 and 23 correspond to Egypt, whereas values for import produces in Table 22 are global average, provided variability in the imports origin. For the optimization scenarios addressed later, however, values for Egypt were taken, as those are linked to the water savings that Egypt undergoes when importing produces. Values on the columns Water Used, Water Imported and Water Exported on Tables 21, 22 and 23 correspond to the product between Footprint and either Production, Imports and Exports, respectively. Cost for imported/exported water is the ratio between merchandise trade and total water volume used for a given produce (See details in Appendix 1).

Table 22. Crop production in Egypt (FAOSTAT, 2013). Top-ten crops ordered by harvested area. The crop footprint was taken from Chapagain & Hoekstra (2004).

Product	FAO code	Production [tons]	Footprint [m3/tonne]	Water used [BCM]	Use/Trade
Wheat	15	9460229	930	8.80	main additional import
Forage and silage, clover	640	53000040	204	10.81	domestic demand
Maize	56	7956587	1031	8.20	main additional import
Rice, paddy	27	5724090	1565	8.96	main export
Tomatoes	388	8533811	162	1.38	main export
Sugar beet	157	10044257	188	1.89	domestic demand
Potatoes	116	4265182	308	1.31	main export
Sorghum	83	761628	909	0.69	additional import
Seed cotton	328	434994	3028	1.32	support textile industry
Sugar cane	156	15780000	140	2.21	main export as refined sugar

Table 23. Egypt's top-ten imported produces in 2013. Wheat and maize rank first in terms of market exchange share. Soybeans and bean-related produces are the most expensive in terms of water footprint. Source: FAOSTAT (2016).

Product	FAO code	Water		
		Footprint [m3/tonne]	Imported [BCM]	Cost
Wheat	15	1334 [4]	13.7	0.20
Maize	56	909 [4]	5.2	0.38
Soybeans	236	1789 [4]	2.8	0.35
Meat, cattle, boneless (beef & veal)	870	15415 [3]	2.8	0.30
Oil, sunflower	268	6792 [3]	3.0	0.21
Oil, palm	257	1098 [3]	0.8	0.80
Cake, soybeans	238	1179 [3]	1.8	0.30
Tea	667	9205 [4]	1.0	0.32
Sugar Raw Centrifugal	162	*	*	*
Broad beans, horse beans, dry	181	2050 [4]	0.6	0.48

1Mekonnen & Hoekstra,2011; 2Brower and Heibloem (1986); 3http://waterfootprint.org/; 4irrigated

Table 24. Egypt's top-ten exported produces in 2013. Oranges rank first in terms of market exchange share and exported water. Potatoes, rice and sugarcane are among Egypt's most harvested and most water demanding crops. Grapes and frozen vegetables are the best paid produces in terms of water footprint. Source: FAOSTAT (2016).

Product	FAO code	Water		
		Footprint [m3/tonne]	Exported [BCM]	Cost [USD/m3]
Oranges	490	602 [4]	0.67	0.74
Crude materials	1293	*	*	*
Cheese, processed	907	3178 [3]	0.17	1.41
Potatoes	116	308 [4]	0.13	1.56
Onions, dry	403	258 [4]	0.09	2.38
Food prep nes	1232	*	*	*
Rice – total (Rice milled equivalent)	30	1673 [1]	0.56	0.35
Grapes	560	537 [4]	0.05	3.87
Sugar refined	164	1782 [1]	0.42	0.41
Vegetables, frozen	473	322 [1]	0.03	4.77

1Mekonnen & Hoekstra,2011; 2Brower and Heibloem (1986); 3http://waterfootprint.org/; 4Chapagain & Hoekstra, 2004

This strategy proposes reducing domestic production of wheat and maize and increasing their importation. At the same time, it foresees cropland reallocation towards more profitable produces in terms of water demand. Two aspects are of interest on Table 24. The footprint column is linked to water demand, thus, the lower the value the better. On the other hand, the water cost tells how well virtual water is paid for. Hence, the higher the better. Under this mindset, candidates for production augmentation are potatoes, onions, grapes and vegetables. By importing wheat and maize, Egypt pays between 0.20 and 0.38 USD per cubic meter of water. On the other hand, by exporting grapes and vegetables, the country is paid between 1.56 and 4.77 USD per cubic meter of water.

Alternatives of cropland reallocation and the corresponding impacts on water demand were found through linear optimization, using a Simplex LP algorithm in Solver, Microsoft Excel. Tables 51 to 53 in the Appendix 1 show goals and constraints of the three different optimizations that were run. Current yields are kept fixed along the optimization scenarios. Hence, a production increase for a given produce is subjected to additional land. In turn, the space is limited to the total harvested area for these six crops, thus more land for one product means less land for another (compensation). Domestic demands for all products are fixed as well (no change in diet takes place). Water demand using the water footprint approach differs from the values in the baseline. Per the water footprint, demand for wheat and maize is 17 BCM; per the baseline, the demand is at 11 BCM. Water savings rendered by each optimization scenario have been, therefore, corrected using a factor equal to 0.647 (11 BCM / 17 BCM) to allow comparisons with the other six strategies.

Three optimization scenarios were assessed for Egypt. The Scenario 1 is the least restrictive one and its results offer a first understanding of the strategy approach. Setting no limits on the reduction of wheat and maize harvested area, along with no limit on the increase in vegetables production, results in full substitution of domestic production of wheat and maize with vegetables, and entire demand of wheat and maize covered by imports. Scenarios 2 and 3 introduce limitations to the production and exports of frozen vegetables. A limit for exports was set at 1.17 million tons in the Scenario 2, this value being the largest country export for 2013 recorded by Belgium (Table 50 in Appendix 1). The Scenario 3, in turn, looks at the limitations in land allocation to vegetables. Hence, a limit at 10% with respect to total arable land was defined based on the shares in countries with total production of vegetables greater than Egypt's (Table 49 in Appendix 1). Details on the linear programming configuration, i.e. objective functions and constraints for each scenario, are found in the Appendix 1.

Table 25. Results the three optimization scenarios in Egypt cropping patterns. Harvested area for selected crops in the current cropping patter (baseline) and the three optimization scenarios, as well as water savings rendered through each optimization. Water savings are corrected with factor 0.647, based on water demand in Egypt's baseline (See details in Appendix 1).

Crop	Baseline	Scenario 1		Scenario 2		Scenario 3	
	Harvested area [1000 Ha]	Harvested area [1000 Ha]	Water savings [BCM]	Harvested area [1000 Ha]	Water savings [BCM]	Harvested area [1000 Ha]	Water savings [BCM]
Wheat	1419	0	8.3	709	5.2	709	5.2
Maize	1030	0		515		515	
Potatoes	160	144		144		144	
Onions, dry	53	44		44		44	
Grapes	64	60		95		104	
Vegetables	127	2606		322		274	
Totals	2854	2854		1829		1829	

Major changes in Sudan

Sudan plays a major global role as well, as it is among the world's five top-producers of sesame seed, featuring the second-best price in 2013 just below China. Sesame, however, is solely rainfed produced, not offering opportunities for water savings in the context of this study.

Sorghum, on the other hand, is extensively produced as well, but for domestic consumption. It is produced in both rainfed and irrigated areas. Irrigated sorghum is responsible for the largest agriculture water withdrawal.

Different to the rationale in Egypt, the strategy in Sudanese territory aims at supporting rainfed sorghum. The implementation of non-water-related agriculture best practices (e.g. better seeds, land leveling, correct use of fertilizers, or reduction in soil compaction), and water-related measures that imply better use of rainfall, can increase current rainfed sorghum yields from 0.7 tons/Ha up to 4 tons/Ha as indicated in the strategy 5 *Yield Improvements*. Rising yields in rainfed areas allows covering current sorghum production solely in rainfed land, leaving irrigation water and land in the schemes free to be allocated for more-profitable uses.

Two scenarios were considered as well, what allows to couple results with those of Egypt. The first one addresses irrigated sorghum in Gezira, and the second one tackles all irrigated sorghum in Sudan. In order to eradicate irrigation in Gezira’s sorghum, yield has to be improved in 350 thousand hectares of current rainfed cropland. On the other hand, improvements have to cover an extension of 420 thousand hectares to eradicate all irrigated sorghum. From Table 26 is to see these scenarios render water savings of 4.4 and 5.7 BCM/year, and imply focusing efforts on about 5% of total sorghum rainfed area.

Table 26. Sorghum production distribution in rainfed and irrigated land. Source AQUASTAT (2016).

Region	Harvested area [1000 Ha]	Yield [tons/Ha]	Production [10^3 tons]	Water demand [BCM/year]
Gezira	522	2.2	1148	4.4
Irrigated (non-Gezira)	156	1.5	234	1.3
Rainfed	7700	0.7	5390	*
Totals	8378		6772	*

Two approaches, one strategy

Scenarios for both Egypt and Sudan were combined into sub-alternatives, in order to provide final results out of the implementation of major changes in cropping patterns. Actions in Sudan render water savings, whereas those in Egypt produce a net water gain into the system through virtual water flows. The scenario 1 in Egypt is a hypothetical aspiration that results quite non-actionable. There are only two countries in the world with harvested areas of vegetables larger than the value suggested by this scenario (China and India, Table 49). The feasible scenarios in Egypt and Sudan were combined as indicated in Table 27. The increase in water availability ranges between 9.6 and 10.9 BCM/year (Table 27).

Table 27. Impact of implementation of major changes in cropping pattern in the water availability.

Sub-strategy	Country		Water savings/gains [BCM]
	Egypt	Sudan	
1	Limits for vegetables production and frozen vegetables exports plus limits in the reduction in domestic wheat and maize production (scenarios 2 and 3)	Yield improvement in 350 [1000 Ha] of rainfed sorghum (scenario 1)	9.6
2	Limits for vegetables production and frozen vegetables exports plus limits in the reduction in domestic wheat and maize production (scenarios 2 and 3)	Yield improvement in 420 [1000 Ha] of rainfed sorghum (scenario 2)	10.9

DISCUSSION

The challenge

Increasing water availability in the Eastern Nile Basin was the challenge assumed for this research. It would be achieved by plunging water demand (savings) and/or introducing more water in the managed water system (gains). The concept of ‘flexibility’ was introduced to challenge the view of water as a limited resource, something found recurrently in the literature. By considering water as a flexible resource, as stated by Islam and Susskind (2012) in the Water Diplomacy Framework, it is possible to shift the conversation focus, moving the spotlight from the traditional approach of ‘how to split what we have’ to ‘how to increase the pie and redistribute’.

There is potential to increase water availability in the Eastern Nile Basin’s agriculture sector. Seven strategies were proposed and assessed in terms of their impact on water savings and gains, and their results suggest all of them are worth considering towards water policy implementation in the region (Figure 16 and Table 28).

Three strategies relate to irrigation in different dimensions, namely efficiency, deficit, and evaporation component of ET. Their impact on water availability (savings) ranges between 1.6 and 3.6 BCM/year. The strategy on Regulated Deficit Irrigation renders the best results, whereas addressing the Evaporation Component of Evapotranspiration is the least impactful.

Moving on, the strategy on Rainfall Exploitation aims at bringing more water into the managed water system. Developing rainwater harvesting schemes to reduce landscape evaporation and recharge aquifers, is something barely found in the literature about this region. This strategy renders an increase in water availability between 2.4 and 4.9 BCM/year.

Finally, the largest increase in water availability stems from strategies on crops management, either by improving yields in existing crops, using less-water-demanding cultivars of the same crops currently grown, or reallocating land and water for high-profitable and less-water demanding crops. Their impact comes up mainly through water savings, but gains are present as well. The strategy on Yield Improvements is the least impactful one in this group. However, its water savings are larger than those achieved by initiatives on irrigation and rainfall exploitation.

The best results in this group, and, thus, in the entire set of strategies, is achieved by Major Changes in the Cropping Pattern. This strategy renders water savings in Sudan and water gains in Egypt to a total between 9.6 and 10.9 BCM/year. A complementary reduction in cropland between 1025 and 1063 thousand hectares is associated to this strategy.

Results allow to claim that the largest increase in water availability is the result of actions that have little to nothing to do with water resources, at least from a traditional standpoint with regards to infrastructure or policy.

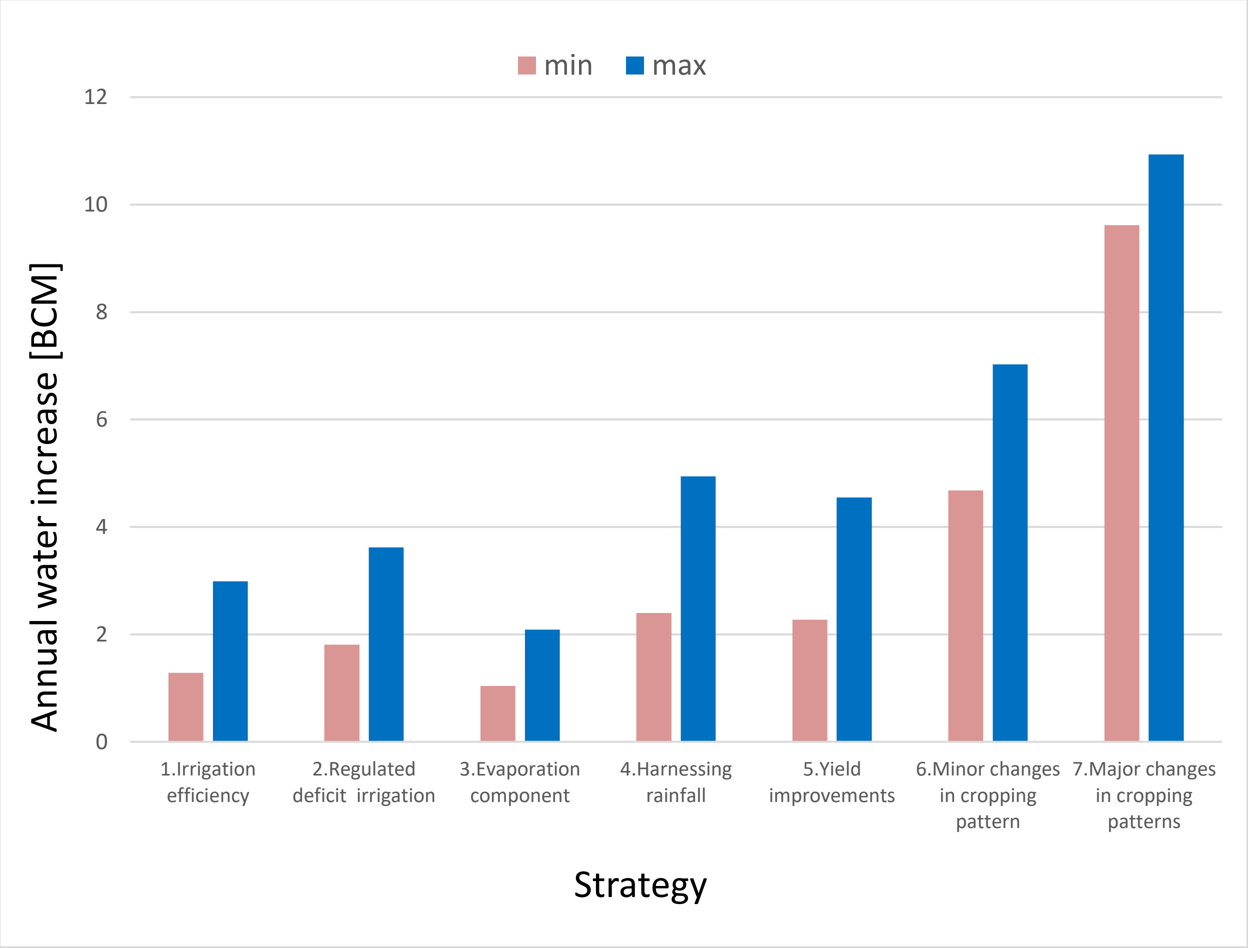

Figure 16. Impact on water availability of strategies in the agriculture sector. Abscissae-axis shows seven strategies broken down into sub-strategies. Ordinate-axis shows annual water increase in Billion Cubic Meters. Maximum and minimum values correspond to assumptions on achievable results stated along the analysis.

Table 28. Summary on strategies characteristics and their impact on water availability. Highlights were added as a contribution towards additional research efforts.

Strategy		Countries of implementation	Crops (region)	Impact on water	Impact on crops	Actions	References	Feasibility (flexibility)	Water increase [BCM]		Highlights	
No.	Name								min	max	Limitations	Challenges
1	Irrigation efficiency	Egypt Sudan	wheat, maize, sugarcane sorghum, wheat, sugarcane	saving	keep	Upgrade from flood and furrow to sprinkler (pivot irrigation) Overall field application efficiency from 68% to 86% in Egypt and 65% to 80% in Sudan	Brouwer, Prins, & Heibloem (1989) Keller & Keller (1995) Simons et al. (2015) Own computations	Implementation between 28% and 56% of irrigated land	1.3	3.0	Efficiency computation Unique value of efficiency throughout territory	Water tariff in Egypt Technology cost
2	Regulated deficit irrigation	Egypt Sudan	wheat, maize, sugarcane wheat, sugarcane	saving	keep	Changes in water productivity. Irrigation at 70% for wheat and maize Irrigation at 75% at tillering for sugarcane	Karrou et al. (2012) Kirda (2002)	Implementation between 28% and 56% of irrigated land	1.8	3.6	Applicability of water productivity values	Water tariff in Egypt
3	Evaporation component	Egypt Sudan	wheat, maize, sugarcane sorghum, wheat, sugarcane	saving	keep	Mulching coverage in Egypt's wheat and maize Improvements in Water Productivity for sugarcane Improvement in Water Use Efficiency in Sudan's sorghum and maize	Millard (1974) Sandhu et al. (1980) Ding et al. (2013) Qin et al. (2015)	Implementation between 28% and 56% of irrigated land	1.0	2.1	Applicability of water productivity and water use efficiency values and results of mulching	Water tariff in Egypt Technology cost
4	Rainfall exploitation	Sudan, Ethiopia & South Sudan	Sub-basins: Blue Nile, Baro-Akobo-Sobat Lower White Nile	gains	none	Rainwater harvesting schemes. Size at 200 thousand hectares according to the White Nile pumping schemes in Sudan, found in FAO-AQUASTAT, 2015	Mekuria et al (2015) Basan Nickisch et al. (2016)	N/A	2.4	4.9	Precipitation values Scheme size Rainwater collection ratio	Maintenance
5	Yield improvements	Egypt Sudan	wheat, maize sorghum, wheat, sugarcane	saving	keep	Best agriculture practices to rise yields to better regional/international levels	Steduto, Hsiao, Fereres, and Raes (2012) FAOSTAT (2014)	Implementation between 28% and 56% of irrigated land	2.3	4.5	Achievability of referential values	Training and support
6	Minor changes in cropping pattern	Egypt Sudan	wheat, maize sorghum, wheat	saving	change	Short-season wheat 90-days maize Best practices in sorghum	'Maize', N.D. Botticelli (2008) Steduto, Hsiao, Fereres, and Raes (2012)	Implementation between 28% and 56% of irrigated land	4.7	7.0	Achievability of referential values	Governmental decision
7	Major changes in cropping patterns	Egypt Sudan	wheat, maize (vegetables, grapes, onions, potatos) sorghum	saving/gain	change	Crops replacement based on virtual water trade	Chapagain & Hoekstra (2004) FAOSTAT (2014) Own computatinos	Limits in vegetables production and frozen vegetables exports in Egypt. Yield improvement limited to irrigated areas in Sudan	9.6	10.9	Virtual water and water trade approach Achievability of referential values	Governmental decision

Feasibility

Finding the right figure for sorghum´s demand in Sudan, the water footprint for vegetables in Egypt, as well as the rainwater harvesting ratio in South Sudan and Ethiopia, is crucial for calculations and conclusions drawn thereafter. However, the main contribution of this work is not there. Even though remarkably quantitative, this research aims at bringing to the discussion table issues that have not been envisioned previously. Strategies were defined upon findings in published literature and data from recognized databases, meaning both numbers and assumptions are scientifically supported. Moreover, local or regional experiences exist for most of the strategies developed, so there is an existing know-how on the subjects. Nonetheless, concerns of feasibility of strategies implementation might rise grounded, for instance, on the socio-economic and political context in the study region. Some of the questions that are addressed in the discussion are: What is the potential for modern irrigation coverage? What are the constraints for its adoption at farm level? What are the opportunities and limitations for mulching implementation? What yields are achievable for sorghum in Sudan? What are the opportunities for vegetables grown and exported in Egypt?

Irrigation and best practices

Efficiency

Irrigation is key to produce more of food and cash crops. It renders higher yields (Schoengold & Zilberman, 2007), while water is used wisely. Water-scarce regions where agriculture is relevant, either because of its contribution to the national economy or local subsistence, should implement efficient irrigation. Only about 10% of the cultivated area in the ENB´s countries is irrigated, most of it in Egypt followed by Sudan. In addition to that, about 90% of irrigation in the region is undertaken traditionally (FAO-AQUASTAT, 2015), through methods such as flood and furrow, which are knowledgeably inefficient. Upgrading towards modern application techniques, such as drip and sprinkler, is as possible as smart, and it is something happening in other water-constrained countries in the Middle East and North Africa, like Morocco, Algeria, Israel and Saudi Arabia.

Efficiency must be evaluated at regional or macro-scale, to avoid negative outcomes. The condition of ‘inefficient’ for the Sudanese irrigation system is not in question; earthen conveyance canals plus surface-wise field application techniques allow estimate efficiency at 65% (or even less), meaning that 35% of agriculture water is lost to non-productive uses. Egypt´s situation is special, nonetheless, and further thinking is required for proper conclusions and actions thereafter. Both Keller and Keller (1995) and Simons et al. (2015) addressed the issue of a locally-inefficient but regionally-efficient irrigation system, where tail farmers benefit from the water drainage ditches to irrigate their lands. According to Keller and Keller (1995), no major water saving opportunities were visible under such circumstances. Their claims, however, were based on the concept of effective Water Use Efficiency, which seems not to discriminate between the beneficial and non-beneficial shares of consumptive water use.

A simple model was built for Egypt's irrigation system. It feeds on the values from a national water balance from FAO-AQUASTAT (2015), accounts for the multi-cycle approach by Simons et al. (2015), and assumes the evapotranspiration break-down at 20 – 80% (evaporation and transpiration shares, respectively), based on findings in Simons et al. (2012). Even though efficiency is something that varies from plot to plot and region to region (e.g. efficiency in the Delta is higher than in the Middle and Upper Nile regions), a unique plot-level efficiency throughout the country was considered for the computations. As result of all this, Egypt's current overall efficiency was found at 68%, what is the starting point for the strategy on Irrigation Efficiency.

Upgrading in field application techniques minimizes water losses to non-productive use. Technologies like drip and sprinkler allow delivering water closer to the root zone for plant transpiration, reducing the soil evaporation and deep percolation fractions. Reducing evaporation translates into direct water savings. On the other hand, in a system with the Egyptian features, reducing percolations is positive from an environmental and productivity-related standpoint (chemical pollution, waterlogging, salinity), but it would jeopardize tail farmers' businesses. Overcoming this require stepping back and recognizing that the actual system takes on a hydrogeological situation that might be understood as an advantage, but also builds up on the mismanagement of irrigation water. Modern irrigation techniques at the plot levels would make more water stay in the canals instead of percolating to the aquifer and running off to the drainage ditches. To cope with this, the current irrigation network should be restored, or eventually redesigned, to bring the water to downstream users along the formal way, i.e. the canals.

The way this strategy is set, water savings stem exclusively from a reduction in the evaporation fraction of ET. Built upon the premise of keeping plant transpiration constant, Table 15 shows that the Return Flow has dropped, and total Agriculture Withdrawal has dropped as well. The difference between current and future values is the water saved at the origins (river, aquifer, or canals), that should be conveyed to downstream users.

Decisions on efficiency or better said total amount of water applied to cropland may have implications on irrigation water quality and crop yield as well. Considering the interaction between efficiency and salinization/pollution is important (Keller & Keller, 1995). Excess water in agricultural fields contributes to the salts leaching from the soil zone (Maliva & Missimer, 2012). Leaching helps maintain a favorable salt balance for optimum crop production, and its requirement depends on water quality and crop's tolerance to salinity; it is also function of the irrigation technique, irrigation frequency, and, to less extent, of soil texture (Keller & Keller, 1995). In Egypt, however, the situation is more delicate, because washed-up salts end up entering either the aquifer or the drainage system. Provided both constitute withdrawal sources for downstream users, salt (as well as pollutants) concentration rises as water flows down to the tail of the irrigation system (Wahaab & Badawy, 2004).

The potential for implementation of modern irrigation was evaluated through a coverage factor that accounts for the percentage of efficient irrigation likely to be achieved in the ENB countries. Besides its use for the strategy on Irrigation Efficiency, it has been applied as a proxy for to evaluate the implementation feasibility of other strategies as well. Its determination involves the use of economics (per capita GDP and value added by agriculture to GDP) and climate (annual precipitation) as metrics to render comparisons. Several countries comparable to Egypt and Sudan were found, but no one meets all the comparability criteria soundly. Precipitation was a criterion impossible to fit, as Egypt's value is one of the lowest in the world. Therefore, and grounded on the fact that Egypt's agriculture is practically 100% irrigated, such metric lost relevance.

A second search took the area equipped for irrigation into account to select comparable countries. An African country, Morocco has 414 thousand hectares of modern irrigation, what represents a 28%. On the other hand, India has more than 2 million hectares of modern irrigation, and even though its impact is not reflected in the country's percentage of efficient irrigation (ca. 3%), the magnitude itself tells what possible at a country level is. Additional countries show interesting values, for instance Zimbabwe, Moldova, Brazil and South Africa in terms of percentage, and China and Brazil in terms of modern irrigation areas.

Regulated Deficit Irrigation

The strategy on Regulated Deficit Irrigation (RDI) aims at using crops' inherent properties to produce more efficiently. By growing water-stress drought-tolerant crops, it is possible to render higher water productivity. In other words, it turns possible to grow the same amount of crops but using less water or, with similar approach, produce more crops with the same amount of water. Some crops are more suitable for RDI implementation, as seen in Kirda (2002) and Karrou et al. (2012), among others. Promising experiences and results are found for some of the most important cereal crops in the region, namely wheat and maize. For sugarcane, even though not represented by a specific study in the region, the literature suggests good response for water deficit during the tillering stage in the growing cycle. With regards to sorghum, the evidence indicates no water saving is possible through RDI, if willing to keep production.

RDI is usually linked to yield drops, hence, more land is needed to keep total productions of crops. Non-irrigated land is abundant in Sudan, of the type of both traditional and mechanized rainfed agriculture. The materialization of GERD, in Ethiopia, would unlock all kind of opportunities on the East of the country. In Egypt, in turn, ambitious reclamation projects are already ongoing or in the pipeline. Therefore, water saved by RDI implementation could be redirected to put new land into production with either efficient, regulated deficit, or both as mandatory techniques for irrigation.

Mulching

An alternate way to reduce the evaporation component of ET (besides modern irrigation implementation) is mulching. Mulching "modifies the hydrothermal regime of the soil surface by reducing soil temperature during summer and acting as a barrier against the loss of water."(Ram et al., 2012). In addition, mulching "typically conserves the soil, improves the soil ecology, stabilizes and enhances crop yield and provides various environmental services", offering, thus, great agro-ecological potential (Erenstein, 2003).

The literature provides experiences on straw and plastic mulching, the first one being found more often. The advantages of mulching are reflected in several studies: Eastham et al. (1999) studied wheat and found drops in evaporation between 27 and 48%; Ding et al. (2013) studied maize and found drops by 50%; Qin et al. (2015) performed a metadata analysis for wheat and maize and discovered that mulching can render average water savings by 20% and 30%, respectively. Sandhu et al. (1980) and Millard (1974) provide insight on sugarcane. The first study found that same yields are possible in mulched areas, but using 45% less water; the second study, in turn, found an increase in water productivity by 19%. Beyond the approach, either yield, water productivity, or water demand, mulching offers proved opportunities to save water.

Despite the goodness of mulching, its massive implementation remains limited because of costs, logistics and environmental issues. Some regions in Africa offer large potential regarding plastic film, but its success is constrained by financial issues, as well as difficulties with the collection and recycling of residues (Qin et al., 2015). Wide adoption in China and India was unlocked by substantial governmental subsidies. Mulching cost can be a determinant in farmers' decision-making, as shown by Ram et al. (2012), who evaluated economics for an irrigated maize-wheat system in India, and concluded that straw mulching enhances profits as long as mulch is costless.

Strategies on irrigation, which aim at saving water, are feasible from a technical point of view. They are, nonetheless, quite far from reality if business-as-usual goes on in terms of water pricing. Adoption of irrigation technology is correlated to an increase in water price (Caswell and Zilberman (1985, 1986) and Dinar and Yaron (1992), found in Schoengold and Zilberman (2007)). Similar relationships could be expected with regards to the adoption of RDI and mulching, as they require economic investment and training. According to Erenstein (2003), who addresses smallholding agriculture, farmer's acceptance "is more likely when mulching offers economic opportunities", specifically short-term returns.

In Egypt, where agriculture takes on between 70% (AQUASTAT, 2016) and 85% (MWRI, 2014) of the country's water withdrawal, and the irrigated area represents more than 70% of the ENB countries' total, irrigation water is given free of charge. Reasons for not charging for water meander through values, morality, religion, and politics (Barnes, 2014). A study by USAID 20 years ago, reported a reduction of 3.5% in agriculture water demand was possible if water charges were in place (Perry, 1996 in Barnes, 2014), but at the same time, it would bring along a reduction of 4.5% in farmers' income, a political cost that nobody is willing to pay (Barnes, 2014). Proper pricing for water will make the adoption of precision irrigation appealing. Modern irrigation will diminish water use, increase yields, and reduce environmental externalities such as water logging and salinization, two issues remarkably relevant in Egypt. Ensuring farmers' rentability under a new tariff framework might demand a shift towards more profitable and water-productive crops. Some farmers might decide on a full reconversion in the economic activity, for instance, into industrial or high-tech business. In any case, governmental support will be needed along the transition to grant success.

Harnessing rainfall

Rainfall is an untapped resource in the Eastern Nile Basin that can bridge the gap once and for all. Whilst some authors claim North Africa ran out of renewable water resources (Qadir et al., 2007) and the region might become hotter and drier (Conway & Hulme, 1993), a recent water balance shows the utilized water is barely 5% of the total water inflow (Water Accounting, 2016. Recall Table 2). Most of rainfall in the region is lost to non-beneficial uses through landscape evapotranspiration in areas of limited use. The heaviest rainfall occurs in the highlands of Ethiopia and South Sudan and the eastern portion of Sudan. Extensive savannahs and shrublands regions exist where poor traditional rainfed agriculture and pastoral activities take place, which could be either complemented or substituted by rainwater harvesting.

Some studies in the region suggest the technique is effective at capturing rainfall and reducing water losses to runoff. Rainwater is kept locally and recharge aquifers that can be tapped later when needed. Herweg and Ludi (1999) and Mekuria et al. (2015) presented options for soil and water conservation mountains in Ethiopia and Eritrea. Basán Nickisch et al. (2016) share an example on rainwater collection for cattle on flat lands in Argentina.

Building on these experiences, the strategy on Rainfall Exploitation proposes bringing more water into the managed system by allocating limited-use lands to be systematized for harnessing rainfall. The water gained through this strategy is currently not accounted for, as it evaporates or is transpired by plants locally to no productive use. Hence, exploiting rainwater should not be an issue for users in lower regions of the basin (downstream users).

The idea of implementing schemes for rainwater harvesting (RWH) stems from the fact that schemes are ancient institutions rooted in the area. The RHW scheme's size was defined based on the New Haifa irrigation scheme, the second largest in the country. No additional consideration mandate such size, and it should be defined based on managemental considerations (e.g. economics, agronomic characteristics, precipitation regime). Runoff tends to be greater when soils is saturated, thus rainwater harvesting should take place, preferably, in regions of intense precipitation, for instance, the Ethiopian Highlands, widely known because their monsoon regime. For this strategy, areas in different countries and precipitation values where assumed following the above-mentioned criteria. Based on maps in Water Accounting (2016) and Awulachew (2012), annual precipitation ranges between 300 and 1000 mm in the selected sites.

As RWH would take place in regions with limited use, opportunities for its implementation, operation and maintenance might be limited and questionable. The strategy shows water gains at ca. 5 BMC/year, but they might well be larger if more land is allotted and technology deployed. In Regions where access to conventional water resources is limited, options like this should be luring. Governmental intervention, transnational agreements, as well as the enactment of water markets could be needed for this approach to take off.

Tapping on crops and cropping patterns

Yields improvements

There is plenty of room for yield improvements in the Eastern Nile Basin, mainly in both traditional and mechanized rainfed areas. Rainfall in Egypt is negligible and agriculture is entirely irrigated. However, this is not the case for the rest of the Eastern Nile Basin, where most agriculture is rainfed, just as in the entire Sub-Saharan Africa. 95% of the total combined agricultural land of Ethiopia, Sudan, and South Sudan is rainfed; hence, it is highly sensitive to climate change. A recent analysis concluded that some African countries will lose virtually their entire rainfed agriculture by 2100 (Mendelsohn et al. 2000 in Mahgoud, Elagib, Gaese, & Heinrich, 2014), something that will undoubtedly deepen the region's food insecurity. Addressing climate change is a long-term shot, but its current effects on food could be substantially overcome by improving yields in agriculture production. Egypt's yield are the highest in the basin (NBI & GIZ, 2012), and some crops perform remarkably well internationally, e.g. maize and sugarcane (Recall Table 8). Sudanese sugarcane production is quite decent as well. Both countries, however, offer opportunities for improvements, conforming to their own context.

The strategy on Yield Improvements pushes for rising yields in irrigated areas up to best-recorded level. Egyptian wheat and maize yields were assumed at international average and maximum value, respectively, using reference figures from Steduto et al. (2012) (Recall Table 8). Such increase represents ca. 30% above current performance. For Sudan, comparisons with other countries producing same crops were carried out using economics, first, and precipitation, second. Sorghum at 4 ton/Ha was assumed, a value between Moldova’s (similar GDP and precipitation) and Egypt’s (same basin). Uzbekistan stands out with ca. 13 tons/ha and perfectly comparable to Sudan under the criteria, but a more conservative yield was believed appropriate. Similar approach was applied for wheat and sugarcane, taking Zambia (continent and GDP), Uzbekistan, and Egypt.

Envisioned yields improvements in Sudan are more ambitious than in Egypt. Yield for sorghum and wheat would be ca. twice and three times the current values, respectively. On the other hand, sugarcane would be improved by only 15%, because it is already at good levels, internationally. With regards to the question as to whether such yields would be achieved, besides the comparability criteria, this research holds on to interesting statements in the literature. Current yields in the rainfed areas could be double or quadruple by improving farming practices (FAO 2007 in Maliva &Missimer, 2012). Succeeding on this, however, demands recognition of faults and supportive policies. This is not the case in Sudan, for instance, where mechanized farming has been given low attention compared to the irrigation schemes, even though it is the reason of Sudan’s agriculture thrive (Britannica, 2016).

Changes in cropping pattern changes

Strategies on changes in cropping pattern render the largest increase in water availability. They have little to nothing to do with water infrastructure. Quite the opposite, their realization might be understood both ways, tied to high-level policy-making as well as profound farm-level decisions.

The strategy on Minor Changes in Cropping Pattern deals with growing different cultivars of the same crops. New cultivars make the difference in water demand because of genetic modifications. Short-season wheat, e.g. the variety Botticelli, is sown in January (a month later) and has a three-months seasons. Yields are expected to be even higher than the highest value in Egypt, according to experiences in irrigated areas of Castile and Leon, Spain (*Botticelli*, 2008), and ongoing efforts in Egypt to increase productivity (GIEWS, 2016). With regards to maize, a hybrid 90-days variety developed by the African company Seed Co was selected for Egypt. No changes in yield are anticipated, and water savings are due to the shorter growing season under irrigation. For sorghum, no especial cultivar was found, and its yield increase would be the result of the implementation of best practices as those addressed within the strategy on Yield Improvements.

The strategy on Major Changes in Cropping Pattern, even though developed at initial stages, offers huge potential for impactful results. The approach brings up two key issues: virtual water trade and land allocation for agriculture use. The optimization exercise in Egypt includes 3 scenarios where 6 crops are assessed within a comprehensive framework that includes water demand for domestic production, water traded by importing/exporting produces, and costs of merchandise exchange. The Scenario 1 considers a full balance in the harvested area, whereas Scenarios 2 and 3 are less restrictive and allow reducing the total harvested land. The approach suggests that Egypt’s domestic production of wheat and maize should be entirely substituted by imports. In addition, land currently utilized for such crops should be reallocated for more profitable and less water-demanding crops like vegetables and grapes.

From the optimization results (Table 25) is to see that Vegetables, in the form of frozen vegetables, are the most rewarding produces. The combination of good price and low water footprint is the driver in the optimization. Grapes, conversely, are linked to a good water export price cost, but play a secondary role in the optimization. It also can be seen that all optimization scenarios render improvements in the money trade balance, which in the current situation is negative.

The feasibility of the strategy in Egypt was assessed by limiting the total harvested area of vegetables and frozen vegetables export levels based on international cases. Such limits were translated into constrains along the optimization scenarios 2 and 3, leaving the scenario as a hypothetical aspiration unlikely achievable. The total harvested area of vegetables was limited to 10% of the arable land (China, Vietnam, Nepal, Philippines, and Lao in Table 49, Appendix 1). Maximum export of vegetables was limited to Belgium's levels (Table 50. Appendix 1). Some of the limitations of this strategy are: i) not considering the full cost structure, for instance net revenues or marginal costs of each crop/good exchange, and ii) not considering the economy of scale of crop production.

On the Sudanese side, the strategy aims at vacating sorghum's current irrigated land and using it for more profitable economic activities. Feasibility is straightforward, compared to Egypt's case, because the implementation area of yield improvements is small compared to the total cultivated sorghum area (less than 10%). Yield improvements should start in the mechanized rainfed areas, where technology, training and institutional organization already exists to certain degree.

Final thoughts

Introducing changes in cereal production in EBN, particularly wheat and sorghum, towards more sustainable and profitable agriculture, and economy is a complex issue. Crop selection looks critical for farm economies (Maliva & Missimer, 2012) and changes in cropping pattern should come along adequate substitution for both subsistence and profits. In Egypt, part of the produced wheat is used for food at the same farm-level (subsistence agriculture). Moreover, agriculture water is free of charge, and all the internally produced wheat is purchased by the government at a competitive price (McGill et al., 2015). There is, therefore, no visible reason to explore alternative products, other than conservational altruism. Some ideas on this regard are found in Abdin and Gaafar (2009), who claimed the modernization in irrigation techniques and changes in cropping patterns should be enforced, and any deviation from these rules causes farmers to be heavily penalized by the law. With regards to Sudan, pricing exists for agriculture water, and its regional variation seems to play a role in the government's and farmers' decisions on crop production (Ahmad, 2000; Mahgoub, 2014).

The allocation of agriculture water in a (perceived) water-scarce region should come along a sound socio-economic and environmental sustainability assessment. An economic study on water allocation in Egypt indicates that pricing for agriculture water is needed to maximize net social benefits among all water-demanding sectors (municipal, industry, agriculture). This is, nonetheless, unlikely to happen in times when farmers, who belong to the most water-demanding sector in Egypt, only pay for the cost of pumping water from below-grade tertiary level canals (Wichelns, 2002). A regional water allocation policy effort is needed to manage water, and cash and food crops production holistically, and enhance the overall corresponding socio-economic benefits out of it.

Finally, a comment on post-harvest losses shed some light on other possible ways to increase water availability. Most strategies deal with water savings and gains in the production of crops. However, little was said about processes after the harvesting season is over. Agriculture productivity, and the related impact of water availability, extends beyond the farm boundaries. "Post-harvest losses may reach 50% in some circumstances; eliminating such losses is equivalent to a 100% increase in crop production" (Libbert and Summer (2010) in Maliva and Missimer (2012)). Hence, plunging water use to a 50% is possible as well, keeping same production. Egypt's government, for instance, is currently working on the construction of silos (GIEWS, 2016), and is expected to reduce post-harvest losses from "about 40% to less than 5%" (Rady & Suif, 2016).

CONCLUSIONS

Review

The Eastern Nile Basin suffers from perceived water scarcity. Regional stakeholders and international experts claim North Africa, and EBN within it, ran out of water. Urbanization, food demand, and climate change pose significant challenges in the region. A closer scrutiny on the water balance and hydrologic processes in the region, however, shows water resources are abundant but they are regionally and temporally scattered. The largest input is in the form of rainfall, considered a non-conventional water resource. Less than 5% of the total water input is managed, and issues of sustainability and equity are visible when looking at the countries' exploitation of water resources. Water is sufficient for current and future uses, but it is mismanaged.

Some events in the last five years threatened the political stability in the region. The secession of South Sudan in 2011, and the beginning of the construction of the Grand Ethiopian Renaissance Dam in 2014 challenged the reigning calm particularly in Egypt and Sudan, the only two countries that benefit from a formal agreement on the use of the Nile waters.

This research builds on the idea that the water problems in ENB will not be solved with more technical knowledge. The literature on the Nile is rich in many aspects already. None of them, however, deals with opportunities for increasing freshwater availability to bridge the apparent supply-demand gap. Thus, focusing on agriculture, the largest land- and water-demanding sector, seven strategies were evaluated. They address irrigation practices, rainwater exploitation, yield improvements and changes in cropping patterns, with emphasis on wheat, maize, sorghum and sugarcane as the most important crops. Opportunities to increase the amount of water available between 1.6 and 10.9 BCM/year were found, either by savings or gains. The highest value of the range represents about 13% of the current Agreement on Nile Waters, and is equivalent ca. 1.9 million hectares of wheat and 1.3 million hectares of sorghum irrigated in Egypt and Sudan, respectively. Such relevant additional water could be used for underpinning economic development in Ethiopia and South Sudan, expanding agriculture land in Egypt and Sudan, introducing new water-dependent economic activities in all countries, or any synergistic combination of them.

Strategies face different challenges in term of implementation feasibility. Regulated Deficit Irrigation is a short-term alternative to reduce water demand that requires mostly training. Rainwater harvesting is highly promising, but ambitious, and experiences in the region are limited and only at experimental scale. Finally, actions on crop management, either by yield improvements or changes in cropping pattern, brought up the most revealing finding: the largest increase in water availability is the result of actions that have little to nothing to do with water resources, at least from a traditional standpoint on infrastructure or policy.

Strategies reveal challenges and opportunities. Water pricing and wheat subsidies in Egypt, smallholding farming in irrigated areas of Egypt and Sudan, as well as socio-economic conditions in Sudan, Ethiopia and South Sudan are the main challenges for successfully implementing any of the strategies. On the other hand, rainfed areas, for instance the mechanized sector in Sudan, offer opportunities to increase yields because some extent of technology and better practices are already in place. In addition to contributing to increase water availability, some strategies offer considerable potential to save land. This might eradicate the need of desert land reclamation and enable the allocation of fertile land for more profitable uses.

Limitations

The main contribution of this research is bringing to the discussion table issues that have not been envisioned previously. As a broad-scope, large scale work, limitations exist that need to be considered in follow-up steps. Some of them lie on the determination of irrigation efficiency, especially for Egypt; the yields and water productivity values taken from other regions of the world and applied in the study area; the linearity assumed for water use in short-season cultivars; the collection ratio for rainwater harvesting, the implementation of the water footprint, and the determination of costs for virtual water trade. In addition, the joint effect of implementing two or more strategies was not evaluated, thus the increase in water availability could be even larger than found (e.g. by changing crop patterns and implementing RDI together).

Next steps

This research should enable two next steps. On the one hand, the construction and implementation of a regional model. On the other hand, the setting out of complementary research to fill in the gaps found. The model could feed on the baseline and other figures assumed along this research. An agent-based model, accounting for both physical and behavioral process, is a good option whose main contribution would be confirming or refuting some of the conclusions drawn here, while, more interesting, assessing the possibilities of overlapping two or more strategies.

In terms of complimentary informational research, four lines of actions could be deployed. The first one should address data collection on flows in irrigation canals and drainage ditches of Egypt and Sudan. Even though not entirely relevant for the scope of this work, it resulted impossible to find such information along the literature review. Secondly, the feasibility of changes in current water-related policy should be evaluated to promote technology adoption, best agricultural practices implementation and, eventually, cropping changes. Thirdly, the environmental implications of the strategies should be assessed, particularly those dealing with water use reduction at farm level and rainwater harvesting. Finally, the global implications of changes in cropping pattern in the region, for instance in the wheat and vegetables market, where Egypt plays or might play a more significant role.

APPENDIX 1

Agriculture baseline

Table 29. Egypt's production for year 2013. Products with harvested area larger than 50 [1000 Ha] hectares. Total harvested area at 6753 [1000 Ha]. Source: database by FAOSTAT (2016).

Product	Harvested area [1000 Ha]	Production [1000 tons]	Average yield [tons/Ha]
Wheat	1419	9460	6.7
Forage and silage, clover	1200	53000	44.2
Maize	1030	7957	7.7
Rice, paddy	597	5724	9.6
Tomatoes	213	8534	40.1
Sugar beet	193	10044	51.9
Potatoes	160	4265	26.6
Sorghum	142	762	5.4
Seed cotton	140	435	3.1
Sugar cane	138	15780	114.1
Vegetables, fresh nes	127	699	5.5
Oranges	119	2886	24.3
Mangoes, mangosteens, guavas	92	835	9.1
Barley	83	130	1.6
Grapes	64	1389	21.6
Groundnuts, with shell	62	205	3.3
Olives	62	542	8.8
Watermelons	61	1895	31.3
Onions, dry	53	1903	36.0

Table 30. Sudan's production for year 2014. Products with harvested area larger than 50 [1000 Ha] hectares. Total harvested area at 17284 [1000 Ha]. Source: database by FAOSTAT (2016).

Product	Harvested area [1000 Ha]	Production [1000 tons]	Average yield [tons/Ha]
Sorghum	8378	6281	0.7
Millet	3151	1245	0.4
Sesame seed	2532	721	0.3
Groundnuts, with shell	2104	1767	0.8
Cow peas, dry	260	80	0.3
Wheat	223	473	2.1
Pulses, nes	102	90	0.9
Yams	80	165	2.1
Broad beans, horse beans, dry	75	160	2.1
Sugar cane	70	5807	83.1

Seed cotton	66	176	2.7
Melonseed	65	50	0.8
Sunflower seed	61	51	0.8

In Tables 31 to 33, the Estimated Annual Water Demand (ETa) follows this expression:

$$ETa[\frac{BCM}{year}] = Harvested\ area[1000\ Ha] \times Depth[mm] \times 10^{-5}$$

Table 31. Harvested area and irrigation requirement in Egypt's irrigated agriculture. Most relevant crops in terms of both harvested area and water demand. Water demand refers to Evapotranspiration only, irrigation efficiency not being included. Source: several as indicated.

Crop production in irrigated Egypt				Estimated annual water demand (ETa)			
Crop	Harvested area		Source	Depth [mm]	Source	Total [BCM]	% of total
	[1000 Ha]	% of total					
Wheat	1418.7	22	FAOSTAT Year 2013	324 472-587	Delta. Simons et al (2012) Wheat/Maize, Middle Egypt - Upper Egypt. Keith, Hussein, Mahdy (1998)	5.6	14
Forage and silage, clover [1]	1200.0	19		357 513-650	Delta. Simons et al (2012) Wheat/Maize, Middle Egypt - Upper Egypt. Keith, Hussein, Mahdy (1998)	5.2	13
Maize [2]	1030.3	16		526 472-587	Delta. Simons et al (2012) Wheat/Maize, Middle Egypt - Upper Egypt. Keith, Hussein, Mahdy (1998)	5.4	13
Rice, paddy	597.1	9		555	Simons et al (2012)	3.3	8
Tomatoes	212.9	3		1670	Abuarab, Shahien, and Hassan (2013)	3.6	9
Sugarcane	138.2	2		1940	Keith, Hussein, Mahdy (1998)	2.7	8
Total irrigated area	6333		AQUASTAT Year 2011	Total agriculture Eta		41.0	
Temporary crop	5535	*		Total agriculture withdrawal (AQUASTAT Year 2011). Considers water reuse		59.0	
Permanent crop	798	*		Ratio of reuse		1.44	

[1] Assumed as berseem based on Table 10 in http://www.fao.org/ag/agp/agpc/doc/counprof/egypt/egypt.html; [2] Reference reports no good representation;

Table 32. Harvested area and irrigation requirement in Sudan's irrigated agriculture. Most relevant crops in terms of both harvested area and water demand. Water demand refers to Evapotranspiration only, irrigation efficiency not being included. Source: several as indicated.

Crop production in irrigated Sudan				Estimated annual water demand (ETa)			
Crop	Harvested area [1000 Ha]	Harvested area % of total	Source	Depth [mm]	Source	Total [BCM]	% of total
Sorghum	678.7	43	AQUASTAT Year 2011	550	Brower and Heibloem (1986)	3.7	22
Wheat	254.6	16		809	Simons et al (2012)	1.3	8
Cotton	157.3	10		991	Simons et al (2012)	1.0	6
Fodder [1]	139.0	9		1846	Brower and Heibloem (1986)	1.7	10
Sugarcane	70.7	5		1940	Keith, Hussein, Mahdy (1998)	1.4	8
Total irrigated area	1563.0		AQUASTAT Year 2011	Total agriculture withdrawal (AQUASTAT Year 2011)		25.9	
Temporary crop	1563.0	*					
Permanent crop	0	*					

[1] Assumed as alfalfa;

Table 33. Harvested area and water requirement in Sudan's rainfed agriculture. Most relevant crops in terms of both harvested area and water demand. Water demand refers to Evapotranspiration only. Source: several as indicated.

Crop production in rainfed Sudan				Estimated annual water demand (ETa)			
Crop	Harvested area [1000 Ha]	Harvested area [% of total]	Source	Depth [mm]	Source	Total [BCM]	% of total
Sorghum	7698.9	49.0	AQUASTAT Year 2011 and FAOSTAT Year 2013	450	Brower and Heibloem (1986)	34.6	43.0
Groundnuts [4]	2059.0	13.1		500	Brower and Heibloem (1986)	10.3	12.8
Sesame	2532.0	16.1		850	Average 2011-2013 rainfall in Gadarif. 3rd International Conference Pulses,Oilseeds,Spices. UNECA-Africa Hall (2013)	21.5	26.7
Millet [5]	3151.2	20.0		450	Brower and Heibloem (1986)	14.2	17.6
Total non-irrigated area (fodder area N/A)	15720.6	98.2		Total agriculture use in non-irrigated areas (green water)		80.6	100.0

[4] Assumed as peanuts; [5] Assumed lowest value in the reference

Note: Cotton, Sugarcane and Vegetables assumed only in schemes; Fodder (barley) no data available outside schemes

In Table 34, own calculations for water productivity follow this formula:

$$WP\left[\frac{Kg}{m^3}\right] = Yield\left[\frac{tons}{Ha}\right] \times Area[1000\ Ha] \times Water\ demand\ [BCM]^{-1} \times 10^{-3}$$

For instance, Sudanese irrigated sorghum has a value of 0.26 Kg/m3 as a result of:

2.2 [tons/Ha] x 678.7 [1000 Ha] x 5.7^{-1} [BCM] x 10^{-3}

The value 5.7 BCM is the agriculture water withdrawal, equals to evapotranspiration over efficiency (ETa/efficiency), in this case 3.7 BCM/0.65. This formula considers that Gezira dominates irrigated sorghum production. The last factor is used for unit conversion.

Table 34. Yields and water productivity values for Egypt, Sudan, and other reference countries. Several sources as indicated.

Crop	Yield [tons/Ha]			Water productivity in irrigation [Kg/m3(Eta)]					Comment
	Reported by reference			Reported by reference			Own calculations		
	General[0]	Egypt[1]	Sudan[1]	General[0]	Egypt[2]	Sudan[2]	Egypt	Sudan	
Wheat	average (3); max average (9); max (15)	6.7	2.1	1.0 - 1.2 max 2.2	1.47 - 1.51*	-	1.7	0.26	*Kg/m3 (Ta) Ta: transpired water
Maize	average (5.3) USA (10) Argentina/China (4.5) Less industrialized countries (1 - 2)	9.6	-		0.83 - 1.2*	-	1.1	-	*Not entirely representative, according to reference
Sorghum	Rainfed: USA (4.7) Argentina/China (4.3) Ethiopia (1.0 - 1.5) Irrigation: (5 - 7), max (12)	-	Average 0.7 Irrigated[3] 1.5 Gezira[3] 2.2	range (1.0 - 1.5) Texas (3.0 - 3.6)	-	-	-	0.26	
Sugarcane	range (30 - 90)	5.5	Average 83.1 Delta lands (Khartoum) 92.7[3]	Biomass (3.5 - 5.5)	-	-	0.2	3.0 (average)	

[0] Steduto, Hsiao, Fereres, and Raes (2012); [1] FAOSTAT Database; [2] Simons (2012); [3] FAO-AQUASTAT

Implementation and results

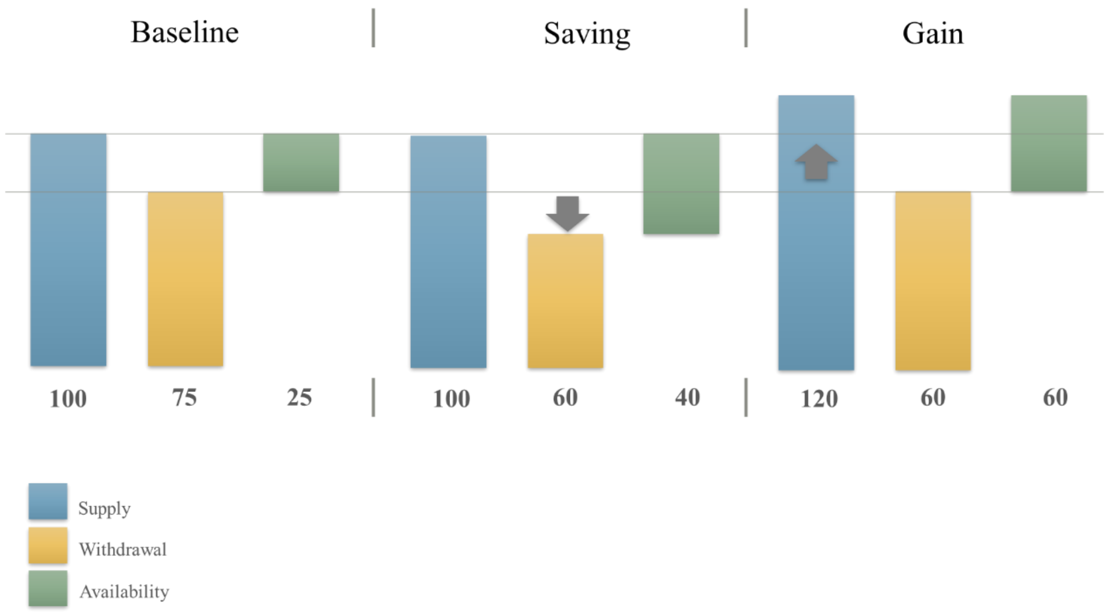

Figure 17. Rationale for increasing water availability. Numbers stand for referential purposes only. In the baseline, there are 100 units of supply (blue box) and 75 units of withdrawal (orange box), the water available for additional purposes being 25 units (green box). The green box can be enlarged by either reducing withdrawals, developing more supplies, or any combination of both.

Below is the supporting material for the assumptions made along the development of strategies.

Table 35. Efficient irrigation in countries comparable to Egypt. Selection based on Gross Domestic Product (GDP) per capita, average precipitation and agriculture share in GDP. Countries with GDP per capita less than 1.20 the value of Egypt for year 2014 (2654 USD2010). Shaded values of GDP per capita are at +- 20% the value of Egypt. Shaded precipitation values shaded are less than 100 mm. Egypt has the lowest value of precipitation in the World Bank list. Shaded agriculture share values are between 6% and 16%. Egypt is ca. at the center of the range. Countries without no records of irrigation were eliminated from the list (Bangladesh, West Bank, Micronesia, Vanuatu, Congo, Marshall Islands). Sources: World Bank, FAOSTAT, and AQUASTAT.

Country Name	GDP per capita (constant 2010 US$)	Average precipitation in depth (mm per year)	Agriculture, value added (% of GDP)	Agricultural land (1000 Ha)	Cultivated area (1000 Ha)	Irrigated area (1000 Ha)	Sprinkler+Localized Irrigation (1000 Ha)	Efficient irrigation respect to irrig. area (%)
Zimbabwe	830	657	14.0	16200.0	4100.0	123.9	123.5	99.6%
Senegal	1011	686	15.8	8918.0	3318.0	69.0	0.0	0.0%
Lesotho	1227	788	8.0	2252.1	252.1	0.1	0.0	0.0%
Mauritania	1338	92	20.8	39711.0	461.0	22.8	0.0	0.0%
Zambia	1617	1020	9.6	23736.0	3736.0	55.4	23.2	41.9%
Moldova	1980	450	15.5	2461.0	2111.0	228.3	160.0	70.1%
Honduras	2279	1976	13.8	3235.0	1475.0	81.6	0.0	0.0%
Bolivia	2317	1146	13.0	37670.0	4670.0	297.2	21.3	7.2%
Philippines	2530	2348	11.3	12440.0	10940.0	1879.0	15.4	0.8%
Bhutan	2531	2200	17.7	519.6	112.6	27.7	0.0	0.0%
Nigeria	2548	1150	20.2	70800.0	40500.0	218.8	0.1	0.0%
Egypt, Arab Rep.	**2654**	**51**	**11.1**	3761.0	3761.0	3610.0	880.0	24.4%
Guatemala	2991	1996	11.4	3720.7	2036.0	312.1	113.5	36.4%
Swaziland	3061	788	6.3	1222.0	190.0	44.8	24.0	53.4%
Ukraine	3123	565	11.8	41275.0	33420.0	731.4	0.0	0.0%
Morocco	3143	346	13.0	30401.0	9401.0	1341.0	414.0	30.9%
Source	World Bank	World Bank	World Bank	World Bank	FAOSTAT	AQUASTAT	AQUASTAT	AQUASTAT

Table 36. Efficient irrigation in countries comparable to Egypt. Countries with more than 1 million hectares of area actually irrigated. Selection based on irrigated area, area equipped for irrigation, and area equipped for efficient irrigation. Sources: World Bank, FAOSTAT, and AQUASTAT

Country	GDP per capita (constant 2010 US$)	Area equipped for irrigation (1000 Ha)	Year	Irrigated area (1000 Ha)	Year	Area equipped for sprinkler+localized (1000 Ha)	Year	Efficient irrigation respect to area eq. for irrig. (%)
India	1699	66334	2008	62286	2008	2024	2004	3%
China	6033	69860	2014	58449	2014	3601	2006	5%
United States	50662	26708	2012	22590	2012	14630	2010	55%
Iran, Islamic Rep.	5937	8700	2009	6423	2006	700	2003	8%
Vietnam	1596	4585	2005	4585	2005	1	2005	0%
Brazil	11705	5400	2010	4454	2006	2781	2010	51%
Turkey	11246	5340	2012	4206	2004	650	2012	12%
Egypt, Arab Rep.	2654	**3610**	**2010**	**3422**	**2002**	**880**	**2010**	**24%**
Spain	29595	3470	2011	3093	2009	2441	2011	70%
Italy	33458	4004	2013	2866	2013	1552	2007	39%
Japan	44386	2500	2010	2600	2006	490	2010	20%
Australia	54233	2546	2006	2378	2013	715	2006	28%
Argentina	12128	2357	2011	2162	2011	408	2011	17%
Turkmenistan	6591	1991	2006	1991	2006	0	2006	0%
Philippines	2530	1879	2006	1879	2006	15	2006	1%
Peru	5861	2580	2012	1808	2012	218	2012	8%
France	41050	2811	2013	1424	2013	2528	2007	90%
South Africa	7604	1670	2012	1399	2008	1285	2012	77%
Azerbaijan	6123	1425	2010	1358	2010	607	2010	43%
Morocco	3143	1458	2011	1341	2012	414	2011	28%
Syrian Arab Republic	2184	1341	2010	1210	2000	298	2010	22%
Saudi Arabia	21031	1620	2004	1191	1999	914	2004	56%
Kazakhstan	10575	1200	2010	1182	2010	41	2010	3%
Chile	14480	1109	2007	1094	2007	307	2007	28%
Kyrgyz Republic	1004	1023	2012	1021	2011	0	2005	0%
Algeria	4701	1177	2012	1012	2012	490	2012	42%
Source	World Bank	AQUASTAT	AQUASTAT	AQUASTAT	AQUASTAT	AQUASTAT	AQUASTAT	AQUASTAT

Table 37. Efficient irrigation in countries comparable to Sudan. Selection based on Gross Domestic Product (GDP) per capita, average precipitation and agriculture share in GDP. Countries with GDP per capita less than 1.20 the value of Sudan for year 2014 (1703 USD2010). Shaded values of GDP per capita are at +- 20% the value of Sudan. Shaded values of precipitation are at +- 20% the value of Sudan. Shaded agriculture share values are between 25% and 35%. Sudan is ca. at the center of the range. Countries without sorghum yield for either 2013 or 2014 were removed from list (Nepal, Comoros, Cambodia, Solomon Islands, Lao PRD, Kiribati, Djibouti, Vietnam). Egypt is out of range in terms of GDP per capita. However, the country lies in the basin, has low values of precipitation and relatively high sorghum yield. Sources: World Bank, FAOSTAT, and AQUASTAT.

Country Name	GDP per capita (constant 2010 US$)	Average precipitation in depth (mm per year)	Agriculture, value added (% of GDP)	Agricultural land (1000 Ha)	Sorghum yield (Tons/Ha)	Cultivated area (1000 Ha)	Irrigated area (1000 Ha)	Sprinkler+Localized Irrigation (1000 Ha)
Niger	386	151	36.5	44782	0.37	16000.0	218.8	0.0
Madagascar	408	1513	25.1	41415	0.57	4120.0	550.0	2.4
Mozambique	493	1032	25.5	49950	0.46	5950.0	40.1	0.0
Malawi	495	1181	30.8	5790	0.96	3940.0	54.0	48.6
Somalia	552	282	..	44125	0.85	1125.0	50.0	0.0
Burkina Faso	624	748	34.2	12300	1.04	6300.0	25.3	4.3
Rwanda	660	1212	33.1	1843	1.44	1432.0	2.0	0.0
Uganda	662	1180	25.3	14415	0.80	9100.0	8.7	2.4
Tanzania	813	1071	31.5	39650	3.74	15650.0	184.3	0.0
Mali	864	282	40.3	41201	0.87	6561.0	139.9	0.2
Chad	966	322	52.6	49935	0.88	4935.0	26.2	3.8
Kenya	1101	630	30.2	27630	0.76	6330.0	135.9	42.6
Pakistan	1115	494	25.0	36280	0.60	31280.0	19270.0	0.0
Mauritania	1338	92	20.8	39711	0.47	461.0	22.8	0.0
Yemen, Rep.	1340	167	..	23546	0.87	1546.0	454.3	0.5
Cote d'Ivoire	1409	1348	22.4	20600	0.32	7400.0	32.5	0.0
Zambia	1617	1020	9.6	23736	0.65	3736.0	55.4	23.2
Ghana	1671	1187	22.4	15700	1.14	7400.0	30.3	6.3
India	1699	1083	17.4	180280	0.85	170000.0	62286.0	2024.2
Sudan	**1703**	**250**	**29.2**	**108815**	**0.64**	17365.0	993.5	0.0
Uzbekistan	1749	206	18.8	26770	12.73	4770.0	3700.0	0.0
Nicaragua	1782	2280	19.1	5065	1.84	1790.0	144.1	0.0
Papua New Guinea	1784	3142	37.8	1190	4.80	1000.0	0.0	0.0
Moldova	1980	450	15.5	2461	2.96	145.0	228.3	160.0
Syrian Arab Republic	2184	252	17.9	13921	2.37	5733.0	1210.0	298.0
Egypt, Arab Rep.	2654	51	11.1	3761	5.38	3761.0	3610.0	880.0
Source	World Bank	World Bank	World Bank	World Bank	FAOSTAT	AQUASTAT	AQUASTAT	AQUASTAT

Strategy on irrigation efficiency

Description of formulae in Table 15

SW, GW and WW: surface water, groundwater, and wastewater

<u>For Current Situation:</u>

$$Evapotranspiration\ = Agriculture\ withdrawal - Return\ flow\ to\ SW\ and\ GW$$

$$Evaporation = 20\%\ Evapotranspiration$$

$$Transpiration = Evapotranspiration - Evaporation$$

$$Local\ efficiency = \frac{Transpiration}{Agriculture\ withdrawal} \times 100$$

$$Overall\ efficiency = \frac{Transpiration}{Agriculture\ withdrawal - Total\ reuse} \times 100$$

$$Reuse\ ratio = \frac{Total\ reuse}{Return\ flow\ to\ SW\ and\ GW}$$

<u>For Hypothetical future situation</u>

Transpiration: constant, equals to Current Situation

$$Evaporation = Transpiration \times \frac{10\%}{90\%}$$

$$Evapotranspiration = Transpiration + Evaporation$$

$$Agriculture\ withdrawal = \frac{Transpiration}{Local\ efficiency}$$

$$Return\ flow\ to\ SW\ and\ GW = Agriculture\ withdrawal - Evapotranspiration$$

$$Total\ reuse = Reuse\ ratio \times Return\ flow\ to\ SW\ and\ GW$$

For Reuse agric SW and GW, same shares as in the Current Situation were considered

Description of formulae in Results (Table 38)

Curr eff: current efficiency

Imp eff: improved efficiency

Coverage: portion or fraction of irrigated land associated to improved performance (sprinkler)

Current coverage: 10% in Egypt; 0% in Sudan

For the current situation, Water Demand has been computed as follows:

$$Water\ Demand_{cp} = ETa \times \left(\frac{coverage_{cp}}{imp\ effic} + \frac{(1 - coverage_{cp})}{effic} \right)$$

For the improved performance, Water Demand follows this formula

$$Water\ Demand_{ip} = ETa \times \left(\frac{coverage_{ip}}{imp\ effic} + \frac{(1 - coverage_{ip})}{effic} \right)$$

$$Water\ increase = Water\ Demand_{cp} - \ Water\ Demand_{ip}$$

Table 38. Results of strategy on irrigation efficiency - Expanded version.

Efficient irrigation coverage at 28% (reference Morocco)

Implementation region			Current performance		Improved performance		Water saving [BCM]	
Country	Irrigation area	Crops	Efficiency	Water demand [BCM]	Efficiency	Water demand [BCM]		
Egypt	All irrigated areas	Wheat	68%	8.1	86%	7.8	0.3	0.8
		Maize		7.8		7.5	0.3	
		Sugarcane		3.9		3.7	0.2	
Sudan	All irrigated areas	Sorghum	65%	5.7	80%	5.4	0.3	05
		Wheat		2.1		2.0	0.1	
		Sugarcane		2.1		2.0	0.1	
Total values				29.7		28.4	**1.3**	

Efficient irrigation coverage at 56% (reference India)

Implementation region			Current performance		Improved performance		Water increase [BCM]	
Country	Irrigation area		Efficiency	Water demand [BCM]	Efficiency	Water demand [BCM]		
Egypt	All irrigated areas	Wheat	68%	8.1	86%	7.3	0.8	1.9
		Maize		7.8		7.1	0.8	
		Sugarcane		3.9		3.5	0.4	
Sudan	All irrigated areas	Sorghum	65%	5.7	80%	5.1	0.6	1.0
		Wheat		2.1		1.8	0.2	
		Sugarcane		2.1		1.9	0.2	
Total values				30.1		26.7	**3.0**	

Strategy on Regulated Deficit Irrigation

Description of formulae in Results (Table 39)

WP: water productivity

Subscripts *cp* and *ip* refer to current performance and improved performance, respectively

Coverage: portion or fraction of irrigated land associated to the improved performance

For current performance:

$$RDI\ area = Total\ area \times coverage$$

$$ETa\ at\ RDI\ area = Total\ ETa \times coverage$$

$$Production\ at\ RDI\ area = Production \times coverage$$

For improved performance:

$$Area = \frac{Current\ performance\ area}{Yield\ drop}$$

$$ETa = ETa\ at\ RDI\ area \times \frac{WP_{cp}}{WP_{ip}}$$

$$Yield_{ip} = Yield_{cp} \times Yield\ drop$$

$$Water\ increase = \frac{(ETa_{cp} - ETa_{ip})}{effic}$$

effic: irrigation efficiency. 68% for Egypt and 65% for Sudan

$$Land\ need = Area_{ip} - RDI\ area$$

Table 39. Results of strategy on Regulated Deficit Irrigation - Expanded version.

Regulated Deficit Irrigation. Implementation coverage at 28% (reference Morocco)

Implementation region			Current performance									Improved performance						
Country	Irrigation area	Crop	Tot. Area [1000 Ha]	Tot. ETa [BCM]	Yield [tons/Ha]	WP [Kg/m3 ETa]	Production [1000 tons]	RDI area [1000 Ha]	Eta at RDI area [BCM]	Production at RDI area [1000 tons]	Action	Yield drop	WP [Kg/m3 ETa]	Area [1000 Ha]	ETa [BCM]	Yield [tons/Ha]	Water increase [BCM]	Land need [1000 Ha]
Egypt	All irrigated areas	Wheat	1419	5.6	6.7	1.53	9460	595.9	2.4	3973	Deficit irrigation at 70% (Karrou et al. 2012)	91%	1.86	654.8	1.3	6.1	0.4	39
		Maize	1030	5.4	7.7	1.30	7957	432.7	2.3	3342		91%	1.83	475.5	1.1	7.0	0.6	29
		Sugarcane	138	2.7	114.1	5.88	15780	58.1	1.1	6628	Deficit at 75% at tillering plus furrow irrigation (Kirda, 2002)	90%	7.06	64.5	0.6	102.7	0.2	4
Sudan	All irrigated areas	Wheat	255	1.3	2.1	0.35	535	106.9	0.6	225	Deficit irrigation at 70% (Karrou et al. 2012)	91%	1.86	117.5	0.1	1.9	0.5	7
		Sugarcane	71	1.4	92.7	4.23	6554	29.7	0.6	2753	Deficit at 75% at tillering plus furrow irrigation (Kirda, 2002)	90%	5.08	33.0	0.3	83.4	0.1	2
																	1.8	**81.4**

Regulated Deficit Irrigation. Implementation coverage at 56% (reference India)

Implementation region			Current performance									Improved performance						
Country	Irrigation area	Crop	Tot. Area [1000 Ha]	Tot. ETa [BCM]	Yield [tons/Ha]	WP [Kg/m3 ETa]	Production [1000 tons]	RDI area [1000 Ha]	Eta at RDI area [BCM]	Production at RDI area [1000 tons]	Action	Yield drop	WP [Kg/m3 ETa]	Area [1000 Ha]	ETa [BCM]	Yield [tons/Ha]	Water increase [BCM]	Land need [1000 Ha]
Egypt	All irrigated areas	Wheat	1419	5.6	6.7	1.53	9460	794.5	3.1	5298	Deficit irrigation at 70% (Karrou et al. 2012)	91%	1.86	873.1	2.6	6.1	0.8	79
		Maize	1030	5.4	7.7	1.30	7957	577.0	3.0	4456		91%	1.83	634.1	2.2	7.0	1.3	57
		Sugarcane	138	2.7	114.1	5.88	15780	77.4	1.5	8837	Deficit at 75% at tillering plus furrow irrigation (Kirda, 2002)	90%	7.06	86.0	1.3	102.7	0.4	9
Sudan	All irrigated areas	Wheat	255	1.3	2.1	0.35	535	142.6	0.7	299	Deficit irrigation at 70% (Karrou et al. 2012)	91%	1.86	156.7	0.1	1.9	0.9	14
		Sugarcane	71	1.4	92.7	4.23	6554	39.6	0.8	3670	Deficit at 75% at tillering plus furrow irrigation (Kirda, 2002)	90%	5.08	44.0	0.6	83.4	0.2	4
																	3.6	**162.7**

Strategy on Evaporation Component of Evapotranspiration

Evaporation fraction for Egypt's wheat is the result of a weighted average computed as follows:

$$Evap\ fraction = 65\%\times 0.16 + 35\%\times 0.50$$

The value 65% corresponds to the share of the Delta with respect to the total agricultural land. The factor 0.16 is the evaporation fraction for the Delta, according to Simons et al. (2012); 0.50 is the fraction assumed for the Middle/Upper Nile, where irrigation is less efficient. The evaporation fraction for maize in Egypt was taken from Simons et al. (2021), as well. Due to lack of specific data, wheat and sorghum in Sudan were assumed having same evaporation fraction as Egyptian maize. For sugarcane, the rational is different. Table 40 and Figure 18 were built using findings from two papers, namely Sandhu et al. (1980) and Millard (1974). The improvement in Water Productivity (WP) is assumed constant for yields either greater than 129 tons/Ha or lower than 75 tons/Ha. In between, a linear-law variation was considered.

.Table 40. Water Productivity improvement vs Yield. Source: own computations.

Yield [tons/Ha]	Improvement in WP [%]
56	81
75	81
93	**60**
114	**36**
129	19
158	19

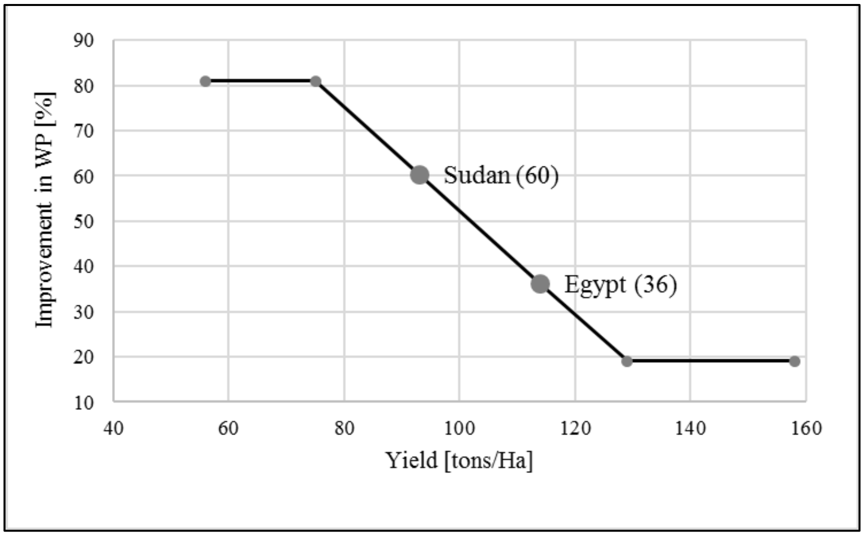

Figure 18. Relation curve for Yield and Improvement in Water Productivity. Source: own computations.

Description of formulae in Results (Table 40)

Computations of ETa for the improved performance follow two different approaches.

For Egypt's wheat and maize

$$ETa_{ip} = ETa_{cp} \times ((1 - coverage) + coverage \times (1 - Evap\ fraction\ drop))$$

For other crops:

$$ETa_{ip} = ETa_{cp} \times ((1 - coverage) + coverage \times \left(1/WUE_{improvement}\right))$$

Evaporation fraction drop for wheat and maize in Egypt is 0.50. Values of Water Use Efficiency (WUE) improvement for sugarcane are 36% and 60% for Egypt and Sudan, respectively. For Sudanese sorghum and wheat, the WUE improvement is 30%.

$$Water\ increase = ETa_{cp} - \ ETa_{ip}$$

Table 41. Water increase by the implementation of strategies on evaporation fraction of Evapotranspiration.

Reduction in Evaporation Fraction. Implementation coverage at 28% (reference Morocco)

Implementation region		Current performance		Improved performance		Water increase [BCM]
Country	Crop	ETa [BCM]	Evap fraction	Action	ETa [BCM]	
Egypt	Wheat	5.6	28%	50% mulching corevage reduces evaporation fraction by 50% (Ding et al, 2013, and by Qin, Hu & Oenema, 2015)	5.4	0.2
	Maize	5.4	30%		5.2	0.2
	Sugarcane	2.7	-	WP improved by 36% (Sandhu, Prihar, and Khera, 1980, and Millard, 1974)	2.5	0.2
Sudan	Sorghum	3.7	30%	WUE improved by 25% for sorghum and wheat (Qin, Hu, & Oenema, 2015)	3.5	0.2
	Wheat	1.3	30%		1.3	0.1
	Sugarcane	1.4	-	WP improved by 60% (Sandhu, Prihar, and Khera, 1980, and Millard, 1974)	1.3	0.1
						1.0

Reduction in Evaporation Fraction. Implementation coverage at 56% (reference India)

Implementation region		Current performance		Improved performance		Water increase [BCM]
Country	Crop	ETa [BCM]	Evap fraction	Action	ETa [BCM]	
Egypt	Wheat	5.6	28%	50% mulching reduces evaporation fraction by 50% (Ding et al, 2013, and by Qin, Hu & Oenema, 2015)	5.2	0.4
	Maize	5.4	30%		5.0	0.5
	Sugarcane	2.7	-	WP improved by 20% (Sandhu, Prihar, and Khera, 1980, and Millard, 1974)	2.4	0.3
Sudan	Sorghum	3.7	30%	WUE improved by 25% for sorghum and wheat (Qin, Hu, & Oenema, 2015)	3.3	0.5
	Wheat	1.3	30%		1.2	0.2
	Sugarcane	1.4	-	WP improved by 60% (Sandhu, Prihar, and Khera, 1980, and Millard, 1974)	1.1	0.3
						2.1

Strategy on Rainfall Explotation

Description of formulae in Results (Table 43)

Values extracted from Water Accounting (wateraccounting.org) for the corresponding sub-basin. Total Rainfall ET taken from Resource Base Sheet. Values about Utilized Land Use (ULU) taken from sheet Evapotranspiration.

$$E \ = ET - T$$

Area of Sub-basin: value taken from FAO´s product Basin and Sub-Basin Delineation in the Nile Basin (http://www.fao.org/nr/water/faonile/)

The Shrubland area was computed as proportional to Shrubland Evapotranspiration as follows:

$$Shrubland\ area = Sub - basin\ area \times \frac{Total\ Shrubland\ ET}{Total\ rainfall\ ET}$$

Precipitation taken from Water Accounting´s special maps 2005-2010, Precipitation

RWH ratio: portion of total rainfall that is harvested and stored. Value according to Table 42.

Table 42. Rainwater collection ratio for different annual precipitation values. Built upon findings in Basán Nickisch et al. (2016) and Mekuria et al. (2015).

Precipitation [mm]	RWH ratio [%]
≤ 300	40%
300 - 700	50%
≥ 700	60%

$$Water\ gains = Area \times Precip \times RWH$$

Table 43. Results of strategy on Rainfall Exploitation - Expanded version.

Sub-Basin	Total rainfall ET [BCM]	ULU ET [BCM]				Area [1000 Ha]		Improved performance					Water gains [BCM]
		Total	Land use 'Shrubland'			Sub-basin	Shrubland	Action	Country	Area [1000 Ha]	Precip [mm]	RWH ratio	
			Total	T share	E share								
Blue Nile	224	86	76	46	31	30820	10498	New 'schemes' in flat areas for rainwater harvesting system and groundwater recharge (INTA 2014 and Mekuria et al, 2015). Schemes size between 100 and 200 thousand hectares according to largest irrigation schemes in Sudan (except Gezira) as found in FAO-AQUASTAT, 2015	Sudan	200	300	40%	0.24
									Ethiopia	200	800	60%	0.96
									Ethiopia	200	1000	60%	1.20
Baro-Akobo-Sobat	233	148	127	70	57	24778	13516		South Sudan	200	1000	60%	1.20
									South Sudan	200	700	60%	0.84
Lower White Nile	142	119	82	32	50	22094	12759		Sudan	200	500	50%	0.50
													4.9

Strategy on Yield Improvements

Description of formulae in Results (Table 44)

$$Area_{ip} = Area_{cp} \times \left((1 - coverage) + \frac{Yield_{cp}}{Yield_{ip}} \times coverage \right)$$

$$ETa_{ip} = ETa_{cp} \times \frac{Area_{ip}}{Area_{cp}}$$

$$Water\ savings = \frac{(ETa_{cp} - ETa_{ip})}{effic}$$

effic: irrigation efficiency. 68% for Egypt and 65% for Sudan

$$Land\ savings = Area_{cp} - Area_{ip}$$

Table 44. Results of strategy on Yield Improvements - Expanded version.

Minor changes in crop patterns. Implementation coverage at 28% (reference Morocco)

Implementation region			Current performance			Improved performance					
Country	Irrigation area	Crop	Area [1000 Ha]	ETa [BCM]	Yield [tons/Ha]	Action	Yield [tons/Ha]	Area [1000 Ha]	ETa [BCM]	Water savings [BCM]	Land savings [1000 Ha]
Egypt	All irrigated areas	wheat	1419	5.6	6.7	Maximum average of 9 tons/Ha (Steduto, Hsiao, Fereres, and Raes, 2012)	9.0	1264	5.2	0.5	103
		maize	1030	5.4	7.7	Maximum in USA (Steduto, Hsiao, Fereres, and Raes, 2012)	10.0	932	5.1	0.5	66
Sudan	All irrigated areas	sorghum	679	3.7	2.2	Intermediate yield between values of Moldova, Syrian Arabic Republic (FAOSTAT, 2014) and Egypt	4.0	550	3.3	0.7	86
		wheat	255	1.3	2.1	Intermediate yield between levels of Uzbekistan (FAOSTAT, 2014) and Egypt	5.5	188	1.1	0.4	44
		sugarcane	71	1.4	92.7	Intermediate yield between levels of Zambia (FAOSTAT, 2014) and Egypt	108.0	66	1.3	0.1	3
										2.3	**301.0**

Minor changes in crop patterns. Implementation coverage at 56% (reference India)

Implementation region			Current performance			Improved performance					
Country	Irrigation area	Crop	Area [1000 Ha]	ETa [BCM]	Yield [tons/Ha]	Action	Relative Yield	Area [1000 Ha]	ETa [BCM]	Water savings [BCM]	Land savings [1000 Ha]
Egypt	All irrigated areas	wheat	1419	5.6	6.7	Maximum average of 9 tons/Ha (Steduto, Hsiao, Fereres, and Raes, 2012)	9.0	1213	4.8	1.2	206
		maize	1030	5.4	7.7	Maximum in USA (Steduto, Hsiao, Fereres, and Raes, 2012)	10.0	899	4.7	1.0	131
Sudan	All irrigated areas	sorghum	679	3.7	2.2	Intermediate yield between values of Moldova, Syrian Arabic Republic (FAOSTAT, 2014) and Egypt	4.0	508	2.8	1.4	171
		wheat	255	1.3	2.1	Intermediate yield between levels of Uzbekistan (FAOSTAT, 2014) and Egypt	5.5	166	0.9	0.7	88
		sugarcane	71	1.4	92.7	Intermediate yield between levels of Zambia (FAOSTAT, 2014) and Egypt	108.0	65	1.3	0.2	6
										4.5	**602.0**

Strategy on minor changes in cropping pattern

Description of formulae in Results (Table 45)

$Area_{ip} = Area_{cp} \times (1 - coverage \times \frac{Yield_{ip}}{Yield_{cp}} + coverage)$ If the result is negative, then.

$Area_{ip} = Area_{cp} \times coverage$

$$ETa_{ip} = \frac{ETa_{cp}}{Area_{cp}} \times \left(coverage \times Area_{cp} \times coef + \left(Area_{ip} - coverage \times Area_{cp} \right) \right)$$

Coef: 0.75 for wheat and maize (shorter growing season); 1.00 for sorghum (no change in growing season length)

$$Water\ savings = \frac{(ETa_{cp} - ETa_{ip})}{effic}$$

effic: irrigation efficiency. 68% for Egypt and 65% for Sudan

$Land\ savings = Area_{cp} - Area_{ip}$

Table 45. Results of strategy on Minor Changes in Cropping Pattern - Expanded version.

Minor changes in crop patterns. Implementation coverage at 28% (reference Morocco)

Implementation region			Current performance			Improved performance				Water increase [BCM]	Land savings [1000 Ha]
Country	Irrigation area	Crop	Area [1000 Ha]	ETa [BCM]	Yield [tons/Ha]	Action	Yield [tons/Ha]	Area [1000 Ha]	ETa [BCM]		
Egypt	All irrigated areas	wheat	1419	5.6	6.7	Short-season wheat (e.g. Botticelli). Sowing January	8.0	1300	4.9	1.0	119
		maize	1030	5.4	7.7	90-days maize, same yield (e.g. hybrid by Seed Co)	7.7	1030	5.1	0.6	0
Sudan	All irrigated areas	sorghum	679	3.7	2.2	Average under irrigation (Steduto, Hsiao, Fereres, and Raes, 2012)	4.0	445	2.9	1.3	679
		wheat	255	1.3	2.1	Short-season wheat (e.g. Botticelli). Sowing January	8.0	107	0.2	1.8	148
										4.7	**435.1**

Minor changes in crop patterns. Implementation coverage at 56% (reference India)

Implementation region			Current performance			Improved performance				Water increase [BCM]	Land savings [1000 Ha]
Country	Irrigation area	Crop	Area [1000 Ha]	ETa [BCM]	Yield [tons/Ha]	Action	Yield [tons/Ha]	Area [1000 Ha]	ETa [BCM]		
Egypt	All irrigated areas	wheat	1419	5.6	6.7	Short-season wheat (e.g. Botticelli). Sowing January	8.0	1260	4.2	2.1	159
		maize	1030	5.4	7.7	90-days maize, same yield (e.g. hybrid by Seed Co)	7.7	1030	4.7	1.1	0
Sudan	All irrigated areas	sorghum	679	3.7	2.2	Average under irrigation (Steduto, Hsiao, Fereres, and Raes, 2012)	4.0	368	2.0	2.6	679
		wheat	255	1.3	2.1	Short-season wheat (e.g. Botticelli). Sowing January	8.0	143	0.6	1.2	112
										7.0	**581.7**

Strategy on major changes in cropping pattern

In Tables 46 to 48, the computations of Water Used, Water Exported, and Water Imported follow this expression:

$$Water\left[\frac{BCM}{year}\right] = Production[tons]\times Footprint\left[\frac{m^3}{ton}\right]\times 10^{-9}$$

Other computations follow these expressions:

$$\%\ value = \frac{Value[1000\ USD]}{Total\ merchandise\ trade\ [1000\ USD]}\times 100$$

$$Water\ cost = \frac{Value\ [1000\ USD]}{Water\ used\ (or\ imported\_exported)[BCM]}\times 10^{-6}$$

Table 46. Crop production in Egypt – Expanded version (FAOSTAT, 2013). Top-ten crops ordered by harvested area. The crop footprint was taken from Chapagain & Hoekstra (2004).

		Production			Use/Trade
Product	FAO code	Production [tons]	Footprint ^{4} [m3/tonne]	Water used [BCM]	
Wheat	15	9460229	930	8.80	main additional import
Forage and silage, clover	640	53000040	204	10.81	domestic demand
Maize	56	7956587	1031	8.20	main additional import
Rice, paddy	27	5724090	1565	8.96	main export
Tomatoes	388	8533811	162	1.38	main export
Sugar beet	157	10044257	188	1.89	domestic demand
Potatoes	116	4265182	308	1.31	main export
Sorghum	83	761628	909	0.69	additional import
Seed cotton	328	434994	3028	1.32	support textile industry
Sugar cane	156	15780000	140	2.21	main export as refined sugar

Table 47. Egypt's top-ten imported produces in 2013 – Expanded version. Wheat and maize rank first in terms of market exchange share. Soybeans and bean-related produces are the most expensive in terms of water footprint. Source: FAOSTAT (2016).

Exports							
Product	FAO code	Quantity [tons]	Value [1000 USD]	% total	Water		
					Footprint [m3/ton]	Exported [BCM]	Cost [USD/m3]
Oranges	490	1108895	493063	1.7%	602 [4]	0.67	0.74
Crude materials	1293	0	297367	1.0%	*	*	*
Cheese, processed	907	52220	234490	0.8%	3178 [3]	0.17	1.41
Potatoes	116	427907	205901	0.7%	308 [4]	0.13	1.56
Onions, dry	403	329736	202553	0.7%	258 [4]	0.09	2.38
Food prep nes	1232	86005	202537	0.7%	*	*	*
Rice – total (Rice milled equivalent)	30	335774	199318	0.7%	1673 [1]	0.56	0.35
Grapes	560	88144	183357	0.6%	537 [4]	0.05	3.87
Sugar refined	164	237634	174127	0.6%	1782 [1]	0.42	0.41
Vegetables, frozen	473	104116	159957	0.6%	322 [1]	0.03	4.77
Total Merchandise Trade			28492100				

[1]Mekonnen & Hoekstra,2011; [2]Brower and Heibloem (1986); [3]http://waterfootprint.org/; [4]Chapagain & Hoekstra, 2004

Table 48. Egypt's top-ten exported produces in 2013- Expanded version. Oranges rank first in terms of market exchange share and exported water. Potatoes, rice and sugarcane are among Egypt's most harvested and most water demanding crops. Grapes and frozen vegetables are the best paid produces in terms of water footprint. Source: FAOSTAT (2016).

Import							
Product	FAO code	Quantity [tons]	Value [1000 USD]	% total	Water		
					Footprint [m3/ton]	Imported [BCM]	Cost [USD/m3]
Wheat	15	10288434	2715936	4.7%	1334 [4]	13.7	0.20
Maize	56	5771770	1984982	3.4%	909 [4]	5.2	0.38
Soybeans	236	1571715	994061	1.7%	1789 [4]	2.8	0.35
Meat, cattle, boneless (beef & veal)	870	181079	830799	1.4%	15415 [3]	2.8	0.30
Oil, sunflower	268	446573	638159	1.1%	6792 [3]	3.0	0.21
Oil, palm	257	707124	624795	1.1%	1098 [3]	0.8	0.80
Cake, soybeans	238	1504821	541045	0.9%	1179 [3]	1.8	0.30
Tea	667	104697	307323	0.5%	9205 [4]	1.0	0.32
Sugar Raw Centrifugal	162	959101	291317	0.5%	*	*	*
Broad beans, horse beans, dry	181	281197	279356	0.5%	2050 [4]	0.6	0.48
Total Merchandise Trade			58294500			31.7	

[1]Mekonnen & Hoekstra,2011; [2]Brower and Heibloem (1986); [3]http://waterfootprint.org/; [4]irrigated

Table 49. Agriculture land and vegetables harvested area for countries with vegetables production greater than Egypt's, year 2013. Source: FAOSTAT (2016).

AreaName	Vegetables, fresh nes (code 463) Area harvested [1000 Ha] (a)	Arable land [1000 Ha] (b)	Arable land and Permanent crops [1000 Ha] (c)	Ratio 1 (a/b) [%]	Ratio 2 (a/c) [%]
China, mainland	9700	105720	121720	9.2	8.0
India	2815	157000	170000	1.8	1.7
Viet Nam	752	6409.5	10231.7	11.7	7.3
Nigeria	740	34000	40500	2.2	1.8
Philippines	600	5590	10940	10.7	5.5
United Republic of Tanzania	290	13500	15650	2.1	1.9
Myanmar	256	10772	12281	2.4	2.1
Nepal	246	2114	2326	11.7	10.6
Brazil	225	76008.1	82808.1	0.3	0.3
Ethiopia	190	15119	16259	1.3	1.2
Bangladesh	181	7678	8508	2.4	2.1
Democratic People's Republic of Korea	166	2350	2580	7.1	6.4
Iran (Islamic Republic of)	158	14878	16684	1.1	0.9
Uganda	144	6900	9100	2.1	1.6
Lao People's Democratic Republic	136	1489	1658	9.1	8.2
Italy	136	6827	9087	2.0	1.5
Thailand	130	16810	21310	0.8	0.6
Egypt	127	2738	3761	4.7	3.4

Table 50. Countries with exports of frozen vegetables greater than Egypt's, year 2013. Source FAOSTAT (2016).

Country	Exports of frozen vegetables [10^3 tons]
Belgium	1169.5
China, mainland	790.5
Poland	448.1
Spain	376.0
Mexico	323.7
Netherlands	249.6
France	204.0
Egypt	104.1

Table 51. Linear program setup for Optimization Scenario 1.

Objective function	Maximize water saving		Value	Unit
Constraints	Harvested area for 6 crops stays the same	=	2854	[Ha]
	Total wheat not lower than current value	>=	19749	[10^3 tons]
	Total maize not lower than current value	>=	13728	[10^3 tons]
	Potatoes production satisfies domestic demand	>=	3837	[10^3 tons]
	Onions, dry production satisfies domestic demand	>=	1573	[10^3 tons]
	Grapes production satisfies domestic demand	>=	1301	[10^3 tons]
	Vegetables production satisfies domestic demand	>=	595	[10^3 tons]
	Trade balance money is greater than current value	>=	-3949	[10^6 USD]

Table 52. Linear program setup for Optimization Scenario 2.

Objective function	Maximize water saving		Value	Unit
Constraints	Harvested area for 6 crops no larger than current value	=	2854	[10^3 Ha]
	Total wheat not lower than current value	>=	19749	[10^3 tons]
	Total maize not lower than current value	>=	13728	[10^3 tons]
	Potatoes production satisfies domestic demand	>=	3837	[10^3 tons]
	Onions, dry production satisfies domestic demand	>=	1573	[10^3 tons]
	Grapes production satisfies domestic demand	>=	1301	[10^3 tons]
	Vegetables production satisfies domestic demand	>=	595	[10^3 tons]
	Wheat harvested area not lower than one half current value	>=	709	[10^3 Ha]
	Maize harvested area not lower than one half current value	>=	515	[10^3 Ha]
	Exports of vegetables less than Belgium's value (1170 [1000 tons])	<=	1170	[10^3 tons]
	Harvested area for wheat does not increase	<=	1419	[10^3 Ha]
	Harvested area for maize does not increase	<=	1030	[10^3 Ha]
	Trade balance money is greater than current value	>=	-3949	[10^6 USD]

Table 53. Linear program setup for Optimization Scenario 3.

Objective function	Maximize water saving		Value	Unit
Constraints	Harvested area for 6 crops no larger than current value	=	2854	[10^3 Ha]
	Total wheat not lower than current value	>=	19749	[10^3 tons]
	Total maize not lower than current value	>=	13728	[10^3 tons]
	Potatoes production satisfies domestic demand	>=	3837	[10^3 tons]
	Onions, dry production satisfies domestic demand	>=	1573	[10^3 tons]
	Grapes production satisfies domestic demand	>=	1301	[10^3 tons]
	Vegetables production satisfies domestic demand	>=	595	[10^3 tons]
	Wheat harvested area not lower than one half current value	>=	709	[10^3 Ha]
	Maize harvested area not lower than one half current value	>=	515	[10^3 Ha]
	Vegetables harvested area at value less than 10% of arable land (2.15 times current area)	<=	274	[10^3 Ha]
	Wheat harvested area not larger than current value	<=	1419	[10^3 Ha]
	Maize harvested area not larger than current value	<=	1030	[10^3 Ha]
	Trade balance money is greater than current value	>=	-3949	[10^6 USD]

Equations in Tables 54 to 57

$$Trade\ balance\ value = \sum Product\ import\ values - \sum Product\ export\ values$$

$$Trade\ balance\ water = \sum Water\ import\ total - \sum Water\ export\ values$$

$$Water\ saving = \sum Water\ used\ in\ baseline - \sum Water\ used\ in\ scenario$$

Table 54. Egypt's current cropping pattern.

	Current cropping pattern					Product import			Water import		Product export			Water export		Trade balance	
Crop	Area [10^3 Ha]	Production [10^3 tons]	Yield [tons/Ha]	Water used [BCM]	Water Footprint [m3/ton]	Imports [10^3 tons]	Value [10^6 USD]	Unit value [USD/ton]	Total [BCM]	Water Footprint [m3/ton]	Exports [10^3 tons]	Value [10^6 USD]	Unit value [USD/ton]	Total [BCM]	Water Footprint [m3/ton]	Value [10^6 USD]	Water [BCM]
Wheat	1419	9460	6.7	8.8	930	10288	2716	264	13.7	1334	0	*	*	0	*	-3949	15.2
Maize	1030	7957	7.7	8.2	1031	5772	1985	344	5.2	909	0	*	*	0	*		
Potatoes	160	4265	26.6	1.3	308	0	0	*	0	0	428	206	481	0.13	308		
Onions, dry	53	1903	36.0	0.5	258	0	0	*	0	0	330	202	614	0.09	258		
Grapes	64	1389	21.6	0.7	537	0	0	*	0	0	88	183	2080	0.05	537		
Vegetables	127	699	5.5	0.2	322	0	0	*	0	0	104	160	1536	0.03	322		
Totals	2854			19.8					15.5					0.30			

Table 55. Results of strategy on major changes in cropping pattern – Expanded version. Optimization scenario 1.

	New cropping pattern					Product import			Water import		Product export			Water export		Trade balance	
Crop	Area [10^3 Ha]	Production [10^3 tons]	Yield [tons/Ha]	Water used [BCM]	Water Footprint [m3/ton]	Imports [10^3 tons]	Value [10^6 USD]	Unit value [USD/ton]	Total [BCM]	Water Footprint [m3/ton]	Exports [10^3 tons]	Value [10^6 USD]	Unit value [USD/ton]	Total [BCM]	Water Footprint [m3/ton]	Value [10^6 USD]	Water [BCM]
Wheat	0	0	6.7	0.0	930	19749	5213	264	18.4	930	0			0.0		11100	28.1
Maize	0	0	7.7	0.0	1031	13728	4721	344	14.2	1031	0			0.0			
Potatoes	144	3837	26.6	1.2	308	0	0		0	0	0	0	481	0.0	308		
Onions, dry	44	1573	36.0	0.4	258	0	0		0	0	0	0	614	0.0	258		
Grapes	60	1301	21.6	0.7	537	0	0		0	0	0	0	2080	0.0	537		
Vegetables	2606	14287	5.5	4.6	322	0	0		0	0	13692	21035	1536	4.4	322		
Totals	2854			6.9					32.5					4.41			

Table 56. Results of strategy on major changes in cropping pattern – Expanded version. Optimization scenario 2.

	New cropping pattern					Product import			Water import		Product export			Water export		Trade balance	
Crop	Area [10^3 Ha]	Production [10^3 tons]	Yield [tons/Ha]	Water used [BCM]	Water Footprint [m3/ton]	Imports [10^3 tons]	Value [10^6 USD]	Unit value [USD/ton]	Total [BCM]	Water Footprint [m3/ton]	Exports [10^3 tons]	Value [10^6 USD]	Unit value [USD/ton]	Total [BCM]	Water Footprint [m3/ton]	Value [10^6 USD]	Water [BCM]
Wheat	709	4730	6.7	4.4	930	15019	3964589	264	14.0	930	0			0.0		-3949.15	11.5
Maize	515	3978	7.7	4.1	1031	9750	3353166	344	10.1	1031	0			0.0			
Potatoes	144	3837	26.6	1.2	308				0	0	0	0	481	0.0	308		
Onions, dry	44	1573	36.0	0.4	258				0	0	0	0	614	0.0	258		
Grapes	95	2056	21.6	1.1	537	0	0		0	0	755	1571094	2080	0.4	537		
Vegetables	322	1765	5.5	0.6	322	0	0		0	0	1170	1797511	1536	0.4	322		
Totals	1829			11.8					24.0					0.8			

Table 57. Results of strategy on major changes in cropping pattern – Expanded version. Optimization scenario 3.

	New cropping pattern					Product import			Water import		Product export			Water export		Trade balance	
Crop	Area [10^3 Ha]	Production [10^3 tons]	Yield [tons/Ha]	Water used [BCM]	Water Footprint [m3/ton]	Imports [10^3 tons]	Value [10^6 USD]	Unit value [USD/ton]	Total [BCM]	Water Footprint [m3/ton]	Exports [10^3 tons]	Value [10^6 USD]	Unit value [USD/ton]	Total [BCM]	Water Footprint [m3/ton]	Value [10^6 USD]	Water [BCM]
Wheat	709	4730	6.7	4.4	930	15019	3964589	264	14.0	930	0			0.0		-3949.15	11.4
Maize	515	3978	7.7	4.1	1031	9750	3353166	344	10.1	1031	0			0.0			
Potatoes	144	3837	26.6	1.2	308				0	0	0	0	481	0.0	308		
Onions, dry	44	1573	36.0	0.4	258				0	0	0	0	614	0.0	258		
Grapes	104	2250	21.6	1.2	537	0	0		0	0	949	1973768	2080	0.5	537		
Vegetables	274	1503	5.5	0.5	322	0	0		0	0	908	1394837	1536	0.3	322		
Totals	1791			11.8					24.0					0.8			

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