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Evaluation of scope for water saving options through reuse of water and desalination in the Nile Basin

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Document Sheet

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The purpose of the technical report series is to support informed stakeholder dialogue and decision making in order to achieve sustainable socio-economic development through equitable utilization of, and benefit from, the shared Nile Basin water resources.

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Photo Front Page: "Rambla Morales desalination plant" by David Martínez Vicente

Phase II Nile Basin Initiative Strategic Water Resources Analysis—Evaluation of scope for water saving options through reuse of water and desalination in the Nile Basin

By Singfoong (Cindy) Cheah, Ph.D.

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Executive Summary

Part One: Water Reuse

Historically, there is substantial water reuse in an “unofficial” mode. In other words, downstream communities have been reusing water that upstream communities dispose of, whether treated or untreated. Such “unofficial” or “unplanned” water reuse exposes the users to germs and pollutants that are dangerous to public health. Unplanned, unmonitored, and unregulated irrigation drainage water reuse could cause soil salinization that in turn can contribute to long-term food insecurity.

In planned or “official” water reuse, the wastewater is treated to protect public health and long- term soil fertility. With climate change, water security is becoming increasingly important so that future generations can have basic water needs, food security, and a sustainable environment. Water reuse can enhance water security through portfolio diversification. Because of water shortages and drought, sometimes extreme seasonal drought within a year, or sometimes drought that spans one to several years, water reuse is increasingly being adopted to meet additional demand in many countries.

According to AQUASTAT, 11,900 MCM drainage water is being reused in Egypt in 2016. Because of the risk of soil salinization, recycling higher volume of drainage water is likely not practical. To facilitate drainage water reuse in other countries, the building of a drainage infrastructure and irrigation efficiency improvements are necessary. Improving irrigation infrastructure through repair of the irrigation scheme, e.g., the Gezira irrigation scheme, or installing canal lining could improve the irrigation efficiency and potentially also increase volume of drainage water for reuse. As described in Technical Report II, full hydrological modeling that includes percolation and flow to the groundwater system would be necessary to obtain accurate water accounting. The 2050 baseline model in Technical Report II show that there could be potential of additional 9,000 MCM water saved from these agricultural interventions, with most of the new saving from efficiency improvements. In the scenario options of Technical Report II, it was shown that investments in agricultural water saving and reuse have the lowest cost per m^3 water saved. Therefore, in the near-term, this is the least cost, largest scope option.

The modeling conducted in this project shows that the scope and cost of municipal water reuse is highly dependent on the nonrevenue water (NRW) of the location. This is because NRW directly affects the volume of wastewater that can be collected, which is a resource in water reuse. If the NRW is lowered to 5% from the current values in the Nile Basin countries, a combined savings of 13,000 MCM is achievable. This value includes 5,000 MCM for municipal purpose from the “saving” through NRW reduction, and 8,000 MCM for agriculture through municipal water reuse for non-potable purpose. This would incur a net present cost of USD 2 to 20 billion as detailed in Technical Report II. The uncertainty is due to (1) range of cost in the distribution of water, and (2) range of the quality the water must be treated to. For example, based on European experience, there is a 5-fold difference in cost if the water was only was to be treated through simple filtration vs. treatment that removes pathogens (references listed in Technical Report I).

In Technical Report II, an alternative option of municipal water reuse for potable purpose is presented, though it is not included in the final scenario—it is left as an option that can be decided upon and taken up later if some countries are interested. In this option, the water is treated to high quality to be reused within the municipality. The total scope is approximately 11,000 MCM if several major municipalities listed in Technical Report II pursue this option. However, this option is expensive—with a net present cost of 20 to 60 billion USD--the detailed mathematics are described in Technical Report II. Note that the total theoretical water saving is actually higher than municipal water reuse for non-potable purpose because part of the water is recycled multiple times, instead of being lost in evaporation and evapotranspiration as in the case of municipal water reuse for agriculture purpose. However, fewer countries would potentially want to engage in this option. Therefore, the total scope is smaller in volume than the combined savings for municipal water reuse for non-potable purpose.

For most countries in the region, the main priority in municipal water would be reduction of NRW and the development of a municipal water and sanitation sector. Municipal water reuse would have to be implemented on a much more intensive scale in arid areas by 2050 or sooner, but potentially even in parts of certain countries such as Ethiopia or Burundi that receive uneven precipitation (large difference between wet and dry seasons).

In the analysis, it is assumed that industrial water reuse will be pursued in all Nile Basin countries. If all countries set up regulations that encourage and/or require industries to recycle water where applicable, there Is a potential of water savings of 2,000 MCM by 2050. It would be most economically efficient if private industries will bear the cost of industrial water reuse.

The following measures focus on country level policies and economic incentives, necessary to achieve optimized conditions for water reuse. When a particular sector, e.g., industrial water reuse, can potentially implement water reuse relatively quickly without waiting for full-blown national regulations/incentives/targets, that sector will have a special section devoted to it.

Formulate clear national strategy

A national strategy, in particular, clarifying the following goals/tactics will be useful:
What sector is the recycled water being used for? If the country was to target water reuse for potable purpose, then it would make sense to have the municipal water board being the “principal” agency and there may be other decisions, e.g., laying out the pipeline in a certain manner while the sanitation and drinking water infrastructures are being built.

Theoretically, individual municipality can have its own policy. For example, even if the country decides to pursue water reuse for non-potable purpose, if a certain municipality is under high water stress, the municipality might decide to invest in water reuse for potable purpose within the city rather than diverting the recycled water to agricultural lands nearly. This could create conflict, however. Ideally, the municipality and neighboring farm lands have an agreed upon vision on water ruse.

Is the water reuse scheme going to be centralized or would it be decentralized as is the case in Japan? As described in more detail in Technical Report II, a decentralized model can succeed but requires clear regulations and enforcement. The bearer of the financial cost for capital, O&M, and a completely new system 20-30 years down the road, when the equipment needs to be replaced or updated, will also need to be spelled out.

Within the national strategy there should be comprehensive data and projection on available supply and demand. With the information as a foundation, the extent of water reuse can either be set as a national and sector target or mandates, with appropriate financial incentives.

Water reuse requires cooperation among ministries overseeing irrigation, municipal water, industrial development, environment, health, and finance. With the strategy spelled out, the relevant parties can draft a national water reuse action plan and clarify the roles of the different ministries.

A well-known human-caused risk is having a non-potable pipe being accidentally connected to potable pipe, inadvertently piping non-potable water into users' homes and facilities. Coordination, clear roles on the responsibilities of the different agencies, and safety protocol can decrease the risk of unintended use.

Certain countries that practice water reuse for potable purpose go through an intermediate step of storing the treated water in an aquifer or reservoir. Storing water in an aquifer has the added advantage that there should be low evaporative loss and the water can even be stored for a time/season when there is a drought or water shortage. If the Nile Basin countries are interested in this method that can potentially improve climate resilience, a firm knowledge of the hydrogeology of the region is essential.

Collect the resource

As described in the opening paragraph, water reuse depends on the availability of wastewater, which is the critical resource. For municipal water reuse, this means a system of wastewater collection needs to be in place. For irrigation drainage water reuse, the water will need to be "collected" or directed to a drain.

Aggressively decrease non-revenue water (NRW)

As detailed in the modeling in Technical Report II, if NRW was left at a high value (as is currently the case in all Nile Basin countries except Rwanda), then the delivered water cost is very high.

Multi- stakeholder approach as those practiced by several cities that saw large reduction in NRW will be an effective approach.

Proper valuation of water

If the water price is too low, then the public does not have as much incentive to conserve water, which can negatively impact the volume of wastewater collected. Proper valuation or pricing of water will provide a strong economic incentive for all users to conserve and recycle water. Equally important, proper valuation allow water utilities to recoup investment in water treatment and water reuse, which can then ensure high quality service and less demand on the national budget.

If the national strategy is to develop water reuse for potable purpose, it is important that the water being offered at a single price, and being treated to a single, high standard. In reality, with adequate sanitation and wastewater collection and treatment, it is not possible to distinguish the water “origin” anyway. However, the public may not realize that the water quality is the same if the pricing or treatment standard is inconsistent.

If the national strategy was to reuse water only for non-potable purpose, then a different price between treated “freshwater” and treated “recycled” water may be viable. However, careful messaging and implementation are necessary if there was an interest to ultimately change the water reuse scheme to potable purpose sometime later.

Measures to protect water quality

In conjunction with the target/mandate/regulation on volume of reuse, there needs to be regulations spelled out for water quality discharged by domestic and industrial users. Without clear regulations and enforcement, there would be very little incentive for upstream user to treat the wastewater discharge. This could create an extremely high burden on downstream water intake and treatment facilities.

Transboundary cooperation is necessary to preserve the water quality for the common good. If all the countries in the Nile Basin Initiative could agree to a water resources plan, it will enhance water quality protection for entire basin.

Measures to protect soil from salinization

Uncontrolled irrigation drainage water reuse could lead to soil salinization problem. It is important that a structure is in place for knowledgeable parties to monitor the irrigation drainage water quality and to determine whether it is suitable for reuse.

Keep track of technology development

In inland regions, currently it is likely to be more cost effective to use conventional water treatment technologies for water reuse. Membrane technologies for water reuse as practiced extensively in countries such as Singapore and Israel produce a concentrated waste stream which is expensive to dispose of inland. It is expensive to build evaporation ponds for the large quantity of concentrated waste that is generated.

Technologies such as Zero Liquid Discharge (ZLD) for membrane technologies is only at the pilot or demonstration stage. Nevertheless, research and testing are ongoing. If a facility is being planned in the future, it would definitely be beneficial to keep tab of the latest in zero or low waste technologies. Depending on the overall design, it may also be possible to add membrane trains and ZLD equipment to an existing water treatment facility. This might provide an economic advantage later as the cost for membrane technologies are still decreasing.

Policies and measures to promote rapid implementation of water reuse in industries

The large variety of industrial processes can make mandating industrial water reuse challenging. However, it is commonly known worldwide that sector such as thermal power generation can implement water reuse without sacrificing economic competitiveness. Internal water reuse, if paid for by the industry owners, would also alleviate public sector funding needs. Therefore, governments can implement the following policies to encourage industrial sectors to reuse water internally.

The most effective policies include:

- Proper valuation of water, including charging industry users a separate water rate compared to domestic users. This measure is common in many countries.
- Tax incentives on companies that implement water reuse. In countries where industries can “write-off” investments from tax expenditures, this incentive might already be in place. Depending on the actual law and regulations, “additional” tax incentive may be suitable.
- Encouragement or regulation on the financial sector to provide funding, e.g., in the form of low interest loan, to industrial entities embarking on water reuse.
- If there was no official regulation, i.e., if water reuse is up to voluntary effort of the industrial sector, then public recognition of companies that engage in water reuse as “green” corporation, “water hero,” etc. could be an important incentive.

Part Two: Water Desalination

Desalination is a process that takes away mineral components from saline water. Desalination can be used for seawater (having a salinity of 30,000 total dissolved solids (TDS) or higher) or brackish water (500 to 30,000 TDS). There are many methods to separate the salt content from the water, with thermal methods utilizing phase changes, i.e., boiling or freezing (in vacuum); electrical method utilizing electric current in combination with a specialized membrane for separating the ions from the water (electrodialysis); and pressure method utilizing high-pressure pump and membrane. Practically all new installations of seawater desalination use the reverse osmosis (RO) technology, which is a process in which under an applied external hydrostatic pressure greater than the osmotic pressure, a solvent will pass through a porous membrane in the direction opposite to that of natural osmosis.

As detailed in Technical Report I, in 2019 Egypt and Kenya have some seawater desalination facilities totaling approximately 160 MCM per year capacity. With a number of projects planned or signed, the capacity could grow to 550 MCM per year in the not too distant future, i.e., probably within 2–4 years. These capabilities are primarily in the coastal area in Sinai, Egypt, and Mombassa, Kenya.

In the modeling conducted for this report, it is estimated that by 2050, more than 4,000 MCM of water from seawater desalination in the Nile Basin, at a net present cost of 9 to 24 billion USD, is a possibility. The cost assumes that nonrevenue water can be reduced to 5% in the region where seawater desalination will be pursued. If nonrevenue water was not reduced, then larger or more new seawater desalination facilities need to be built to provide the same amount of water. The volume of freshwater produced from seawater desalination could supplement up to 20% of the water demand in the Mombassa and Dar es Salaam areas, and potentially up to 40% of the water demand in major municipal areas in Egypt that are within 160 km from the coast.

For brackish water desalination, it is estimated that 2,000 MCM of freshwater can be produced from the available brackish water resource in the region. The net present cost needed is 2 to 10 billion USD. Out of all the water reuse and desalination methods modeled in this project, brackish water desalination has the largest cost and scope range. This is because of the wide salinity range of brackish water and lack of data on brackish water availability and replenishment rate.

To accomplish desalination at the scale outlined above, 5–8% of the national electricity generation capability of Egypt in 2050 might be used on desalination alone, assuming the electricity generation capacity in 2050 is doubled that of the capacity in 2019.

The first three policies and incentives described below are issues that should be considered to successfully implement brackish water desalination. Measures 4 and 5 primarily affect seawater desalination. The last three measures have effects on both brackish and seawater desalination.

Integrated groundwater management

In general, most countries do not have specific policy that protects brackish water resource. Even though there are some surface brackish water source in the Nile Basin, e.g., Lake Turkana, most of brackish water originates from aquifers, i.e., brackish water source is often groundwater source (the reverse is not true). Therefore, brief description of the policies that protect groundwater resource would encompasses the protection of significant fraction of the brackish water resource.

The governance of groundwater, can be complicated. Ideally, a conjunctive management of surface and groundwater or an integrated groundwater management approach, is used. In this approach, the management authority considers the aquifer-surface water links, as well as cross-sectional issues with economics, energy, climate, agriculture, and the environment, i.e., is "thinking beyond the aquifer."

a) Critical to the integrated groundwater management approach is to have good data on the resource, which provide answers to questions such as:

- Aquifer recharge rate;
- Quality of the water— The quality of the groundwater should include salinity data as a function of depth. Unlike surface water, where for example, the water quality of a lake is sometimes given in a single descriptive value, the water chemistry in an aquifer (or multiple aquifers in one land area) is a 3-dimensional set of data.
- Interdependence of the groundwater to surface springs, ecological areas, etc.

b) To develop plans suitable for the region, the Nile Basin countries should develop regional expertise and explore and embrace new technologies that can possibly speed up collection and interpretation of groundwater data.

c) Proper regulation of the water withdrawal to ensure that fossil aquifers are not depleted in a rate that there will be no water left for future generations. Recharge of groundwater with "recycled water" may be one way to extend the life of the aquifer.

d) Policies to regulate well drilling and water withdrawal to ensure the water is not over extracted or the wells are damaged are also necessary. For example, in Egypt, some groundwater wells were clogged by debris, resulting in the wells being not usable and abandoned.

Protect brackish groundwater for future generations

A key policy to encourage long-term use of brackish groundwater is to limit contamination to the groundwater. Pollution to groundwater in general can be extremely costly to treat or nonreversible in some cases. For example, microbes that would have degraded organic pollutants in surface water often do not survive in the low oxygen condition of groundwater. If investment was made by assuming brackish water source of a certain quality and subsequently the water was polluted, then the investment would have been wasted or the cost to install additional treatment could be significant.

Keep track of technology development

Disposal of brine (the concentrated salt water) generated from brackish water desalination is problematic. It is expensive to build evaporation ponds for the large quantity of brine that is generated. Technologies such as Zero Liquid Discharge (ZLD) is only at the pilot or demonstration stage. Nevertheless, research and testing are ongoing.

If a facility is being planned in the future, it would definitely be beneficial to continually keep tab of the latest in zero or low waste technologies. Even after the completion of a facility, it may still be possible to add “modules” that can allow the system to produce less waste.

Coordination with climate change adaptation planning

With the potential change in coastline due to climate change associated sea level rise, locating multiple billion-dollar seawater desalination plants too close to the current coast line may result in literally, “stranded asset,” i.e., the plant or critical infrastructure could be flooded during the lifespan of the plant. Coordination between the water resources ministry, land planning, and national climate change adaptation planning office would hopefully help to make wise investment and site selection in this regard.

For regions close to the coast, water utilities may have the option of desalinating brackish groundwater rather than seawater. However, withdrawing groundwater near the coast might lead to saltwater intrusion. Groundwater overdraft could result in land subsidence. With the seawater rising as a result of climate change, both risks need to be evaluated carefully.

Protect ecological systems

Seawater desalination has a major impact on the marine life especially near the seawater intake and brine release sites. Seawater intake site essentially consists of giant pumps that pump millions of gallons of water. Even with filters, plankton, larvae of marine life, fish eggs can still be pumped in and be destroyed.

The brine or waste stream that is being released is composed of a mixture of salt water (at a salinity two to more times that of seawater) and pretreatment chemicals that include organic compounds, metals, etc. Brine discharge at a single site could impact marine life as some of the compounds could be toxic. Measures such as multiport diffuser far out from the coast could reduce damage to marine life. The intake and disposal would need to be designed on a case-by-case basis based on local geology, ocean current pattern, and marine life.

Coordinated development of power generation capability

Desalination requires stable supply of electricity. Shutting down a desalination plant due to power outage could result in costly, irreversible damage. Therefore, regions that rely on desalination for a water need to have stable electricity supply.

Depending on the electricity price of the region, energy comprises 40–55% of the O&M of seawater desalination. In the high economic development scenario, desalination could end up using 8% of the electricity generation capability of country such as Egypt. Coordinated development of power generation and water desalination or guaranteed power purchase would ensure that the desalination plants have access to stable supply of electricity without causing excessive drain in the electricity sector of the country.

Improve the financial and utility sectors

Besides energy, the most important component of the cost of producing freshwater from seawater is interest payment on the loan. Obtaining financing at a good interest rate is important to achieve favorable water production cost. This will be an area that requires action in the finance, trade, and economic development ministries to achieve strong balance sheet and economic outlook over a number of years.

Aggressively decrease non-revenue water (NRW)

As detailed in the modeling in Technical Report II, decreasing NRW decreases the per m^3 cost of delivered water. With an expensive treatment technology such as desalination, it would not make economic sense if 30 to 45% of the treated water is lost as NRW (those values are current reported NRW in the Nile Basin countries except for Rwanda).

Summary

In summary, there is no *one-size-fits-all* approach to promote brackish and seawater desalination for long-term benefit. In almost every single country, collaboration among ministries overseeing municipal development, environment (marine and freshwater), health, and finance is necessary and beneficial.

Discipline in reducing NRW, steps to ensure long-term sustainability of groundwater resources, coordination with climate adaptation plans, and efforts to ensure strong economic growth and the concomitant ability to obtain good financing will facilitate favorable desalination water cost for the region.

PART I: CURRENT PRACTICES OF WATER REUSE AND DESALINATION

1.1. Introduction

Studies carried out by the Nile Basin Initiative has indicated that the degree of water shortage in Nile Basin countries may be more severe in the future. In addition, due to climate change certain regions receive precipitation that do not follow historical climate patterns and experience intra-annual water shortage. Therefore, an evaluation of potential freshwater sources to ensure a secure future is beneficial. As the technologies to reuse water or to desalinate brackish and seawater become more mature and the membrane treatment cost is decreasing in general, it is projected that water reuse and/or desalination could play an important role, particularly when projecting 20–30 years into the future. This project studies existing water reuse and desalination practices in Nile Basin countries and worldwide and use the information to project scenarios of water reuse and desalination in the near and distant future.

1.1.1. Classification

A preliminary survey of literatures on technology, economic, and policy aspects of water reuse and desalination worldwide and Nile Basin countries was conducted. Classification of water reuse and desalination can be based on the type of wastewater to be collected, on the treatment method, or on the target purpose in which the water is being reused for. In this project, the classification for water reuse will be based on the collection method. The classification for desalination is based on total dissolved solid (TDS) or salt concentration.

Further research on worldwide practices indicates it would be useful to further classify reuse of municipal water to two categories, potable and non-potable, to further take into consideration the differences in policy and implementation in these two categories. Therefore, overall the classification for this project includes 6 categories:

(i) Reuse of municipal water for non-potable use, these uses include agriculture, industry, and landscaping;
(ii) Reuse of municipal water for potable use;
(iii) Reuse of industrial water;
(iv) Reuse of agricultural drainage water for agricultural purpose;
(v) Desalination of seawater, usually defined as desalination of water with TDS > 33,000 ppm, even though the average seawater salinity is 35,000 ppm.
(vi) Desalination of brackish water, defined as containing 500 to 30,000 ppm salt (0.05 to 3.0 %). Brackish water often is found in estuaries, mangroves, and saline groundwater source.

1.1.2. Limitations on cost information

Because quite a number of the water reuse and desalination in the Nile Basin countries are at the beginning phase (budgeted but no tender awarded) or currently at small-scale, the cost for water produced (at a scale to actually make an impact on water supply) and a number of the lessons learnt are extracted from worldwide examples.

1.2. Water reuse in general

In the water cycle, which is also known as the hydrologic cycle or the hydrological cycle, water moves continuously above and below the surface of the earth. Water evaporates from the ocean or other water bodies, condenses to forms clouds, precipitates as rain, snow, or hail, and then infiltrate soils, flows in groundwater aquifer, or flows downstream in rivers or temporarily resides in lakes or other water bodies.

With human beings and other natural plants and animals that consume then release waste, the water is continuously used by one group of users and then reused by downstream users. Water reuse had in fact occurred for many generations and with the lower density of population in centuries past, the dilution process by the river and the natural solid removal through settling, adsorption, and absorption rendered the addition of waste imperceptible to human vision or taste.

The population of the world has increased 40-fold from 2,000 years ago, while the amount of freshwater available has not. In fact, due to pollution, the total available freshwater has probably decreased. Meanwhile, the available freshwater per capita has definitely decreased because of the population increase.

In many regions that lack proper sanitation or have insufficient wastewater treatment, multiple sources of untreated wastewater (unplanned wastewater discharge) is being released into drains and waterways. Such water eventually makes its way into surface or groundwater system and the culminative large volume of untreated water cannot effectively be diluted or absorbed by natural means. When downstream population use the water, they can be exposed to high pathogen and contaminant levels and resulted in higher rates of illness and loss in economic productivity. Such de facto reuse is termed *unplanned water reuse* and have been documented in several Nile Basin countries and [1] [2] [3] other countries in the world.

To protect the health and safety of downstream users, to preserve the health of ecosystem, and to ensure the availability of clean water for future generations, wastewater treatment has to be in place for effective, economical integrated water management system.

In the prevalent water management practices worldwide, water reuse is defined as the use of *treated* wastewater for beneficial purposes, which increases a community's available water supply and makes it more reliable, especially in times of drought. The term "planned" is usually left out from the phrase, with "water reuse" implying the planned use of treated wastewater.

1.2.1. Reuse of municipal water for non-potable purpose

Municipal water reuse for non-potable purpose in Nile Basin countries and other parts of the world

As the water scarcity increases due to increase in population increase and frequency of drought, water reuse for non-potable purpose is widely practiced in many countries such as the United States, the European Union, and MENA (The Middle East and North Africa) countries.

To reuse the water for non-potable purpose, a system for wastewater collection is a prerequisite. After collection, the water is partially treated, i.e., not to human potable standard, but to a standard deemed adequate for the non-potable purpose chosen. These chosen purposes include but are not limited to landscape irrigation, agriculture, wetland recharge, and industrial uses.

In 2011, CEDARE published a 2030 strategic vision for treated wastewater reuse in Egypt. In the report, it was estimated that out of about 7 billion m^3 of wastewater produced per year in Egypt, 3.7 billion m^3 was untreated [4]. The CEDARE report advocated for building water treatment capabilities, new codes, and to reach the goal of treating up to 5.8 billion m^3 of wastewater (up to secondary treatment) by 2030 for agricultural purpose.

It was not clear whether the vision was adopted by the government, though In a separate publication, it was estimated that in 2011, Egypt generated 8.5 billion m^3 of wastewater, with 4.8 billion m^3 treated, and 0.7 billion m^3 of the treated wastewater reused successfully [5].
In 2016 further work on drafting new water codes was conducted [6]. In addition, currently Egypt has several projects planned in order to reuse municipal water for non-potable purposes.

In 2019 one of the largest and most expensive water treatment projects in Egypt was announced. This \$739 million, 5 million m^3/d plant will treat wastewater from the Bahr-al-Baqr drainage system and be used for agricultural purpose in the Sinai Peninsula [7]. The capital cost for the facility is thus \$148/m^3/day, with the actual water production cost not yet known [7]. This capital cost does not include conveyance as the irrigation and drainage system in that area of Egypt is already built.

The water, sanitation, and reuse effort in the city of Kampala, Uganda, has received considerable attention in several publications by the International Water Association [8][9]. According to the International Water Association, up to 87,000 m^3 of the wastewater that is treated is being reused [8]. It appears most of the reuse is either unplanned or for wetland recharge though after reviewing more than 10 documents and contacting personnel at the Uganda National Water and Sewerage Corporation it is still not possible to obtain exact breakdown. This may be because the several new sanitation plants are still being built and budgeted [10], while the population is growing rapidly, making the water infrastructure constantly in flux.

In Addis Ababa, Ethiopia, it was reported that there was still much disposal of wastewater into rivers and streams flowing through the city [11]. Farmers who use the Akaki River for irrigation ended up reusing the municipal water in an unplanned manner [11]. Independent condominium owners sometimes invest in their own water treatment and water reuse facilities. For example, Emefcy Group Limited supplied a \$400,000 membrane aerated biofilm reactor to a condominium complex [12]. In 2016, the Water and Sanitation Authority in Addis Ababa opened an international tender for a 10,000 m^3 water treatment to be reused in agriculture [13]. The project was completed in 2018. Both facilities are relatively small, and potentially because of the need to save space in the condominium in the first case, resulting in the relatively more expensive treatment choice of membrane bioreactor.

Technologies

The basic technologies used for treating municipal water for non-potable purpose can be the same as those used in conventional water treatment and sanitation practices. In the primary treatment step, a sedimentation process is used to remove solids and sludge. Secondary treatment is then employed to substantially degrade the biological content. This can be achieved using aerobic biological process, trickling filter, activated sludge, etc. The treatment steps that follow will depend on the water quality standards for which the non-potable use is subject to.

Economy

The total cost for municipal water reuse for non-potable purpose is the sum of the cost of water treatment, cost of infrastructure (piping and pumps) and the cost of the electricity for pumping. Because the water is not treated to potable standard, a separate piping and storage system for the treated water is necessary in the typical centralized water and wastewater treatment system present in developed countries. In some cases, the cost for the separate piping and storage infrastructure can be larger than the treatment cost. Because the conveyance cost and brine disposal depend on terrain, other relevant local conditions and regulations, the generalization of the overall cost of municipal water reuse for non-potable purpose can be complicated.

If the municipal wastewater was treated for industry use, a survey of the practice around the world gave a range of USD \$0.35 in China to \$1.3 in Honolulu, USA [14].

For municipal water reuse for landscaping and agriculture, the following discussion will first focus on treatment cost, followed by a discussion of the economy of scale and the conveyance cost.

A study on several European cities estimated that using treated wastewater for landscaping cost approximately USD \$0.14–0.62/m^3 (estimated using an exchange rate of 1 Euro to 1.1 USD). Another report by the European Union estimates that treatment cost itself ranges from USD \$0.09 to \$0.23 [15]. An in-depth study conducted in the United States estimated municipal water reuse for non-potable purpose has a cost of approximately USD \$0.46/m^3 [16]. These studies give a range of USD \$0.1–0.6/m^3 for treatment.

One way to lower the treatment cost is to take advantage of the economy of water treatment, which applies to even some of the most basic step, such as coagulation that is used to assist the sedimentation process. For example, Figure 1 below shows the economy of scale of the coagulation process.

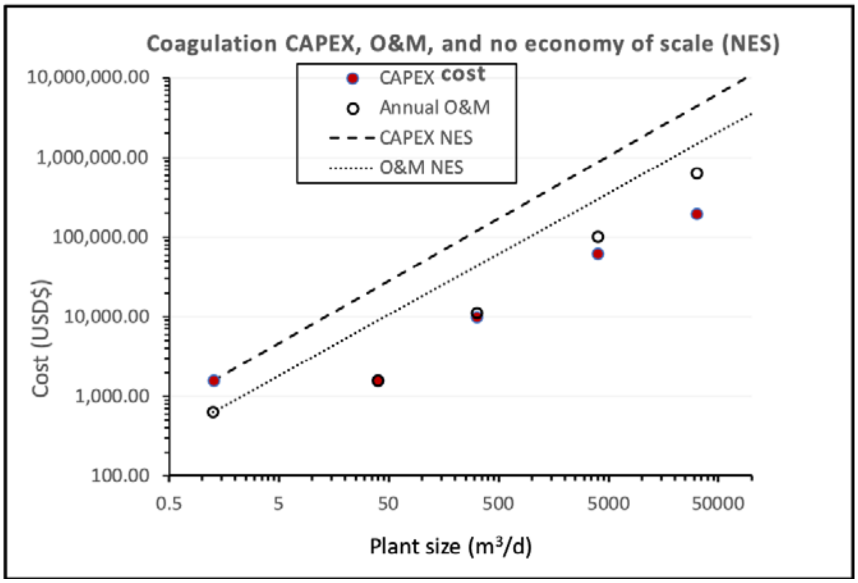

Figure 1. Capital cost (red solid symbols) and annual O&M (empty black circles) for the coagulation process compared to capital cost and O&M without economy of scale (black dashed and dotted line, respectively).

With the economy of scale issue, one might conclude that a small number of large treatment plants would provide favorable cost. However, when the agricultural irrigation is outside of the municipal area besides the cost of separate piping for non-potable water described above, there is additional cost for conveyance and for the energy to pump the treated water to agricultural land.

The energy for conveyance could be 0.5 to 1.0 kWh/m^3 or even higher [15]. Assuming an electricity cost of \$0.1 per kWh, then the treatment and electricity cost together is \$0.33/m^3. The infrastructure cost is highly dependent on terrain and distance from the municipal area to the agricultural area, which can be in the range of \$0.1 to \$0.5/m^3 assuming it is not highly hilly terrain.

Overall the cost for reuse of municipal wastewater (including conveyance) for agricultural purpose in European countries can range from a low of \$0.24/m^3 (taking the low of the treatment, electricity, and infrastructure) to a high of \$0.83/m^3. A publication by the International Water Association put the high estimate at \$1.6/m^3 in cases where long conveyance and high brine disposal cost are in involved [17].

In summary, it will be necessary to properly balance treatment and conveyance cost, i.e., examining and experimenting with water treatment and wastewater treatment facilities are decentralized, e.g., intermediate in size scatter around the municipalities, resulting in fewer separate conveyance (pipes, small canals) being required.

For municipal areas where there are large areas of green space, e.g., parks, farms within the city, reuse of treated wastewater for landscaping, agriculture, etc. can be an excellent option with the relatively low treatment cost and minimal conveyance required.

Issues

Water quality

Proper treatment would result in water of adequate quality for the intended purpose. In most cases, using treated wastewater for non-potable purpose is preferable to using untreated wastewater, which is de facto, but unsafe reuse.

Environmental

Water for non-potable purpose can be beneficial for the environment if the water is treated properly to an adequate quality to preserve a healthy, sustainable environment. The water quality needed would depend on the intended purpose of the reuse.

Legal & institutional constraints

Water reuse for non-potable purpose can involve considerable coordination. Often the standards for drinking water, agricultural drainage water, wastewater discharge (both volume and the chemical and biological content be within a certain limit) are set at the national level. Therefore, successful water reuse involves the coordination of the departments of agriculture, health, water and/or natural resources, environment, infrastructure, and finance. Each of these ministries can have jurisdiction on parts of the project and/or national plan and an integrated water resource management approach will be critical for its success. For large projects that require long term planning of the country’s monetary budget and potentially foreign aid and/or loan, agreement and cooperation between the Ministry of Finance and Foreign Affairs would ensure the country’s long-term interests are being prioritized and articulated in a united fashion.

Acceptance

Water reuse for non-potable purpose is generally well-accepted by the public.

Measures of success

A successful program would treat the water to an appropriate standard for the intended purpose, e.g., agriculture. It would help improve the health and sanitation for the region at an appropriate cost.

Findings and key lessons learned

Reusing wastewater for agriculture has been reported to increase crop yields [18], with earlier study that showed that with properly treated wastewater the benefit-cost ratio is on the order of 1.2–2.2, depending on the type of crops and treatments [19].

1.2.2. Municipal water reuse for potable purpose

Municipal water reuse for potable purpose in Nile Basin countries and other parts of the world

Many scientists and policy makers believe municipal water reuse for potable purpose is necessary in many regions of the world in the future. Some of the most successful countries in municipal water reuse are Singapore and Namibia. In Singapore, currently water reuse supplies 35% of the water need and is projected to supply up to 55% of the water need in the future [20]. In Namibia, direct potable reuse has been practiced for 50 years [21]. Currently there does not seem to be active/documented water reuse for potable purpose in the Nile Basin countries.

Technologies and trends

To produce water suitable for potable purpose, after the primary and secondary treatment processes described in the "Municipal water reuse for non-potable purpose" section, the water can go through tertiary and even fourth step. In all cases a final step in disinfection and then directly recycled or blend with incoming treated "freshwater" for direct potable reuse [22], [23]. Several studies have shown this option to be economically efficient, since it eliminates the need for much additional piping, as discussed in section 2.1.3 of this document (Municipal water reuse for non-potable purpose—Economy).

With the general improvement in membrane technologies such as reverse osmosis that is used in desalination and can also be used in water reuse, the cost of water reuse for potable purpose is expected to drop with time.

Economy

Estimated levelized cost of producing water for potable purpose from wastewater cost approximately \$0.7–1.6/m^3 [24]. The low end values are for water reuse facilities in Namibia, which uses conventional methods that do not require extensive brine disposal; and Singapore, which uses membrane techniques but has favorable brine disposal [21].

Issues

Water quality

The treated wastewater can be of a quality as any freshwater [25][23], provided proper treatment has been conducted and the conveyor system is of sufficient quality, e.g., not containing multiple broken junctures where contaminants can seep in.

Environmental

Reuse of municipal water for potable purpose overall has positive environmental effect by minimizing the disposal of wastewater to the environment. The process may produce brine, if a membrane technology is used. Proper treatment of the brine would be necessary to minimize environmental effects in an inland area (see section 4.2.4.2 Brackish water desalination--Environmental).

Legal and institutional constraints

Municipal water reuse for potable purpose do have obstacles, the primary two being public perception and coordination among different agencies. Even though highly treated wastewater is in fact biologically and chemically purer than what society generally associates with “original” or “pure fresh” water (e.g., water coming from a stream) [25], [26], much of the population worldwide still generally considers treated wastewater to be inferior [27], [28].

The second impediment to municipal water reuse is in many aspects bear resemblance the institutional set-up required for municipal water reuse for non-potable purpose. In this case, successful water reuse involves the coordination of the departments of health, water and/or natural resources, environment, infrastructure, and finance.

Such coordination is not limited to the national, large project level. At the local scale, there need to be agreement among water utilities, water wholesalers and retailers (in a more decentralized system), wastewater management companies, public work officials, and the communities involved. If the waste collection and water treatment are owned and operated by different companies, then the two entities would need to reach commercial agreement on pricing, and the funding of network that convey wastewater to treatment site, potential further conveyance of partially treated water to tertiary and/or advanced treatment to potable standards, or potential conveyance to intermediate “storage” site such as groundwater recharge or reservoir.

In general, when there are many agencies and departments involved, the more complex the negotiations could be. There could also be the potential of disagreement over financing and responsibilities, i.e., which agency controls the management of funds for infrastructure build and which entities are responsible for the final delivery of services and the quality of the services rendered. These issues need to be clarified clearly and at the early stage of the planning process.

In the implementation of water reuse in places such as Singapore, where the population density is high and decisions tend to be centralized within the government, the incentives to cooperate can be chiefly came from government studies. Along the same vein, the decisions on how to implement the overall quite complex infrastructure could strictly be based on technology and economics data. In places such as California, the USA, the pressure for the multitude of local organizations and water providers to cooperate came chiefly from water scarcity (e.g., drought that extended from 2011 to 2016), the need to improve the reliability of water supply in addition to existing sources (e.g., from the Colorado River and snow melt in the Sierra Nevada), and environmental impact of wastewater discharge [25].

Acceptance

To overcome the potential negative perception and reporting of the quality of water reuse, some key lessons from countries where successful water reuse has been implemented are:

A strategy of effective education and public awareness needs to be initiated and carried out broadly, ideally, at least several years before the implementation of the water reuse project. In survey conducted in California, USA, residents who are educated about the advanced wastewater treatment process are much more likely to view water reuse for potable purpose favorably [27].

Such educational and public awareness campaigns can include advertisements, social network campaign, community outreach and engagement, tours of facilities to experience water reuse firsthand [29]. In the case of water reuse in Singapore, the Prime Minister himself kicked off the campaign and created a photo op by drinking the recycled water, called NEWater by the Singapore government, in a national parade in 2002 [30].

The term “NEWater” also illustrates the tactic certain water utilities used to emphasize that it is water that has been purified, and to simultaneously deemphasize the treated water connection with sewage and wastewater.

Prior to the public awareness and educational campaign, it is relevant and useful to conduct surveys to understand more the local conception of water reuse. A report published by the WateReuse Foundation contains results of a previous study and provide a list of questions as examples that can be used in such a survey [31].

In a separate study conducted by the University of Queensland, the researchers found that communication campaigns that emphasizes low risk of drinking recycled water can be the key to increasing public support [32]. However, the study was relatively small. More research on how to successfully integrate effective message and implementation of a new technology in different regions of the world would be useful.

To have the substance that support or “back up” any successful public education and awareness campaign, a prerequisite is successful implementation of the water reuse technology and proven positive track record of the local utilities or water treatment companies or authorities. In the case of Windhoek, Namibia, the wastewater to potable water treatment facility has been successfully operated for 50 years [33]. The successful operation instilled in the citizens of that city a confidence in their local water utilities.

Key lessons learned
Municipal water reuse can be particularly successful and even be the best choice for a densely populated area with limited water availability. There are several reasons that would be the case. From the perspective of wastewater being a resource, a densely populated area tends to produce large volume of resource, the wastewater. Recycling the water within the municipal area would minimize the cost of a separate set of piping for non-potable water and building a conveyor system to transport the water to agricultural areas that may be far from the municipality. Lastly, because of the economy of scale of wastewater treatment and recycling technologies, treating large volume of wastewater within the municipality is often cost competitive.

A second option for water reuse to potable water is to have the recycled water stored in an intermediate facility such as surface reservoir or groundwater [25]. This option has several advantages. One is that though there is an additional piping to convey the water to a reservoir or a groundwater percolation site, overall there is not the necessity of a separate set of piping to convey intermediately treated water to many separate locations (as in the case of conveying non-potable water to many different industrial sites or even further away to agricultural areas).

The other advantage of this configuration is that by having a step that separates the treated wastewater from the drinking water the public tends to receive the new set-up more readily. Lastly, the storage site can also serve to store for drought or low rainfall seasons and the production and consumption variability in a given year.

1.2.3. Industrial water reuse

Industrial water reuse in Nile Basin countries and other parts of the world
Worldwide the industries that are known to consume a lot of water include food and beverage, and the energy sector. The quality of industrial water available for treatment and reuse vary significantly, with certain industries, e.g., plating containing high metal content, while water and beverage industry containing high organic content. Consequently, there is a wide range of industrial water reuse possibilities. Many of the basic suite of technologies are similar to other types of water reuse technologies. The exact configuration and requirements for the treated water would vary in individual cases, which also affect the cost.

The “best” industries to conduct water reuse depend on the industries existing in a particular location. However, there are a few industries that are very common and usually site their facilities near a large water body to use freshwater—encouraging or regulating water reuse within the facilities of these industries would be tremendously useful to the water supply and sometimes water quality of the country. These water reuse schemes are:

- Boiler blowdown minimization and reuse [34]
- Demineralizer rinse water reuse: demineralizers are found in many industrial water operations to produce high quality water for use as boiler feedwater and other

industrial processes. The water used for rinsing the demineralizer can be reuse with onsite treatment [34]
- Food and beverage industry: many food processing, e.g., dairy processing and beverage bottling industry produce high volume of effluent. A survey by the WateReuse foundation found that reusing part of the water for process clean-up is relatively simple. The wastewater produced, if left untreated, can result high biological oxygen demand (BOD) and environmental cost, and on-site water treatment and recycling using conventional biological treatment or membrane bioreactor could be potential options [35].
- Textile industry can use a large quantity of water and an analysis shows that wastewater treatment for reuse in this industry can be cost effective [36].

News of individual plants being installed in certain countries are available occasionally. For example, Aquatech supplied an engineering solution that treat a combination of wastewater and raw water intake from the Nile for an ethylene plant in Egypt in 2016. This reduces the freshwater demand of the plant by 70%, from 62,000 m^3/day to 19,000 m^3/day.

However, to obtain quantitative region wide estimate of industrial water reuse in the Nile Basin countries, the country advisors will need to provide statistics collected for each country so that the data can be tabulated and analyzed.

Technologies

The quality of the industrial wastewater and the treatment necessary depends on many parameters:

- the quality of the raw water entering the process;
- the industrial process that generates the water, e.g., wash water, process filtrates, process backwashes, boiler and cooling tower blowdowns;
- reactions and chemical additives used in the industrial processes;
- temperatures of the water;
- pressure of the industrial process, which affects the pressure of the steam, if it was used or produced in the process;
- quality of the water needed for the next operation.

Some of the basic building blocks of the technologies used are similar to those used in municipal water reuse, e.g., membrane separation. The specific technologies depending on the water source and the intended purpose. An article by Pan et al., e.g., listed 28 different technologies [37]. A civil or environmental engineering water treatment textbook will contain the detailed scientific principles describing each technology.

Economy

The actual process cost depends on the treatment needed, size of the operation (size of the treatment and internal piping reconfiguration necessary), the ability of a particular industry plant to raise funds (interest rates, payment terms), shipping cost from the manufacturer to the site.

For boiler blowdown, the wastewater is still very hot. By minimizing the boiler blowdown water and having a well-designed wastewater recycling system would recapture a sizable portion of the thermal energy [38]. Therefore, just minimizing boiler blowdown can in fact ***saves*** the plant owners money in the long term [38] because (1) less freshwater is needed, incurring saving in water cost, (2) the thermal energy recovered means less expenditure on fuel cost. By incorporating the water reuse, there can potentially be additional savings in regions that charge a fee for wastewater discharge.

To achieve this saving, the owner of a thermoelectric plant that uses boiler blowdown would generally need a capital investment of \$1,000–\$2,000 per m^3/day for boiler water treatment, e.g., installation of an ultrafiltration system [39] and a control system to minimize boiler water blowdown.

Issues

Water quality

For boiler blowdown water, because the wastewater is very hot, it can have high ion concentrations as it accumulates impurities as it is being conveyed from one part of the facility to another. The wastewater, if not treated properly before being recycled, can cause scaling and even corrosion problem.

For water used in food and beverage industry, proper sanitation practice is important to prevent spread of germs if the water is being reused for further rinsing or usage.

Environmental

In general, treatment and reuse of industrial wastewater, or at the minimum treatment of industrial wastewater before being discharged are beneficial to the environment. This lessens the contaminant load of the aquatic systems. In addition, once through boiler blowdown water can cause thermal pollution that is harmful to fish and other aquatic organisms, besides wasting valuable thermal energy and having higher carbon footprint.

Legal and institutional constraints

A proper industrial wastewater reuse policy is important to balance two aspects of critical importance: one aspect being enhancing water availability and environmental quality through water reuse, the other being not to impose excessively strict regulations that can discourage small businesses from flourishing. For example, many food and beverage industry operators, e.g., bakery and cheese makers in developing countries are still small-scale, low profit operations. Small-scale water reuse equipment tends to have high capital cost per volume of water treated. Focusing on small-scale water users at the early phase of encouraging industrial water reuse could disincentivize small entrepreneurs.

Thermoelectric power plants are big water users. Once through power generation cooling system abstracts 43–168 l/kWh power generated at a consumptive loss of 0.38–2.1% of water abstracted [40]. As described in the economy section, a properly installed water reuse system in a thermoelectric plant that uses boiler water blowdown can actually save money in the long term. Regulating or encouraging the power industry to reuse the water is thus likely to be win-win in several fronts—saving water, beneficial to the environment, while saving the thermoelectric generation company money.

Acceptance

One impediment to increasing industrial water reuse is certain companies treat their processes as proprietary and hence not willing to share success stories. Government recognition and awards, economic incentives may smooth the path for more “share and learn” among corporations.

Lessons learned

On the government side, there are a number of policies that can promote industrial water reuse by individual facility owner and operator. In a white paper commission by GEWater [41], it was found that the following policies can stimulate industrial water reuse:

- Education and outreach: government program that provide information on treatment and reuse opportunities; awards and certification programs are examples of programs that can encourage individual industrial owner and operator to embark on further action in water reuse.
- Economic incentives: this could include appropriate pricing of the water, in particular for high volume users to incentivize the industry owners to embark on water saving and water reuse measures. In addition, subsidies or tax write-offs for water reuse could be an effective measure to encourage water reuse in industrial sector.
- Mandates and regulations: stringent enforcement on water discharge and regulations that require industries to reduce water usage are effective in changing the industry actions.

1.2.4. Irrigation drainage water reuse

Irrigation drainage water reuse in Nile Basin countries and other parts of the world

Because of the large size of withdrawal for agricultural purpose, reuse of irrigation drainage water is often viewed favorably. Irrigation drainage water reuse refers to the capture of excess water from agricultural land, the storage of the water (in a pond, reservoir, drainage ditch), and the use of the stored water to irrigate crops. In both the “open” and “closed” systems described below, both an agricultural drainage system and a conveyor system to collect and move the used drainage water need to be in place for drainage water reuse.

The “open” irrigation drainage water recycling system is practiced frequently in Egypt. In this case, the drainage water is captured in a main collector drain and is then used to irrigate a different field. Mixing of freshwater with the drainage water can help bring higher quality water into the field. Depending on the slope gravity itself might suffice. In such an “open” system the basic infrastructure is in place, though as the salinity increases, more and more treatment prior to reuse will need to be implemented to protect the long-term fertility of the farmland.

In a direct use or closed loop system, the drainage water is recirculated within the same field. Usually a pond is used for water storage. In this case the cost for drainage water would include pond construction and water conveyance. In estimating the cost of pond construction, literature in the aquaculture can potentially be used as an estimate.

Among the Nile Basin countries, Egypt has the most extensive irrigation drainage system and the most widespread use of irrigation drainage water recycle. The estimate of drainage water reuse is 3 billion m^3 in 2002 (Box 9, ref [42]), and 6 billion m^3 in 2013 [43]. However, the implementation of irrigation drainage water recycle in Egypt needs to be improved to ensure sustainable agriculture and long-term soil fertility. Many municipalities and industries in Egypt often use agricultural main drains as a conduit to dispose of their untreated wastewater [42]. As a result a number of the key indicators of water quality, e.g., total dissolved solid (TDS), biological oxygen demand (BOD), chemical oxygen demand (COD) are much higher than the limits set in the law [42].

In addition to the centralized official drainage water reuse, there is significant unofficial reuse in Egypt, where farmers pump water from the irrigation drainage collector drains directly onto their fields [42], which may inadvertently led to degradation of soil quality.

Technologies

Certain regions may treat the drainage water before it is being reused, while other regions may reuse the drainage water if it was determined that the salinity content is not too high to cause soil salinization problem and the water is biologically safe. If the drainage water can be minimally treated to remove salts, it could potentially provide benefits to the crop and decrease fertilizer needs for the irrigation of a different field. If pesticide is applied and the drainage water is captured and then reused in the same field that is likely not a problem [44]. However, if the pond serves to capture runoff from multiple fields and if the evaporation rate in the area is high, it could potentially be a problem and more site-specific research is necessary.

Economy

The cost for irrigation drainage water reuse depends on the local conditions, including topography, aridness, drainage water quality, and treatment needed before reuse. In cost analysis conducted by The San Joaquin Valley Drainage Implementation Program and the University of California Salinity/Drainage Program it was concluded that it could be economical to reuse drainage water [45]. However, the specific economic benefit depends on the site.

According to FAO, after the construction of irrigation system, the main cost of irrigation is operation and maintenance of pumps. In a very rough estimate of the cost irrigation drainage water reuse, it is assumed that the drainage system is already in place, and the type of reuse is the “open” irrigation drainage reuse commonly practiced in Egypt. In such a case, the new or additional cost associated with reuse is similar to that of irrigation, which is pump operation and maintenance [46]. Since solar irrigation pump has been cost competitive, a very rough estimate of the capital cost associated with drainage water reuse can thus be made by using the capital cost of a solar water pumping system. Currently the main data for this type of pump is in South Asia, which indicates a range $84–780 per hectare [47].

Issues

Water quality

The reuse of agricultural drainage water involves water that is potentially rich in not just pathogens, may contain additional salt, fertilizers, and pesticides. In certain countries, a fee is charged for disposal of post-drainage water. In the San Joaquin Valley in California, USA and several other areas there are reports of drainage water with high boron and selenium [42], [48], which requires further treatment.

Environmental

In addition to the centralized official drainage water reuse, there is significant unofficial reuse in Egypt, where farmers pump water from the irrigation drainage collector drains directly onto their fields [42], which may inadvertently led to degradation of soil quality.

In Egypt, it has been reported that 37% of the irrigation area is already subject to salinity problem [42] . This is partly due to inadequate drainage e (resulting in waterlogging) and partly due to the use of low-quality water (e.g., untreated municipal waste) for irrigation [42]. In these areas, further irrigation drainage water recycling without treatment is not advisable. To alleviate the salinity problem, the irrigation drainage water will need to be desalinated. Though the cost of brackish water desalination has dropped significantly, the large volume of water needed for irrigation potentially still make treatment of irrigation drainage water uneconomical.

Legal and institutional constraints

The potential negative consequences of some of the reuse practices indicate that an integrated, carefully regulated process needs to be in place to control salinity, waterlogging, water pollution, and long-term health of the land. This is an area that transboundary cooperation could be useful. Some of the Nile Basin countries share similar geology, climate, and economics, as a result lessons learned from a Nile Bain country may be much more applicable and transferable than lessons learnt in other regions.

Acceptance

Agricultural drainage water reuse is accepted by the farmers.

Measures of success

A successful program would have efficient drainage water reuse, proper implementation of salinity control when necessary to minimize soil salinization problem.

Lessons learned

Depending on the need of a country or region, agricultural drainage water reuse does not have to be all go towards traditional or conventional agriculture. More research and experiments are in place to introduce salt tolerant crops in parts of the farm or closer to the delta. Aquaculture and shrimp farming have also proved economically successful in a number of countries.

Despite the soil salinization problem, Egypt has been quite successful in drainage water reuse. For example, Egypt has the largest aquaculture industry in Africa [49] even though it is an arid country. The aquaculture water is supplied mostly from reuse of agricultural drainage water [50]. Fish reared in drainage water could potentially accumulate heavy metals, however.

1.3. Greywater use

Greywater use in decentralized systems, e.g., individual household and condominium complexes, refers to the use of water for laundry, dish washing and other household activities that produce greywater non-potable uses such as landscaping, agriculture, or washing of parking lots.

In individual household, greywater use is essentially the same as unplanned or unofficial water reuse that is already practiced in many countries. In certain condominium complexed where the water is treated per the homeowner association then the type of greywater use is more similar to water reuse for-potable purpose. However, the small scale and decentralized nature of this category make estimate on water savings challenging except in municipalities where extensive data collection and survey are already in place.

1.4. Desalination general

Desalination is a process that takes away mineral components from saline water. Desalination is typically classified by the salinity of the water being treated, with brackish water classified as 500 to 30,000 total dissolved solid (TDS), and seawater as greater than 30,000 TDS. Brackish water can be found in estuary, saline surface water such as saline lake, and saline groundwater.

1.4.1. Seawater desalination

Seawater desalination in Nile Basin countries and other parts of the world

Seawater contains on the average 3.5% or 35,000 total dissolved solid (TDS). The Indian Ocean is the seawater source for Kenya and Tanzania; it has salinity between 32,000 and 37,000 TDS. The Mediterranean and the Red Sea are seawater sources for Egypt. They have salinity in the range of 38,000 and 36,000–41,000 TDS, respectively, because the rate of evaporation is higher than freshwater dilution from rivers in these two seas.

Several NBI countries have seawater desalination facilities or are embarking on more capabilities. Egypt currently has 58 water desalination plants, representing 440,000 m^3/d of capacity. Most of the plants are of relatively small size, e.g., the Dahab plant (at the Gulf of Aqaba) and Hurgada and Sharm El-Sheikh plant (at the Red Sea coast), all of which are seawater desalination plants. In the very near future, Egypt plans to build 35 new desalination facilities, contributing a total of 1,353000 m^3/d of capacity [51]. When all these plants are in operation, they can provide 0.5 billion m^3 of water per year to the country.

In Kenya, two contracts were awarded in 2018 by Mombasa County to build two desalination plants [52]: one at a size of 100,000 m^3 by day to be built by Almar Water Solutions, a Spanish company; the other at a size of 30,000 m^3/day, to be built in Likoni by the Aqua Swiss company. The combined capital cost for the two plants is USD$157 million, corresponding to a capital cost of $1,208/$m^3$/day.

Technologies

There are many methods to separate the salt content from the water, with thermal methods utilizing phase changes, i.e., boiling or freezing (in vacuum); and electrical methods in combination with specialized membranes for separating the ions from the water. Commercial, large-scale desalination has traditionally been conducted with reverse osmosis (RO), multi-effect distillation (MED), multi-stage flash distillation (MSF), and electrodialysis reversal (EDR).

Multi-effect distillation and multi-stage flash both consist of multiple stages of distillation, taking advantage of the difference in water boiling point as a function of pressure to recover as much of the thermal energy as possible. Because of the necessity to recover heat energy at relatively small thermal gradient, high quality, long lasting, heat exchanging material is needed. For MED, the process is often conducted at low temperature, e.g., 70 °C, to avoid corrosion and scaling, which introduces the necessity of pumps to create low pressure or partial vacuum.

Because of the high energy needed [53], large-scale thermal desalination is only practiced in oil-rich regions such as the middle east or in older, legacy plants, e.g., some in the Caribbean.

Most new installations of seawater desalination use the reverse osmosis (RO) technology, which is a process in which under an applied external hydrostatic pressure greater than the osmotic pressure, a solvent will pass through a porous membrane in the direction opposite to that of natural osmosis. For seawater, the applied external pressure needs to be at least 55 to 69 bars (800 to 1,000 psi). To improve the water recovery, certain plants operate a second stage at higher pressure, up to 138 bars.

Even though the membranes (whether RO or electrodialysis reversal (EDR)) can successfully separate out the alkaline salts (sodium chloride, etc.), often chemicals still need to be added to prevent scaling caused by alkaline earth salts, e.g., salts containing calcium or magnesium. The exact configuration will depend on the chemical make-up in the area and the operation parameters, e.g., water recovery of the plant (how much water is extracted from single or double pass of the seawater through the membranes). Such engineering decisions are decided on a case-by-case basis depending on the local geochemistry and regulations.

Economy

The cost of seawater RO desalination compared to thermal desalination technologies are shown in Table 1.

Table 1. Water production, capital, operation and maintenance, and energy usage of the three most common large-scale seawater desalination technologies.

Seawater desalination technology	Water production cost ($/m^3)	Capital cost ($/m^3/day)	Operation and maintenance ($/m^3)	Energy usage (kWh/m^3)	References
Seawater desalination	0.5–2.3	800–2,300	0.3–1.0	2.4–4.5 (Includes pretreatment & intake)	[54]–[56]
Multi-effect distillation (thermal)	0.5–1.0 (Achieved in oil-producing countries, i.e., low fuel cost)	1,750	Depending on fuel cost	1.5–2.5 electrical plus 150–220 kJ/kg thermal	[57]
Multi-flash distillation (thermal)	0.5–1.7 (Achieved in oil-producing countries, i.e., low fuel cost)	1,300–1,600	Depending on fuel cost	3.5–5.0 electrical plus 250–300 kJ/kg thermal	[57]

The cost of seawater desalination is heavily dependent on energy price and the interest paid on the capital. The capital in turn has a large economy of scale (Figure 2). Figure 3 below shows the approximate capital and O&M breakdown for seawater desalination. Actual cost breakdown will depend on the project, e.g., the actual fraction paid for energy is generally in the range of 40 to 55% depending on electricity tariff negotiated between the desalination facility and the local provider. The site design (intake and discharge configuration, permitting complexities and cost, etc.) can also influence capital quite substantially.

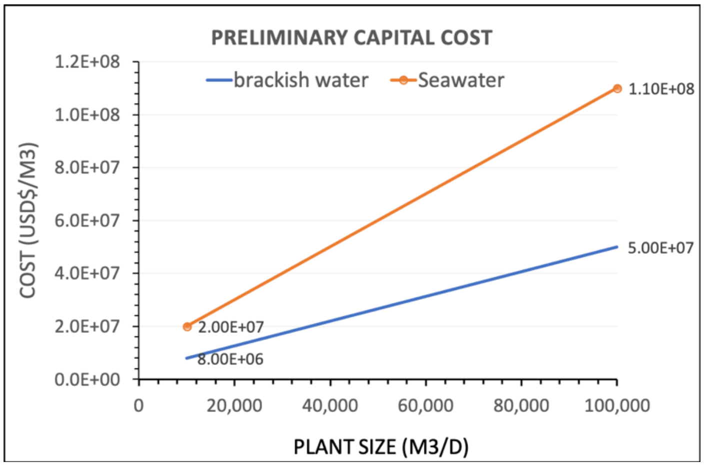

Figure 2. Capital cost of seawater and brackish water desalination as a function of plant size.

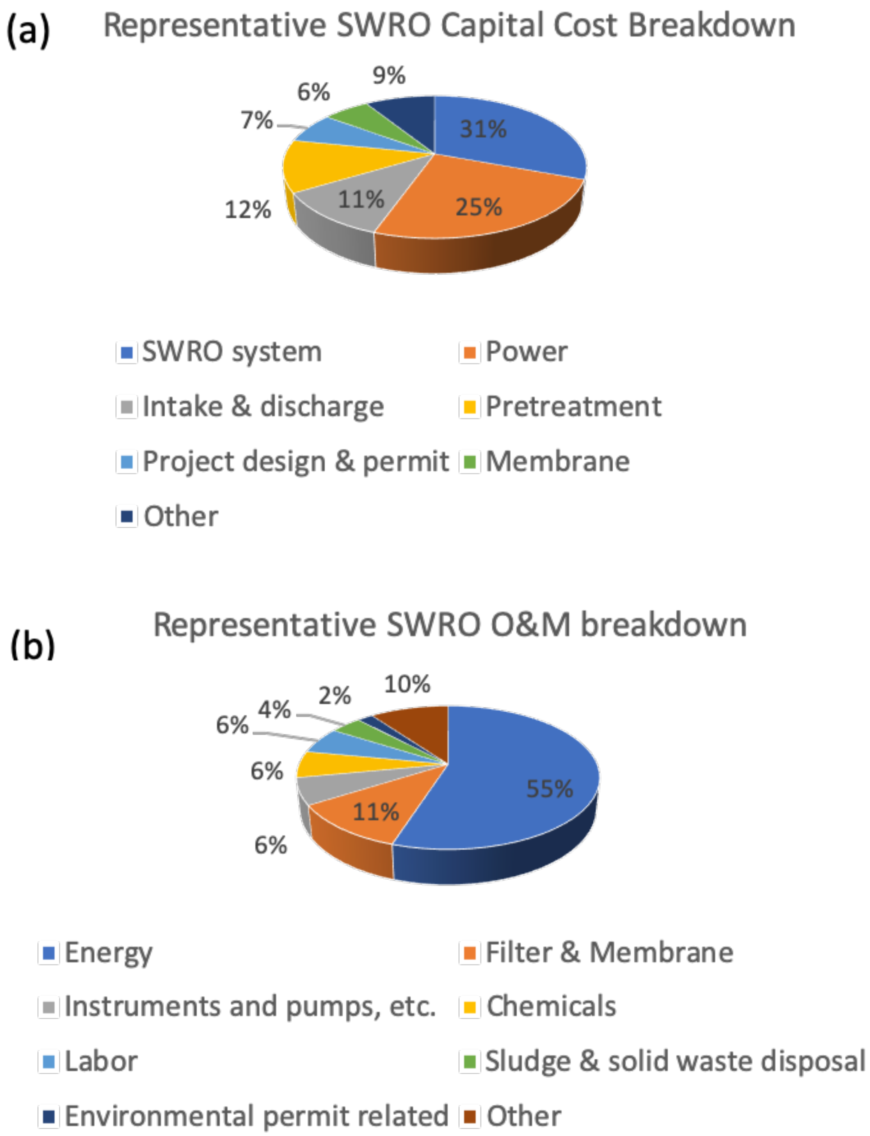

Figure 3. Representative capital (a) and O&M (b) cost breakdown of seawater desalination.

In the last 20 years, the RO technology has seen its price dropped significantly
With the combination of capital and O&M, the current best-in class water production cost for medium and large-size plants and the forecasted water production cost in 2021 and 2036−2050 together with the references are listed in Table 2.

In 2019, a new contract was awarded for a water production cost of USD \$0.49/m^3 in United Arab Emirates. Even though the plant does not have a dedicated renewable energy plant, a solar farm is being built in the same region and the low water production cost is partly due to the low electricity price from the solar farm.

Table 2. Estimated water production cost based on seawater RO as a function of time.

	2016 [58]	2021 forecasted [58]	2019 lowest	2036-2050 forecasted [58], [59]
Cost of water (USD $/m^3)	0.8–1.2	0.6–1.0	0.49	0.3–0.5
Capital (USD $/m^3/day)	1,200–2,200	1,000–1,800		500–900

Issues

Water quality

The water quality produced from reverse osmosis or thermal desalination is free of chemicals and germs.

Environmental

The concentrate or brine produced from thermal desalination process is of higher temperature than ambient, which can be harmful to the marine life and is a source of thermal pollution. The high carbon footprint of the process results in high emission of greenhouse gas.

The concentrate or brine produced from membrane processes is of high salinity, low oxygen content, and can contain chemicals added during the pretreatment step (see section 4.1.2). Disposal of the brine can cause problems in particular if there are corals and fisheries near shore [60]. Proper design to carry the brine further out to the sea could sometimes alleviate the problem.

Legal and institutional constraints

In areas where seawater desalination is the main viable choice, and where prices are not of major concern, then the location, design of seawater intake, and brine disposal are often the next main negotiating points with the Ministry of Environment or other equivalent ministries. This is often a circular process, as seawater intake and brine disposal can affect the overall price tag. In regions where environmental regulations are stringent, e.g., California, USA, the environmental constraint can turn out to be the most significant part of the negotiations [61].

Acceptance

Seawater desalination generally is well-accepted by the local population, particularly in areas where water is scarce, and the desalinated water is the only practical freshwater source.

Measures of success

A successful plant would be one that is well-designed and can operate to the expected life (20 years or more) with as low environmental impacts as manageable or agreed upon.

Lessons learned

In many seawater desalination plants, a build-own-operate type of contract is negotiated, i.e., the contractor would build then operate the plants for a number of years. The water produced is sold at an agreed upon price. This type of contract often would produce water at the lowest price. This is partly because the build-own-operate type contract provides incentives to the contractor to produce water at the lowest price possible, and also because of the complexity of seawater desalination operations, resulting with the cost can being more predictable when an experienced operator takes on the pilot testing and determination of operation parameters.

Because electricity is a major component of the seawater desalination, negotiating electricity price and guaranteed electricity deliverance can be a major part of the contract negotiations.

1.4.2. Brackish water desalination

Brackish water is classified as water containing 500 to 30,000 total dissolved solid (TDS). It is not as saline as seawater, but it is still too saline for human consumption or agriculture in general. Brackish water can be found in estuary, saline surface water such as saline lake, and saline groundwater.

Brackish water desalination in Nile Basin countries

Compared to seawater desalination, the use of brackish water as a water source is of relatively small extent worldwide. However, according to Fluence, the use of brackish groundwater desalination is on the rise [62].

A number of Nile Basin countries have saline groundwater resource, namely Egypt, Ethiopia, Tanzania, Kenya, and Sudan (deep brackish groundwater in the case of Sudan). Figure 4 below shows groundwater and brackish groundwater that has salinity more than 5,000 TDS or 5 g/l. It does not include brackish groundwater in Sudan, e.g., because the aquifer close to the surface in Sudan contains freshwater, while saline water in the deeper Nubian Sandstone Formation contains only local pockets of higher salinity [63].

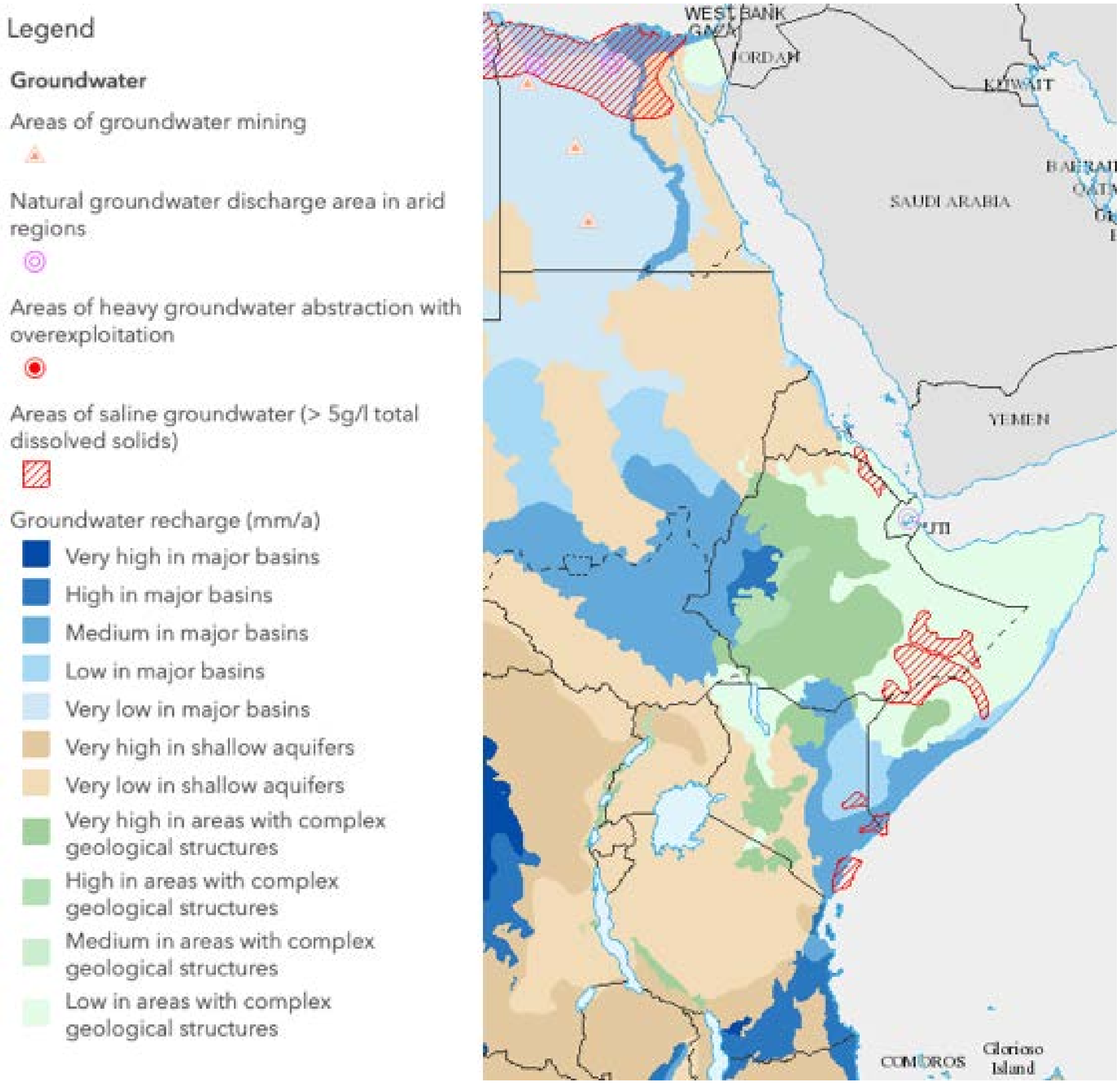

Figure 4. Groundwater resources in Nile Basin countries. Areas with red dashes contain groundwater with salinity more than 5 g/l [64].

There are a number of brackish water sources in Egypt, e.g., the Nile Valley aquifer with a salinity of < 1,500 ppm in the south and closer to 5,000 ppm at the delta; the renewable Coastal Aquifer with a salinity of 1,000–6,000 ppm at 0–70 m depth; and the Nubian Sandstone Aquifer with a salinity of 1,500–3,500 ppm at 0–30 m depth [65]. A FAO report shows an estimated renewable groundwater resource of 6 billion m^3, though there was no breakdown of brackish vs. freshwater in this estimate [42]. The non-renewable Nubian Sandstone Aquifer at varying salinity depending on depth and location is estimated have an exploitable volume of > 100 billion m^3 [65]. Because it is a fossil aquifer, withdrawal from the Nubian Sandstone will need to be carefully planned and monitored.

Most current brackish groundwater desalination installations in Egypt are of small-scale, generally ranges between 500 and 10,000 m^3/d [65]. In the long term, one of the areas in Egypt where brackish water desalination could be economical and sustainable may be the coastal area near the Red Sea. Part of this water is at shallow depth or even occurs as springs, therefore the cost of pumping the groundwater to the surface is relatively low. The brine and concentrate can be pumped into the sea without excessive cost. Desalinating the brackish water will take much less electrical energy than desalinating the high salinity seawater in the Red Sea. However, careful management is necessary to prevent saltwater intrusion from the sea, which can degrade the brackish water quality.

Another country where brackish groundwater desalination has been explored is Ethiopia. In 2014, USAID funded a small-scale brackish water desalination in the Afar region [66], an area where freshwater has to be trucked in.

Technologies

Brackish water desalination can be conducted using similar technologies as seawater desalination: distillation, reverse osmosis, and electrodialysis reversal (EDR). Unlike seawater, however, EDR could potentially be more cost advantageous since the power consumption of EDR is proportional to the salt content of the water. Because brackish water has lower salinity than seawater, the electricity needed can be significantly less than that to desalinate seawater, resulting in lower desalination cost.

Economy

The estimated cost of brackish water desalination is in the range of USD\$0.3–1.1/m^3. A pilot test of a new brine discharge technology (see Section 4.2.4.2) suggests a cost of \$0.6 to \$0.9/m^3 [67] with a new zero waste technology is achievable. Therefore, the cost of brackish water desalination is close or in the range of water reuse, in general. However, note that this estimate for brackish water desalination does not include the cost of pumping groundwater while the range for water reuse is wide when collection and redistribution are included.

Though the added cost of evaporation pond or Zero Discharge Desalination is high, brackish water desalination also offers another potential savings compared to municipal water reuse because brackish water may need minimal pretreatment (due to the groundwater already being filtered by the geologic components).

Issues

Water quality

The water quality produced from reverse osmosis or thermal desalination is free of chemicals and germs.

Environmental

Though there are a number of surface brackish lakes in the Nile Basin countries, the majority brackish water resource appears to be groundwater. One impediment of using brackish groundwater is that before the resource can be utilized, there needs to be geophysical data indicating the presence of brackish groundwater. In addition, information on the replenishment of the aquifer is important to establish that it is a renewable resource. Finally, data on the salinity of the aquifer is needed. For a complex aquifer, the salinity can vary at different parts and different depths. In many parts of the world, the geophysical data are not available or not of enough detail to make long-term decisions on.

The biggest impediment to brackish water desalination, in particular large-scale desalination, is the disposal of the brine or concentrate. In modern membrane technologies, a brine or concentrate is produced alongside the freshwater. Current set-up typically produces a brine that is approximately 10-15% of the original volume of the water to be treated. To dispose of this brine, there are typically three options, which can be combined. Option one is to discharge the brine to the ocean, option two is to construct evaporation ponds to produce salt, option three is to use the brine for salt-tolerant crops or aquaculture such as shrimp farming. Currently brine discharge to the ocean is the lowest cost option. Consequently, inland brackish water desalination, where brine disposal to the sea is prohibitively expensive, is not cost competitive and not feasible.

Recently, several companies developed different versions of zero or minimal discharge technologies. For example, the Bureau of Reclamation funded a pilot-study of Zero Discharge Desalination, which is estimated to produce freshwater at a cost of \$0.6 to \$0.9/m^3 [67]. However, large scale demonstration of this technology has not been undertaken by private companies.

In all cases, ensuring the brackish groundwater or surface water source is renewable will provides long-term, sustainable solution.

Legal and institutional constraints

In contrast to multi-agency coordination that is necessary for water reuse, the jurisdiction on desalination may potentially be rested primarily on one agency in a country. Such jurisdiction depends on each country’s legal and administrative framework. However, the withdrawal and disposal of the concentrate from desalination may have transboundary implications if the aquifer lies beneath more than one country.

Acceptance

Brackish water desalination generally is well-accepted by the local population, particularly in areas where water is scarce, and the desalinated water is the only practical water source.

Lessons learned

There are several advantages and disadvantages of brackish water desalination compared to water reuse and seawater desalination. One advantage of brackish water desalination compared to water reuse is that the during the percolation of the water to the aquifer there is natural filtering, adsorption, absorption of particles and organic materials. Consequently, brackish groundwater could have lower turbidity and organic content than wastewater and generally require less pretreatment prior to the desalination step.

1.5. Performance metrics

The metrics are chosen to reflect socio economic parameters that are important in the near future and up to 2050.

The performance metrics (Table 3) that would be used in comparison of technologies are the water production cost (expressed in dollars/m^3), capital cost, operation and maintenance (O&M) cost, energy usage (expressed in kWh/m^3), qualitative indications on potential institutional complexities and whether the method is suitable for high density cities.

Table 3. Performance metrics of the different water reuse and desalination method.

Water reuse & desalination method	Water production cost ($/m^3)	Capital cost ($/m^3/day)	Operation and maintenance ($/m^3)	Energy usage (kWh/m^3)	Legal/institutional constraint	Beneficial for high population and GDP	References
Municipal non-potable	0.3–1.6	9–400 (does not include conveyance)	0.05–0.6 (European data)	0.3–1.2	Need extensive coordination	Yes	[7][14][15][24] Low end is for favorable brine disposal; high end is with long conveyance
Municipal potable	0.7–1.6	700–2000	0.4–1.3	0.8–3.0	Need extensive coordination. Strategic campaign needed for acceptance.	Yes	[16], [21], [24] Include Africa data; low end is for favorable brine disposal
Industrial	Varies. Could be negative, i.e., saves rather than costing money. See section 2.3.3.	Varies e.g., 1,000–2,000 for cooling tower water recycling	Depends on industry, country, and intended use	Depends on industry and location	Minimal if water is reused by the same entity. Oversight by Ministry of Industry	Yes	[39][38]
Agricultural drainage water	Depends on local terrain, aridness, and water quality	$84–780 per hectare (low end, assume	Pump maintenance and fuel	Depends on terrain	Need coordination among water, environment, and		[47] This uses up water for

		irrigation in place & no treatment)			agriculture departments		downstream user
Brackish water desalination	0.3–1.1	300–1,200	0.2–0.9	0.8–1.6	Need oversight so that do not over withdraw groundwater. Need transboundary coordination if aquifer goes over boundaries.		[67], [68] High end estimated with zero waste method
Seawater RO desalination (for thermal technologies see Table 1)	0.5–2.3	800–2,300	0.3–1.0	2.4–4.5 (Includes pretreatment & intake)			[54]–[56]

1.6. Conclusions

Water reuse and desalination can be very important to supplement and increase water supply in a region. In a dense municipal water, water reuse can potentially more than half of the water demand, freeing up water for other purposes such as agriculture in the country. In addition, water reuse can in some cases help a region deal with periodic drought, if the system is designed in an integrated manner.

These two technologies, however, incur additional financial and electricity cost. In deciding whether they are good option for a region, there are several decision steps.

1. Determine whether demand exceeds supply, at least part of the year.
2. Determine whether the excess demand can be met by efficiency improvement.
3. Determine whether the resources are available.
    - In the case of water reuse, is wastewater being collected and partially treated? If no wastewater is collected, then the locals may still be reusing the water in an unofficial or unplanned manner, though it might be in a mode hazardous to health.
    - Is seawater or brackish water available?
4. If the resource is available and if the demand cannot be met by efficiency improvements, then the decision moves into determining which of the water reuse or desalination methods is the economically viable option.

In determining the economically viable option, the selection is highly dependent on local condition.

1. As shown in the graphs on water reuse and desalination, economy of scale applies to many processes. Operating a water treatment or desalination technology above a certain size would provide water at a more favorable water production cost per m^3.
2. However, piping and conveyance is a very significant cost of the water infrastructure. Local, small-scale batch systems that provide safe drinking water and sanitation systems may be the favored option in the near to medium term.
3. In the case of water reuse, additional conveyance may be required if the intended destination is far from the source.
4. ***An optimization of treatment and distribution/conveyance cost is necessary.*** With data for a particular location, modeling and optimization can be performed.
5. The necessity of optimizing treatment and conveyance cost shows a few examples where water reuse and desalination are likely to be tremendously useful to supplement water supply. These are potentially:
    a. Dense municipal area where there is insufficient freshwater supply, and where the resource (wastewater) and use (for potable or non-potable) are close to each other. Dense municipal area is also where wastewater, if untreated, can be seen and smelled easily, and thus exerts pressure for actions to be taken. However, if the sanitation system is still generally insufficiently developed, wastewater reuse for potable purpose is unlikely to gain the trust of the public in the near future;

b. Industrial on-site water recycle is very common worldwide and can often be cost competitive with the right incentives, regulations, and enforcement;
c. Agricultural irrigation drainage water reuse can have large impact if the post-drainage water is still relatively clean and can potentially be reused as is or when mixed with additional freshwater;
d. For development near the coast where water supply is insufficient, seawater desalination can often be a good choice;
e. In dense municipal area near the coast, i.e., in places where two resources, wastewater and seawater, are both available, water reuse is still the more economical option.

For other locations and purposes, e.g., reuse of municipal wastewater for agricultural land outside of the municipal area, or reuse of agricultural drainage water that needs substantial treatment, much more information is needed for cost-benefit analysis.

As Whittington et al. [69] and others have pointed out, as communities experience economic growth, more households and firms will prefer the advantages of large-scale, reliable, piped water and sanitation services. As reliable water, energy, and communication infrastructure tend to increase business confidence and further investment, the benefit of water reuse and desalination, together with adequate wastewater infrastructure, would eventually outweigh the cost.

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PART II: SCOPE AND SCENARIOS FOR WATER REUSE AND DESALINATION IN THE NILE BASIN

2.1. Introduction

Studies carried out by the Nile Basin Initiative has indicated that the degree of water shortage in Nile Basin countries may be more severe in the future. In addition, due to climate change certain regions receive precipitation that do not follow historical climate patterns and experience intra-annual water shortage. Therefore, an evaluation of potential freshwater sources to ensure a secure future is beneficial. As the technologies to reuse wastewater and to desalinate saline water become more mature and the cost is decreasing, it is projected that water reuse and desalination could play an important role in the future. This project studies existing water reuse and desalination practices in Nile Basin countries and worldwide and use the information to project scenarios of water reuse and desalination in the near-term (5 to 10 years) and to the year 2050. The technologies covered include:

- water reuse for non-potable purpose;
- water reuse for potable purpose
- industrial water reuse
- irrigation drainage water reuse;
- brackish water desalination;
- seawater desalination.

The methodology for the net present cost and scope is described in detail in Appendix A to C. Unless otherwise given in more detail in this report (mainly in the irrigation drainage reuse section), the low- and high- end per unit capital, operation and maintenance (O&M) for the different technologies are the same as those listed in Technical Report I.

2.2. Municipal water reuse

In the prevalent water management practices worldwide, water reuse is defined as the use of *treated* wastewater for beneficial purposes, which increases a community's available water supply. The term "planned" is usually left out from the phrase, with "water reuse" implying the planned use of treated wastewater.

Municipal water reuse could be for non-potable or potable purpose. The municipalities can decide later on which option they want to pursue. In this project, both options are explored.

2.2.1. Municipal water reuse for non-potable purpose

To reuse the water for non-potable purpose, a system for wastewater collection is a prerequisite. After collection, the water is partially treated, i.e., not to human potable standard, but to a standard deemed adequate for the purpose chosen. These chosen purposes include but are not limited to landscape irrigation, agriculture, wetland recharge, and industrial uses.

Criteria for successful implementation

The criteria for successful implementation of water reuse for non-potable purpose are shown in the list below.

(a) The existence of demand for water reuse, which stemmed from insufficient quantity of water that can be sustainably withdrawn to meet the local water needs;
(b) The resource for water reuse is the collected wastewater, therefore water reuse can only be implemented in areas where wastewater is collected;
(c) The sites where the resource (wastewater) is collected and the site where the water will be reused need to be within a reasonable distance so that there is no excessive water loss in conveyance and to ensure the financial cost need in building the canals and pipes, etc. for conveyance is not excessive.
(d) The time period when water is needed matches the time period in which the wastewater is produced. If this condition does not prevail, water storage method would be necessary. For example, if the municipal wastewater was collected and treated at a *constant* rate during the year but the sector for intended reuse, e.g., agriculture, primarily only needs the water during dry season or only during a limited crop-growing season, then there might be a big surplus of treated wastewater during the rest of the year. In such a case, a reservoir to store water in the low demand period would be necessary. This intermediate storage would increase both cost and losses through reservoir seepage and evaporation. In addition, there are additional safety issues to ensure the reservoir does not complicate potential flooding issues during the wet season.

A note on the wastewater collection issue is also added here to briefly address centralized vs. distributed system. In most countries, the wastewater is collected in municipal-scale sanitation system, via a sewage pipes or a collection truck system. The collected wastewater is then treated in a centralized treatment plant. Generally, the centralized treatment system has economics of scale and has the lowest cost per volume of freshwater produced.

However, distributed water reuse can be implemented effectively if the wastewater, e.g., from an apartment block, is collected, treated, then used on-site or within a short distance. Japan is the only industrialized country that tends to have water reuse system in a distributed fashion, e.g., in an apartment block [1], [2]. In general, distributed small-scale system has a higher cost per m^3 water produced. To ensure the water being released meets the local standards a lot more inspections may be necessary to regulate the many individual wastewater treatment units and to ensure that new system is put in place when the units become inoperative.

Measures for improving the gains from water reuse for non-potable purposes

An important measure to improve the gains for water reuse is to increase the quantity of the raw material, i.e., increase the volume of the wastewater that can then be collected, then treated and reused. To achieve this, two key measures needed are the development of the sanitation or wastewater collection sector and a system to increase the return flow.

In many municipal areas, significant water is lost through nonrevenue water (NRW), which affects how much wastewater is eventually collected. The percentage of NRW that is physical vs commercial is location dependent, though in general 75% of NRW is attributed to physical loss [3] such as leakage in pipes. Therefore, upgrading the piping system and conducting required maintenance can both help reduce NRW.

Once the wastewater is collected and treated, it would be wasteful if there was a large conveyance loss during the conveyance of the wastewater to the intended destination or during storage. Therefore, measures to improve conveyance efficiency and minimize loss during water storage can significantly improve the gain of water reuse. Lining the transfer canal would decrease the loss of the treated wastewater through seepage and percolation. The "storage" or "banking" or "recharge" of water in a groundwater system [4] could also potentially decrease water loss, provide resilience for drought season, and offer the advantage of a final, natural filtration step that further clean the water. However, this requires sites that are geologically suitable and needs to be determined on a case-by-case basis.

Geographic locations where water reuse and desalination can be successfully implemented

In the near-term, to implement water reuse for non-potable purpose, the criterion that the region needs to have a wastewater collection system is used. Egypt, which collects 54% of its wastewater, is the only country in the Nile Basin that fits this criterion currently. In fact, Egypt already reuses some of that wastewater (both treated and untreated) for irrigation.

In the longer term (up to 2050), it is assumed that all municipalities in the Nile Basin will have a wastewater collection system in place. Therefore, in the long term, one of the criteria should be whether there is a potential need for water reuse, i.e., whether the water that can be withdrawn sustainably cannot meet the water demand. Because this project is an overall survey of the entire Nile Basin and because currently only the demand data are provided by NBI, an alternative simpler criterion is used. If the local precipitation is less than 1,000 mm, then it is considered a potential location to implement water reuse for non-potable purpose.

Using this simplified interim criterion some municipalities in Egypt, Rwanda, and Sudan are included (Table 1). The list also includes Kampala, Uganda, which is already implementing limited water reuse (described in Technical Report I) and Gitega, Burundi, which is reported to experience water shortage [5]. Gondar, a UNESCO heritage site and tourism center in Ethiopia, is also included, even though it has a precipitation of 1,037 mm. This is because locations that have large number of tourists tend to have the revenue to invest in sanitation and water resources development. In addition, the investment often pays off well because it could bring in more tourism and agricultural revenue.

Table 4. Potential locations for municipal water reuse for non-potable purpose in the long-term, i.e., up to 2050.

Country	Burundi	DRC	Egypt	Ethiopia	Kenya	Rwanda	S. Sudan	Sudan	Tanzania	Uganda
Location	Gitega	--	El Minya Qena Asyut El Giza Cairo Alexandra	Mekele Gondar	--	Kigali	--	Khartoum Ad Damazin	_	Kampala

Scope for municipal water reuse for non-potable purpose

The scope for municipal water reuse depends on the volume of wastewater collected, and the losses through evaporation and leakage in the water treatment process, as well as losses that occur when the treated water is stored in reservoirs. The volume of wastewater collected in turns depends heavily on NRW, or the equivalent of irrigation conveyance efficiency in the municipal system. Details of the mathematics linking NRW to scope are in Appendix A.

A list of the NRW in Nile Basin countries is presented in Table 2. Many of the values are obtained from the African Infrastructure Knowledge Platform, hosted by the African Development Bank Group [6]. Whenever possible, values from sources that analyze the water and sanitation of individual countries in an in-depth fashion are used.

Table 5. NRW for Nile Basin countries and the data sources.

Country	Burundi	DRC	Egypt	Ethiopia	Kenya	Rwanda	S. Sudan	Sudan	Tanzania	Uganda
NRW (%)	29	39	30	31	47	9	26	40	47	33
Source of data	AIKP	AIKP	CAPMAS	AMCOW	AIKP	AIKP	AIKP	AIKP	AIKP	AIKP

AIKP: African Infrastructure Knowledge Platform.
CAPMAS: Egyptian Central Agency for Public Mobilization and Statistics [7].
AMCOW: Report on water supply and sanitation in Ethiopia [8].

Scope and net present cost (NPC) calculated for municipal water reuse for non-potable purpose, using a discount rate of 8% and an inflation rate of 2%, implemented in a 20-year time frame, are shown in Table 3. Two different scopes are shown, one at the NRW levels of the individual countries in 2019, the other at an NRW of 5%. With an NRW of 5%, 40% of the water withdrawn for municipal water purpose can be delivered to the intended purpose (farms, gardens, etc.). With an NRW of 30%, only 30% of the water withdrawn can be delivered, primarily because the higher NRW resulted in less wastewater being collected. The results show that effort to improve the NRW from the current values not only has the effect of conserving water within the municipality, but also increasing the recycled water that is delivered to farmlands or irrigation schemes.

An accurate scope of water savings could only be obtained through a hydrological model that fully account for water balance. Upstream water reuse for non-potable purpose, where the recycled water is eventually mostly lost in evapotranspiration, could result in lower volume of water available for municipal water withdrawal, which then result in lower volume of wastewater collection. In the current model, the volume of water reuse in upstream region is a lot smaller in volume than that in downstream region and therefore the error is relatively small and will be resolved in hydrological water balance conducted later.

Using Egypt as an example, Figure 1 shows the scope of water saved without improvement on the current NRW of the country, using the low-end value in capital and O&M, and assuming the infrastructure will be built in an even pace over 20 years. Therefore, the capital expenditure, shown in 2019 dollars, is the same every year. As the infrastructure size increases every year, the O&M increases and more water is produced. Figure 2 shows the scope of water saved if the NRW is 5%. The maximum water saved is almost 2,000 MCM more while the expenditure is approximately the same.

The NPC has a large range because there is considerable range in how each country can define or regulate the quality the water to be treated to. For example, in Tunisia, regulations are made so that water for reuse has to be treated to a higher standard if it was used for crops such as vegetables [9]. Based on European experience, there is a 5-fold difference in cost if the water was only was to be treated through simple filtration vs. treatment that removes pathogens [10]. Besides water standards, other local factors such as terrain and distribution cost also have large impact on the cost.

Table 6. Potential scope and NPC of water reuse for non-potable purposes for Nile Basin countries.

Country	Scope (MCM)		NPC range (mil $)
	2019 NRW	5% NRW	
Burundi	60	80	20–220
DRC	0	0	0
Egypt	5,00	7,000	2,000–20,000
Ethiopia	30	40	10–110
Kenya	0	0	0
Rwanda	30	30	10–80
S Sudan	0	0	0
Sudan	250	400	80–1,100
Tanzania	0	0	0
Uganda	30	40	9–110

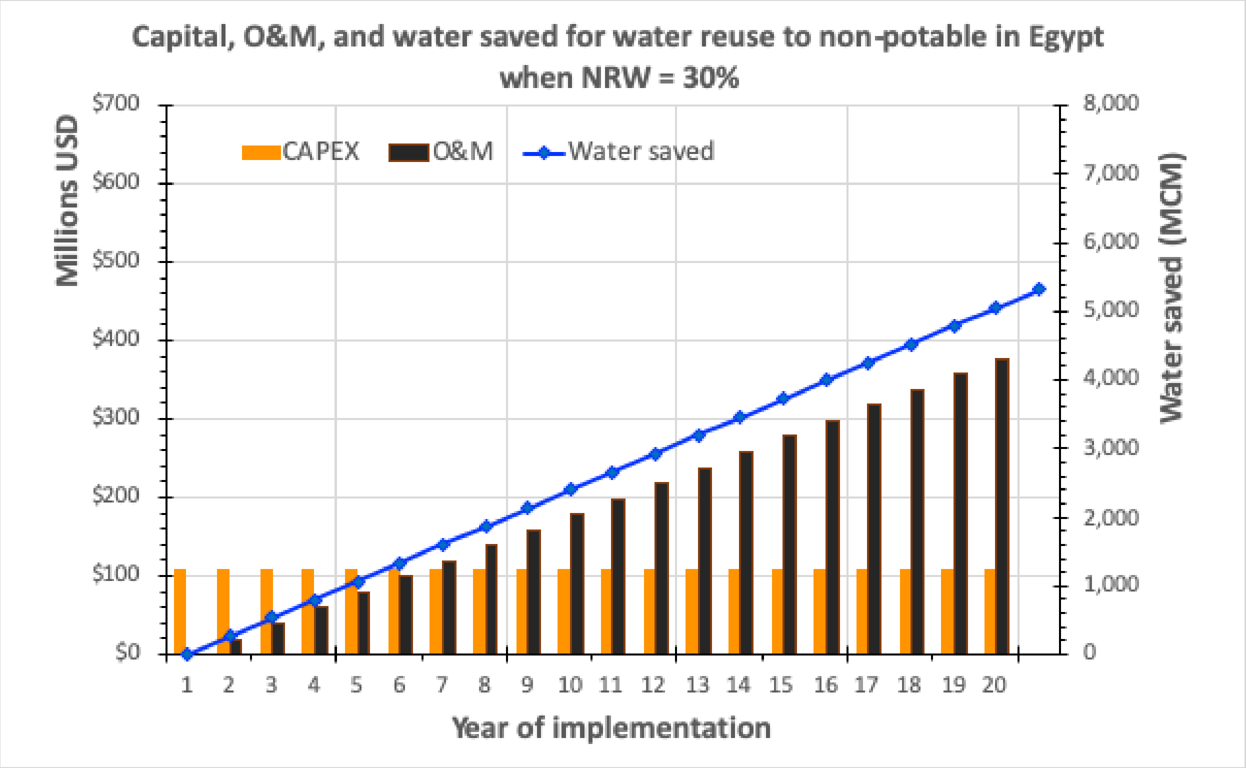

Figure 5. Low-end capital, O&M, and water saved for water reuse to non-potable purpose in Egypt over a 20-year period when NRW remains at a value of 30%.

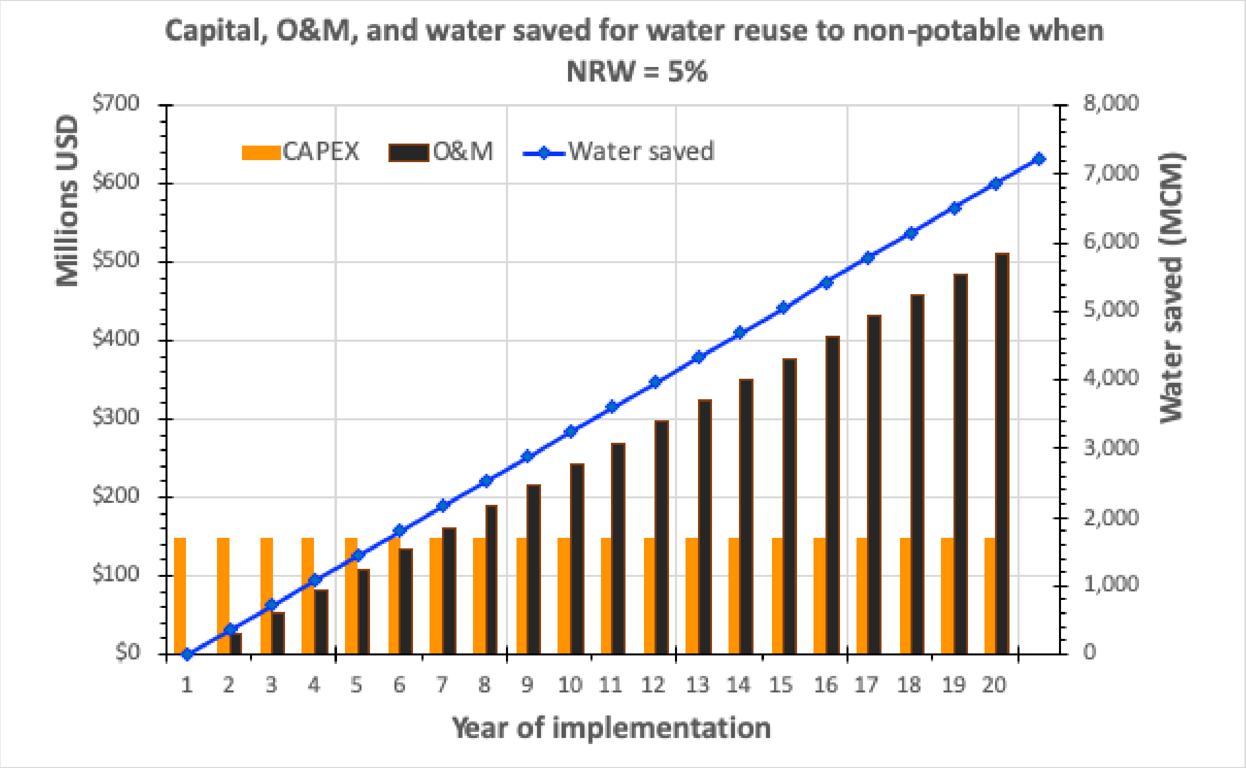

Figure 6. Low-end capital, O&M, and water saved for water reuse to non-potable purpose in Egypt over a 20-year period if NRW is 5%.

Implications of successful implementation on standards for water quality of effluent discharges

In general, the standards for water quality of effluent discharges should not be affected significantly *if* the region/country already has *stringent* quality requirements. If the current water quality standard in the country only covers conventional water constituents such as microbes, BOD (biological oxygen demand), toxic chemicals, then additional standards that covers salt content, endocrine substances, pharmaceutical discharges from household, would need to be introduced.

In inland countries or regions, a combination of treatment processes that do not produce a concentrate waste stream such as the one produced from reverse osmosis is preferable in the near future. Such treatment processes, e.g., microfiltration in combination with advanced oxidation and biologically activated carbon [11], can produce water quality just as high as that from reverse osmosis. If an inland region does embark on the use of reverse osmosis, then regulations that limit the disposal of this concentrate need to be in place.

Besides water quality, the permit for *quantity* of discharge could be affected because reuse of municipal wastewater would reduce natural discharge to streams and groundwater. The reduced quantity could have an indirect effect on water quality.

Transboundary water quality implications

Water reuse for non-potable purposes can affect transboundary water quality in several ways.

(a) *Water quality in shared surface water.* The reused water could contain unsafe, high concentrations of salt and other organic compounds. The drainage of the recycled water into river or lake could bring the overall water quality to an unhealthy level for aquatic life and downstream consumption. This could impact any transboundary water bodies. A key example would be Lake Victoria, where the runoffs and streams from several countries flow into. The lake already suffers eutrophication due to excessive nutrients stemming from activities in the catchment such as intensive cultivation, animal husbandry, and deforestation. Treating wastewater before it is carried by stream runoffs into the lake would help improve the water quality. Reusing the water (after treatment) but then letting the reused water to flow into the lake without further treatment could make the eutrophication situation deteriorates and cause further changes in the ecology of the lake. It would be prudent for countries that share Lake Victoria or other transboundary water bodies *to standardize or at least coordinate policies and water quality standards* for water reuse.

(b) *Groundwater.* If the reused water percolate into groundwater aquifer, some of the contaminants may be filtered out, but some may not. Since groundwater flows slowly, potentially across national boundaries, this could create transboundary groundwater aquifer water quality problems in the long term.

(c) *Quantity of water.* Significant water reuse for non-potable purpose could reduce return flow to surface and groundwater. This is because of increased agriculture or landscaping that could increase overall evaporative losses of water. The reduced return flow could result in transboundary water quality and quantity issues.

(d) As described in Technical Report I, some water reuse treatment method can produce a small volume of concentrated waste in addition to the much larger volume of freshwater. Disposal of concentrated waste in inland countries can be expensive. It is extremely important that all countries cooperate and either choose methods that do not produce the concentrate waste or dispose of the concentrate waste via methods (zero waste technologies described in Technical Report I, deep well injection, etc.) that do not impact transboundary water.

2.2.2. Municipal water reuse for potable purpose

As in the case of municipal water reuse for non-potable purpose, a system for wastewater collection is a prerequisite for municipal water reuse for potable purpose. However, in this case, the wastewater is fully treated to a high standard for domestic and industrial uses. In many developed countries, the standard used is potable standards for human. Currently there is no documented water reuse for potable purpose in the Nile Basin countries. However, Namibia in Africa is one of the first country that has a successful water reuse for potable system and this could be an option for some of the Nile Basin countries in the longer time frame (to 2050).

Water reuse for potable purpose is modeled for informational purpose in case the Nile Basin countries want to explore this option in the future. The scope and cost from the water reuse for potable option are *not* included in the scenarios presented at the end of this report.

Criteria

The criteria for successful implementation of water reuse for potable purpose would include those listed below.

(1) Existence of a demand for water reuse;
(2) there needs to be strong institutions and well-established trust between the users and the water treatment utilities or operators. Municipal water reuse for potable purpose cannot be imposed by the state; it needs strong user buy-in and support to be successful;
(3) similar to the case of water reuse for non-potable purpose, the wastewater will need to be collected;
(4) the sites where the resource (wastewater) is collected and the site where the water will be reused are close.

Measures for improving the gains from water reuse for potable purposes

A number of the measures to improve the gains are similar to those listed for water reuse for non-potable purposes (Section 2.1.2). Key measures are to develop the infrastructure to collect the raw material, i.e., wastewater, and to decrease NRW. Of equal importance, building trust between the users and water providers through long-term excellent service, even before the water reuse campaign has started, is essential for successful implementation.

Geographic locations

The locations where planned water reuse for potable purpose can be successfully implemented are those the criteria listed in Section 2.2.1 are satisfied and have low NRW. Some locations that potentially can implement water reuse for potable purpose in the long timeframe (to 2050) are listed in Table 4. A number of cities in Egypt that have water shortages are listed. In Sudan, El Obeid, which is in an area of low precipitation and is an important transportation hub, might also be a candidate.

Table 7. Potential locations for municipal water reuse for potable purpose.

Country	Burundi	DRC	Egypt	Ethiopia	Kenya	Rwanda	S. Sudan	Sudan	Tanzania	Uganda
Location	--	--	El Minya Qena Asyut El Giza Cairo Alexandra	--	--	--	--	El Obeid	--	--

Scope for municipal water reuse for potable purpose

Using the method outlined in Appendix A, municipal water reuse for potable purpose could provide 60% of the water needs of the city if the NRW was 5% but as low as <30% if the NRW was 30%. The impact of NRW on municipal water reuse for potable purpose is even more significant than that for municipal water reuse for non-potable purpose because NRW affects not only wastewater being collected, but also the delivery of the recycled water (mixed with freshwater) to the municipality in the reuse for potable case. As shown in Appendix A, the recycling can be an infinite cycle though it needs constant replenishment of freshwater due to losses in in the treatment process and in reservoirs.

Using Egypt as an example, Figure 3 shows the scope of water saved without improvement on the current NRW of the country, using the low-end value in capital and O&M, and assuming the infrastructure will be built in an even pace over the 20 years. Because of the importance of NRW and the expense required for municipal water reuse for potable purpose, Figure 4 shows a suggested development pathway where the first 10 years focus solely on NRW reduction, while the next 20 years focused on the implementation of the water reuse for potable purpose infrastructure.

Water reuse for potable purpose is quite an expensive proposition, and the NPC and scope are listed in Table 5. Nevertheless, some countries who want to ensure water security for their municipalities or who are able to have high return on investment through industrial, financial, and tourism development in their cities might consider this an option in long-term planning (to the year 2050).

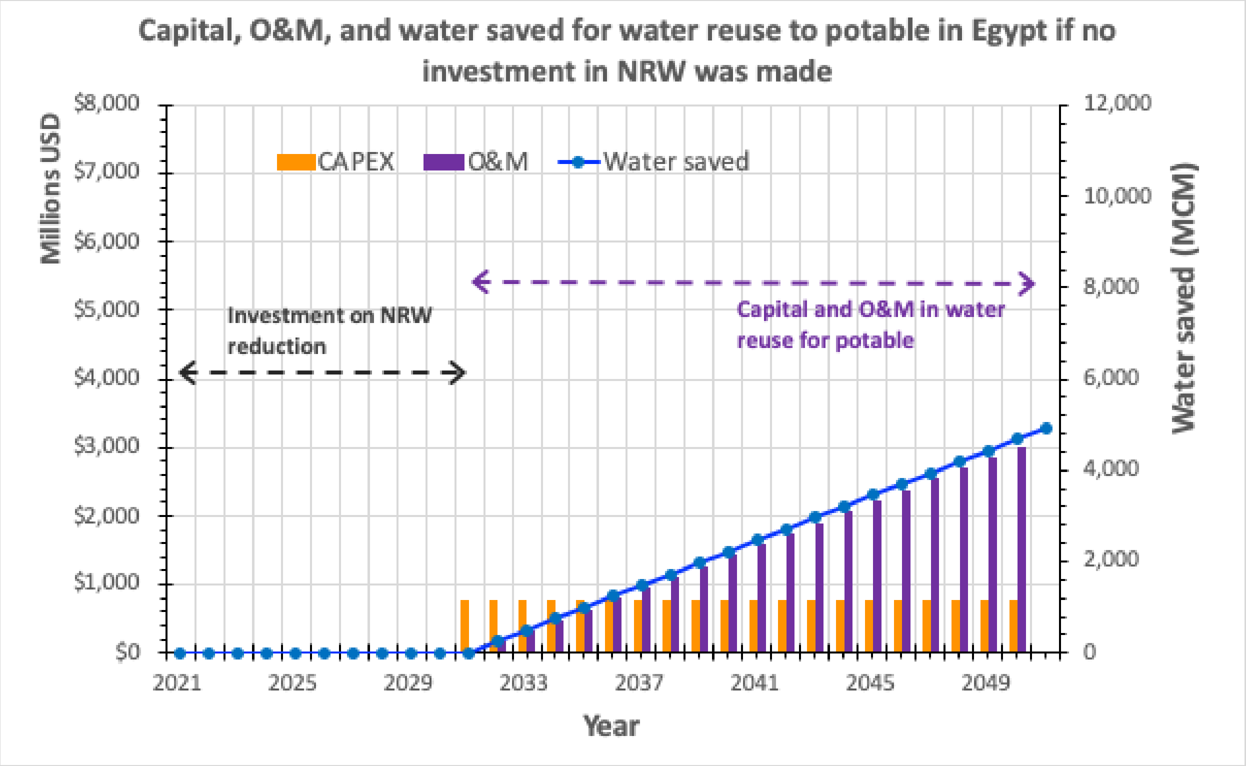

Figure 7. Low-end capital, O&M, and water saved for water reuse to potable purpose in Egypt over the period 2031 to 2050 if no prior investment on NRW reduction was made.

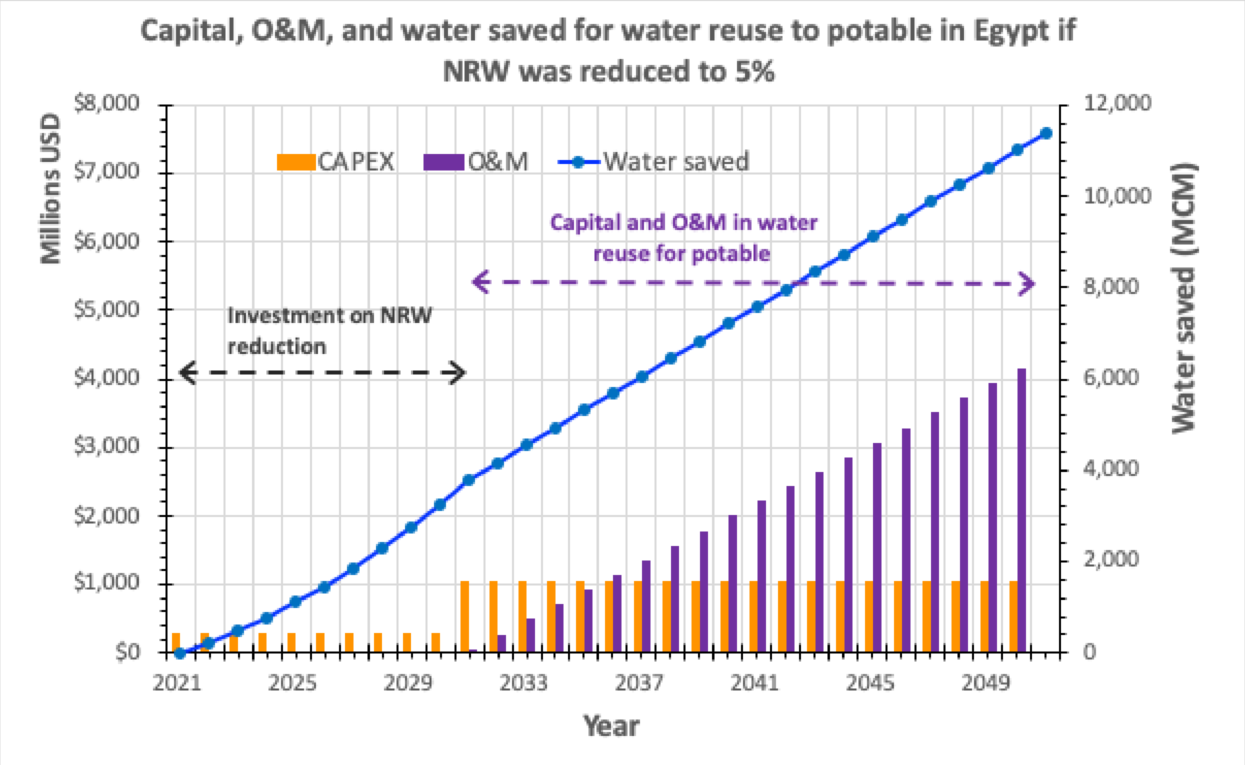

Figure 8. Low-end capital, O&M, and water saved for NRW reduction (2021–2030) and water reuse to potable purpose (2031–2050) in Egypt. This plot is made assuming the sanitation and wastewater collection sectors are already in place in 2020, i.e., the cost for 2021-2030 is for NRW reduction only.

Table 8. Net present cost of water reuse for potable purposes for Nile Basin countries.

Country	Scope (MCM)		
	2019 NRW	5% NRW	Cost range (mil $)
Burundi	0	0	0
DRC	0	0	0
Egypt	5,000	11,000	13,000–53,000
Ethiopia	0	0	0
Kenya	0	0	0
Rwanda	0	0	0
S Sudan	0	0	0
Sudan	20	50	700–3,000
Tanzania	0	0	0
Uganda	0	0	0

Implications of successful implementation on standards for water quality of effluent discharges

The implications of successful implementation on standards for water quality of effluent discharges are similar to those described in Section 2.1.5.

Transboundary water quality implications

The transboundary water quality implications are similar to those described in Section 2.1.6.

2.3. Industrial water reuse

Worldwide, the industries that are known to consume a lot of water include food and beverage, and the energy sector. The exact configuration and requirements for the treated water would vary in individual cases, which also affect the cost. Many of the basic suite of technologies are similar to other types of water reuse technologies.

Criteria

The criteria for successful implementation of industrial water reuse would include the following:

(1) The return flow in the particular industrial process being considered is high.
(2) The cost for implementation of industrial water reuse does not cause excessive burden on the industry.
(3) If the reused water is for internal process, i.e., reuse within the industrial plant, then the implementation of water reuse should not degrade the water quality requirements of the internal process. Note that this is seldom the case if the water was properly treated and monitored, in combination with the equipment being properly maintained.
(4) If the water is not reused internally, then the intended location of water reuse (e.g., landscaping, agriculture, etc.) needs to be within reasonable distance from the industrial water generation site.
(5) If a partly treated industrial water was to be further cleaned using nature-based solutions such as natural or artificial wetland, then the concentrations and/or of trace elements, organic compounds, microbes, etc. need to be below certain levels that the wetland is capable of treating/filtering.
(6) If the treated water was to be delivered off-site directly, e.g., to agricultural lands, then the water needs to be treated to the required standard of the intended purpose.

Measures for improving the gains

From the perspectives of the owners and operators of an industry, one of the gains of a highly efficient internal or on-site water reuse would be their ability to control and ensure adequate and reliable water supply. In addition, depending on the cost for industrial waste discharge, internal water reuse could even save the owners and operators money in the long term though there is a pay-off period needed.

A second measure to improve the gain from industrial water reuse is to incorporate heat energy capture/recycling when appropriate. Often water is used in industrial sector for cooling of equipment. It has been shown that heat and water recovery together can save many companies money in the long run [12].

To improve the gains for industrial water reuse, the role of government could be financial, e.g., through tax relief. The industrial owner that practice water reuse could also gain benefits in reputation if the government and civic societies give public recognition to companies that preserve and enhance the common good.

Locations

Because data on specific locations where there are strong industries were extremely challenging to obtain, it is assumed that all countries in the Nile Basin countries will embark on industrial water reuse in the current project.

Scope of industrial water reuse

The scope and net present cost for industrial water reuse, implanted from 2031 to 2050, are shown in Table 6, they are estimated for the entire country because of the lack of data on basin-specific industrial development and demand. The saving from industrial water reuse is industrial- and plant- specific. Because the detailed data are not available, several assumptions are made. It is assumed that 40% of the industries would engage in water reuse. Among industries that embark on water reuse activities, it is estimated that 50% by volume is from thermoelectric plant. That is because thermoelectric plants tend to consume a lot of water, so a single plant can consume the equivalent of many other plants. In addition, thermoelectric plants tend to be large, and can therefore use their existing equipment as collateral for addition loan for water reuse implementation. For these thermoelectric plants, 98% return flow, and 98% delivered for reuse are quite commonly achievable. For the other industries such as food and beverage, the gains would be a lot lower and 20% delivered for reuse is used as an estimate. The low end capital and O&M, as well as water saved, for all Nile Basin countries, are shown in Figure 5.

In the near term, for countries with low industrial development, they may not necessarily put industrial water reuse at high priority. Therefore, is estimated that only 10% of the industries would engage in industrial water reuse in the near-term (up to 10 years from 2020). For Egypt, it is classified as low to medium development (based on per capita income), therefore it is estimated that 20% of the industries would engage in water reuse in the next 10 years. The scope for water savings is quite minimal for the near-term and no separate table is made, though the values are in the spreadsheet.

Table 9. Net present cost of industrial water reuse for Nile Basin countries.

	Scope (MCM)	Cost range (mil $)
Burundi	5	6–35
DRC	50	60–350
Egypt	2,000	2,000–13,000
Ethiopia	20	20–120

Kenya	100	130–700
Rwanda	7	9–50
S Sudan	80	100–500
Sudan	30	30–180
Tanzania	9	10–60
Uganda	20	20–120

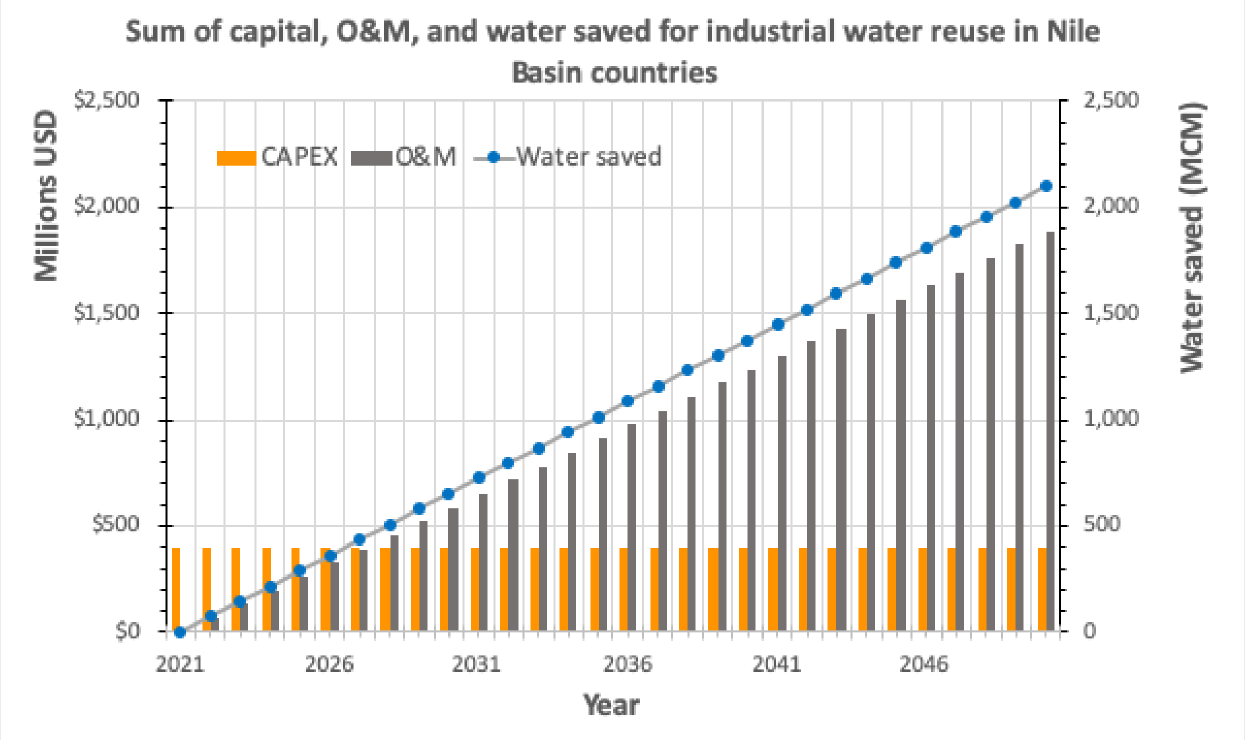

Figure 9. Low end estimate of capital, O&M, and water saved for industrial water reuse in Nile Basin countries.

Implications of successful implementation on standards for water quality of effluent discharges

It is anticipated that the water discharge from industrial usage would need to fall within water standards designed by the Ministry of Environment and/or Ministry of Industry of the Nile Basin countries involved. If the water reuse is for the purpose of agriculture, then the Department of Agriculture may be the government agency responsible for setting the water standards.

If there was a suitable design of nature-based solutions, e.g., further clean-up by plants in natural or “synthetic” wetland, the water entering the wetland would need to be treated to an intermediate, scientifically determined standards that ideally are codified in formal water discharge regulations and permits. It would be necessary to consider the effectiveness of nature-based solutions to determine the quantity and quality of water discharge, as well as monitoring systems.

Transboundary water quality implications

The transboundary water quality implications are similar to those described in Section 2.1.6.

2.4. Irrigation drainage water reuse

Currently Egypt is already recycling approximately 11,900 MCM of irrigation drainage water. For the other countries in the basin, planned irrigation drainage water reuse is not reported.

Criteria

In irrigation drainage water reuse for conventional or saline agriculture, the drainage water is collected and redistributed among farmers. The water collected can be reused directly if the chemical composition is suitable, or it may need to be treated first, or it can be mixed with freshwater, i.e., through blending or cyclical use, to achieve the required water standards. The criteria for successful implementation would include those listed below.

(1) Water and soil quality, as reuse of drainage water that has a high salt load it could cause salinization of the soil. It is important that overall sustainability of the agriculture, whether conventional or saline, is maintained. The two primary considerations are that the drainage water is of sufficiently good quality that
    a. it will not bring about soil degradation;
    b. It will not bring adverse effects to the crops.
(2) The residue after drainage water reuse can be highly concentrated with salts and/or pesticides and/or fertilizers. The disposal of the residue needs to be properly managed.
(3) If treatment of the drainage water is necessary, then economically the cost of treatment should not exceed the gain from irrigation drainage water reuse.
(4) In irrigation drainage water reuse for wildlife habitats and wetlands, the drainage water is diverted to ensure adequate water flow for a healthy ecosystem. According to the a report by the United Nations Food and Agricultural Organization [13], the primary concern is the possible presence of trace elements such as selenium, molybdenum, and mercury that are often toxic and may bioaccumulate in the food chain. In other words, the criterion for successful implementation is to have the concentrations of trace elements, that may be toxic, to be below levels recommended by biologists and natural resource managers with deep local knowledge of the needs and tolerance of the specific wildlife present.

Measures for improving the gains

To improve the gains for irrigation drainage water reuse, one measure is to build the drainage infrastructure so that the drainage water can be collected, the other is to increase irrigation return flow so that there is actually drainage water to recycle with. Two methods that may improve return flow, irrigation scheme rehabilitation and canal lining, are discussed briefly in this section.

Figure 6 shows typical water balance in an irrigation project, which helps to illustrate the two types of return flow: beneficial and non-beneficial. Some water that is not returned to the drainage is actually beneficial, e.g., seepage that makes positive contribution to groundwater storage that could be productive in the long term, or evapotranspiration from food crops that is essential to crop growth and cloud formation.

However, evapotranspiration from weeds in farmland or irrigation canals that are not well maintained, which does not contribute to agricultural productivity or even form part of a beneficial ecosystem, particularly in a climate that is not conducive to form clouds (the moisture is lost from the region for good), can be considered non-beneficial evaporation and evapotranspiration.

In effort to increase return flow to the drainage system, it would be efficient to target the non-beneficial evapotranspiration and evaporation. Proper level of seepage and evapotranspiration control would require understanding of the local geology and overall water resource management strategy.

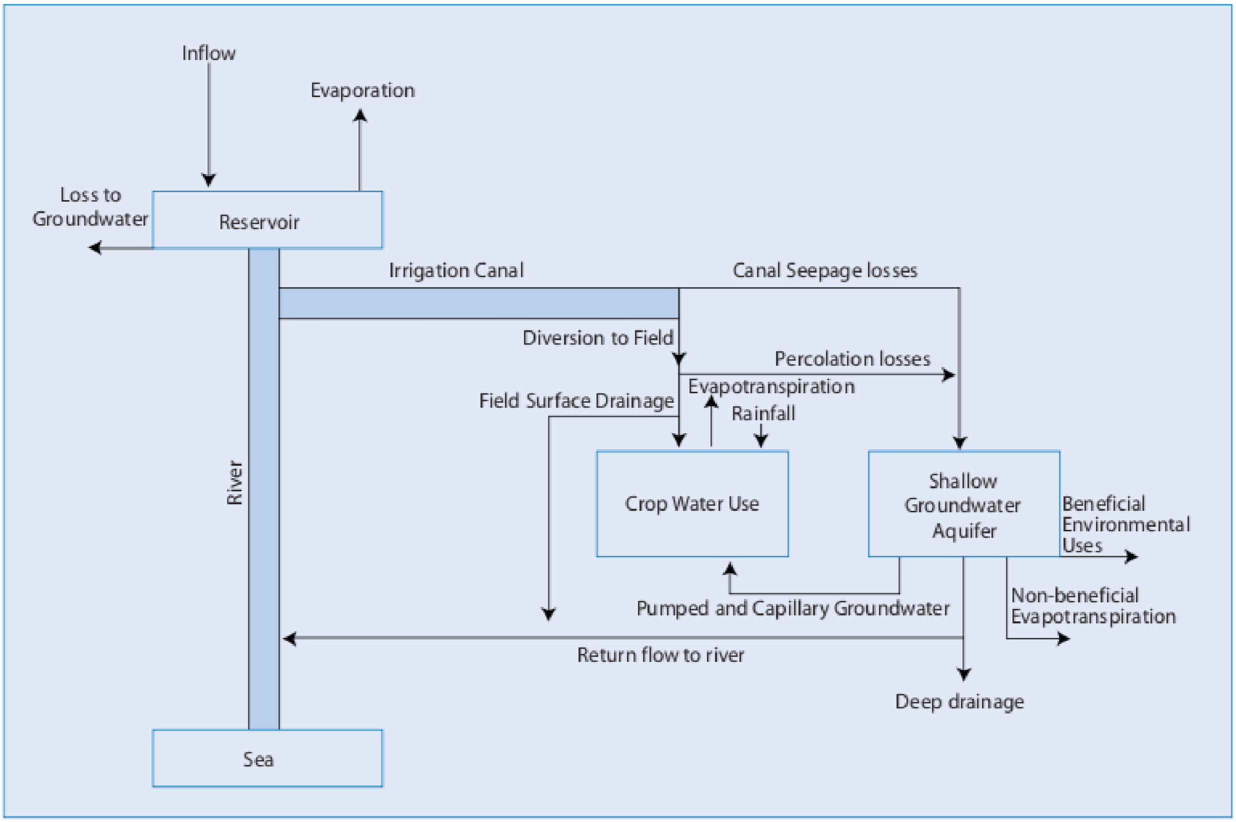

Figure 10. Typical water balance of irrigation projects.

Locations

Potential locations for irrigation drainage water reuse and water saving based on a combination of irrigation system rehabilitation, canal lining, and new/additional drainage system are listed in Table 7. The literature and rationale for their selection are described in the following sections.

Irrigation system rehabilitation and agronomic practice improvements

In irrigation literature, there are many reports have shown that irrigation scheme that is not maintained can consume more water than necessary. Therefore, irrigation scheme improvements that can potentially improve beneficial return flow, important for eventual irrigation drainage water reuse, is included the estimate of scope and cost.

A list of potential locations for near-term irrigation rehabilitation is shown in Table 7. The regions that need irrigation rehabilitation in the near future are selected based on FAO profiles of Nile Basin countries and other publication that indicates the possibility of increased irrigation efficiency in sub-Saharan Africa [14]. For example, in the FAO country report for Kenya [15], it is indicated that Kenya’s irrigation is facing significant challenges. In the FAO country report of Tanzania [16], it is indicated that at least 54,830 hectares out of the 245,514 hectares of irrigation equipped area in Tanzania needs rehabilitation. Furthermore, 117,000 ha of traditional irrigation scheme in Tanzania has water use efficiency of only 15 to 30%. These data suggest 20 to 50% of the irrigated area would achieve higher water efficiency if those areas are rehabilitated. The reports do not provide a breakdown of the irrigated areas in Tanzania that is located in the Nile Basin part, but it seems safe to estimate that the Nile Basin part of the country has a similar percentage of irrigation scheme needing rehabilitation as the whole country.

Another location that has low water use efficiency is the Gezira scheme in Sudan. Data provided by the Nile Basin Initiative, which was synthesized from baseline irrigation usage and requirement data compiled by the International Water Management Institute consultants, show that the irrigation return flow in Sudan is 616 MCM, or 4.4% of the irrigation supply requirement. Independent reports by the World Bank and research organizations indicated irrigation returns in several of the irrigation schemes in Sudan can be at least partly be attributed to sedimentation [17] weed growth (Figure 7) that clog up the irrigation and drainage system [18], a result of insufficient operation and maintenance over a number of years [19]. The water lost through weed and sediments is the type of non-beneficial evapotranspiration that irrigation improvements would decrease.

Figure 11. Weeds at the head-end and tail-ends of a minor canal (Tuweir) in the Gezira irrigation scheme in Sudan [20].

For Sudan, while the state of the irrigation infrastructure was identified as a major hindrance to improving return flow, inequities and over irrigating to compensate in certain fields [21] also occurred and could be a secondary factor in optimizing return flow. Institutional investment in personnel to monitor drainage water quality and implementation of sustainable irrigation drainage reuse in Sudan (and potentially other Nile Basin countries) is necessary to preserve long-term agricultural viability.

Besides Sudan, other countries or irrigation schemes that would benefit from agronomic practice improvements include the Abay Basin in Ethiopia [22] and small-scale agriculture in Uganda [23]. For example, the FAO study on Abay Basin found that farmers often irrigate based on water availability, rather than based on crop requirements. This leads to wastage of water and water shortage for downstream farmers within the same basin. Improvements in irrigation practices would take time and funding. It is beyond the scope of this project to identify funding needed. A simple estimate is added to the spreadsheet for Ethiopia and Uganda in the near-term scenario to account for potential irrigation and agronomic practice capacity building. In the long term (2050 scenario), all countries in the Nile Basin area have the potential to improve the irrigation efficiency.

Canal lining

Canal lining could decrease seepage to the groundwater system and may or may not be recommended for upstream regions. Canal lining in the delta area might be a “safer bet” since there is no downstream area where the groundwater flow could be affected. However, studies to determine whether a decrease in seepage to groundwater could increase the risk of seawater intrusion should be conducted. Details of the water saving and cost estimate of canal lining are in Appendix B.

New drainage system

On the irrigation drainage infrastructure in the long term (up to 2050), it is estimated that all countries in the region, with the exception of Egypt, could potentially embark on building drainage system in 30% of the irrigated land. Egypt is the exception because it already has extensive drainage system. The value of 30% is chosen because survey of irrigation schemes around the world found that more than 80% of them do not have drainage [24]. Based on the experience in Egypt, it had been reported that improved drainage accounted for 5% in agricultural production value [25] or 15–25% of the crop yield [26], [27], depending on the crop and specific study. Because improved drainage can improve agricultural yield, it is expected the percentage of irrigated land with drainage infrastructure would likely increase in the Nile Basin area as food security becomes more important with population increase. The increased monetary value of agricultural production and the improved food security are part of the consideration on the investment in drainage and also on irrigation rehabilitation.

Table 10. Potential locations for irrigation improvements in the near- (to 2030) and long-term (to 2050).

Country	Burundi	DRC	Egypt	Ethiopia	Kenya	Rwanda	S. Sudan	Sudan	Tanzania	Uganda
Near term: rehabilitation and agronomic practice	--	--		Agronomic practice improvements	Rehabilitation in areas that have maintenance backlog	--	--	Rehabilitation in Gezira and potentially other areas	Rehabilitation in areas that have maintenance backlog	Agronomic practice improvements
Near term: canal lining			Delta area							
2050: drainage infrastructure	√	√	√	√	√	√	√	√	√	√

Scope

The per hectare cost of irrigation scheme rehabilitation is estimated from the FAO country report of Kenya [15], and from a World Bank estimate [28]. In the case of the World Bank estimate (2008), the cost to rehabilitate and to upgrade a hectare is adjusted to 2019 dollars assuming an inflation rate of 3%. The actual water saving from irrigation efficiency improvement is highly location dependent. Because the current return flow in Sudan, Tanzania, and Kenya are very low, it is estimated that irrigation rehabilitation in some areas in the countries would reduce the inefficiency by at least 50%, which could have led to water savings of 25%. In order to be on the conservative side, the potential water saving is calculated using a 20% figure.

The combined net present cost for irrigation improvements and drainage water reuse are listed in Table 8. The low-end capital and O&M, as well as water saving assuming a 20-year equal installment implementation are plotted in Figure 8. Though the calculation showed a fairly large capital investment, we must bear in mind that rehabilitating the irrigation system would likely generate multiple benefits in addition to return flow, perhaps most importantly a potentially higher crop yield with proper control of irrigation and drainage.

Table 11. Net present cost for 2050 baseline scenario to improve irrigation efficiency and allows for additional drainage water reuse in all countries except for Egypt. For Egypt, the net present cost and scope are listed for irrigation canal lining.

	Scope (MCM)	Cost range (mil $)
Burundi	2	8–20
DRC	--	--
Egypt	3,700	700–3,000
Ethiopia	2,000	500–1,200
Kenya	130	50–140
Rwanda	7	8–20
S Sudan	400	100–250
Sudan	3,000	2,000–5,000
Tanzania	90	30–70
Uganda	30	20–50

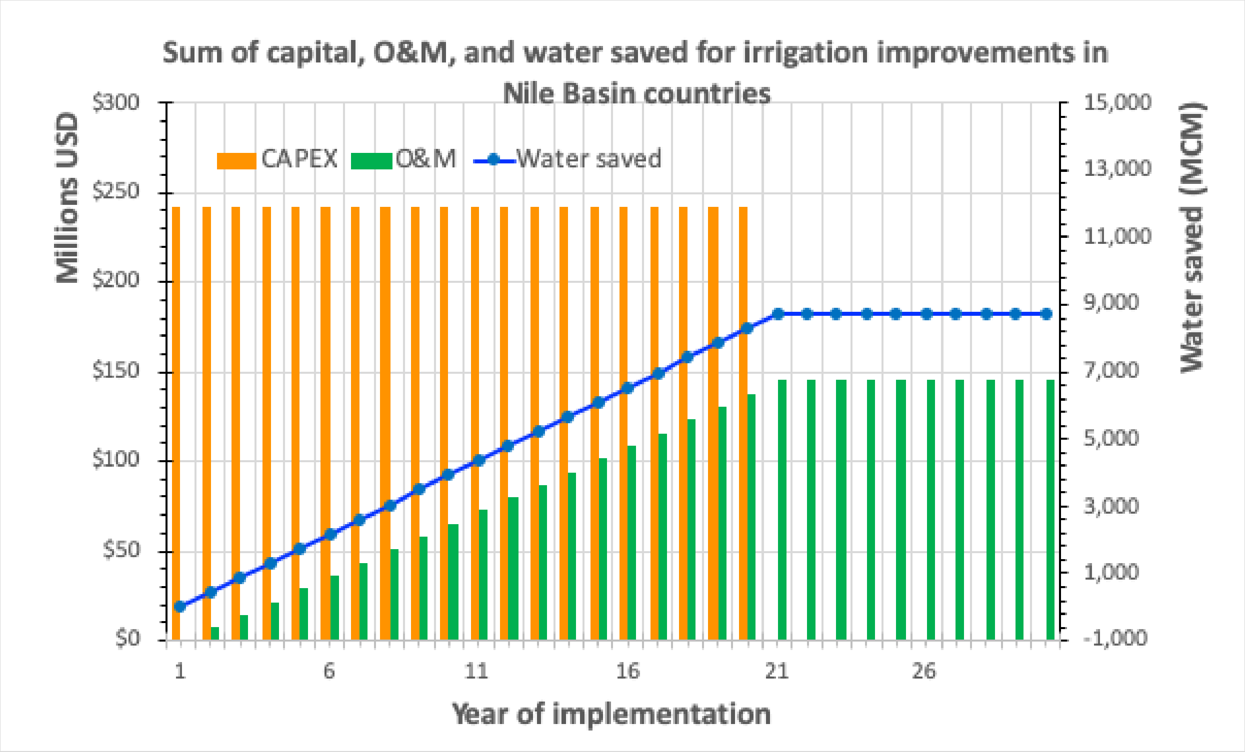

Figure 12. Estimated low-end total capital, O&M, and water saved from irrigation improvements and drainage water reuse in Nile Basin countries. In this model, the irrigation improvements and drainage water reuse will be implemented in equal installment for 20 years.

Implications of successful implementation on standards for water quality of effluent discharges

Successful implementation would require clear understanding of the soil environment in the area so that drainage water reuse is compatible with agricultural sustainability. This would require setting standards and procedures for reuse, and to implement an effective monitoring and evaluation plan, to ensure long-term agricultural and environmental sustainability.

Transboundary water quality implications

Successful implementation by upstream regions could lead to concentration of nutrient and salt in the agricultural and river run-off. This could lead to eutrophication in water bodies that receive water from many agricultural lands, e.g., Lake Victoria and downstream regions.

2.5. Brackish water desalination

Brackish water is classified as water containing 500 to 30,000 total dissolved solid (TDS). It is not as saline as seawater, but it is still is too saline for human consumption or agriculture in general. Brackish water can be found in estuary, saline surface water such as saline lake, and saline groundwater. Desalination, the removal of salt, from brackish water could be accomplished using thermal or membrane methods as described in Technical Report I. Because membrane methods are more economical, the following discussions are based on the membrane method.

Criteria

The criteria for successful implementation of brackish water desalination are:

1. There should be in-depth information of the brackish water source to ensure there is sufficient quantity to justify the building of a desalination facility and water distribution network since both types of infrastructure need to operate over long-term to recoup the investment.
2. The salinity and the chemistry of the brackish water should not fluctuate significantly by season or over time. The membranes used and the pretreatment steps are determined individually for each site based on the salinity and the other components of the water, e.g., other components that may precipitate as solid. If the water chemical content changes, the pretreatment might not be effective for the new chemical composition.
3. If brackish groundwater source is to be used, it needs to be not too deep so that the pumping cost is not excessive.
4. The resource must be nearby, i.e., the site where the water is used is close to the brackish water source.
5. The site must have access to reliable electricity supply. Damage to the membranes could result if saline water was left inside the membrane casing for extended period of time but this is partly dependent on the chemistry of the specific brackish water.

Measures to improve the gains

To improve the gains from brackish water desalination the following actions are beneficial.

1. A thorough investigation the relevant aquifer. The information and the reasons they are needed are listed below.
    a. Accurate hydrogeology information is needed to determine how much water is available to be sustainably used. Relevant hydrogeology information includes the size of the aquifer, its thickness and depth, and the rate in which the aquifer is being replenished.
    b. Chemical composition can inform potential users on whether the water needs to be desalinated, and how extensive the pretreatment step(s), which can be a substantial part of the brackish water desalination cost, need to be. In addition, the presence of certain ions such as calcium and sulfate could affect the water recovery (fraction freshwater recoverable) during desalination, further affecting the overall water production cost.
2. Develop expertise in the use of new topographical mapping method such as radar for hydrogeological study, which can save cost and time.

Locations

Table 9 lists a few sites where brackish groundwater might be a resource. In addition, brackish groundwater near the coast of Kenya could also be potential water source but seawater intrusion might be of concern. Brackish water in Tanzania using surface saline water is probably only for remote communities and small scale.

Table 12. Potential locations brackish desalination in Nile Basin countries.

Country	Burundi	DRC	Egypt	Ethiopia	Kenya	Rwanda	S. Sudan	Sudan	Tanzania	Uganda
	--	--	Regions with sustain-able brackish water aquifers	Afar	--	--	Port Sudan Red Sea coastal area	--	--	--

Scope

There is insufficient information on the actual brackish water resource available in the Nile Basin. For sustainability and long-term planning, it is important to know the replenishment rate of the groundwater. In Egypt, e.g., the volume of renewable groundwater has been estimated by FAO to be 6 ,000 MCM [29], though there was no breakdown on the salinity of the groundwater. A separate publication put the available coastal brackish groundwater in Egypt to be 2,000 MCM, and potentially more than 100,000 MCM reserve of fossil brackish groundwater [30], though there is no definitive replenishment rate.

The other countries that have the potential for brackish water desalination are Sudan and Ethiopia. For Sudan, the possible site is near the Port Sudan area [31], with a scope of only one MCM. For Ethiopia, the brackish groundwater is in the southeast, with complex geology [32]. For this project, no estimate of the water savings in brackish water desalination is made for Ethiopia.

In the modeling, a simple estimate that the recharge rate of the fossil water in Nubian Sandstone is 1,000 years, which is a reasonable estimate for fossil water. Therefore, the available brackish groundwater from Nubian Sandstone is minimal and most of the available brackish groundwater is from the coast, resulting in a total available brackish water being 2,100 MCM per year for the Nile Basin area. Assuming NRW of 5%, the actual volume of freshwater deliverable is 2,000 MCM. If the NRW is not improved from its current level in Egypt and Sudan, then the actual volume of water delivered is only 1,500 MCM.

The scope and NPC for brackish water desalination in the Nile Basin is listed in Table 10. For Egypt, the NPC Is estimated to be between 2 to 10 billion USD. There is a large range in the cost, mainly because of three factors: (1) brackish water by definition has a large range of salinity (2,000 ppm to just below seawater) and thus treatment cost, (2) there is no information on how deep the wells need to be drilled to access the groundwater, and (3) the uncertainty in the future development in zero waste technology described in detail in Technical Report 1.) that is needed for in inland areas. Figure 9 shows the low-end annual capital and O&M, and the gain in the water produced in Egypt, assuming equal size investment in new facility annually over a 20 -year period.

Table 13. Scope and cost of Brackish water desalination by 2050.

	Scope (MCM)	Cost range (mil $)
Burundi	--	--
DRC	--	--
Egypt	2,000	2,000–10,000
Ethiopia	--	--
Kenya	--	--
Rwanda	--	--
S Sudan	--	--
Sudan	1*	1–5
Tanzania	--	--
Uganda	--	--

*Estimate based on the demand of the population at Port Sudan

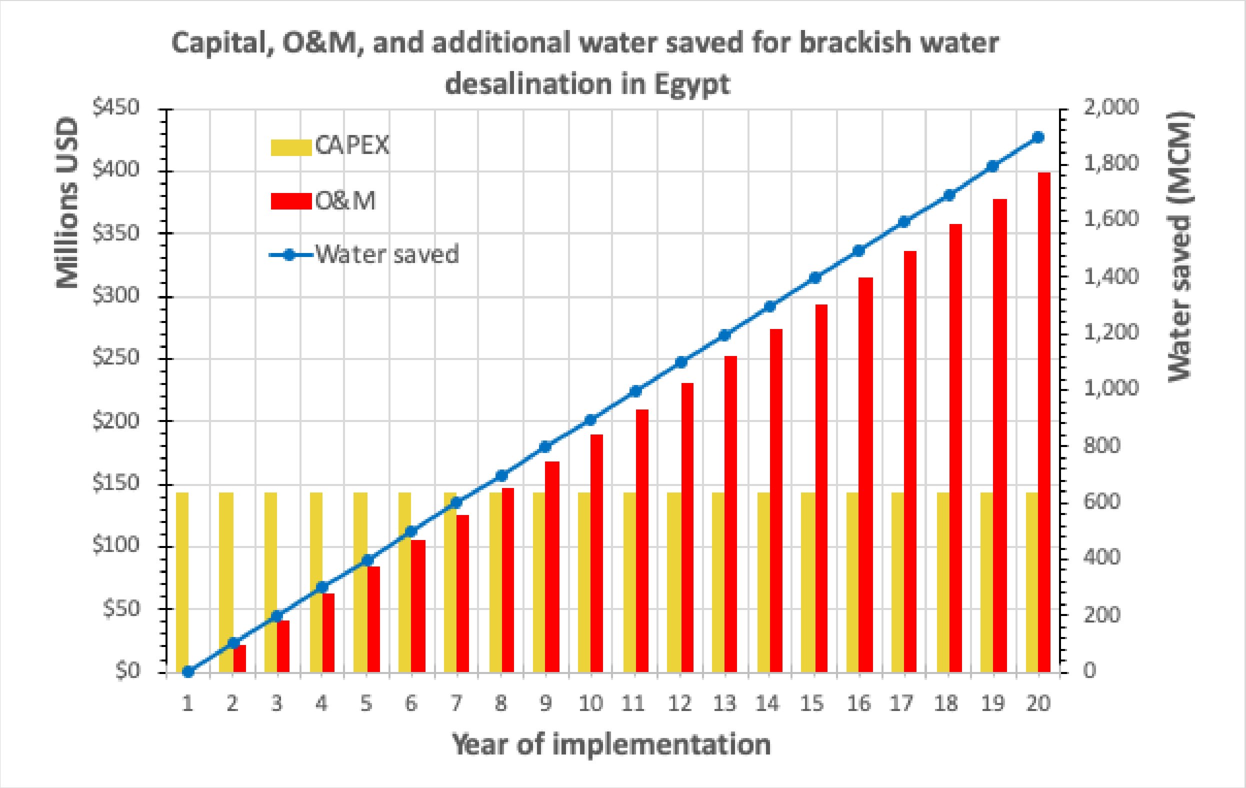

Figure 13. Low end capital, O&M, and additional water saved for brackish water desalination in Egypt.

Implications of successful implementation on standards for water quality of effluent discharges

A concentrate waste stream is produced during brackish water desalination. The discharge of the waste stream needs to be carefully regulated. Such disposal includes the use of zero waste technology, deep well disposal, or other methods so that the high salinity waste does not contaminate freshwater source (Technical Report I).

Transboundary water quality implications

It is important that any country that practice brackish water desalination does not discharge the concentrate waste stream into commonly shared water bodies such as Lake Victoria.

2.6. Seawater desalination

Seawater contains on the average 3.5% or 35,000 total dissolved solid (TDS). Most new installations of seawater desalination use the reverse osmosis (RO) technology, which is a process in which under an applied external hydrostatic pressure greater than the osmotic pressure, a solvent will pass through a porous membrane in the direction opposite to that of natural osmosis. More details of the technologies and economics of desalination are in Technical Report I.

Criteria

The criteria for successful implementation of seawater desalination are in the list below.

(1) The resource must be nearby, i.e., the site must be close to the open sea.
(2) The topography needs to be suitable for construction of the intake and outfall pumping and piping structures. For example, if the seashore is a cliff, desalination would not work.
(3) The marine environments where seawater intake and outfall are to take place are not protected areas (national park or marine conservation areas).
(4) The site must have access to reliable electricity supply. Conventional water treatment plants can be closed temporarily if the water utilities or government stop payment. However, seawater desalination plant can cease to function if there was a shutdown for a few days.
(5) Because electricity comprises 40–55% of seawater desalination O&M, the tariff for electricity should not have large uncertainty every year; most seawater desalination contracts would include a long-term contract on electricity tariff negotiated with the electricity producer of the area.
(6) Financial stability and a commitment for O&M. As is the case for reliable electricity supply, Significant damage to the membranes and cessation of operation of the entire plant can result if the system was not maintained in good operation mode.

Measures to improve the gains:

Two of the biggest components of the cost of seawater desalination are interest paid on capital and the electricity price that the desalination plant has to pay. Therefore, one of the measures to improving the gain from seawater desalination is to reform the economy and financial sectors to increase investors' confidence so as to achieve lower interest rate being charged for the capital investment.

Locations

As described in the criteria section, locations for seawater desalination are those that are near the coast. Among Nile Basin countries, Egypt, Kenya, Sudan, and Tanzania are next to the sea. Sudan, however, does not have many cities next to the sea. Port Sudan at the Red Sea coast can potentially obtain additional freshwater through brackish groundwater, rather than through seawater desalination. Table 11 lists some of the potential locations.

Table 14. Potential locations seawater desalination in Nile Basin countries.

Country	Egypt	Kenya	Tanzania
	El Giza Cairo Alexandra (All three are within 160 km of coast)	Mombasa—small percentage of seawater desalination may provide alternative in case of severe drought.	Zanzibar; Dar Es Salaam—small percentage of seawater desalination may provide alternative in case of severe drought; Tanga and Mtwara—not likely unless rapid growth of these cities.

Scope

Currently Egypt has 440,000 m^3/d (or approximately 160 MCM per year) and Zanzibar, Tanzania also has limited seawater desalination capacity. More details are in Technical Report 1. Recently awarded or planned development [33][34] would bring the capacity in the Nile Basin area to 550 MCM per year in the near future.

In the long term, seawater desalination could theoretically be considered an unlimited resource for municipalities near the coast. With the potential of further reduction in seawater desalination cost [35], it is estimated that seawater desalination could even be economically for regions that are up to 160 km from the coast, with the understanding that transport of seawater further inland would be expensive. An estimate is therefore made of the cost incurred to satisfy at least some of the municipal water demand of Cairo, El Giza (160 km from the coast), and Alexandra metropolitan areas.

As will be discussed in Section 7.1, currently water reuse is for potable purpose is still lower cost than seawater desalination. As shown in Section 2.2, water reuse for potable purpose, if *well* implemented, could satisfy 60% of the needs of the municipality. Therefore, it is assumed that even in an extremely water scarcity situation, municipalities would choose to provide its water needs through water reuse first before supplementing the water reuse with seawater desalination. Therefore, an upper limit of using seawater desalination for 40% of the municipal need was chosen (even though in the 2050 baseline scenario discussed in Section 7.2, water reuse is used for non-potable purpose because otherwise the burden as a % GDP would seem too high). In addition, the model in this project shows that the electricity needed to desalinate enough seawater to supply 40% of the demand of the Egyptian municipalities that are within 160 km from the coast could comprise 4–7% of the national electricity generation capacity in 2050. This estimate is made assuming the Egyptian national electricity generation capacity in 2050 is double the capacity in 2019. With such a high electricity demand, it seems more reasonable to improve on water efficiency and to reuse water before considering a higher scope of seawater desalination.

For Mombasa and Dar Es Salaam, the model estimated that these regions might consider investing in seawater desalination to provide up to 20% of the needs of the municipal area. Such investment could be beneficial if there was large extreme in precipitation and the inhabitants in the region prefer to have the flexibility and additional water security through a source that is not seasonal dependent.

The potential scope and NPC of seawater desalination are listed in Table 12 while the water saving and low-end cost, assuming equal installment of cost and infrastructure over a 20-year period, are shown in Figure 10. Unlike the case of municipal water reuse, where the resource is limited and the scope at 5% and higher NRW are shown, the resource for seawater desalination is theoretically unlimited. Therefore, the scope of freshwater delivered is fixed in this case, while the range of NRW-dependent NPC is shown.

The seawater desalination NPC is calculated by including both seawater desalination and water transportation cost, which is estimated using physics equations and economic values presented in Zhou and Tol [36]. Unlike the other treatment methods that use best known 2019 cost, the modeling of seawater desalination uses a lower cost than its 2019 values because the cost of seawater desalination is expected to decrease further [35]. However, a conservative estimate is made, i.e., using an average between the current and the lowest cost presented in Caldera and Breyer [35].

Table 15. Potential scope and net present cost of seawater desalination in Nile Basin.

	Scope (MCM)	Net present cost (mil $)
Burundi	--	--
DRC	--	--
Egypt	4,000	9,000–23,000 at NRW=5% (12,000–32,000 at NRW=30%)
Ethiopia	--	--
Kenya	0.3	1–2
Rwanda	--	--
S Sudan	--	--
Sudan	--	--
Tanzania	4	8–21
Uganda	--	--

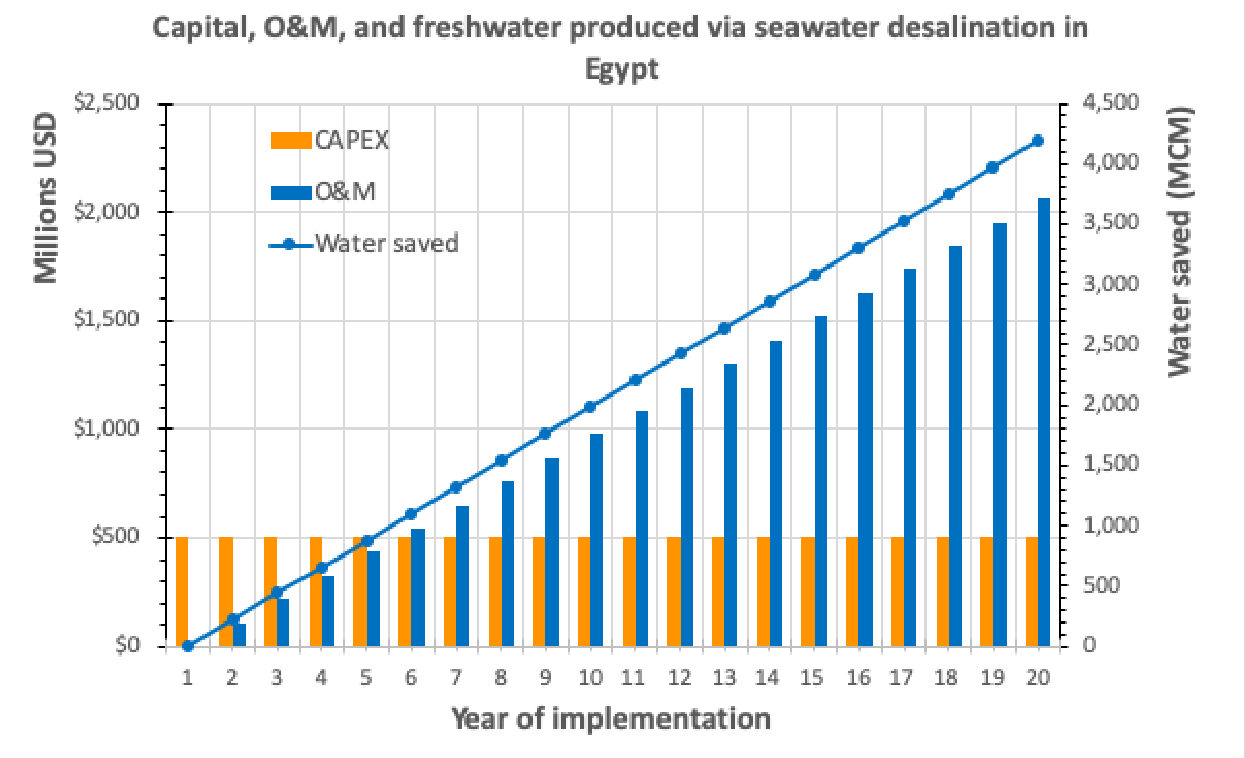

Figure 14. Low-end capital, O&M, and water supplied from seawater desalination in Egypt.

Implications of successful implementation on standards for water quality of effluent discharges

The implications of successful implementation of seawater desalination will be beneficial to the water quality. For effluent discharge, the location and the method are important. In the criteria section, it was indicated that the effluent should not be discharged near marine protected areas. Further, diffuser type discharge that limit sudden release of a large plume of concentrate is recommended.

Transboundary water quality implications

Significant seawater desalination could be a transboundary if plants are located near national boundaries and the ocean current prevail in a direction that could bring the concentrate waste containing pretreatment chemicals into the marine boundary of another country.

2.7. Options and scope for water reuse and desalination for different socio-economic scenarios projected for 2050

In each section that focuses on individual water reuse or desalination technology, a suggestion of location, scope, and cost over 20-30-year implementation is outlined. This method yielded a potential scenario for 2050, where multiple technologies practiced by a number of countries contribute to satisfy the water demand.

The analysis also allows for an estimate of levelized cost of water (LCOW) production. In a rigorous LCOW analysis, actual data on the expected plant life is necessary. In a simplified version used in the model, a 30-year plant life is used, which is actually typical of water treatment plant. Therefore, the LCOW in the current analysis is estimated as the NPC divided by the water produced/saved over the period 2021 to 2050. Knowledge of LCOW and the scope of water saved is then fed into a simplified decision tool to help decide which water sectors to target, particularly in the near-term.

2.7.1. Water use sectors to which the option contribute

As documented in the criteria section of the different water reuse and desalination technologies, multi-criteria decision model and many site-specific geological and chemical information are necessary to determine which water treatment, reuse, or desalination method will be suitable for a location. For a basin-wide model, multi-criteria nodes in the hydroeconomic model may allow for optimization of the various treatments in different locations.

For this analysis, a simplified model examining the cost and the resource availability is used to select the approaches with the largest impact at lowest cost. Figure 11 shows the cost per volume of water delivered if NRW was reduced to 5% compared to the case of NRW staying in the current percentages in Nile Basin countries. Decreasing the NRW to 5% results in a much lower cost per volume of water delivered because the low NRW ensures that the laboriously and expensively treated/desalinated water does not go to waste on its way to its intended purpose.

The effect of NRW is particularly large on water reuse for potable purpose, which is typically practiced in municipal areas in arid regions (e.g., Israel, or Windhoek, Namibia). Figure 11 shows that at an NRW of 5%, the low-end cost per m^3 of municipal water reuse for potable purpose is comparable to that of water reuse for non-potable purpose. Therefore, water reuse for potable purpose can be an economical option, particularly for municipalities that can derive a much higher value from the water than agricultural sectors. For example, in Singapore, the high-quality water from water reuse is used in the high-tech industrial, tourism, and financial sectors that generate very high income.

In Figure 11, brackish water desalination has a relatively high average cost per m^3. This is because the estimate covers desalination of water of a large range of salinity. Low salinity brackish water (2,000 to 5,000 ppm) generally has a per m^3 cost that is in the same range of municipal water reuse for potable purpose.

Figure 11 also shows that seawater desalination still has the higher per m^3 cost. If brackish and seawater desalination were used for municipal purpose, after the first round of usage there should be substantial amount of wastewater to be recycled. With that consideration, if there was limited brackish groundwater resource and if there was a municipality near the groundwater withdrawal site or the sea, it would be more efficient to first use the desalinated water for the municipality, then treat and reuse the wastewater for agriculture and irrigation.

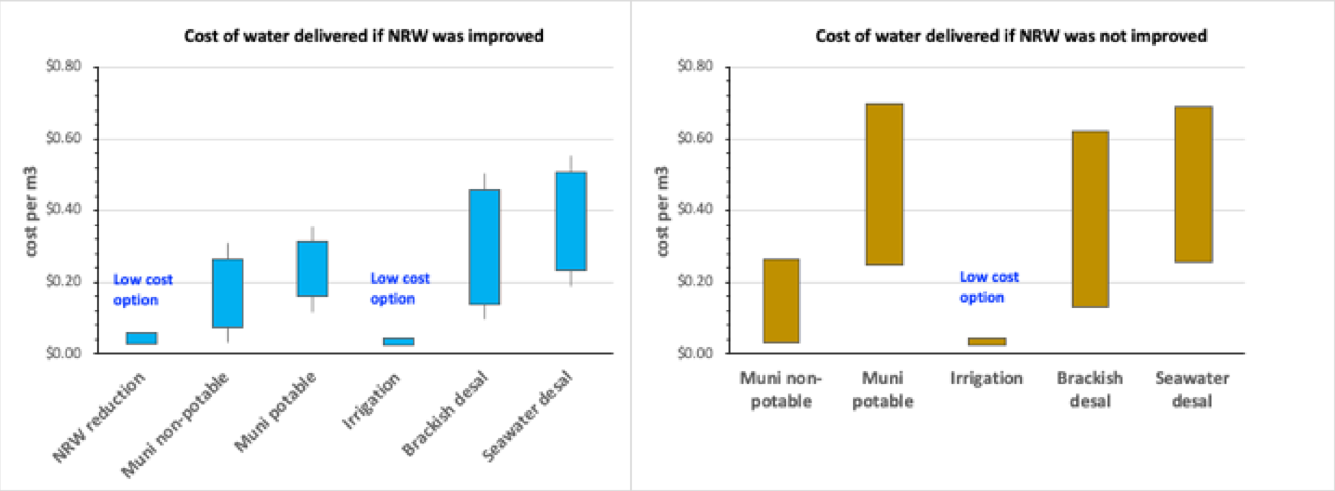

Figure 15. Range in cost per m^3 of water delivered if NRW was reduced to 5% (left) or if no NRW improvement was in place (right).

The ideal methods of intervention should ideally not just be low cost but also result in large volume water savings. Figure 12 shows both cost and scope: the yellow circles show the average cost to deliver or save one m^3 of water, while the blue circles show the reciprocal of the scope (1/scope), or the inverse of resource availability. Plotted this way, the lower the value of a blue circle, the larger the water savings. The ideal method would have both the yellow and blue circles having small values. The dashed circles show three such interventions that roughly fit the requirement: irrigation improvements, NRW reduction, and municipal water reuse for non-potable purpose.

Irrigation improvements and drainage water reuse (labeled “irrigation”) have low cost and large scope. A sensitivity analysis was conducted and it was found that even if the water saving estimate was less than that calculated in this project, irrigation intervention would still be among the two lowest cost options.

Municipal water reuse for non-potable purpose would also be an effective intervention, with large scope and a per volume cost that is lower than other reuse and desalination methods. A limitation on economical implementation of municipal water reuse for non-potable purpose is that NRW is still high in many countries, resulting in the higher cost per m^3 that is shown on the right side of Figure 11. NRW reduction has a very favorable cost per m^3 of water saved. Therefore, it would be more cost-effective to first focus on irrigation improvements and NRW reduction. In 10 years or so, individual municipality or a small region, having already reap the water savings from these measures, can evaluate resources then make the investment. They could also potentially decide at that point whether to pursue water reuse for potable or non-potable purpose.

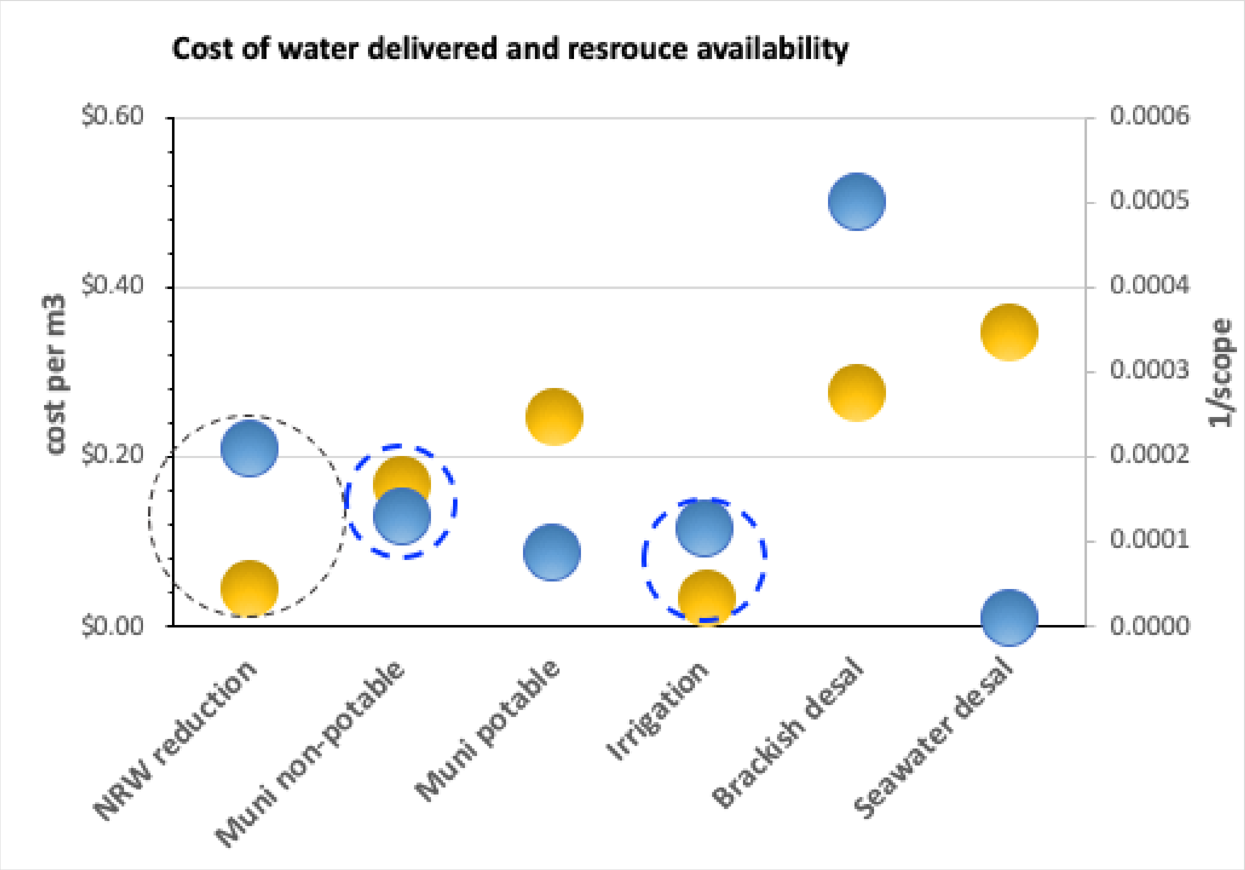

Figure 16. Average cost per m^3 of water delivered (yellow circles) and the inverse of the water saved (blue circles).

2.7.2. Contribution of the options towards meeting water demands

An accurate scope of water savings could only be obtained through a hydrological model that fully account for water balance. The actual volume of water available through water reuse would be dependent on the volume of water withdrawn for municipal, industrial, and irrigation purposes. However, the data available from NBI are demand-focused. Appendix C describes the iterative process used to partially account for both demand and supply to estimate water savings from the different interventions discussed in Sections 2 to 6.

Table 13 shows the scope of different water efficiency improvements, water reuse, and desalination in four scenarios. In a hydrology model, the “saving” from water efficiency improvements does not factor as long-term “source,” but rather should result a decrease in demand. However, as discussed in Sections 2 to 6, the efficiency improvements are essential to *enable* efficient water reuse and desalination. The scope and cost of water reuse and desalination are also derived assuming improvements in efficiency. Therefore, the volumes “saved” from efficiency improvements are also listed.

The near-term scenario assumes total water withdrawal for municipal, industrial, and agricultural purposes can be sustainably kept at 103,000 MCM (the sum of the 2019 withdrawal, more details in Appendix C). For this scenario, irrigation rehabilitation in Sudan, Tanzania, and Kenya, agronomic practice improvements in Ethiopia and Uganda, and canal lining are envisioned as listed in Table 7. Municipal water reuse is limited because the state of the wastewater collection sector is still only intermediate between the 2019 value and 100%., and the NRW is projected to be still at 15% for all countries. Seawater desalination is assumed to contribute to only 10% of the municipal water needs within 160 km from the coast. Using these parameters in the model, more than half of the “saving” is in efficiency improvements, particularly in the irrigation sector. The NPC is estimated at 7–27 billion USD, which uses the timeframe 2021 to 2030 in the calculations. To account for the possibility that the authorities in the Nile Basin might want to speed up the implementation, the NPC is simply listed as >7 billion USD in Table 13.

In the be baseline scenario for 2050, total water withdrawal is kept at 103,000 MCM, and NRW is reduced to 5% in the entire Nile Basin. Irrigation scheme rehabilitation and new drainage are implemented in 30% of all countries except for Egypt, which already has an extensive drainage system. The locations for water reuse and desalination are those described in Sections 2.1.3, 3.3, 4.3, 5.3, and 6.3 of this report. Compared to the near-term case, water reuse and desalination now contributes more volume than efficiency improvements alone. The combination of new, additional water reuse and desalination can contribute approximately 18,000 MCM in the Nile Basin area. The improvements in NRW and irrigation efficiency resulted in a “saving” of 12,000 MCM. Therefore, the total new “saving “could be approximately 30,000 MCM. These values do not include the 11,900 MCM of irrigation drainage water reuse that Egypt is reported to be practicing in 2019.

In the 2050 demand-based scenario, all the locations for water reuse and desalination are the same as the 2050 baseline scenario. However, the demand is fixed at 180,000 MCM, which is the sum of all the 2050 municipal, irrigation, and industrial water demands (details in Appendix C). In this exercise, it was found that a total water withdrawal of 130,000 MCM could be necessary. In Table 13, the water “savings” for this scenario are reported as % of the total demand because the calculated water “savings” volumes, which depend on the volumes of wastewater collected, which in turn depend on water withdrawal, would not be possible if the water withdrawal volume was not feasible to start with.

A last scenario where climate change causes more unpredictable precipitation, resulting in prevalence of drought is also modeled. This scenario models the case where total water withdrawal for municipal, industrial, and agricultural purposes is 72,000 MCM. In the drought scenario, water reuse for non-potable purpose is practiced in all countries. In addition, a campaign to rehabilitate 100% of the irrigated areas and to improve agronomic practice is in place. Seawater desalination is slated to provide 50% of the municipal water demand within 160 km from the coast. The rest of the conditions are the same as in the 2050 baseline model. The additional water reuse and desalination can contribute approximately 17,000 MCM of water “saving”. As is the case in the 2050 baseline, the volume from reuse and desalination is larger than that from efficiency improvements.

Table 16. Approximate water savings and total net present cost under several hypothetical scenarios. All volumes are in MCM.

	Near-term (MCM)	2050 Baseline (MCM)	2050 Demand-based (MCM)	2050 Drought (MCM)
Water demand			180,000	
Water withdrawal	103,000	103,000	130,000	72,000
Locations	[a]	Sections 2–6	Sections 2–6	[b]
NRW reduction	1,000	5,000	^4%	4,000
Muni non-potable	3,000	8,000	^6%	7,000
Industrial	200	2,000	^2%	2,000
Irrigation efficiency	6,000	7,000	^5%	10,000
Drainage reuse	*	*2,000	^*1%	*2,000
Brackish desal	2,000	2,000	^1%	2,000
Seawater desal	1,000	4,000	^3%	4,000
Total reuse	3,000	12,000	^9%	11,000
Total desalination	3,000	6,000	^4%	6,000
Total efficiency improvements (NRW & irrigation)	7,000	12,000	^9%	14,000
NPC (USD)	>7 billion	20–80 billion	30–110 billion	20–80 billion

[a,b] Any deviation in location and implementation scope from those described in Sections 2–6 is described in the current section.

^The "savings" are given in % of the total demand of 180,000 MCM as this model requires a volume of water withdrawal, and consequently volume of water "savings" that may not be realistic.

*The volume indicated is for new, additional drainage water reuse. It does not include the 11,900 MCM irrigation drainage water reuse currently practiced by Egypt.

2.7.3. Likely tradeoffs

A tradeoff in successful contribution of water reuse and desalination to water demand is the energy requirement of the treatment methods. Seawater desalination is particularly energy intensive. The calculation indicates that for Egypt, the electricity used for water reuse and desalination alone, not including electricity for basic water treatment and sanitation, can be 6 to 16% of the national electricity generation capacity at 2050 (the electricity generation capacity is estimated to double in size between 2019 and 2050). Because the extent of water reuse and desalination is significantly less in other countries and because there is no information on the electricity generation capacity in the Nile Basin portion of many countries, the percent of electricity consumption in other countries is not calculated in this project.

Reusing irrigation drainage water could result in the accumulation of salt in soils that can degrade soil quality. The irrigation drainage water or water from municipal water reuse for non-potable purpose may also contain contaminants such as pharmaceuticals or medicine that household dispose of in waste water, these components are potentially be challenging to be degraded/removed and might have a negative effect on aquatic life.

2.7.4. Estimate of capital investment

The estimated net present cost is listed in the individual sections. An additional method of analysis was conducted in which the annual cost (combined capital and O&M) from 2021 to 2050 for the “extra/additional” water resources development (NRW reduction, municipal water reuse to non-potable, irrigation improvements, and desalination) was calculated as a percentage of the “projected” GDP of the same period (Figure 13). The “projected” GDP was in turn calculated assuming GDP growth of 3% per annum from 2019 to 2050. Of course, these estimates could be far-off from the actual GDP growth, since some countries had more than 10% growth over the last decade (e.g., Ethiopia) while some countries could possibly see contraction due to pandemics and climate change. Nevertheless, such estimate helps give an illustration of the magnitude of the cost.

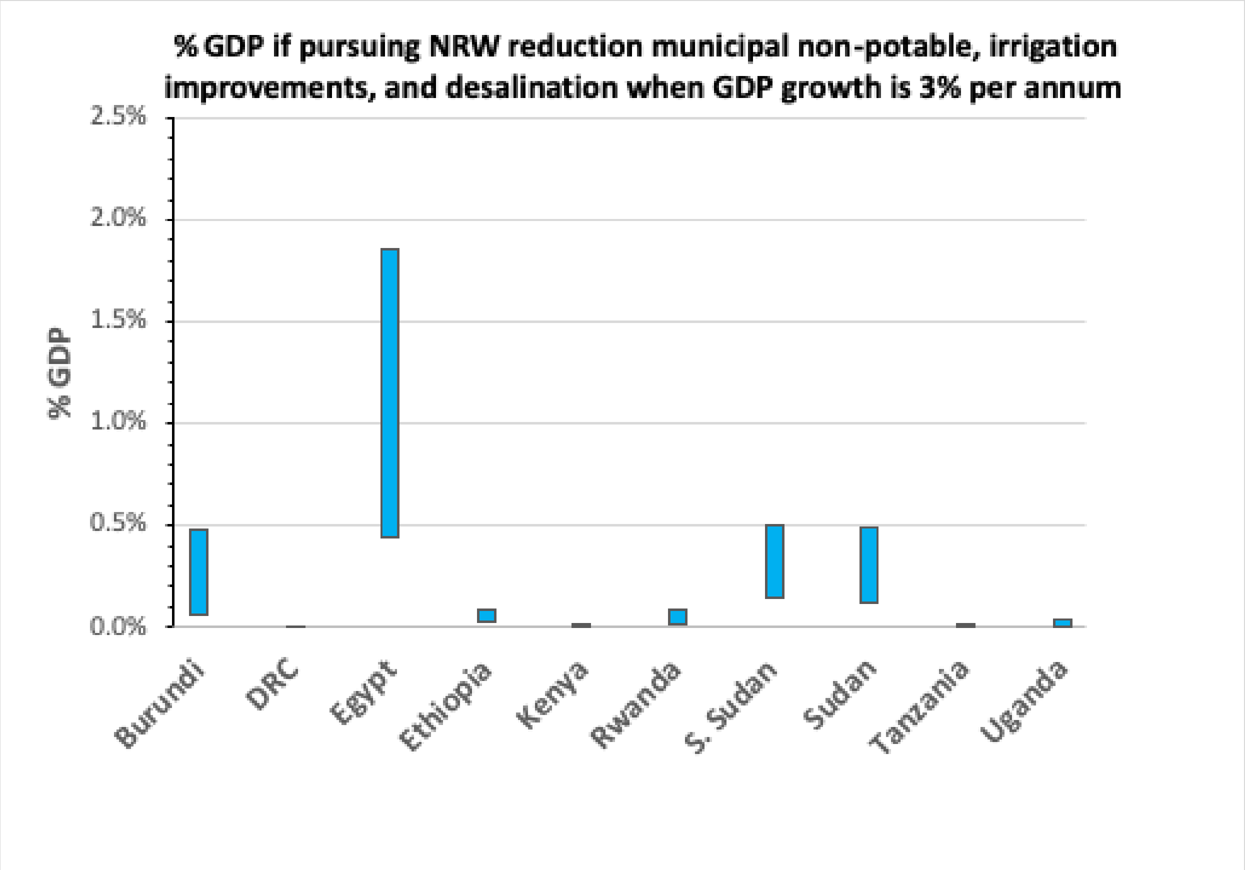

Figure 17. Average % GDP of each Nile Basin country needed for water reuse and desalination.

In an analysis for the World Bank, Hutton and Varughese [37] determined that Sub Saharan Africa and Northern Africa will need to spend 2% and 0.5%, respectively, of their GDP to achieve the United Nations Sustainable Development Goal (SDG) targets 6.1 (drinking water) and 6.2 (sanitation and hygiene) by 2030. Since development of the sanitation sector is essential for the ability to collect wastewater for water reuse, a rough estimate of the total water sector expenditure can be made, by adding the percentages from the current study with those from the World Bank study. This rough exercise suggests that all Nile Basin countries might end up spending approximately 2% of GDP on water resources. For Nile Basin countries that are in the Sub-Saharan region that are not water scarce but need to develop their municipal and irrigation systems, most of the expenditure from 2020 to 2050 would likely be on basic sanitation and wastewater collection, as well as efficiency improvements. For the arid region in the north that currently has a more developed sanitation and irrigation systems, most of the expenditure needed from 2020 to 2050 would be on efficiency improvements, reuse, and desalination, though the basic sanitation system also still need investment. It should be noted that this rough analysis covers some minimal desalination outside of the Nile Basin in Kenya and Tanzania, but does not include the water reuse sector outside of the basin.

2.8. Conclusions/Summary/Discussion

Water reuse and desalination can help fill the gap in water supply for Nile Basin countries. Given the large projected increase in demand, water reuse and desalination in isolation cannot fill the entire gap. Water reuse and desalination, in conjunction with demand management through improvements in the efficiency of irrigation and municipal water systems, will be necessary to ensure sufficient water in the future.

Appendix A. Municipal water reuse – Relation between water saving, NRW, and other losses.

The municipal water demands for 2019 and 2050 were based on data and projections that NBI provided in August 2019 under the scenario of annual GDP growth of 3.0% and water price growth of 0.5%. Data on annual precipitation and proximity to agricultural lands that can use any municipal water treated for reuse were researched and tabulated in the excel file submitted to NBI. If a region has precipitation below 1,000 mm annually or has been reported to face water shortage problem, then the region is rated to have a potential demand or need for municipal water reuse. The % potential demand is multiplied or pro-rated with the % wastewater collection as well as the % NRW of the country to determine how much wastewater can actually be collected for reuse. Similar procedure was used for municipal water reuse for potable purpose.

The following explanation describes the calculation of the % of water withdrawal that would eventually being delivered as recycled water after being going through the municipal water cycle. Consider the case of where 100 m^3 of treated water is produced, in this case the actual water delivered to the end-user is (Volume exiting treatment plant)*(100-NRW)%. Out of the water delivered to the end-user, a percentage is consumed and not returned to the local water cycle. This consumptive loss can be due to, e.g., water used in food cooking that is consumed and then partially lost through perspiration and respiration, or water used in gardening that is lost through evapotranspiration. The rest of the non-consumed water is either directly returned to the local water cycle as direct return flow to the environment (e.g., water spilled on the ground during activities such as gardening, car washing, etc. that is slowly percolated to groundwater or rivers) or returned to the municipal wastewater collection system. In most well-developed sanitation systems, the % that is returned to the municipal wastewater system is in the range of 80 to 90%.

During water treatment, a certain percentage of water is lost. A study of traditional water treatment in the Damietta governorate in Egypt showed that the % of water lost in treatment plant ranges from 6 to 24% [38]. Other treatment method, e.g., reverse osmosis (RO), typically has 15–25% of the original volume being rejected as concentrate. In the modeling in this project, an average of 25% loss in water treatment plant is assumed.

If the treated water is not used immediately, then often the water is stored in a reservoir, where the evaporative and seepage loss can be substantial. For example, studies in India show that evaporative and seepage loss can be on the order of 33% per year [39]. For municipal water reuse for non-potable purpose, we will assume some of the water might be used immediately, and use the estimate that the sum of reservoir and conveyance loss is 33%. A summary of the volume of recycled reaching its destination as a function of water withdrawal is shown in Equation (1).

Volume of recycled water reaching non-potable destination = Volume of water withdrawal * (1-NRW) * return flow * (1-treatment loss)* (1-sum of reservoir and conveyance loss)………Equation (1)

Using treatment plant loss = 25%, reservoir + conveyance loss = 33%, NRW = 5%, and return flow (return to wastewater collection) = 88%, the net recycled water that can be delivered to an irrigation scheme is 42% of the freshwater abstracted or withdrawn from a natural water source (river, groundwater, reservoir). Once the recycled water arrives at its intended destination, the recycled water enters into a separate water cycle where most of the water is consumed by the crop and lost through evapotranspiration. In other words, the recycled water for non-potable purpose can only be reused once. The fraction that is returned to the groundwater and surface water after can be accounted for in a hydrology model.

Municipal water for potable purpose

The precipitation criterion chosen for municipal water reuse is more stringent, with the annual precipitation to be below 500 mm for this type of reuse to be considered necessary. This is because municipal water reuse takes considerable institutional arrangement and expense, and it is generally expected that a country or region would not embark on this effort unless there is significant water scarcity, i.e., strong incentive.

In this scenario, the water that is not lost during conveyance, treatment, evapotranspiration, or NRW is theoretically cycled *indefinitely* within the municipal water cycle. Using the same values for losses detailed in the municipal water for non-potable purpose, the infinite cycle can be modeled as a mathematical expansion of equation (1). With the expansion, we can approximate the scope of municipal water reuse for potable purpose to be >60% in a highly efficient system where NRW is 5%. Note that this strictly engineering model was not done with full hydrological water balance, i.e., it does not include the loss to environmental return flow from seepage to the surface and groundwater system that would have augmented water supply.

In summary, though the water can be reused multiple times, overall the system will still require additional freshwater input from a river, groundwater, or the sea. The actual value derived from water reuse would also be lower in regions where evaporation from reservoirs and water treatment plants is more than the estimates used in the current model.

Appendix B. Methodology and assumptions in the estimate of the scope and cost of canal lining.

A discussion and calculation on irrigation canal lining is included because of NBI's interest in using this method to increase return flow. As seen in Figure 6, though canal lining can reduce seepage loss and improve water conveyance efficiency, not all the water 'saved" would end up in the drainage return flow. This is because there is still water loss through non-beneficial evapotranspiration, percolation losses, etc. The exact loss depends on the soil, hydrogeology, crop, among other factors.

To estimate the benefit of canal lining on irrigation drainage return flow it is assumed that out of the 30% conveyance loss calculated for several countries (provided by NBI), 50% is seepage loss, with the other 50% being evaporative loss. If we further assume that the liner (1) is effective in preventing 100% of the seepage loss in the drainage leg, and (2) only half of the saving by preventing seepage loss in the 'incoming' water makes it to the drainage leg, then the final water saved and available for drainage water reuse can be estimated as 15% of the total conveyance loss. Assuming 80% of the increased return to drainage is not too saline for drainage water reuse, then an additional 12% water savings can be achieved. These estimates might be too high since it assumes the same incoming water flow when liners are used. In actual operations, if the liner reduces seepage loss in the 'incoming' or water delivery irrigation canal, then less water is needed to be supplied (unless there is salt concern), and the farmer or irrigation official would likely respond by decreasing the incoming water flow, resulting in a smaller volume going into the drainage canal.

Recently a newspaper article announced that Egypt is implementing canal lining in the delta area. The actual estimate from the Egyptian government turns out to be almost twice of the estimated volume calculated in this model.

Two methods of cost calculations are presented. One is use an estimate by the World Bank that irrigation canal lining adds 30–40% to the total cost of the irrigation system [40]. However, the actual irrigation cost or investment can vary significantly from site to site depending on the nature of the crops, source of water, and topographical, pedological, and geological conditions

[41]. Values obtained from the literature are tabulated in the excel spreadsheet and the lower and upper values for canal lining are used in estimating the cost.

Appendix C. Scenario, scope, and cost of water reuse and desalination based on estimated demands and water withdrawal

The scope of brackish water withdrawal depends on the available brackish water resource that can be realistically, sustainably used. The scope of seawater desalination is potentially infinite, though the option is expensive and can contribute to marine pollution if many countries practice the option. The scope of water reuse depends on the volume of wastewater collected or drainage water available, which in turns depends on the water withdrawal volume, which is a function of both demand and supply.

In the current project, an iterative process is used to help account for the need to account for both water withdrawal and demand in sizing water reuse facilities. In the first iteration, a demand-based scenario is model. The scenario uses the 2050 municipal and irrigation water demands provided by NBI. For the 2050 industrial water demand, it uses values that are twice the 2019 industrial water withdrawal listed in AQUA STAT. The small error due to the industrial demand in AQUASTAT actually represent the industrial demand of the entire country, rather than the portion in the Nile Basin, is considered negligible compared to the much larger irrigation demand. Summing the demands in the different sectors yielded a total water demand of 180,000 MCM. The model then assumes water withdrawal is not limited to estimate the water withdrawal, reuse, and desalination that are necessary to satisfy the high demand.

Though the demand-based, water abundant scenarios could be informative for planners interested to know the extent water reuse and desalination could supply additional water, it could over-estimate the scope and cost of water savings. This is because the water saving and the infrastructure cost could have been calculated from a volume of wastewater that could never have been collected because the model resulted in a water withdrawal that was too large and not realistic to start with.

Consequently, iterations where the calculations start with alternately with total water demand and withdrawal volumes are necessary. In the second iteration, a 2050 baseline model is conducted using the 2019 water withdrawal and the % water savings from the demand-based model as starting points. The 2019 withdrawal value is deemed the “baseline” because the 2019 demand was mostly being met. The sum of the 2019 municipal water and irrigation water withdrawals from NBI and 2019 industrial water demand from AQUASTAT equals 103,000 MCM. The municipal, industrial, and irrigation withdrawal of each country is adjusted to a smaller value that is pro-rated based on the 2050 demand data provided by NBI (the demand data that totaled 180,000 MCM).

Since the 2050 baseline exercise uses a likely more realistic total water withdrawal, the cost estimates it produces are likely more realistic. The net present cost shown in Sections 2 to 6 and the % GDP in Section 7 are derived from the 2050 baseline scenario. All the treatment methods are assumed to be invested over 20 years, except for the capital phase of NRW reduction (assumed to be carried out 10 years), and industrial water reuse (assumed to be invested over 30 years or continuously because industrial plants tend to adopt new technologies continuously). The net present cost is calculated using a discount rate of 8%, and an inflation of 2%.

One other scenario, drought, is also modeled. In this scenario, there is only 72,000 MCM water available for withdrawal (75% of the 2019 withdrawal). In this case, adjustment in the extent of water reuse and desalination has to be made several times to arrive at a volume of reuse and desalination that are deemed realistic and yet still can help meet the demand.

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