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Addressing Water Scarcity in the Nile Delta: Virtual Water, Fresh Water, and Desalination

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Abstract

Water scarcity has direct implications for food security in arid regions. Egypt faces an escalating situation of water scarcity, as its renewable fresh water resources are fixed and the population is growing rapidly. The per capita supply of fresh water is already dangerously low and predicted to plummet even further by the year 2025. This paper critically analyzes three different approaches to the water scarcity problem in Egypt: importing virtual water, using Nile water more efficiently, and creating new sources of fresh water with desalination. The advantages and disadvantages of each approach are reviewed. This exposes a number of fundamental trade-offs that must be resolved. Discussion and recommendations are made as to which solution is most viable.

Keywords

Egypt, food security, water scarcity, virtual water, Nile, desalination.

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1. Introduction

Because Egypt is the most populous country in the Middle East, it is important to address the issue of water scarcity, as it has direct implications for food security (IPCC, 2008; Khalifa et al., 2000; UNFCC, 2010). There are three possible solutions to the problem of water scarcity in Egypt. Currently, the most popular approach is to import virtual water in the form of food, as Egypt is the single largest importer of wheat worldwide. The second approach is to ensure that Nile water resources are being used efficiently; currently, more than 85 percent of Nile water is used for agriculture (Kader and Rassoul, 2010). Third, an alternative approach is to create new sources of fresh water using desalination technology, coupled with renewable energy. Egypt has a large untapped supply of solar energy, giving way to future potential for renewable-based desalination projects. Each of these solutions are reviewed critically, and discussed in terms of their viability, trade-offs, and barriers. Beforehand, it is important to fully understand the extent to which water scarcity is an acute problem in Egypt.

As the most populous country in the Middle East and North Africa (MENA) region, water scarcity threatens the food security and water security of many people in Egypt. The nation's population is approaching 90 million and the annual growth rate is around 1.7 percent; in effect, the population is increasing by one million people every year (Khalifa et al., 2000). Egypt's population is projected to increase well over 100 million in the next 15 to 20 years (Khalifa et al., 2000; UN, 2012). Therefore, by the year 2050, it will be a challenge to ensure food security for an additional 30 to 40 million Egyptians (Khalifa et al., 2000) considering that the majority of the country is a desert landscape. Egypt's total land area is 99.55 million hectares, but only 2.87 million hectares are fertile (FAOSTAT, 2011a). Furthermore, this small portion of arable land only exists because Egypt is endowed with a renewable source of surface water. As much as 97 percent of Egypt's fresh water comes directly from the Nile River (NBI, 2005). But even though this water resource is renewable, its carrying capacity is limited. Current surface and ground water resources are only enough to support a population of 50 million (Allan, 2011).

There are also external factors that contribute to – and exacerbate – Egypt's problem of water scarcity. Throughout history, one of the dominant factors has been the competing interests surrounding the consumption of water from the Nile River (NBI, 2005; UNWater, 2007). Including Egypt, there are 10 riparian user countries in the Nile Basin (Burundi, Democratic Republic of the Congo, Rwanda, Kenya, Tanzania, Uganda, South Sudan, and North Sudan) (NBI, 2013). As the population and living standards of other riparian countries continue to increase drastically, inevitably, so will water consumption. Intensified agricultural activity in the Nile Basin will likely reduce the amount of water that drains into the Nile tributaries. Because Egypt is the end-user of this resource, there are legitimate concerns that these changes will negatively impact water flow of the Egyptian Nile. Another publicized threat to Egypt's water supply is Ethiopia's use of the Blue Nile tributary. As much as 83 percent of the Egyptian Nile is fed from water sources in Ethiopia, including tributaries such as the Subat, Otbara, and Blue Nile rivers (NBI, 2005). The latter of which, independently, represents 48 percent of the water supply to the Egyptian Nile (NBI, 2005). Ethiopia has started constructing a massive hydroelectric dam on the Blue Nile, which may negatively impact water flow into Egypt (George, 2013). Although there are ongoing diplomatic negotiations between the two countries (Kharsany, 2013; Kortam, 2013) – with the goal of avoiding any military conflict (Verhoeven, 2013) and ensuring that Egypt's water supply will not be diminished (AlJazeera, 2013; WikiLeaks, 2010) – this an excellent example of how water scarcity in Egypt will be unavoidably exacerbated by growing water consumption in other countries.

Another external contributor to water scarcity in Egypt is climate change. Rising sea level will negatively impact the Nile Delta, which is where the majority of agriculture and human activity in Egypt occurs. Climate scientists at the Intergovernmental Panel on Climate Change (IPCC) have issued warnings with 'high-confidence' that, as a result of sea level rise, coastal systems and low-lying areas will be increasingly impacted by the adversities of flooding, erosion, and inundation (IPCC, 2014). Sea level rise, and increases in seawater temperature, will negatively impact the ecology of key fisheries and estuaries, inundate valuable agricultural land, contaminate groundwater from the intrusion of seawater, and there is already evidence of increased soil salinity and reduced soil organic matter in agricultural lands near the Egyptian coast (Barrocu and Dahab, 2010; El-Nahry and Doluschitz, 2010; IPCC, 2008; UNFCC, 2010). Twelve to 15 percent of the most fertile lands in the Delta will be damaged as a result of inundation or salinization (UNFCC, 2010).

Estimated mean annual temperature increases between 1.0 and 2.0 degrees Celsius will have an adverse impact on precipitation in the Nile Basin area and the strategic sub-basins that feed the Egyptian Nile (i.e. Blue Nile sub-basin, Lake Victoria sub-basin). Rises in temperature will also increase annual rates of evapotranspiration – the measurement of combined moisture loss from soil and leaf surface evaporation – and this will significantly reduce the amount of runoff into the Nile (Conway, 2005; Conway and Hulme, 1996; IPCC, 2008). Depending on the climate scenario used for calcualtions, the impact on water flow to the Nile will be a 20 to 60 percent reduction, (Gleick, 1991; Strzepek et al., 2001). Respectively, it is predicted that there will be a 15 percent and 19 percent reduction in the productivity of wheat and maize crops in Egypt by the year 2050 as a result of climate change (UNFCC, 2010). Furthermore, there will be an 11 percent reduction in rice productivity (UNFCC, 2010). The only crop that may benefit from climate change is cotton - by a 17 percent increase (UNFCC, 2010). The total water demand of crops will also increase as a result of higher annual temperatures, increasing the amount of water needed for irrigation by more than 16 percent (El-Shaer et al., 1997). Climate change represents a dangerous, and growing, external driver for water scarcity problems in Egypt.

The United Nations categorizes water scarcity based on a population's annual per capita share of water. On an annual basis, the availability of less than 1,000 cubic metres of water per capita is considered to be a situation of water scarcity. A nation is in a state of 'absolute scarcity' if this figure decreases below 500 cubic metres (UNWater, 2007, 2012). Egypt's estimated annual share of water is around 700 cubic metres per capita (Abdel-Gawad, 2008). By some estimates, Egypt's annual per capita share of water is going to decrease to 600 cubic metres per capita by 2025, and as low as 350 cubic metres by 2040 (UNFCC, 2010). It is certain that Egypt faces a progressively severe situation of water scarcity. With limited fresh water resources, rising population pressure, increasing living standards, and the threat of climate change, Egypt must cope with – what has been termed as – a situation of 'physical' water scarcity (Molden et al., 2007; NBI, 2005). Effectively, considering the size of the population, Egypt is not endowed with enough fresh water resources to be self-sufficient in food production. Therefore, because the human population exceeds the Nile's carrying capacity, Egypt's food security can only be guaranteed by finding viable solutions to the problem of water scarcity.

2. Virtual Water

The most popular solution to water scarcity in Egypt is to import 'virtual water'. Virtual water can be defined as the water embedded in the production of a commodity. In commodity manufacturing, water is required throughout the entire production chain. Whether secondary/industrial products, or primary/agricultural products, water is an unavoidable component in the means of production. In the case of an agricultural commodity (e.g. wheat), water is heavily consumed for irrigation purposes. We should also account for the fact that water is consumed in the production of associated fertilizers and pesticides. Water is even consumed during the harvest and post-harvest processing of an agricultural commodity (El-Sadek, 2010a; Hoekstra and Chapagain, 2007). Virtual water, as termed by Allan (1998), is the given quantity of water intrinsically represented – or embedded – in the value of an agricultural good. The water is said to be 'virtual' because it was already consumed, and no longer exists in original form (Allan, 1998).

Because cereal imports can be viewed as virtual water imports, both food security and water security can be understood by looking at a country's trade balance (Allan, 1998; Liu et al., 2009). In this regard, Egypt is not self-sufficient in food production and is extremely dependent on food imports, particularly wheat. The staple grain of the Egyptian diet is wheat (Allan, 2011; FAOSTAT, 2011a), a crop which requires significant amounts of water to produce. As much as 1,000 litres of water are required to produce a single kilogram of wheat (Hamza and Mason, 2005; Wichelns, 2001). Therefore, rather than importing vast quantities of water as a raw resource in order to grow wheat, it is easier to import water in the form of calories. Egypt is currently the world's single largest importer of wheat and the fourth largest importer of maize (FAOSTAT, 2011b, 2011c; WFP, 2013). Annually, Egypt imports around 33 billion cubic metres (BCM) of virtual water in the form of food (Allan, 2011), or almost 25 percent of its total water resources (El-Sadek, 2010a). Egypt currently imports 7 BCM/yr in wheat alone; roughly the same amount of food needed to feed the additional 30 to 40 million people that currently exceed the Nile's carrying capacity (Allan, 2011).

There are advantages to importing virtual water, particularly because it can be a viable solution to physical water scarcity. For every kilogram of food that is imported, this means there is more water that can be used for other purposes (e.g. household consumption, manufacturing). The question is whether the economic value of saved water exceeds the economic value of imported food. For water scarce countries with low foreign reserves, there are fundamental opportunity costs in the allocation of water resources (Wichelns, 2001). By importing food instead of producing it locally, Egypt manages to save an estimated 3.6 BCM of Nile water every year (Allan, 2011; Hoekstra, 2009). The price Egypt pays for its virtual water is extremely nominal, approximately \$0.16/m3 (Hoekstra, 2009). Realistically, the true value of this cost is even lower than what is represented in the dollar price, because this does not account for externalized costs, such as labour, land, and other environmental externalities (Hoekstra, 2009).

International markets naturally reallocate water resources from comparatively advantaged regions, which have soil moisture surpluses (e.g. North America, Eastern Europe), to comparatively disadvantaged regions (e.g. Middle East, North Africa), which have soil moisture deficits (Allan, 1998). If a water scarce country industrializes – and successfully specializes in what their comparative advantage is – it will be affordable and logical for them to purchase virtual water from net water exporting countries (e.g. Canada, Australia, Russia, Ukraine). This is because water scarce countries (e.g. Saudi Arabia, United Arab Emirates, Libya) do not have a comparative advantage in food production (Allan, 1998; Hamza and Mason, 2005; Liu et al., 2009; Ricardo, 1821). Even if a population is required to import a large portion of its needed calories, this does not mean they are de facto food insecure. Despite the different uses of terminology, it is very important to understand that 1) food security, and 2) food self-sufficiency, do not imply the same concept (FAO, 2006; Pinstrup-Andersen, 2009; Wheida and Verhoeven, 2007; WorldBank, 1986). Experts often explain how water scarce countries should strategically position themselves through industrialization, so that they can afford to import food from countries that have water surpluses (Allan, 2003; Ramirez-Vallejo and Rogers, 2004; Yang and Zehnder, 2002b; Zehnder, 1999).

There are significant economic gains to be made from the import of virtual water. This is seen when looking at a domestic supply and demand graph for wheat in Egypt (Fig. 1). Demand curve D represents the incremental willingness/ability of consumers to pay for wheat, and supply curve S represents the incremental cost of growing wheat for local producers. In the absence of global markets and free trade, market equilibrium would prevail at the local price PL and the equilibrium quantity of wheat consumed is QA. When there are global markets and open trade, wheat will be sold at the international price PW and the quantity of wheat consumed is QD. Egyptian farmers reduce local production from QA to QB, so that their cost of production equals the international price. QD minus QB will be the quantity of wheat Egypt imports. Although many Egyptian wheat producers must shift from growing wheat to other crops, this still demonstrates the many benefits from trading virtual water. The price of wheat is significantly lowered and many Egyptians, who were previously unable to afford wheat at the local price, now have access to staple food. The local resources that were being used for wheat production will be reallocated to more profitable/lucrative pursuits (e.g. cash crops, value added manufacturing). Furthermore, farmers that continue to produce wheat also benefit because the costs of production are reduced (Wichelns, 2001).

Despite the evident advantages to virtual water trade, there is wide discussion on how to properly manage the global virtual water economy (Hoekstra, 2009; WWC, 2004), as there are fundamental trade-offs to this solution. Reliance on cheap food imports may inhibit healthy competition in domestic markets and, as a result, Egyptian agriculture will be damaged economically. As seen in Figure 1, international trade has a negative impact on Egyptian wheat farmers. Given the opportunity cost of saved water resources, this would not be an issue if the resources were allocated to the next best alternative (e.g. cash crops). However, in reality this does not occur. Quite frequently, scarce water resources will be continually used to grow crops that have less marginal value than the true incremental cost of the resource itself (Wichelns, 2001). Furthermore, even though they may have a higher market value, many alternative cash crops will actually end up consuming more water than cereal crops (Warner, 2003). For example, the seasonal water requirement of wheat is between 450 and 650 mm, and that of cotton is between 700 and 1300 mm (FAO, 2013a-a, 2013b-b). Egyptian scholars also criticize virtual water because it offers favourable political and economic benefits to the net food exporters, most of which are developed/Western countries (El-Sadek, 2010a).

Relying too heavily on virtual water will likely hurt Egypt's economic and political autonomy. Dependency on foreign imports may change the perception of the Egyptian public in regards to the effectiveness of their government, and even the national identity surrounding their own independence/autonomy as a people. Even though food security and food self-sufficiency are not the same concept, they are still widely understood as such (Wichelns, 2001). Similar to how Western nations became almost exclusively reliant on the Organization of the Petroleum Exporting Countries for the export and price setting of petroleum resources, there are fears that water-scarce MENA countries will rely on an informal cartel of water-rich countries for their food supply. If the virtual water economy is dominated by an oligopoly of water rich nations, who set international commodity prices de facto, Egypt will certainly be a price-taker and will need to ensure that it can afford the global price of food (Warner, 2003). If Egypt does not develop/industrialize fast enough, and is unable to debit the cost of bulk food imports, foreign food bills will be paid on credit or using foreign currency reserves, which will hurt the national economy and the value of the Egyptian pound (El-Sadek, 2010a).

Overall, the most demonstrated weaknesses of virtual water is how, already, Egypt is increasingly vulnerable to commodity price fluctuations in the global market (Headey and Fan, 2008; Trostle, 2010). Current commodity prices are artificially low as a result of minimal trade barriers (e.g. taxes and tariffs) and a heavily subsidized agricultural sector in Western developed countries. Therefore, it is arguable that cheap global grain depends on unsustainable trade distortions (Warner, 2003). Furthermore, as populations increase throughout the water scarce regions of the world, growing demand for food imports will adversely affect the stability of international food prices. In other words, not only will water scarce countries be vulnerable to market scares and prices shocks, but their rapidly increasing demand for food will actually be one of the contributing factors to market instability (Yang and Zehnder, 2002a). Finally, with the pressures of spiraling food demand and artificially low grain prices, climate change also threatens market stability. Climate scientists at the IPCC have issued warnings with 'high-confidence' that climatic variability will contribute to market instability, causing drastic and unpredictable changes in global food prices (IPCC, 2014). Excellent examples of this are the food price spikes in 2007/2008 and 2010/2011, along with the subsequent social and political outcomes.

If commodity prices increase suddenly, how will lesser-developed, water-scarce, trade-dependent countries afford a steady inflow of food? (Warner, 2003) What will the social and political outcomes be in a situation of food scarcity? Or a situation of wheat scarcity? These are important questions, especially when considering that almost 40 percent of household income in Egypt is spent on food (Sternberg, 2013). Bread accounts for one third of an Egyptian's caloric intake (Sternberg, 2013). In Egyptian Arabic, the word most commonly used for bread is not the literal word, Khobz. Instead, bread is referred to as Aish, a word which means 'life' (Black, 12 April 2008; Mahr, 31

January 2011; Stackman, 16 Jauary 2008). Bread is a necessary part of life in Egypt, and therefore an extremely contentious issue - recall the 1977 Egyptian Bread Riots, where more than 70 people were killed (Mahr, 31 January 2011; Sternberg, 2013). Recent events illustrate how interplay between the issues of food access and climate change can quickly ignite civil unrest in a water-scarce country like Egypt. In 2007, key food-producing areas were impacted by adverse climatic events. Northern Europe experienced spring-time drought and floods during harvest; Southeast Europe experienced drought; Ukraine and Russia had drought for the second consecutive year; large parts of the U.S. were afflicted with prolonged late-season frost; the Canadian growing season was hit by uncharacteristically intense heat waves; Australia had drought for the third consecutive year; along with drought and late-season frost in Turkey, Argentina, and Northwest Africa.

These climatic events resulted in a significant drop in global average grain yields for the second year in a row, which had only occurred three times in the previous 37 years. Uncharacteristically low grain production resulted in grain hoarding and widespread alarm throughout the global market environment (Trostle, 2010). From January to May of 2008, rice prices increased 190 percent; maize prices increased 43 percent; wheat prices increased 23 percent (Headey and Fan, 2008). In one day alone, after Kazakhstan's government announced export restrictions, the price of wheat increased by 25 percent (Walt, 27 February 2008). Over a five-year span, from 2003 to 2008, the Global Food Price Index has more than doubled (FAO, 2014), but the majority of this increase occurred in the first five months of 2008 (Headey and Fan, 2008). During this time, the price of Aish increased by 500 percent in some Egyptian bakeries (Telegraph, 8 April 2008). There were food riots in major cities throughout Egypt, which resulted in deaths and injuries (CNN, 14 April 2008; Telegraph, 8 April 2008). The government was forced to issue export bans on wheat and rice, and extend other social support systems to ameliorate public dissatisfaction (Trostle, 2010). Climatic and food-price driven civil unrest was again amplified in 2010/2011.

Although climate change and food price instability were not the underlying social/political causes of the Arab Spring or the Egyptian Revolution, they were the triggering factors. This demonstrates how the interplay between these two issues negatively and suddenly impacts water-scarce countries that rely heavily on virtual water imports (Perez, 4 March 2013). Similar to 2007/2008, the Arab Spring began with adverse global weather conditions. In 2010, important food-producing areas of the word were affected by uncharacteristically adverse weather conditions. As a result of drought and heat-waves, wheat production decreased by 33 percent in Russia, 19 percent in Ukraine, 14 percent in Canada, and 9 percent in Australia (Sternberg, 2013). Drought and winterkill frost also hurt wheat production in the United States and Kazakhstan (Johnstone and Mazo, 2013). On the other hand, wheat consumption increased in China by almost two percent, at the same time that there was century-record drought in the nation's main wheat-growing regions, which produces 22 percent of the country's food supply. Although, production only decreased by half a percent, the threat of massive drought caused widespread alarm within the Chinese government, from fear of the historically devastating droughts and famines of the 1950's and 60's (Sternberg, 2013).

China quickly began to purchase bulk quantities of wheat on the international market before the full potential impact of the drought hit. Because anywhere from six to eight percent of global wheat production is traded across borders, it is easy for irregular market activity (e.g. large purchases) to offset market balance and cause price changes. China is the largest wheat producer and consumer in the world, and therefore acts as a price-setter in commodity markets. China's large purchases of wheat in 2010/2011 – in conjunction with low yields in wheat producing regions – caused sharp price increases (Sternberg, 2013). Russia and Ukraine also implemented export restrictions and bans, which drove prices even higher (Johnstone and Mazo, 2013). Global wheat prices doubled in an eight month period, from $USD 157 per metric ton in June 2010 to $USD 326 per metric ton in February 2011 (Sternberg, 2013). In July 2010, the price of wheat was four U.S. dollars per bushel, but by February 2011 the price was nine U.S. dollars (Johnstone and Mazo, 2013). There were also price spikes in maize, soybean, and sugar commodities (Johnstone and Mazo, 2013).

This had direct implications for the food security of poor, water-scarce, wheat-importing countries in the MENA region. The world's top nine importers of wheat are in the Middle East, and many households spend 35 to 40 percent of income on food (with the exception of Israel and other Gulf countries) (Sternberg, 2013). The International Grains Council estimates that in the last six months of 2010, Egypt only received 1.6 million tons of wheat from Russia, compared with 2.8 million tons in the last six months of 2009 (Johnstone and Mazo, 2013). In March 2011, the United Nations Food and Agriculture Organization (FAO) announced that global food prices were at an all-time high. Even before prices hit their all-time high records, protestors took to the streets in Tunisia, Jordan, Yemen, and Egypt, symbolically throwing baguettes at armed officials (Fig. 2) (Johnstone and Mazo, 2013). Seven of these wheat-importing countries experienced widespread civil unrest during 2011, many of which lead to popular uprising and dramatic overhaul of governments and regimes (e.g. The Jasmine Revolution, The Egyptian Revolution) (Mahr, 31 January 2011; Sternberg, 2013).
The Egyptian Revolution, along with the 2007/2008 Food Price Crisis, are excellent examples of how the main trade-off in relying on virtual water is the increasing volatility in global weather patterns and, subsequently, uncertainty in global market conditions (Johnstone and Mazo, 2013; Perez, 4 March 2013; Sternberg, 2013)2. In the Egyptian context, there are even further problems from relying heavily on virtual water. Particularly, because Egypt has a renewable source of real water: the Nile River. It seems irresponsible to depend so heavily on virtual water imports if Egypt does not manage its current water resources efficiently. Other MENA countries have a much greater need for using virtual water as a solution to water scarcity. Arid countries like Libya, Jordan, or Saudi Arabia do not have renewable water resources that match that of the Nile (Wichelns, 2001). Therefore, because Egypt has a relative water-advantage to other MENA countries, efficient use of Nile water resources is also important for solving the problem water scarcity (Horlemann and Neubert, 2006; Wichelns, 2001).

3. Nile water deficiency

Despite being in a state of water scarcity, Egypt is fortunate to have large quantities of fresh Nile water. Under colonial treaties, still enforced today, Egypt is guaranteed a minimum of 55.5 BCM/yr from the total 84 BCM/yr produced by the Nile (Kharsany, 2013; Owen, 1981). There are also renewable underground water aquifers, replenished by natural percolation. These aquifers can safely yield as much as 8

BCM/yr (Gamal et al., 2005). These fresh water resources are not being consumed in the most optimal/efficient way, exacerbating Egypt's situation of physical water scarcity (Doss and Milner, 2001; Gohar and Ward, 2011). Because the Nile is primarily used for agriculture, there are three points at which water can be used more efficiently: application, consumption, and drainage.

3.1 Application: irrigation technologies

Egypt uses large-scale dams and a vast canal system to store and distribute water (Elarabawy et al., 1998; Owen, 1981, 1999). The canal system (Fig. 3 & 4) – established during Ottoman and British dominion – is an outdated irrigation technology, and the infrastructure is deteriorating (Bakry and Khattab, 1992; Moustafa, 1997). Some figures estimate that there is a 10 to 15 percent annual loss in Field Irrigation Efficiency (FIE) as a result of non-optimal water application technologies (Ward, 2010). Throughout the MENA region, average water use efficiency is around 50 to 60 percent, whereas best-practice situations under similar arid conditions in Australia and the United States are over 80 percent efficient (Hasan, 2013). The predominant irrigation method in Egypt is surface flooding. In an arid climate, this method is much less efficient than modern sprinkler and drip irrigation technologies (Fig. 5 & 6). These technologies offer an agronomic, and economic solution to water scarcity.

FIE measures the fraction of moisture plants consume from the total amount of moisture applied. Compared to sprinkler and drip, plants consume a much smaller fraction of the total moisture applied when irrigated by surface flooding (Abdelkader and Derbala, 2003). The FAO estimates that FIE for surface flooding, sprinkler, and drip is 60 percent, 75 percent, and 90 percent respectively (Gersfelt, 2007). Under many agronomic circumstances – particularly on sandy soils in arid regions - sprinkler irrigation, drip irrigation and subsurface drip irrigation have proven to increase FIE in comparison to surface flooding (Abdelkader and Derbala, 2003; Ayars et al., 1999; Christiansen, 1942; El-Hendawy et al., 2008; Sadras et al., 2011; Ward, 2010). These technologies are more efficient because water is applied in controlled quantities, at controlled frequencies, more rapidly, and applied in closer proximity to the plant root zone; reducing moisture losses from evapotranspiration (Assouline, 2002; Ayars et al., 1999; Batthiki and Abu-Hammad, 1994). Crops irrigated using modern irrigation technologies have equal or higher yields, and fewer incidents of pests and disease (Ayars et al., 1999; Camp, 1998; Christiansen, 1942). Ibragimov et al (2007) compared drip irrigation with flood irrigation on a cotton crop, and they found that drip irrigation saved 42 percent of applied water, increased the water use efficiency of cotton by over 100 percent, and increased yields by 10 to 19 percent (Ibragimov et al., 2007). Empirical research on the economics of irrigation in arid regions analyzes price elasticity among different farmers, those using efficient irrigation technologies vs. farmers using inefficient irrigation technologies. Findings demonstrate that farmers who use more efficient irrigation technologies have a less elastic demand for irrigation water, implying that they valorize water more effectively and are able to afford higher water prices (Frija et al., 2011; Poussin et al., 2008; Varela-Ortega et al., 1998). If more farmers used efficient irrigation technologies, the government might be able to remove water subsidies and raise water taxes, which in turn also mitigates water scarcity because water subsidies promote irresponsible and inefficient consumption habits (Darwish, 2014). Water subsidies also make alternative solutions (e.g. desalination) less competitive, cost wise – similar to how oil subsidies make renewable energy less cost-competitive (Huttner, 2013). Over the last 20 years the Egyptian government has started modifying irrigation systems (Abdelkader and Derbala, 2003; NBI, 2005). There has been significant effort to use modern irrigation technologies in the 'New Lands' (rehabilitated desert land). Modern irrigation technologies have been used for land reclamation in the Tushka, Western Desert, Gulf of Suez, East Port-Said and North-Sinai, among others. Sprinkler and drip irrigation are being used in all of these regions (Abdelkader and Derbala, 2003). The New Lands are mostly outside the Nile drainage basin and delta area, where farmers are often legally required to use either sprinkler or drip (Gersfelt, 2007). There has been a slow transition towards the use of modern irrigation technologies in Egypt, both in the New Lands and the Old Lands (the Nile Delta), due to the intensive capital investment it requires of the farmer (Abdelkader and Derbala, 2003).

Even though they are becoming increasingly affordable, the initial capital cost of these technologies is perhaps the biggest disadvantage. Many farmers cannot afford to invest in expensive drip and sprinkler systems. Depending on the technology, and the company selling it, it can cost between $USD 250 and 1000 to install a drip irrigation system on a single hectare of horticultural crops (Polak et al., 1997). More expensive solar drip irrigation technologies cost $USD 47,500 per hectare (Burnery, 2010). Additionally, these systems are best designed for medium to large sized farms – most profitable for farms upwards of 30 hectares (Bosch et al., 2013) – however, the average farm in Egypt (>50 percent) consists of small fragmented plots <1.0 ha per holding (FAO, 2003; Frija et al., 2011; IFAD, 2003; Pereira et al., 2002). Uneducated farmers also face a learning curve associated with sprinkler and drip irrigation. To fully benefit from the use of these technologies, it is required to implement precise watering regiments specialized for each crop that is grown in a given rotation. Farmers will tend to over-water if water prices are low and under-water if prices are high (Barth, 1999; Pereira et al., 2002). There are also drawbacks associated with system maintenance, in the event of tube clogging, leakage, or other mechanical failures that occur over time (Barth, 1999). There are socio-political barriers between the government and farmers. There is disagreement over who should be responsible for operating and managing water resources: decentralized versus centralized management. Farmers would rather have the government oversee the management of water resources – assisting them towards using better irrigation methods – whereas the government feels the opposite, and that this is the responsibility of the farmer (Moustafa, 2004). Another criticism of drip irrigation technology is that it will have an adverse impact on Nile hydrology. Because the technology will improve water use efficiency and increase yields, this will lead farmers to crop more intensively. This may reduce the amount of irrigation runoff that returns to the Nile, possibly lowering the water supply for farmers downstream and negatively impacting Nile ecosystems. However, this is a problem that can be addressed with proper planning and resource management (Gohar and Ward, 2011).

There are challenges and barriers to using efficient irrigation technologies to help solve water scarcity problems. However, minor drawbacks of advanced irrigation technology should not be the definitive reason for preventing their adoption because, ultimately, they are much more efficient at using scarce water resources than the traditional system.

3.2 Consumption: plant water use efficiency

It is important to grow moisture efficient plants in arid regions, where water for irrigation is scarce (El-Shaer et al., 1997; Sivamani et al., 2000). There are a number metrics that measure plant evapotranspiration, water consumption, and how efficiently a plant is consuming and using moisture. A commonly accepted measurement is Water Use Efficiency (WUE). Plant WUE can be defined as the ratio between the weight of dry matter produced and the quantity of water consumed (Farooq et al., 2009). Although Egypt already grows a number of water-efficient crops (e.g. clover, cotton), water scarcity will be reduced by cultivating fewer water-intensive crops (i.e. rice, sugarcane) (El-Sadek, 2010b; Gohar and Ward, 2011). According to the average number of Ha cultivated, the most important crops are clover (berseem), wheat, maize, rice, and cotton (El-Sherif, 1997; FAOSTAT, 2012). According to the average yield of Kg/Ha, other important crops include sugar cane, onions, citrus, barley, legumes, and potatoes (FAOSTAT, 2012).

Total water requirements (maximum evapotranspiration) of sugarcane in a single growing season is 1500 to 2500mm, whereas sugar beet is 550 to 750mm (FAO, 2013a-b, 2013b-a). Sugar beet accumulates high levels of Glycinebetaine, which is an organic compound that is thought to help regulate osmotic pressure and maintain cell structure in plants when under water stress (Asharaf and Foolad, 2007). Sugar content of sugar beet is 25 percent higher than that of sugarcane (Erdal et al., 2007). The disadvantage of growing sugar beet is that it can only access moisture in the first 60cm of soil, and no more than 5 percent of moisture is accessed between the lower 100 and 150cm of the soil profile (Jaggard et al., 2009). Many species of sugar beet do not perform as highly in arid regions as they do in other temperate areas. There is a need to breed improved cultivars that perform well across a broader range of environments, including dry conditions, and that have better rooting ability (Jaggard et al., 2009). Conventional breeding methods can screen for traits that reduce water consumption, such as short-duration life cycle, reduced leaf area, high osmotic adjustment ability, and deep rooting ability (Nguyen et al., 1997). Cotton is already a very robust plant, well suited for arid environments (Rosenow et al., 1983), but it still has a very high water requirement; between 700 and 1300 mm (FAO, 2013a-a). Egypt's cotton sector will benefit from cultivating the most water-efficient types of cotton. There are traits that can reduce the consumption of water in cotton, such as short-growth duration, early maturation, high photosynthetic capacity, and taproot elongation. One of the disadvantages for improved varieties of cotton is that drought tolerance and high WUE may compromise yields, particularly if photosynthetic energy is reallocated to increase root growth (Pace et al., 1999). The greatest challenge will be to ensure that water-efficient varieties have comparable yields.

There are also possible benefits from the genetic engineering of water-efficient plants. Sivamani et al (2000) tested a variety of transgenic wheat that, when expressing the drought resistant barley gene HVA1, exhibited an increase in WUE. When subjected to water stress, transgenic plants were able to produce more dry weight per unit than the non-transgenic control (Sivamani et al., 2000). Sawahel (2004) had similar results when studying production of Glycinebetaine in transgenic rice – transgenic test subjects exhibited higher WUE than the non-transgenic control (Sawahel, 2004). Berseem is already one of the most drought tolerant species of clover (Lazaridou and Koutroubas, 2004). However, it is still negatively impacted by moisture stress (Iannucci et al., 2000). Abogadallah et al (2011) tested a variety of transgenic Berseem that, when expressing the drought resistant Arabidopsis gene HARDY, exhibited an increase in WUE and produced as much as 55 percent more fresh weight than the control (Abogadallah et al., 2011). However, a barrier to the use of genetically engineered plants is that they still show inconclusive ability to adapt under water stress, and will require further testing before commercial use in any water scarce country (Asharaf and Foolad, 2007; Sivamani et al., 2000). Hundreds of papers have claimed to improve WUE in plant species by using genetic engineering, but many of these new plant species have not been properly field tested in arid regions (where the abiotic stress of intense evapotranspiration actually exists) (Abogadallah et al., 2011). Finally, there is a consensus that the trait of drought tolerance is very complex and involves the concerted performance of many different genes, which makes the genetic engineering of viable water-efficient species very challenging (Abogadallah et al., 2011).

3.3 Drainage: wastewater management

Wastewater management helps ensure that Nile waters are being used efficiently. Wastewater management also strengthens Egypt's self-sufficiency in food production. There is potential to 1) reuse and 2) recycle wastewater for irrigation purposes, and to 3) reduce the amount of water being wasted. There are two types of wastewater: A) municipal, and B) agricultural.

Currently, only 0.7 BCM of municipal wastewater are recycled for irrigation. It is possible to increase this figure up to 3 BCM/yr (Wahaab and Omar, 2011). Egypt produces between 5.5 and 6.5 BCM of municipal wastewater annually (Wahaab and Omar, 2011). It is important to manage municipal wastewater properly – if not to produce fresh water for irrigation, then to prevent the pollution of other fresh water resources – however it is more important to manage agricultural wastewater. Egypt uses 85 percent of its water for agriculture, therefore irrigation drainage makes up the vast majority of wastewater resources (Kader and Rassoul, 2010). The most attractive reason for reusing agricultural drainage water is that it is so plentiful. Egypt produces as much as 16 BCM of agricultural drainage annually (Abdel-Khalek et al., 2003). Currently, around 4.5 BCM of drainage water are reused annually for irrigation. It is possible to increase this figure up to 8 or 9 BCM/yr (Abdel-Azim and Allam, 2005; Abdel-Khalek et al., 2003; Wahaab and Omar, 2011). The benefits of properly managing municipal and agricultural wastewaters are that Egypt can improve its self-sufficiency in food production. Since 1988, an estimated one million feddans (420,000 hectares) in the delta have depended on reused drainage water for irrigation. To date, there are large-scale pilot projects using treated municipal wastewater for irrigation on some 70,139 hectares, or two percent of Egypt's total arable land (Wahaab and Omar, 2011). Recycled and reused waters can also be used for desert reclamation and reforestation projects (Abdel-Khalek et al., 2003). Finally, reusing and recycling are not the only two forms of management; agricultural drainage needs to be managed by reducing the amount of water being wasted. A vast subsurface drainage network connects more than 85 percent of Egypt's arable land (Wahba et al., 2005). The design of this drainage system is not optimal because it actually drains too rapidly. Crop yields – including wheat, clover, maize, rice, and cotton – can be increased if moisture was not drained so quickly and, rather, if moisture was able to absorb into the lower layers of the soil profile, near the bottom-half of the plant root zone. This would act as a temporary water bank, and irrigation frequencies might be reduced (Abdel-Dayem and Ritzema, 1990; Moustafa, 1998; Wahba et al., 2005).

Wastewater management is a viable solution for combating water scarcity because it ensures that Nile waters are being used more efficiently. Nonetheless, there are challenges that come with this solution. The recycling of municipal wastewater – also known as grey water – requires a large system of pipes and treatment facilities. There are significant infrastructure costs associated with investment in recycling municipal wastewater, along with health and environmental safety issues (Kader and Rassoul, 2010). The government is also a barrier to the recycling of municipal wastewater. There are national policies on the management of wastewater, along with various administrative levels in government that oversee the management and application of wastewater resources, but bureaucracy tends to moves slowly (Abdel-Azim and Allam, 2005). With the reuse of agricultural drainage water, the number one trade-off is the risk of increased soil salinity. This will limit the full utilization of all agricultural wastewaters. Water intrusion from the Mediterranean also adds further salinity to reused wastewaters. Even with 8 BCM/yr of reused wastewater, the Ministry of Water Resources and Irrigation intentionally lets an additional 8 BCM/yr drain into the sea. This is to regulate soil salinity in the Delta region (Abdel-Khalek et al., 2003). Drainage water salinity is between 1000 to 2000 ppm – for readers' reference, seawater salinity is 35,000 ppm – and these waters must be mixed with additional fresh water for dilution, before being used for irrigation (Abdel-Azim and Allam, 2005; Khalifa, 2011). Salinity is a recurring issue that farmers cope with throughout Egypt, particularly in the Delta. There are agricultural methods (e.g. crop rotation, leaching/flooding) that can mitigate the effects of soil salinity from irrigating with wastewater. However, these are only effective up to a certain extent. Reuse of agricultural wastewaters serves as a viable solution for mitigating water scarcity in Egypt, but the scale of this solution has some limitations.

4. Desalination

An alternative solution to water scarcity is to create alternative sources of fresh water. It is estimated that between 1990 and 2025 Egypt's fresh water supply will expand by 16 percent, while fresh water consumption will expand by 27 percent (NBI, 2005). Another estimate says that by 2017 Egyptian fresh water resources will expand by four percent from 1999 levels, whereas consumption will expand by 32 percent (Hamza and Mason, 2005). This demonstrates the extent of Egypt's physical water scarcity challenge, in the face of growing population pressure. In the long-term, if Egypt becomes fully efficient in its use of Nile water, creating new sources of fresh water may become necessary. This can be done using desalination technologies. Desalination has a number of both advantages and disadvantages.

Seawater, or brackish water, can be desalinated by one of two common methods. Fresh water can either be evaporated from the brine (saline water), or it can be separated using a semi-permeable membrane (filter). Respectively, these are called phase-change and membrane processes. Between these two processes, there are many methods for desalinating brackish water and seawater: multi stage flash, thermal vapor compression, multi-effect distillation, and electrodialysis.

However, membrane processes are often more efficient than phase-change processes, particularly the reverse osmosis (RO) method. Reverse osmosis is likely the most cost-effective, energy efficient, and widely used method of desalination (Fig. 7) (Abdel-Jawad et al., 1999; Afify, 2010; Allam et al., 2002; Darwish, 2014; El-Ghonemy, 2012; El-Kady and El-Shibini, 2001; El-Sadek, 2010b). The price of RO in the 1990s was \$1.50/m3, today the cost is as low \$0.5/m3, or lower (El-Kady and El-Shibini, 2001; Molina and Casana, 2010). Afify (2010) explains that usually RO is the most versatile technology, but that electrodialysis is more affordable for desalination of brackish groundwater (El-Sadek, 2010b). Brackish groundwater with a salinity of 2,000 to 10,000 ppm can be desalinated at a competitive cost for isolated regions and new communities in remote areas (El-Sadek, 2010b). This can produce fresh water for human consumption. It can also produce partially saline water that can be used for irrigation on lands cultivating halophytic (salt tolerant) forage plants for livestock (Ashour et al., 1997). Brackish groundwater is as much as two to three times more affordable to desalinate than seawater (Afify, 2010), but it is nonrenewable (Zarzo et al., 2013). The eastern desert region on the Red Sea coast and the Northern desert region have large quantities of brackish water stored in shallow aquifers (El-Kady and El-Shibini, 2001).

One of the barriers inhibiting the adoption of desalination is its high initial capital investment (Huttner, 2013). Around 30 percent of the costs for producing water from seawater through RO are for repayment on the initial capital investment, however the greatest cost is from energy consumption, about 50 percent (Fig. 8) (Molina and Casana, 2010). Desalination can have negative environmental impacts through its intensive energy consumption, producing greenhouse gasses (Chaibi, 2000; El-Ghonemy, 2012). Saudi Arabia already burns an equivalent of 1.5 million barrels of crude oil daily generating the electricity needed to desalinate water, producing an annual 0.5 BCM/year (Darwish, 2014). However, with Concentrating Solar Power (CSP) technology, desalination can be far more environmentally sustainable, and more affordable than fossil, wind, or solar photovoltaic energy sources (Childs et al., 1999; El-Ghonemy, 2012; El-Kady and El-Shibini, 2001; El-Sadek, 2010b; Moser et al., 2013). Arid regions may not have an abundance of water, but they certainly have an abundance of untapped solar energy (Blanco et al., 2013; Chaibi, 2000; Perret et al., 2005). Egypt has a high average area-time for global solar radiation, between 19 and 24 megajoules/m2 per day (El-Kady and El-Shibini, 2001). In fact, it is economically desirable to have technological synergies. The energy costs of combining solar harnessing plants with desalination plants are much less than if both functioned independently (Blanco et al., 2013; Ong et al., 2012). Heat that is lost in the production of electricity from solar radiation can be harnessed and redirected towards water production, or redirected towards mechanisms that produce electricity for water production (Moser et al., 2013). Concentrating solar power (CSP) systems that produce heat to drive electricity-producing mechanisms, which power saltwater reverse osmosis systems (SWRO) are the most viable method (Darwish, 2014). However, Egypt relies heavily on tourism as one of its top three sources of national revenue. Therefore, desalination plants that require coastal real-estate will inevitably be competing with one of Egypt's most important industries (Blanco et al., 2013; Gray, 1998; IntelligenceUnit, 2002; Shaalan, 2005; Tohamy and Swinscoe, 2000). Another environmental concern is the brine effluent produced by desalination plants (Afify, 2010;

El-Sadek, 2010b). For every cubic metre of desalinated water as much as one and a half cubic metres of brine are produced. Desalination plants are only able to filter about 40% of the water intake. The other 60% has increased concentration of salt, higher temperatures, and is often discharged back into the ocean. This can negatively impact water quality and marine ecology in the vicinity of a desalination plant (El-Sadek, 2010b). There are also unknown ecological impacts of using desalinated water on farms; Zarzo et al (2013) cited problems with Boron toxicity in desalinated water, negatively impacting orange and lemon trees – Egypt has a large citrus production sector (Zarzo et al., 2013).

In theory, there are benefits to using desalinated water for agriculture (e.g. unlimited water supply regardless of weather conditions, seawater is a virtually inexhaustible resource, reduced soil salinity, reduced water consumption) (Zarzo et al., 2013). However, using desalination for agriculture will only become viable if the economic value of water becomes high enough to outweigh the costs of treating saline and brackish water. If you compare the costs of importing virtual water versus producing desalinated water – respectively, priced at \$0.16/m3 and \$0.5/m3 – then desalination is only viable for municipal and industrial applications, and not yet viable for food production (El-Kady and El-Shibini, 2001; El-Sadek, 2010b; Hoekstra, 2009). Agricultural activity consumes immense quantities of water in comparison to industry and human drinking needs (Allam et al., 2002; Bremere et al., 2001; El-Sadek, 2010b). In Egypt's case, agriculture makes up 85 percent of consumed water, whereas industry and household water consumption make up nine percent and six percent, respectively (El-Kady and El-Shibini, 2001). Furthermore, arid soils often require even more water to sustain crops because of higher levels of evapotranspiration (Goosen et al., 2003; Perret et al., 2005).

4.1 Greenhouses

Although desalination may not be suitable for producing enough water to sustain field crops, because of high levels of evapotranspiration, desalination may be viable for agriculture in controlled indoor environments. Greenhouse structures significantly reduce evapotranspiration (Fernandes, 2003; Perret et al., 2005). Therefore, combining greenhouses with a solar distillation method – phase-change desalination process – plant life can be sustained indoors. This is best suited for remote areas (e.g. Northern Desert, Sinai, Eastern Desert) that only have access to saline or brackish water (Afify, 2010; Chaibi, 2000). Even though this solves some of the inefficiencies associated with using desalinated water for outdoor food production, solar distillation greenhouses still have operational trade-offs. There is a large initial capital investment that must be accounted for. Solar distillation greenhouses are not viable because of heat and moisture problems associated with the technology (Chaibi, 2000; Selcuk and Tran, 1975). This makes the desalination process inefficient, and the indoor climate is also not optimal for cultivating plant species.

However, there are some new greenhouse technologies that may have corrected a lot of these inefficiencies by enhancing the way greenhouses function. The seawater greenhouse method focuses only on arid coastal regions. This method is far more efficient because of its improved thermodynamic function, using a simple open-air humidification-dehumidification process, along with drip irrigation (Fig. 9) (Goosen et al., 2003). The driving force of this system is the difference between the temperature of the solid surface of the greenhouse heated by solar energy, and the temperature of cold water drawn from below the sea surface (Goosen et al., 2001b). The primary method of desalination is by saturating the air to its dew point and then condensing the moisture from the air, producing fresh water (Perret et al., 2005). Because seawater greenhouses are intended for arid coastal regions, they are more economical than other methods because they can incorporate renewable wind energy for powering the necessary water pumps and ventilation fans (Goosen et al., 2001b). Field tests of this system show that the amount of desalinated water produced was in excess of the water requirement for plants inside the greenhouse, therefore a large area of additional crops can be sustained outdoors under a shade canopy (Goosen et al., 2001a; Perret et al., 2005; Sabalani et al., 2003). The system was first tested in the Canary Islands, and other projects have since started in Oman, Qatar, and Jordan. This technology may be adapted to Egypt's North Desert coast along the Mediterranean, or to the Eastern Desert coast along the Red Sea. Given the environmental pressure that Egypt's spiraling population is putting on the Delta region, it would be good for the government to pursue sustainable development projects in these areas to relieve some of the population pressure (Afify, 2010).

It is difficult to compare the costs of large-scale desalination plants with seawater greenhouses. At face value, sweater greenhouses cost much less than large desalination plants. A seawater greenhouse project costs around $USD 2 million and a desalination plant project can cost anywhere between $USD 20 million and $USD 2 billion. The costs will depend on what type of technology a plant will be using, what type of renewable energy it relies on, the geography/climate of both the plant and greenhouse locations, the size and production capacity of each facility, and the purpose of the facility (e.g. isolated versus connected, commercial versus municipal, household versus agricultural). However, we can gauge potential costs by considering the required energy units (kilowatt hours) it takes to produce a single water unit (cubic metres). A desalination plant consumes between 1.5 and 5.5 Kwh/m3 (Blanco et al., 2013; Moser et al., 2013). A seawater greenhouse consumes between 1.16 and 2.3 Kwh/m3 (Goosen et al., 2001b; IRENA, 2012; Sabalani et al., 2003). Seawater greenhouses have a much smaller production capacity than large-scale desalination plants, but may be more affordable on a per-unit basis.

There are still bottlenecks in the efficiency of the technology with regards to the design of the moisture condensing unit and the velocity of airflow moving through the greenhouse (Perret et al., 2005). Even though seawater greenhouses improve the possibility of using desalination to produce food, the idea is still relatively new, the precise implementation of this system will vary between geographic areas, and high initial capital investment will limit widespread adoption throughout the MENA region (Goosen et al., 2001b; Goosen et al., 2003).

5. Discussion

Overall, three key observations stand out from this analysis. First, virtual water imports are necessary to maintain food and water security in Egypt now and for the foreseeable future. Second, efficient irrigation techniques hold the promise of saving billions of cubic metres of water every year, but the barriers that prevent the adoption of such technologies are significant. Third, desalination shows promise in the long-term but requires technological innovation. It is only logical to say that Egypt needs to take a highly diversified approach to the issue of water scarcity. Therefore, all three strategies will be required in order to meet Egypt's water requirements over the 21st century, in the short-term, mid-term, and the long-term.

5.1 Short-term: virtual water

Virtual water imports are the short-term imperative for solving water scarcity in Egypt, and ensuring food security for a population that drastically exceeds the carrying capacity of its environment. Egypt's cereal baseline demand is projected to increase by 36 percent by the year 2017 (El-Sadek, 2010a). Egypt will likely not be self-sufficient in food production in the near future, and so instead must position itself strategically to exploit water surpluses of other countries. Virtual water is not only important because it is necessary from a geo-resource perspective, but it is important from an economic perspective. Virtual water can be extremely affordable and cost-effective. As described, the real cost of virtual water is low because of environmental and production chain externalities. Because of the opportunity-cost of saved water resources, virtual water also allows scarce water resources to be used in more profitable ways. Having said this, even though virtual water imports are extremely necessary and advantageous, there remains a looming threat of economic and political crises. In the late 2000's and early 2010's, we witnessed how dependence on food exports resulted in socio-economic and political turmoil in Egypt. Climate-related spikes in the international price of wheat caused widespread protests in Egypt, and were even the triggering event that lead to regime change in early 2011. Macro-economic factors make virtual water a risk-burdened strategy for Egypt. Price instability in global commodity markets is the fundamental trade-off that comes with the benefits of virtual water. For this reason, Egypt must buffer against these risks by maximizing the efficiency of what fresh water resources are available.

5.2 Mid-term: Nile water efficiency

When it comes to the problem of water scarcity, Egypt is a very unique situation. Egypt is an outlier in the MENA region. It suffers from the same physical water scarcity as many other countries, however its fresh water resources are far greater than its neighbours. The very reason that Egypt is the most populous country in the Middle East today is perhaps because of its large freshwater resources, which drastically increase its natural carrying capacity. Therefore, over the mid-term period of the 21st century, Egypt must resolve the problem of water scarcity, relative to its geographical position in the region, and relative to its natural endowments. Efficient irrigation technologies and water management strategies can save billions of cubic meters of Nile water every year. The reuse of agricultural drainage water will make available water resources that have previously been lost each year. Modern irrigation technologies improve crop WUE most effectively when used on arid soils. However, there are monumental socio-economic and administrative barriers to these strategies. Wastewater management systems require extensive infrastructure investments and also run the risk of increasing soil salinity. Irrigation technologies are not ideal for the type of small and fragmented land holdings characteristic of Egypt, and there are educational learning curves associated with the best-practice use of these technologies. Furthermore, there has been historical disagreement between farmers and governments as to who should manage the improvement of irrigation and drainage infrastructure, and who should foot the bill for these improvements.

5.3 Long-term: desalination

With regards to desalination, it is important to recall the macro-economic risks associated with virtual water, and to remember that Egypt's population already exceeds the carrying capacity of the Nile. Therefore, Egypt must consider the long-term need to expand its fresh water resources. Desalination technology is the only strategy for significantly expanding Egypt's freshwater resources. These technologies have improved over the last sixty years, reducing the price of desalinated water by as much as a third. Renewable energies that tap into Egypt's irradiation resources have made desalination more environmentally sustainable, as opposed to using fossil fuels in the past. Desalination technologies, paired with greenhouse technology, make the possibility of food production more realistic. There has been considerable progress, but high demand for desalination does not yet exist, so this technology has only just started moving out of the fringe. The cost of desalinated water may have decreased on a per-unit basis, but the start-up and energy costs of these technologies are still extremely capital intensive investments; financially out-of-reach and low on the priority list of weak governments that are already struggling to make basic expenditures. Also, we are still uncertain about the extent to which this technology will have a negative impact on aquatic environments. Overall, these technologies are relatively new and the impetus for their use has not fully materialized. Ultimately, desalination will only become more attractive in the long-term as the demand and cost of water increases worldwide, and as the technology continues to improve.

6. Recommendations

By way of summary, three key recommendations emerge from this analysis that, when taken together, will help promote more sustainable and long-term water security. Egypt is in a difficult situation when it comes to solving the problem of water scarcity. None of the presented solutions are without barriers and trade-offs. Therefore, we should resolve these trade-offs by comparing strengths and weaknesses of each solution and by considering the necessary action that must be taken over the short-term (next five to 10 years), the mid-term (next 20 to 40 years), and in the long-term (next 40+ years).

6.1 Virtual water: next five to 10 years

Undoubtedly, virtual water will always be a crucial component in Egypt's toolkit of solutions for water scarcity, and it is the most urgent strategy that needs managing. Over the next five to 10 years, it is recommended that Egypt assertively checks and manages its dependency on virtual water. This must be done on both an international and domestic level. The 1995 World Trade Organization Agreement on Agriculture made binding commitments among member states to globally improve market access to commodities (e.g. wheat) by reducing trade-distorting agricultural subsidies. Multi-lateral disagreements on these commitments have effectively suspended the more recent Doha Development Round. Therefore, on an international level, it is recommended that Egypt and other water scarce nations form coalitions to advocate for emergency non-trade considerations to be made on the issue of water scarcity, with regards to irrigation subsidies and, more specifically, annual fluctuations in global climate and water availability (Gualtieri, 2008). However, because Egypt does not have the political ability to push large multi-lateral discussions forward – compared to that of India or China – there must also be localized action. Strong policies should be made, under the assumption of imminent and increasingly frequent price shocks. Egypt must strengthen its economy and bolster the ability of its government in order to cope with price shocks, and to afford continually rising food prices. The global food price index reached two record highs in the first 15 years of the 21st century. Given the pressures of global population growth, climate change, and the lack of change in price distorting behaviour by other countries, there is very little reason to assume that food prices will not continue to increase, and continue to increase irregularly. During Mesopotamian times, Egypt was considered the breadbasket of the region, and would guard against climate induced grain shortages by using a buffer stock scheme. It is recommended that the strategy of buffer stocks be revisited and studied in a modern-day context. In light of the recent price shocks, there has already been discussion around forming a collaborative wheat buffer stock scheme between developed, exporting countries and underdeveloped, importing countries - Egypt is included in this discussion (Bosworth and Lawrence, 1982; Thompson et al., 2012). It is also proposed that Egypt set a benchmark of 40 to 55 percent self-sufficiency in food production (El-Sadek, 2010a; Horlemann and Neubert, 2006). This is an attainable mid-term goal, if Nile waters are used efficiently.

6.2 Nile water efficiency: next 20 to 40 years

To use Nile waters more efficiently in the next 20 to 40 years it is important to begin modernizing irrigation methods with recommended drip technology, as drip technology is more efficient than sprinklers in arid environments. To overcome the social and political barriers of adopting drip irrigation, first, the government should assist food producers towards improved private control and management of their irrigation waters. Egypt's Ministry of Water Resources and Irrigation, and the Irrigation Advisory Service will need to continue engaging in a Participatory Irrigation Management Strategy by establishing and strengthening more Water User Associations (WUA's) throughout the country. There are successful case studies on WUA's worldwide, and they have shown to be successful in Egypt. This type of multi-stakeholder group will improve water management and collaboration among government ministries and agricultural water users; it will also act as an in-situ form of extension service. WUA's will improve water efficiency using present irrigation technologies, and will lay down the administrative and educational groundwork for the adoption of drip technologies (AQUASTAT, 2009; Batt and Merkley, 2010; Brown, 2003; Hvidt, 1996). Research in Tunisia suggests that farmers are more able to adopt and benefit from drip irrigation when they are members of a WUA (Frija et al., 2011; Poussin et al., 2008). To overcome the economic barriers of adopting drip irrigation (e.g. startup costs), WUAs will help in terms of increasing farm profitability, but there will need to be additional support systems offered to the poorest farmers (Cornish, 1998). Research and evaluation on drip irrigation adoption and management with WUAs in the Nile Delta are critically needed. Lastly, Egypt is the oldest leading country in the MENA region when it comes to reusing drainage waters. As far back as the 1920's, there are records on the reuse of agricultural wastewater in Egypt (Abdel-Khalek et al., 2003). Therefore, it is recommended that the Egyptian government seek financial support from international development agencies and the International Bank for Reconstruction and Development to modernize its wastewater management systems over the next 20 to 40 years.

6.3 Desalination: 40+ years

In the short-term, Egypt cannot afford to invest as heavily in desalination as other MENA and Gulf countries. In the short-term, Egypt must focus on the approaches of virtual water, and Nile water efficiency. Desalination will only become viable in the long-term, after 40 or 50 years, if at all. Currently, desalination is only viable for remote regions where the cost of piping fresh water outweighs the cost of installing desalination systems. Desalination technology will become a more viable approach as the global price of water increases, and the cost of the technology decreases. It will be important to invest in renewable solar energy, as this is the only way desalination will be both environmentally and economically affordable. There are already a number of important CSP pilot projects in Egypt, funded by the government and the World Bank. Desalinated water is mostly suited for producing fresh water for domestic and industrial purposes, and cannot be used for irrigating field crops. However, the viability of concurrent greenhouse-desalination systems can be investigated, as there may be a possibility for food production with this technology in arid coastal regions.

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Conflict of Interest Statement

The author declares no conflict of interest with respect to the research, authorship, and/or publication of this article.

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